

Republic of Iraq
Ministry of Higher Education
And Scientific Research
University of Babylon
Collage of Engineering
Department of Material engineering



Experimental Analysis of In- situ Composite Al-Si Eutectic Alloy

A Thesis

Submitted to College of Engineering of the University of Babylon in
Partial Fulfillment of the Requirements for the Degree of Master of
Science in Material Engineering/Metallurgy

By

Awham Jumea Salman
(BSc. In Material Engineering)
(2002)

Supervised by

Dr. Najim A. Saad
(Ass. Prof.)

Dr. Alaa A. Ateia
(Lecturer)

(2009) A.D



وزارة التعليم العالي والبحث العلمي
جامعة بابل
كلية الهندسة
قسم هندسة المواد

التحليل العملي لمركب في موقعه الأصلي لسبيكة أليوتكتك (الألمنيوم _ سيلكون)

أطروحة

مقدمة الى قسم هندسة المواد كلية الهندسة جامعة بابل
كجزء من متطلبات نيل شهادة الماجستير في علوم
هندسة المواد/هندسة معادن

من قبل

أوهام جمعة سلمان
(بكالوريوس هندسة مواد)
(2002)

بإشراف

د. علاء عبد الحسن عطيه
(مدرس)

د. نجم عبد الأمير سعيد
(أستاذ مساعد)

2009م

بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

وَيَسْأَلُونَكَ عَنِ الرُّوحِ قُلِ الرُّوحُ
مِنْ أَمْرِ رَبِّي وَمَا أُوتِيتُمْ مِنَ الْعِلْمِ إِلَّا
قَلِيلًا

صدق الله العظيم

{ سورة الإسراء / آية 85 }

Dedication

To my Mother and father

To my sisters and brothers

To my friends

With my love and respect

Awham

2009

CHAPTER ONE

GENERAL INTRODUCTION

CHAPTER TWO
DIRECTIONAL EUTECTIC
SOLIDIFICATION

CHAPTER THREE
ALUMINUM-SILICON
EUTECTIC ALLOY

CHAPTER FOUR
EXPERIMENTAL
PROCEDURE & COMPUTER
MODELING

CHAPTER FIVE
RESULTS & DISCUSSION

CHAPTER SIX
CONCLUSIONS
&SUGGESTIONS FOR
FUTURE WORKS

الخلاصة

أن (In Situ Composite Materials) تعرض عدة من الاختيارات الواسعة من حيث نوع التقوية , الحجم , الربط بين طور التقوية و الأرضيه ,الكسر الحجمي, وفهم الآليات التي تسيطر على الخواص الميكانيكية لتسمح للقرارات الأكثر ذكاء عند انتاج ماده مركبه لتطبيق معين.

يُزَوَّ دُ هذا البحث نظرة عامّة مِنْ الخواص الميكانيكية لتقوية سبيكة ألْمنيوم- سيلكون بواسطة توجيه نظام أليوتكتك بآثْ جَاهِ مَعْنِي. ولقد صممت و صُنِعَتْ وحدة تجمّد خاصّة لضمان التوجيه الصحيح لنمو نظام أليوتكتك .

نوعان من مواد العزل استعملت لعزل قالب الكربون الفولاذي لوحدة التجمّد (رمل جاف وصوف زجاجي). ولقد وجدَ أن العازل الثاني يَكُون مناسبَ في دَمَج النمو وتوجيه نظام أليوتكتك مع تدفق الماء البارد خلال الوحدة.

البنية الناتجة تشدّ ملّ أستطاله صَغِير لطور بيتا (السيلكون) أي توجيه ملحوظ لنظام أليوتكتك المُتزايدة في اتجاه تسرب الحرارة.

الصلادة، الشد، لانضغاط والصدمة تحسّنت و عَكُسَ هذه النتائج مباشرة تأثير النمو الإتجاهي لنظام أليوتكتك على تحمل أنواع مختلفة من الأحمال .

Abstract

In-situ composites offer such a wide selection of reinforcement types, size, bonding between compounds (reinforcement and matrix), volume fractions, and understanding the mechanisms controlling mechanical properties will allow more intelligent decisions to be made when tailoring a composite system for a specific application.

This research provides an overview of the mechanical properties of reinforced Al-Si alloy by unidirectional of the eutectic system in specific direction. A special solidification unit have been designed and prepared to ensure the correct orientation of growing eutectic system.

Two types of insulation materials have been used to insulate the carbon steel mold of solidification unit, (dry sand and glass wool). The second type insulator found to be favorable in augmenting the growth and unidirectional of eutectic system with the cold water flow through the unit.

The produced microstructure consists of little elongated $\beta(\text{Si})$ -phase that means noticeable orientation of the growing eutectic system in the direction of heat sink.

Hardness, tension, compression and impact properties have improved and these results reflect directly the effect of unidirectional growth of eutectic system on the response to the multi-types of loading.

Acknowledgment

*First of all, profusely all thanks for **ALLAH** Lord of all creation who enable me to achieve this work.*

I take this opportunity to thank my supervisors, Dr. Najim A. Saad and Dr. Alaa A. Ateia for their guidance, encouragement and support throughout the course of this work.

I would like to thank Miss (engineer)"Khansa Sami" and also all staff members at the workshops and materials engineering laboratories for their help throughout my work.

I am grateful to my family and especially to my mother and father, and also to my sisters and brothers for their assistance, encouragement and support during the period of preparing this work.

Finally, I would like to extend my appreciation to all my colleagues in Babylon University for their continuous supporting, cooperation and help throughout my students years.

*Awham Jumea Salman
2009*

CHAPTER ONE**GENERAL INTRODUCTION****1.1 Introduction**

Composite materials are among the oldest and newest of structural materials. The oldest concept of composite is simply the mixing of two or more materials to rectify some shortcomings of a particular useful component [1]. The common example of a natural composite material is wood, which consists of long cellulose fiber held together by amorphous lignin[2]. The other example is early cannons, which had barrels made of wood, reinforced with brass because a hollow cylinder of wood easily bursts under internal pressure. In ancient time, bricks were made up of clay and straw following this principle. Combination of straw and mud to make huts is still in use today in villages in our country. Similarly, ordinary steel covered with paint to protect it from rusting can be regarded as a composite. If this is regarded true, and then almost engineering materials are composites of some kind[1].

In modern technology, the concept of combining two dissimilar materials has acquired a broader significance: the combination has its own distinctive properties. In terms of strength or resistance to heat or some other desirable quality, a composite material is superior to either of the constituting components taken alone or entirely different from either of them. The principal attraction is stiffer and stronger than anything made ever before. At present, they are used principally to meet severe demands of supersonic flight, the exploration of space and ventures into the deep sea water of oceans[1].

There are two major reasons for the current interest in composite

materials. The first, is simply the need for materials that will out perform the traditional monolith materials. The second and more important in the long run is that composites offer engineers the opportunity to design totally new materials with the precise combination of properties needed for specific tasks [1].

1.2 Definition of Composite Materials

Practically everything is a composite material in some sense. For example, a common piece of metal is a composite (polycrystal) of many grains (or single crystals).

A composite material, consists of two or more physically and/or chemically distinct, suitably arranged or distributed phases, with an interface separating them. It has characteristics that are not depicted by any of the components in isolation. Most commonly, composite materials have a bulk phase, which is continuous, called the matrix, and one dispersed, non-continuous, phase called the reinforcement, which is usually harder and stronger [3, 4, 5].

1.3 Classification of Composite Materials

There are various ways to classify composite materials,

(A). On the basis of matrix used

The multiphase composites are divided into three categories:

1. Metal-matrix composites (MMCs).
2. Ceramic-matrix composites (CMCs).
3. Polymer-matrix composites (PMCs).

(B). On the basis of the geometry of the reinforcement

They are classified as:

1. Fibrous composite.

2. Particulate composite.
3. Flakes composite.

Knowing that, fibers are one dimensional element, and flakes are two dimensional elements whereas particle has all the three dimensions [1].

1.4 In-situ Composite Materials

In-situ composites are multiphase materials where the reinforcing phase is synthesized within the matrix during composite fabrication. This contrasts with ex-situ composites where the reinforcing phase is synthesized separately and then inserted into the matrix during a secondary process such as infiltration or powder processing. In-situ processes can create a variety of reinforcement morphologies, ranging from discontinuous to continuous, and the reinforcement may be either ductile or ceramic phases[6].

There are a number of processes and classes of in-situ composites, including processes where the precipitation of reinforcements occurs in the liquid state and processes where precipitation occurs in the solid state. Processes in which precipitation occurs in the liquid state include those occurring with low undercoolings, such as traditional and directionally solidified eutectics; rapid solidification in which a supersaturation is created by rapidly cooling a liquid with the reinforcement constituents already in solution; and processes in which a large supersaturation is created by rapidly bringing the constituents of the reinforcement together to react. Solid-state in-situ processes include internal oxidization, displacement reactions, reactive milling, mechanical alloying, and cryomilling. There are also traditional eutectoid reactions that can be considered solid-state in-situ reactions if an alloy of ferrite and cementite is considered a composite [6].

In situ production of reinforcements, matrices and inter-phases is a promising strategy for reducing the costs of preparing high-performance metal-ceramic complexes. Among the advantages offered by in situ composites over conventional materials are improved thermodynamic stability, fine scale of reinforcements and the elimination of fiber coating[7].

Many in situ composites show potentials for high-temperature structural applications, but they need simultaneous improvements in oxidation and fracture resistance [8].

1.4.1 Types of In-situ Composite Materials

1. Particle In-situ Composite Materials: - (Precipitation Hardening)

The method to produce particle in-situ composite materials is the precipitation hardening. A precipitation hardening or hardening is produced by solution treating and quenching an alloy in which a second phase is in solid solution at the elevated temperature but precipitates upon quenching and aging at a lower temperature[9].

For precipitation hardening to occur, the second phase must be soluble at an elevated temperature but must exhibit decreasing solubility with decreasing temperature. Usually there is atomic matching, or coherency, between the lattices of the precipitate and the matrix. The requirement of a decreasing solubility with temperature places limitation on the number of useful precipitation hardening alloy systems[9].

The age hardening aluminum alloys and copper-beryllium alloys are common example [9].

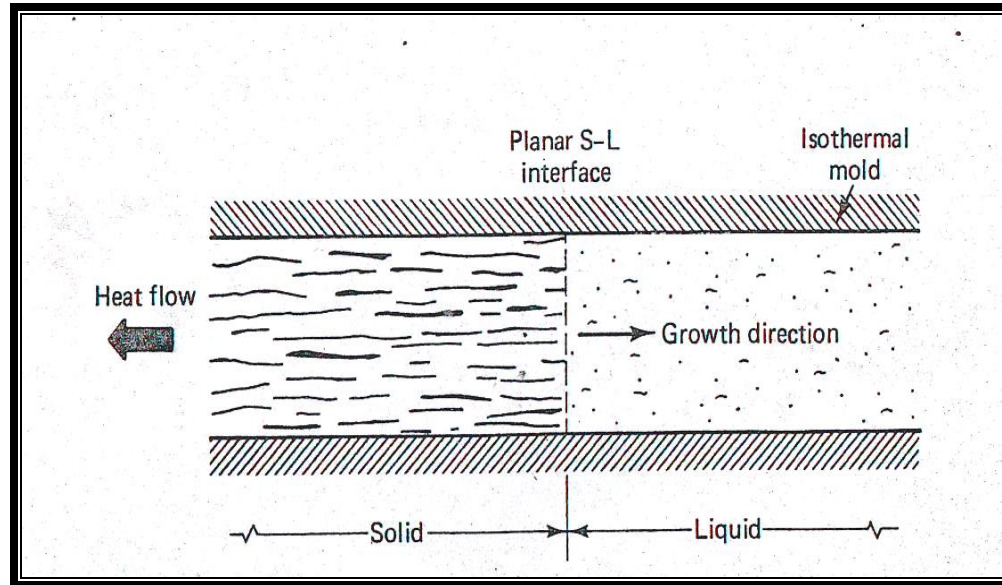
Solidification processing of cast metal-matrix particulate composites, contains in reinforcements generated in situ, is particularly attractive due to the composites' simplicity, flexibility in operation, and potential to reduce

the final production costs. As noted earlier, a comprehensive understanding of the process will have to be developed before commercial exploitation of these cast in-situ composites in order to fabricate components. Studies on the key processing steps are the primary requirements for the control of the macro/microstructure, mechanical properties, and also for continuous processing of components to near net shape [10].

2. Fiber In-situ Composite Materials: - (Unidirectional Eutectic Solidification)

A fiber that can be produced by directional solidification of cast alloys actually is part of the alloy being precipitated from the melt as the alloy solidifies. This type of transformation usually involves eutectic alloys in which the molten material decomposes into two or more phases at constant temperature. When the solidifying phases are unidirectional, the product is known as a directionally solidified eutectic. Ceramic matrix composites can also be fabricated to contain in situ fibers similar to the all-metal systems [11].

Unidirectional solidification , means the solidification is controlled in such a way as to extract the heat in one direction, As can be seen in figure (1.1)[12].



Figure(1.1)

Unidirectional solidification of a eutectic alloy, the solid contains microstructure constituents aligned parallel to the growth direction [12].

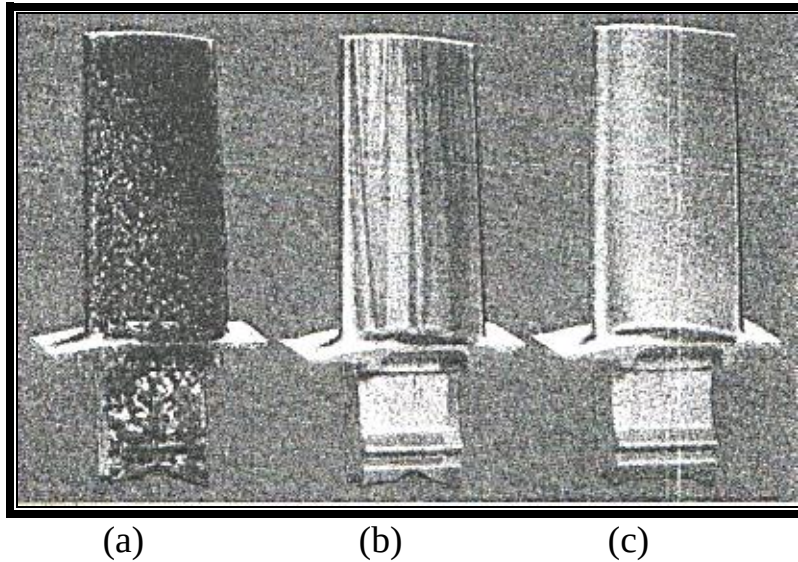
If we have eutectic structure and use the unidirectional solidification method. The resulting growth morphologies are as follows:-

1. Both phases form lamellae aligned parallel to each other.
2. The second phase appears in the form of filaments aligned in the first phase constitute the matrix.
3. Whatever lamellae or filaments are formed, the generated structure exhibits a certain degree of macroscopic order.
4. The direction of preferred orientation coincides with the direction of heat extraction [13].

1.4.2 Applications of Fiber In-situ Composite Materials

In general, applications for directionally solidified eutectic composites are limited compared to other fiber-reinforced materials. One reason for their low utilization is related to the fixed eutectic composition; no variation of constituent volume fractions is possible. Also, they are relatively costly to produce, and result in the lowest melting temperature material of the alloy system under consideration [12].

In addition, directional solidification of eutectic alloys offers improved creep strength and resistance to thermal fatigue, due the absence of transverse grain boundaries. Creep is permanent deformation that occurs over a period of time in components subjected to a constant stress; typically below the room-temperature elastic limit. Such deformation is also temperature dependent and increases with increasing temperature. Because of such improved thermal properties, this type of composite has been applied to aircraft engine turbine buckets or blades. These components are blade-shaped airfoils in turbines, which “catch” the hot gases of combustion and essentially power the engine. Accordingly, these parts are subjected to very severe operating conditions (i.e., high temperature, stress, and corrosive atmospheres) [12, 14, 15].



Figure(1.2)

Turbine blades manufactured by three different processes: (a) conventional casting-equiaxed grains; (b) directional solidification-columnar grains; (c) single crystal-one grain [12].

1.5 Literature Review

Generally, the unidirectional solidification of eutectics was first studied by Winegard, et al. in 1952. However, only in about 1960 was this technique considered seriously for the production of composite materials. Bending tests firstly performed in 1958 by Webb and Forgeng on Cr-filaments extracted from a randomly cast (Cu-Cr) eutectic demonstrated the monocrystal-like nature of the filaments and their exceptionally high strength. The whisker-character of Cr-fibers extracted from a unidirectional solidified (Cu-Cr) eutectic was later proved by Lemkey and Kraft. These authors found for the filaments strength values in the order of (10 GN/m^2) and an elongation at rupture of the order of 2% [13].

Further studies carried out by Hertzberg and Kraft on the rupture behavior, e.g. rupture mode of the fibers, interface features, and adhesion at the interface between matrix and fibers, gave an essential contribution in

proving the composite nature of the (Cu-Cr) eutectic . Since then a large number of eutectic systems have been studied. A detailed list is given by Hogan et al., and by Kurz and Sahm , at the moment more than 400 systems are known .This fact shows clearly the lively interest of research institutes in the field of unidirectional solidification of both binary and more complex systems[13].

One may note that the systems which receive the most attention are the Al-and Ni-base composites in view of their possible exploitation as heat-resistant materials, but a number of other systems are becoming more and more attractive especially in view of an application in non-structural fields [13].

Many efforts have been directed to growing an in-situ fiber phase in the Al-Si eutectic alloy, and following is the review of available works:-

M.A. Martorano et al [16] carried out experiments of the Columnar to-Equiaxed Transition in directional solidification of Al-Si alloys with Si contents ranging from 3 to 11 % and identical thermal conditions. Convection associated with the pouring of the liquid metal was suppressed by using a thin Aluminum Nitride base to seal the insulated cylindrical sleeve at the bottom and keeping the Al-Si melt in the furnace for a long time. After homogenization of the melt temperature, solidification was initiated by removing the furnace from the mold and raising a water-cooled copper chill to touch the bottom of the high thermal conductivity Aluminum Nitride base. Cooling curves recorded by seven thermocouples located every 20 mm from the bottom of the casting were compared with predictions of a one-dimensional model, suggesting that heat transfer in the solidifying metal was by conduction only. Measured Columnar to-Equiaxed Transition positions were similar for all alloy compositions, indicating a weak effect of

the Si content. Further conclusions drawn from the simulations were already provided in the previous section.

K. Ohsasa et al [17] studied the frequency of heterogeneous nucleation during the solidification of Al-Si binary alloy was estimated by comparing experimentally obtained macrostructures of castings with numerically simulated ones. A molten alloy was unidirectionally solidified from a water-cooled copper chill in an adiabatic mold. The location of columnar to equiaxed transition in the solidified alloy ingot was measured. A numerical simulation for grain structure formation based on the Monte Carlo method was carried out, and the frequency of heterogeneous nucleation in the alloy was evaluated by producing similar structure with the experimental one. The frequency of heterogeneous nucleation was expressed as a probabilistic function with an exponential form of undercooling that determines the probability of nucleation event in the simulation. The value of the exponent is regarded as the nucleation parameter. The nucleation parameter of Al-Si binary alloy varied with initial Si content.

R.E. Napolitano et al [18] findings from the investigation of solidification morphologies resulting from the low velocity directional solidification of Al-Si eutectic alloys are discussed. The development of a primary array of angular silicon rods is examined, and the twinned structure of the faceted silicon phase is shown to be an essential contributor to the mechanisms of growth, branching, spacing selection, and the evolution of $\langle 100 \rangle$ Si texture within the two-phase microstructure.

Taylor A. Groll [19] studies the effect of solidification rate on the secondary dendrite cell size that was examined by taking photomicrographs of five different samples of an Aluminum alloy A356 . they found that, the microstructural features of the samples are consistent with that of an as-cast

Al-Si alloy. As the solidification rate of the alloy decreases, the ultimate tensile and yield strengths, and occurrences of porosity increase. As the solidification rate of the alloy increases, the dendrite cell size and size of porosity decrease.

K.Nogita et al [20] investigate the quench modification involved the refinement of silicon due to high cooling rates, and thus high transformation rates. Growth rates exceeding 1mm/s have been quoted as a criterion for obtaining a quench modified eutectic microstructure. Finding that the eutectic in Al-Si alloys may evolve with widely different spatial distributions and is significantly affected by trace levels of several elements, particularly those known to also affect eutectic silicon morphology (modifiers). The morphology of eutectic silicon is not directly related to either the thermal parameters of the eutectic or the eutectic solidification mode.

M.F. Zhu , C.P.Hong [21] studies the a modified cellular automaton model that has been developed in order to predict the evolution of dendritic and eutectic microstructures in solidification of alloys. The modified cellular automaton model accounts for the aspects including the heterogeneous nucleation of a new phase, the growth of primary dendrites and two eutectic solid phases from a single liquid phase, as well as the coupling between the phase transformation and solute redistribution. The present model was applied to predict the primary dendritic growth and eutectic structure formation during practical casting solidification of Al alloys. The simulated results were compared with those obtained experimentally. The model can also be applied to model irregular eutectic growth patterns in eutectic and hypoeutectic Al-Si alloys.

Yuhong Zhao and Hua Hou[22] used , the two phase field models for

free interface of dendrite growth as sharp interface model and diffusion interface have been introduced; and microstructure evolution in solidification process is studied by phase field model, model of the phase field model and its numerical solution are introduced, the dendrite growth process of Al-Si alloy in solidification process is simulated, and the simulation results have been analyzed. The comparisons of dendrite morphology between simulated results and investigations by others are also presented, which proved that the dendrite morphology are similar in trunks and arms growth, so proved the developed phase field program is accurate.

M. Jeyakumar et al[23] investigates the tradeoff between gas microporosity and primary silicon formation as a function of cooling rate during solidification of near-eutectic Al-Si alloys. In order to minimize microporosity formation and improve mechanical properties, Al-Si alloy castings are generally cooled at a faster rate, using steel or cast iron chills, near the critical regions. While this method works well for the A356 castings with Si content of about 7%, the effect of primary silicon formation needs to be considered for near-eutectic alloys with Si compositions close to 12.6%. Finding the quench and Universal Metallurgical Simulator and Analyzer experiments carried out using Al-Si binary eutectic alloys without grain refiner or modifier additions clearly indicate that there exists a range of cooling rates (near the eutectic) where a perfect eutectic microstructure without microporosity or primary Si formation can be achieved. At cooling rates below this regime, micropores begin to nucleate and grow. At cooling rates above this regime, formation of primary Si is observed. This critical cooling rate regime was found to be between 2-3 °C/s.

1.6 Aim of the Work

The scope of this work covers a unidirectional solidification of Al-(12%wt) Si. Many factors affecting the effectiveness of the solidification in this manner, such as, molten metal temperature, method of solidification (i.e. mold material, insulation and the method by which the heat sink in one direction to augment or supporting the eutectic solidification in one direction) are studied as well. These as well as the modeling equations of heat transfer(temperature distribution) were modified by using an ANSYS-code (version-5.4) hopes to fully understand the process at hand.

So the aims of present work are summarized as follows:-

1. Controlling the direction of grown eutectic phase in order to use as an in-situ fiber in a eutectic Al-Si alloy containing almost 12wt% of silicon.
2. Computer modeling by using an ANSYS-code (version-5.4) of solidification processes in order to specify the efficiency of insulation material (temperature distribution) used and in order to specify the modeling solidification time and comparing it with the experimentally predicted solidification time.
3. Reporting and studying the microstructure evolution under different conditions of solidification along the solidified material throughout the monitoring of eutectic phase orientation.
4. Evaluation of hardness, compression, tension and impact toughness of the material produced at different conditions of solidification and comparing the result with the properties of non-unidirectional solidified material that produced experimentally.

CHAPTER TWO

DIRECTIONAL EUTECTIC SOLIDIFICATION**2.1 Eutectic**

The eutectic or eutectic mixture is a mixture of two or more solid phase at a composition that has the lowest melting point, and where the phases simultaneously crystallise from molten liquid solution at this temperature, see figure (2.1). The term comes from the Greek 'eutektos', meaning 'easily melted'. Alloys of the eutectic composition are said undergo a eutectic reaction as the single phase liquid solidifies into a multiple phase solid [24, 25, 26].

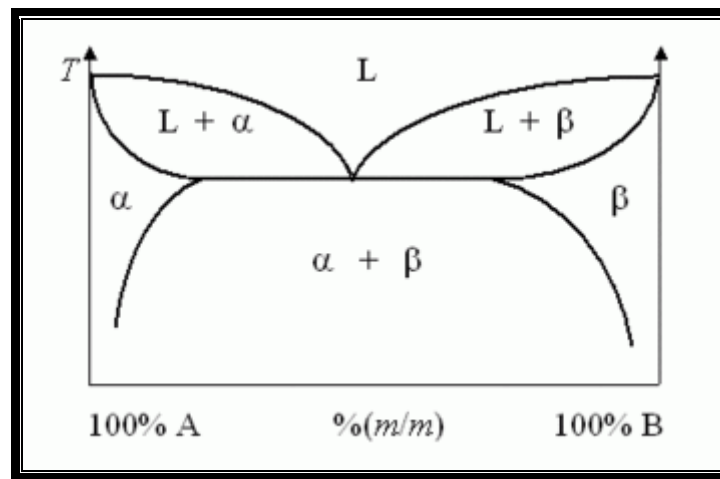


Figure (2.1)
A simple binary eutectic system [24].

2.1.1 Metallic Eutectics

The term is often used in metallurgy to describe the two or more component materials having the relative concentrations specified at the eutectic point.

An alloy freeze, one component of the alloy crystallizes at one temperature and the other at a different temperature. With a eutectic alloy, the mixture freezes as one at a single temperature. A eutectic alloy therefore has a sharp melting point, and a non-eutectic alloy exhibits a plastic melting range. The phase transformations that occur while freezing a given alloy can be understood using the phase diagram by drawing a vertical line from the liquid phase to the solid phase on a phase diagram; each point along the line describes the composition at a given temperature [25].

A number of workers have also carried out an investigation with the aim of predicting the type of morphology in a new system. In practice the problem here was to find out when filament lamellae are formed.

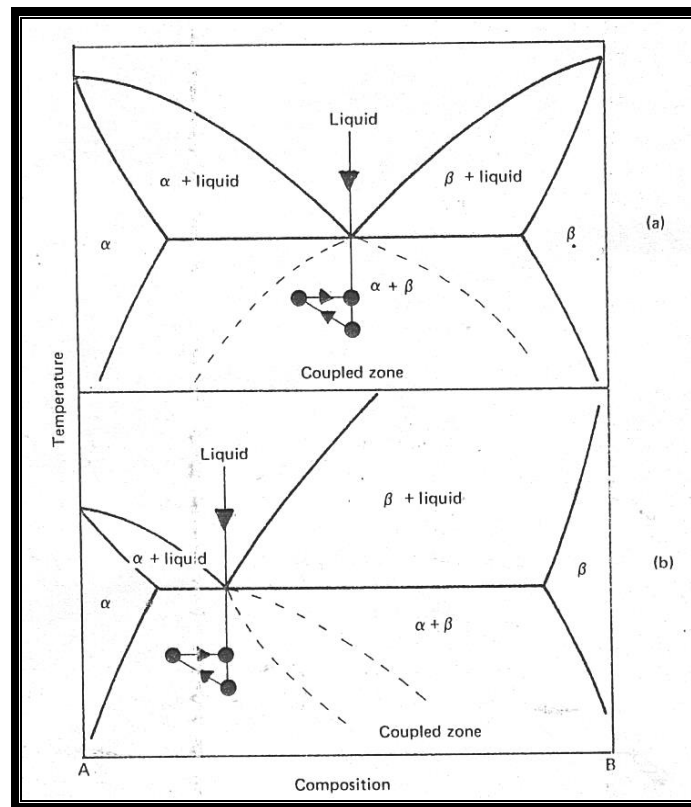
In general, systems having a volume fraction of the second phase greater than 30% give lamellar structures, while a filament structure is preferentially generated in those systems having a volume fraction of the second phase smaller than 30%. This leads us to suppose that the relative interfacial surface, and therefore the relative interfacial energy, is a determining factor. Since this is a function of the volume fraction, the structure having the minimum interfacial area and thus the minimum energy is the prevalent one. There are, however, exceptions to this rule.

Various different types of eutectic solidification are possible and there are usually classified as normal and anomalous [24, 27].

In normal structures the two phases appear either as alternate lamellae, or as rods of the minor phase embedded in the other phase. Normal

structures occur when both phases have low entropies of fusion, and phase diagrams in which the metals were of similar melting point.

Anomalous structures, on the other hand, occur in systems when one of the solid phases is capable of faceting, i.e. has high entropy of melting and formed in systems with metals of different melting temperatures [24].



Figure(2.2)

- (a) Phase diagram typical of a system showing a normal eutectic structure.
- (b) Phase diagram typical of a system showing an anomalous eutectic structure [24].

There are many type of eutectic morphologies lamellar, needle shaped, acicular, globule crystals [13].

2.2 Eutectic Solidification

Solidification involves the extraction of heat from the liquid and the motion of the solid–liquid interface [28, 29]. The rate of solidification is determined mainly by heat extraction through thermal diffusion and convection. However, solidification microstructure is a complex function of the rate of solidification (v), temperature gradients ($\hat{G}$), composition (C) and several material characteristics such as phase equilibrium reactions, nucleation and growth kinetics of the phases and crystallographic constraints. A perspective of evolution of microstructure during solidification is presented in the light of our current understanding of solidification processing. Particular attention is paid to the effect of system size and resultant scale dependence of the microstructure and segregation profile. We emphasize the fact that our current knowledge allows us to have quantitative understanding [28].

Solidification of a eutectic alloy from the melt or liquid phase produces two composite solid phases, in contrast to the simpler case when the liquid phase solidifies into a single solid phase. The two solid phases are characterized by differing solute concentrations; the equilibrium concentrations in each phase are given by the phase diagram for the eutectic system, which gives the relations between temperature and solute concentration for each of the thermodynamic phases in the system. A number of different geometrical arrangements of the two solid phases are possible, depending on the alloy system and on the processing conditions. For example, the solid phases can form in adjacent layers or lamellae, or one phase can form rods that are embedded in the other phase. Both grow continuously from the melt. Since a large number of important binary alloy systems have eutectic phase diagrams, such systems have been studied

extensively. It is desirable to be able to predict the geometrical patterns of growth and their associated length scales in order to better understand and possibly control the processing of eutectic materials [30, 319].

2.2.1 Nucleation in Eutectic Solidification

The eutectic reaction occurs by a nucleation and growth process in common with all solidification processes. The nucleation events commences at a temperature below the eutectic temperature with the heterogeneous nucleation of one of the eutectic phase on nucleus present in the liquid, and is completed by the heterogeneous nucleation of the second eutectic phase on the first. As understanding of heterogeneous nucleation is desirable because the nucleation of one eutectic phase by another is a possible origin of an epitaxial orientation relationship which, if formed at nucleation, may persist during growth and influence both structure, and properties[13].

The nucleation temperature (T_n) can influence the eutectic grain on cell size and the solidification conditions nucleation under which initial growth occurs. Homogeneous nucleation is described briefly and then developed to consider the factors that control the heterogeneous nucleation of eutectic phases [13].

2.2.2 Growth of Lamellar Eutectics

Figure (2.3) shows how two phases can grow cooperatively behind an essentially planar solidification front. As the A-rich α phase solidifies excess B diffuses a short distance laterally where it is incorporated in the B-rich β phase. Similarly the A atoms rejected ahead of the β diffuse to the tips of adjacent α lamellae. The rate at which the eutectic grows will depend on how fast this diffusion can occur and this in turn will depend on the

interlamellar spacing λ . Thus small interlamellar spacing should lead to rapid growth[27].

