R.T.
YILDIZ TECHNICAL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

THE EFFECT OF HIGH VELOCITY STIRRED MOLTEN ALUMINUM ON THE CASTABILITY AND MICROSTRUCTURE

VEDAT TOPALOĞLU

MSc. THESIS
DEPARTMENT OF METALLURGICAL AND MATERIALS ENGINEERING
PROGRAMME OF EXTRACTIVE METALLURGY

SUPERVISOR
PROF. DR. AHMET EKERİM

ISTANBUL, 2012

R.T.

YILDIZ TECHNICAL UNIVERSITY

GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

THE EFFECT OF HIGH VELOCITY STIRRED MOLTEN ALUMINUM ON THE CASTABILITY AND MICROSTRUCTURE

A thesis submitted by Vedat TOPALOĞLU in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE** is approved by the committee on 27.09.12 in Metallurgical and Materials Engineering Department, Extractive Metallurgy Programme.

Thesis Supervisor

Prof. Dr. Ahmet Ekerim

Yildiz Technical University

Co- supervisor

Assist. Prof. Dr. Derya Dışpınar

Istanbul University

Examining Committee Members

Prof. Dr. Ahmet Ekerim

Yıldız Technical University ________________________

Prof. Dr. Mustafa Çiğdem

Yıldız Technical University ________________________

Assist. Prof. Dr. Derya Dışpınar

Istanbul University ________________________

ACKNOWLEDGMENTS

I wrote this thesis in Aachen during my Erasmus – Student Exchange Program 2011-2012. Thank to my home university - Yildiz Technical University, especially Metallurgical and Materials Engineering Department for supporting me to come RWTH Aachen University.

I would like to express my grateful thanks to RWTH Aachen Foundry Institute Family, especially Dr. Matthias Bünck and MSc. Sebastian Tewes for providing opportunity to improve my technical skills and for their supports, supervision, assistance, and guidance on the all aspects. 'Vielen Dank für Alles!'

I would like to thank to Prof. Dr. Ahmet Ekerim – my supervisor from Yildiz Technical University and Dr. Derya Dispinar – my co-supervisor from Istanbul University for their helps and supports, inspirations to bring this thesis into action in Germany.
And my dear friends thank you all for your supports, best wishes, motivations and everything that you did for me from kilometers away.

Finally, my mom, my dad and my sister, and my whole family; there are no words to express my feelings for your never-ending support and belief in me. Thanks to God for that i have unique family like you. I would like to thank to my family in my language: 'Sizin gibi bir aileye sahip olduğum için dünyanın en şanslı insanıyım!'.

September, 2012

Vedat TOPALOĞLU

TABLE OF CONTENTS

Page

LIST OF SYMBOLS

F	Form filling factor
x	Gap measurement of the Bolt test specimen
d	Diameter of the Bolt test cylinders
R	Semi diameter of the Bolt test cylinders
λ_e	Dendrite arm spacing value
l_d	Length of the dendrite
n_d	Number of the dendrite arms
V	Magnification of the microscope

LIST OF ABBREVIATIONS

AMS	Alloy memory structure
IADS	International Alloy Designation System
DAS	Dendrite Arm Spacing
AA	Aluminum Association
ASTM	American Society for Testing and Materials
ANSI	American National Standards Institute
UNS	Unified Numbering System
RPT	Reduced Pressure Test
DI	Density Index

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

THE EFFECT OF HIGH VELOCITY STIRRED MOLTEN ALUMINUM ON THE CASTABILITY AND MICROSTRUCTURE

Vedat TOPALOĞLU

Department of Metallurgical and Materials Engineering

MSc. Thesis

Supervisor: Prof. Dr. Ahmet Ekerim

Co-supervisor: Assist. Prof. Dr. Derya Dışpınar

The effect of high velocity stirring (the AMS technique) on castability of A356 and A380 alloys was investigated. The experiments were carried out with different applications such as addition of Micro100 (0,1 and 1wt%), pouring at different temperatures (between 600 and 750 ˚C) and mechanical stirring (3000 rpm) to understand the effects of these parameters on the form filling capability and fluidity, hence castability. For spiral tests, sand spiral molds were produced with core shooting machine (cold box) and used for A356, A356 AMS and A380 alloys.

For Bolt tests, bolt die was used but it was integrated to tilt casting machine. The effect of melt superheat clearly increased the fluidity. However, the effects of Micro100 treatment on fluidity were not observed. Effect of the AMS method on the fluidity of A356 alloy was not seen due to the high scatter of the results. There was no significant difference in the microstructure (i.e. DAS) between the conventional and AMS techniques.

Keywords: Al-Si alloys, A356, A380, Castability, Fluidity, AMS

YILDIZ TECHNICAL UNIVERSITY

GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

ÖZET

ERGİMİŞ ALUMİNYUMUN YÜKSEK HIZDA KARIŞTIRILMASININ DÖKÜLEBİLİRLİK VE MİKROYAPI ÜZERİNDEKİ ETKİSİ

Vedat TOPALOĞLU

Metalurji ve Malzeme Mühendisliği Anabilim Dalı

Yüksek Lisans Tezi

Tez Danışmanı: Prof. Dr. Ahmet Ekerim

Eş Danışman: Yard. Doç. Dr. Derya Dışpınar

Yüksek hızda karıştırmanın (AMS tekniği) dökülebilirlik üzerine etkisi A356 ve A380 alaşımları üzerinde araştırılmıştır. Deneysel çalışmalar, akışkanlık, kalıp doldurma kabiliyeti ve dolayısıyla dökülebilirlik üzerinde etkili olan parametreleri açıklayabilecek şekilde Mikro100 (0,1 and 1ağ%) ekleme, değişik sıcaklıklarda döküm ve mekanik karıştırma (3000 rpm) çeşitli uygulamalar içermektedir.

Spiral testler için otomatik makine ile cold box olarak üretilen kum kalıplar kullanılmış ve A356, A356 AMS ve A380 alaşımları dökülmüştür. Bolt testleri için ise tilt döküm makinasına entegre edilmiş bolt metal kalıp kullanılmıştır. Döküm sıcaklığının artırılmasının akışkanlığı artırıcı yöndeki etkisi açıkça görülmüş, ancak Micro100 ilavesinin akışkanlık üzerine etkisi görülememiştir. AMS tekniğinin etkisi A356 alaşımı üzerinde incelenmiş ancak deneysel sonuçların standart sapması sağlıklı bir yorum yapılmasına engel olmuştur. Mikroyapısal incelemelerde (DAS), konvansiyonel ve AMS uygulanmış alaşımın mikroyapısında önemli bir fark gözlemlenmemiştir.

Anahtar Kelimeler: Al-Si alaşımları, A356, A380, Dökülebilirlik, Akışkanlık, AMS

YILDIZ TEKNİK ÜNİVERSİTESİ

FEN BİLİMLERİ ENSTİTÜSÜ

CHAPTER 1

INTRODUCTION

1.1 Literature Review

Aluminum alloys are used in many applications and industries over the decades. The largest market for aluminum alloys is the automotive industry and also they are widely used in other applications such as marine engines and aerospace [1].

Casting parts can be produced with variable processes to achieve desired properties such as mechanical and microstructural.

The testing devices for the castability analyses were selected to be as: Casting spiral for the fluidity (sand mold), Bolt test specimen for the form filling behavior.

The materials were chosen as the most used alloys commercially, A356 and A380. On the other hand the Micro100 master alloy was used to determining effect of oxides on fluidity and form filling capability.

The castability of alloys is explained as their ability to be cast with a given shape with a given process [2]. Alloy dependent phenomena that determine castability are fluidity, solidification, oxide formation, hot tearing and porosity [3].

The fluidity and the form filling capability properties are the key topics in this thesis. The term "fluidity" in the foundry is used to explain the distance a molten metal can flow in a mold of a constant cross-sectional area before it solidifies. The fluidity plays an important role on the castability and the final properties [2].

The properties of aluminum alloys, casting methods, the effective parameters and phenomena on fluidity such as solidification, melt cleanliness, melt superheat, composition, mold characteristics, porosity and oxide formations were explained, and then experiments will be represented.

During the experiments, the melt superheat, Micro100 addition and the AMS technique (as a high velocity stirring) was applied and the effect of these applications on the fluidity and the form filling capability of A356 and A380 alloys were investigated and pulled out together with the AMS effect.

1.2 Aim of the Thesis

The objective of this thesis work is to carry out a study on the castability and microstructure of high velocity stirred molten aluminum. Therefore the thesis should find a result that helps to understand the effect of AMS-stirring which should improve the properties of existing aluminum alloys according to literature.

1.3 Hypothesis

The AMS technique is an innovative melt treatment technique that includes stirring the melt using a rotating electromagnetic field and it was also patented by BergerConsult e.k. With the effect of electromagnetical field finer grains, lower porosity levels can be achieved. Furthermore these effects can be repeatable in case of remelting and casting situations. That is why it is called as 'Alloy Memory Structure (AMS)'. However tool costs of electromagnetical systems and also stirring problems and inclusions which can't be eliminated such as bifilms, are disadvantages of electromagnetical processes. With an idea of alloy memory structure can be created with high velocity mechanical stirring, this study is implemented [27].

CHAPTER 2

STATE OF THE ART

2.1 Aluminum Alloys

Alloy composition determines the potential for achieving physical and mechanical properties. For this purpose, they are designed to produce characteristics which include castability, desired performance capabilities [4].

Typical specialties of aluminum and its alloys are: Light weight, strength, linear expansion, excellent machinability, formability, high thermal/electrical conductivity, high corrosion resistance, high ductility non-magneticity, and zero-toxicity.

Classification of aluminum alloys is established by the International Alloy Designation System (IADS) and explained as wrought and cast alloys. In this thesis, researches are based on aluminum cast alloys [5, 6].

Nowadays aluminum alloys finds very large usage area in different applications (e.g., aerospace, automotive, etc.). Patents which are based on aluminum alloys issued for thousands of alloy compositions. However most of them contain a relatively limited number of alloying elements [6, 7].

2.1.1 Alloying Elements

All alloying elements can be explained in three principal groups: basic alloying elements, dopants and impurities. On the other hand, same elements can play different roles in alloys, and it depends on the alloys character.

For all alloy combinations, only four basic elements are used: metals; zinc, magnesium and copper; and semiconductor silicon. These elements are called basic or principal, because they are used in relatively large amounts in aluminum alloys to define their microstructure and properties. For example, the Mg content in Al-Si alloys with 7%Si or 9%Si is only ≈ 0, 3%, that means only this small amount is enough to define the alloy's strength. In this sense, Mg is principal alloy in Al-Si alloys. On the other hand, in Al-Si alloys, Mn can be present 0.5% or more, but it shows in small additions the effect that neutralizes the harmful influence of iron-principal role.

Relatively large amounts of principal alloying can be introduced because they are characterized by considerable solubility in (Al). Only seven elements can exceed maximum solubility 1% in (Al), and they are; magnesium, copper, silicon, lithium, manganese, germanium and silver [8].

Effects of alloying elements can be explained in common usage as following;

Antimony is used to refine the Al-Si eutectic at concentration levels ≈0.10%. This element's effect is essentially modification, but a distinctly lamellar eutectic rather than fine fibrous form results. Antimony's effect (altering the eutectic structure) is depends on an absence of phosphorus and on an adequately rapid rate of solidification. On the other side, antimony reacts with either sodium or strontium to form coarse intermetallics that affect negatively the castability and metallurgical structure [7,8].

Beryllium addition of only a few ppm is effective in reducing oxidation losses and associated inclusions in Mg-containing compositions. Concentrations that >0.04%, beryllium affects the composition and form of iron-containing intermetallics and improves strength and ductility [7].

Bismuth addition at concentrations greater than 0.1% improves the machinability of cast aluminum alloys [7].

Boron reacts with other metals to form borides, such as AlB_2 , TiB_2 . Titanium boride forms stable nucleation sites that interact with active grain-refining phases such as Ti-Al_3 for grain refinement. Reducing tool life in machining operations and forming coarse or agglomerated inclusions with detrimental effects on mechanical properties and ductility are effects of metallic borides. Borides also contribute to sludging, the precipitation of intermetallics from liquid solution in furnaces and toughing [7].

Cadmium addition at concentrations higher than 0.1% improves machinability.

Calcium is a weak Al-Si eutectic modifier and it increases hydrogen solubility. At trace concentration levels, it is often responsible for casting porosity. It is also adversely affects ductility in Al-Mg alloys at greater than 0.005% concentration levels [7, 8].

Chromium additions are made in low concentrations to room-temperature aging and thermally unstable compositions in which germination and grain growth are known to occur. Typically form of Chromium is $CrAl_7$ that shows extremely limited solid-state solubility and useful in suppressing grain-growth tendencies. In certain alloys, chromium improves corrosion resistance and increases quench sensitivity at higher concentrations [7].

Copper improves strength and hardness in the as-cast and heat treated conditions. 4 to 5.5% Cu included alloys respond most strongly to thermal treatment and display relatively improved casting properties. Generally Copper reduces corrosion resistance and increases stress-corrosion susceptibility in specific compositions and material conditions. Contrarily, low concentrations of copper in Al-Zn alloys inhibit stress corrosion. On the other hand, copper reduces hot tear resistance and increases the potential for interdendritic shrinkage [7].

Iron improves hot-tear resistance, decreases the tendency for die sticking or soldering in die casting and ductility. It reacts to form intermetallic phases, the most common which are $FeAl_3$, $FeMnAl_6$ and α-AlFeSi. These insoluble phases are responsible for improvements in strength, especially at elevated temperature, but also the embrittlement of the microstructure. Increasing iron content also increases intermetallic phases and it adversely affects casting considerations such as feeding characteristics [7, 8].

Lead improves machinability when it is used at concentrations greater than 0.1%. [7]

Magnesium is used for strength and hardness development in heat treated Al-Si alloys and more complex Al-Si alloys which include copper, nickel etc. $MgSi_2$ plays a hardener role and displays a useful solubility limit corresponding to approximately 0.7% Mg, more than these values, there is no further strengthening occurs or matrix softening takes place. So 0.4 to 0.7% Mg range is used for common high-strength Al-Si alloys. Binary Al-Mg alloys are generally used in applications which are requiring a bright surface finish, excellent response to chemical finishing, corrosion resistance, and attractive combinations of strength and ductility. Common composition range is 7-10% Mg and more than 7%Mg are heat treatable [7, 8].

Manganese is normally called as an impurity in casting compositions and controlled to low levels in most gravity cast compositions. I is very important element in work-hardened wrought alloys through which secondary foundry compositions may contain higher manganese levels. In absence of work hardening, manganese offers no significant benefits in cast aluminum [7].

Mercury is used in compositions that provide cathodic protection as sacrificial anodes, especially in marine environments [7].

Nickel is generally used with copper to enhance elevated-temperature properties and also reduces coefficient of thermal expansion [7].

Phosphorus is used for refining primary silicon phase formation in hypereutectic Al-Si alloys when it is in AlP_3 form. At ppm concentrations, phosphorus coarsens the eutectic structure in hypoeutectic Al-Si alloys and reduces the effectiveness of common eutectic modifiers, sodium and strontium [7, 8].

Silicon has an important role that is the improvement of casting characteristics in aluminum alloys. Addition of Si dramatically improves fluidity, hot tear resistance and feeding characteristics. In most common aluminum alloys, silicon plays major role. Commercial alloys span the hypoeutectic and hypereutectic ranges up to %30 Si.

Increasing Si content improves fluidity and form filling capability. Al-Si alloys are typically more resistant to solidification cracking and display excellent castability and feeding characteristics [7, 8].

Silver is used at concentrations of 0.5 to 1.0% in only limited range of Al-Cu premium strength alloys. Silver promotes to precipitation and stress corrosion resistance [7].

Sodium modifies the Al-Si eutectic. Sodium can be effective at concentrations of 0.01% when there is no phosphorus. Sodium is used with phosphorus to reduce its effectiveness on refining the primary Si phase. Less than 0.005% Sodium is embrittling in Al-Mg alloys.

In molten aluminum, sodium is rapidly lost and because of its high vapor pressure, so the modifying effects are transient. During the modification, sodium must be added periodically to maintain modification levels.

Sodium addition method is also important, because sodium increases surface tension and can increase hydrogen content. Over-modification causes increasing misrun tendencies in gravity casting. Sodium provides effective Al-Si eutectic modification under all solidification conditions [7, 8].

Strontium modifies Al-Si eutectic too. It shows its effect in very small amounts and common range of strontium is 0.008 to 0.04%. In higher solidification ranges lower concentrations can be used. Higher concentrations of strontium cause casting porosity; also it adversely affects degassing efficiency [7, 8].

Tin improves antifriction characteristics and is therefore useful in bearing applications. It can be used up to 25% in casting alloys. Also addition of tin improves machinability [7].

Titanium is used for grain refining in aluminum casting alloys, often in combination with smaller amounts of boron. Most operable phase is $TiAl_3$ with lattice spacing closely matched to that of aluminum. Titanium excess of the stoichiometry of TiB2 is necessary for effective grain refinement. It is often used for reducing cracking tendencies in hot-short compositions [7, 8].

Zinc has no significant benefits in aluminum casting. Accompanied by the addition of copper and/or magnesium, however zinc results in attractive heat treatable or naturally aging compositions [7, 8].

2.1.2 Aluminum Casting Alloys

Casting alloys and wrought alloys have parallel compositions in many respects. Desired properties and hardening can be reached by the addition of alloying elements and heat treatment. Without significant role of work hardening, the use on purposes of some alloying elements can show difference in casting and wrought alloys [4].

Castability is the most important consideration of difference between wrought and casting aluminum alloy compositions. Therefore wrought products have simple round and rectangular cross sections by casting processes. In contrast with wrought alloys, casting processes can minimize the depth and maximize the uniformity of the solidification front, solidification in engineered castings with complex shapes and variable rates of solidification present different demands on alloy solidification behavior.

Cracking tendencies during and after solidification and internal shrinkage dictate alloys for shape casting can be minimized [4].

Castability is not defined clearly. It can be explained with the suitability of a composition for solidification in specific process to produce defect-free sound castings.

For example, castability for gravity casting is related to fluidity as the measure of mold-filling capability that explains hot cracking tendency and feeding characteristics. Result of these the flow of metal during the solidification to avoid or minimize the formation of shrinkage voids can be promoted [4].

Fluidity is complex function that can be quantified and mathematically defined. The strongest effect on fluidity is temperature above the liquidus and degree of superheat. Alloy compositions at conventional pouring temperatures are those of eutectic or near eutectic are more fluid.

Usually in narrow solidus-liquidus ranges and in greater percent liquid at the eutectic temperature, improved feeding characteristics are seen [4].

Element effects on elevated temperature strength and on solidification rate dominate the tendency for solidification and post solidification cracking.

The casting alloys used in the greatest volumes contain silicon in excess of that of most wrought alloys. Solidification results in shaped casting are improved by fluidity, elevated-temperature resistance to cracking, and feeding characteristics that sufficient amounts of silicon impart. The optimal silicon concentration depends on the casting process. For example higher heat flux characterized processes use alloys with higher silicon contents since fluidity is improved. Result of this, feeding, shrinkage, solidification zones of process are controlled. In general, castability is associated with alloys of reduced solidification range. On the other hand, there are too many common foundry alloys that do not rely on silicon for casting performance [4, 9].

2.1.2.1 Specifications

Numerous specifications and standards are relevant with aluminum castings. In United States, Aluminum Association (AA) registers alloy chemistry and thermal practices. Procurement specifications and standards are developed and maintained by, among others, ASTM and Military and Federal agencies. Procurement methods are usually not referenced. These methods are radiographic and penetrant inspection, test procedures for determination of chemical, mechanical, and physical properties, and other required procedures. In many cases, purchaser can write specifications for specific part or applications.

Aluminum alloy chemistry specifications include the effects of elements;

- Major alloying elements define the ranges of elements that control castability and property development.
- Minor alloying elements controls solidification behavior, modify structures, refine primary phases, refine grain size and form, reduce oxidation, adjust phase formation.
- Impurity elements influence castability and the form of insoluble phases that at times limit or promote desired properties.
- Desired properties and microstructures are reached by these elements that are used in certain limits.

2.1.2.2 Alloy Designations

Designation systems and alloy nomenclature for aluminum casting alloys are not internationally standardized. Many nations have developed and published their own standards. Also some firms have their own standards. These nomenclatures are typically referenced by government agencies and technical associations and societies

The Aluminum Association (AA) Casting Alloy Designation System and temper systems are the most common system in United States. This designation system uses four numeric digits. The meanings digits are;

- First digit; principal alloy constituent(s)
- Second and third digits; specific alloy designation (number has no significance but is unique)
- Fourth digit; casting or ingot designation.

Also in this system, preceding letters can be used for expanding the numerical designations range. For example: 356.0 and A356.0.

Following Categories of this designation are defined:

- 1xx.x, pure aluminum (99.00% or greater)
- 2xx.x, aluminum-copper alloys
- 3xx.x, aluminum-silicon _ copper and/or magnesium
- 4xx.x, aluminum-silicon
- 5xx.x, aluminum-magnesium
- 6xx.x, unused series

- 7xx.x, aluminum-zinc
- 8xx.x, aluminum-tin
- 9xx.x, aluminum _ other elements

Forth digit (the right of the decimal point) explains product form;

- 0 denotes castings
- 1 denotes standard ingot
- Denotes ingot having composition ranges narrower but within those of standard ingot.

Designations in the form xxx.1 and xxx.2 include the composition of specific alloys in remelt ingot form suitable for foundry use. Designations in the form xxx.0 in all cases define composition limits applicable to castings.

Same alloys usually have same alloying element and impurity limits for castings. But if the ingot is remelted, iron and silicon contents tend to increase magnesium content decreases. As a result, ingot chemistry for some alloys may be different from those specified for castings. ANSI (American National Standards Institute) lists the alloy designations without fourth digit.

Aluminum Association Casting Temper Designation System uses letters and numbers to define the major types of thermal treatments applicable to engineered castings:

- F, as-cast
- O, annealed
- T4, solution treated and aged
- T5, precipitation hardened
- T6, solution heat treated, quenched, and precipitation hardened
- T7, solution heat treated, quenched, and overaged.

For example, a 356.0 alloy casting that has been solution heat treated, quenched and artificially aged is shown as 356.0-T6. Also to indicate the system 'P' is used after temper designation. (e.g., T4P)

The UNS (Unified Numbering System) Alloy Designation System is another widely known alloy classification system. Covering all metallic alloy systems is the advantage of this system. This system is essentially an adaptation of the Aluminum Association alloy designation system to fit the UNS format. UNS numbers are includes the three digits to the left of the decimal point in the AA system and adding A9 (for aluminum alloys) and a digit reflecting the letter prefix to the alloy designation. Alloys without a letter prefix, the next numeric digit after A9 is a 0, with A prefix; 1, with B prefix; 2 and so forth.

For example 356.0 becomes A90356; A356.0 becomes A91356; C356.0 becomes A93356 in the UNS Alloy Designation System.

This system is not widely used for aluminum alloys as certain other classes of alloys.

2.1.3 Al-Si Alloys

More than %90 of all castings constitutes Al-Si alloys that comprise 4% to 22% Si as a major alloying element. Silicon offers excellent castability, fluidity, crack resistance, corrosion resistance. These mechanical, corrosion and casting properties of Al-Si alloys ease of their use in industry. All these properties are defined by the chemical composition and microstructure. Conditions of melting, casting and heat treatment define microstructure [4, 9].

Aluminum-silicon alloys exhibit low specific gravity and coefficients of thermal expansion. In hypereutectic aluminum-silicon alloys, refinement of the pro-eutectic silicon phase by phosphorus additions is essential for casting and product performance [4].

According to binary Al-Si phase diagram the alloy compositions can be divided into three categories; hypoeutectic (4 to 9% Si), hypereutectic (14 to 22% Si) or eutectic (10 to 13% Si). The upper limit (22% Si) is defined by the need to obtain at least the minimal level of plasticity because of brittle silicon phase. The lower limit is defined by the need to attain a relatively narrow solidification gap and, consequently, good alloy castability [9].

Main phases (α-Al solid solution and silicon crystals) and also the volume fractions and morphologies of components can attribute the properties of specific alloys [9, 10].

The Al-Si equilibrium diagram and microstructures of hypoeutectic, eutectic and hypereutectic alloys are given in Figure 2.1. These microstructures should be modified to perform good mechanical properties.

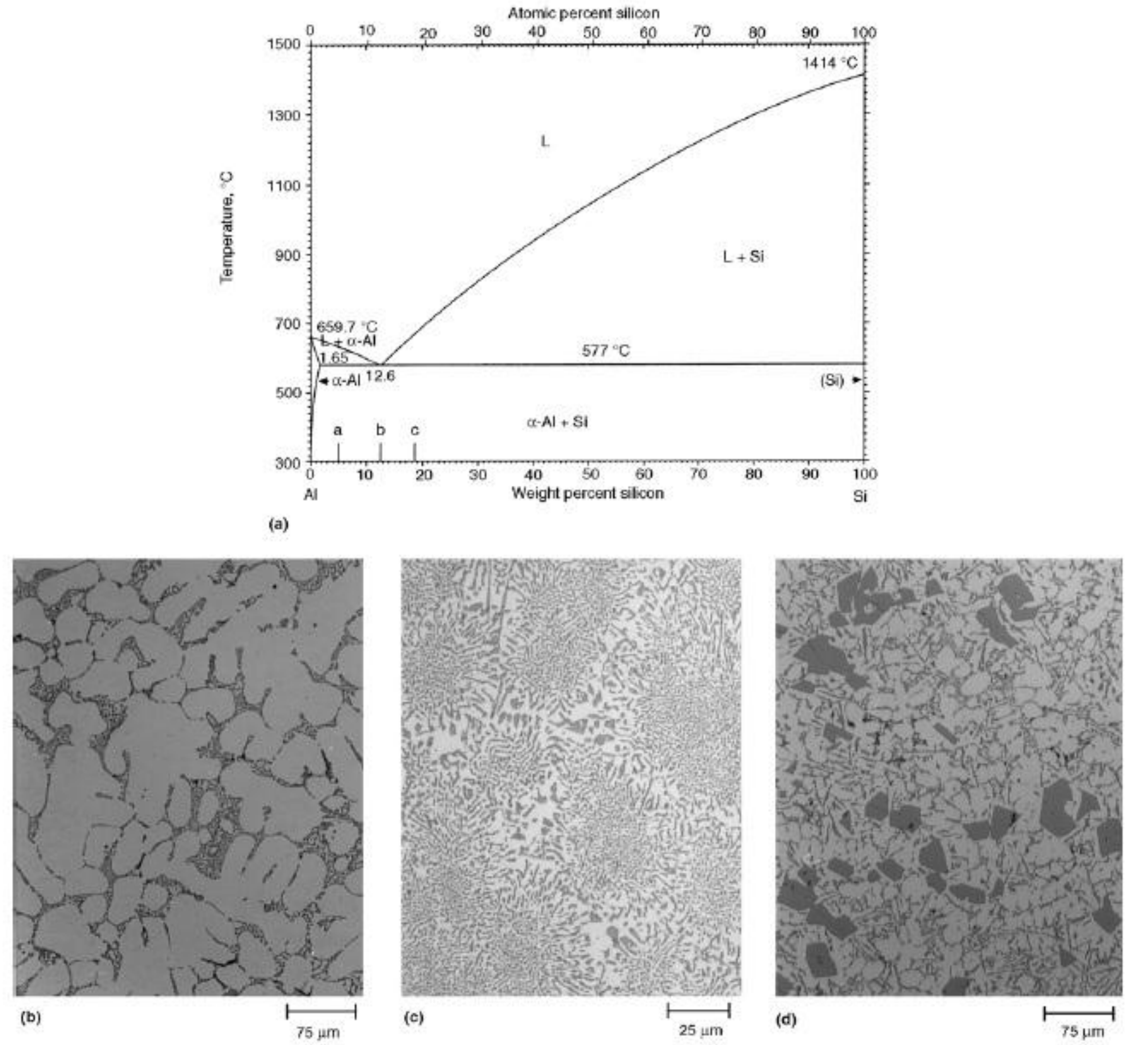


Figure 2.1 Commercial cast aluminum-silicon alloys. (a) Al-Si equilibrium diagram. (b) Microstructure of hypoeutectic alloy (1.65-12.6 wt% Si). 150. (c) Microstructure of eutectic alloy (12.6% Si) 400X (d) Microstructure of hypereutectic alloy (>12.6% Si). 150X [10]

Binary Al-Si alloys have low strength and poor machinability. Also they close to eutectic composition (11, 7% Si). The strength, ductility and castability of Al-Si hypoeutectic alloys can be improved by Al-Si eutectic modification. This can be achieved by controlled addition of sodium and/or strontium. In unmodified state, lamellar or acicular eutectic silicon well dispersed in the aluminum matrix. The polyhedral primary silicon particles are also observed frequently because of non-equilibrium cooling. Addition of small amounts of strontium (0.005% to 0.01% Sr) modifies partially the structure into both lamellar and fibrous eutectic. Concentrations of 0.02% Sr provides the full modification with a completely fibrous structure. End of this modification, the alloy becomes hypoeutectic alloy because aluminum dendrites appear more frequently in the microstructure [4, 9, 10].

2.1.3.1 Al-Si-Mg Alloys

Addition of magnesium to Al-Si alloys provides outstanding casting characteristics with excellent properties after heat treatment. It also provides corrosion resistance and a low level of thermal expansion is retained. The mechanical properties of several Al-Si-Mg alloys can reach the premium-strength range, while they are not as strong as high-strength Al-Cu and Al-Si-Cu alloys. Addition of beryllium improves strength and ductility by affecting the morphology and chemistry of the iron-containing intermetallic. On the other hand, eutectic modification procures higher strength, substantially increased elongation, improved casting properties. Magnesium concentration falls within range from 0.2% to 0.6% and very rarely exceeds 1%. This directly follows the Al-Si-Mg phase diagram (Figure 2.2). The lower limit is defined by the need sufficient dispersoid hardening due to precipitation of secondary phases β' and β'' (Mg_2Si). The upper limit is must ensure the relatively small volume fraction of Mg-bearing eutectic phases (e.g. Mg_2Si) in order to reach a required level of plasticity. Magnesium is the most effective alloying element on mechanical properties of aged Al-Si alloys (per 1% added).For this reason concentration limit of Mg is very narrow. The optimum Mg concentration depends on the other alloying elements and also the selected heat treatment process [4, 9].

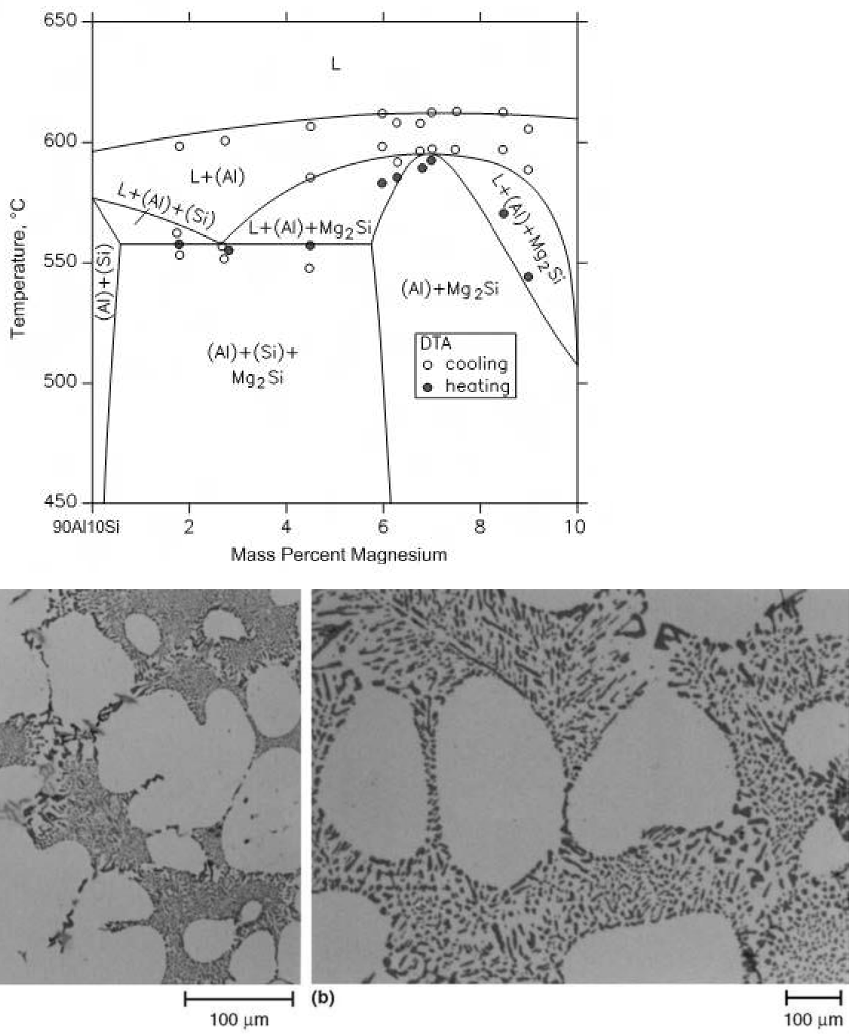


Figure 2.2 Al-Mg-Si phase diagram and Microstructures of AlSi7Mg (Alloy 356.0). Light microscope micrographs; etched with 1% HF. (a) As-cast modified, 150X. (b) As-cast modified, 750X [10, 11]

2.1.3.2 Al-Si-Cu Alloys

The most widely used aluminum casting alloys contains silicon and copper. Also they are used in very different amounts in alloys. Copper improves strength and machinability, and silicon improves castability and reduces hot shortness. For more complex castings and for permanent mold and die casting processes, alloys contain higher hypoeutectic concentrations of silicon are better suited.

Al-Si-Cu alloys that include less than 5.6% Cu are heat treatable, but more important alloys of this family contain magnesium. Heat treatment response is enhanced, leading to a very attractive range of properties including premium strength capabilities. The addition of Fe obtains the formation of intermetallics that improves the mechanical properties. The microstructure of A380 alloy and the effect of Fe addition is seen in Figure 2.3.

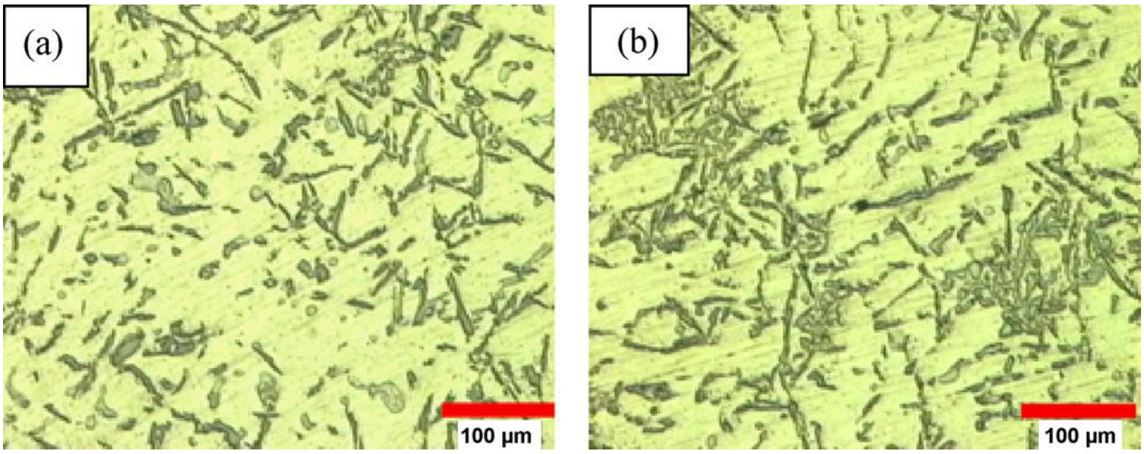


Figure 2.3 Microstructure of the alloys in the as-cast condition. (a) alloy A380, (b) A380 alloy with addition of 0.7Fe [12]

On the other hand many hypereutectic Al-Si alloys contain Cu that contributes to matrix hardening and elevated temperature strength. Modification with Sr is also used for these group alloys [4, 9].

2.1.4 Typical applications

2.1.4.1 Binary Al-Si Alloys

Alloys 443.0, 444.0, A444.0, 413.0 and A413.0 have specialties like low-density, weldability, corrosion resistance and pressure tightness. Sand and permanent mold binary Al-Si alloys are used in casting of automotive parts, domestic food and pump applications. Alloy 443.0 is especially used for strength needed parts. Alloy 444.0 and A444.0 shows high ductility and they are used in areas that need impact resistance. Alloy 413.0 and A413.0 are close to eutectic composition; because of this they have high fluidity. They can be used in large-area, thin-walled, high detailed or complex casting parts. Typical applications of binary Al-Si alloys are;

- Architectural panels and spandrels
- Outdoor lamp housings
- Lawn mower decks
- Outdoor grills
- Marine components
- Cooking utensils

- Parts used in food, dairy, and beverage processing
- Medical and dental equipment
- Electronic cabinet frames and components
- Tire molds
- Escalator and moving sidewalk tread plates and parts
- Highway railing posts

2.1.4.2 Al-Si-Mg Alloys

Alloy 356.0 and A356.0 have excellent casting characteristics and corrosion resistance. Also tensile and physical properties can be improved with heat treatment. As a result of this, these alloys are used in a great variety of applications including machinery, automotive, military and aerospace parts.

Alloy 357.0, A357.0, 358.0 and 359.0 display higher tensile properties that also can be improved by heat treatment. They are used in some special structural applications.

Alloy 365.0 and $AlMg_3Mn$ are results of developments in high integrity die casting and they contain low-iron and Mn.

Typical applications of Al-Si-Mg alloys are;

- Automotive space frames
- Automotive wheels
- Truck wheels
- Axle and differential housings
- Pump bodies
- Meter bodies
- Compressor bodies
- Intake manifolds
- Cylinder heads
- Dies for plastic injection molding
- Machine parts
- Truck and bus frames and chassis components
- Suspension saddles
- Aircraft pylons, canopies, flaps, speed-brakes hatch covers, and other fittings
- Impellers

- Wave guides
- Electronic cases
- Fuel pumps
- Missile bodies, fins, and other structural parts
- Industrial beam heads
- Brake cylinders
- Automobile cross members and suspension components

2.1.4.3 Al-Si-Cu Alloys

Alloy such as 308.0, 319.0, 360.0, 380.0 and 384.0 display good casting characteristics, higher strength and hardness with improved machinability, reduced ductility and lower corrosion resistance. These alloys and general-purpose alloys are often produced in the as-cast condition. Hardness, stability and machinability can be improved by artificial aging.

Typical applications of Al-Si-Cu alloys are;

- Machinery
- Transmission cases
- Engine blocks
- Gas meters and regulators
- Gear blocks
- Gear cases
- Fuel pumps
- Impellers
- Instrument cases
- Lawnmower decks
- Intake manifolds
- Cylinder heads
- Clutch housings
- Oil pans
- Outboard motor propellers, motor parts and housings
- Industrial beam heads
- Brake cylinders
- Automobile cross members and suspension components

2.1.4.4 Al-Si-Cu-Mg Alloys

Alloys such as 328.0, 333.0, 354.0, 355.0 and C355.0 offer excellent strength and hardness with some sacrifices in ductility and corrosion resistance. They have good casting characteristics but not as good as Cu-free Al-Si alloys. They are generally used in heat treated conditions for optimal properties.

Alloy C355.0 with low iron is a higher strength version of 355.0. When premium strength casting processes are used, even higher tensile properties can be obtained with heat treated alloy 354.0. They are commonly cast in sand and permanent mold [4, 9].

Typical applications of Al-Si-Cu-Mg alloys are;

- Engine cooling fans
- Clutch housings
- Crankcases
- High-speed rotating parts such as fans and impellers
- Structural aerospace components
- Air compressor pistons
- Fuel pumps
- Compressor cases
- Rocker arms
- Timing gears
- Machine parts

Some commercial applications of aluminum alloys that are cylinder heads, rocker arms and engine block, are shown in Figure 2.4.

Figure 2.4 Some applications of aluminum alloys [17,18,19].

2.2 Castings Technology of Aluminum Alloys

2.2.1 Casting Process Selection

Casting process of specific part producing is influenced by many factors. Process selection is strongly influenced by desired properties of part that are often basis for defining alloy candidates that in turn influence the range of process choices.

The most important criteria of process selection are;

- Casting process considerations: requirements for fluidity, resistance to hot tearing, minimization of shrinkage tendencies
- Casting design considerations: draft, wall thickness, internal passages
- Mechanical property requirements: strength and ductility, hardness, fatigue strength, toughness, impact strength, specification limits
- Physical property requirements: electrical and thermal conductivity, specific gravity, expansion characteristics.
- Process requirements: machinability, brazeability, weldability, impregnation, and chemical finishing

- Service requirements: pressure tightness, corrosion resistance, wear resistance, elevated-temperature strength, dimensional and thermal stability
- Economics: volume, productivity, process yield, material costs, tooling costs, cost of machining, welding, and heat treatment

Many aluminum alloy castings can be produced by different methods. Dimensions, design features and material property requirements play role on choosing process. According to all these specialties, the most effective process is chosen.

Casting design important role on process selection. Size, shape, complexity, wall thickness and required dimensional accuracy are subjects of design considerations. For example, complex internal parts can usually be made by sand, plaster or investment casting, because it can be impossible or impractical to produce in permanent mold or pressure die casting.

Conformance of specification requirements including mechanical and physical properties may limit process choice. Metallurgical characteristics, cooling rates and solidification conditions also plays important role on choosing casting process.

Major factor in the choice of casting method is the number of castings. When only one or a few parts required, loose or simple patterns may be used for sand cast prototypes. Tooling cost dominates when the production is limited. For larger production volumes, tooling costs, though significant, become less important. For this kind of production volumes, automated systems are chosen.

Costs are strongly influenced by process choice. Tooling costs plays major role that associated with die and permanent mold casting are justified by higher level of production or product reproducibility.

Quality factors are also important in the selection of casting method. The degree of internal soundness, mechanical properties, performance characteristics that are a reflection of alloy chemistry, molten metal quality, solidification conditions, microstructural features are subjects of quality. Generally, all produced parts must be proper to desired quality standards [4].

2.2.2 Expendable and Non-expendable Mold Processes

Aluminum casting processes can be categorized depending variety of molds. For example, in the sand casting, also plaster and investment castings, the mold can’t be used again after casting is produced. That means the mold is temporary, non-reusable that has to be broken to remove the cast product. However, dies and permanent molds can be used recursively until the end of bench life that is limited by the number of castings. They are called as nonexpendable, long-lasting or permanent molds.

Mold filling technic is the second important factor for categorization of aluminum castings. The molten metal can flow by gravity into the mold or is forced under pressure. System with pressure requires permanent molds or dies.

Molten metal is normally introduced to mold cavity in an arrangement that is called as the gating systems. They are extensively designed for minimizing turbulence and preventing aspiration [4, 7, 13].

2.2.2.1 Sand Casting

This process is one of the most versatile metal forming process and it provides important freedom of design in terms of shape, size and product quality. Sand casting processes are classified according to mold sand that is bonded.

Resin Binder Processes: the organically bonded systems include no-bake binders, heat-cured binders.

Bonded Sand Molds : the inorganic bonds and include such process as green sand molding, dry sand molding, skin dried molds, loam molding, sodium-silicate-carbon dioxide systems phosphate bonded molds.

Unbonded Sand Molds: dry, unbounded, free-flowing sand surrounds the pattern such as lost foam and vacuum molding processes.

Green sand means the use of uncured bonding systems that are usually a blended mixture of sand, clay and water. Dry sand process uses resins, oil or other chemical binging agents to precoat the molding sand. As a result, the dry sand mold is thermally or chemically cured. The other dry sand process uses CO_2 gas with sodium silicate in the sand blend to form a silica gel bond.

The most predominant type of base sand is silica sand that classified in two categories: naturally bonded and synthetic sand. Naturally bonded sand includes clays. The usage of this sand as a mold is determined by type of metal being cast, casting quality, economics, and the degree of consistency demanded by the final product. Synthetic sands are used with bonding agents to produce the desired molding characteristics.

The most important effect on selection of base sand is sand grain structure. Mold permeability, density, and the other desired parameters can be reached by true sand selection.

Compressive strength and permeability are important parameters of molding sand. The sand molds are routinely tested for quality assurance. The mold must save its shape during the casting and solidification period. On the other hand, the mold must be sufficient to allow escape of the generated gases. If not, mold pressures increase, metal can blow from the mold. Generated gases are not always a disadvantage, because their pressure can help prevent metal penetration into the sand. As a result of this burned-on sand grains on products decreases, machining and cleaning problems are minimized.

Particle size and shape, moisture and binder contents and the degree of compaction applied in forming are plays effective roles on compressive strength and permeability.

Permeability is closely related with the amount and size of the voids (gaps) between densely packed sand grains. Size distribution, shape and packing pattern of the grains determines the size of voids. Two sizes of rounded sand grains and the size of voids in a mold face for a coarse and fine sand (in almost same total void area per cubic unit of volume). These distribution criteria also govern the dimensional stability of the base sand.

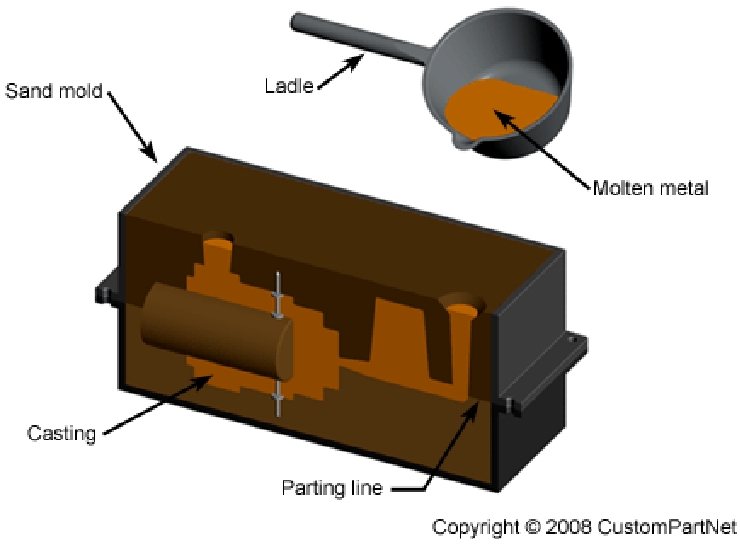
Typical sand casting advantages are versatility in wide variety of alloys, shapes and also sizes. As a result of reduced dimensional solidification resistance, alloys that considered hot short can be cast easily. Lower mold strength allows casting parts with widely varying section thicknesses and intricate designs. Chemically bonded molds that display greater rigidity then green sand molds, shows these advantages.