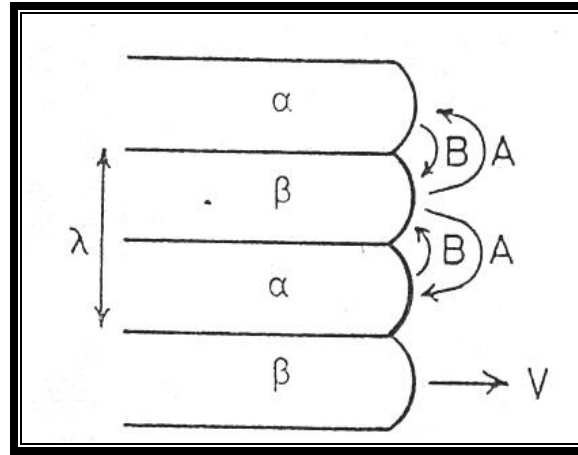


Figure (2.3)

Interdiffusion in the liquid ahead of a eutectic front [27].

However there is lower limit to determine the need to supply the α/β interfacial energy, $\gamma_{\alpha\beta}$. For an interlamellar spacing, λ , there is a total of $(2/\lambda) \text{ m}^2$ of α/β interface per m^3 of eutectic. Thus the free energy change associated with the solidification of 1 mol of liquid is given by

$$\Delta G(\lambda) = -\Delta G(\infty) + 2 \gamma_{\alpha\beta} V_m / \lambda \quad (2.2)$$

Where V_m is the molar volume of the eutectic and $\Delta G(\infty)$ is the free energy decrease for very large values of λ . Since solidification will not take place if $\Delta G(\lambda)$ is positive, $\Delta G(\infty)$ must be large enough to compensate for the interfacial energy term, i.e. the eutectic / liquid interface must be undercooled below the equilibrium eutectic temperature T_E , Figure (2.4). If the total undercooling is ΔT_o it can be shown that $\Delta G(\infty)$ is then given approximately by

$$\Delta G(\infty) = \Delta H \cdot \Delta T_o / T_E \quad (2.3)$$

Where ΔH is an enthalpy term. The minimum possible spacing (λ^*) is obtained by using the relation $\Delta G(\lambda^*) = 0$, whence ,

$$\lambda^* = 2\gamma_{\alpha\beta}T_E V_m / \Delta H \cdot \Delta T_o \quad (2.4)$$

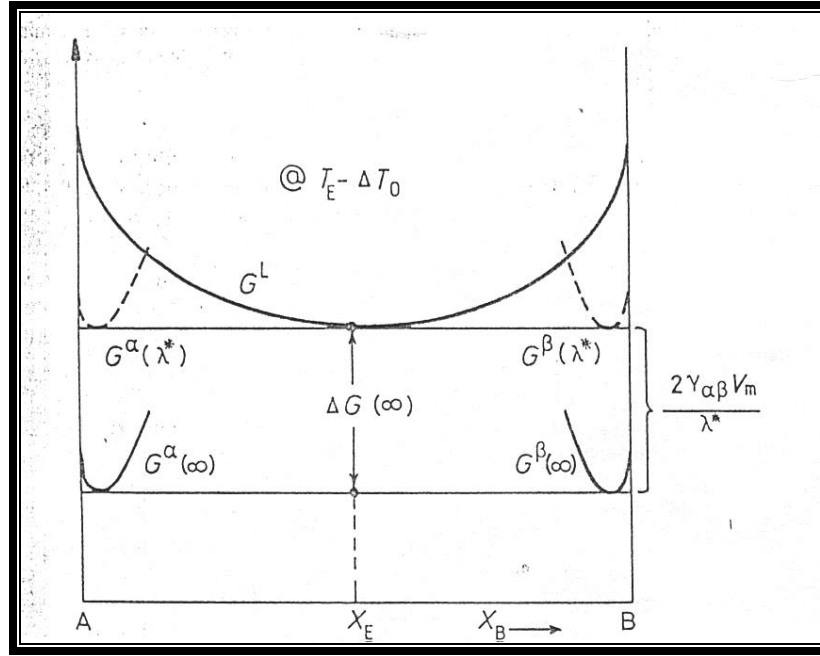


Figure (2.4)

Molar free energy diagram at a temperature ΔT_o below the eutectic temperature, for the case $\lambda = \lambda^*$ [27].

When the eutectic has this spacing, the free energy of the liquid and eutectic is the same, i.e. all three phases are in equilibrium. This is because the α/β interface raises the free energies of the α and β from $G^\alpha(\infty)$ and $G^\beta(\infty)$ to $G^\alpha(\lambda^*)$ and $G^\beta(\lambda^*)$ as shown in Figure (2.4). The cause of the increase is the curvature of the α/L and β/L interfaces arising from the need to balance the interfacial tensions at the $\alpha/\beta/L$ triple point, Figure (2.3). In general, therefore the increase will be different for the two phases, but for simple cases it can be shown to be $2\gamma_{\alpha\beta}V_m/\lambda$ for both, Figure (2.4)[27].

Let us now turn to the mechanism of growth. If solidification is to occur at finite rate there must be a flux of atoms between the tips of the α

and β lamellae and this requires a finite composition difference. For example the concentration of B must be higher ahead of the α phase than ahead of the β phase so that B ejected from the α can diffuse to the tips of the growing β . $\lambda = \lambda^*$ growth will be infinitely slow because the liquid in contact with bottom phases has the same composition, X_E in Figure (2.4). However if they chose spacing is greater than λ^* less free energy is locked in the interfaces G^α and G^β are correspondingly reduced, Figure (2.5 a). Under these circumstances the liquid in local equilibrium with the α phase has a composition $X_B^{L/\alpha}$ which is richer in B than the composition in equilibrium with the β phases $X_B^{L/\beta}$ [27].

If the α/L and β/L interfaces are highly mobile it is reasonable to assume that growth is diffusion controlled in which case the eutectic growth rate (v) should be proportional to the flux of solute through the liquid. This in turn will vary as $D \cdot dC/dl$ where D is the liquid diffusivity and dC/dl are the concentration gradient driving the diffusion. (l is measured along the direction of diffusion as shown in Figure(2.5 b). In practice, dC/dl will not have single value but will vary from place within the diffusion zone.) dC/dl should be roughly proportional to the maximum composition difference ($X_B^{L/\alpha} - X_B^{L/\beta}$) and inversely proportional to the effective diffusion distance which, in turn, will be linearly related to the interlamellar spacing (λ). Thus we can write

$$v = k_1 D (\Delta X / \lambda) \quad (2.5)$$

Where k_1 is a proportionality constant and $\Delta X = X_B^{L/\alpha} - X_B^{L/\beta}$ as given in Figure(2.5).

ΔX will itself depend on λ for when $\lambda = \lambda^*$, $\Delta X = 0$, and as λ increases will tend to a maximum value, ΔX_o , say. Therefore it is reasonable to write

$$\Delta X = \Delta X_o (1 - \lambda^*/\lambda) \quad (2.6)$$

The magnitude of ΔX_o can be obtained by extrapolating the equilibrium liquidus lines of the phase diagram ($\lambda = \infty$) as shown in Figure (2.6). For small undercoolings

$$\Delta X_o \propto \Delta T_o \quad (2.7)$$

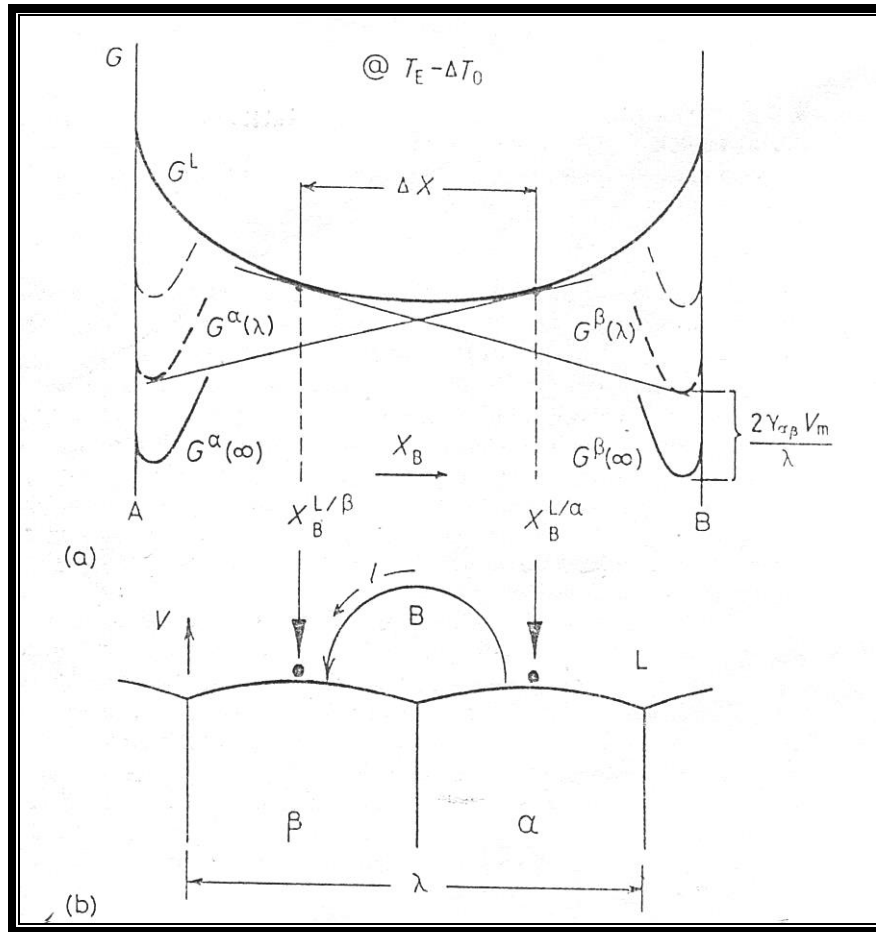


Figure (2.5)

(a) Molar free energy diagram at $(T_E - \Delta T_o)$ for the case $\lambda^* < \lambda < \infty$, showing the composition difference available to drive diffusion through the liquid. (b) Model used to calculate the growth rate [27].

The dashed lines in Figure (2.6) are the liquidus lines for $\lambda^* < \lambda < \infty$. ΔX is simply given by the extrapolation of these lines as shown. Combining the above equations gives

$$v = k_2 D \Delta T_0 (1/\lambda) (1 - (\lambda^*/\lambda)) \quad (2.8)$$

Where k_2 is another proportionality constant. This equation shows that by varying the interface undercooling (ΔT_0) it possible to vary the growth

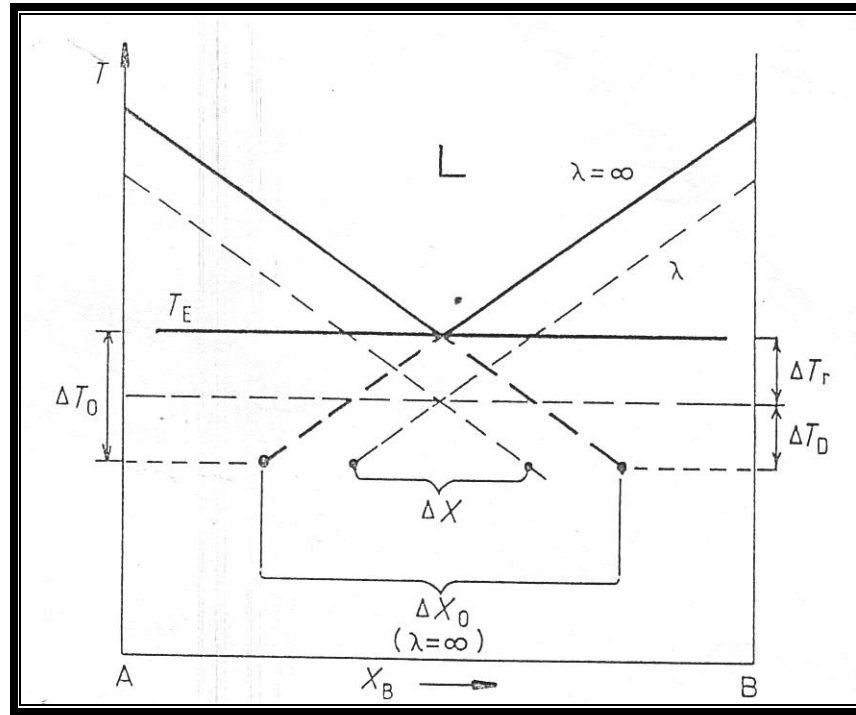


Figure (2.6)
Eutectic phase diagram showing the relationship
between ΔX and ΔX_0 [27].

rate (v) and spacing (λ) independently. It is therefore impossible to predict the spacing that will be observed for a given growth rate. However, controlled growth experiments show that a specific value of λ is always associated with a given growth rate. Examination of equation (2.8) shows that when $\lambda = 2\lambda^*$, the growth rate is a maximum for a given undercooling, or, alternatively, the required undercooling is a minimum for a given growth

rate. If it is assumed that growth occurs under these optimum conditions the observed spacing $\lambda_o = 2\lambda^*$ and the observed growth rate is given by

$$V_o = k_2 D \Delta T_o / 2\lambda^* \quad (2.9)$$

However, from Equation (2.4), it is seen that $\Delta T_o \propto 1/\lambda^*$ so that the following relationships are predicted:

$$V_o \lambda_o^2 = k_3 \quad (\text{constant}) \quad (2.10)$$

and

$$V_o / (\Delta T_o)^2 = k_4 \quad (\text{constant}) \quad (2.11)$$

There is in fact no physical basis for choosing $\lambda = 2\lambda^*$ and similar expressions can also be obtained using other assumptions concerning the spacing. Equations (2.10) and (2.11) are often found to be obeyed experimentally[27].

2.3 Eutectic Leading Phase

In order to control the structure of eutectic alloys it is important to know whether the primary crystals of the eutectic alloy are leading phase or non-leading phase. This is because whereas non-leading phase primary crystals do not have much effect on the formation of the eutectic grain zone, leading phase primary crystals cause the formation of equiaxed eutectic grains. To distinguish between leading phase and non-leading phase. This is soon revealed by casting a hyper-eutectic alloy and a hypo-eutectic alloy whose compositions resemble the eutectic composition extremely closely, and comparing their solidified structures[32].

The phase in which primary crystals exist independently of the eutectic matrix is the non-leading phase, and the phase in which primary crystals form a core in the center of the equiaxed eutectic grains is the

leading phase [32]. In table (2.1) have listed the eutectic leading phases for many eutectic systems.

Table (2.1)
Leading phase of eutectic alloys [32].

Alloy	Leading phase	Alloy	Leading phase
Ag-Bi	Ag	Al-Si	Si
Ag-Cu	Cu	Al-Sn	Al
Ag-Ge	Ge	Al-Zn	Al
Ag ₃ Sn-Sn	Ag ₃ Sn	Bi-BiPb ₂	Bi
Al-AlSb	AlSb	Bi-Cd	Bi
Ag ₃ Sb-Sb	Sb	Bi-Sn	Bi
Al-Ge	Ge	Cd-Pb	Cd
Al-Al ₉ Co ₂	Al ₉ Co ₂	Cd-Sn	Cd
Al-CuAl ₂	CuAl ₂	Cd-Zn	Zn
Al-NiAl ₃	NiAl ₃	Fe-C	C
Fe-Fe ₃ C	Fe ₃ C		

2.4 Nonequilibrium Crystallization

The processes discussed above refer to conditions near to equilibrium, i.e. at very slow cooling. Besides developing coring in the crystals of the α – and β -solid solutions, an increase in the cooling rate may lead to considerable changes in the structure and phase content of the solidified alloys [33, 34].

Nonequilibrium crystallization may impart a purely eutectic structure to these alloys. Such a structure is said to be quasi-eutectic because it has a composition differing from that of the eutectic represented by a diagram of phase equilibrium [33].

2.5 Unidirectional Solidification of Eutectic

Principally, a eutectic structure forms by the transformation of liquid alloy to two solid. Also recall that this reaction is invariant; it takes place at a fixed composition and a constant temperature. Ordinarily, the eutectic structure produced during solidification tends to be random with respect to distribution of the micro structural constituents. But if the solidification process of a eutectic alloy is precisely controlled, for example by removing heat from the liquid at a constant rate in one direction, and a planar solid-liquid interface can be maintained, the resulting structure will be aligned in the direction of heat flow. This procedure, referred to as unidirectional solidification, is illustrated schematically in figure (2.7) [12].

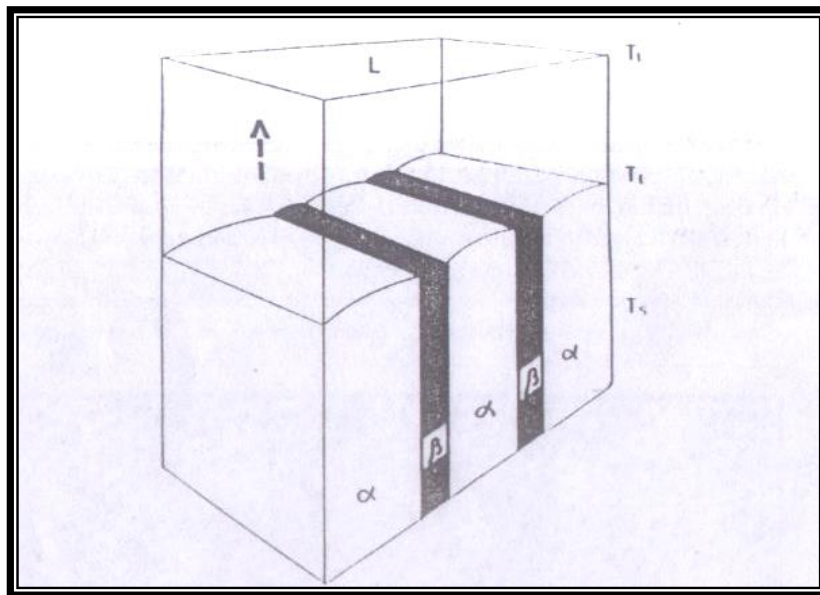


Figure (2.7)

Formation of a lamellar structure (α and β phases) in a unidirectional solidification of a eutectic. The solidification front is perpendicular to the direction of growth (direction of arrows). T_L , T_E and T_S are the temperatures of the liquid (L), the solidification front and the solid, respectively [12].

2.5.1 Mechanical Behavior

A unidirectional solidified eutectic thus exhibits a microstructure resembling a fiber-reinforced metal-matrix composite. Depending on the particular alloy system involved, one of the constituents may behave as the reinforcement while the other acts as the matrix[12].

One exceptionally important aspect of this type of composite material is the nature of the bond between reinforcing phase and surrounding matrix. Studies of the deformation experienced in these materials have been conducted by both light and electron microscopy. Such examinations have revealed that load transfer from the matrix to the “fiber” is very efficient, and that typically the fiber or whisker fails rather than the interface. This observation strongly suggests that an excellent bond is obtained between the microstructure phases, which are what might be expected, subsequent chemical reactivity between the phases is also minimized in this type of composite system [12].

The regularity of the morphology depends mainly on;

1. The thermal gradient ($\hat{G}$) existing at the solidification front.
2. The solidification rate (v), i.e. the velocity at which the solidification front moves [13, 35].

When uniaxial heat flux is realised, e.g. by extracting the molten alloy from a vertical furnace. A liquid-solid interface normal to the direction of the heat extraction is formed. Under strictly controlled conditions this liquid-solid interface is planar and moves at constant velocity through the entire length of the ingot. The two phases α and β formed at the interface follow the solidification front movement leading to the lamellar morphology with the single lamellae oriented along the direction of heat extraction.

The lamellar composite and fibrous composite structures are obtained

only in the case where the solidification front is planar, perpendicular to the direction of the growth (heat extract) and the numbers of the parameters are affected, such as the thermal gradient, the solidification rate, the impurities, etc.

The analytically the condition for planar front solidification of binary alloys at compositions in the two phase region is given by ($\hat{G}/v$ ratio)

$$\hat{G}/v \geq -m (C_E - C_0)/D \quad (2.13)$$

where $\hat{G}$ is the thermal gradient, v the solidification rate, m the slope of the liquidus curve, C_E and C_0 the eutectic and the alloy composition and D the diffusion coefficient in the liquid [13].

Every eutectic alloy has the critical (G/v ratio) that has to be exceeded in order to ensure completely aligned eutectic growth during directional solidification [13, 36].

The morphology of a single system, however, does not remain constant when the solidification parameters are changed. The influence of the gradient seems to be minimal. While in some systems the influence of the solidification velocity is considerable. In some systems, the lamellae- to rods transitions have been observed by increasing the solidification rate, while in others the opposite effect can be noted. In each case however, the transition is gradual. At very low rates some systems present degenerate structures.

The interlamellar distance is also a function of the solidification rate and varies according to the following relationship:

$$(\lambda^2) v = A \quad (2.14)$$

Where λ is the interlamellar distance, v the solidification rate, and A is a constant for the given system. Above relation is important, because it represents the beginning of a quantitative description of eutectic growth. While a more sophisticated relationship has been proposed:

$$(\lambda^2) v = a (1+b/\lambda) \quad (2.15)$$

This equation characterizes an eutectic system having two constants instead of one.

The structures obtained by (growth in situ) at low rates are the most stable at high temperatures. This is because they are coarser and therefore Ostwald ripening is minimized. On the other hand the structures obtained at higher rates or those plastically deformed grow more quickly because the structure is finer or because of the presence of microscopic deformation due to plastic processing [13].

CHAPTER THREE**ALUMINUM –SILICON EUTECTIC ALLOY****3.1 Introduction**

In this section, a review of the basics of aluminum-silicon system and the present understanding of the evolution of aluminum-silicon eutectic alloys will be presented.

Evidently, aluminum-silicon foundry alloys have gained increasingly uses, particularly in engineering applications such as automotive parts and structural components, in the past decades. Liquid treatment of aluminum-silicon alloys, including fluxing, is one of the most important operations toward successful casting of these foundry alloys [37].

Aluminum alloys are grouped according to the major alloying elements they contain. The 4XXX group is alloyed with silicon for ease of casting [38, 39]. Silicon is good in metallic alloys used for casting. This is because it increases the fluidity of the melt, reduces the melting temperature, decreases the contraction associated with solidification and is very cheap as a raw material. Silicon also has a low density(2.34gcm^{-3}), which may be an advantage in reducing the overall weight of the cast component. Silicon has a very low solubility in aluminum; it therefore precipitates as virtually pure silicon, which is hard and hence improves the abrasion resistance [38].

Further, aluminum-silicon eutectic is an anomalous eutectic because it constitutes a metal (aluminum) and a non-metal (silicon). Evolution of an anomalous eutectic has not been completely understood till date. To add to the confusion, the aluminum-silicon eutectic undergoes a change in morphology upon addition of certain elements e.g. strontium or sodium. This process is often referred to as eutectic modification [40].

3.2 The Aluminum-Silicon Phase Diagram and Equilibrium Cooling

Aluminum-silicon system is a simple binary eutectic with limited solubility of aluminum in silicon and limited solubility of silicon in aluminum. The solubility of silicon in aluminum reaches a maximum (1.65 wt%) at the eutectic temperature [40].

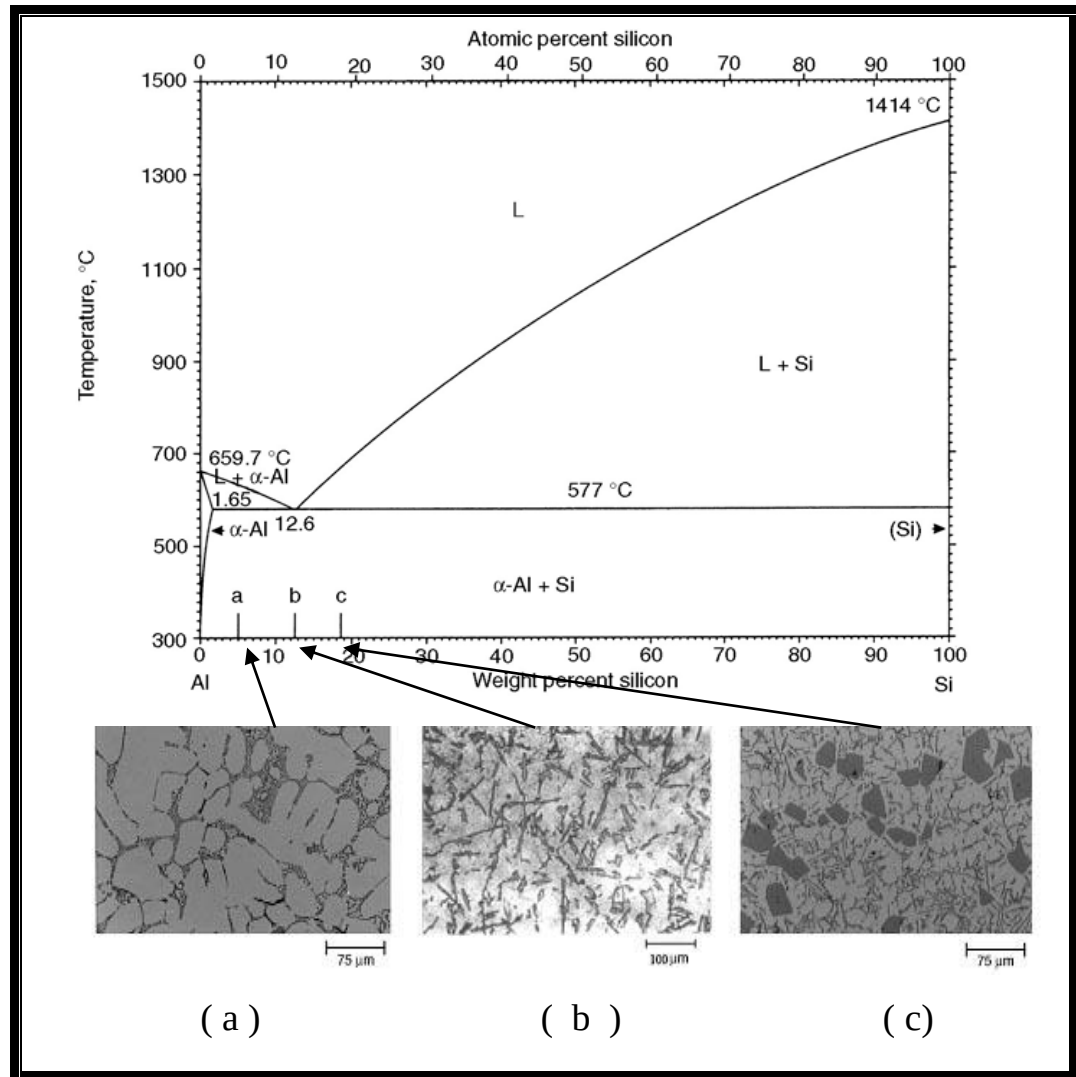


Figure (3.1)

depicts the contemporary aluminum-silicon phase diagram.(a) Hypoeutectic alloy, (b) Eutectic alloy,(c) Hypereutectic alloy [41].

There is only one invariant reaction in this diagram, namely:



In equation (3.1), L is the liquid phase, α is predominantly aluminum, and β is predominantly silicon. It is now widely accepted that

the eutectic reaction takes place at 577°C and at a silicon level of 12.6%. Figure (3.1) shows that the aluminum-silicon eutectic can form as follows:

1. Directly from the liquid in the case of a silicon concentration of 12.6% (i.e., for a eutectic aluminum-silicon alloy),
2. In the presence of primary aluminum in the case of silicon contents <12.6% (i.e., for hypoeutectic aluminum-silicon alloys), and
3. In the presence of primary silicon crystals in the case of silicon contents >12.6% (for hypereutectic aluminum-silicon alloys) [40].

Typical eutectic structures of binary alloys form by the simultaneous growth of two phases from the liquid; therefore they may exhibit a variety of microstructures that can be classified according to two criteria:

- a. Lamellar vs. fibrous morphology of the individual phases, and
- b. Regular vs. irregular growth of the individual phases[40].

Figure (3.2) shows the microstructure of the aluminum-silicon eutectic. In general, when there are approximately equal volume fractions of the two phases, eutectics of binary alloys exhibit a lamellar structure. On the other hand, if one phase is present in a small volume fraction, this phase tends to be fibrous. As a rule of thumb, the eutectic microstructure obtained will tend to be fibrous when the volume fraction of the minor phase is less than 0.25, otherwise it will tend to be lamellar. If both phases in the eutectic are non-faceted, the eutectic will exhibit a regular morphology. In this case, the microstructure is made up of either lamellae or fibers having a high degree of regularity and periodicity. On the other hand, if one phase is faceted, the eutectic morphology is often irregular. Even though the volume fraction of silicon in the aluminum-silicon binary is less than 0.25, the typical aluminum-silicon eutectic is closer to a lamellar structure than to a fibrous one. This is usually attributed to the

strong anisotropy of growth of silicon and to the relatively low interfacial energy between silicon and aluminum [40].

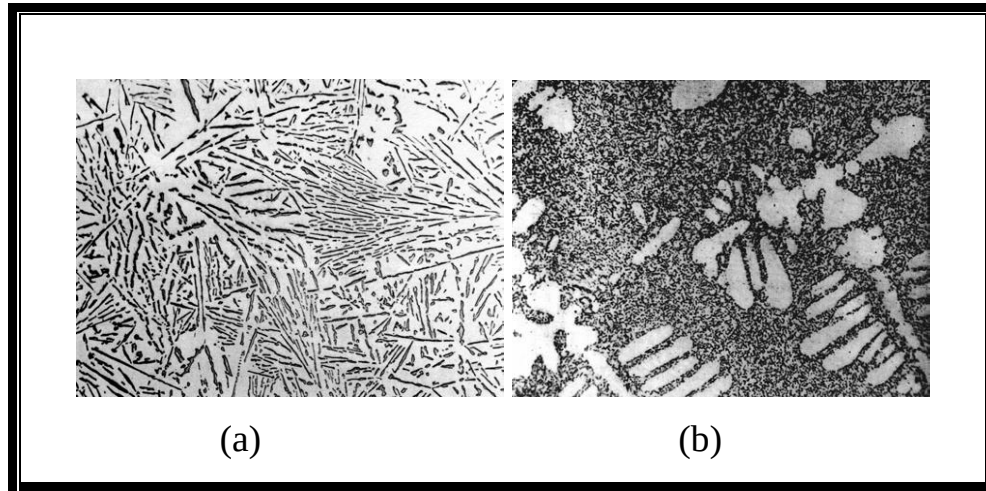


Figure (3.2)

Al-12.6wt% Si alloy (a) Slowly cooled 200X (b) Chill Cast 500X [40].

Gwyer and Phillips [40] determined the composition and temperature of the eutectic reaction in the Al-Si binary system to be 11.7%Si and 577°C respectively. Though the eutectic temperature is in accord with the currently accepted value, the eutectic composition was later changed to 12.2 ± 0.1 atom %Si. The initial error in establishing the eutectic point is due to the fact that the temperature of formation of the primary constituents (aluminum and silicon), as well as the temperature of the Al-Si eutectic plateau are cooling rate dependent. Primary silicon undercools more than primary aluminum hence the eutectic structure forms at 10-12°C below the eutectic temperature without appreciable recalescence. Consequently, at higher cooling rates, the system behaves as though the eutectic point is shifted to higher silicon contents and the eutectic temperature is depressed. Figure (3.2) illustrates this apparent shift in the eutectic point. Figure(3.2)(a), which depicts the microstructure of a eutectic aluminum-silicon alloy that is slowly cooled, shows no primary aluminum; on the other hand, Figure (3.2)(b), which depicts the

microstructure of the same alloy cooled at a relatively faster rate, shows primary aluminum dendrites [40].