Sand casting includes only practical limitations in the size of casting parts. Minimum wall thickness of sand casting parts is normally 4mm, but thicknesses as little as 2 mm can be achieved. The other disadvantages are relatively low dimensional accuracy and poor surface finish. Chemically bonded sands provide improved surface finish and dimensional accuracy, and also relatively unlimited shell life that depend on the binder type.

Precision methods in forming and assembly of dry sand mold components offer improved dimensional tolerances. Also the surface quality can be improved by using finer grade of facing sand in the mold process. As a result of low solidification rates, strength is typically lower.

Improving mechanical properties can be possible by using sands such as zircon and olivine with higher heat capacity than silica and by using copper, iron or steel chills at strategic locations in the mold.

Sand casting needs minimum tooling and equipment costs when smaller numbers of castings are to be produced [4, 7].



.

Figure 2.5 Sand casting [14].

Sand Molding

The mold is formed by compacting the preconditioned sand over the pattern. Compacting process of sand can be apply by using manual or pneumatic rams; for pattern plates (match plates), machines use jolt/squeeze mechanisms to ensure mold integrity. Better uniformity and very high mold production rates can be reached by using automatic molding machines [4].

Patterns can be made of wood, composite or metal plates containing the casting impression or may consist of loose pieces assembled in the form to be cast. After compaction period, the pattern is carefully removed and the cavity in the shape of casting to be made appears. The separation of the pattern from the mold becomes easier if there is a dusting of calcium carbonate or other parting compound on the pattern surface. Also small amount of vibration can help to remove of pattern [4].

The runners and in-gates can be integral to the pattern or they can be cut into the sand by the molder. The sprue pattern is separately placed on the pattern before the sand is introduced.

For internal passages or undercuts included castings, dry sand cores may be used. In those situations, the mold includes additional impressions, locating points or prints for precisely positioning the cores after pattern removal and before final mold assembly. Rarely, to support the core position, aluminum chaplets can be used. After solidification, casting parts are removed from the mold physically. Physical removal includes vibration.

Foundry technique plays an important role on casting quality. Proper molten metal processing, metal-handling and gating design and practices including the selective use of chills are necessary for obtaining sound castings.

The principles of sand casting are relatively simple but there are a large number of process variations in use that typically involve expendable pattern materials and molding methods [4, 7].

Core Making

Core making process has three periods; coating a refractory with binder (mixing), compacting the mixed material into the desired shape and then curing (hardening) the compacted mass. Briefly, the sand mixture is placed in the pattern box and compacted so that it precisely fits the pattern.

The hardness of greensand molds depends on the amount of compaction applied to the mold. Where chemical binders are used, molds are chemically hardened after light compaction.

Medium and high production applications exceptionally need the cold and heat-cured processes. Automotive, pipe fitting, air conditioning and refrigeration components can be example of high-production operations. The no-bake processes are generally used for short-run production quantities.

Methods and materials have a wide variety, but core making processes are generally categorized according to curing method and binder type. The three major systems are listed;

Cold Box Processes

- Phenolic urethane/amine
- Furan/SO_2
- (Acrylic/epoxy)/SO_2 (free radical cure process)
- Sodium silicate/CO_2
- Phenolic ester

Heat-Cured Processes

- Shell process
- Core oil (oven bake)
- Phenolic hot box
- Furan hot box
- Furan (furfuryl alcohol) warm box

No-Bake Processes

- Furan/acid
- Phenolic/acid
- Alkaline phenolic/ester
- Silicate/ester
- Phenolic urethane/amine
- Polyol isocyanate
- Alumina phosphate

Mixing

Special mullers are needed to mix the sand and other dry components efficiently with water or binders. This period can be accomplished easily except the oven-bake and shell processes.

Most shell process sands are hot coated in paddle/plow-type mixers using solid or liquid novolac resins. Hot coating process includes a solid flake or liquid novolac resin usage in state of a dispersed and preheated to 130-175°C. After resin is dispersed in solution, hardener (10-17% weight of resin) that has already dissolved in water, added in sand mix. Lubricant can be added nearly and of the process.

Sand mix moisture rate can be between 1.5 to 2.5%. After the addition of water/hardener solution, immediately cold air is blown into the mixer to cool and dry the sand. For every processes, the coating process is performed in a paddle-type mixer that is generally has a system (fluid bed, screen or cyclone) to cool and complete of drying period of the coated sand.

A wide variety of mixing equipment are used to disperse binders uniformly over the sand. In cold or heat activated processes, batch or continuous mixers can be used. For batch mixers, sand ingredients are measured volumetrically before mixing.

Revolving mixer or vibratory motion for 20s to 5 min. is enough to prepare mixed sand. After preparation of mixed sand, the sand is transferred to the core making station.

Continuous mixers are almost essential for no-bake core making operations; they can also be used for cold or heat-activated processes with the exception of the shell process. In continuous mixers, sand and additives are continuously metered and entered to the chamber that contains revolving mixers of various designs. After mixing process, prepared sand is discharged. However in the no-bake processes, discharged sand goes directly into the core box for compacting. Prepared sand for the cold and heat-cured processes is generally discharged into a storage hopper above a core making machine. [7, 14, 15].

Compacting

Compacting process must be applied to dense cores sufficiently. In that case grain-to-grain bonding can be provided to prevent metal penetration between the sand grains. Hand ramming the prepared sand into the core box is usual procedure for no-bake cores. However, high-production operations need mechanical methods.

Compacting process commonly is commonly applied with core blowing machines. Prepared sand is added to a chamber. This chamber is then sealed except for blow ports that are placed directly over inlet ports (investment areas) of the core boxes. The core boxes have air relief vents. Compressed air (40 to 100 psi) with a large volume is suddenly sent above the sand chamber to force the sand into the core box through the investment area. The carrier air goes out through the vents that are located in the core boxes. After blowing period, the blow air is turned off, the pressure in the chamber is reduced, and the core boxes are disengaged from the blow ports. All of these periods are generally controlled with electrically, mechanically or with the help of computer systems and they need only seconds to complete. [7, 14, 15].

Curing

According to chosen sand-binder system, compacted sand cores needs curing to achieve desired rigidity. In the cold box processes, the appropriate gases for curing are carbon dioxide, sulfur dioxide, tertiary amines or methyl format. In curing period, the gas is forced through the compacted sand and chemical reactions occur to create rigid bonds between sand grains. Excess curing gas is purged from the cured core with compressed air, and the cores are removed from the core box as hardened cores.

Curing period of heat activated processes have differences such as prepared sand is blown into the heated core box. The heat activates curing agents from the latent hardeners in the sand mix and curing occurs.

For no-bake cores need time to react the binders, and that is generally 30 s to 1 h. The cores are rigid enough to be removed from boxes for using. Additional curing may continue for several hours.

In core-oil process, cores are placed in ovens after removing from the boxes and baked for 1h or longer. The baking time depends on the section thickness. After this period cured cores are allowed to cool to ambient temperature [7, 14, 15].

2.2.2.2 Permanent Mold Casting

This metal casting method has some similarities to both sand casting and die casting. Casting period of metal and waiting for solidification of desired shaped part is similar to sand casting. However sand casting uses and expandable mold that is destroyed for removing the cast part. Permanent mold casting and die casting processes use metal molds (dies), which are usually made from cast iron or steel and reusable for several thousand cycles. Permanent mold casting is often referred to as gravity die casting because of casting in metal die without forcibly injection.

Permanent mold casting is commonly used for high volume production of small, simple metal parts with uniform wall thickness. Additionally this process has less tolerant of alloy variations than the most expendable mold processes. Al-Si, Al- Si-Mg, and Al-Si-Cu (Mg) alloys are typically casted this process. However, iron and steels can be cast using graphite molds. In the casting of hot-short alloys in which liquidus-solidus range and elevated-temperature strength combine to increase the tendency for cracking during and after solidification, mold rigidity is a challenge.

Gears, gear housings, pipe fittings and other automotive and aircraft components such as impellers, pistons and wheels are common permanent mold casting products. The permanent mold casting process consists of the following steps:

Mold preparation – Mold is pre-heated (150 to 260°C) to allow better metal flow and also reduce defects. Then, a ceramic coating is applied to mold cavity surfaces to smooth part removal and increase the mold lifetime.

Mold assembly - Mold parts that can be two or more part that changes according to complexity of cast part and cores are assembled.

Pouring – The molten metal is poured at a slow rate and flows through a runner system to fill the mold cavity under the gravity force effect.

Cooling - The molten metal is allowed to cool and solidify in the mold.

Mold opening – After solidification, assembled mold halves are opened and cast part is removed.

Trimming - During cooling, the metal in the runner system and sprue solidify attached to the casting. This excess material is now cut away.

The schematic view of the permanent mold casting is as seen in Figure 2.6.

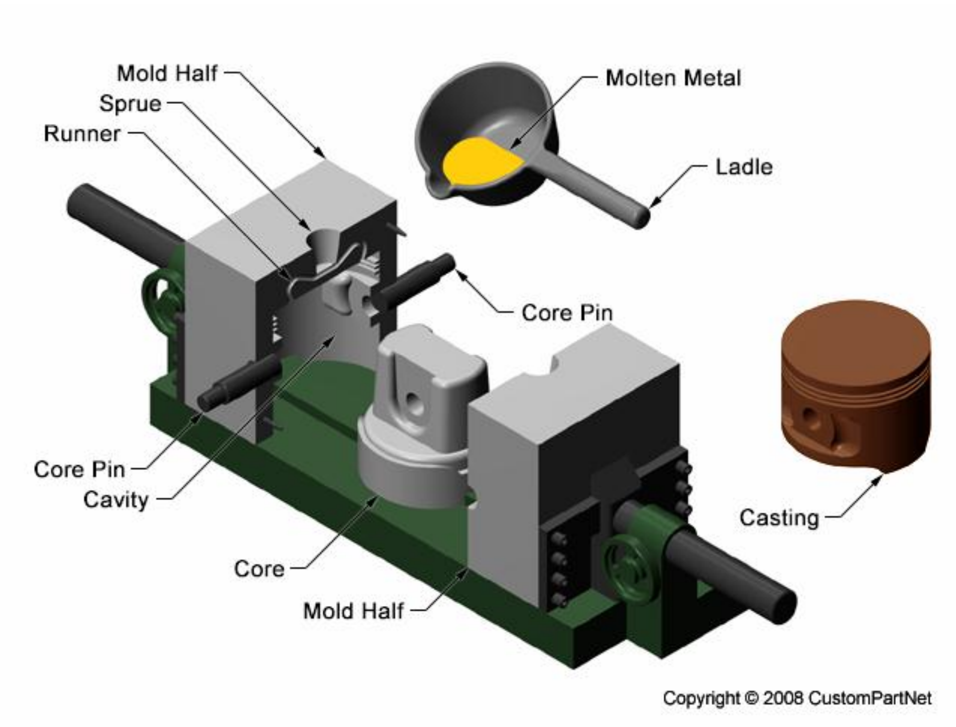


Figure 2.6 Schematic view of Permanent Mold Casting Process [22].

Some variations of permanent mold casting are existed with using these basic steps:

Slush Casting – This method is used to produce hollow parts without use of cores. The molten metal is poured into the mold and it starts to solidify at the cavity surface. When the molten metal reaches to the desired wall thickness, the remaining slush is poured out of the mold.

Low Pressure Permanent Mold Casting – The molten metal is forced to mold by low pressure air (< 1 bar). Pressure provides to reduce shrinkage during cooling. As a result, finer details and thinner walls can be casted.

Vacuum Permanent Mold Casting – In contrast with low pressure casting, vacuum pressure is used to fill the mold. [4, 7 ,22]

The comparison of the sand casting and permanent mold casting is given in the Table 1. They have different specialties that are really effective on desired properties of cast parts.

Table 2.1 Comparison of sand casting and permanent mold casting method [16]

Property Name	Sand Casting	Permanent Mold Casting
Shapes	Thin-walled: Complex, Solid: Cylindrical, Solid: Cubic, Solid: Complex (Flat, Thin-walled: Cylindrical, Thin-walled: Cubic)	Thin-walled: Complex, Solid: Cylindrical, Solid: Cubic, Solid: Complex (Flat, Thin-walled: Cylindrical, Thin-walled: Cubic)
Part size	Weight: 1 oz - 450 ton	Weight: 2 oz - 660 lb
Materials	Metals, Alloy Steel, Carbon Steel, Cast Iron, Stainless Steel, Aluminum, Copper, Magnesium, Nickel (Lead, Tin, Titanium, Zinc)	Aluminum, Copper, Magnesium (Metals, Alloy Steel, Carbon Steel, Cast Iron, Stainless Steel, Lead, Nickel, Tin, Titanium, Zinc)
Surface finish - Ra (μin)	300 - 600 (125 - 2000)	125 - 250 (32 - 400)
Tolerance (in.)	± 0.03 (± 0.015)	± 0.015 (± 0.01)
Max wall thickness	0.125 - 5 (0.09 - 40)	0.08 - 2
Quantity	1 - 1000 (1 - 1000000)	1000 - 100000 (500 - 1000000)
Lead time	Days (Hours)	Months (Weeks)
Advantages	Can produce very large parts, Can form complex shapes, Many material options, Low tooling and equipment cost, Scrap can be recycled, Short lead time possible	Can form complex shapes, Good mechanical properties, Many material options, Low porosity, Low labor cost, Scrap can be recycled
Disadvantages	Poor material strength, High porosity possible, Poor surface finish and tolerance, Seondary machining often required, Low production rate, High labor cost	High tooling cost, Long lead time possible
Applications	Engine blocks and manifolds, machine bases, gears, pulleys	Gears, wheels, housings, engine components

2.3 Castability of Aluminum Alloys

The aim of choosing different casting methods is to reach optimal mechanical and microstructural properties with low cost. The fluidity of molten metal is the most important issue, that must be optimized for all casting methods to improve castability of molten metal and as a result of this the cast part can be produced with desired properties.

The castability of alloys can be explained as: a measure of their ability to be cast with a given shape with a given casting process.

The feeding mechanism plays an important role on the castability of aluminum alloys (Figure 2.7). This effect is directly connected with solidification mechanism.

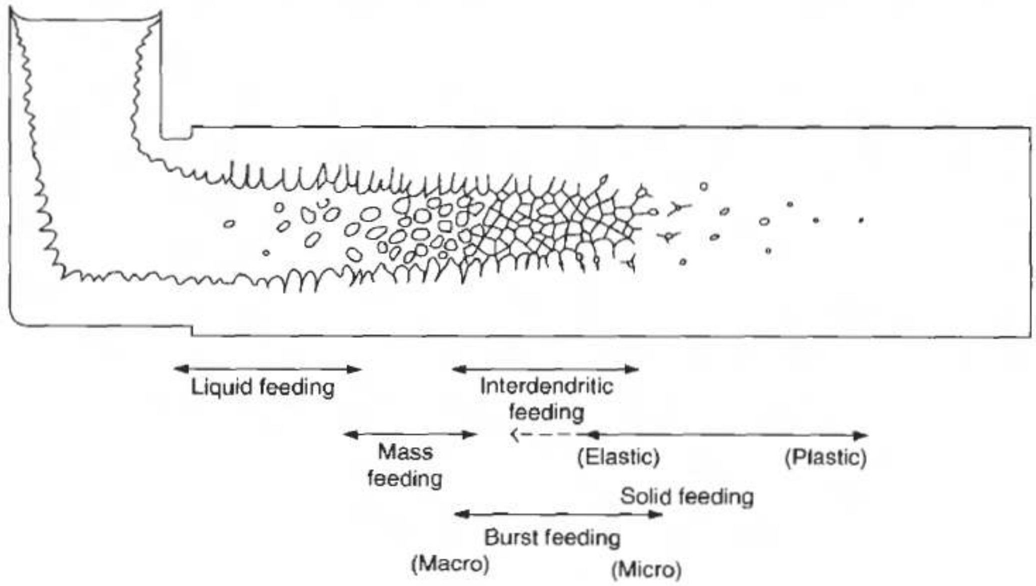


Figure 2.7 Schematic representation of the, five feeding mechanisms in a solidifying casting [30].

Aluminum alloys are promising metals to meet good mechanical properties due to their low density, high specific strength and specific stiffness combined with good castability.

Castability of alloys is directly relevant with fluidity of molten metal that is also effected by metallurgical factors, solidification type and mold characteristics. The fluidity limits the castability of alloys and their properties and also poor fluidity affects the soundness of cast part and final quality negatively, for example incomplete filling of the mold.

Mold (form) filling capability characterizes the fluidity of molten metal. This is common typical property to evaluate because it is affected very strongly by the conditions of molten metal and casting method. Molten metal fluidity can be determinated using the pencil probe or spiral probe. In these methods, it is possible to measure fluidity as a flow length (in or mm) of solidified molten metal in sand or metallic molds [2, 9, 31].

2.3.1 Bolt Penetration Test Method

This method is used for determine the form filling capability of molten metal and was introduced by S.Engler and R.Ellerbrok in 1974 [44]. Previously different methods were used such as pin and ball specimen tests and also spiral test method. However in spiral test method, the length of initial run so the part of the spiral can be measured and the molten metal don’t fill the edges of the flow channel. As a result, these methods have shown only a conditional reliability and precision on the form filling capability measurements.

The conventional bolt method is based on the die with two cylinders which are touch on a line and so on both sides form a tapered gab. Penetration of the liquid metal in this column describes the form filling capability. The position of the cylinders is given in Figure 2.8.

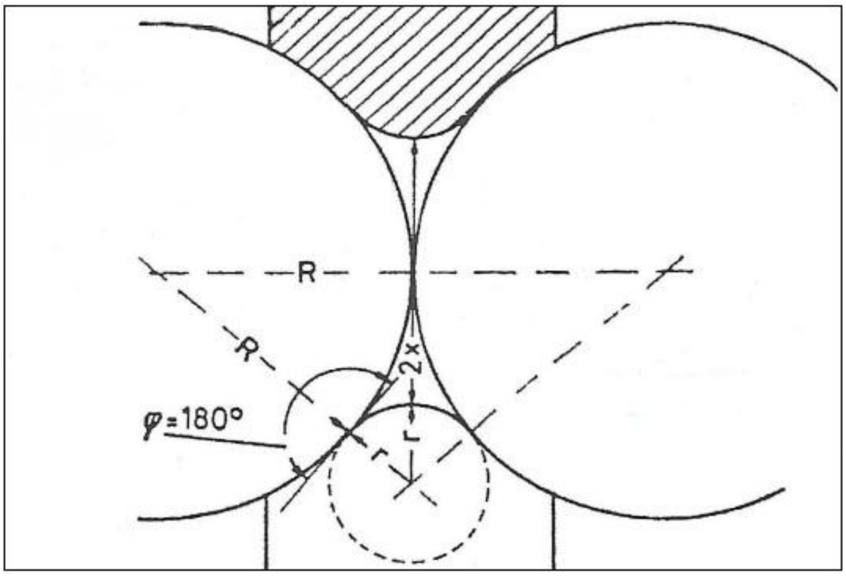


Figure 2.8 Schema for calculating the form filling factor [44].

As a measure of the form filling capacity of reciprocal value of the diameter $(1/d)$ is used, which according to the formula:

$$F = (1/d) = \frac{R - x}{x^2}$$

The calculated value is referred to form filling factor (F). R identifies the semi diameter of the bolt cylinders and x identifies the half distance between the measurement edges (gap measurement).

The biggest advantage of this method, the form filling capability in various metallostatic pressure can be determined, that means the distance between the measurement edge for different filling levels and so the form filling factor are calculated. The measuring process can be realized by using manual measurement instruments or automatically with image analysis computer software.

The bolt die is preheated before experiments to minimize the effects of thermal shocks. After castings the specimens are taken and the gaps are measured in different filling levels. The form filling factor is evaluated or the gap measurements in different conditions can be compared on diagrams. The conventional bolt die parts and the casted specimen with the gap is seen in Figure 2. 9.

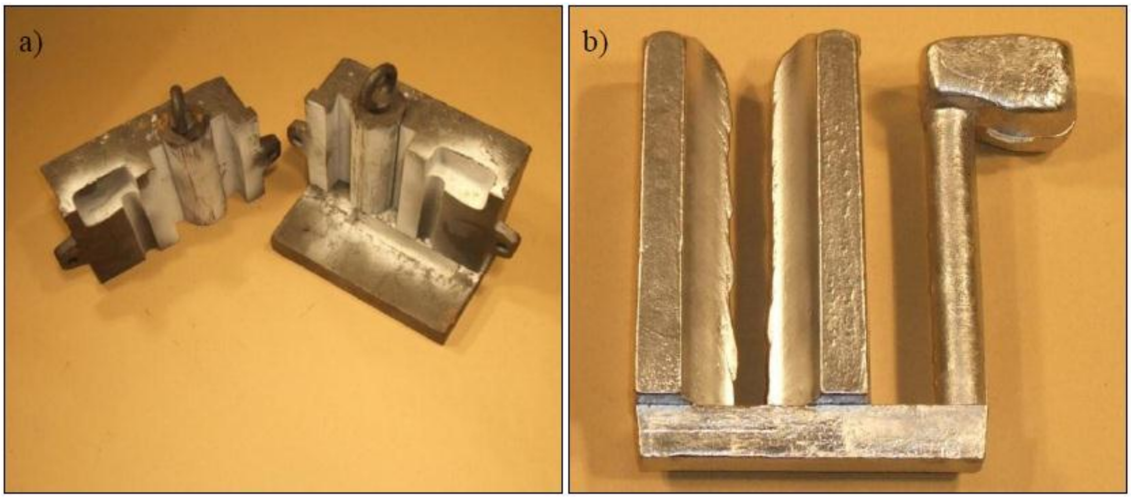


Figure 2.9 Conventional bolt test die (a) and specimen (b).

In conventional method, preheating and assemble of the die for experiments is a problem because of nonuniform heat distribution and loss of time. This situation affects the results of tests. Therefore the automatic systems such as casting machines can be used with integration of the bolt die [44].

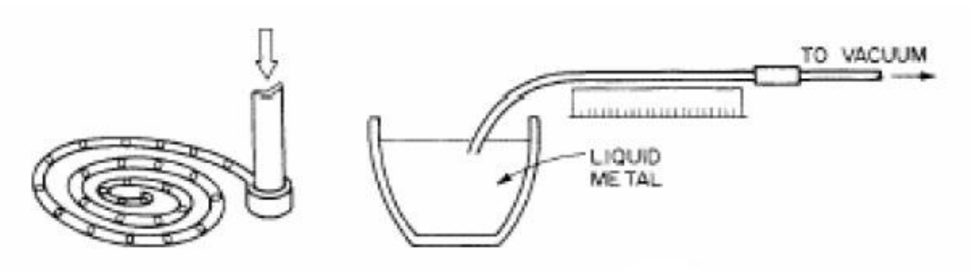
2.4 Fluidity of Aluminum Alloys

In casting technology, fluidity refers to the characteristic length that the molten metal can flow before it is stopped by solidification. This term also refers the form (mold cavity) filling capability of molten metal.

The fluidity of aluminum alloys influences directly the castability of molten aluminum and also the casting properties. Fluidity is complex parameter that is affected by properties of molten metal and mold, pouring conditions and solidification mechanism and these parameters are affected by each other [2, 31].

2.4.1 Spiral and Vacuum Test Methods

There are two common test methods is seen in Figure 2.10 for measuring fluidity of molten metal: Spiral test, and vacuum test



a) b)

Figure 2.10 Schematic view of (a) spiral test and (b) vacuum test [1]

Spiral test method requires sand or metallic mold and the melt is poured into a spiral shaped channel with a cross-sectional area. The output data is flow length of molten metal in the channel. In this process, selection of the mold material is an advantage because the test is correlated with the specific casting procedure of interest, for example sand spiral test for sand castings.

Vacuum test uses a glass tube under a reduced pressure to measure the flow length of molten metal and evaluate the fluidity.

Rod die and fork die testing methods are also available, they use dies with straight channels to pour molten metal and measure the flow length.

The sand mold is shown in Figure 2.11, is made of quartz sand by using core shooting machine. Quartz sand offers a very good heat conditions which are same for every cast. However the grain size of sand is adversely effective on fluidity behavior. Rough surfaces are formed by coarse sized grains.

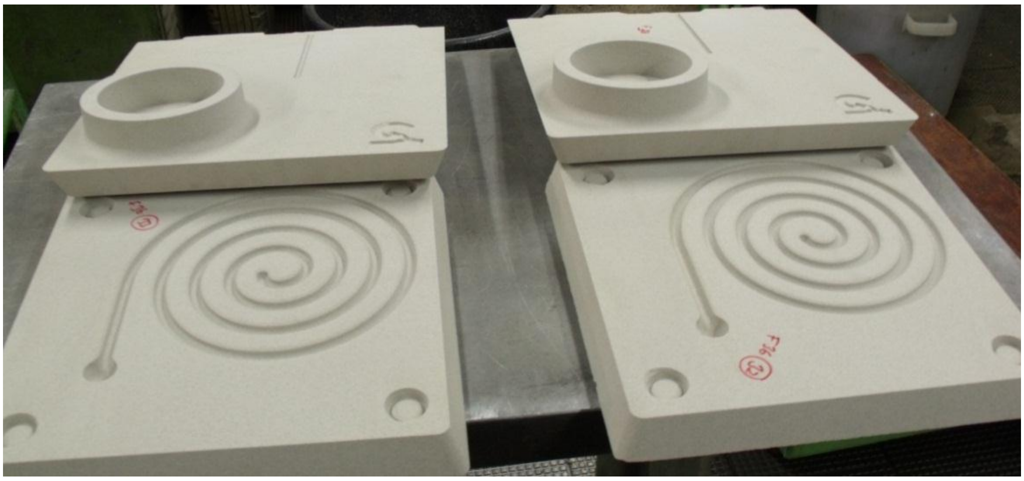


Figure 2.11 Sand spiral mold parts

Sand spiral method includes these steps for testing the fluidity of molten metal: Preparing the sand molds (this step is told in Section 2.2.2) and then clamping the sand mold parts. Pouring base and stopper should be preheated to improve the control capability of heat conditions. The example of the system is seen in the Figure 2.12. Using stopper is necessary for stabilization of pouring rate to get comparable results for every casting trial. After pouring, cooled spirals are moved out from the die or sand mold. The last part of this test method is measuring the spiral lengths with a tapeline or different methods to get information that can be transferred into diagrams [2, 44].

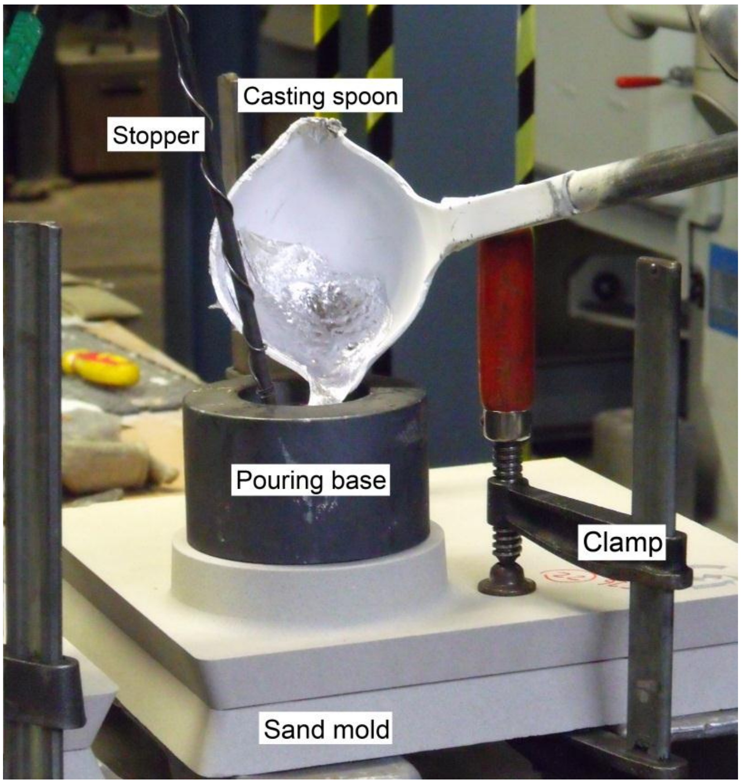


Figure 2.12 Sand spiral casting trial.

2.5 Metallurgical Factors

2.5.1 Composition and trace addition

The fluidity of Al-alloys is significantly affected by alloy additions because different compositions can influence viscosity, surface tension, freezing range and solidification mode of alloys. If the metal purity increases, the fluidity increases rapidly.

Pure metals and also eutectic alloys have high fluidity levels. Addition of impurities significantly reduces the fluidity of pure aluminum. However the fluidity of alloys is increased as the fraction eutectic increases and reaches the maximum level at the eutectic composition.

Maximum fluidity of Al-Si alloys is reached at 17-18wt. % Si content. This level is above the eutectic composition (12wt. %). Previous studies explain that aluminum dendrites are present due to a skewed coupled zone at eutectic composition which means that the dendrites disappear at higher Si content than eutectic. After maximum level, an addition of Si reduces the fluidity [2, 31].

Researchers that studied on pure aluminum and Al-Si alloys, show that Ti, Fe, Zr, Cr, Mn and Cu addition are slightly decrease the fluidity of molten metal. However combined concentration of Fe, Mn and Zn increased the fluidity of AlSi8Cu3 alloy.

Mose et al. [32] investigated effects of individual and combined Fe, Mn, Cr additions on the fluidity of Al-Si7Mg and Al-Si5Cu3 alloys with using sand spirals and reported following results:

Fe addition decreases the fluidity above critical content of Fe in alloy Al-Si7Mg and Al-Si5Cu3, a combination of 0.3% Mn, 0.6%Cr with 0.6%Fe increases the fluidity by %13 in alloy Al-Si5Cu3.

The maximum fluidity of Al-Si, Al-Cu and Al-Mg alloys are shown in Figure 2.13. Al-Cu alloy shows the maximum fluidity at the eutectic compound (33 wt. % Cu), but Al-Mg and Al-Si alloys shows the maximum fluidity at higher Si/Mg content than eutectic (Figure 2.13).

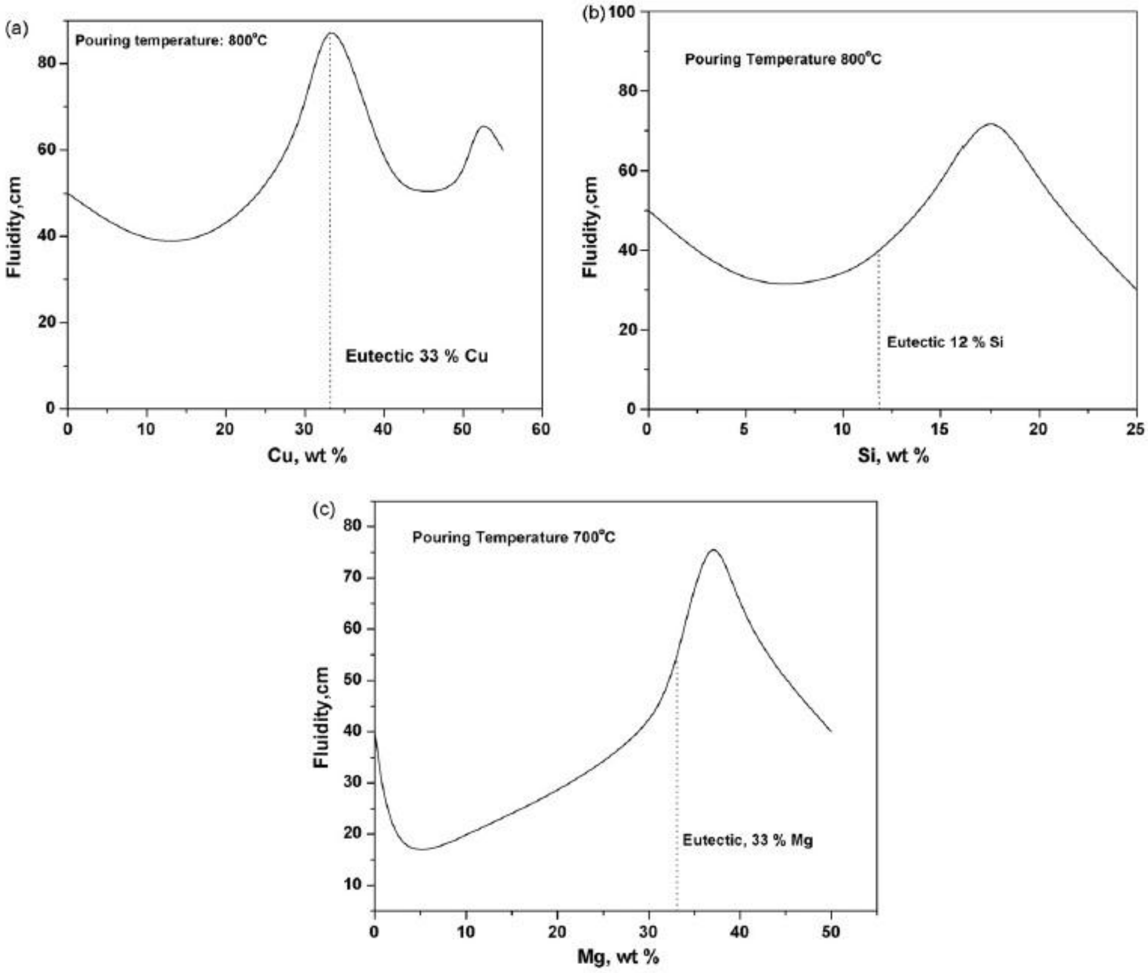


Figure 2.13 Spiral fluidity of binary (a) Al–Cu [3], (b) Al–Si [3] and (c) Al–Mg alloys cast in permanent mold [31]

2.5.2 Melt Superheat

Increase of superheat reduces viscosity and as a result of this fluidity increases. On the other hand solidification characteristics and cooling rate are affected by superheat and thus the fluidity of molten metal [31].

A linear relationship between fluidity and pouring temperature for aluminum alloys was explained in previous researches. Increasing the pouring temperature, that also means the melt superheat, retards the nucleation and growth of fine grains and as a result of this fluidity increases. Increasing melt superheat up to about 100-150 ˚C for Al-Si hypereutectic alloys, cannot show significant gain in fluidity and that is probably because of turbulence in the flowing metal stream [2, 33].

Haldar and Ravindran et al.[34] researched the fluidity of Al-Si alloys with a spiral test in sand mold and explained that flow length and velocity, hence fluidity are increased with an increase superheat and Si level.

2.5.3 Viscosity

The viscosity of molten metals does not significantly change the fluidity with the increasing temperature and/or slight changes in composition. Viscosity has no effect on the measurements of fluidity that are done with commercially fluidity tests and for most sand castings.

Previous researches show that the fluidity of molten metal which is measured by spiral test, does not depend on its viscosity. Consequently, the effects of viscosity such as surface tension of fluidity in casting can be omitted as long as metal maintains the liquid state during pouring [2].

2.5.4 Surface tension

Molten metals are typically non-wetting liquids and this provides backpressure resisting the advance of metal in the mold. In thinner section castings the backpressure becomes larger due to surface tension. Lower surface tension promotes wetting of the mold by the melt, would cause the mold to be quickly filled, particularly the narrow sections.

The surface tension of molten Al is significantly reduced by many minor alloying elements such as Li, Bi, Pb, Mg, Sb, Ca and Sn. However, the influence of surface oxide film in Al alloy eliminates the effect of surface tension [31, 35].

2.5.5 Oxide Formation

All metals and alloy react with the air to form oxides and/or nitrides. This tendency remains with the increasing temperature.

A solid surface film of oxide that occurs with the oxidation of liquid metal in various atmospheres plays an important role in melting and casting operations. Oxidation is origin for reasons of many problems in these operations.

For solid metals, the oxide films may be protective against oxidation and also influence the dissolution of hydrogen. The oxide films can be continuous or discontinuous as a result of atomic volume of compounds in molten metal. A continuous protective film limits the diffusion of oxygen atoms and thus limits the oxidation. However discontinuous films cannot prevent the penetration of oxygen by breaking the film and thus the oxidation increases according to linear law.

Molten aluminum is an extremely reactive for oxygen and for pure aluminum; oxidation starts by the rapid formation of amorphous alumina layer within milliseconds, where they called as 'young oxides' built a protective layer. To prevent oxide films, vacuum of less than 10^{-40} atmospheres is required [1, 36].

Oxides forms depend on the melt composition. Iron, copper, zinc, manganese have a little effect on oxidation process. However protective oxide film formation can be disturbed by small amount of Mg addition because of amorphous Al_2O_3 surface morphs into mixed oxide $MgO.Al_2O_3$ [1].

Oxide formations that are shown in Figure 2.14, are affective on mechanical properties.

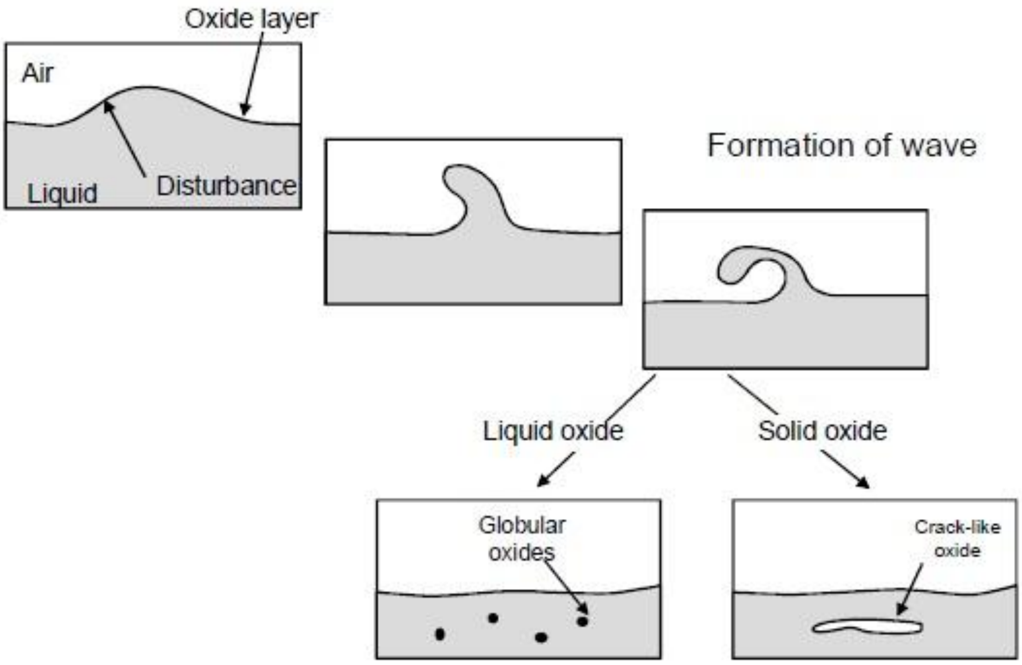


Figure 2.14 Formation of the oxide inclusions [1]

Aluminum has a dry skin oxide formation and this oxide form begins to be a problem when they submerged into the melt. Pouring aluminum into a mold rapidly causes turbulent manner, hence the oxide films fold over itself so that oxide to oxide contact occurs. As a result of handling, transfer or pouring the melt in turbulent manner, may become filled with huge density of cracks. Solid alumina films and molten aluminum don't knit together and generate crack-like defects which remain in the casting. These cracks can be incorporated into castings as following situations:

- The oxide skin of the charged metal is automatically incorporated during melting.
- Broken oxide films due to surface turbulence during handling or transfer of molten metal.
- Dross can be carried under surface with entrained air during pouring higher speeds and heights.
- The metal stream can separate and rejoin together at some distant location. (Because of the geometry of casting.)

As a result of this crack defects, casting will probably have less reliable in service. On the other hand they results often in leakage problems that are required a liquid or gas. These entire problems affect negatively the filling capability as matter of course fluidity of molten metal [1, 36].

Previous researches show that the oxide films raise the surface tension and reduce the filling capability of molten metal, especially at low pouring temperatures [37].

2.5.6 Melt Cleanliness

The fluidity of molten metal decreases due to increasing of contaminant that means the amount of inclusions in the molten metal. Inclusions reduce the critical fraction of solid to stop the flow.

Previous researches show that removing the inclusions decreases significantly the fluidity of Al-alloys. Researchers used different methods such as purging with inert and/or halogen gasses, fluxes, ultrasonic treatment etc. and they reported that, gas mixtures are more effective than inert gas alone for effective purging [31, 2].

Kwon and Lee et al. [38] studied the effect of oxide inclusions on the fluidity of Al-4.5wt%Cu-0.6wt%Mn and A356 alloys and explained that the significant effect of oxide inclusions on fluidity of molten metal especially at low pouring temperatures.

2.5.7 Grain Refinement

The effect of grain refinement involves complex mechanisms and depends on many factors: alloy composition, solidification type, properties of grain refiner, holding time and temperature in furnace etc. Put in a nutshell, chemical composition, and hence solidification type and morphology plays an important role.

Solidification of short freezing range alloys (for example Al-7wt%Si alloys) results with free equiaxed grains in the melt. This type solidification shows better fluidity than solidification of large freezing alloys that solidify with mushy morphologies (for example Al-Mg alloys) and dendrites which aggravates the flow. In this situation, grain refinement shows the greatest effect on solidification morphologies.

Previous researches show that grain refiners downsize grains and as a result of this the flow capability of molten metal increases. For Aluminum alloy Ti and B is common grain refiners that can be also used in combined addition. They shows their effects above critical amounts in molten metal [2, 3].

Kwon and Lee et.al [38] studied on A356 alloys with addition of Al-/5Ti-/B and reported that, increasing of fluidity depends on the degree of grain refining and reducing the size of grains provides better fluidity conditions.

2.5.8 Modification

Modification is a common industrial process for producing Al-Si alloys. Modification elements are called modifiers, change the eutectic structure from lamellar to fibrous morphology and improve ductility of Al-Si alloys. For Al-Si hypoeutectic alloys, modifiers can show the significant effect when the Si content is close to eutectic composition.

Previous researches show that the additions of Na, Na+Sr, Ti, Na+Ti, Na+Sr+Ti decrease the fluidity of aluminum alloys. However the additions of S, Sb, Sb+Ti, S+Ti increase the fluiditiy of aluminum alloys. On the other hand modification by Mg increases the fluidity only high temperatures (≈800˚C). The reason for this situation can be that Mg forms phases which have high heat of fusion and hence delays the solidification of the alloy [2, 31].

Prukkanon et al. [39] investigated the effects of Sc modification on the fluidity of an A356 alloy and reported that the fluidity increased with higher mean shape factor, which was from the effect of Sc modification.

2.6 Effect of Solidification Morphology on Fluidity

2.6.1 Solidification Mechanisms

Fluidity is generally inversely related to the solidification range. Effect of solidification mechanisms can be explained as following: Fluidity is reversely related with solidification range, hence pure metals and eutectic alloys (low solidification range) have higher fluidity.

For pure metals and eutectic alloys, solidification starts at the wall of mold and continues by the growth of columnar grains with planar interface as metal flows through the channel. This flow stops when the columnar grains meet and the pinching by the grains from the channel wall occurs (Figure 2.15 a).

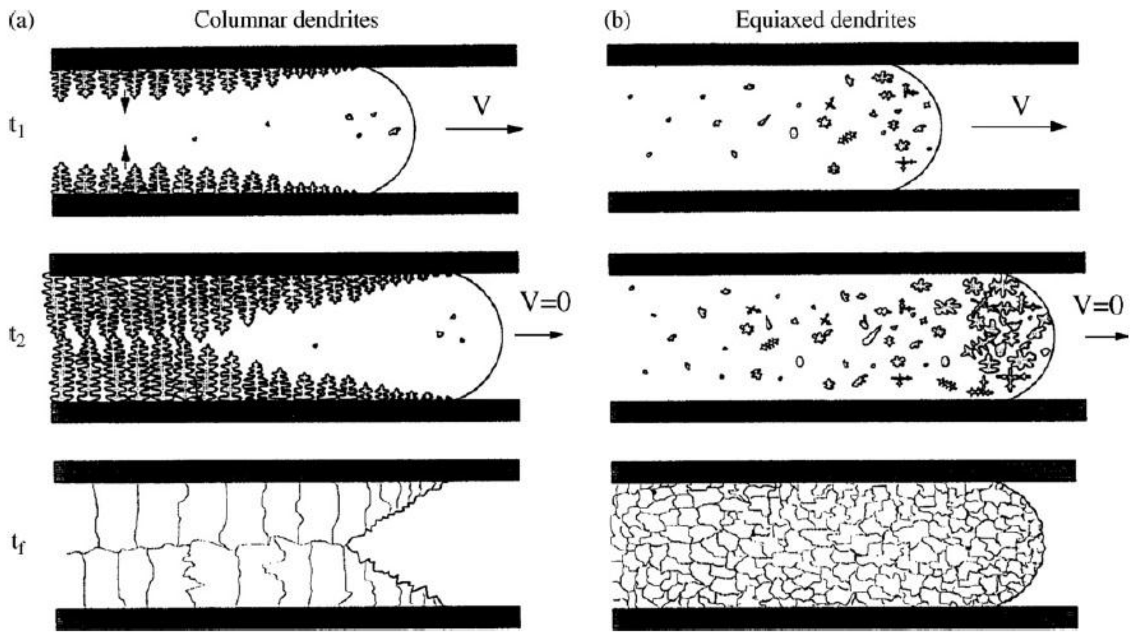


Figure 2.15 Different mode of solidification of alloys: (a) columnar growth and (b) equiaxed growth [31]

For alloys that have larger solidification ranges, independent crystallization in main liquid mass is produced by constitutional undercooling and other phenomena. The mode of solidification changes from growth of columnar grains more or less planar grains grow front (for pure metals and eutectic alloys) to the equiaxed dendrite formation or columnar dendrites where the dendrite arms fracture forming equiaxed grains (large solidification range alloys). These free crystals in the liquid metal follows the downstream until the critical fraction solid is reached and stops the flow by choking at the tip of solidified metal (Figure 2.15 b). This situation reduces the fluidity [2, 31, 35].

The hindrance causes by crystals with irregular growth surfaces in large solidification range alloys is much greater than that comparatively smooth crystallization interface front of pure metals and eutectic alloys. As a result of this; fluidity of pure metals and eutectic alloys are greater than large solidification range alloys and this explains why the eutectic and near eutectic alloys are used for foundry processes [2,31].

2.6.2 Solidification of Silicon

Silicon is the most frequently used alloying element with improving effects on castability. Maximum solubility of silicon in aluminum is about 1.5wt% and this value exceeds 5 to 17wt% in aluminum foundry alloys. Silicon is normally present in its elemental form and its heat fusion is about five times that of aluminum, that's why the silicon increases fluidity significantly.

Silicon expands on solidification and counteracts the solidification shrinkage of aluminum: pure aluminum shrinks by 6.7%, but it can be reduced with 12wt% Si to about 4.5% in eutectic Al-Si alloy [2].

Silicon has a fan shaped morphology in metallographic sections and this kind of eutectic structure is known as lamellar structure, causes poor mechanical properties compared the modified structures.