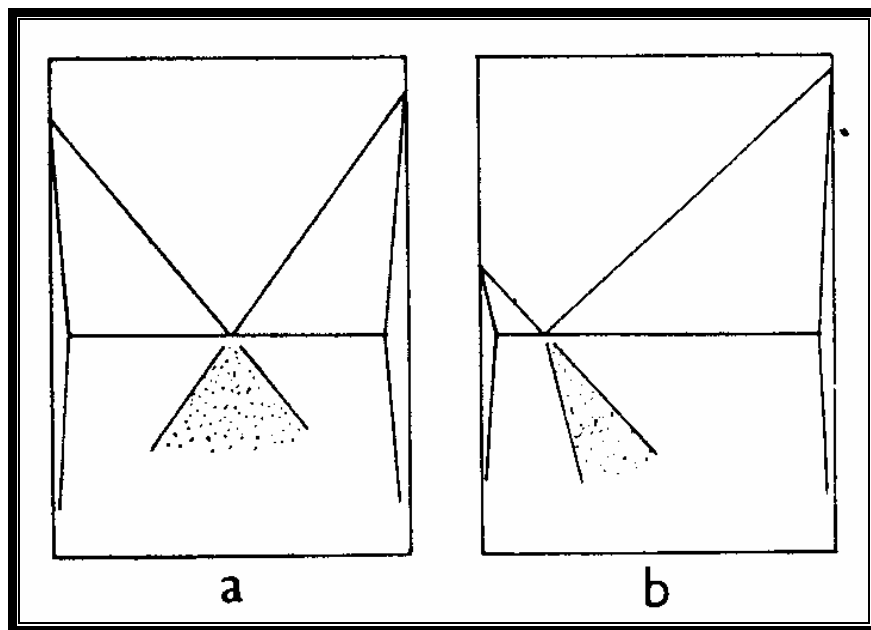


Figure (3.3)
Coupled zone in (a) symmetrical and (b) asymmetrical Phase diagrams [40].

Depression of the eutectic temperature with increased cooling rate may be explained on the basis of the coupled region effect. Coupled regions represent fields within the phase diagram where the two phases of the eutectic are organized in the solid in such a way as to allow diffusion in the liquid to occur effectively at a duplex solid/liquid front. Regions of coupled growth are shown schematically in figure (3.3) for both a symmetric and an asymmetric hypothetical phase diagram. In Al-Si system, silicon is a non-metal, which has directed covalent bonding. Hence silicon phase tends to grow anisotropically to give faceted crystals. Silicon phase needs more under-cooling for its growth than the isotropic aluminum phase. Thus the coupled region in such a system is asymmetric. Apart from cooling rate, addition of some chemical elements like sodium or strontium in minute quantities resulted in shifting the

eutectic point to the right as well as depressing the eutectic temperature [40].

3.3 The Thermal Parameters

In this section, discuss the effect of thermal parameters on solidification of aluminum-silicon alloys. During the solidification of metals, the melt conditions determine the morphology of the solidifying phase. Melt conditions include both thermal conditions and chemical conditions. Thermal conditions during solidification consist of three parameters: cooling rate, thermal gradient ($\hat{G}$) and interface velocity (R). Cooling rate is the rate at which heat is extracted from the melt. Higher cooling rate is known to yield finer structures. The cooling rate is inversely related to the secondary dendrite arm spacing. Thermal gradient ($\hat{G}$) is the change of temperature with distance. Thermal gradient of liquid ahead of the solid/liquid interface determines the constitutional under-cooling of the liquid. Constitutional under-cooling is known to result in cellular and dendritic morphology. Interface velocity (R) is the rate at which the solid/liquid interface moves. High interface velocity implies lesser time for equilibrium growth to take place. Thus, microstructures obtained at higher interface velocities have finer structure and sometimes metastable structures. Cooling rate is the product of thermal gradient and interface velocity. Comprehensive study of the different microstructures possible in a system is done by studying the system at various values of temperature gradient and interface velocity[40].

The summary of tensile and compressive properties of directionally solidified Al-Si eutectic alloy given in table (3.1). Show that the yield and tensile strength increase with increasing growth velocity[24].

Table (3.1)
Tensile and compressive properties of directionally solidified Al-Si eutectic alloy[24].

Structure	Growth velocity $\mu\text{m s}^{-1}$	<u>Tensile properties</u>			<u>Compressive properties</u>		
		0.2% proof stress Nmm^{-2}	UTS Nmm^{-2}	Elongation %	0.2% proof stress Nmm^{-2}	UTS Nmm^{-2}	Elongation %
[100]Angular	1.5	57.8	109	6.8	330	400	0.6
Flake	45	53.8	142	8.5	92.6	—	—
Flake -fiber	450	60.6	155	12.5	—	—	—
Flake -fiber	1300	63.6	157	8.8	104.2	—	—
Chill cast		101.5	220	3.8	150		

CHAPTER FOUR
EXPERIMENTAL PROCEDURE &
COMPUTER MODELING

4.1 Introduction

In this chapter, a set of experiments, conducted to further our understanding of the evolution of aluminum-silicon eutectic will be discussed. Various parameters used in the experiments as well as the modeling along with the materials used to conduct the experiments. It is followed with a step by step description of the procedures used.

A set of experimental approaches were simultaneously undertaken to study the evolution and a unidirectional solidification of the eutectic microstructure. This phase will be very important in the reinforcement process of the matrix which will be very important in the reinforcement process of the Al matrix as an in-situ composite material.

A multi-pronged approach was necessary because of the number of issues that needs to be resolved in order to arrive at a comprehensive understanding of this complex phenomenon. The following is the list of the experiments conducted in this study:-

1. Modeling process using a finite element method by an ANSYS-code (version - 5.4) including a full scale modeling of an unidirectional solidification set up in order to determine an accurate estimation of the temperature distribution with the time under various conditions of thermal insulations of the used molding.
2. Nucleate and growing up of the eutectic phase by melting and solidification the molten alloy in unidirectional manner by using

the solidification unit that designed and produced for this purpose.

The first set of experiments has been done with a reconsidering of the following:-

1. Molten alloy temperature.
2. Pouring temperature.
3. Application of various types of insulation materials to the mold of solidification unit. Then continuous cold water flow through the lower part of the solidification unit, from a suitable reservoir.

The choices of such parameters are adopted according to the results of computer modeling as it is remembered before. The temperature distribution and the heat sink that clearly obvious in the results of modeling part, helping to specify the above parameters.

Eventually, microstructure observations in step by step which give a clear picture on how to control and augmenting the nucleation and growth of the eutectic phase under different solidification conditions.

4.2 Materials Used

(Al-12%Si) alloy was used in the form of ingots. The average chemical composition of this alloy is given in table (4.1) as shown below. The chemical composition analyses i.e. x-ray fluorescence analysis were performed in the Ministry of Scientific and technology /office of water treatment by using the equipment(X – MET 3000 TX, horizon 600 series, model 2004). All the material used ingots were received from the Iraqi local markets.

Table (4.1)

Average chemical composition analysis of the Al-Si alloy in this work.

Element	Si	Fe	Cu	Mn	Ni	Al
wt%	11.9665	0.5532	0.0752	0.0721	0.0101	Bal.

4.3 Procedure

4.3.1 Alloy Preparation for Melting:-

Al-Si alloy ingot was received in (40 x 40 x 150 mm). The alloy small blocks were then ground by using a silicon carbide paper and cleaned in an ethanol to remove any surface impurities. The alloy blocks are now melted by using a graphite crucible with a volume of 1000 gm capacity) by the using of an electric resistance furnace number 2 type (SOLA BASIC 51222), (see figure (4.4)).

4.3.2 Thermal Analysis:-

An approximately 250 grams of the alloy was taken, heated by using an electric resistance furnace number 2 and heated to 750°C. The sample was held at 750°C until the furnace and the melt were in equilibrium. The sample was then cooled slowly beside the furnace on an open door. The temperature was measured by an Infrared thermocouple type (AR 8725S) by subject its light in the center of crucible.

Data of a thermocouple was recorded until the alloy completely solidified then recorded the solidification temperature of alloy.

4.3.3 Experimental Apparatus:-

A schematic and photographic of the apparatus are shown in figures (4.1) and (4.3). Two types of electric resistance furnace have been used to conduct the melting and heating practices (see figure (4.4)). The following is

a list of the apparatus that used in the melting and sampling processes:-

1. Unidirectional solidification unit that including a carbon steel mold with dimensions as shown in figure (4.1).
2. Cold water tank, the flow was done by gravity. The function of the cold water is to work as a heat sink by increasing the heat transfer and dissipation at the bottom side of the mold. The temperature of the cold water was kept at (5°C).
3. Thermocouple (Model TE9-RB10) has been used to monitoring the drop in the molten material temperature. The thermocouple was inserted between the mould and the insulation materials.
4. Mold was made from low carbon steel with the dimensions shown in figure (4.1).

The insulation materials generally defined as a material that retarding of heat energy, the function of such materials are:-

1. Conserve energy by reducing heat loss or gain.
2. Facilitate the temperature control of process.
3. Prevent vapor flow and water condensation on cold surfaces.

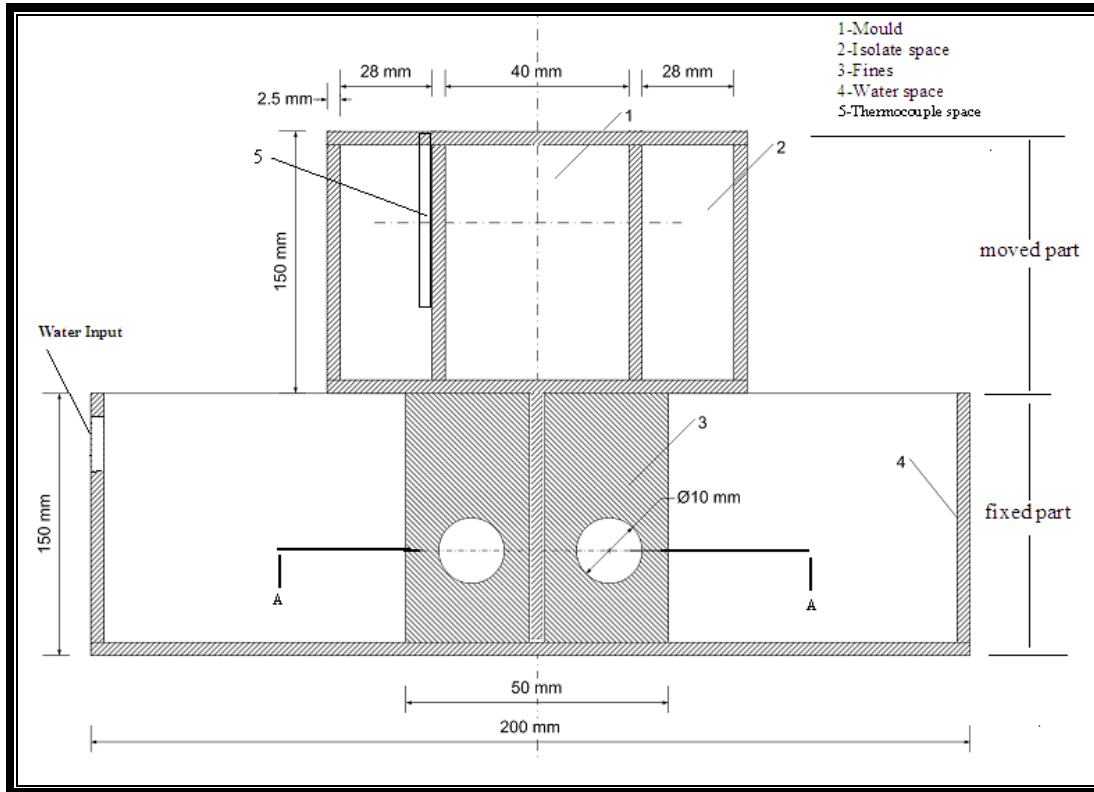


Figure (4.1)
A schematic diagram of the unidirectional solidification unit.

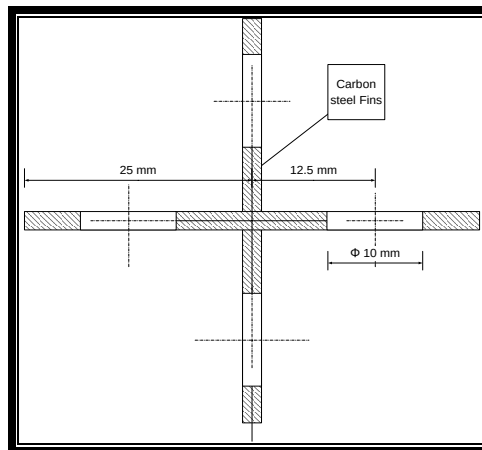


Figure (4.2)
A schematic diagram of the section A-A in the unidirectional solidification unit as labeled above.

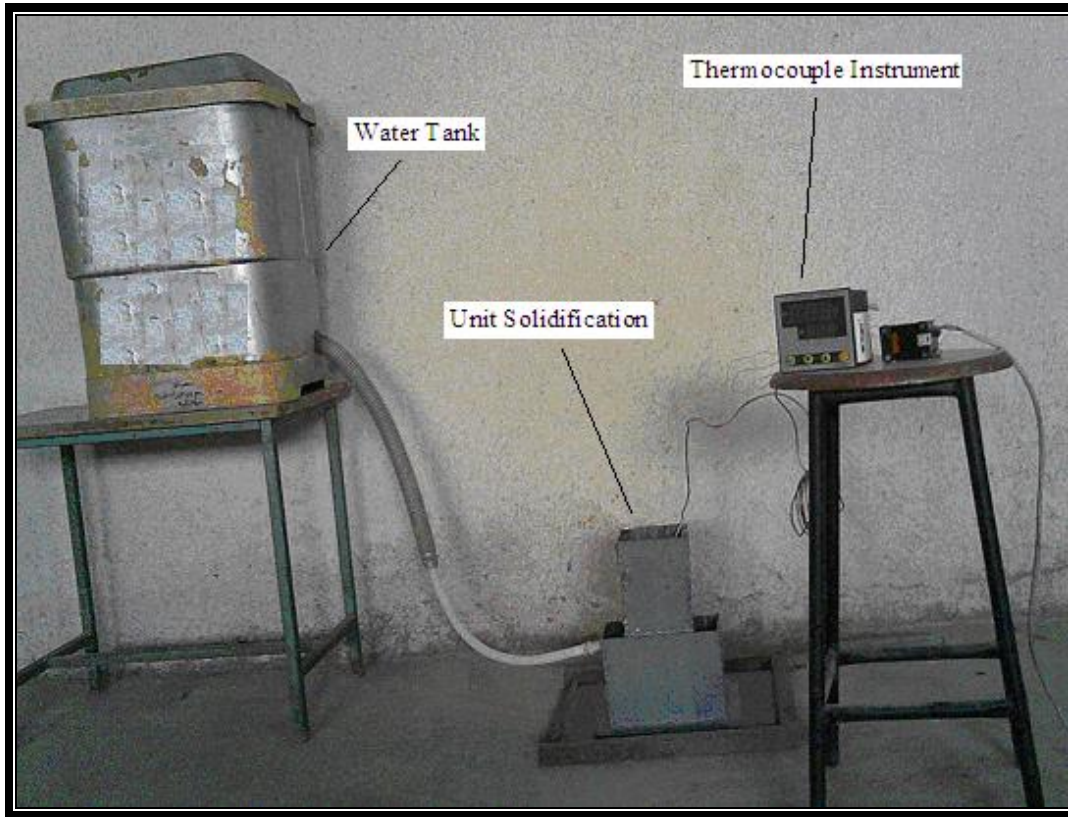


Figure (4.3)

A photographic picture shows the apparatus that used in the solidification practices.

Two types of insulation material have been used in this work as following:-

1. Fibrous insulation (glass wool) which is composed of small diameter fibers that finely divide the air space. The application of the glass wool insulator in this work has been done manually and the fibers material is pressed with the help of tool to ensure a best insulation properties.
2. Sand, it is a granular material which is composed mainly from silica with a particle size ($\approx 0.3\text{mm}$).

Thermal conductivities of the insulation materials above are mentioned in table (4.2) in order to facilitate the process of understanding and developing the experimental and the modeling part of work. These materials having low thermal conductivity in comparison with the other materials (see reference [42]). This property defined as the amount of heat flux that would pass through a certain material (i.e. insulation) depending on the temperature gradient over that material [42].

Thermal conductivity plays an important role in many heat and mass transport. Phenomena as it are a function of parental number [42] it is denoted by (K).commonly used unit is (W.m/m². °C).

Table (4.2)
Thermal conductivities of insulation materials[42].

Type of insulation material	Thermal conductivity (K)W.m/ m ² . °C
Sand	0.33
Glass wool	0.038

4.4 Melting and Sampling Procedure

Prior to the experiments, a small blocks were cut from the ingots of Al-Si alloy. These blocks were freshly surface ground by the using of 180 and 400 grit silicon carbide papers and then cleaned by using the solution of ethyl alcohol for five minutes and then removed out of alcohol only before the experiment. The following is the list of the procedure steps that adopted for the producing of samples in different conditions of solidification:-

1. The specimens were heated at the rate of approximately 5°C/min till

- the eutectic alloy melted by using a graphite crucible and an electric resistance furnace number 2 that used in the thermal analysis (see 4.3.2).
2. Temperature was monitored with an external thermocouple that equipped with the furnace. The temperature was raised till 700°C.
 3. Three runs were performed representing the three conditions of solidification as follows:-
 - a. Without any insulated mold and no water flow (i.e. free mold insulation).
 - b. With a sand insulation and cold water flow through the unit.
 - c. With a glass wool insulation and cold water flow through the unit.
 4. The moving part of the uni-directional solidification unit is now ready for heating in the second electric resistance furnace type (RECTRADEUAR) that prepared for this purpose (number 1, see figure(4.4)). The moving part of the solidification unit must be heated to the same molten metal temperature (i.e. 700°C). An elapsed time must be left now to get a homogenization heating of the moving part of solidification unit.
 5. Care must be taken to ensure that, the metal does not overheat. The recommended pouring temperature for alloy under investigation is usually $(700 \pm 10^\circ\text{C})$. Note that, the upper part of solidification unit are now ready (i.e. preheated to 700 °C) and out of heating furnace at the right place on the lower part of solidification unit. The measurements of temperature was done by using the thermocouple attached to the mold (see 4.3.3).
 6. The cold water tank valve is now in on- condition and the flow are

now stable with a reasonable flow rate,(ice cubes were added to set the water temperature at 5 °C).

7. Continuous monitoring of the temperature by the data of thermocouple.
8. Using various insulation materials:-
 - a. Sand insulation mold.
 - b. Glass wool insulation mold.



Figure (4.4)
Equipment of electric furnaces.
1. (REC TRADEUAR) type.
2. (SOLA BASIC 51222) type.

4.5 Productions of Samples Ingots

Several sets of ingot samples are now produced according to the steps that proceeded in (section (4.4)), with a high attention during each step of melting and molding practices. These precautions are very important to ensure the uni-directional solidification of the eutectic phase in all samples as the work has aimed.

The following table (4.3) shows, the general plane of ingot samples numbering and the condition that adopted in this work:-

Table (4.3)
General plane of ingot samples production.

Set of sample no.	Solidification condition	
	Mold insulation type	Cold water flow
1	Free	Without
2	Sand	With
3	Glass wool	With

In order to check the uni-directional solidification of ingot samples, sectioning of samples must be done in a direction parallel to the direction of heat sink (i.e. into the bottom direction).

4.6 Modeling Process

4.6.1 Introduction

A numerical modeling of unidirectional solidification (temperature distribution) of (Al-Si) system has been performed in this work. This analysis was implemented by the using of ANSYS-code (version - 5.4). It is based on the finite element method (FEM), and following is the steps of this process:

4.6.2 Model Constitute

FEM model was built in order to simulate the temperature distribution of (Al-Si) eutectic system with varying insulation materials, several assumptions are assumed to conduct the numerical analysis for this process. These assumptions:

1. Two dimensions model was built, to facilitate the problem modeling.
2. Taking the temperature distribution after 3min from pouring alloy (Al-12%Si)
3. Free convection on outer sides, are assumed homogeneously.
4. Just one side (i.e. bottom) is without insulation (i.e. the side were cold by water).
5. Initial condition of melting alloy (Al-Si) is at 700 ° C.
6. Transit solidification was proposed for this case of solidification.
7. One type of element is used to mesh an alloy to be solidified and the insulation materials.
8. Neglected the phase change and assumed only one phase (liquid) and neglect solidified alloy.
9. Neglected heat convection by fins and neglect the speed of any fluid (air, water).

4.6.3 Geometry of Sub. Model

The model was built according to dimensions that adopted in the experimental work that represent the solidification unit (mould and insulation materials). The model geometry of this system is shown in figure (4.5).

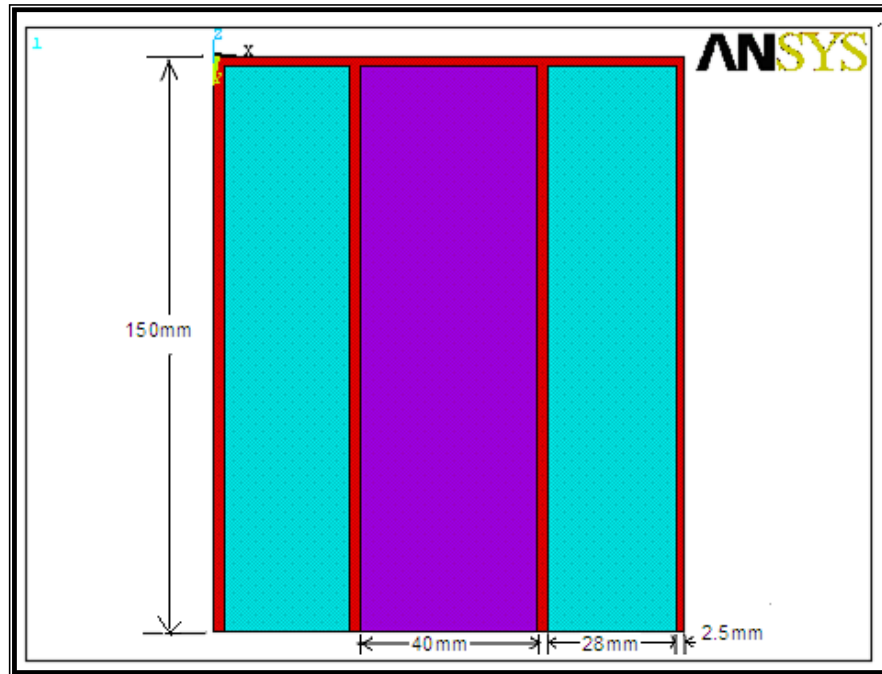


Figure (4.5)
Geometry of sub model adopted for numerical analysis.

4.6.4 Finite Element Model

The geometry of model is meshed now to study the temperature distribution after 3min from pouring alloy. Mash sizes are determined including the scanning for all portion of ingot and mould. Element plane 77 is used to model the ((Al-Si) alloy and insulation of mould) .Finite element model and mesh size are shown in figure (4.6).

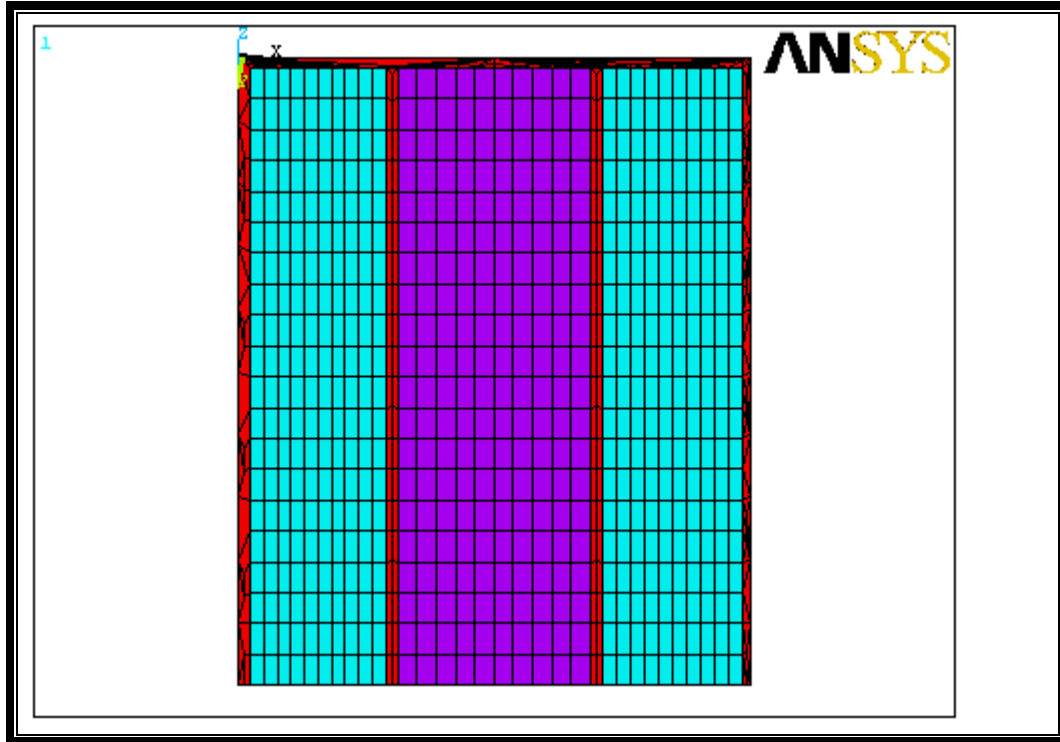


Figure (4.6)
Finite element model assumptions.

4.6.5 Mathematical Formulation

FEM of casting process is based on the classification of heat transfer flow in two dimensions. The conditions of heat transfer during this solidification process of casting alloy are included the following:-

1. Heat conduction within the Al-Si alloy.
2. Heat conduction from ingot (Al-Si) system to the insulation material and mold surfaces.
3. Heat convection (free convection) to the outer surfaces of mold and fluid .

When a temperature gradient exists in a body, we say that the energy is transferred by conduction and that the heat-transfer rate per unit area is proportional to the normal temperature gradient:

$$q/\hat{A} \sim \partial T/\partial x \quad (4.1)$$

When the proportionality constant is inserted,

$$q = -K \hat{A} \partial T/\partial x \quad (4.2)$$

where q is the heat-transfer rate and $\partial T/\partial x$ is the temperature gradient in the direction of the heat flow. The positive constant K is called the thermal conductivity of the material[43].

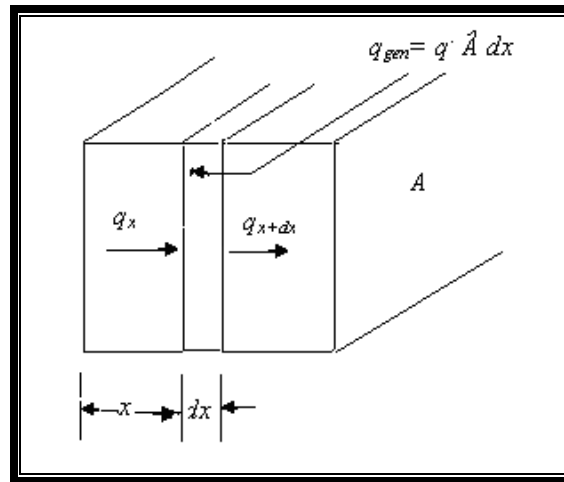


Figure (4.7)

Elemental volume for one-dimensional heat-conduction analysis [43].

Consider the one-dimensional system shown in figure (4.7). If the system is in a steady state, i.e., if the temperature does not change with time, then the problem is a simple one, and we need only integrate equation (4.1) and substitute the appropriate values to solve for the desired quantity. However, if the temperature of the solid is changing with time, or if there are heat sources or sinks within the solid, the situation is more complex. We

consider the general case where the temperature may be changing with time and heat sources may be present within the body. For the element of thickness dx the following energy balance may be made:

Energy conducted in left face + heat generated within element
 = change in internal energy + energy conducted out right face

These energy quantities are given as follows:

$$\text{Energy in left face} = q_x = -K \hat{A} \partial T / \partial x$$

$$\text{Energy generated within element} = \dot{q} \hat{A} dx$$

$$\text{Change in internal energy} = \rho c \hat{A} (\partial T / \partial t) dx$$

$$\text{Energy out right face} = q_{x+dx} = -K \hat{A} \partial T / \partial x \big|_{x+dx}$$

Where $\dot{q}$ = energy generated per unit volume, W/m³.

c = specific heat of material, J/kg. °C.

ρ = density, kg/ m³.

Combining the relations above gives:

$$\partial / \partial x (K (\partial T / \partial x)) + \dot{q} = \rho c (\partial T / \partial t) \quad (4.3)$$

This is the one-dimensional heat-conduction equation[43].

To express the overall effect of convection between:

1. The outer wall of mold and air (in case of free mold insulation conditions).
2. The outer wall of the solidification unit and air (in cases of sand and glass wool mold insulation conditions).
3. The outer wall of the solidification unit and water (in cases of sand and glass wool mold insulation conditions).

used Newton's law of cooling:

$$q = h \hat{A} (T_w - T_\infty) \quad (4.4)$$

Here the heat- transfer rate is related to the overall temperature difference between the wall (T_w) and fluid (T_∞) and the surface area ($\hat{A}$). the quantity h is called the convection heat- transfer coefficient[43].

4.6.6 Material Used in Model

The material behavior is modeled in the simulation process by the using of isotropic thermal transfer in different type of insulation materials and (Al-Si) alloy. This behavior is described by assuming the initial properties of (thermal conducting, specific heat and enthalpy) for each material(Al-Si eutectic alloy, Steel, Sand, Glass wool, air, water) .

4.6.7 Boundary Conditions

The bounding conditions are applied on system are as follows:-

1. Initial temperature (700 ° C) for (Al-Si) alloy.
2. Taking the result after 3 min of pouring of alloy .
3. Film coefficient is (0.014) for free convection.

4.6.8 Paramedic Study

The most paramedics studied in the numerical analysis are the distribution of temperature with varying of insulation materials.

4.6.9 Results Output

Results are recorded as a contour result and query point through any portion of casting system (ingot and mold). These results are followed with time step. The temperature distribution recorded with type of insulation material.

4.7 Sample Preparation for Microscopic Analysis

The samples were prepared in consistent with the standard metallographic techniques. The ultimate objective of such a process was to obtain a flat scratch free, mirror like surface.

From a viewpoint of an ideal sample ready for microstructure examination it must satisfy the following measures [44]:

1. Be representative sample.
2. Have minimum deformation after sectioning, grinding and polishing.
3. Free from grinding and polishing scratches, pits and staining from the etch or subsequent corrosion.
4. A sample polished so that inclusions are presented intact.
5. Enough flatness to allow high magnification.

Such measures are satisfied through a series of subsequent processes as ordered below:

4.7.1 Sectioning

Each sample was cut to a convenient length parallel to the y-axis (i.e. the solidification direction) enables handling during subsequent grinding and polishing. Water was used as a coolant to avoid overheating that may be lead to any phase transformations.

4.7.2 Grinding

This is the process of abrading the sectioned specimen in a sequence of steps using progressively finer abrasive papers (180, 400, 600, 800, 1000, 1200, 2000 grit size).

A series of parallel scratches were introduced and successively removed and replaced by finer scratches. Only light pressure was applied in order to

maintain the specimen flat and eliminate all scratches introduced by the previous paper. Water was used as a coolant and lubricant to facilitate hand grinding.

The specimen had been rinsed between papers to avoid transferring abrasives. The grinding was done on a rotary grinding wheel.

Grinding revealed a flat surface, free of nicks, burrs and all scratches introduced were made invisible. Grinding has done with using of grinding machine type (MP200V).

4.7.3 Polishing

Polishing stage is highly required to ultimately produce a scratch-free, highly polishing and flat surface ready for subsequent etching and microscopy, by using cloth polishing and Alumina liquid.