Small amounts of sodium, strontium, calcium, antimony and cerium completely change the morphology of the silicon eutectic from large flakes to fibrous structure. According to previous researches, these elements modify the structure by disturbing growth step of the silicon. As a result of this, repeated twinning occurs and hence the fibrous structure is formed [35].

2.6.3 Hot tearing and Segregations

The thermal contraction and solidification shrinkages can cause significant stresses. In these stress regions, the strength is low because they are not completely solidified and hot spots occur. Hot tears are formed when the feeding and permeability in the mushy zone is low. According to Hot tearing susceptibility of alloys is greatly influenced by solidification behavior of molten metal in the mushy zone. Long freezing range alloys have higher tendency to hot tear and also this phenomenon occurs in the sand castings because of the slower solidification rate [2, 33, 40].

The following conditions can be applied to avoid hot tearing:

- Controlled contracting
- Coherent network establishing
- Presence of liquid phase on the dendrites and grain boundaries
- After coherency, significant temperature decreasing
- Low permeability after solidification to prevent feeding of liquid in tears.

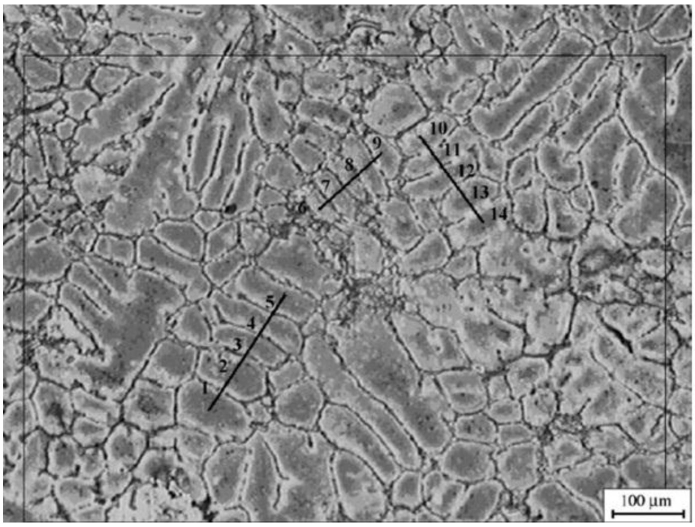
The segregation behavior of alloying elements in aluminum alloys can explain the alloy dependence of hot tearing. When the alloying element content is relatively lower than the eutectic composition (deep eutectic systems such as Al-Cu, Al-Mg) the alloy segregation occurs in the beginning and the solidification continues at the relatively constant temperature. And of the solidification microsegregations are result in sharp temperature drop and extensive thermal contraction is stress the casting when is vulnerable to tearing [2].

2.6.4 Dendrite Arm Spacing (DAS)

During the solidification of aluminum alloys, dendritic structure commonly observes. The grains may include thousands of dendrites. This structure affects the mechanical properties of the alloy to a great extent. Dendrite arm spacing usually refers to the spacing between the secondary arms of dendrites. The mechanical properties of most cast alloys are dependent on secondary arm spacing. A decrease of DAS is accompanied by an invariably improvement on mechanical properties of the cast alloy.

Solidification conditions are the most important effect on DAS. A reduce of cooling rate increases the DAS and this causes the decrease of the ultimate strength. In traditional casting procedures, dendrite morphology shows same specialties within wide range of cooling rate. However, primary dendrite arms get smaller and secondary and higher order ones may disappear at very high cooling rates. As a result of this DAS (primary, secondary or higher order spacing) is used as a measure of the effect of solidification conditions on dendritic structure [20, 30,35].

Measurement of the dendrite arm spacing is based on counting the number of the dendrite arms on specific axis and in specific length and calculating the DAS with the following equation as seen in Figure 2.16.



$$\lambda_e = \frac{l_d}{n_d V}$$

λ_e= dendrite arm spacing

l_d=measured length of the dendrite

n_d=number of dendrite arms

V=magnification of the microscope

Figure 2.16 Measurement of secondary dendrite arm spacing for aluminum alloy [20]

Cruz et.al [25] researched effect of dendrite arm spacing on mechanical properties of Al-Si and Al-Sn alloys and explained that d, creasing dendrite arm spacing increases ultimate tensile strength, yield strength and also wear resistance.

2.7 Effect of Mold Characteristics on Fluidity

2.7.1 Mold Materials

The material of mold affects the solidification time, as a result of this fluidity of molten metal. The flow lengths (fluidity) in different mold materials are related to the solidification time and also effective superheat (can be explained as conductivity of mold material) [35].

Previous researches show that fluidity in stainless steel tubes is higher than in quartz tubes and also silica sand spirals shows lower fluidity than zircon sand because of zircon sand's higher chilling power.

A rough surface of mold hinders the metal flow by increased frictional forces while smooth surface increases the fluidity. This roughness is related to the grain size of the molding material, which explains the preference for fine grained sand flow channels for fluidity testing [31].

2.7.2 Permeability of Mold

Increased permeability of mold provides higher fluidity. The gasses that present in the mold or generated during mold pouring the mold wall can escape easily, if the mold permeability is enough. Otherwise these gasses obstruct the flow of molten metal and reduce fluidity. On the other hand, to help these gasses to escape from the mold, special vent channels and open risers can be arranged [31].

2.7.3 Mold Coating

Mold coatings play an important role on reducing the heat transfer between the molten metal and mold and thus increase fluidity but this may get longer the cycle time. The molten metal can flow in the mold to fill the mold cavity if it has enough heat to stay liquid for enough time.

The coatings of mold can affect the heat transfer conditions only during the first small fraction of a second, and then solidification process starts. During solidification the effect of heat transfer is neglected.

Fluidity is explained by flow distance in mold and can be increased by mold coating significantly. Previous studies show that mold coatings such as carbon black and hexachloroethane increase the fluidity of molten metal [31, 41].

2.7.4 Mold Temperature

Due to chilling effect of mold, molten metal has a lower fluidity when it poured in room or lower temperature. Hence, pre-heating the mold and pouring into hot mold increases the fluidity.

Castability of Al alloy is affected largely by mold temperature. Previous researches show that Al alloys which are poured into the mold that has a temperature approaching solidus temperature of Al may result in considerable increase in the casting fluidity [31].

2.8 Porosity Phenomena

Porosity, in cast aluminum products, is closely related with the occurrence of low mechanical properties. The main reasons that cause porosities are:

- An incomplete liquid metal feeding which causes volumetric shrinkage
- Reduced solubility of hydrogen upon solidification.

These reasons show the importance of controlling shrinkage and gasses in metal to reduce porosity formations. Porosity types are explained according to size: macro and micro porosity and according to reasons of occurrence: shrinkage and gas porosity.

O. Savas et al. [42] explained that the effective parameters on porosity formation in Al-Si alloys are: dissolved hydrogen in molten alloy, melt cleanliness, heat conditions and process parameters.

2.8.1 Shrinkage Porosity

This type of porosity comes off the density difference between solid and liquid alloy phases. During the solidification, the volume of the liquid decreases and the surrounding liquid flows tries to compensate it. Inadequacy of the liquid metal to feed and compensate to this volume shrinkage causes porosities that can be either small-distributed pores or large pore.

Interdentritic feeding is considered to be the one of the difficult stages for the creation of porosity defects. Long freezing range alloys have this style solidification mechanism [1, 2, 42].

2.8.2 Gas Porosity

This type of porosity comes off the difference solubility of hydrogen in the solid and in the liquid metal and it is also called ‘homogenous pore nucleation’. During the solidification, some of the gas is rejected from solution. The rejected gas causes porosity by diffusing into bifilms (porosity inside) and expands the central gap.

Oxide films and non-metallic inclusion in liquid metal influences the porosity formation and mechanical properties of aluminum alloys.

Previous researches showed that the presence of oxides/inclusions, hence metal quality, plays a more effective role on porosity formation and mechanical properties than hydrogen content [1, 2, 42].

2.8.3 Degassing

During the melting and curing the aluminum, there are many sources to hydrogen: atmospheric humidity, fluxes, grain refiners, scrap, damp tools and also combustion products. On the other hand, these factors get together with the atmospheric oxygen and forms the oxides and inclusions.

Hydrogen can be removed from the melt by degassing. Inert gas bubbles collect the hydrogen because of hydrogen diffusion into the bubbles as a result of the pressure difference between the melt and gas. This diffusion depends on following parameters:

- Surface area between the melt and gas
- Degassing time

Reducing non-metallic inclusions and also excellent stirring that assists in homogenizing the temperature and chemical composition of the melt is possible with degassing with inert gasses (argon and/or nitrogen.) [1, 42].

2.8.4 Reduced Pressure Test Method

The standard reduced pressure test (RPT) appears to be able to provide an indication of metal quality but has so far resisted quantification, so using it as a comparative assessment should be the best. The reduced pressure test is a foundry floor tool which allows the operator to qualitatively assess the cleanliness of a batch of molten aluminum, allowing corrective action to be followed. The main principle of this technique is based on the formation of gas porosity when liquid aluminum is cooled under the reduced pressure. The size of the porosity formed is magnified by the effect of the reduced pressure, resulting in a visibly porous sample is as shown in Figure 2.17.

This method involves the solidification of two melt samples, one at atmospheric pressure and the other one under a partial vacuum (Figure 2.18). A comparison of densities of the samples (Density Index-DI) gives a numerical indication of the melt quality [1,21,22].

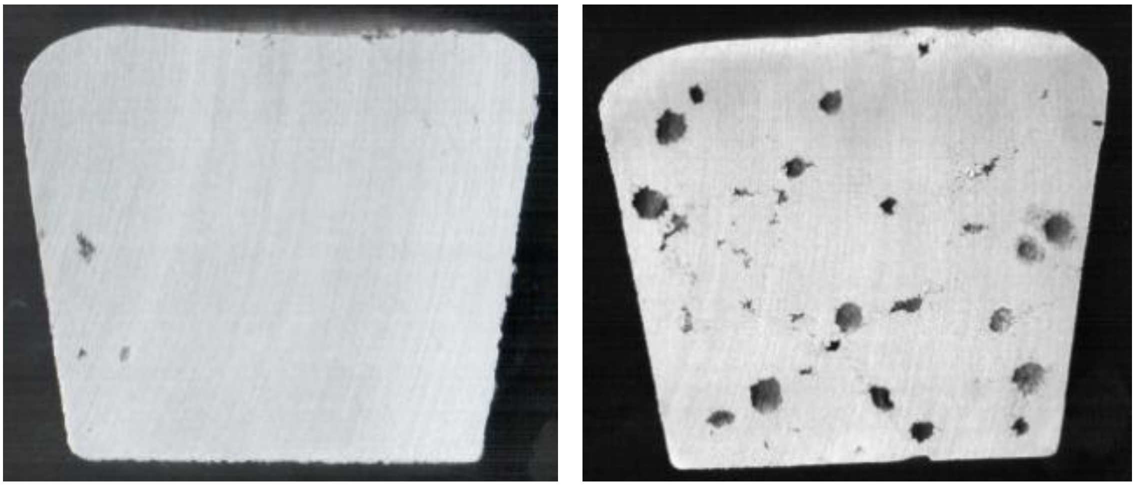


Figure 2.17 RPT Samples solidified at air (left), under reduced pressure (right)[21]

Figure 2.18 RPT Tester and Samples

The apparent density is weight in the air and water according to the principles of Archimedes. The measured densities give the indexes to use the comparable quality criteria for the melt [1, 21, 22, 24].

Density index is calculated with the following equation:

$$Density\ Index\ (DI) = \frac{Datm - Dvac}{Datm} \times 100$$

2.9 The AMS (Alloy Memory Structure) Technology

Fine grain structures are often desired in solidification processes to increase the homogeneity of the properties of alloys and limit the formations of internal defects and surface exudations. Several methods can be used to refine grains:

- Addition of inoculation substances (grain refiners) such as TiB_2 and TiC,
- Use of rapid solidification conditions,
- Stirring the melt by mechanical or by electromagnetic stirring fields.

The melt stirring exhibits two effects that contribute to grain refinement: (a) penetration of the flow the mushy zone and remelting dendrite arms, (b) the thermal gradient in the liquid is lowered, thus extending the undercooled region and favoring ta columnar to equiaxed transition [26].

Physical and chemical treatments (grain refining, laser or plasma treatment) show some negative effects such as impurities and local overheating that reduces the quality of cast parts. Furthermore chemical treatments (refinements) bring along undesired reactions.

Stirring under electromagnetic field doesn't cause the negative effects of chemical and physical treatments because this process doesn't include contact with melt [27].

The AMS Technology is an innovative melt treatment technique that was developed and patented by BergerConsult e.k. This technique includes the melt treatment and solidification control stirring the melt using a rotating electromagnetic field that provides the transfer of heat and mass transfer.

High velocity stirring of the melt within the module provides:

- A high homogeneity
- A high number of nuclei, hence a fine globular structure (drop of temperature through defined cooling time)

Applied magnetics energy increases the surface tension and impacts the latent heat of solidification range is extended. The following improvements are to be achieved by this modification:

- Consistent distribution of macro- and micro-structure
- Fine globular formation of macrostructure with low dendrite arm spacing
- Lower gas content, reduction of porosity
- Improvement of the mechanical properties
- Reduction of casting temperature in the high pressure die casting and gravity die casting up to 100 ° c.

The most important characteristic of AMS technology is that the generated properties by the magnetic treatment are persistent even after cooling and remelting. That is the reason of it is called 'Memory-Effect'.

These parameters can be adjusted according to the relevant requirements. In this way the material properties according to BergerConsult e.k. can be set, to gain technological and economic advantages:

- Extension of tool life
- Producing thin-walled castings
- Energy savings through lower casting temperature
- Reduction of cycle times
- More homogeneous heat conduction
- Reduction of casting defects

There are two possibilities available to perform this technique as following:

- The melt is transferred to the AMS module and after treatment and degassing it sends to the die directly to produce cast part (Figure 2.19 way 1)
- The treated melt can be send to molds to produce treated ingots that can be remelted and used later. (Figure 2.19 way 2) [27,43,44].

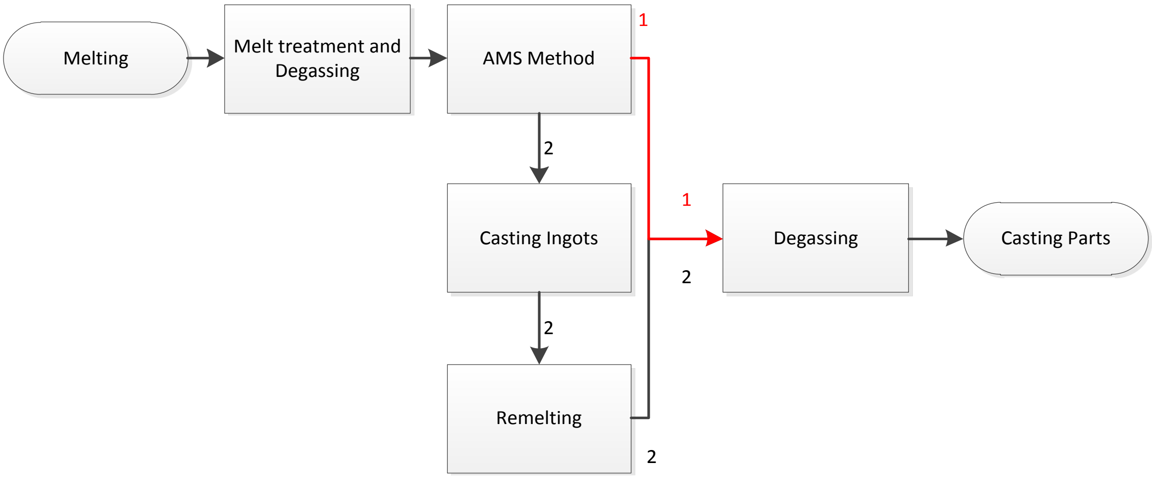


Figure 2.19 Schematic view of AMS technique variations

Previous researches show that the AMS technology increases the flowability and also form filling capability of molten metal significantly. Furthermore mechanical properties are improved and dendrite arm spacing values are reduced. However, a significant effect on form filling capability could not be seen [27].

Apelian et.al [28] researched the removal of inclusions and reported that: an externally applied electromagnetic force acts upon the melt, and as a reaction to this externally applied force, the inclusions moved in the opposite direction as a result of Newton's third law and as a result of this inclusions were separated from the melt.

Yoon et.al [29] studied on the effects of electromagnetic force on the removal of alumina particles in molten A356 aluminum alloy and reported that: an electromagnetic force was induced into conductive aluminum melt and nonconductive alumina particles moved well in the reverse direction of the electromagnetic force and their velocity increased proportionally to the force.

CHAPTER 3

MATERIALS AND METHODS

3.1 Materials

3.1.1 Alloys

In this study, fluidity properties of A380 and A356 were investigated. They are two of the most common cast alloys that are commercially used in industry. Furthermore Micro100 aluminum oxide rods are used for examining of oxide film effect on fluidity [45].

The designations, specialties and compositions of A380 and A356 alloys are as shown in Table 3-1, Table 3-2 and Table 3-3.

Table 3.1 Designations of alloys

USA AA / ASTM	ISO	EN AC-	FRANCE	GERMANY	ITALY UNI	UK / INDIA	USA SAE	JAPAN
A380	Al-Si8Cu3Fe	46 500	A-S9U3A-Y4	G-AlSi8Cu3 (226)	5075 3601	LM 24	306	AC 4B ADC10
A356	Al-Si7Mg	42 000	A-S7G	G-AlSi7Mg	3599	LM 25	323	AC 4C

Table 3.2 Specialties of Alloys

A380	Suitable for large, intricate and thin walled castings in all types of molds, also used where corrosion resistance or ductility is required.
A356	Suitable where good corrosion resistance combined with thermal properties are required. Strength is attained by heat treatment.

Table 3.3 Composition of Alloys

Alloy	Cu	Mg	Si	Fe	Mn	Ni	Zn	Pb	Sn	Ti
A380	3.0 - 4.0	0.3	7.5 - 9.5	1.3	0.5	0.5	3	0.3	0.2	0.2
A356	0.2	0.2 - 0.6	6.5 - 7.5	0.5	0.3	0.1	0.1	0.1	0.05	0.2

3.1.2 Micro100

As an oxide source, Micro100 metallic master alloy (Al_2O_3) rods were used for treatment of molten metal. Micro100 converts the shrink holes, big and irregular pores into micro porosities and it was added into the melt in different amounts (0,1 and 1wt%) to understand the effect of oxide treatment on fluidity. The basic reason for using the Micro100 treatment was the verification of a possible effect of micro oxides evoked by AMS on the increase of the fluidity.

This product has some advantages as following [46]:

- It can be used for all aluminum alloys
- It prevents sink
- 700˚C is enough for reaction
- Easy dissolution without any rest in short time
- Mechanical values don't reduce because of Micro100
- Enables casting without shrink holes.

3.2 Methods

3.2.1 Melting

Melting processes were realized with Naberterm Typ T20/H. Cutted ingots (45 kg/charge) were melted at 800 ˚C (furnace temperature) in graphite crucibles.

3.2.2 Degassing

Degassing was applied to reduce the gas content and impurity level in acceptable values to get comparable results with low density indexes. Degassing was realized with Argon 4.6 (purity > 99,996) that was blown with graphite lance at the rate of 3 liter/min. This purging process was applied for 20min. The setup of the degassing operation is given in Figure 3.1.

Figure 3.1 Degassing Process

To get reliable and reproducible results during the experiments, numbers of parameters should be kept in minimum to explain one specific parameter. Degassing provided clean melt (acceptable gas and inclusion level) to understand obviously the high velocity stirring effect on castability during the experiments.

3.2.3 The AMS Technology

Alloy memory structure was achieved by stirring the melt electromagnetically in previous researches. However, in this study, high velocity stirring was applied mechanically to understand if it is possible to achieve alloy memory structure with mechanical stirring.

The basic difference is mechanical stirring can be applied without heavy turbulences and also the tool cost are lower than the electromagnetical stirring method. Mechanically stirring creates lower density and lower viscosity, as a result of this density difference, solid particles can be left from the melt.

Stirring rod type and also temperature of the melt during the stirring becomes very important factors. Stirring rod which can be seen in Figure 3.2 has cylindrical shape to apply stirring and share forces without turbulence. It was also coated to avoid from reactions between steel rod and aluminum melt. On the other hand, the melt should stay in liquid state during stirring. The shape and dimensions of stirring rod and also process temperature were chosen as secure these conditions.

The AMS process was realized by a T type stirring rod mounted mixer (drilling machine) to mix at 3000 rpm velocity for 1 minute (Figure 3.2 and 3.3). 9kg graphite crucible was used for the melt and it was coated with isolation fabric. When the stirring step was stopped, the temperature of alloy was about 820 ˚C.

After degassing and reduced pressure test, high velocity stirred metal poured into sand spiral molds and bolt test die. As seen in Figure 3.2, two iron ingots (as a weight) were put on the cover to fasten it. This provides better heat isolation and avoid from air contact during stirring. After this construction, the stirring rod was assembled with a mixer and mixing was applied.

The stirring velocity should be high to block turning of the melt mass bodily without stirring effect in crucible. In this situation share forces can't be applied and stirring can't be achieved. The stirring can be applied in furnace without temperature drops. However, during the stirring, the cover of the crucible can be displaced or the crucible can be broken. As a result of this the melt can be sprung on hot resistances of the furnace.

Figure 3.2 The AMS module and coated stirring rod

After 1 minute stirring time, the surface of molten metal was seen as continuous thin oxide layer without extreme slug/oxide formation (Figure 3.3).

Figure 3.3 The view of high velocity stirred aluminum

3.2.4 Reduced Pressure Test

This method was only used for checking the hydrogen level if it is in acceptable tolerances and tests are applied without decelerating the experiments. As a result of this, index values were chosen between 2-5%.

Vacuum density tester was used to solidify the samples (Figure 3.4).

- After every melting, degassing periods and also micro oxide addition and stirring periods two samples were taken.
- Samples are poured into preheated test cups (200 ˚C).
- One of the samples solidified under vacuum (80mbar.) and the other one solidified in normal air conditions. This step took 5 minutes.
- The density indexes of samples were measured automatically with Archimedes test device (Figure 3.4) after quenching the samples. This device gives instructions and asks for measuring weight of samples in air and then in water, so the samples should be put according to instructions into holders. The device calculates the density index (DI) automatically.

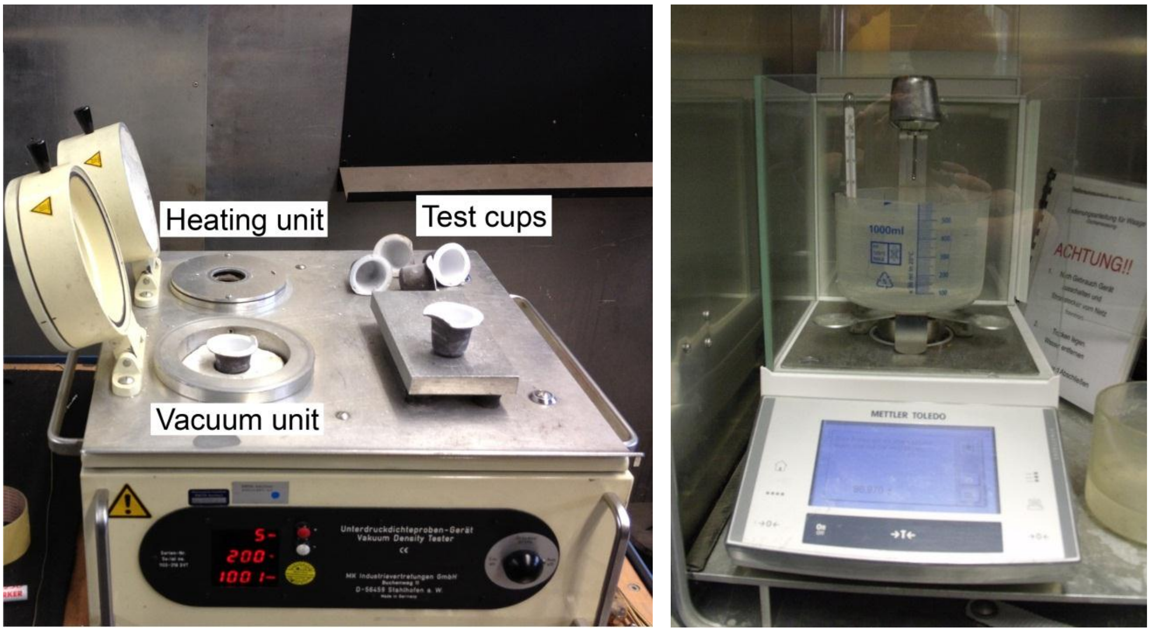


Figure 3.4 Vacuum test (RPT) and Archimedes test devices

- The density indexes were checked if the gas content of molten metal is in acceptable tolerances to continue the experiments. DI values for tests of conventional castings ≤ 2% and for AMS applied castings ≤ 4% (spiral test) and ≤5% (bolt test).
- When the gas content (density indexes) was too high, degassing was applied again.

3.2.5 Sand Core Making and Spiral Tests

In this study, a new sand spiral mold was used to evaluate the fluidity of aluminum alloys. It was particularly designed to investigate the AMS behavior. One part of study was also evaluating the accuracy of the new mold with an older one.

- Making sand spiral cores was the first step of this study. Silica sand mixed with binder and activator according to content values in Table 3.4.

Table 3.4 Sand mixing ingredients table

Sand Type	Binder	Activator	Mixing Time
F36 Silica 50kg	Gasharz 6966 400g	Activator 7624 400g	4 Minute

- After sand mixing step, mixed sands transferred to core shooting machine to form sand spiral molds. Core shooting periods are shown in Figure 3.5.

- Core shooting process realized with Röperwerk Core Shooting and Hardening Machine (FCJ 12 C-K) that was operated with Siemens Simatic Op7 control system.
- Assembled plastic mold of the mold was filled with sand which was send into the mold with high pressured air in only a few seconds.
- After this step sand cores were cured with amine gas at 2.2 bar (Figure 3.6)
- Curing period provided the ultimate strength of the sand mold. The process ended with stripping and then core removal steps.

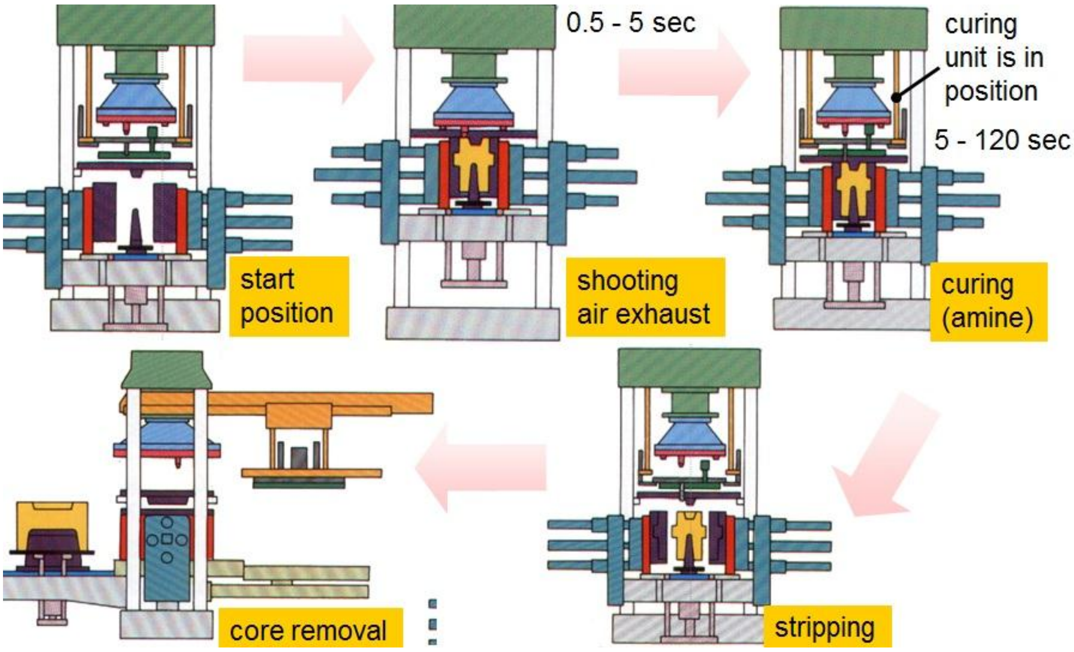


Figure 3.5 Core shooting steps-schematic view [23].

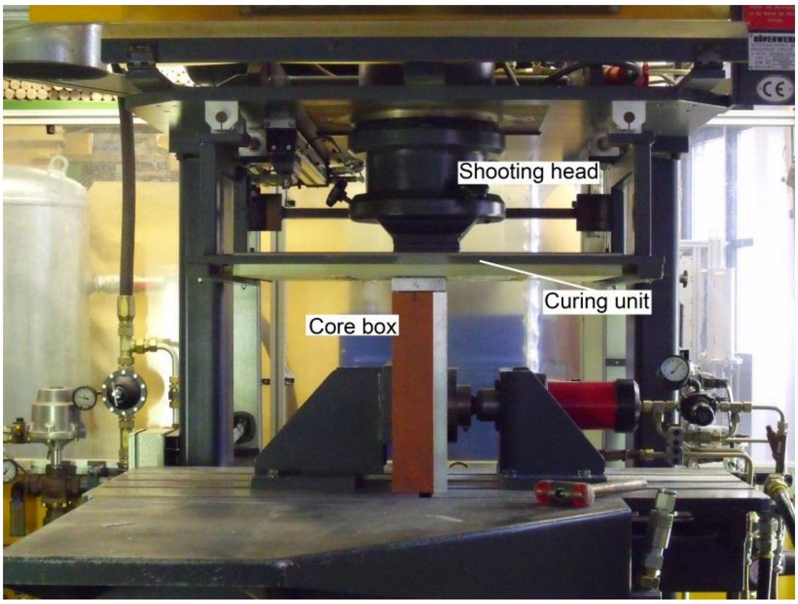


Figure 3.6 Curing step of core shooting process

- Produced sand cores are cleaned with pressure air to avoid from sand particles in flow channels. Assembled sand cores were clamped to let molten metal to flow in only flow channels (Figure 3.7).
- Before pouring the alloys, pouring base and stopper coated with graphite and then preheated (250˚C). Furthermore, the stopper was integrated one K-type thermocouple (Ni-CrNi, max 1100 ˚C)
- Molten metal poured into sand spiral molds at determined temperatures (Figure 3.7).
- After solidification, sand molds are broken and spirals are removed from the sand molds.
- The spiral lengths are measured with measuring paper that includes spiral draw and measuring scale on it and the measurements are transferred to diagrams.

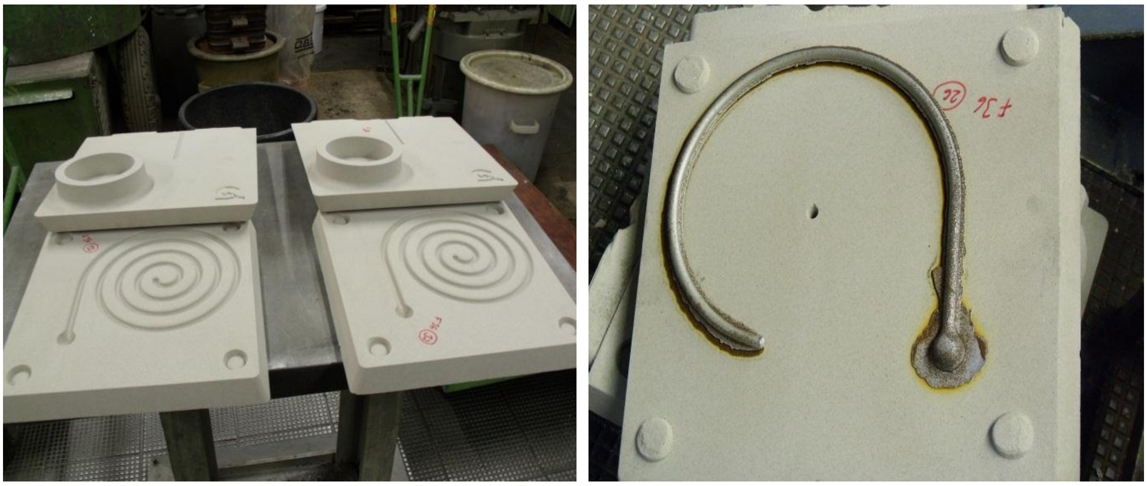


Figure 3.7 Sand spiral molds and spiral cast.

3.2.6 Bolt Penetration Test

In this study, tilt casting machine is used for bolt tests, so the bolt die that was designed for tilt casting machine (Figure 3.8), was integrated to the tilt casting machine (Figure 3.9) to provide better heat and time conditions.

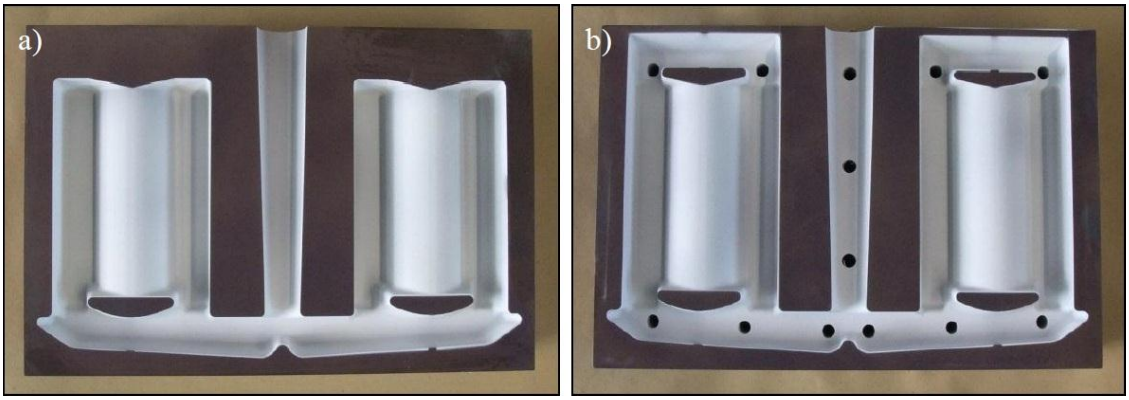


Figure 3.8 Bolt die parts: fast/fixed (a), moveable (b)

- Firstly, spoon and casting chamber preheated (250˚C) with blow torch fire and also five samples were poured for warming the Bolt die.
- The test steps include filling the pouring of chamber of the tilt casting machine with molten metal, waiting for temperature drop in determined level, casting and leaving the bolt specimen. In this step the thermocouple that was located above pouring chamber, determined the melt temperature.
- The casting experiments are realized at determined temperatures that are given in Section 4.1.

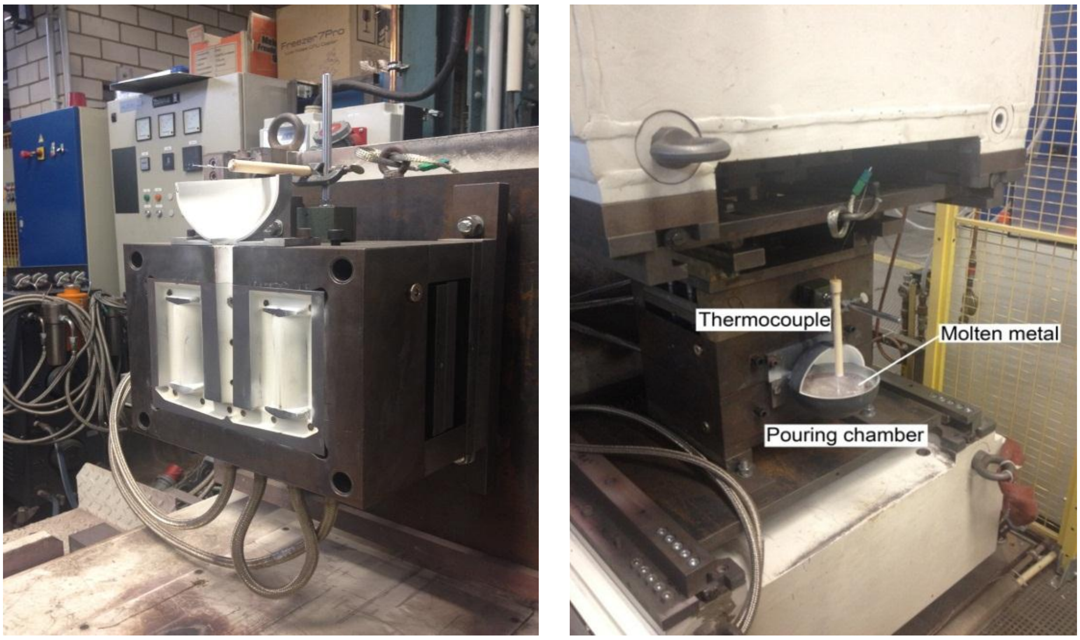


Figure 3.9 The Bolt test die on tilt casting machine (pouring position) and pouring chamber (loading position)

- After cooling period the samples are scanned (Canon Canoscan 4400F) at 1:1 scale and the gaps are measured in Photoshop CS5.

- Measurements were realized by using reference lines that shows the metallostatic heads which are seen in Figure 3.10. The top flat surface accepted as 0 level and the gaps were measured in every 2 cm (total 4 measurements). The values are collected in tables and the standard deviations are calculated.
- During the experiments unexpected temperature drops were occurred and also after every casting pouring chamber cleaned from solidified thin metal layers.

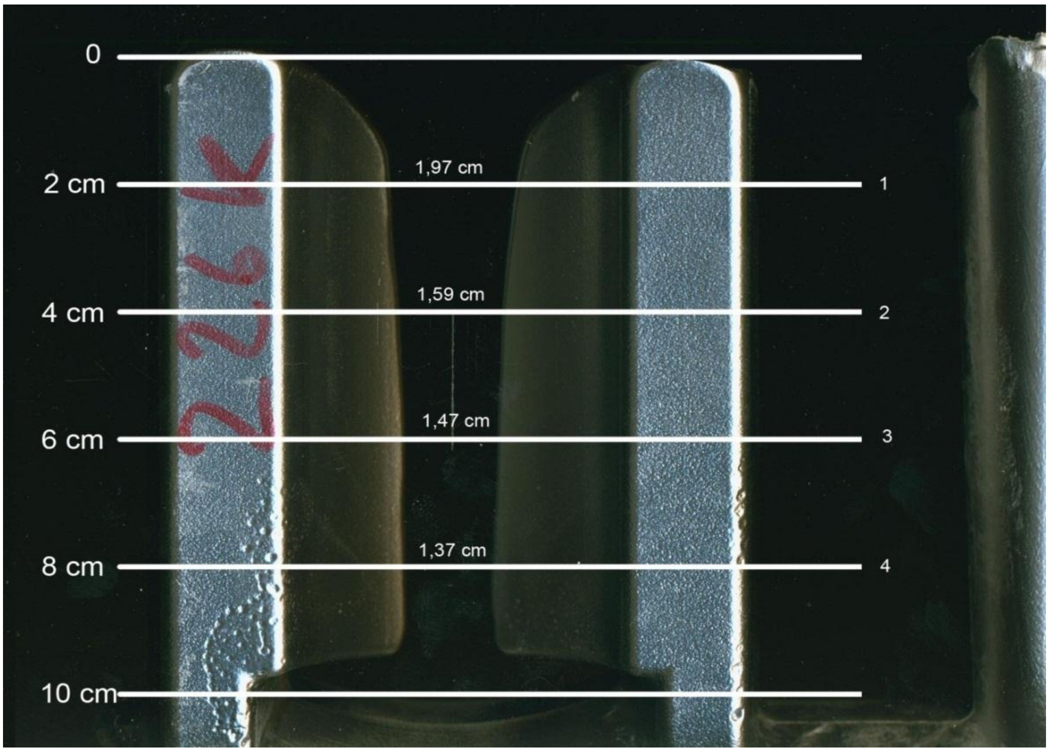


Figure 3.10 Measurement of gaps in Bolt Test

- Heating the tools and pouring chamber was caused loss of time, some experiments couldn't be done at determined temperatures.
- The Bolt specimens generally had some surface defects caused by the coating. They can be seen in Figure 3.10 and also rough surface.
- Finally, the measurements with standard deviations are transferred to diagrams.

3.2.7 Dendrite Arm Spacing

DAS analyses were done to understand the effect of AMS with high velocity mechanical stirring on microstructure. This analysis is applied for preliminary experiments on A356 alloy.

After conventional metallographic processes, dendrite arm spacing analysis was applied with help of the Photoshop CS5 as an image analysis. Line analysis method was applied to evaluate the DAS like explained in Section 2.6.4.

For every image 6 line analyses were done and average values were taken for the diagram. DAS analysis applied A356 conventional and AMS microstructures are shown in Figure 3.11.

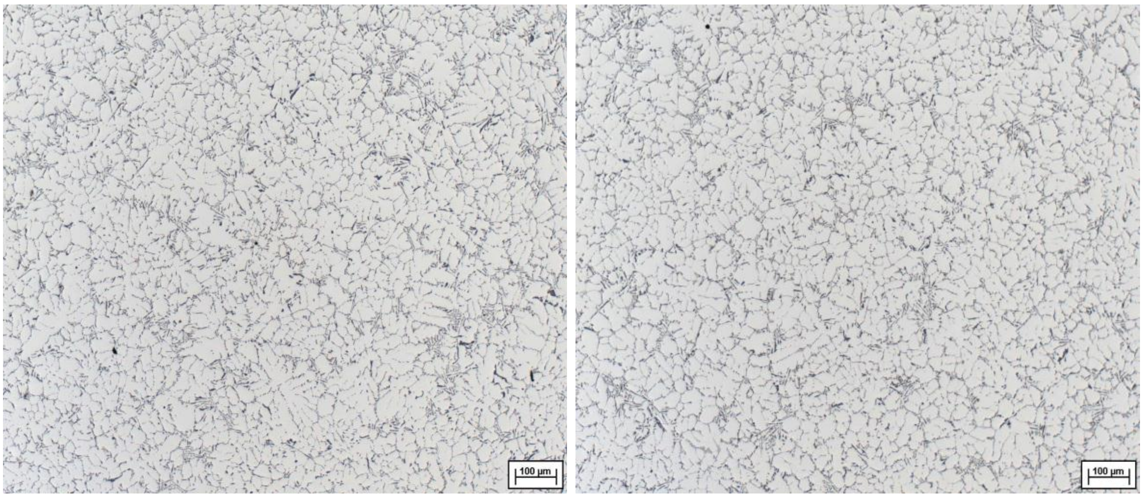


Figure 3.11 Microstructures of A356 conventional (left) and AMS (right)

CHAPTER 4

RESULTS

4.1 Experimental Findings

This part includes Bolt test results, sand spiral test results and also dendrite arm spacing measurements.

Firstly some preliminary sand spiral tests were done to compare the results with old spiral mold that has different channel shape (includes sharp edges) and also rougher surface than the new ones. In preliminary experiments, for A380 alloy, spiral test applied and the cast temperatures were 610 and 700 ˚C. This experiment was done to understand the AMS effect on fluidity. Furthermore, for A356 alloy, sand spiral test were applied at 720 ˚C with conventional and AMS technique to understand the effect of AMS. After this experiments dendrite arm spacing analysis were done for A356 alloy and tried to evaluate changes in microstructure. This part constructed basic knowledge about the AMS effect on fluidity and also microstructure.

The result of experiments showed that the new spiral mold have lower standard deviations than the old die. The old die couldn’t exhibit good performance because of sharp edged channel type and also rough surface conditions. Furthermore, experiments with new design showed that the stopper usage plays an important role in reliable results. All these conditions gave information about experimental conditions and as a result of these experiments continued with new spiral molds.

According to spiral test diagram of A380 alloy (Figure 4.1), superheat effect can be seen obviously. Furthermore high velocity stirring showed increasing effect on fluidity and also the effect of superheat were increased by AMS effect. At low temperatures experiment results were more reliable than high temperatures because of high standard deviations that resulted from experimental conditions. Nonetheless, the AMS effect causes a distinct increase of the flow length.

As seen in Figure 4.2 the experimental results that achieved with new sand spiral mold have better scatter than the old one (Figure 4.1). The average flow lengths seem almost same but the scatter of values has big differences. New sand mold provided nearly linear scatter, thus it gave more reliable results (Figure 4.2).