4.7.4 Etching

This was the last step before visual inspection. It involved a short treatment for 15 sec in an etchant solution prepared as:

0.5%HF+99.5%H₂O (distilled) [44, 45]

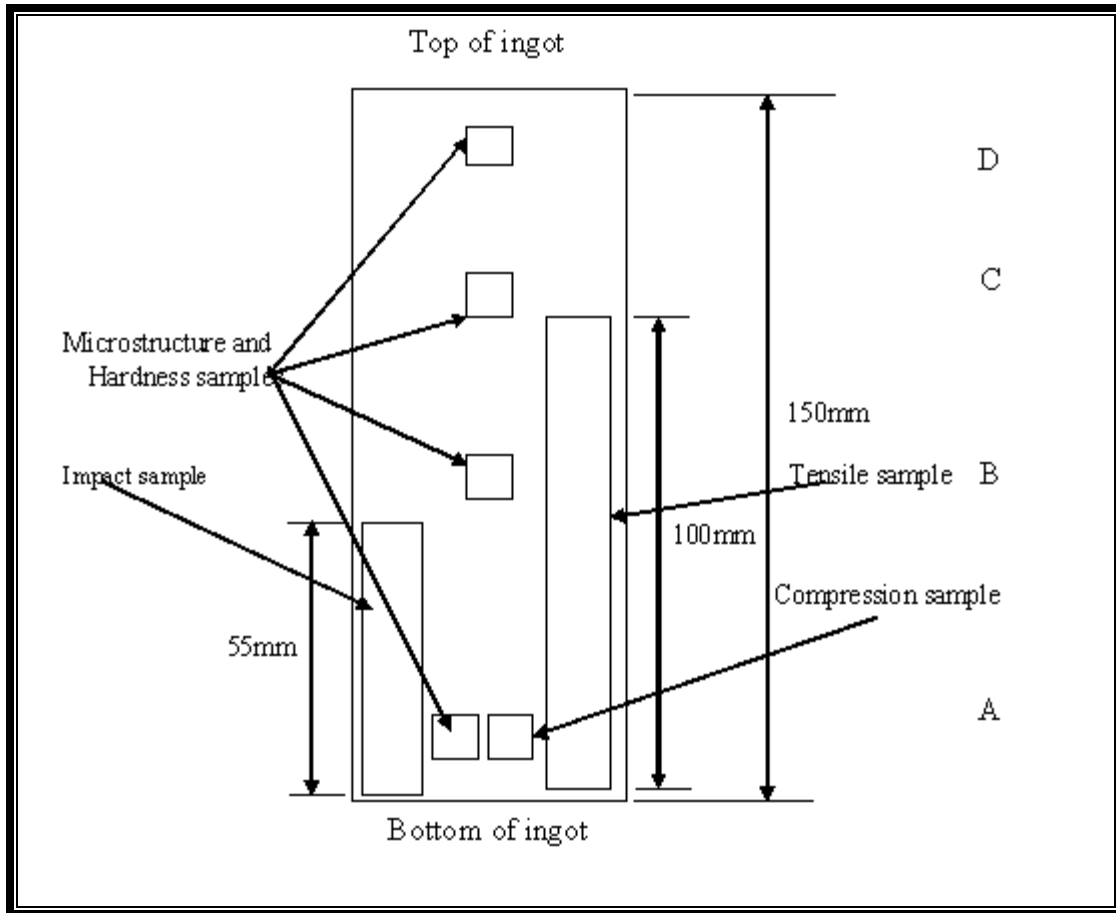
It revealed various structural characteristics of the samples by the preferential attack of the constituents and grain boundaries.

Etching was performed by repeated dipping of the sample in the reagent. It would be stopped by immediate washing with distilled water, rinsed with ethylalcohol and dried by air.

Standard metallographic examinations using optical microscopy (Union / ME-3154) type was used to reveal the samples structures.

4.8 Mechanical Testing

Many mechanical testing have been done . The samples of testing were cutting from bottom part of ingot in the direction of heat sink, see figure (4.8).



Figure(4.8)
The places that have been cutting from it the samples.

4.8.1 Hardness Test

Hardness is a measure of a materials' resistance to localized plastic deformation (e.g., a small dent or a scratch).Early hardness tests were based on natural minerals with a scale constructed solely on the ability of one material to scratch another that was softer [46].

Appropriate grinding and polishing was done before subject specimens to hardness tests[44].

In Brinell tests, a hard, spherical indenter is forced into the surface of the metal to be tested [34]. A Brinell hardness testing machine was used to conduct the test with a load of 500 Kg for 30 sec. using a steel ball with a 10 mm diameter [44, 46].

This is expressed by the formula

$$\text{BHN} = P / ((\pi D/2) (D - \sqrt{D^2 - d^2})) \quad (4.5)$$

Where P = applied load, kg

D = diameter of ball, mm

d = diameter of indentation, mm

It will be noticed that the units of the BHN are kilograms per square millimeter [9]. In this test used the "Material Testing Unit" that shown in figure (4.10).

4.8.2 Tensile Test

The engineering tension test is widely used to provide basic design information on the strength of materials and as acceptance test for the specification of materials. In the tension test, a specimen is to a continually increasing uniaxial tensile force while simultaneous observations are made of the elongation of the specimen. An engineering stress-strain curve is constructed from the load-elongation measurements [9].

The sample dimensions that used was (Lt=100, Lc=30, Lo=14, b=6, r=12) as shown in figure (4.9) [47].

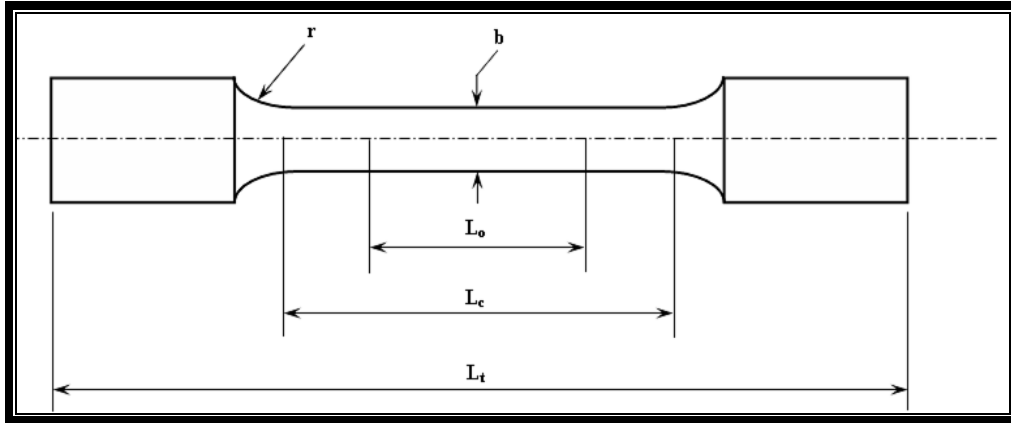


Figure (4.9)
Tensile test specimen [47].

Since both the stress and the strain are obtained by dividing the load and elongation by constant factors, the load-elongation curve will have the same shape as the engineering stress-strain curve. The two curves are frequently used interchangeably[9].

At low speed and room temperature were measured tensile properties. Used the (Material Testing Unit), see figure (4.10).



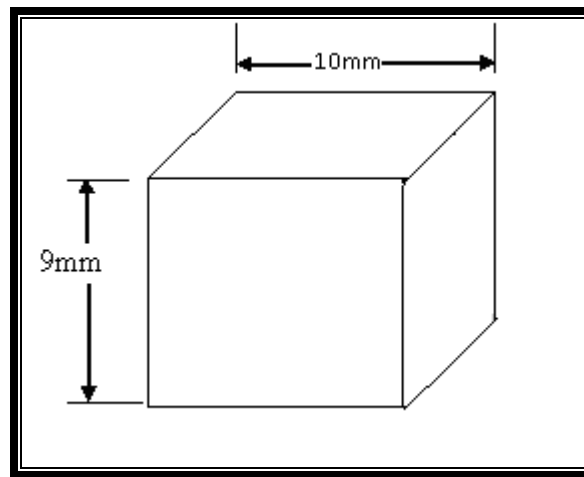
Figure (4.10)
Equipment of Material Testing Unit.

4.8.3 Compression Test

It consists of compressing a sample between parallel platens; the height / diameter ratio has to be lower than a critical value in order to eliminate the possibility of instability (buckling).

In compression testing, a cylinder or a parallelepiped cube (with one side- the parallel to the loading direction-longer than the other two) is subjected to compression between two parallel plates. The plates should have a self-alignment system. And they often ride on one or two hemispherical caps.

The specimen that used in this test was the cube short sample ($d^* \cdot 0.9 = h$), where ' d^* ' the length of top section = 10mm, ' h ' the height of sample, [47], as shown in figure (4.11).



Figure(4.11)
Comparison test specimen.

In this test, the samples subject to the same magnitude of the load to study the behavior of them through compression load.

4.8.4 Impact Test

Various types of impact tests are used to determine the tendency of a material to behave in a brittle manner. This type of test will detect differences between materials which are not observable in a tension test. The results obtained from impact tests are not readily expressed in terms of design requirements, since it is not possible to measure the components of the triaxial stress condition at the notch.

The notch is located in the center of the test specimen, which is supported horizontally at two points. The specimen receives an impact from a pendulum of a specific weight on the side opposite to that of the notch. The specimen fails in flexure under impact [48].

1Degree=2Joule

Impact testing was performed on Charpy testing machine using 55mm length with 45° V notch, 2mm deep with 0.25 mm root radius as Shown in figure (4.12).

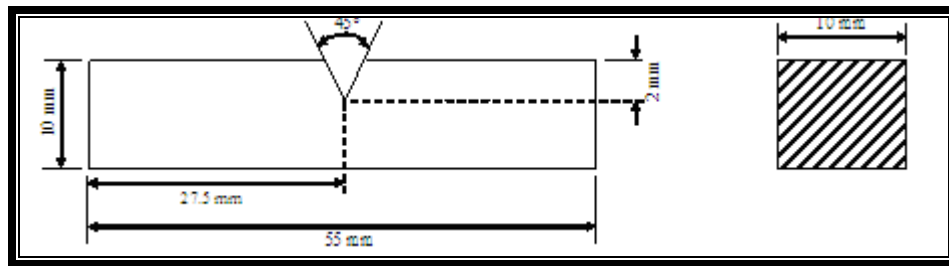


Figure (4.12)
Impact test specimen.

The equipment that used in this test was (FIT-300(N)) type, shown in figure (4.13).



Figure(3.13)
Equipment of Impact.

4.9 X-Ray Diffraction Analysis

The X-ray diffraction analysis is a vital tool in which the constituent phases can be monitored. This analysis covered a selected sample from the three conditions of solidifications. The analysis has been done for all selected samples in the Ministry of Sciences and technology /office of materials sciences by using Equipment (Lab XRD-6000 Shim ADZU x-Ray Diffract meter). The measure conditions are (Target: Cu, length wave: $1.54060 \text{ \AA}$).

From "Bragg law", " d_{hkl} " the radius of the sphere can be calculated describing the locus of the reciprocal lattice point (hkl), as shown:

$$(2/\lambda') \sin\Theta = 1/d_{hkl} \quad (4.6)$$

Where λ' is the length wave.

Θ is the angle of deviation of the diffracted beam [14].

CHAPTER FIVE

RESULTS & DISCUSSION

5.1 Introduction

In this chapter, the results obtained in each parts of work that including the computer model of temperature distribution and experimental will be presented and followed by the discussion of results. Since the results of the computer modeling are interrelated with the experiments, the discussion will be combined i.e. for modeling and experiments.

The results are presented and discussed under various aspects such as thermal analysis, effect of insulation material on the nucleation, growth of eutectic system and mechanical properties such as (impact, tensile, compression and hardness properties) and also the microstructure evolution of eutectic system.

First, can see the microstructure of alloy before any processes of pouring, see figure(5.1).

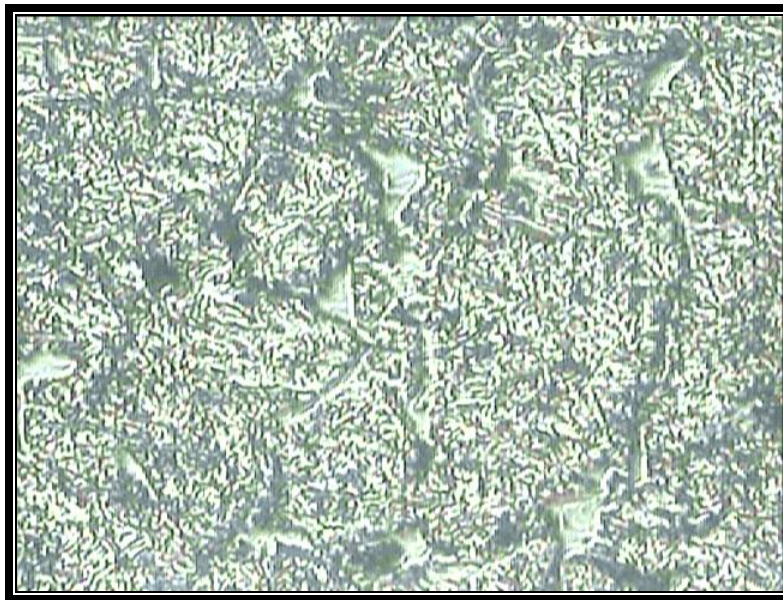


Figure (5.1)
Microstructure of alloy before any process of pouring 200X.

The thermal analysis of the alloy under investigation was performed at section (4.3.2). The solidification temperature was 550 °C. The eutectic temperature in this work supposes to still constant (the values are identical to some extent with the standards) since there is no additions of modifiers like Sr or Na but the other elements also effect on the solidification temperature and other properties.

The technique that used during the production and improvement of the grown eutectic system during the solidification process has been proposed, designed and manufactured according to many assumptions that adopted in this work such as:-

1. The molten alloy should be kept in its pouring temperature as much as possible at the mold.
2. Preventing any heat dissipations through the walls and keeping only one direction as a heat sink.
3. The heat sink direction promoted the direction and growing the β -phase.

The examinations of the produced in-situ composite materials at different conditions are discussed in details. These discussions are parallel for each type of results which are computer modeling and experimental.

5.2 Discussion of Modeling & Experimental Results

5.2.1 Discussion of Microstructure Evolution and Mechanical Properties in Free Mold Insulation Conditions :-

Figure (5.2) shows the temperature gradient distribution contour across the solidification system in the case of mold free of insulation (i.e. free solidification) after 3 min. of pouring.

The numerical model shows a logical distribution of temperature across the system (alloy, steel, air) and the difference of temperature between the alloy and outer surface of wall shows the no high (626-595)°C because escape the heat in the direction of sides. The predicted and measured temperature monitoring is in good agreement. Taking into consideration that the thermocouple (was put at the side of mold) reading in every 30 seconds until the solidification is completed. The decrease in the temperature with the time is clear in the figure (5.3) that recorded from the thermocouple that put beside the outer surface of the mould.

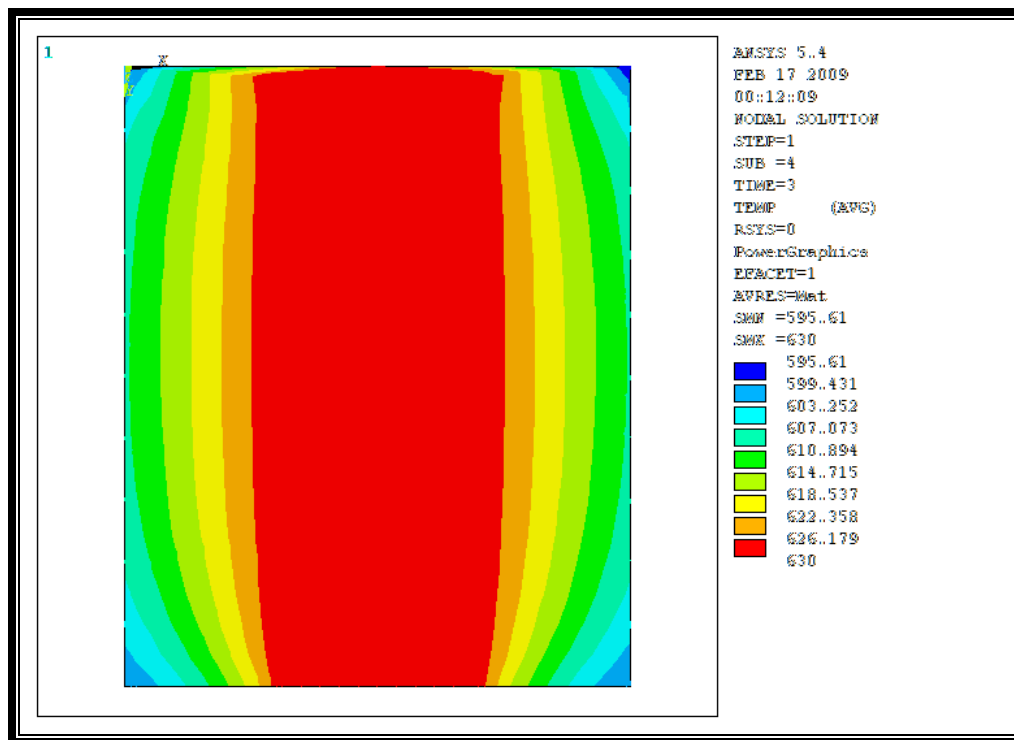


Figure (5.2)
 Temperature distribution gradient across the solidification system at the free mold insulation conditions after 3 min. of pouring (results in °C).

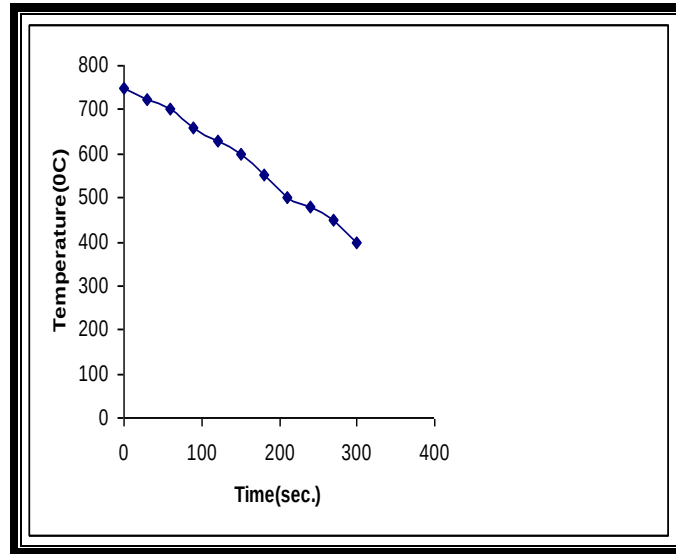


Figure (5.3)

The relation between the temperature and the time in case of free mold insulation condition that recorded from the thermocouple that used in experimental procedure.

These temperature distributions are reflected directly on the experimental part of work (i.e. during the experiments of samples production by using the unidirectional solidification unit without any insulation material and also no cold water flow through the unit. The molten metal (i.e. Al –Si alloy) is in thermodynamic instability during solidification;[22] the β - phase nuclei can nucleate and grow due to the crystallization driving force, the solidified interface between the growing β -phase and the solidified matrix would become unstable under the following conditions:-

1. solute fluctuations.
2. heat disturbances.

The solute fluctuations are no longer working especially at the progress of solidification (i.e. %Si constant), while the heat disturbances still the main parameter that affecting the process of second phase (i.e. β -

phase) nucleation and growth. The microstructure observations as shown in figure (5.4) in the case (free mold of insulation conditions).

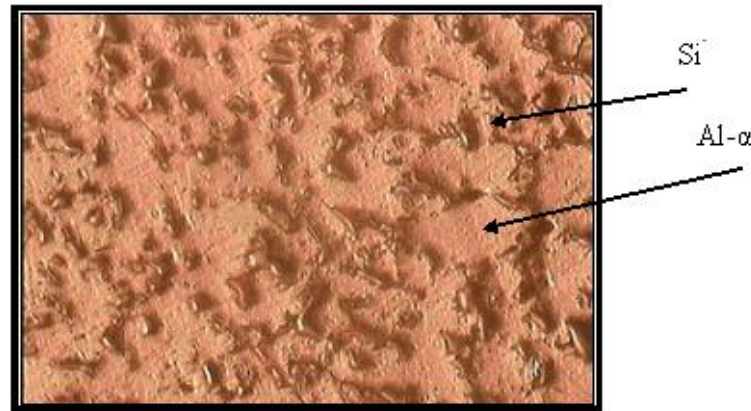


Figure (5.4)
Optical microscopy of alloy at (free mold of insulation) conditions(200X).

The irregular orientation and distribution of eutectic phase in figure above are coming as a result of irregular little growth of individual phase (i.e. the β -phase). The β -phase appears in the microstructure above could be seen in most commercial Al-Si eutectic alloy casting that solidified in this regime (i.e. free mold insulation condition) or free solidification with no modifiers addition to the molten material such as sodium or strontium.

5.2.1.1 Discussion of Mechanical Properties of Produced Alloy at Free Mold Insulation Conditions

According to the experimented procedure adopted to produce the samples in this case (i.e. free mold insulation condition). The mechanical properties evaluation includes:-

1. Hardness Results Discussion:-

Brinell hardness testing survey on all the outside area of solidified Al-Si eutectic alloy supporting the results that obtained from the

microstructure observations above. The hardness results are almost equal or homogeneous at all the outside area of material under investigation as can be seen in figure (5.5).

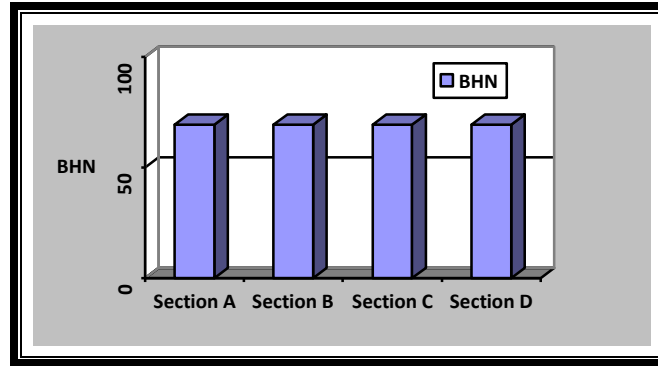


Figure (5.5)

Brinell harness survey at the four specified sections of the alloy under free mold insulation conditions.

As it was stated above, the reason behind such equal or homogeneous results of hardness is the homogeneous grain size distribution along the material under these conditions of solidification. The little grown β -phase and its heterogeneous orientation did not improve the hardness results. That will give an idea about the effect of β -phase orientation and its growth on the subsequent conditions of solidification.

2. Tensile & Compression Strength Properties:-

Figure (5.6) shows the stress- strain curve of the samples produced at (free mold insulation condition). These tests coming to evaluate the effect and the role of the β -phase in the reinforcement process of the Al- matrix and also to see the effect of cooling rate on the grain size of the matrix and its role in the direction of second phase. The behavior seems to be very close to the brittle material in behavior each type of loading (i.e. tension and compression).

The reasons behind such behavior are the effect of the following:-

1. Much micro-segregation in solid solution state.
2. Irregular distribution of primary Silicon due to the escape the heat from the material by air during the solidification process.
3. At, this conditions of solidification, where the cooling rate is low, the gas porosity nucleates and grows as expected (i.e. no degasser added).
Taking into consideration that the material is not homogenized or heat treated (i.e. as cast condition).

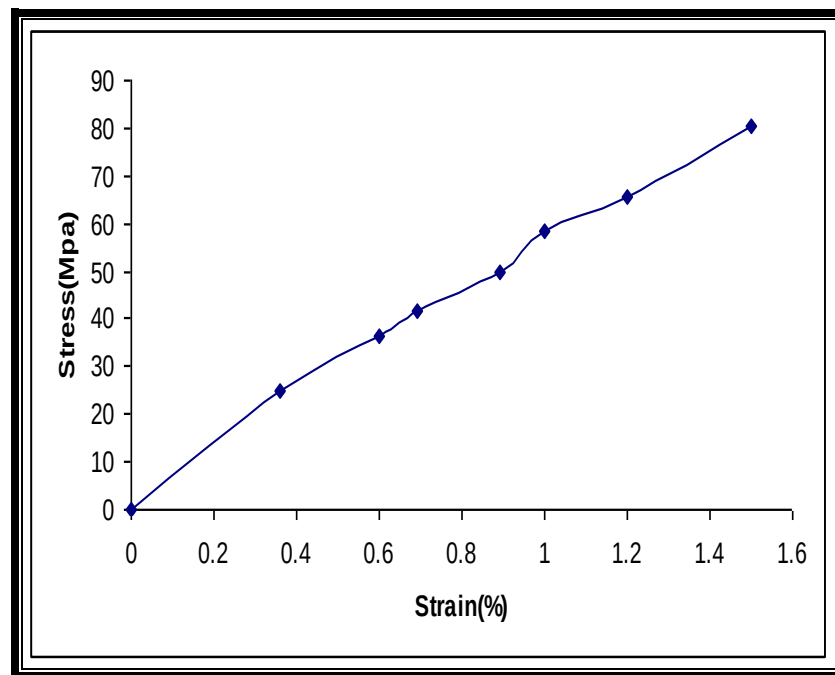


Figure (5.6)
Stress-strain curve of the Al-Si eutectic alloy under tension load at (free mold insulation conditions).

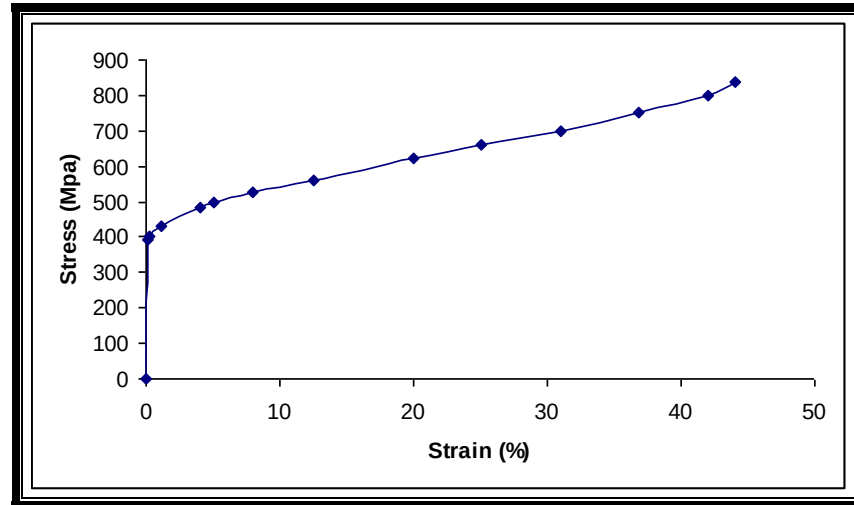


Figure (5.7)

Stress-strain curve of the Al-Si eutectic alloy under compression load at (free mold insulation conditions).

Compression results as shown in figure (5.7), shows the beginning or starting of material yielding at lower stresses (i.e. 392 Mpa), and when the applied stresses reach the value of (838 Mpa), the strain becomes (44%). These values give an indication that the material is weak under such loading that because of the irregular of orientation β -phase in the α -matrix.

3. Impact Toughness Results Discussion:-

Impact toughness of Al-Si eutectic alloy mainly depends on shape, size and distribution of α -Al grains and silicon morphology.

The absorbed energy of the samples of free mold insulation conditions is (1.8 Joule). This value is characterized to be very low (i.e. the material is classified as a brittle material).

The irregularity of the little grown β -phase with the large grain size of matrix induces poor ductility to the cast material.

5.2.2 Discussion of Microstructure Evolution and Mechanical Properties in Sand Mold Insulation Conditions :-

The possibility of monitoring in details, the evolution of eutectic structure and its orientation in specific direction in order to use as an in- situ reinforcement phase of aluminum matrix is fundamental in this work. In order to have the correct understanding of the final microstructure and metallurgical behavior of the produced casting alloy under the conditions of using an efficient insulation material (i.e. dry sand).

A liquid alloy, placed into the unit solidification (i.e. unidirectional solidification unit) (see experimental procedure), the temperature now falling down starting from the bottom end of mold, this falling in temperature coming as a result of cooling by cold water flow at the end bottom of mold that exposed to cooling directly. The efficiency of end cooling is augmented by connecting a large scale double fin (i.e. in order to increase the surface area of the mold end). The heat transfer now is increased in this direction while it is seized in other directions of mold where it is insulated by dry sand. The amount of heat transfer is dependent on various factors [49]:-

- 1- Geometry of the mold and the type of mold material used (which is constant a long the experiments types).
- 2- The insulation conditions (i.e. thermal properties and physical properties of the material used as an insulator).
- 3- The presence of cooling devices.

Figure (5.8) shows the temperature distribution modeling of the solidification system in the mold that insulated from four sides with dry sand after 3 min. of pouring as it was stated in the experimental part. It can be seen from the temperature distribution that, the difference of temperature

between the alloy and outer surface of wall was (623-571)°C. The difference is higher from the first case (free mold insulation conditions) because preventing escape the heat in the direction of sides.

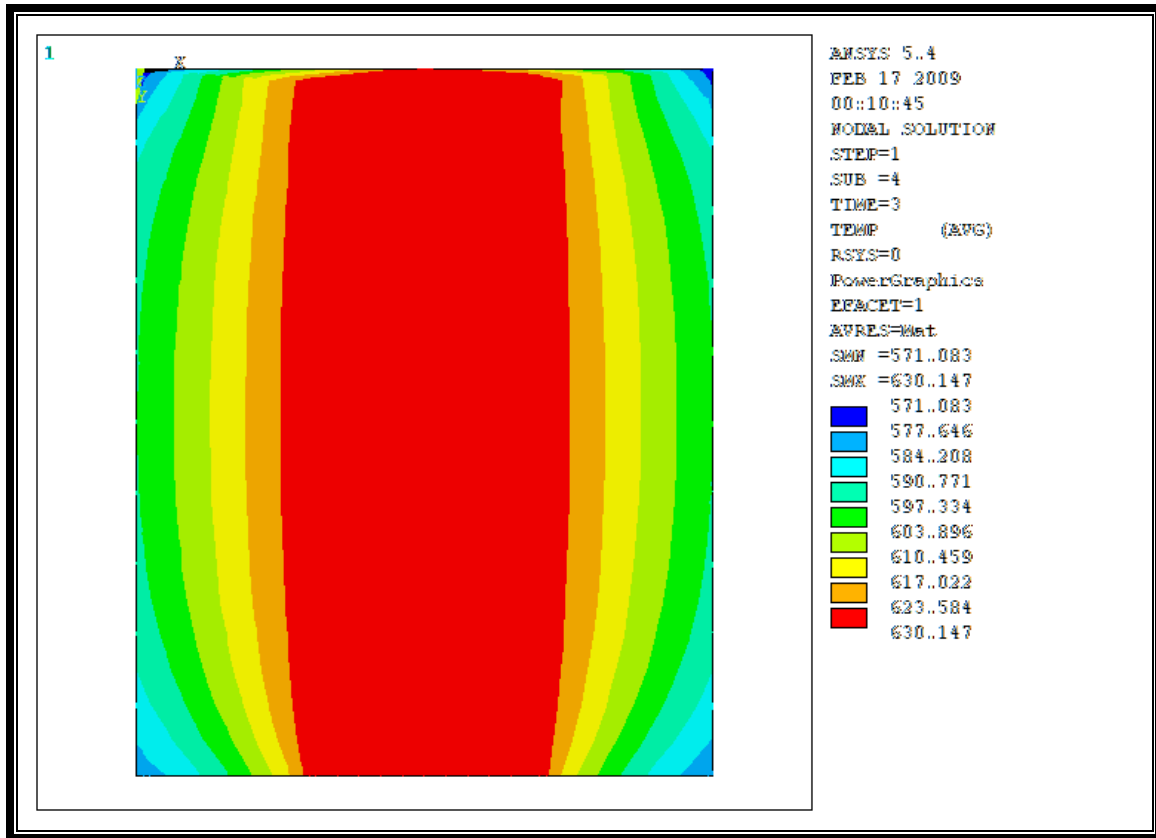


Figure (5.8)

Temperature distribution gradient across the solidification system at the sand mold insulation conditions after 3 min. after pouring(results in °C).

Figure (5.9) shows the relation between the temperature and the time for solidification that recorded from the thermocouple that inserted between the mould and the insulation material(in the solidification unit).

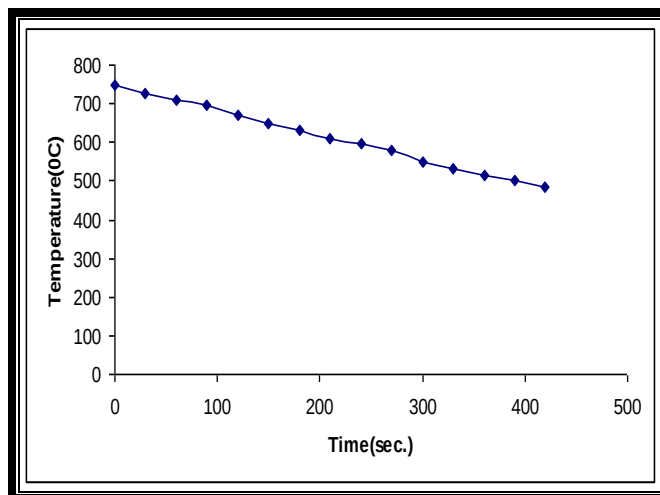


Figure (5.9)

The relation between the temperature and the time in case of sand mold insulation condition that recorded from the thermocouple that used in experimental procedure.

Figure (5.10) represents a schematic representation of the ingot obtained from the casting or solidification process, this figure shows the four sections that specified along the height or y-axis of ingot at almost equally distance. These sections are generalized to all the conditions of solidification that adopted in this work. Micro-structural observations have been conducted at each specific section as shown in figure (5.10), where the samples are cut under careful conditions and parallel to the y-axis (i.e. solidification direction).

The microstructures are taken parallel to the Y-axis at specific locations across the ingot. Figure (5.10) shows four of micrographs obtained under the solidification conditions adopted in this step. These samples at those locations represent four different cooling rates regimes according to its location distance from the cooled bottom end.

From figure (5.10) described above, microstructure micrograph at section (D) , where the cooling rate is very low. Now since the cooling rate

is low at this section, a so expected gas porosity and microporosity nucleates and grows with the formation of primary Si due to the high alloy content of silicon.

At, section (C) where a moderate cooling rate could be achieved at this condition of solidification process, a truly and obvious flaky structure forms without any microporosity or primary Si formation. The microstructure shows a clear growing of flaky β -phase that growing discontinuously as shown in section (C) still uncompleted and mis-oriented to the right wanted direction.

Sections(A,B) microstructure is different to some extent from the above sections microstructure. This microstructure is attributed by the following:-

1. Microstructure of the ingot generally consists of a α -phase aluminum and a second phase consists of a flake-shape β -phase(Si).
2. A little elongated grain structure could be seen clearly at this section, the reason behind such elongated structure is the pulling process of solidification by the active cooling at the bottom end of solidification unit.
3. The orientation of β -phase becomes more aligned with the y-axis approximately (60%) as the material solidifying close to bottom end of mold.
4. The orientation now step by step becomes less oriented in the y-axis due to the decrease in cooling rate with the height of ingot and also due to the efficiency of insulation material.

It is clear from above discussion, which, the growth of β -phase need a sufficient time. Preferential segregation of Al & Si occurs at high cooling rates due to shorter time available for diffusion.

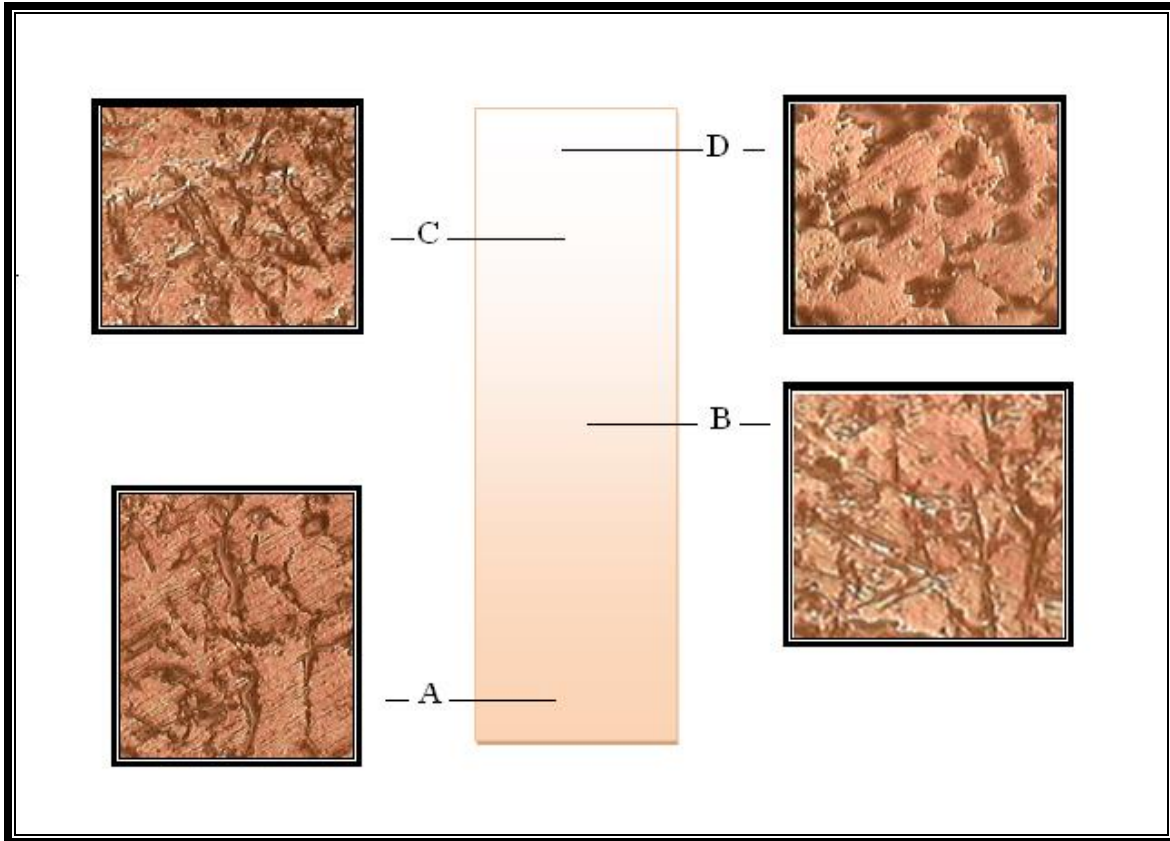


Figure (5.10)

A schematic representation of the ingot and the microstructure evolution at each section in case of sand mold insulation conditions (200X).

5.2.2.2 Discussion of Mechanical Properties of Produced Alloy at Sand Mold Insulation Conditions

1. Hardness Testing Results Discussion:-

The Brinell hardness testing survey on all the outside area of solidified Al-Si eutectic alloy in these conditions can make a supporting of the results obtained from the microstructure observations above. The hardness results are now different from that obtained in condition number one. The bar chart

shown in figure (5.11) shows the Brinell hardness number variations at the pre-specified sections that indicated in figure (5.10).

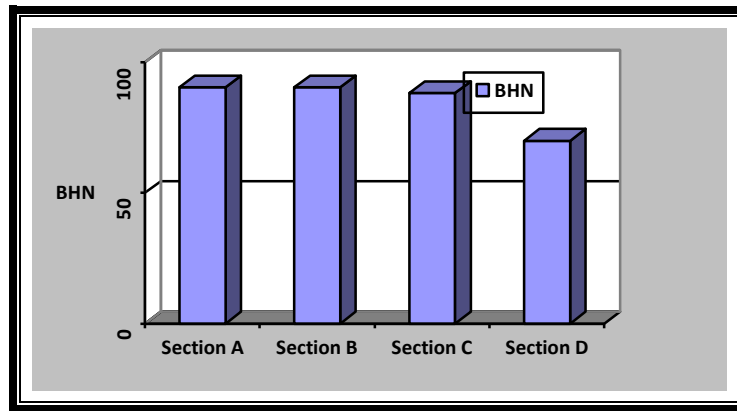


Figure (5.11)

Brinell hardness survey at the four specified sections of the alloy surface under the conditions of sand mold insulation.

The reasons behind such variation in results of hardness are the non homogeneous grain size distribution along the material under these conditions of solidification, the clear growth of β -phase and its better orientation in the required direction of solidification. That will augment the idea about the role of β -phase orientation and growth on the improvement of mechanical properties of the material that reinforced with this phase.

2. Tensile and Compression Test Properties:-

Figure (5.10) as it was stated above shows, the key of how the microstructure has changed along the y-axis of solidified ingot. This microstructure affects directly the mechanical behavior of material produced according to this condition.

Tensile tests has been conducted only in section (A) according to figure (5.10), keeping in mind that the tensile specimen needs at least (100 mm) long of ingot(i.e. multi-microstructure). The tensile test results show a clear improvement in comparison with the case of free mold insulation

conditions, the ultimate tensile strength has been improved, comparing will be done according to the fracture strength that required for each specimen(see figure (5.12)).

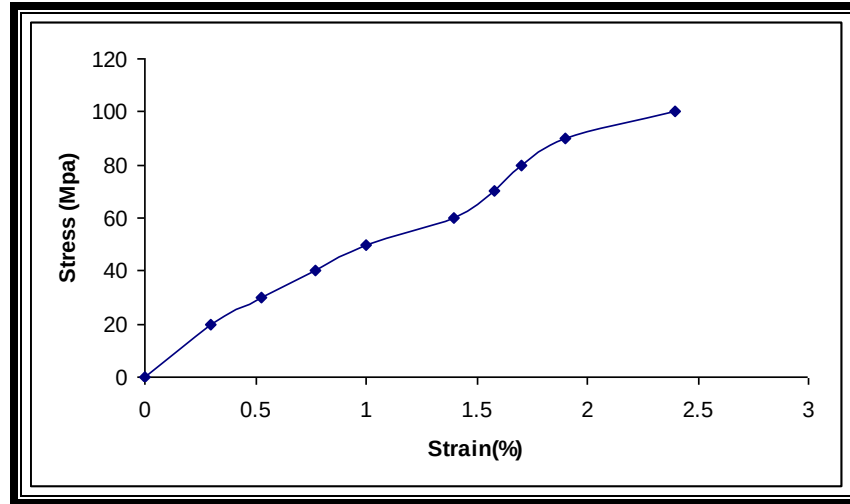


Figure (5.12)

Stress-strain curve of the Al-Si eutectic alloy under tension load at (sand mold insulation conditions).

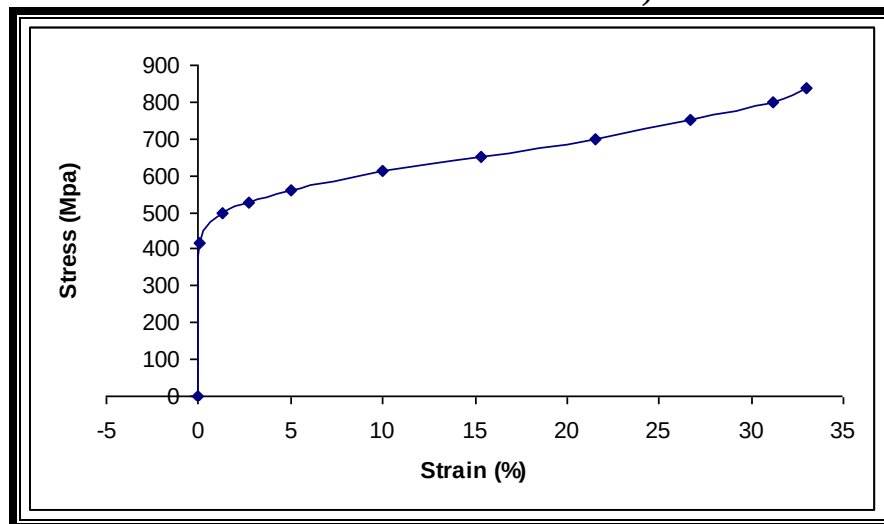


Figure (5.13)

Stress-strain curve of the Al-Si eutectic alloy under compression load at (sand mold insulation conditions).

From figure (5.13), compression results shows the beginning of material yielding at higher stresses (i.e. 415 Mpa), and when the applied

stresses reach the value of (838 Mpa), the strain becomes (33%). These values give an indication that the material becomes stronger under such loading comparing with the material produced under the conditions of free mold insulation solidification.

1. It is known that, the behaviors of the investigated alloy under the conditions of free mold insulation are almost brittle behavior (see 5.2.2).
2. Figure (5.12) shows a clear improvement in tensile properties. The reason behind such improvement is the development of grown β -phase firstly (i.e. it becomes flaky-shape with an improved length) and secondly its better orientation in the direction of y-axis (i.e. solidification axis).
3. This behavior is so expected due to the high cooling rate at the bottom end of the mold and also due to the grain refinement of fast cooling part of ingot at the area close to the bottom end.
4. Now, as the solidified ingots have sectioned away from the bottom, the tensile properties have decreased continuously until it reaches a very close values of the case of free mold isolation conditions.
5. The better grown and unidirected β -phase plays as an in-situ fiber which is the reason behind such indicated reinforcement in the alloy under investigation.

3. Impact Toughness Properties :-

In order to assess the toughness of the produced ingots or samples, impact tests are conducted according to the specified section that indicated previously in section (A).

Now, if a comparison has been made between the impact toughness data at section (A) of the conditions above and the results obtained from the impact test of the conditions of free mold insulation, one can conclude that a noticeable development has occurred at this conditions of solidification. The energy absorbed by the sample at section (A) in figure (5.9) jumped from (1.8 Joule) in the case of free mold insulation conditions to be (2 Joule) in case of sand mold insulations.

The reasons behind such improvement could be summarized as follows:

1. Noticeable elongation in the grain structure at the section (A), where the cooling rate is high.
2. Better orientation of grown β -phase in the direction parallel to the required solidification axis.

Less interfacial energy between the β -phase and the α -matrix.

The flaky shapes β -phase concentrate the stresses at the tips of the phase that enhancing the fracture of specimens, so that the efforts have been directed to get continuous fiber phase instead of discontinuous.

5.2.3 Discussion of Microstructure Evolution and Mechanical Properties in Glass Wool Mold Insulation Conditions :-

The third condition adopted in this work in order to produce a directed grown β -phase is the use of a glass wool insulation material around the mold (i.e. high density glass wool). The mold now insulated from above and four sides, except the bottom end which is free to cool by the cold water flow and the large surface fins area that equipped at this point.

The very low thermal conductivity of the high density glass wool ($0.038 \text{ W.m/m}^2 \cdot ^\circ\text{C}$) helps to prevent almost all the heat energy that transfer across the mold walls to the atmosphere and then it can help to maintain the molten material at the pouring temperature at sufficient time more than the two above cases (i.e. free mold insulation and dry sand mold isolation cases) as can be seen in the following figure (5.14) that shows a relation between the time and temperature for a three cases of mold insulation that recorded from the thermocouple that used in experimental procedure.

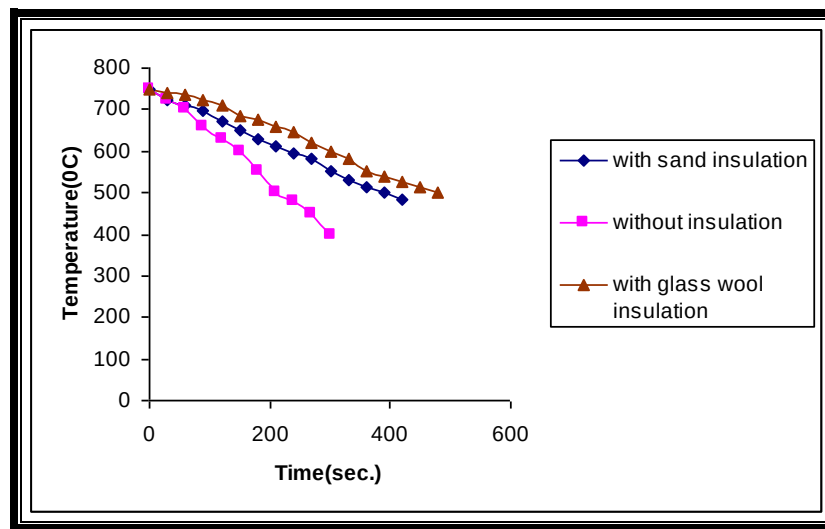


Figure (5.14)

The relation between the time and temperature for a three cases of mold insulation that recorded from the thermocouple that used in experimental procedure.

The long time maintaining of molten material at the pouring temperature at this condition in compared with the other two conditions and the continuity of cold water flow through the lower part of the unidirectional solidification unit allows the heat energy to escape in only in one direction and then it works to drawing the growth process of the β -phase in the specified direction(i.e. required direction).

The computer modeling as shown in figure down (5.15), shows the temperature gradient distribution along the solidification system at the conditions where the mold is insulated by the high density glass wool. From the figure shown the difference of temperature between the alloy and outer surface of wall was (622-559)°C. The difference is higher from the other cases (free mold insulation conditions, sand mold insulation conditions) because preventing escape the heat in the direction of sides, using glass wool as insulation material to maintaining temperature of melting alloy .

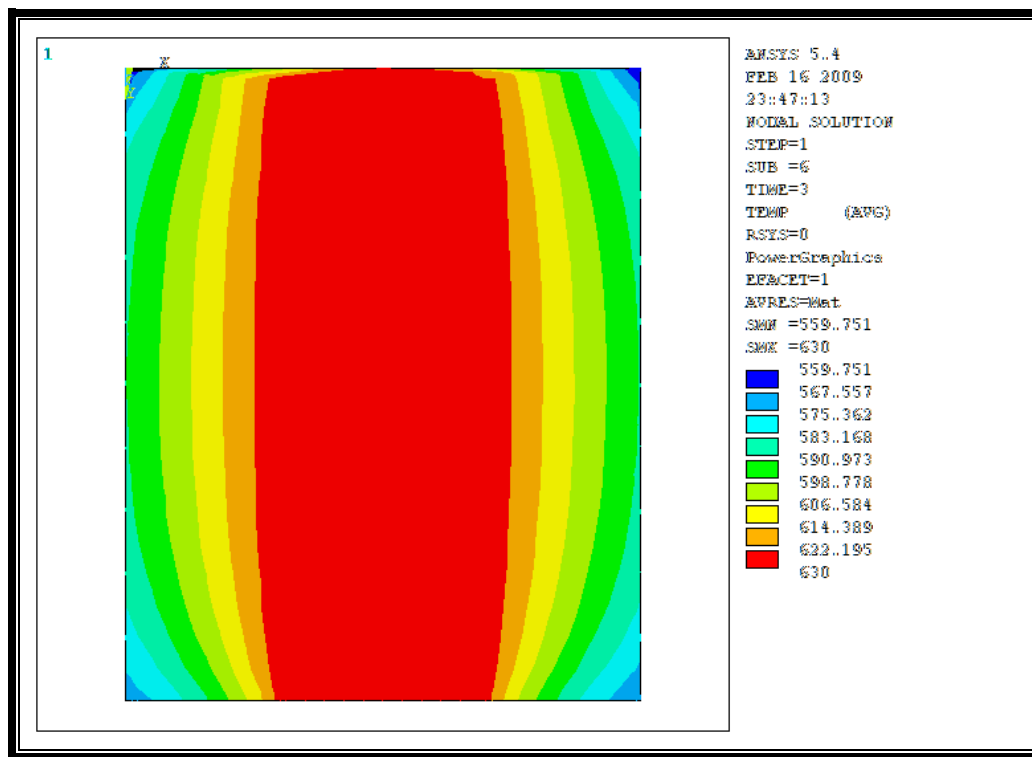


Figure (5.15)

Temperature distribution gradient across the solidification system at the glass wool mold insulation conditions after 3 min. after pouring(results in °C).

A large time now available under conditions (i.e. glass wool insulation mold), and this time allows more diffusion activities which is the reason behind the nucleation and growth of second phase (i.e. β -phase).

The microstructure observations show an extinct improvement in the processes of β -phase growing, along the y-axis. Four sections also taken to monitor the microstructure variations along the material. The microstructure consists mainly from α -grains of aluminum and flaky shapes β -phase as can be seen in figure (5.16) .

Sections (A,B) shown the increasing of β -phase length which is directed in good percentage in the direction of heat sink. The other benefits of the solidification in this manner are the elongation of grain at the first sections along the y-axis and that because the prevent the heat escape from the wall by the glass wool material. That will reflected directly on the mechanical properties evaluations.

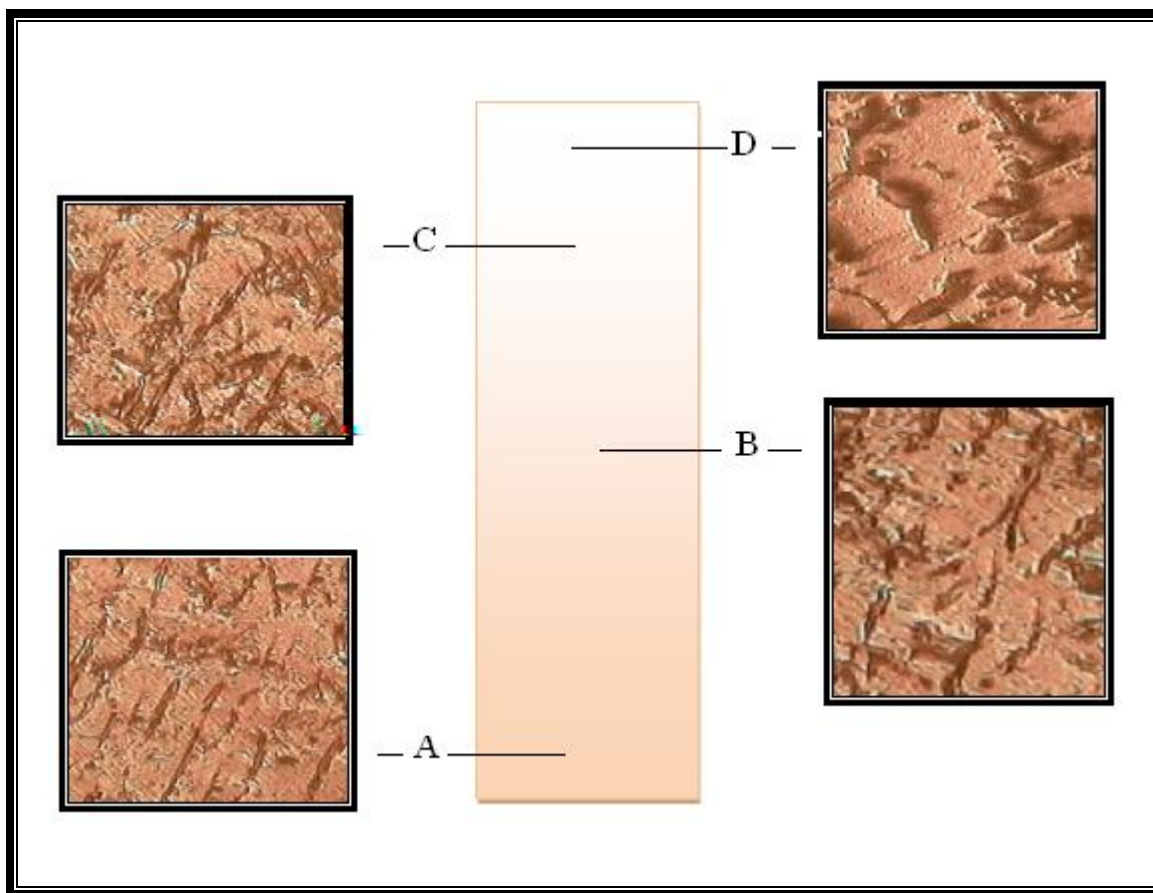


Figure (5.16)

A schematic representation of the ingot and the microstructure evolution at each section in case of glass wool mold insulation conditions(200X).

5.2.3.1 Discussion of Mechanical Properties of Produced Alloy at Glass Wool Mold Insulation Conditions

1.Hardness Testing Results Discussion:-

The final Brinell hardness testing survey is conducted to evaluate how much progresses have been done by using this conditions of solidification (i.e. high density glass wool insulation material). The test covers all the outside area of solidified Al-Si eutectic alloy in this conditions. This survey is very important as a first indication of how much the microstructure has changed. The hardness results are now different from that obtained in two conditions above. The bar chart shown in figure (5.17), shows the Brinell

harness number variations at the pre-specified sections that indicated in figure as shown.

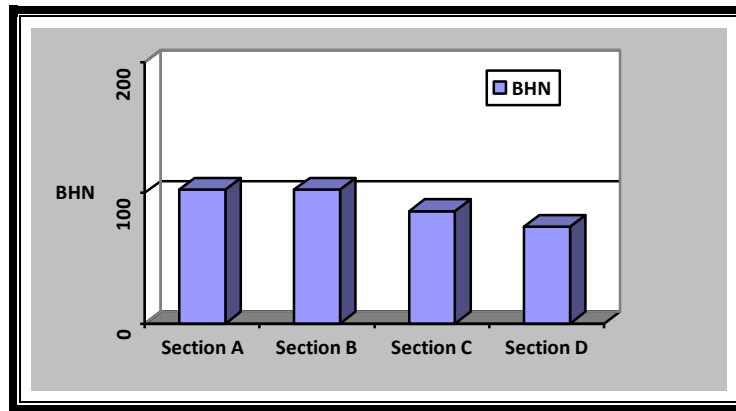


Figure (5.17)

Brinell hardness survey at the four specified sections of the alloy surface under the conditions of glass wool mold insulation conditions.

The reasons behind such improvement in hardness number especially at sections (A,B) are the change of the microstructure near the end bottom of the mold. This change in microstructure is due to the high cooling rate at this sections (i.e. section A,B) where the heat transfer is seized in efficient manner except from the bottom end of mold.

According to the figure (5.14), a long time resulted until the complete solidification of ingots at this condition (i.e. glass wool insulation mold). It is clear that, the diffusion kinetics now found sufficient time to work properly in this condition, but the better mold insulation (i.e. keeping or maintaining pouring temperature) leading to lower the cooling rate , that means a compromising now working between the reinforcement of α - grains with the directional eutectic growing and the grain coarsening resulted from a long time of solidification.

As a result, the activities of diffusion contributions take the priority in growth and enhancing also the grain refinement of the resulted

microstructure to some extent. The orientation are now more easy to gided due to the long time maintaining at the liquid state and the concentration of heat flow in unidirectional (i.e. Y-axis)

2. Tensile and Compression Test Properties:-

The response of produced composite material now reinforced by this manner to the multi-types of loading through the mechanical properties testing is different now. Key of how the microstructure has changed along the y-axis of solidified ingot. This microstructure reflects directly the mechanical behavior of material produced according to these conditions.

Tensile test has been conducted in multi-sections in interference manner, keep in mind that the tensile specimen need at least (100 mm) long of ingot. The tensile test results show a clear improvement in comparison with the other cases of insulation conditions, see figure (5.18).

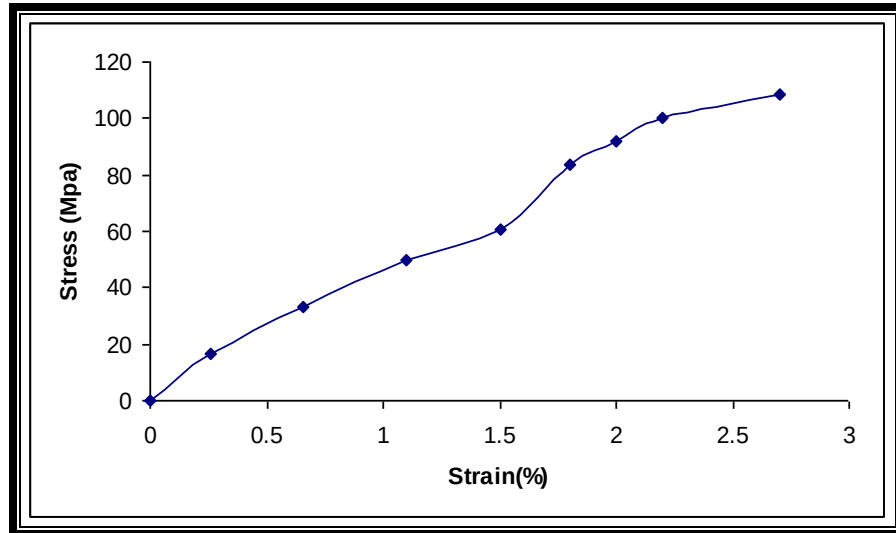


Figure (5.18)

Stress-strain curve of the Al-Si eutectic alloy under tension load at (glass wool mold insulation conditions).

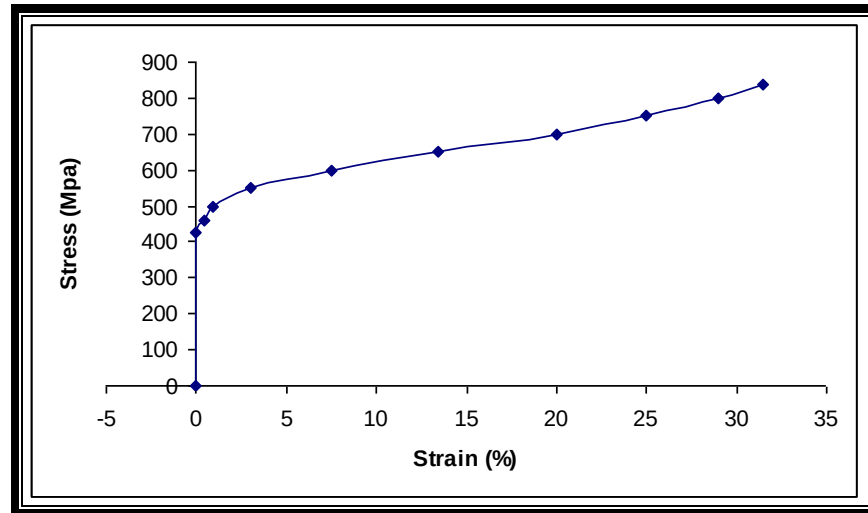


Figure (5.19)

Stress-strain curve of the Al-Si eutectic alloy under compression load at (glass wool mold insulation conditions).

Compression results show the beginning of material yielding at higher stresses (i.e. 426 Mpa), and when the applied stresses reach the value of (838 Mpa), the strain becomes (31.5%), see figure(5.19). These values give an indication that the material becomes stronger under such loading comparing with the material produced under the conditions of free mold insulation solidification.

1. It is known that, the behavior of the investigated alloy under the conditions of free mold insulation is almost brittle behavior (see 5.2.2).
2. Figure (5.18) shows a clear improvement in tensile properties. The reason behind such improvement is the development of grown β -phase firstly (i.e. it becomes flaky-shape with an improved length) and secondly its better orientation in the direction of y-axis (i.e. solidification axis).

3. This behavior is so expected due to the high cooling rate at the bottom end of the mold and also due to the grain refinement of fast cooling part of ingot at the area close to the bottom end.
4. Now, as the solidified ingots have sectioned away from the bottom, the tensile properties have decreased continuously until it reaches a very close value of the case of free mold insulation conditions.
5. The better grown and unidirectional β -phase plays as an in-situ fiber which is the reason behind such indicated reinforcement.

3. Impact Toughness Properties :-

In order to assess the toughness of the produced ingots or samples, impact tests are conducted according to the specified section that indicated previously in section (A).

The tests show a noticeable improvement have documented in the case of (glass wool mold insulation conditions) rather than the cases of free mold insulation conditions and sand mold insulation conditions., one can conclude that a noticeable development have occurred at this conditions of solidification. The energy absorbed by the sample at section (A) in this case (i.e. glass wool mold insulation condition) is jumped to be (2.5 Joule).

The reasons behind such improvement could be summarized as follows:

1. Noticeable grain elongation at the section (A), where prevent escape the heat from the wall was perfect from the sand mold insulation conditions because of the less of thermal conductivity.
2. Very better orientation of grown β -phase in the direction parallel to the required solidification axis.

3. The interfacial energy between the grown phase and the matrix in this case is less from the above two cases.

figure (5.20) can show the accumulative impact properties of all solidification conditions.