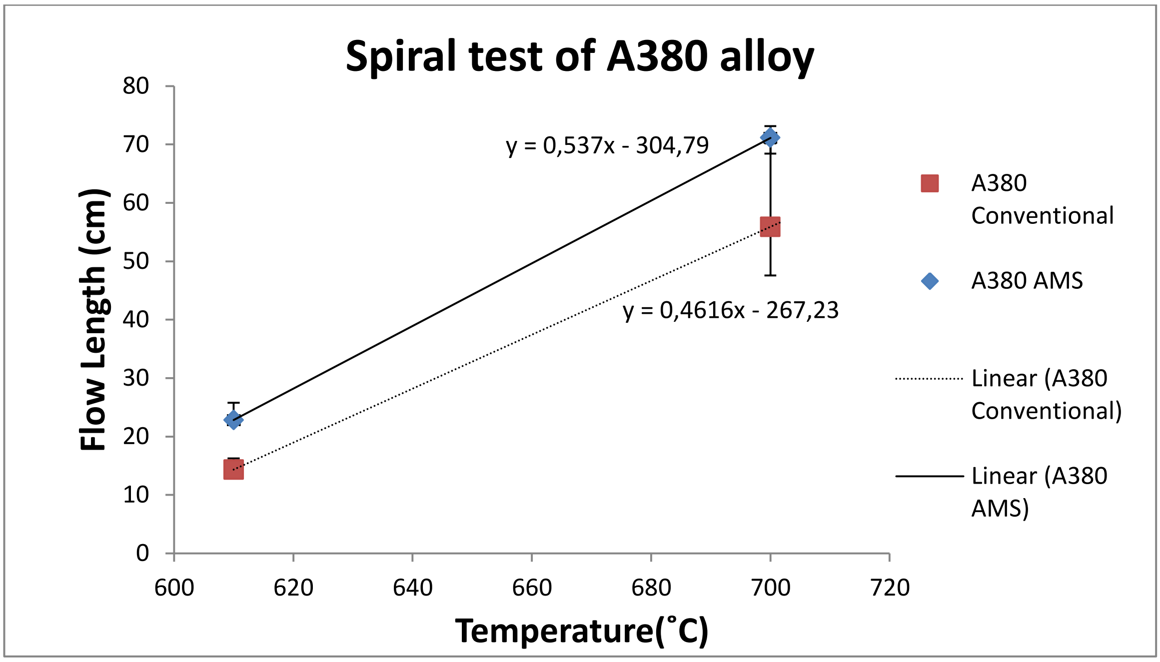


Figure 4.1 Spiral test of A380 alloy (old spiral mold)

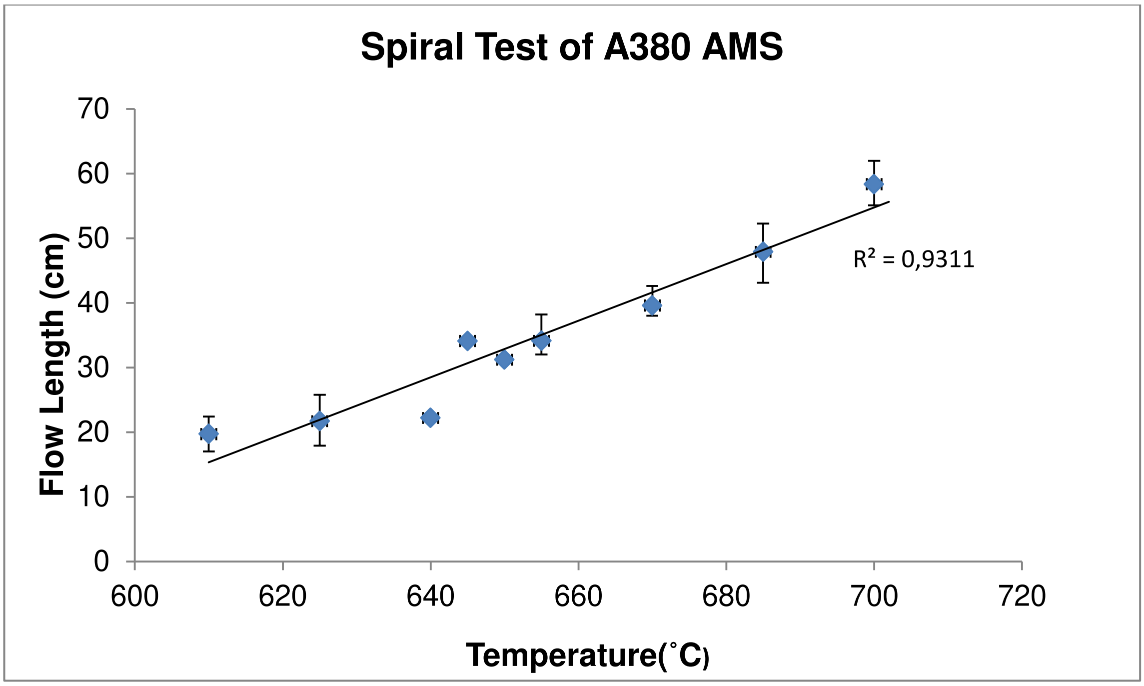


Figure 4.2 Spiral Test of A380 AMS (new spiral mold)

In addition, superheat of the melt shows same linear increasing flow length within spiral tests of A356 alloy in Figure 4.2.

Spiral test of A356 alloy with old molds gave unreliable results because of experiment conditions. According to diagram (Figure 4.3) high velocity stirring applied A356 alloy achieved better fluidity level but standard deviations prevent to explain this effect.

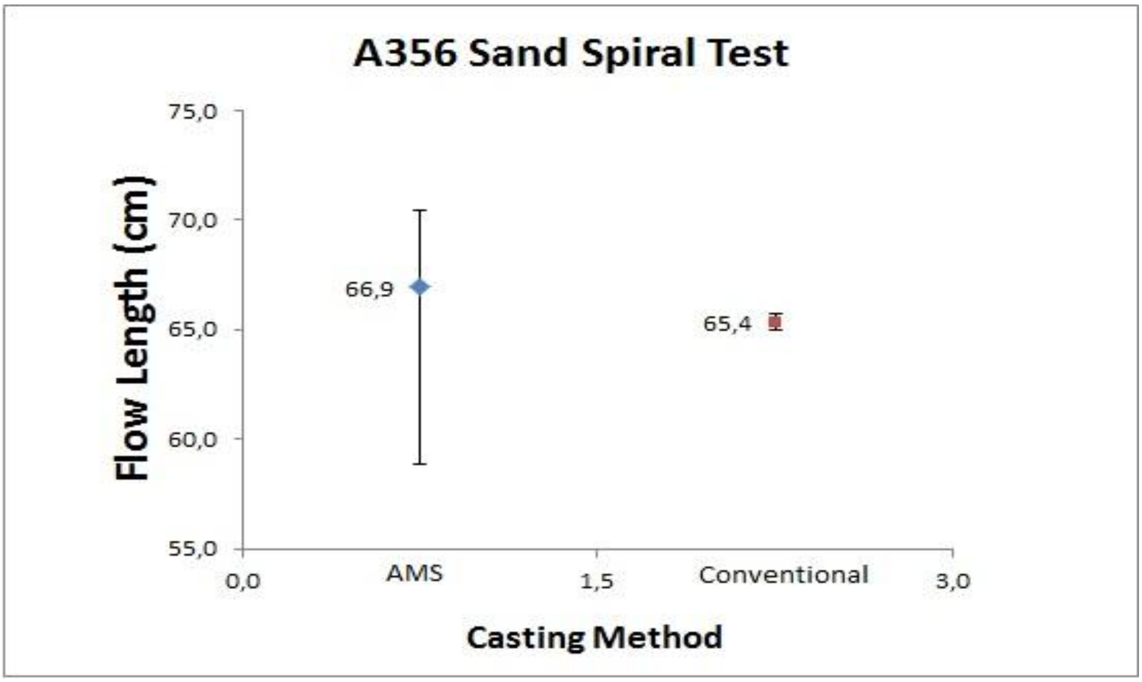


Figure 4.3 Spiral test of A356 alloy

DAS analysis results support this situation as seen in Figure 4.4. Because of high standard deviations, doing reliable comparison is not possible.

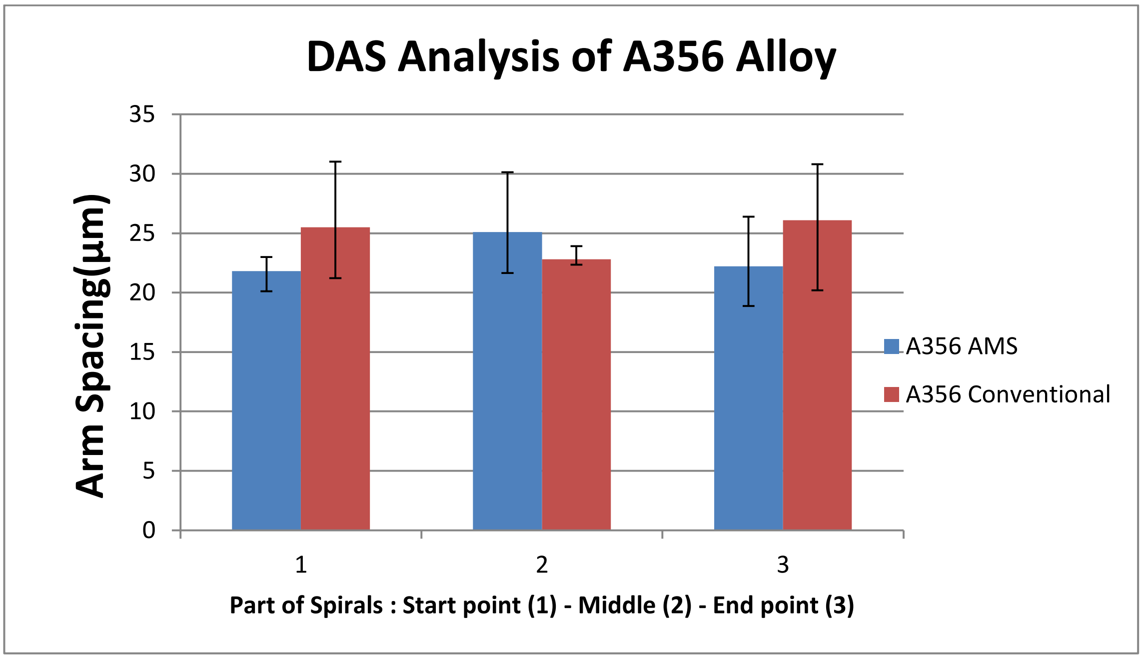


Figure 4.4 DAS analysis of A356 Alloy

These analyses were done by taking samples from the start, end and middle sections of the spiral casts. As can be seen in Figure 4.4, the measurements from the start points of the spirals, conventional casting has higher DAS and higher scatter of results compare to AMS casts. The middle section of samples shows the opposite situation with the start points. This time AMS casts shows higher DAS and high scatter. At the end points, both alloys show very close results and almost same scatter that within the same range. However, it is important to note that the difference in DAS from start to end point is within +/-5 µm. This cannot be considered to be a significant change. It can be concluded that there is no difference in the microstructure of both alloys depending on the throughout the spirals.

After preliminary experiments for A380 alloy, Bolt test is applied conventional casting with addition of Micro100 and for each addition five castings at 680˚C were done. Spiral test was applied at 610,625,640,655,670,685 and 700 ˚C with the AMS method and three specimens casted for each temperature.

For A356 alloy, Bolt test was applied at 720 ˚C with AMS and conventional method and five casting was taken for each method. Spiral test is applied at 630,645,660,675,690,705 and 720 ˚C with AMS and conventional method and tree specimens casted for each temperature in every method. However some castings were poured at different temperatures because of unexpected conditions for example instant heat changes, tool temperatures.

Flow chart of experiments that shows the steps of this study is seen as in Figure 4.5. A356 and A380 ingot were cut and melted in a furnace which has graphite crucibles. Degassing step is also applied with graphite lance by Argon 4.6. Acceptable density index for first period of experiments was maximum 2%. These standard procedures were applied for every casting experiment. After these procedures, tests were realized as shown in Figure 4.4.

Especially after AMS trials, acceptable density indexes were %4 (for spiral test) and %5 (for bolt test) because they are applied one after another and the melt wasn't waited to avoid extreme temperature drops.

Experiments and other preparations were realized as told in Section 3.2.

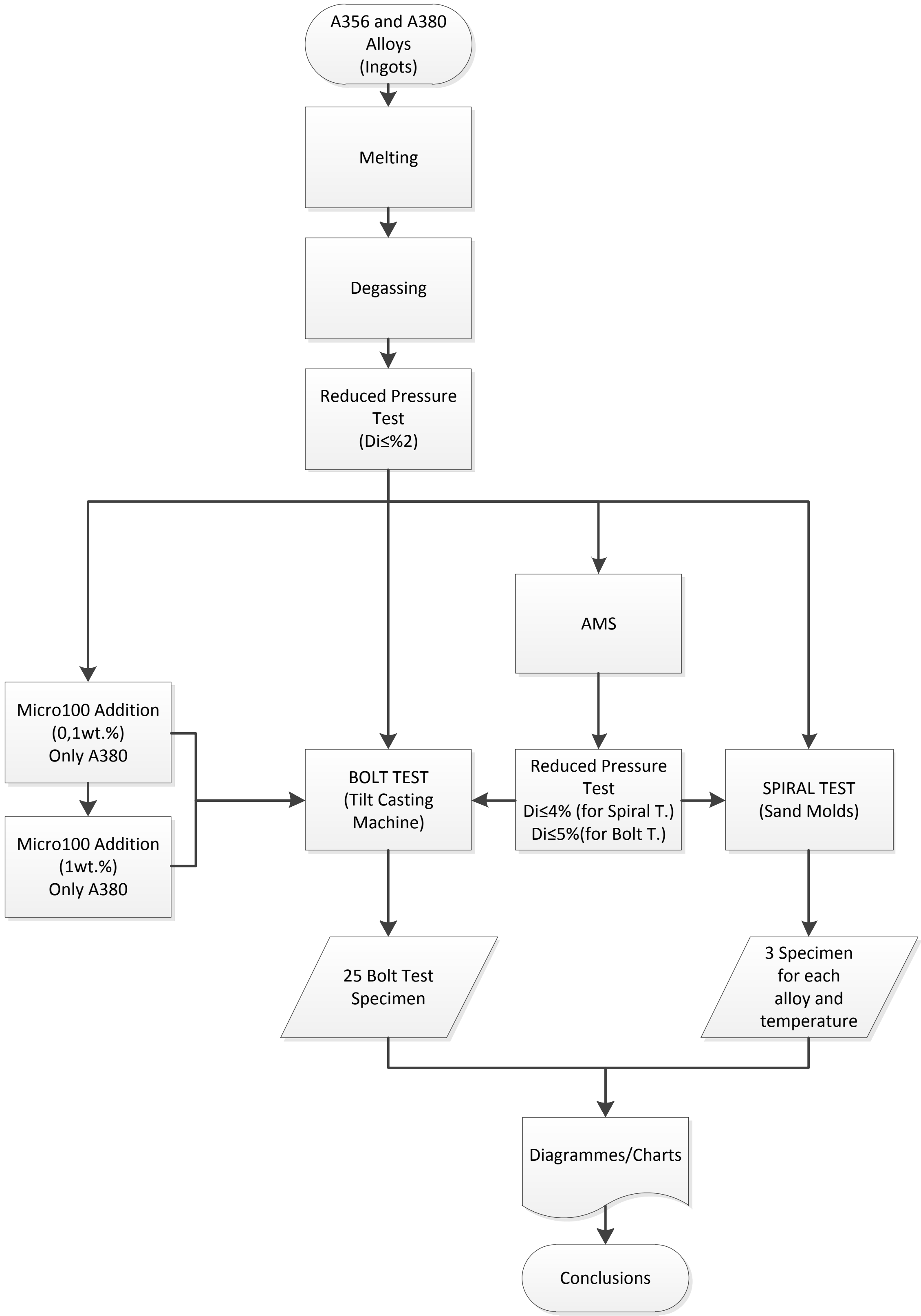


Figure 4.5 Flow Chart of Experiments

As seen in the Figure 4.6, the gap dimensions are reducing according the measurement level (depth). This difference is caused by feeding type of the die and the melt goes inside from bottom of the die.

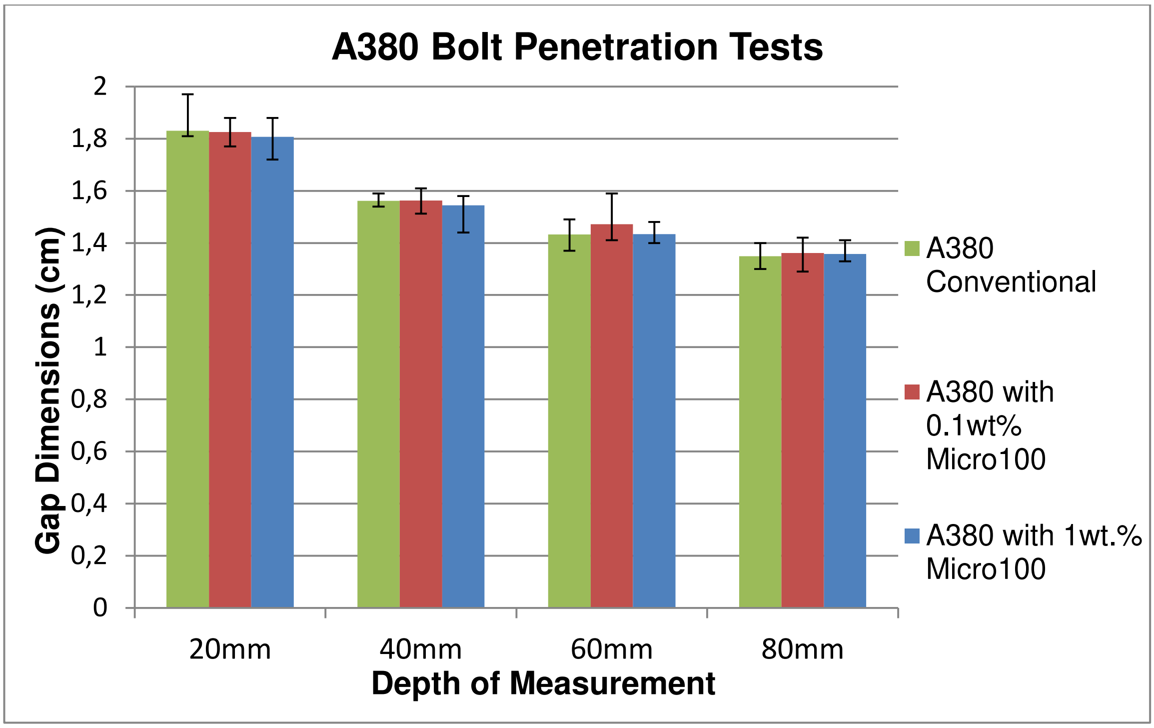


Figure 4.6 Bolt Penetration Test for A380 alloy - Effect of Micro100 addition.

According to diagram in Figure 4.6, addition of Micro100 in different amounts cannot show the expected effect on form filling capability. The gap dimensions and also scatters are almost similar. It can be concluded; in this test Micro100 addition couldn't show any significant effect.

As seen in Figure 4.7, Bolt test of A356 which was done to explain high velocity stirring effect on form filling capability, show increasing values with small standard deviations. AMS method has higher gap dimensions at every measuring level. This result explains that, the AMS reduced the form filling capability of A356 alloy contrary to expectations.

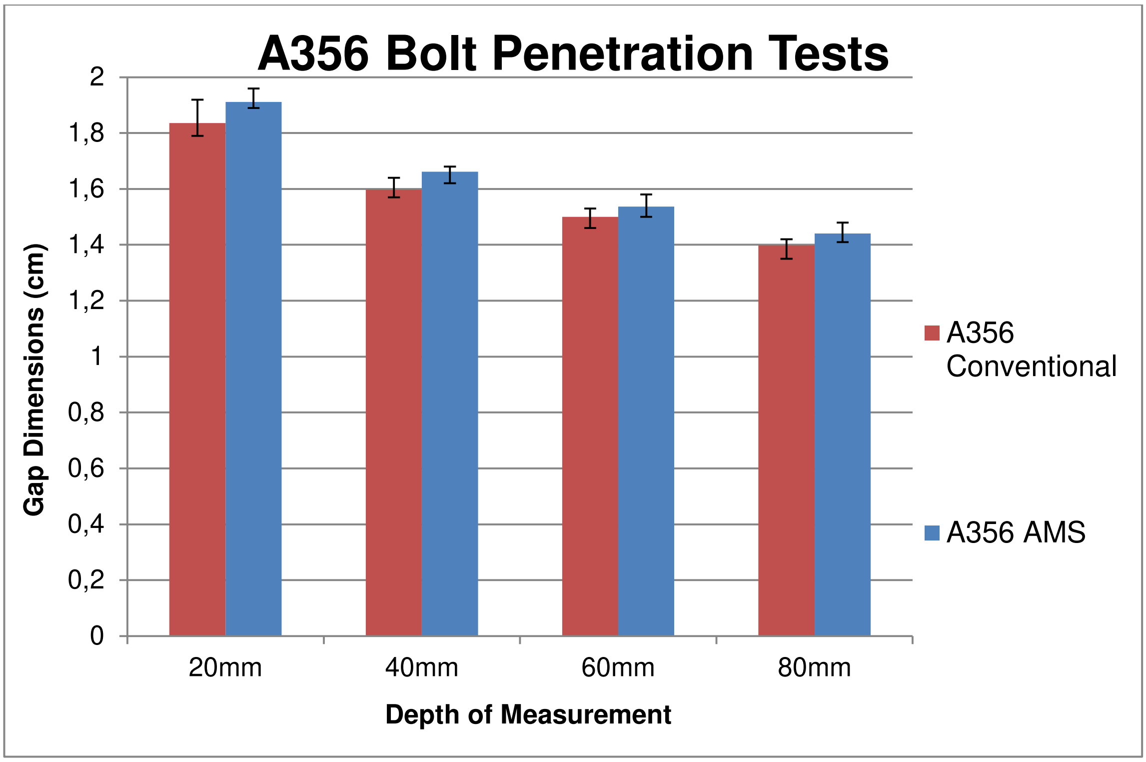


Figure 4.7 Bolt Penetration Tests of A356 alloy - Effect of the AMS technique.

According the Figure 4.7 the gap dimensions were increased maximum %4 by AMS. Furthermore, spiral test results of A356 alloy support this effect of AMS.

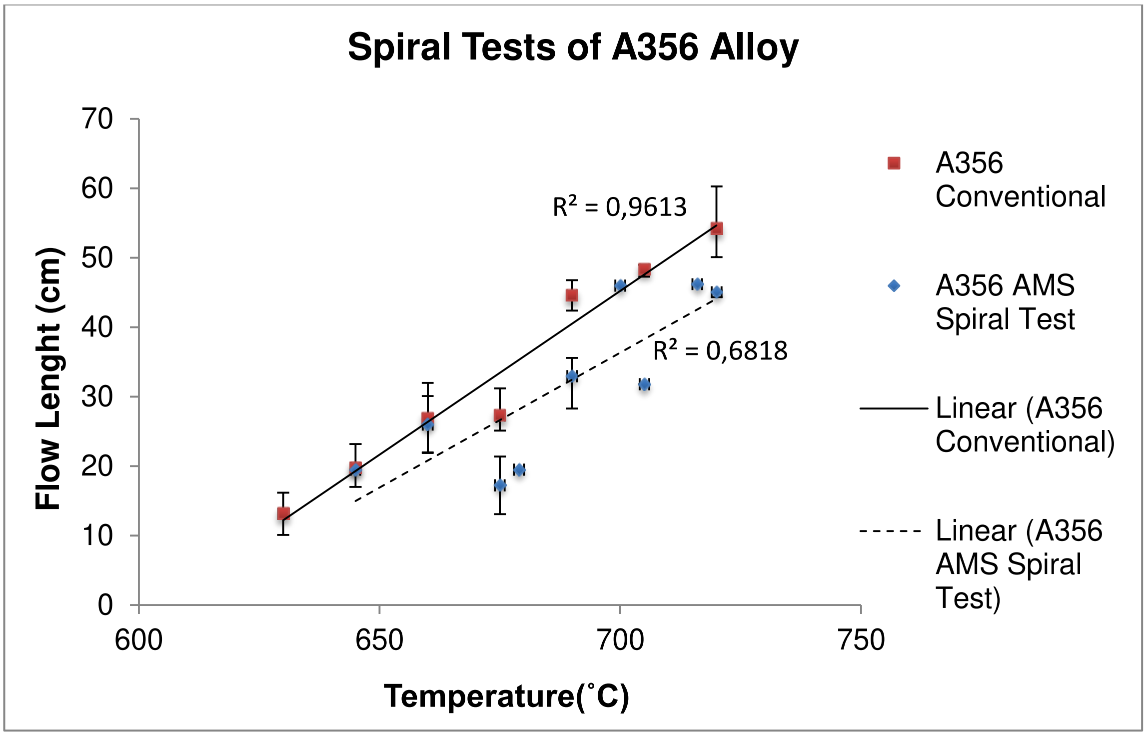


Figure 4.8 Spiral tests of A356 Alloy

According to Figure 4.8, spiral lengths (flow lengths) of A356 alloy are both AMS and conventional casting method, are increasing with the temperature linearly. However the higher scatters of the spiral lengths of the AMS don't let to talk about significant effect of high velocity stirring.

Microstructures of A356 alloy that was applied high velocity stirring and conventionally casted, as seen in Figure 4.9 with 10µ scale and they were done in preliminary experiments.