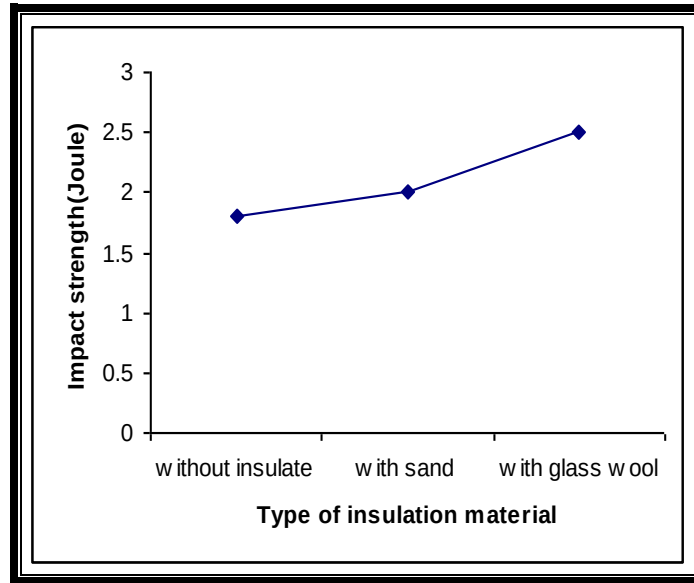


Figure (5.20)

The accumulative impact strength of all solidification conditions.

5.3 The Results of X-Ray Diffraction Analysis

From the charts of X-ray diffraction for samples appeared that there are no any new phases in the structure. And also appeared that the only the Al- and Si-phases. The figures(5.21),(5.22) and(5.23) ,and from the tables (5.1) ,(5.2) and (5.3)shown the X-ray diffraction charts and data for the three types of insulation.

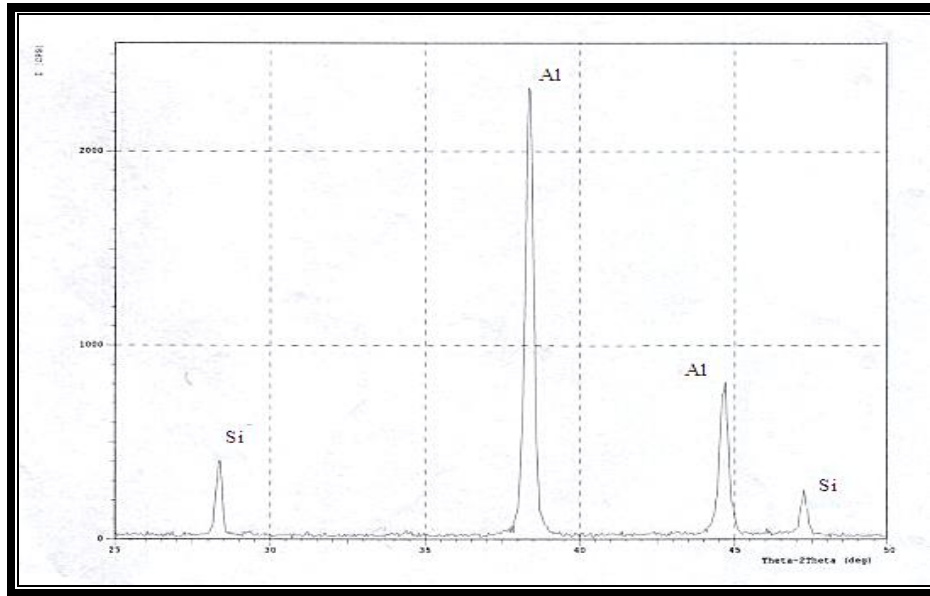


Figure (5.21)

Result of X-ray diffraction analysis for the ingot without insulation.

Table (5.1)

Result of X-ray diffraction analysis for the ingot with free mold insulation conditions.

2Θ	$d_{hkl}(A^0)$	phase
28.4	3.140	Si
38.4	2.342	Al
44.75	2.023	Al
47.3	1.920	Si

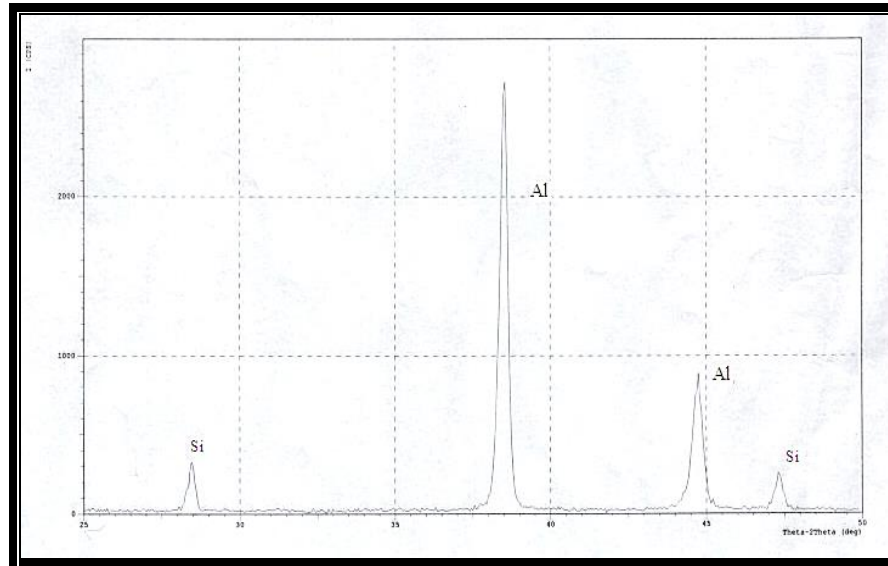


Figure (5.22)
Result of X-ray diffraction analysis for the ingot with sand insulation.

Table (5.2)
Result of X-ray diffraction analysis for the ingot with sand mold insulation condition.

2θ	$d_{hkl}(A^0)$	phase
28.4	3.140	Si
38.6	2.330	Al
44.7	2.023	Al
47.4	1.916	Si

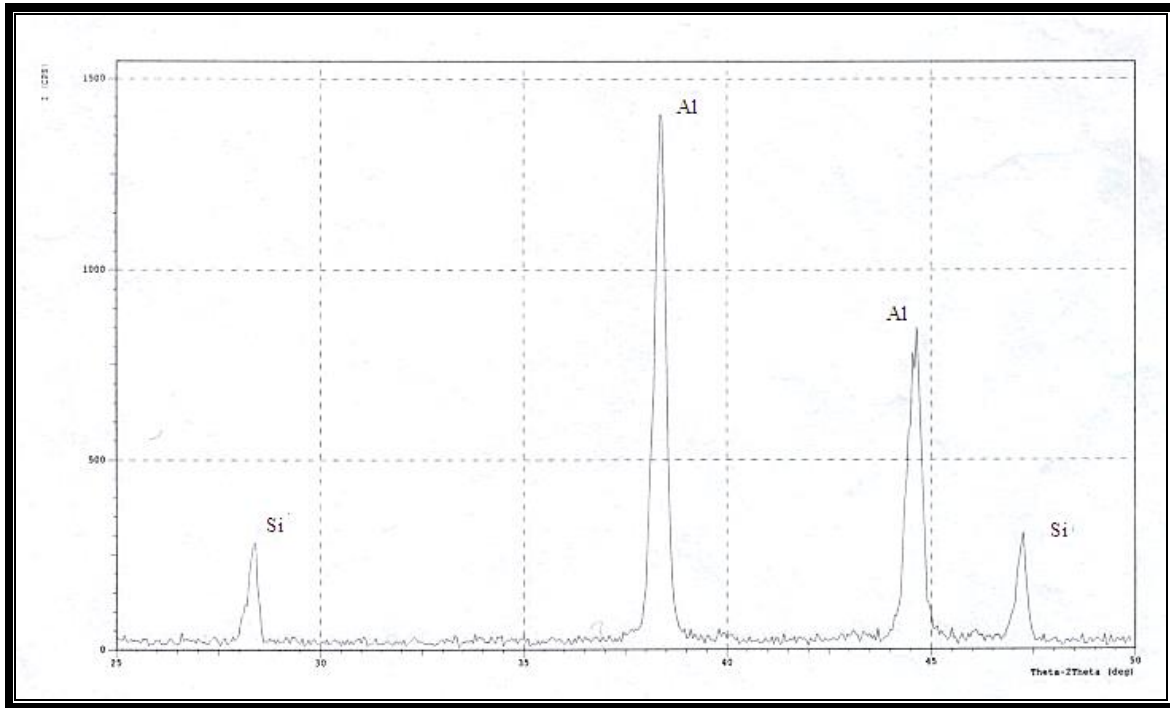


Figure (5.23)

Result of X-ray diffraction analysis for the ingot with glass wool insulation.

Table (5.3)

Result of X-ray diffraction analysis for the ingot with glass wool mold insulation conditions.

2θ	$d_{hkl}(A^{\circ})$	phase
28.4	3.161	Si
38.4	2.342	Al
44.6	2.029	Al
47.25	1.922	Si

CHAPTER SIX

CONCLUSIONS & SUGGESTIONS FOR FUTURE WORKS

6.1 Conclusions

According to results of present work, the following can be concluded:-

1. The microstructure of Al-Si eutectic alloy is affected directly by the method by which the alloy can solidify.
2. It is possible to improve hardness, tension, compression and impact properties by making the molten eutectic alloy solidifying in one direction.
3. The unidirectional solidification of eutectic alloy can assist the nucleation and growth of the second eutectic phase in one direction.
4. Better insulation of mold adopted in this work is by the using of high density glass wool around the mold , with keeping the bottom side free to cool fast by cold water flow and large surface area of equipped fin.
5. The numerical model is agreed with the experimental practices that recommend using the glass wool with the bottom mold cooling by cold water flow.
6. Some elongation in the grains near the mold bottom end resulted from a pulling solidification or cooling in one direction.

6.2 Suggestions for Future Works

The following recommendations for further works:-

1. Using a modified Al-Si eutectic alloy with Na or Sr.
2. Using of grain refinement to investigate the effects on the unidirectional solidifications.
3. Studying the other properties such as creep or fatigue of investigated alloy under the adopted three conditions of solidifications.
4. Simulate the produced microstructure numerically and studying the interfacial energy effects between the grown phase and matrix.

Examining committee approval sheet

We certify that have read this thesis entitled (*Experimental Analysis of In- situ Composite Al-Si Eutectic Alloy*) and as an examining committee,we have examined the student (*Awham Jumea Salman*) in contents and that is related to it, and that in our opinion it meets the standard of a thesis for the degree of Master of science in Material Engineering.

Signature

Ass. Prof. Dr. Ali H. Atewi

Committee Chair

Date: / /2009

Signature

Ass. Prof. Dr. Fadl A. Hashm

Committee Member

Date : / / 2009

Signature

Lecture Dr. Ahmed O. Jasm

Committee Member

Date : / / 2009

Signature

Ass. Prof. Dr.Najim A. Saad

supervisor

Date : / / 2009

Signature

Lecture Dr.Alaa A. Ateia

supervisor

Date : / / 2009

Approval of the Department of

Material Engineering

Head of Material Engineering Department.

approval of the College

of Engineerng

Dean of the College of Engineering.

Signature

Lecture Dr. Ahmed O. Jasm

Date : / / 2009

Signature

Ass. Prof. Dr. Salah T. Ali

Date : / / 2009

List of contents

No.	Title	Page
	Abstract	I
	List of figures	II
	List of tables	V
	List of symbols	VI
	List of contents	VIII
	CHAPTER ONE: GENERAL INTRODUCTION	
1.1	Introduction	2
1.2	Definition of Composite Materials	3
1.3	Classification of Composite Materials	3
1.4	In-situ Composite Materials	4
1.4.1	Types of In-situ Composite Materials	5
1	Particle In-situ Composite Materials: - (Precipitation Hardening)	5
2	Fiber In-situ Composite Materials: - (Unidirectional Eutectic Solidification)	6
1.4.2	Applications of Fiber In-situ Composite Materials	8
1.5	Literature Review	9
1.6	Aim of the Work	14
	CHAPTER TWO : DIRECTIONAL EUTECTIC SOLIDIFICATION	
2.1	Eutectic	16
2.1.1	Metallic Eutectics	17
2.2	Eutectic Solidification	19
2.2.1	Nucleation in Eutectic Solidification	20
2.2.2	Growth of Lamellar Eutectics	20
2.3	Eutectic Leading Phase	26
2.4	Nonequilibrium Crystallization	27
2.5	Unidirectional Solidification of Eutectic	28
2.5.1	Mechanical Behavior	29
	CHAPTER THREE: ALUMINUM –SILICON EUTECTIC ALLOY	
3.1	Introduction	33
3.2	The Aluminum-Silicon Phase Diagram and Equilibrium Cooling	34
3.3	The Thermal Parameters	38
	CHAPTER FOUR: EXPERIMENTAL PROCEDURE& COMPUTER MODELING	
4.1	Introduction	41

4.2	Materials Used	42
4.3	Procedure	43
4.3.1	Alloy Preparation for Melting	43
4.3.2	Thermal Analysis	43
4.3.3	Experimental Apparatus	43
4.4	Melting and Sampling Procedure	47
4.5	Productions of Samples Ingots	49
4.6	Modeling Process	50
4.6.1	Introduction	50
4.6.2	Model Constitute	50
4.6.3	Geometry Sub. Model	51
4.6.4	Finite Element Model	52
4.6.5	Mathematical Formulation	53
4.6.6	Material Used in Model	56
4.6.7	Boundary Conditions	56
4.6.8	Paramedic Study	56
4.6.9	Results Output	56
4.7	Sample Preparation for Microscopic Analysis	57
4.7.1	Sectioning	57
4.7.2	Grinding	57
4.7.3	Polishing	58
4.7.4	Etching	58
4.8	Mechanical Testing	59
4.8.1	Hardness Test	59
4.8.2	Tensile Test	60
4.8.3	Compression Test	62
4.8.4	Impact Test	63
4.9	X-Ray Diffraction Analysis	64
	CHAPTER FIVE: RESULTS & DISCUSSION	
5.1	Introduction	67
5.2	Discussion of Modeling & Experimental Results	68
5.2.1	Discussion of Microstructure Evolution and Mechanical Properties in Free Mold Insulation Conditions	68
5.2.1.1	Discussion of Mechanical Properties of Produced Alloy at Free Mold Insulation Conditions	71
5.2.2	Discussion of Microstructure Evolution and Mechanical Properties in Sand Mold Insulation Conditions	75
5.2.2.1	Discussion of Mechanical Properties of Produced Alloy at Sand Mold Insulation Conditions	79
5.2.3	Discussion of Microstructure Evolution and Mechanical	83

	Properties in Glass Wool Mold Insulation Conditions	
5.2.3.1	Discussion of Mechanical Properties of Produced Alloy at Glass Wool Mold Insulation Conditions	87
5.3	The Results of X-Ray Diffraction Analysis	92
	CHAPTER SIX : CONCLUSIONS & SUGGESTIONS FOR FUTURE WORKS	
6.1	Conclusions	97
6.2	Suggestions for Future Works	98
	References	99

List of figures

No.	Title	Page
1.1	Unidirectional solidification of a eutectic alloy, the solid contains microstructure constituents aligned parallel to the growth direction	7
1.2	Turbine blades manufactured by three different processes	9
2.1	A simple binary system	16
2.2	(a) Phase diagram typical of a system showing a normal eutectic structure. (b) Phase diagram typical of a system showing an anomalous eutectic structure	18
2.3	Interdiffusion in the liquid ahead of a eutectic front	21
2.4	Molar free energy diagram at a temperature ΔT_o below the eutectic temperature, for the case $\lambda = \lambda^*$	22
2.5	(a) Molar free energy diagram at $(T_E - \Delta T_o)$ for the case $\lambda^* < \lambda < \infty$, showing the composition difference available to drive diffusion through the liquid. (b) Model used to calculate the growth rate	42
2.6	Eutectic phase diagram showing the relationship between ΔX and ΔX_o	25
2.7	Formation of a lamellar structure (α and β phases) in an unidirectional solidification of a eutectic. The solidification front is perpendicular to the direction of growth (direction of arrows). T_L , T_E and T_S are the temperature of the liquid (L), the solidification front and the solid, respectively	28
3.1	depicts the contemporary aluminum-silicon phase diagram.(a) Hypoeutectic alloy, (b) eutectic alloy,(c) Hypereutectic alloy.	34
3.2	Al-12.5wt% Si alloy (a) Slowly cooled 200X (b) Chill Cast 500X	36
3.3	Coupled zone in (a) symmetrical and (b) asymmetrical phase diagrams	37
4.1	A schematic diagram of the unidirectional solidification unit	45
4.2	A schematic diagram of the section A-A in the unidirectional solidification unit as labeled above	45
4.3	A photographic picture shows the apparatus that used in the solidification practices	46
4.4	Equipment of electric furnaces	49
4.5	Geometry of sub model adopted for numerical analysis	52

4.6	Finite element model assumptions	53
4.7	Elemental volume for one-dimensional heat-conduction analysis	54
4.8	The places that have been cutting from it the samples	59
4.9	Tensile test specimen	61
4.10	Equipment of Material Testing Unit	61
4.11	Comparison test specimen	62
4.12	Impact test specimen	63
4.13	Equipment of Impact	64
5.1	Microstructure of alloy before any process of pouring 200X	67
5.2	Temperature distribution gradient across the solidification system at the free mold insulation conditions after 3 min. of pouring (results in °C)	69
5.3	The relation between the temperature and the time in case of free mold insulation condition that recorded from the thermocouple that used in experimental procedure	70
5.4	Optical microscopy of alloy at (free mold of insulation) conditions(200X)	71
5.5	Brinell harness survey at the four specified sections of the alloy under free mold insulation conditions	72
5.6	Stress-strain curve of the Al-Si eutectic alloy under tension load at (free mold insulation conditions)	74
5.7	Stress-strain curve of the Al-Si eutectic alloy under compression load at (free mold insulation conditions)	74
5.8	Temperature distribution gradient across the solidification system at the sand mold insulation conditions after 3 min. after pouring(results in °C)	76
5.9	The relation between the temperature and the time in case of sand mold insulation condition that recorded from the thermocouple that used in experimental procedure	77
5.10	A schematic representation of the ingot and the microstructure evolution at each section in case of sand mold insulation conditions (200X)	79
5.11	Brinell hardness survey at the four specified sections of the alloy surface under the conditions of sand mold insulation	80
5.12	Stress-strain curve of the Al-Si eutectic alloy under tension load at (sand mold insulation conditions)	81
5.13	Stress-strain curve of the Al-Si eutectic alloy under compression load at (sand mold insulation conditions)	81

5.14	The relation between the time and temperature for a three cases of mold insulation that recorded from the thermocouple that used in experimental procedure	84
5.15	Temperature distribution gradient across the solidification system at the glass wool mold insulation conditions after 3 min. after pouring(results in °C)	85
5.16	A schematic representation of the ingot and the microstructure evolution at each section in case of glass wool mold insulation conditions(200X)	87
5.17	Brinell hardness survey at the four specified sections of the alloy surface under the conditions of glass wool mold insulation conditions	88
5.18	Stress-strain curve of the Al-Si eutectic alloy under tension load at (glass wool mold insulation conditions)	89
5.19	Stress-strain curve of the Al-Si eutectic alloy under compression load at (glass wool mold insulation conditions)	90
5.20	The accumulative impact strength of all solidification conditions	92
5.21	Result of X-ray diffraction analysis for the ingot without insulation	93
5.22	Result of X-ray diffraction analysis for the ingot with sand insulation	94
5.23	Result of X-ray diffraction analysis for the ingot with glass wool insulation	95

List of tables

No.	Titles	Page
2.1	Leading phase of eutectic alloys	27
3.1	Tensile and compressive properties of directionally solidified Al-Si eutectic alloy	39
4.1	Average chemical composition analysis of the material used	43
4.2	Thermal conductivities of insulation materials	47
4.3	General plane of ingot samples production	50
5.1	Result of X-ray diffraction analysis for the ingot with free mold insulation conditions	93
5.2	Result of X-ray diffraction analysis for the ingot with sand mold insulation conditions	94
5.3	Result of X-ray diffraction analysis for the ingot with glass wool mold insulation conditions	95

References

- (1) A. K. Bhargava, "Engineering materials polymers, ceramics and composite " , 2005 , Prentice-Hall of India.
- (2) R. S. Khurmi, R. S. Sedha, "Material science", 1989, Second Edition, S. Chand & Company Ltd.
- (3) M. M. Schwartz, "Composite materials handbook", 1984, McGraw-Hill Book Company, USA.
- (4) Mathew phlip & Bill Bolton, "Technology of engineering materials", 2002, First published, Butterworth-Heinemann, Britain.
- (5) Valery V. Vasiliev& Evgeny V. Morozov, "Mechanics and analysis of composite materials", 2001, First edition , Elsevier Science Ltd, Netherlands.
- (6) R.M.A.Aikin,Jr., "The Mechanical properties of In-Situ Composites",1997, The journal *JOM*,49(8), pp. 35-39, The Minerals, Metals & Materials Society.
- (7) Fishman, S.G., Lewis, D., Singh, M , "In situ composite materials", 1995, Advanced Materials & Processes, <http://www.highbeem.com/> .
- (8) Kwai S .Chan, Robert E. Beissner, David L.Davidson, "Development of a computational material science-based methodology for alloy/composite design", 1999, Southwest Research Institute, <http://www.swri.org>.
- (9) George E. Dieter, "Mechanical metallurgy", 1976, Second edition, McGraw-Hill series, USA.
- (10) Abdulhaqq A. Hamid, P.K.Ghosh, SC.Jain,and Subrata Ray, "Processing, microstructure, and mechanical properties of cast in-situ Al(Mg,Mn)- Al₂O₃(MnO₂) composite",2005,Indian Institute of Technology Rookee,surayfmt@iitr.ernet.in.

- (11) "In Situ Fibers ",1989, CRC Press LLC, About.com, <http://www.about.com>.
- (12) Peter A. Thornton and Vito J. Colangelo, "Fundamentals of Engineering Materials", 1985, Prentice-Hall, U.S.
- (13) G.Piatti, "Advances in composite materials", 1987, Applied Science Publishers Ltd, London.
- (14) R.E.Smallman and R.J.Bishop,"Modern physical metallurgy and materials engineering science, process, applications"1999, Sixth edition, Butterworth-Heinemann, Britain.
- (15) Michael F.Ashby and David R.Jones, "Engineering materials 1 an introduction to microstructures processing and design" , 2005, Third edition, Cambridge university.
- (16) M.A. Martorano, C. Beckermann, and Ch.-A. Gandin, "A solutal interaction mechanism for the columnar to-equiaxed transition in alloy solidification",2003, Metallurgical and materials transactions, VOL. 34A, pp.1657-1674.
- (17) K. Ohsasa, H. Shirosawa, and T .Narita ,"Prediction of the solidification structure of casting and heterogeneous nucleation",2003, Journal of University of Science and Technology Beijing, Vol.10, No.3, pp.43-47.
- (18) R.E. Napolitano, H. Meco, and C. Jung ,"Faceted solidification morphologies in low-growth-rate Al-Si eutectics", JOM • April 2004, Smart ImagingTechnologies,pp.16-21.
- (19) Taylor A. Groll ,"Effect of solidification rate on cast microstructure ",2004, Padnos College of Engineering and Computing Grand Valley State University.
- (20) K.Nogita, S.D. McDonald, A.K. Dahle, "Modification of Al-Si alloys",

2004, Institute of Materials Engineering Australasia Ltd, Materials forum, Vol.28, pp.945-950.

(21) M.F. Zhu, C.P. Hong, "Modeling of dendritic and eutectic microstructures in solidification of aluminum alloys",2004, Institute of Materials Engineering Australasia Ltd, Materials forum, Vol.28, pp.895-900.

(22) Yuhong Zhao, Hua Hou , "Simulation for microstructure evolution of Al-Si alloys in solidification process",2006, Institute of Physics Publishing, Journal of Physics: Conference Series 29 ,pp. 210–219.

(23) M. Jeyakumar, Suresh Sundarraj, S. Vijayalakshmi, G. S. Vinodhkumar, "Cooling rate effect on microporosity and primary silicon formation in eutectic aluminum-silicon alloy",2007, International Conference on Advanced Materials and Composites, Oct 24-26, pp.150-157.

(24) Roy Elliott BSc,PhD, "Eutectic solidification processing crystalline and glassy alloys",1983, First published, University of Manchester, England.

(25) "Eutectic point" , From Wikipedia , the free encyclopedia,2007, [http://en.wikipedia.org/wiki/Eutectic point](http://en.wikipedia.org/wiki/Eutectic_point).

(26) Prof. Stephen Nelson , "Two component(Binary) Phase Diagrams", 2004, Tulane University.

(27) D.A.Porter and K.E.Esterling, "phase transformations in metals and alloys",1981, First published, Van Nostrand Reinhold Co. Ltd, England.

(28) G Phanikumar and K Chattopadhyay, "Solidification microstructure development ", 2001, Indian Institute of Science, *Sadhana*, Vol. 26, Parts 1 & 2, pp. 25–34.

(29) J.N.DPuont, "Mathematical modeling of solidification paths in ternary alloys: limiting of cases of solute redistribution",2005, *Sadhana*, Vol. 26, Parts 1 & 2, February–April 2001, pp. 25–34..

- (30) Ludo Froyen and Fabienne Lemoisson, "Solidification of intermetallics in space", 2003, Katholieke Universiteit Leuven, <http://www.kuleuven.ac.be/>.
- (31) José Eduardo Spinellia, Otávio Fernandes Lima Rochab, Amauri Garciaa, "The influence of melt convection on dendritic spacing of downward unsteady-state directionally solidified Sn-Pb alloys", 2006, Materials Research, Vol. 9, No. 1, pp.51-57.
- (32) Atsumi Ohno, "Solidification the separation theory and its practical applications", 1987, Springer-Verlag Berlin Heidelberg, Germany.
- (33) Albert G. Guy and John J. Hren, "Elements of physical metallurgy", 1974, Third Edition, Addison-Wesley Publishing Company, USA.
- (34) Yu. M. Lakhtin, "Engineering physical metallurgy and heat treatment", 1977, MIR publishers, Moscow, Translated from the Russian by Nicholas Weinstein.
- (35) Nikolas Provatas, Quanyong Wang, Mikko Haataja, and Martin Grant, "Seaweed to Dendrite Transition in Directional Solidification", 2003, The American Physical Society, Physical review letters, VOL. 91, No. 15, pp. 155502-1 – 155502-4.
- (36) Rajiv Sampath and Nicholas Zabaras, "A finite variable method for the thermal design of eutectic directional solidification processes in an open-boat configuration", 2001, Taylor & Francis, Numerical Heat Transfer, Part A, 39, pp. 655-683.
- (37) J. Kajornchaiyakul, R. Sirichaivejakul, N. Moonrin, "Solidification characteristics and mechanical properties of hypoeutectic aluminum-silicon alloy containing sulfur", 2005, National Metal and Materials Technology Center, Bangkok, Thailand.
- (38) R. Cornell and H. K. D. H. Bhadeshia, "Aluminum-silicon casting

- alloys", 1999, Materials Word, University of Cambridge.
- (39) E. Paul DeGarmo, J. T. Black, Ronald A. Kohser, "Materials and processes in manufacturing", 2005, Eighth edition, Prentice, Hall of India.
- (40) Hema V. Guthy, "Evolution of the eutectic microstructure in chemically modified and unmodified aluminum silicon alloys", Master thesis, 2002, Worcester Polytechnic Institute.
- (41) Matgorzata Warmuzek, "Aluminum-silicon casting alloys atlas of microfractographs", 2004, ASM International.
- (42) الدكتور خالد احمد الجودي, "مبادئ تكييف الهواء و التثليج", 1986, جامعة البصرة, كليه الهندسة.
- (43) J.P Holman, "Heat transfer", 1976, Fourth edition, McGraw-Hill, USA.
- (44) Mohamed A. Ahmed AL-Said, "Production and mechanical properties of leaded aluminum bearing alloys", 1998, Master thesis, Baghdad.
- (45) John E. Hatch, "Aluminum: properties and physical metallurgy", 1984, First edition, Metals Park, Ohio, American Society for Metals.
- (46) William D. Allister, JR., "Materials science and engineering an introduction 2000, Fifth edition, University of Utah.
- (47) الدكتور قحطان الخزرجي, عادل محمود حسن, "المواد الهندسية و اختباراتها", 1987, جامعة بغداد.
- (48) Marc Andre´ Meyers, "Mechanical behavior of materials", 1999, USA.
- (49) M. Rappaz, "solidification processes :constitutive equations and microstructures", proc conf. modeling of casting welding and advanced solidification processes VI TMS(1993), pp.67-91.

Supervisors Certificate

We certify that this thesis entitled," *Modeling and experimental analyses of in situ –grown composite to improve the mechanical and physical properties in eutectic system*". Prepared by (*Awham Jumea Salman*) under our supervision at the Department of Materials Engineering/ College of Engineering/ University of Babylon in partial fulfillment of the requirements for the degree of Master of Science in Materials Engineering.

Signature

Name : Dr.Najim A. Saad

(supervisor)

Date : / / 2009

Signature

Name :Dr.Alaa A. Ateia

(supervisor)

Date : / / 2009

Table of symbol

Symbol	Definition	Unit
MMCs	Metal-matrix composites	/
CMCs	Ceramic-matrix composites	/
PMCs	Polymer-matrix composites	/
α	Alpha phase	/
β	Beta phase	/
v	The rate of solidification	$\mu\text{m/s}$
$\hat{G}$	Temperature gradients	$^{\circ}\text{C/mm}$
C	Composition	/
T_n	The nucleation temperature	$^{\circ}\text{C}$
λ	The interlamellar spacing	mm
$\gamma_{\alpha\beta}$	The α/β interfacial energy	J/m^2
$G(\lambda)$	The free energy change associated with the solidification of 1 mol of liquid	J/mol
$\Delta G(\infty)$	The free energy decrease for very large values of λ	J/mol
V_m	The molar volume of the eutectic	m^3
T_E	The equilibrium eutectic temperature	$^{\circ}\text{C}$
ΔT_o	The total undercooling	$^{\circ}\text{C}$
ΔH	Enthalpy term	J/mol
λ^*	The minimum possible spacing	mm
G^{α}	The free energy of the α	J/mol
G^{β}	The free energy of the β	J/mol
$X_B^{L/\alpha}$	The composition of liquid in local equilibrium with the α	wt%
$X_B^{L/\beta}$	The composition of liquid in local equilibrium with the β	wt%
D	The liquid diffusivity	m^2/s
dC/dl	The concentration gradient driving the diffusion	atoms/m^3
k_1	Proportionality constant	/
k_2	Proportionality constant	/
k_3	Proportionality constant	/
k_4	Proportionality constant	/
ΔX	The composition difference	wt%
ΔX_o	The composition difference at ΔT_o	wt%
m	The slope of the liquidus curve	/
C_E	The eutectic composition	/
C_O	The alloy composition	/

A	Constant	/
a	Constant	/
b	Constant	/
R	Interface velocity	$\mu\text{m/s}$
FEM	Finite element method	/
q	The heat-transfer rate	W
K	The thermal conductivity	$\text{W.m/m}^2.\text{°C}$
$\hat{A}$	Area	m^2
$\partial T/\partial x$	The temperature gradient in the direction of the heat flow	°C/m
$\partial T/\partial t$	The temperature gradient with time	°C/sec
$\dot{q}$	Energy generated per unit volume	W/m^3
c	Specific heat of material	J/kg. °C
ρ	Density	kg/ m^3
h	the convection heat- transfer coefficient	$\text{W /m}^2.\text{°C}$
T_w	The wall temperature	°C
T_∞	The fluid temperature	°C
BHN	Brinell hardness number	Kg/mm^2
P	Applied load	kg
D	Diameter of ball	mm
d	Diameter of indentation	mm
t	Depth of the impression	mm
Π	22/7	/
Lt	Total length for tensile sample	mm
Lc	length of reduced section for tensile sample	mm
Lo	Gauge length for tensile sample	mm
b	Width of tensile sample	mm
r	Radius of curvature for tensile sample	mm
d^*	The length of top section for compression sample	mm
h^*	The height of sample	mm
λ'	the length wav	Å^0
d_{hkl}	the radius of the sphere describing the locus of the reciprocal lattice point (hkl)	Å^0
Θ	the angle of deviation of the diffracted beam	degree

Republic of Iraq
Ministry of Higher Education
And Scientific Research
University of Babylon
Collage of Engineering
Department of Material engineering



Experimental Analysis of In- situ Composite Al-Si Eutectic Alloy

A Thesis

Submitted to College of Engineering of the University of Babylon in
Partial Fulfillment of the Requirements for the Degree of Master of
Science in Material Engineering/Metallurgy

By

Awham Jumea Salman
(BSc. In Material Engineering)
(2002)

Supervised by

Dr. Najim A. Saad
(Ass. Prof.)

Dr. Alaa A. Ateia
(Lecturer)

(2009) A.D



وزارة التعليم العالي والبحث العلمي
جامعة بابل
كلية الهندسة
قسم هندسة المواد

التحليل العملي لمركب في موقعه الأصلي لشبكية أليوتكتك (الألمنيوم _ سيلكون)

أطروحة

مقدمة الى قسم هندسة المواد كلية الهندسة جامعة بابل
كجزء من متطلبات نيل شهادة الماجستير في علوم
هندسة المواد/هندسة معادن

من قبل

أوهام جمعة سلمان
(بكالوريوس هندسة مواد)
(2002)

بإشراف

د. علاء عبد الحسن عطيه
(مدرس)

د. نجم عبد الأمير سعيد
(أستاذ مساعد)

2009م

بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

وَيَسْأَلُونَكَ عَنِ الرُّوحِ قُلِ الرُّوحُ
مِنْ أَمْرِ رَبِّي وَمَا أُوتِيتُمْ مِنَ الْعِلْمِ إِلَّا
قَلِيلًا

صدق الله العظيم

{ سورة الإسراء / آية 85 }

Dedication

To my Mother and father

To my sisters and brothers

To my friends

With my love and respect

Awham

2009

CHAPTER ONE

GENERAL INTRODUCTION

CHAPTER TWO
DIRECTIONAL EUTECTIC
SOLIDIFICATION

CHAPTER THREE
ALUMINUM-SILICON
EUTECTIC ALLOY

CHAPTER FOUR
EXPERIMENTAL
PROCEDURE & COMPUTER
MODELING

CHAPTER FIVE
RESULTS & DISCUSSION

CHAPTER SIX
CONCLUSIONS
&SUGGESTIONS FOR
FUTURE WORKS

الخلاصة

أن (In Situ Composite Materials) تعرض عدة من الاختيارات الواسعة من حيث نوع التقوية , الحجم , الربط بين طور التقوية و الأرضيه ,الكسر الحجمي, وفهم الآليات التي تسيطر على الخواص الميكانيكية لتسمح للقرارات الأكثر ذكاء عند انتاج ماده مركبه لتطبيق معين.

يُزَوَّ دُ هذا البحث نظرة عامّة مِنْ الخواص الميكانيكية لتقوية سبيكة ألُمَنيوم- سيلكون بواسطة توجيه نظام أليوتكتك بآثَ جَاهِ مَعْنِي. ولقد صممت و صُنِعَتْ وحدة تجَمِّدِ خاصّة لضمان التوجيه الصحيح لنمو نظام أليوتكتك .

نوعان من مواد العزل استعملت لعزْل قالب الكاربون الفولاذي لوحدة التجمّد (رمل جاف وصوف زجاجي). ولقد وجدَ أن العازل الثاني يَكُونُ مناسبَ في دَمَجِ النمو وتوجيه نظام أليوتكتك مع تدفق الماء البارد خلال الوحدة.

البنية الناتجة تشدُّ مَلْأستطاله صَغير لطور بيتا (السيلكون) أي توجيه ملحوظ لنظام أليوتكتك المُتزايدة في اتجاه تسرب الحرارة.

الصلادة، الشد، لانضغاط والصدمة تحسّنت و عَكُسُ هذه النتائج مباشرة تأثير النمو الإتجاهي لنظام أليوتكتك على تحمل أنواع مختلفة من الأحمال .

Abstract

In-situ composites offer such a wide selection of reinforcement types, size, bonding between compounds (reinforcement and matrix), volume fractions, and understanding the mechanisms controlling mechanical properties will allow more intelligent decisions to be made when tailoring a composite system for a specific application.

This research provides an overview of the mechanical properties of reinforced Al-Si alloy by unidirectional of the eutectic system in specific direction. A special solidification unit have been designed and prepared to ensure the correct orientation of growing eutectic system.

Two types of insulation materials have been used to insulate the carbon steel mold of solidification unit, (dry sand and glass wool). The second type insulator found to be favorable in augmenting the growth and unidirectional of eutectic system with the cold water flow through the unit.

The produced microstructure consists of little elongated $\beta(\text{Si})$ -phase that means noticeable orientation of the growing eutectic system in the direction of heat sink.

Hardness, tension, compression and impact properties have improved and these results reflect directly the effect of unidirectional growth of eutectic system on the response to the multi-types of loading.

Acknowledgment

*First of all, profusely all thanks for **ALLAH** Lord of all creation who enable me to achieve this work.*

I take this opportunity to thank my supervisors, Dr. Najim A. Saad and Dr. Alaa A. Ateia for their guidance, encouragement and support throughout the course of this work.

I would like to thank Miss (engineer)"Khansa Sami" and also all staff members at the workshops and materials engineering laboratories for their help throughout my work.

I am grateful to my family and especially to my mother and father, and also to my sisters and brothers for their assistance, encouragement and support during the period of preparing this work.

Finally, I would like to extend my appreciation to all my colleagues in Babylon University for their continuous supporting, cooperation and help throughout my students years.

*Awham Jumea Salman
2009*

CHAPTER ONE**GENERAL INTRODUCTION****1.1 Introduction**

Composite materials are among the oldest and newest of structural materials. The oldest concept of composite is simply the mixing of two or more materials to rectify some shortcomings of a particular useful component [1]. The common example of a natural composite material is wood, which consists of long cellulose fiber held together by amorphous lignin[2]. The other example is early cannons, which had barrels made of wood, reinforced with brass because a hollow cylinder of wood easily bursts under internal pressure. In ancient times, bricks were made up of clay and straw following this principle. Combination of straw and mud to make huts is still in use today in villages in our country. Similarly, ordinary steel covered with paint to protect it from rusting can be regarded as a composite. If this is regarded true, and then almost engineering materials are composites of some kind[1].

In modern technology, the concept of combining two dissimilar materials has acquired a broader significance: the combination has its own distinctive properties. In terms of strength or resistance to heat or some other desirable quality, a composite material is superior to either of the constituting components taken alone or entirely different from either of them. The principal attraction is stiffer and stronger than anything made ever before. At present, they are used principally to meet severe demands of supersonic flight, the exploration of space and ventures into the deep sea water of oceans[1].

There are two major reasons for the current interest in composite

materials. The first, is simply the need for materials that will out perform the traditional monolith materials. The second and more important in the long run is that composites offer engineers the opportunity to design totally new materials with the precise combination of properties needed for specific tasks [1].

1.2 Definition of Composite Materials

Practically everything is a composite material in some sense. For example, a common piece of metal is a composite (polycrystal) of many grains (or single crystals).

A composite material, consists of two or more physically and/or chemically distinct, suitably arranged or distributed phases, with an interface separating them. It has characteristics that are not depicted by any of the components in isolation. Most commonly, composite materials have a bulk phase, which is continuous, called the matrix, and one dispersed, non-continuous, phase called the reinforcement, which is usually harder and stronger [3, 4, 5].

1.3 Classification of Composite Materials

There are various ways to classify composite materials,

(A). On the basis of matrix used

The multiphase composites are divided into three categories:

1. Metal-matrix composites (MMCs).
2. Ceramic-matrix composites (CMCs).
3. Polymer-matrix composites (PMCs).

(B). On the basis of the geometry of the reinforcement

They are classified as:

1. Fibrous composite.

2. Particulate composite.
3. Flakes composite.

Knowing that, fibers are one dimensional element, and flakes are two dimensional elements whereas particle has all the three dimensions [1].

1.4 In-situ Composite Materials

In-situ composites are multiphase materials where the reinforcing phase is synthesized within the matrix during composite fabrication. This contrasts with ex-situ composites where the reinforcing phase is synthesized separately and then inserted into the matrix during a secondary process such as infiltration or powder processing. In-situ processes can create a variety of reinforcement morphologies, ranging from discontinuous to continuous, and the reinforcement may be either ductile or ceramic phases[6].

There are a number of processes and classes of in-situ composites, including processes where the precipitation of reinforcements occurs in the liquid state and processes where precipitation occurs in the solid state. Processes in which precipitation occurs in the liquid state include those occurring with low undercoolings, such as traditional and directionally solidified eutectics; rapid solidification in which a supersaturation is created by rapidly cooling a liquid with the reinforcement constituents already in solution; and processes in which a large supersaturation is created by rapidly bringing the constituents of the reinforcement together to react. Solid-state in-situ processes include internal oxidization, displacement reactions, reactive milling, mechanical alloying, and cryomilling. There are also traditional eutectoid reactions that can be considered solid-state in-situ reactions if an alloy of ferrite and cementite is considered a composite [6].

In situ production of reinforcements, matrices and inter-phases is a promising strategy for reducing the costs of preparing high-performance metal-ceramic complexes. Among the advantages offered by in situ composites over conventional materials are improved thermodynamic stability, fine scale of reinforcements and the elimination of fiber coating[7].

Many in situ composites show potentials for high-temperature structural applications, but they need simultaneous improvements in oxidation and fracture resistance [8].

1.4.1 Types of In-situ Composite Materials

1. Particle In-situ Composite Materials: - (Precipitation Hardening)

The method to produce particle in-situ composite materials is the precipitation hardening. A precipitation hardening or hardening is produced by solution treating and quenching an alloy in which a second phase is in solid solution at the elevated temperature but precipitates upon quenching and aging at a lower temperature[9].

For precipitation hardening to occur, the second phase must be soluble at an elevated temperature but must exhibit decreasing solubility with decreasing temperature. Usually there is atomic matching, or coherency, between the lattices of the precipitate and the matrix. The requirement of a decreasing solubility with temperature places limitation on the number of useful precipitation hardening alloy systems[9].

The age hardening aluminum alloys and copper-beryllium alloys are common example [9].

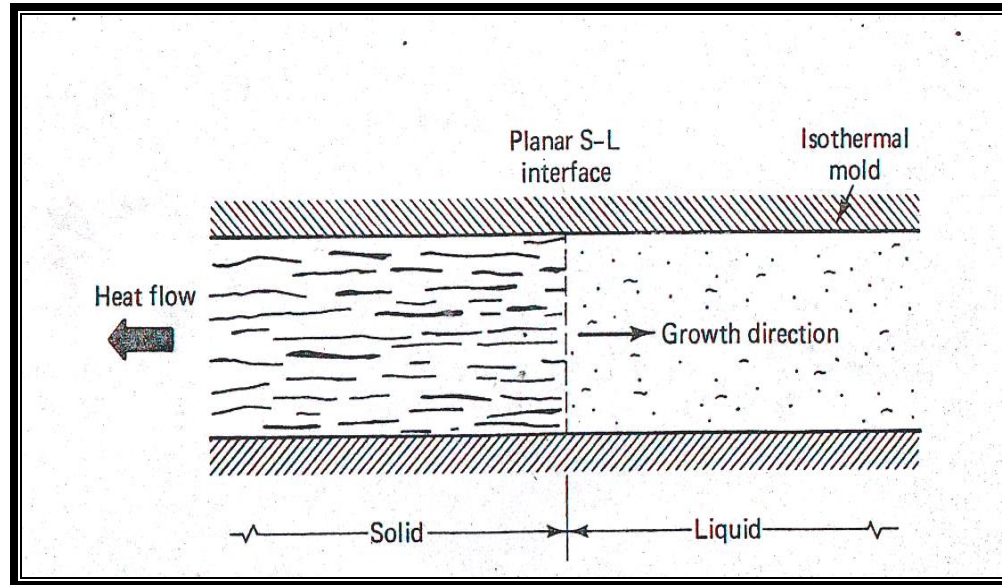
Solidification processing of cast metal-matrix particulate composites, contains in reinforcements generated in situ, is particularly attractive due to the composites' simplicity, flexibility in operation, and potential to reduce

the final production costs. As noted earlier, a comprehensive understanding of the process will have to be developed before commercial exploitation of these cast in-situ composites in order to fabricate components. Studies on the key processing steps are the primary requirements for the control of the macro/microstructure, mechanical properties, and also for continuous processing of components to near net shape [10].

2. Fiber In-situ Composite Materials: - (Unidirectional Eutectic Solidification)

A fiber that can be produced by directional solidification of cast alloys actually is part of the alloy being precipitated from the melt as the alloy solidifies. This type of transformation usually involves eutectic alloys in which the molten material decomposes into two or more phases at constant temperature. When the solidifying phases are unidirectional, the product is known as a directionally solidified eutectic. Ceramic matrix composites can also be fabricated to contain in situ fibers similar to the all-metal systems [11].

Unidirectional solidification , means the solidification is controlled in such a way as to extract the heat in one direction, As can be seen in figure (1.1)[12].



Figure(1.1)

Unidirectional solidification of a eutectic alloy, the solid contains microstructure constituents aligned parallel to the growth direction [12].

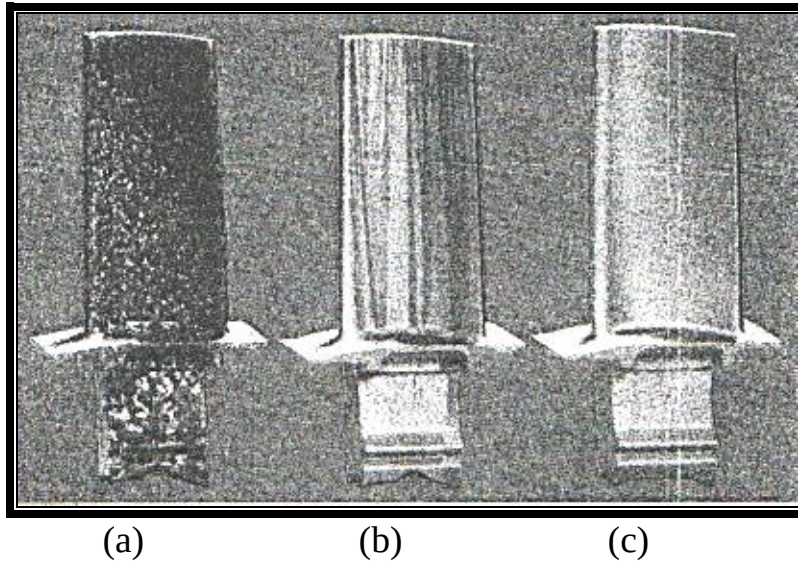
If we have eutectic structure and use the unidirectional solidification method. The resulting growth morphologies are as follows:-

1. Both phases form lamellae aligned parallel to each other.
2. The second phase appears in the form of filaments aligned in the first phase constitute the matrix.
3. Whatever lamellae or filaments are formed, the generated structure exhibits a certain degree of macroscopic order.
4. The direction of preferred orientation coincides with the direction of heat extraction [13].

1.4.2 Applications of Fiber In-situ Composite Materials

In general, applications for directionally solidified eutectic composites are limited compared to other fiber-reinforced materials. One reason for their low utilization is related to the fixed eutectic composition; no variation of constituent volume fractions is possible. Also, they are relatively costly to produce, and result in the lowest melting temperature material of the alloy system under consideration [12].

In addition, directional solidification of eutectic alloys offers improved creep strength and resistance to thermal fatigue, due the absence of transverse grain boundaries. Creep is permanent deformation that occurs over a period of time in components subjected to a constant stress; typically below the room-temperature elastic limit. Such deformation is also temperature dependent and increases with increasing temperature. Because of such improved thermal properties, this type of composite has been applied to aircraft engine turbine buckets or blades. These components are blade-shaped airfoils in turbines, which “catch” the hot gases of combustion and essentially power the engine. Accordingly, these parts are subjected to very severe operating conditions (i.e., high temperature, stress, and corrosive atmospheres) [12, 14, 15].



Figure(1.2)

Turbine blades manufactured by three different processes: (a) conventional casting-equiaxed grains; (b) directional solidification-columnar grains; (c) single crystal-one grain [12].

1.5 Literature Review

Generally, the unidirectional solidification of eutectics was first studied by Winegard, et al. in 1952. However, only in about 1960 was this technique considered seriously for the production of composite materials. Bending tests firstly performed in 1958 by Webb and Forgeng on Cr-filaments extracted from a randomly cast (Cu-Cr) eutectic demonstrated the monocrystal-like nature of the filaments and their exceptionally high strength. The whisker-character of Cr-fibers extracted from a unidirectional solidified (Cu-Cr) eutectic was later proved by Lemkey and Kraft. These authors found for the filaments strength values in the order of (10 GN/m^2) and an elongation at rupture of the order of 2% [13].

Further studies carried out by Hertzberg and Kraft on the rupture behavior, e.g. rupture mode of the fibers, interface features, and adhesion at the interface between matrix and fibers, gave an essential contribution in

proving the composite nature of the (Cu-Cr) eutectic . Since then a large number of eutectic systems have been studied. A detailed list is given by Hogan et al., and by Kurz and Sahm , at the moment more than 400 systems are known .This fact shows clearly the lively interest of research institutes in the field of unidirectional solidification of both binary and more complex systems[13].

One may note that the systems which receive the most attention are the Al-and Ni-base composites in view of their possible exploitation as heat-resistant materials, but a number of other systems are becoming more and more attractive especially in view of an application in non-structural fields [13].

Many efforts have been directed to growing an in-situ fiber phase in the Al-Si eutectic alloy, and following is the review of available works:-

M.A. Martorano et al [16] carried out experiments of the Columnar to-Equiaxed Transition in directional solidification of Al-Si alloys with Si contents ranging from 3 to 11 % and identical thermal conditions. Convection associated with the pouring of the liquid metal was suppressed by using a thin Aluminum Nitride base to seal the insulated cylindrical sleeve at the bottom and keeping the Al-Si melt in the furnace for a long time. After homogenization of the melt temperature, solidification was initiated by removing the furnace from the mold and raising a water-cooled copper chill to touch the bottom of the high thermal conductivity Aluminum Nitride base. Cooling curves recorded by seven thermocouples located every 20 mm from the bottom of the casting were compared with predictions of a one-dimensional model, suggesting that heat transfer in the solidifying metal was by conduction only. Measured Columnar to-Equiaxed Transition positions were similar for all alloy compositions, indicating a weak effect of

the Si content. Further conclusions drawn from the simulations were already provided in the previous section.

K. Ohsasa et al [17] studied the frequency of heterogeneous nucleation during the solidification of Al-Si binary alloy was estimated by comparing experimentally obtained macrostructures of castings with numerically simulated ones. A molten alloy was unidirectionally solidified from a water-cooled copper chill in an adiabatic mold. The location of columnar to equiaxed transition in the solidified alloy ingot was measured. A numerical simulation for grain structure formation based on the Monte Carlo method was carried out, and the frequency of heterogeneous nucleation in the alloy was evaluated by producing similar structure with the experimental one. The frequency of heterogeneous nucleation was expressed as a probabilistic function with an exponential form of undercooling that determines the probability of nucleation event in the simulation. The value of the exponent is regarded as the nucleation parameter. The nucleation parameter of Al-Si binary alloy varied with initial Si content.

R.E. Napolitano et al [18] findings from the investigation of solidification morphologies resulting from the low velocity directional solidification of Al-Si eutectic alloys are discussed. The development of a primary array of angular silicon rods is examined, and the twinned structure of the faceted silicon phase is shown to be an essential contributor to the mechanisms of growth, branching, spacing selection, and the evolution of $\langle 100 \rangle$ Si texture within the two-phase microstructure.

Taylor A. Groll [19] studies the effect of solidification rate on the secondary dendrite cell size that was examined by taking photomicrographs of five different samples of an Aluminum alloy A356 . they found that, the microstructural features of the samples are consistent with that of an as-cast

Al-Si alloy. As the solidification rate of the alloy decreases, the ultimate tensile and yield strengths, and occurrences of porosity increase. As the solidification rate of the alloy increases, the dendrite cell size and size of porosity decrease.

K.Nogita et al [20] investigate the quench modification involved the refinement of silicon due to high cooling rates, and thus high transformation rates. Growth rates exceeding 1mm/s have been quoted as a criterion for obtaining a quench modified eutectic microstructure. Finding that the eutectic in Al-Si alloys may evolve with widely different spatial distributions and is significantly affected by trace levels of several elements, particularly those known to also affect eutectic silicon morphology (modifiers). The morphology of eutectic silicon is not directly related to either the thermal parameters of the eutectic or the eutectic solidification mode.

M.F. Zhu , C.P.Hong [21] studies the a modified cellular automaton model that has been developed in order to predict the evolution of dendritic and eutectic microstructures in solidification of alloys. The modified cellular automaton model accounts for the aspects including the heterogeneous nucleation of a new phase, the growth of primary dendrites and two eutectic solid phases from a single liquid phase, as well as the coupling between the phase transformation and solute redistribution. The present model was applied to predict the primary dendritic growth and eutectic structure formation during practical casting solidification of Al alloys. The simulated results were compared with those obtained experimentally. The model can also be applied to model irregular eutectic growth patterns in eutectic and hypoeutectic Al-Si alloys.

Yuhong Zhao and Hua Hou[22] used , the two phase field models for

free interface of dendrite growth as sharp interface model and diffusion interface have been introduced; and microstructure evolution in solidification process is studied by phase field model, model of the phase field model and its numerical solution are introduced, the dendrite growth process of Al-Si alloy in solidification process is simulated, and the simulation results have been analyzed. The comparisons of dendrite morphology between simulated results and investigations by others are also presented, which proved that the dendrite morphology are similar in trunks and arms growth, so proved the developed phase field program is accurate.

M. Jeyakumar et al[23] investigates the tradeoff between gas microporosity and primary silicon formation as a function of cooling rate during solidification of near-eutectic Al-Si alloys. In order to minimize microporosity formation and improve mechanical properties, Al-Si alloy castings are generally cooled at a faster rate, using steel or cast iron chills, near the critical regions. While this method works well for the A356 castings with Si content of about 7%, the effect of primary silicon formation needs to be considered for near-eutectic alloys with Si compositions close to 12.6%. Finding the quench and Universal Metallurgical Simulator and Analyzer experiments carried out using Al-Si binary eutectic alloys without grain refiner or modifier additions clearly indicate that there exists a range of cooling rates (near the eutectic) where a perfect eutectic microstructure without microporosity or primary Si formation can be achieved. At cooling rates below this regime, micropores begin to nucleate and grow. At cooling rates above this regime, formation of primary Si is observed. This critical cooling rate regime was found to be between 2-3 °C/s.

1.6 Aim of the Work

The scope of this work covers a unidirectional solidification of Al-(12%wt) Si. Many factors affecting the effectiveness of the solidification in this manner, such as, molten metal temperature, method of solidification (i.e. mold material, insulation and the method by which the heat sink in one direction to augment or supporting the eutectic solidification in one direction) are studied as well. These as well as the modeling equations of heat transfer(temperature distribution) were modified by using an ANSYS-code (version-5.4) hopes to fully understand the process at hand.

So the aims of present work are summarized as follows:-

1. Controlling the direction of grown eutectic phase in order to use as an in-situ fiber in a eutectic Al-Si alloy containing almost 12wt% of silicon.
2. Computer modeling by using an ANSYS-code (version-5.4) of solidification processes in order to specify the efficiency of insulation material (temperature distribution) used and in order to specify the modeling solidification time and comparing it with the experimentally predicted solidification time.
3. Reporting and studying the microstructure evolution under different conditions of solidification along the solidified material throughout the monitoring of eutectic phase orientation.
4. Evaluation of hardness, compression, tension and impact toughness of the material produced at different conditions of solidification and comparing the result with the properties of non-unidirectional solidified material that produced experimentally.

CHAPTER TWO

DIRECTIONAL EUTECTIC SOLIDIFICATION**2.1 Eutectic**

The eutectic or eutectic mixture is a mixture of two or more solid phase at a composition that has the lowest melting point, and where the phases simultaneously crystallise from molten liquid solution at this temperature, see figure (2.1). The term comes from the Greek 'eutektos', meaning 'easily melted'. Alloys of the eutectic composition are said undergo a eutectic reaction as the single phase liquid solidifies into a multiple phase solid [24, 25, 26].

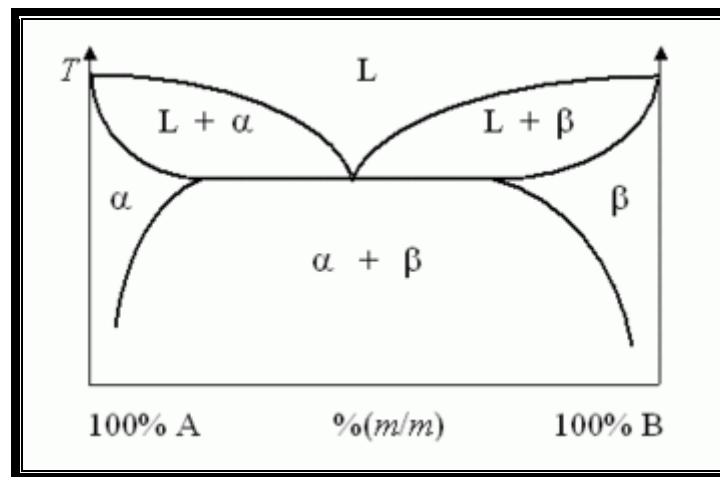


Figure (2.1)
A simple binary eutectic system [24].

2.1.1 Metallic Eutectics

The term is often used in metallurgy to describe the two or more component materials having the relative concentrations specified at the eutectic point.

An alloy freeze, one component of the alloy crystallizes at one temperature and the other at a different temperature. With a eutectic alloy, the mixture freezes as one at a single temperature. A eutectic alloy therefore has a sharp melting point, and a non-eutectic alloy exhibits a plastic melting range. The phase transformations that occur while freezing a given alloy can be understood using the phase diagram by drawing a vertical line from the liquid phase to the solid phase on a phase diagram; each point along the line describes the composition at a given temperature [25].

A number of workers have also carried out an investigation with the aim of predicting the type of morphology in a new system. In practice the problem here was to find out when filament lamellae are formed.

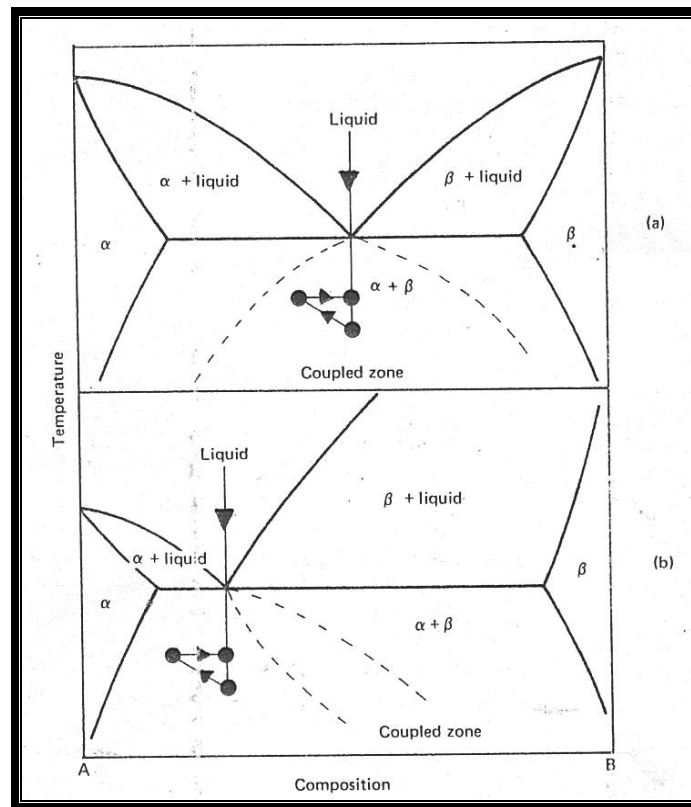
In general, systems having a volume fraction of the second phase greater than 30% give lamellar structures, while a filament structure is preferentially generated in those systems having a volume fraction of the second phase smaller than 30%. This leads us to suppose that the relative interfacial surface, and therefore the relative interfacial energy, is a determining factor. Since this is a function of the volume fraction, the structure having the minimum interfacial area and thus the minimum energy is the prevalent one. There are, however, exceptions to this rule.

Various different types of eutectic solidification are possible and there are usually classified as normal and anomalous [24, 27].

In normal structures the two phases appear either as alternate lamellae, or as rods of the minor phase embedded in the other phase. Normal

structures occur when both phases have low entropies of fusion, and phase diagrams in which the metals were of similar melting point.

Anomalous structures, on the other hand, occur in systems when one of the solid phases is capable of faceting, i.e. has high entropy of melting and formed in systems with metals of different melting temperatures [24].



Figure(2.2)

- (a) Phase diagram typical of a system showing a normal eutectic structure.
- (b) Phase diagram typical of a system showing an anomalous eutectic structure [24].

There are many type of eutectic morphologies lamellar, needle shaped, acicular, globule crystals [13].

2.2 Eutectic Solidification

Solidification involves the extraction of heat from the liquid and the motion of the solid–liquid interface [28, 29]. The rate of solidification is determined mainly by heat extraction through thermal diffusion and convection. However, solidification microstructure is a complex function of the rate of solidification (v), temperature gradients ($\hat{G}$), composition (C) and several material characteristics such as phase equilibrium reactions, nucleation and growth kinetics of the phases and crystallographic constraints. A perspective of evolution of microstructure during solidification is presented in the light of our current understanding of solidification processing. Particular attention is paid to the effect of system size and resultant scale dependence of the microstructure and segregation profile. We emphasize the fact that our current knowledge allows us to have quantitative understanding [28].

Solidification of a eutectic alloy from the melt or liquid phase produces two composite solid phases, in contrast to the simpler case when the liquid phase solidifies into a single solid phase. The two solid phases are characterized by differing solute concentrations; the equilibrium concentrations in each phase are given by the phase diagram for the eutectic system, which gives the relations between temperature and solute concentration for each of the thermodynamic phases in the system. A number of different geometrical arrangements of the two solid phases are possible, depending on the alloy system and on the processing conditions. For example, the solid phases can form in adjacent layers or lamellae, or one phase can form rods that are embedded in the other phase. Both grow continuously from the melt. Since a large number of important binary alloy systems have eutectic phase diagrams, such systems have been studied

extensively. It is desirable to be able to predict the geometrical patterns of growth and their associated length scales in order to better understand and possibly control the processing of eutectic materials [30, 319].

2.2.1 Nucleation in Eutectic Solidification

The eutectic reaction occurs by a nucleation and growth process in common with all solidification processes. The nucleation events commences at a temperature below the eutectic temperature with the heterogeneous nucleation of one of the eutectic phase on nucleus present in the liquid, and is completed by the heterogeneous nucleation of the second eutectic phase on the first. As understanding of heterogeneous nucleation is desirable because the nucleation of one eutectic phase by another is a possible origin of an epitaxial orientation relationship which, if formed at nucleation, may persist during growth and influence both structure, and properties[13].

The nucleation temperature (T_n) can influence the eutectic grain on cell size and the solidification conditions nucleation under which initial growth occurs. Homogeneous nucleation is described briefly and then developed to consider the factors that control the heterogeneous nucleation of eutectic phases [13].