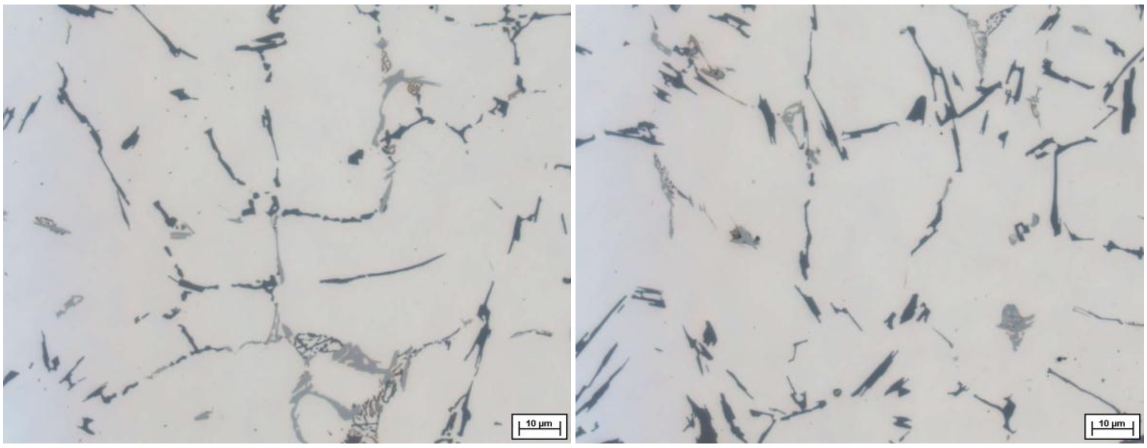


Figure 4.9 Microstructure of A356: AMS (left), Conventional (right)

Under normal conditions, low DAS (finer grains), and high eutectic fraction signifies better fluidity conditions. According to visual inspection of these microstructures, eutectic fractions and grain size average almost in same values. This inference also can be supported DAS results.

4.2 Die Design and Construction

As the sand spiral test results have shown, the new mold design could stand up, therefore the sand spiral mold measurements transferred to the die to achieve comparable results by doing experiments on the fluidity for future studies. The new die design has same flow channel type and dimensions with spiral sand molds. As a result of this same pouring conditions will be provided to comparisons. This helps to understand the effect of higher cooling rate and also solidification mechanisms on fluidity in future studies. The heating system and board of old die can be used for the new one, and that provides economy.

In this part some improvement possibilities of redesigned mold are explained.

First of all, the design should be in ideal conditions to achieve desired properties and also security levels. Beside of this, mold accuracy, costs, lifecycle, usage facility, safety etc. specialties must be ensured.

Improvements of mold are restricted by geometrical properties that are transferred from existing sand mold. As a result of this situation, improvements can be applied for practical usage, safety, technical properties.

The mold which is redesigned may be used with table that is connected with tougher support unit. Existing unit can cause problem when the surface of working area is rough. On the other hand the support unit can be fixed to the ground to be sure about safety. Also this support unit includes parts to help transportation of the mold.

Measurement scale can be added to redesigned mold, so that the measurement part of spirals can be finalized in shorter time. Producing new measurement equipment which is made of sheet metal can be helpful on this situation. On the other hand with external measurement equipment can measure the length of spirals sensitively.

The upper mold is fixed to lower mold by hinges through one edge. However, during the casting, mold parts must be fixed to each other properly. This situation reduces the process rate. As a solution, the upper mold can be integrated with pneumatic system, so mold parts can be left from each other in parallel position. Similarly this helps to fix all areas of mold at the same time effectively. This technic provides quickly setting the molds for next castings.

Thermocouples should be installed (or added) to the various locations in the mold to ensure and control temperature distribution (Figure 4.10). Furthermore, fixed thermocouples can be used on specific points of the upper and lower mold parts such as starting, middle and ending points of the spiral such as T1, T2 and T3(upper and lower die position). Thermocouples can also be located at the corners to determine the temperature level of die completely such as Tx, Ty, Tz (upper and lower die position). The other possibility is measuring the oil temperature between entrance and exit of the heating channel such as Ta and Tb. It can be controlled and verified by the simulation progress. They can be located on different thermal gradient areas on upper and lower die parts and also more than three thermocouples can be used for being sure about temperature distribution.

The die could be coated with some type of a ceramic coating to extend its life-cycle and avoid from mold – melt reactions, also sticking problems.

On the other hand, with the aim of increasing experimental sensibility, mold can be designed with two spirals. At the same time and same temperature casting two spirals improves the investigation sensibility.

According to results of simulation, heating system of mold can be optimized. Flow rate of oil can be optimized and oil with different viscosity can be used. The re-designed spiral die and channel type of it are seen as in Figure 4.11.

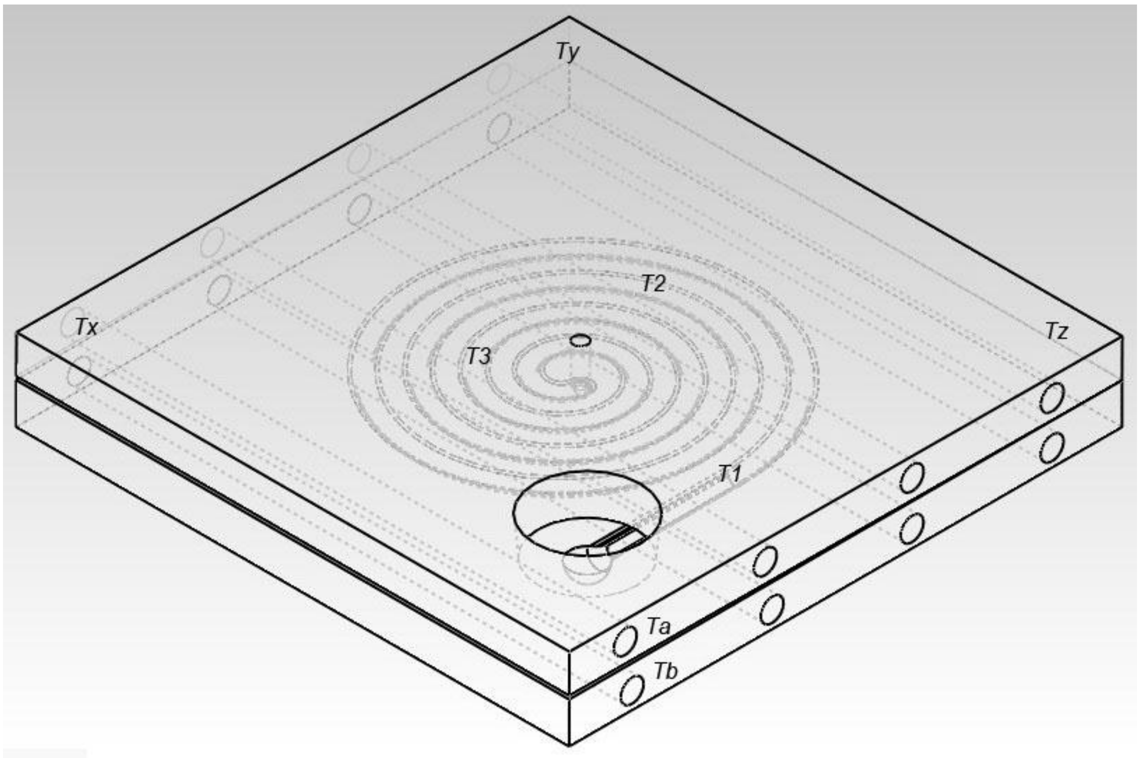


Figure 4.10 Possible thermocouple locations

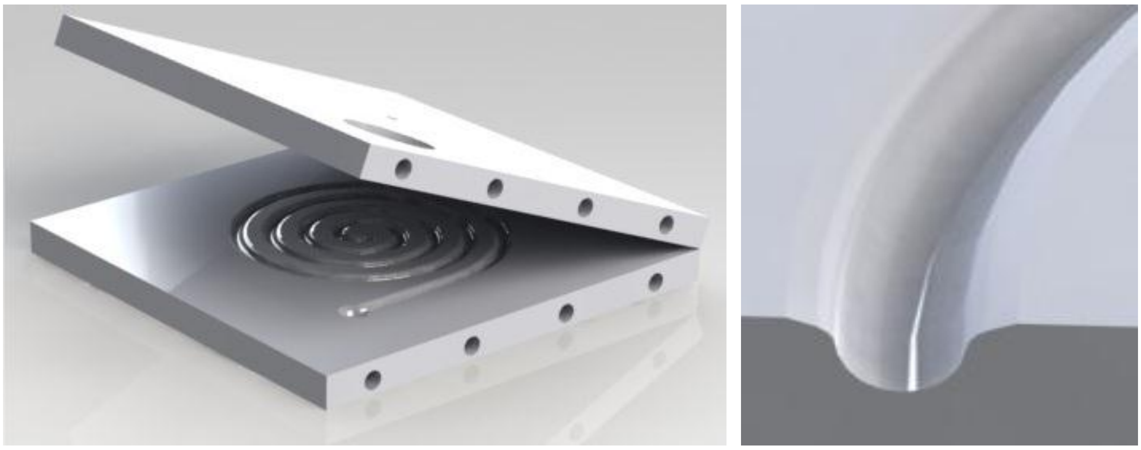


Figure 4.11 New die and its channel type

CHAPTER 5

SUMMARY AND DISCUSSION

In this study, effect of high velocity stirring (the AMS technique) on castability of A356 and A380 alloys are investigated. The literature survey is based on the fluidity of aluminum alloys and related phenomena such as metallurgical factors (melt composition, modification, superheat and viscosity), solidification mechanisms, porosity and oxide formations and also mold characteristics. On the other hand different casting methods, effective parameters on these methods and desired properties were explained.

The experiments are carried out with different applications such as addition of Micro100, pouring at different temperatures and mechanical stirring to understand the effects of these parameters on the form filling capability and fluidity, hence castability.

For spiral tests, sand spiral molds are produced with core shooting machine (cold box) and used for A356, A356 AMS and A380 alloys.

In preliminary experiments A380 alloy was investigated. High velocity stirring increased the fluidity in spiral tests. However high standard deviations prevented certain arguments. Furthermore A356 alloys investigated in preliminary experiments. Sand spiral tests and also DAS analysis couldn't explain the exact effect of AMS because of same reason with A356 tests. High standard deviations caused by experiments with rough surfaced sand molds without stopper usage.

For Bolt tests, bolt die was used but it was integrated to tilt casting machine and A380, A380 + 0.1wt.% Micro100, A380 + 1wt.% Micro100 were casted to understand the Micro100 effect on form filling capability and also A356 and A356 AMS alloys were casted to effect of high velocity stirring on the form filling capability.

Spiral die was re-designed in the same dimensions with sand spiral to experience comparable properties between them for future studies.

As a result of experiments, the Micro100 effect could not be seen significantly, increasing melt superheat increased the fluidity and the AMS method reduced the form filling capability of A356 and A380 alloys because the used AMS-alloys were poured more than a year before, the decreasing casting properties could also be as a result of decreasing memory effect. This situation was not verifiable in this thesis. Nonetheless, micro oxides seem not to be the reason for better casting properties.

With the Bolt test experiments, the effect of Micro100 master alloy on the form filling capability of A380 alloy was investigated. Pouring was carried out at 680˚C and additions were done in order of 0.1wt.% and 1wt.% Micro100.

As can be seen in Figure 4.6, there is not much difference in the Bolt Penetration test results of A380, A380 0.1 wt.% Micro 100 and A380 1wt% Micro 100 additions. The gap measurements were close to each other for each depth.

It would have been expected that there would be a significant difference between the pure alloy and Micro 100 additions. Because of Micro100 additions, big and irregular pores should be turn to micro porosities, in that case penetration capability would be increased. However it was not observed in this work.

This situation could be occurred because of following parameters;

- Heat conditions might not be enough to effective distribution of Micro100 that was added as rod.
- After reaction of Micro100 surface films might be occurred and sank during the pouring.

The AMS technique was also tried in spiral test of A380 alloy. As can be seen in Figure 4.8, there is a linear relationship between temperature and fluidity length of A380 AMS. As the temperature was increased, fluidity was increased.

With Bolt test experiments, the effect of high velocity stirring (the AMS technology) on the form filling capability of A356 alloy was investigated. Pouring was done at 720˚C.
In the literature [43] the AMS technique is existed as innovative method to improve form filling capability. In certain previous researches [44], improving the form filling capability cannot be seen. The results of this experiment in Figure 4.6 show that the AMS method increased the form filling capability of A356 alloy. This difference could occur because of:

- Stirring efficiency
- Sink of oxide films into the melt by the stirring
- Thermal drops

With the spiral test experiments the effect of high velocity stirring (the AMS technology) on the fluidity of A356 alloy was investigated. Pouring was realized at 720 ˚C and sand spiral molds are used. According to literature, the fluidity of A356 alloy would be increased, hence the flow lengths would get longer. However, in this experiment, expected results could not be reached because of the number of AMS applied samples were not enough and the heat conditions cannot be secured, hence standard deviation value was too high. In Figure 4.7, reducing effect of AMS can be seen but the data is not trustable to compare.

On the other hand, in Figure 4.8,the effect of melt superheat can be seen obviously. The increasing of pouring temperature raised the fluidity of A356 alloy.

According to these results, mechanical and magnetic stirring parameters should be probed again and heat conditions should be secured to reach for useful experimental information.

CHAPTER 6

CONCLUSIONS

According to results of experiments, these following conclusions accessible:

- Preliminary experiments were done under effects such as rough surfaced spiral molds and also without stopper that causes high standard deviations. As a result of this the effect of high velocity stirring couldn't be seen obviously on DAS and the fluidity. On the other hand A380 alloy showed better results that explained the increasing effect of high velocity stirring on fluidity.
- The effect of melt superheat was experienced obviously. As expected, higher pouring temperatures increase linearly the fluidity of aluminum alloys. This situation can be seen obviously in spiral test results of A356, A356 AMS and A380 AMS.
- Micro100 should make the fluidity as a result of this form filling capability better by treatment that includes reducing porosity sizes. However the form filling capability of A380 alloy was not significantly affected by 0.1wt. % and 0.1wt. % Micro100 addition. As a result of these effects of Micro100 treatment could not be seen.
- Contrary to expectations high velocity stirring reduced the form filling capability of A356 alloy.
- Effect of the AMS method on the fluidity of A356 alloy cannot be understood because of high standard deviations and insufficient number of specimens.
- Visual inspection of microstructure of A356 alloy was in harmony with DAS results to explain that couldn't be seen significant effect of high velocity stirring.
- Re-designed die can be used for future works to experience the effect of mold material on the fluidity and also the fluidity behavior of specific alloys in different mold materials.

- In addition to process parameters, experimental conditions showed strong effect on experimental results.

Finally, no significant effect of mechanical stirring and micro oxide treatment on the casting properties could be determined at all.

REFERENCES

[1] Dispinar D., (2005). Determination of Metal Quality of Aluminium and Its Alloys, PhD Thesis, the University of Birmingham, Birmingham.

[2] Sabatino M. D., (2005). Fluidity Of Aluminium Foundry Alloys, PhD Thesis, Norwegian University of Science and Technology (NTNU), Trondheim.

[3] Sabatino M. D., Arnberg L., (2009). "Castability Of Aluminium Alloys", Transactions of The Indian Institute of Metals, 62(4-5):321-325.

[4] Kaufman J. G., Rooy E. L., (2004). "Aluminum Alloy Castings: Properties, Processes, and Applications", ASM International, December 2004, ISBN: 0-87170-803-5.

[5] Aluminum Design, http://www.aluminiumdesign.net/why-aluminium/properties-of-aluminium/, 27 July 2012.

[6] Udompol T., (2007). "Aluminum and its alloys", Presentation, Suranaree University of Technology, May-Aug 2007.

[7] ASM Metals Handbook, (1998). 9th Ed., Vol. 15, "Casting", ASM International, ISBN 0-87170-007-7.

[8] Gruzleski J.E., Closset B.M., (1999). "The Treatment of Liquid Aluminum-Silicon Alloys", American Foundrymen's Society, Inc., USA, ISBN 0-87433-121-8.

[9] Zolotorevsky V. S., Belov N. A., Glazoff M. V., (2007). "Casting Aluminum Alloys", Elsevier Ltd. Al, 2007, ISBN 978-0-08-045370-5.

[10] Warmuzek M., (2004). "Aluminum-Silicon Casting Alloys: Atlas of Microfractographs", ASM International, May, ISBN: 0-87170-794-2.

[11] Raghavan V. , (2007). "Phase Diagram Evaluation", Journal of Phase Equilibria and Diffusion, Vol. 28, ASM International.

[12] Shabestari S.G. , Parshizfard E., (2011). "Effect of semi-solid forming on the microstructure and mechanical properties of the iron containing Al–Si alloys", Journal of Alloys and Compounds, Volume 509, Issue 30,28 July, Pages 7973-7978.

[13] Casting and Forgings News, http://www.castings-forgings-news.com/castings/ShowPage.aspx?pageID=1570, 27 July 2012.

[14] Custompartnet, http://www.custompartnet.com/wu/SandCasting, 27 July 2012.

[15] Castings Technology International, http://www.castingstechnology.com/public/services/technologies/TECMouldingTechnologies.asp, 27 July 2012.

[16] Custompartnet, http://www.custompartnet.com/wu/shell-mold-casting, 27 July 2012.

[17] Speed Way Motors, http://www.jp-alphatec.com/en/img/products/010_b.jpg, 27 July 2012.

[18] Thick Performance, http://www.tickperformance.com/slp-ls3-aluminum-off-set-rocker-arm-package-1-85-ratio/, 27 July 2012.

[19] Chevrolet C5 C6 Corvette American Metal Racing, http://www.corvette.zorly.com/2008/09/new-2009-c6-chevrolet-corvette-zr1.html, 27 July 2012.

[20] Zeren M., (2005). "Effect of copper and silicon content on mechanical properties in Al–Cu–Si–Mg alloys", Journal of Material Processing Technology, Issue 169, March 2005, Pages 292–298.

[21] Tan E., Tarakcılar A.R., Dıspınar D., Colak M.,Kayıkcı R., (2011). "Reproducibility of Reduced Pressure Test Results in Testing of Liquid Aluminum Gas Levels", 6th International Advanced Technologies Symposium (IATS'11), 16-18 May 2011, Turkey.

[22] Djurdjevic M.B., Odanovic Z., Pavlovic-Krstic J., (2010). "Melt Quality Control At Aluminum Casting Plants", Assocation of Metallurgical Engineers of Serbia (AMES), March 2010, UDC: 621.747:669.71.

[23] RWTH Aachen Foundry Institute, (2012). Casting Technology 2, "Chemically Bonded Sand Presentation", Aachen.

[24] Dıspınar D., Campell J., (2004). "Determining the Aluminum Melt Quality using Reduced Pressure Test", 10th Denizli Materials Symposium and Exhibition, April 2004, Denizli.

[25] Cruz K.S, Meza E.S., Fernandes F.A.P, Quaresma J.M.V., Casteletti L.C., Garcia A., (2010). "Dendritic Arm Spacing Affecting Mechanical Properties and Wear Behavior of Al-Sn and Al-Si Alloys DirectionallySolidified under Unsteady-State Conditions", The Minerals, Metals & Materials Society and ASM International, 2010, DOI: 10.1007/s11661-009-0161-2.

[26] Campanella T., Charbon C., Rappaz M., (2004). "Grain Refinement Induced by Electromagnetic Stirring: A Dendrite Fragmentation Criterion", Metallurgical and Materials Transactions, October 2004, Vol 35A-3201.

[27] Sydorenko S., (2009). Verbesserung der Qualität von Gussstücken durch elecromagnetische Schmelzebehandlung, PhD Thesis, der Otto von Guericke University, Magdeburg.

[28] Makarov S., Apelian D., Ludwig R., (2009). "Inclusion Removal and Detection in Molten Aluminum: Mechanical, Electromagnetic and Acoustic Techniques", American Foundry Society.

[29] Yoon E., Kim J., Choi J., Kwon H., (2002). "Effects of Electromagnetic Force on The Removal of Alumina Particles in Molten A356 Aluminum Alloy", Journal of Materials Science Letters 21, 2002, 739-742.

[30] Campell J., (2003). "Castings - Second Edition", Elsevier Science Ltd.

[31] Ravi K.R.,Pillai R.M., Amaranathan K.R., Pai B.C., Chakraborty M., (2007). "Fluidity of Aluminum Alloys and Composites: A review", Journals of Alloys and Compounds, February 2007, 456 (2008) 201–210.

[32] Mose B.R., Maranga S.M., (2009). "Effect of Minor Elements on the Fluidity of Secondary LM25 and LM27-Type Cast Alloys", American Foundry Society.

[33] Dewhirst B.A., (2008). Castability Control in Metal Casting via Fluidity Measures: Application of Error Analysis to Variations in Fluidity Testing, PhD Thesis, Worcester Polytechnic Institute, December 2008.

[34] Haldar A., Ravindran C., (2008). "Effect of Superheat and Silicon Level on Flow Characteristics and Silicon Morphology on Thin Section LFC Hypereutectic Al-Si Alloys", American Foundry Society.

[35] Ajdar R., (2001). The Effect of Mold Materials on Solidification, Microstructure and Fluidity of A356 Alloy in Lost Foam Casting, MSc Thesis, University of Toronto.

[36] Campell J., Harding R.A., (1994). "The Filling of Castings – Talat Lecture", European Aluminum Assocation.

[37] Di SabatinoM., Arnberg L., Rorvik S., Prestmo A., (2005). "The Influence of Oxide Inclusions on the Fluidity of Al–7 wt.%Si alloy", Materials Science and Engineering A, 413–414, 272–276.

[38] Kwon Y., Lee Z., (2003). "The Effect of Grain Refining and Oxide Inclusion on the Fluidity of Al-4.5Cu-0.6Mn and A356 alloys", Materials Science and Engineering, A, 360 (2003) 372-376.

[39] Prukkanon W., Srisukhumbowornchai N., Limmaneevichitr C., (2009). "Influence of Sc Modification on the Fluidity of an A356 Aluminum Alloy", Journal of Alloys and Compounds, 487 (2009) 453–457.

[40] Apelian D., (2009). "Aluminum Cast Alloys: Enabling Tools for Improved Performance", North American Die Casting Association.

[41] Dewhirst B., Li S., Hogan P., Apelian D., (2008). "Castability Measures for Diecasting Alloys: Fluidity, Hot Tearing, and Die Soldering", International Conference High Tech Die Casting, Montichiari.

[42] Savas O., (2005). Aluminyum Silisyum Döküm Alaşımlarında Mikro Porozite Oluşumuna Etki Eden Faktörlerin İncelenmesi, MSc Thesis, Sakarya University, Sakarya.

[43] Berger Consult e.K., http://www.bergerconsult.de/index.php?sec=02&page=001Aluminium&lang=ENG, 27 July 2012.

[44] Schenke G., (2011). Langzeiteffekte einer elektromagnetischen Schmelzebehandlung auf Aluminium-Silizium Legierungen, Diplomarbeit, RWTH Aachen University, Aachen.

[45] Cast and Alloys, http://www.cast-alloys.com/products/lm_chart.htm, 28 July 2012.

[46] Schaefer Chemische Fabrik GmbH, http://www.schaeferchem.de/ESpezialanwendungen.html, 29 July 2012.

CURRICULUM VITAE

PERSONAL INFORMATION

Name Surname : Vedat TOPALOĞLU

Date of birth and place : 11.11.1987 Üsküdar

Foreign Languages : English, German

E-mail : vedattopaloglu@hotmail.com.tr

EDUCATION

Degree	**Department**	**University**	**Date of Graduation**
Master	Metallurgy and Materials Engineering	Yildiz Technical University	2012
Undergraduate	Metallurgy and Materials Engineering	Istanbul University	2010
High School	Gebze Sarkuysan High School	-	2005