2.2.2 Growth of Lamellar Eutectics

Figure (2.3) shows how two phases can grow cooperatively behind an essentially planar solidification front. As the A-rich α phase solidifies excess B diffuses a short distance laterally where it is incorporated in the B-rich β phase. Similarly the A atoms rejected ahead of the β diffuse to the tips of adjacent α lamellae. The rate at which the eutectic grows will depend on how fast this diffusion can occur and this in turn will depend on the

interlamellar spacing λ . Thus small interlamellar spacing should lead to rapid growth[27].

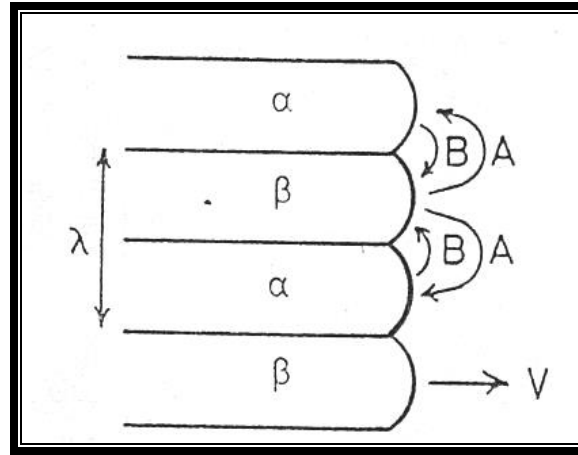


Figure (2.3)

Interdiffusion in the liquid ahead of a eutectic front [27].

However there is lower limit to determine the need to supply the α/β interfacial energy, $\gamma_{\alpha\beta}$. For an interlamellar spacing, λ , there is a total of $(2/\lambda) \text{ m}^2$ of α/β interface per m^3 of eutectic. Thus the free energy change associated with the solidification of 1 mol of liquid is given by

$$\Delta G(\lambda) = -\Delta G(\infty) + 2 \gamma_{\alpha\beta} V_m / \lambda \quad (2.2)$$

Where V_m is the molar volume of the eutectic and $\Delta G(\infty)$ is the free energy decrease for very large values of λ . Since solidification will not take place if $\Delta G(\lambda)$ is positive, $\Delta G(\infty)$ must be large enough to compensate for the interfacial energy term, i.e. the eutectic / liquid interface must be undercooled below the equilibrium eutectic temperature T_E , Figure (2.4). If the total undercooling is ΔT_o it can be shown that $\Delta G(\infty)$ is then given approximately by

$$\Delta G(\infty) = \Delta H \cdot \Delta T_o / T_E \quad (2.3)$$

Where ΔH is an enthalpy term. The minimum possible spacing (λ^*) is obtained by using the relation $\Delta G(\lambda^*) = 0$, whence ,

$$\lambda^* = 2\gamma_{\alpha\beta}T_E V_m / \Delta H \cdot \Delta T_o \quad (2.4)$$

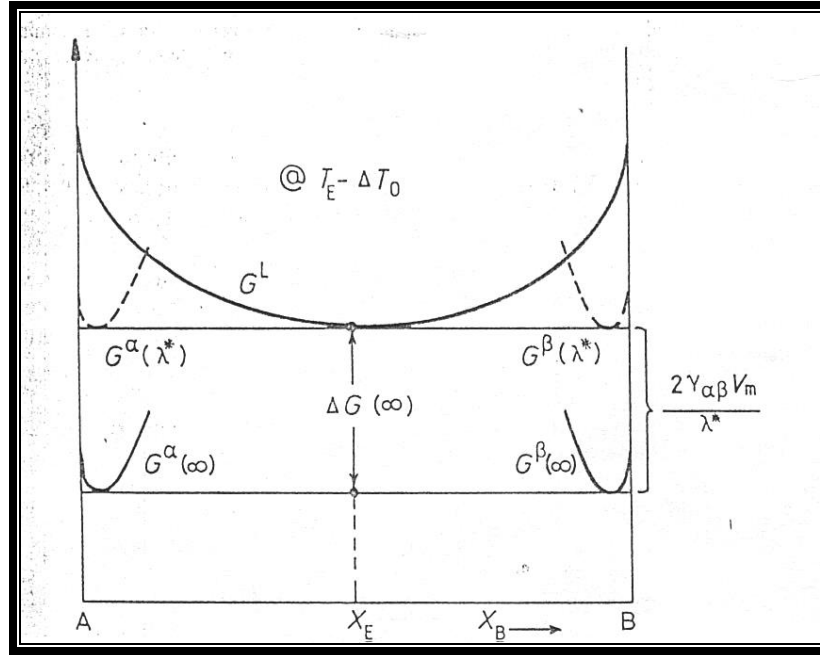


Figure (2.4)

Molar free energy diagram at a temperature ΔT_o below the eutectic temperature, for the case $\lambda = \lambda^*$ [27].

When the eutectic has this spacing, the free energy of the liquid and eutectic is the same, i.e. all three phases are in equilibrium. This is because the α/β interface raises the free energies of the α and β from $G^\alpha(\infty)$ and $G^\beta(\infty)$ to $G^\alpha(\lambda^*)$ and $G^\beta(\lambda^*)$ as shown in Figure (2.4). The cause of the increase is the curvature of the α/L and β/L interfaces arising from the need to balance the interfacial tensions at the $\alpha/\beta/L$ triple point, Figure (2.3). In general, therefore the increase will be different for the two phases, but for simple cases it can be shown to be $2\gamma_{\alpha\beta}V_m/\lambda$ for both, Figure (2.4)[27].

Let us now turn to the mechanism of growth. If solidification is to occur at finite rate there must be a flux of atoms between the tips of the α

and β lamellae and this requires a finite composition difference. For example the concentration of B must be higher ahead of the α phase than ahead of the β phase so that B ejected from the α can diffuse to the tips of the growing β . $\lambda = \lambda^*$ growth will be infinitely slow because the liquid in contact with bottom phases has the same composition, X_E in Figure (2.4). However if they chose spacing is greater than λ^* less free energy is locked in the interfaces G^α and G^β are correspondingly reduced, Figure (2.5 a). Under these circumstances the liquid in local equilibrium with the α phase has a composition $X_B^{L/\alpha}$ which is richer in B than the composition in equilibrium with the β phases $X_B^{L/\beta}$ [27].

If the α/L and β/L interfaces are highly mobile it is reasonable to assume that growth is diffusion controlled in which case the eutectic growth rate (v) should be proportional to the flux of solute through the liquid. This in turn will vary as $D \cdot dC/dl$ where D is the liquid diffusivity and dC/dl are the concentration gradient driving the diffusion. (l is measured along the direction of diffusion as shown in Figure(2.5 b). In practice, dC/dl will not have single value but will vary from place within the diffusion zone.) dC/dl should be roughly proportional to the maximum composition difference ($X_B^{L/\alpha} - X_B^{L/\beta}$) and inversely proportional to the effective diffusion distance which, in turn, will be linearly related to the interlamellar spacing (λ). Thus we can write

$$v = k_1 D (\Delta X / \lambda) \quad (2.5)$$

Where k_1 is a proportionality constant and $\Delta X = X_B^{L/\alpha} - X_B^{L/\beta}$ as given in Figure(2.5).

ΔX will itself depend on λ for when $\lambda = \lambda^*$, $\Delta X = 0$, and as λ increases will tend to a maximum value, ΔX_o , say. Therefore it is reasonable to write

$$\Delta X = \Delta X_o (1 - \lambda^*/\lambda) \quad (2.6)$$

The magnitude of ΔX_o can be obtained by extrapolating the equilibrium liquidus lines of the phase diagram ($\lambda = \infty$) as shown in Figure (2.6). For small undercoolings

$$\Delta X_o \propto \Delta T_o \quad (2.7)$$

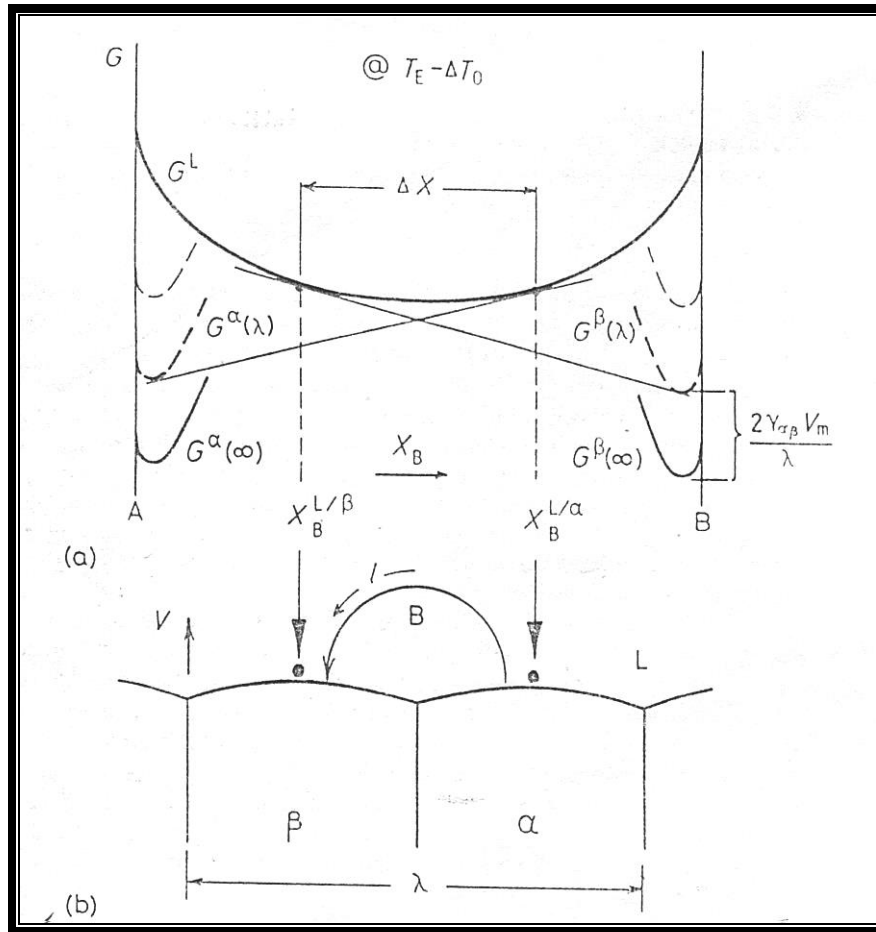


Figure (2.5)

(a) Molar free energy diagram at $(T_E - \Delta T_o)$ for the case $\lambda^* < \lambda < \infty$, showing the composition difference available to drive diffusion through the liquid. (b) Model used to calculate the growth rate [27].

The dashed lines in Figure (2.6) are the liquidus lines for $\lambda^* < \lambda < \infty$. ΔX is simply given by the extrapolation of these lines as shown. Combining the above equations gives

$$v = k_2 D \Delta T_0 (1/\lambda) (1 - (\lambda^*/\lambda)) \quad (2.8)$$

Where k_2 is another proportionality constant. This equation shows that by varying the interface undercooling (ΔT_0) it possible to vary the growth

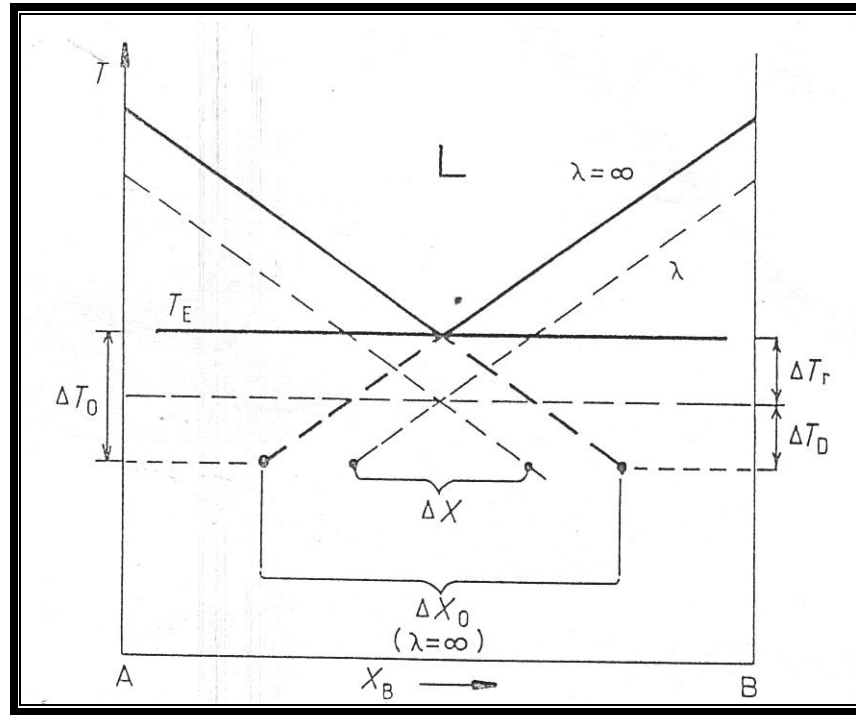


Figure (2.6)
Eutectic phase diagram showing the relationship
between ΔX and ΔX_0 [27].

rate (v) and spacing (λ) independently. It is therefore impossible to predict the spacing that will be observed for a given growth rate. However, controlled growth experiments show that a specific value of λ is always associated with a given growth rate. Examination of equation (2.8) shows that when $\lambda = 2\lambda^*$, the growth rate is a maximum for a given undercooling, or, alternatively, the required undercooling is a minimum for a given growth

rate. If it is assumed that growth occurs under these optimum conditions the observed spacing $\lambda_o = 2\lambda^*$ and the observed growth rate is given by

$$V_o = k_2 D \Delta T_o / 2\lambda^* \quad (2.9)$$

However, from Equation (2.4), it is seen that $\Delta T_o \propto 1/\lambda^*$ so that the following relationships are predicted:

$$V_o \lambda_o^2 = k_3 \quad (\text{constant}) \quad (2.10)$$

and

$$V_o / (\Delta T_o)^2 = k_4 \quad (\text{constant}) \quad (2.11)$$

There is in fact no physical basis for choosing $\lambda = 2\lambda^*$ and similar expressions can also be obtained using other assumptions concerning the spacing. Equations (2.10) and (2.11) are often found to be obeyed experimentally[27].

2.3 Eutectic Leading Phase

In order to control the structure of eutectic alloys it is important to know whether the primary crystals of the eutectic alloy are leading phase or non-leading phase. This is because whereas non-leading phase primary crystals do not have much effect on the formation of the eutectic grain zone, leading phase primary crystals cause the formation of equiaxed eutectic grains. To distinguish between leading phase and non-leading phase. This is soon revealed by casting a hyper-eutectic alloy and a hypo-eutectic alloy whose compositions resemble the eutectic composition extremely closely, and comparing their solidified structures[32].

The phase in which primary crystals exist independently of the eutectic matrix is the non-leading phase, and the phase in which primary crystals form a core in the center of the equiaxed eutectic grains is the

leading phase [32]. In table (2.1) have listed the eutectic leading phases for many eutectic systems.

Table (2.1)
Leading phase of eutectic alloys [32].

Alloy	Leading phase	Alloy	Leading phase
Ag-Bi	Ag	Al-Si	Si
Ag-Cu	Cu	Al-Sn	Al
Ag-Ge	Ge	Al-Zn	Al
Ag ₃ Sn-Sn	Ag ₃ Sn	Bi-BiPb ₂	Bi
Al-AlSb	AlSb	Bi-Cd	Bi
Ag ₃ Sb-Sb	Sb	Bi-Sn	Bi
Al-Ge	Ge	Cd-Pb	Cd
Al-Al ₉ Co ₂	Al ₉ Co ₂	Cd-Sn	Cd
Al-CuAl ₂	CuAl ₂	Cd-Zn	Zn
Al-NiAl ₃	NiAl ₃	Fe-C	C
Fe-Fe ₃ C	Fe ₃ C		

2.4 Nonequilibrium Crystallization

The processes discussed above refer to conditions near to equilibrium, i.e. at very slow cooling. Besides developing coring in the crystals of the α – and β -solid solutions, an increase in the cooling rate may lead to considerable changes in the structure and phase content of the solidified alloys [33, 34].

Nonequilibrium crystallization may impart a purely eutectic structure to these alloys. Such a structure is said to be quasi-eutectic because it has a composition differing from that of the eutectic represented by a diagram of phase equilibrium [33].

2.5 Unidirectional Solidification of Eutectic

Principally, a eutectic structure forms by the transformation of liquid alloy to two solid. Also recall that this reaction is invariant; it takes place at a fixed composition and a constant temperature. Ordinarily, the eutectic structure produced during solidification tends to be random with respect to distribution of the micro structural constituents. But if the solidification process of a eutectic alloy is precisely controlled, for example by removing heat from the liquid at a constant rate in one direction, and a planar solid-liquid interface can be maintained, the resulting structure will be aligned in the direction of heat flow. This procedure, referred to as unidirectional solidification, is illustrated schematically in figure (2.7) [12].

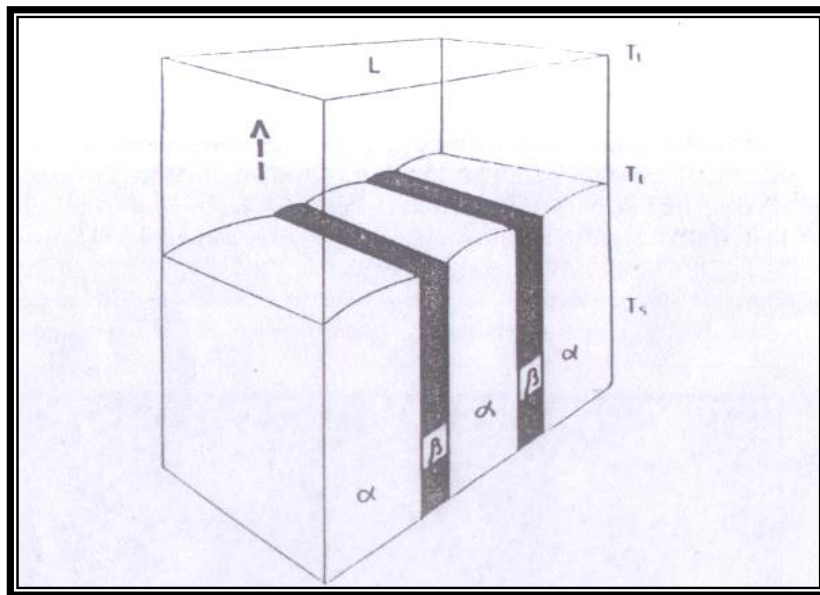


Figure (2.7)

Formation of a lamellar structure (α and β phases) in a unidirectional solidification of a eutectic. The solidification front is perpendicular to the direction of growth (direction of arrows). T_L , T_E and T_S are the temperatures of the liquid (L), the solidification front and the solid, respectively [12].

2.5.1 Mechanical Behavior

A unidirectional solidified eutectic thus exhibits a microstructure resembling a fiber-reinforced metal-matrix composite. Depending on the particular alloy system involved, one of the constituents may behave as the reinforcement while the other acts as the matrix[12].

One exceptionally important aspect of this type of composite material is the nature of the bond between reinforcing phase and surrounding matrix. Studies of the deformation experienced in these materials have been conducted by both light and electron microscopy. Such examinations have revealed that load transfer from the matrix to the “fiber” is very efficient, and that typically the fiber or whisker fails rather than the interface. This observation strongly suggests that an excellent bond is obtained between the microstructure phases, which are what might be expected, subsequent chemical reactivity between the phases is also minimized in this type of composite system [12].

The regularity of the morphology depends mainly on;

1. The thermal gradient ($\hat{G}$) existing at the solidification front.
2. The solidification rate (v), i.e. the velocity at which the solidification front moves [13, 35].

When uniaxial heat flux is realised, e.g. by extracting the molten alloy from a vertical furnace. A liquid-solid interface normal to the direction of the heat extraction is formed. Under strictly controlled conditions this liquid-solid interface is planar and moves at constant velocity through the entire length of the ingot. The two phases α and β formed at the interface follow the solidification front movement leading to the lamellar morphology with the single lamellae oriented along the direction of heat extraction.

The lamellar composite and fibrous composite structures are obtained

only in the case where the solidification front is planar, perpendicular to the direction of the growth (heat extract) and the numbers of the parameters are affected, such as the thermal gradient, the solidification rate, the impurities, etc.

The analytically the condition for planar front solidification of binary alloys at compositions in the two phase region is given by ($\hat{G}/v$ ratio)

$$\hat{G}/v \geq -m (C_E - C_0)/D \quad (2.13)$$

where $\hat{G}$ is the thermal gradient, v the solidification rate, m the slope of the liquidus curve, C_E and C_0 the eutectic and the alloy composition and D the diffusion coefficient in the liquid [13].

Every eutectic alloy has the critical (G/v ratio) that has to be exceeded in order to ensure completely aligned eutectic growth during directional solidification [13, 36].

The morphology of a single system, however, does not remain constant when the solidification parameters are changed. The influence of the gradient seems to be minimal. While in some systems the influence of the solidification velocity is considerable. In some systems, the lamellae- to rods transitions have been observed by increasing the solidification rate, while in others the opposite effect can be noted. In each case however, the transition is gradual. At very low rates some systems present degenerate structures.

The interlamellar distance is also a function of the solidification rate and varies according to the following relationship:

$$(\lambda^2) v = A \quad (2.14)$$

Where λ is the interlamellar distance, v the solidification rate, and A is a constant for the given system. Above relation is important, because it represents the beginning of a quantitative description of eutectic growth. While a more sophisticated relationship has been proposed:

$$(\lambda^2) v = a (1+b/\lambda) \quad (2.15)$$

This equation characterizes an eutectic system having two constants instead of one.

The structures obtained by (growth in situ) at low rates are the most stable at high temperatures. This is because they are coarser and therefore Ostwald ripening is minimized. On the other hand the structures obtained at higher rates or those plastically deformed grow more quickly because the structure is finer or because of the presence of microscopic deformation due to plastic processing [13].

CHAPTER THREE**ALUMINUM –SILICON EUTECTIC ALLOY****3.1 Introduction**

In this section, a review of the basics of aluminum-silicon system and the present understanding of the evolution of aluminum-silicon eutectic alloys will be presented.

Evidently, aluminum-silicon foundry alloys have gained increasingly uses, particularly in engineering applications such as automotive parts and structural components, in the past decades. Liquid treatment of aluminum-silicon alloys, including fluxing, is one of the most important operations toward successful casting of these foundry alloys [37].

Aluminum alloys are grouped according to the major alloying elements they contain. The 4XXX group is alloyed with silicon for ease of casting [38, 39]. Silicon is good in metallic alloys used for casting. This is because it increases the fluidity of the melt, reduces the melting temperature, decreases the contraction associated with solidification and is very cheap as a raw material. Silicon also has a low density(2.34gcm^{-3}), which may be an advantage in reducing the overall weight of the cast component. Silicon has a very low solubility in aluminum; it therefore precipitates as virtually pure silicon, which is hard and hence improves the abrasion resistance [38].

Further, aluminum-silicon eutectic is an anomalous eutectic because it constitutes a metal (aluminum) and a non-metal (silicon). Evolution of an anomalous eutectic has not been completely understood till date. To add to the confusion, the aluminum-silicon eutectic undergoes a change in morphology upon addition of certain elements e.g. strontium or sodium. This process is often referred to as eutectic modification [40].

3.2 The Aluminum-Silicon Phase Diagram and Equilibrium Cooling

Aluminum-silicon system is a simple binary eutectic with limited solubility of aluminum in silicon and limited solubility of silicon in aluminum. The solubility of silicon in aluminum reaches a maximum (1.65 wt%) at the eutectic temperature [40].

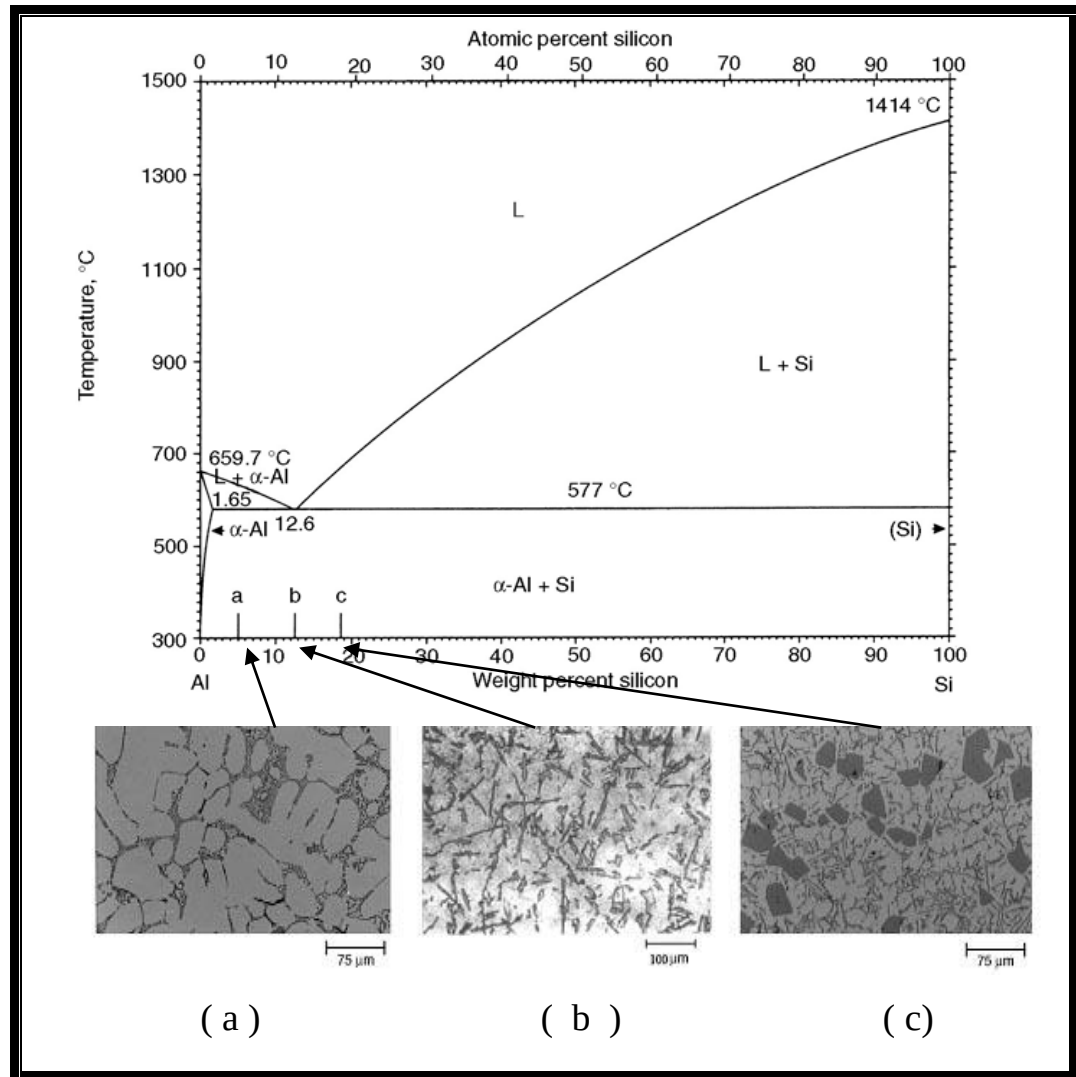


Figure (3.1)

depicts the contemporary aluminum-silicon phase diagram.(a) Hypoeutectic alloy, (b) Eutectic alloy,(c) Hypereutectic alloy [41].

There is only one invariant reaction in this diagram, namely:



In equation (3.1), L is the liquid phase, α is predominantly aluminum, and β is predominantly silicon. It is now widely accepted that

the eutectic reaction takes place at 577°C and at a silicon level of 12.6%. Figure (3.1) shows that the aluminum-silicon eutectic can form as follows:

1. Directly from the liquid in the case of a silicon concentration of 12.6% (i.e., for a eutectic aluminum-silicon alloy),
2. In the presence of primary aluminum in the case of silicon contents <12.6%(i.e., for hypoeutectic aluminum-silicon alloys), and
3. In the presence of primary silicon crystals in the case of silicon contents >12.6% (for hypereutectic aluminum-silicon alloys) [40].

Typical eutectic structures of binary alloys form by the simultaneous growth of two phases from the liquid; therefore they may exhibit a variety of microstructures that can be classified according to two criteria:

- a. Lamellar vs. fibrous morphology of the individual phases, and
- b. Regular vs. irregular growth of the individual phases[40].

Figure (3.2) shows the microstructure of the aluminum-silicon eutectic. In general, when there are approximately equal volume fractions of the two phases, eutectics of binary alloys exhibit a lamellar structure. On the other hand, if one phase is present in a small volume fraction, this phase tends to be fibrous. As a rule of thumb, the eutectic microstructure obtained will tend to be fibrous when the volume fraction of the minor phase is less than 0.25, otherwise it will tend to be lamellar. If both phases in the eutectic are non-faceted, the eutectic will exhibit a regular morphology. In this case, the microstructure is made up of either lamellae or fibers having a high degree of regularity and periodicity. On the other hand, if one phase is faceted, the eutectic morphology is often irregular. Even though the volume fraction of silicon in the aluminum-silicon binary is less than 0.25, the typical aluminum-silicon eutectic is closer to a lamellar structure than to a fibrous one. This is usually attributed to the

strong anisotropy of growth of silicon and to the relatively low interfacial energy between silicon and aluminum [40].

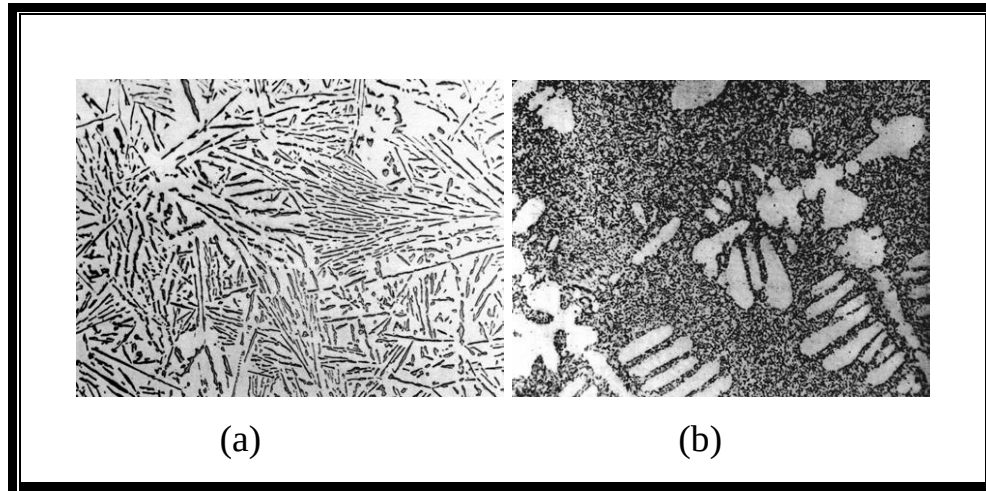


Figure (3.2)

Al-12.6wt% Si alloy (a) Slowly cooled 200X (b) Chill Cast 500X [40].

Gwyer and Phillips [40] determined the composition and temperature of the eutectic reaction in the Al-Si binary system to be 11.7%Si and 577°C respectively. Though the eutectic temperature is in accord with the currently accepted value, the eutectic composition was later changed to 12.2 ± 0.1 atom %Si. The initial error in establishing the eutectic point is due to the fact that the temperature of formation of the primary constituents (aluminum and silicon), as well as the temperature of the Al-Si eutectic plateau are cooling rate dependent. Primary silicon undercools more than primary aluminum hence the eutectic structure forms at 10-12°C below the eutectic temperature without appreciable recalescence. Consequently, at higher cooling rates, the system behaves as though the eutectic point is shifted to higher silicon contents and the eutectic temperature is depressed. Figure (3.2) illustrates this apparent shift in the eutectic point. Figure(3.2)(a), which depicts the microstructure of a eutectic aluminum-silicon alloy that is slowly cooled, shows no primary aluminum; on the other hand, Figure (3.2)(b), which depicts the

microstructure of the same alloy cooled at a relatively faster rate, shows primary aluminum dendrites [40].

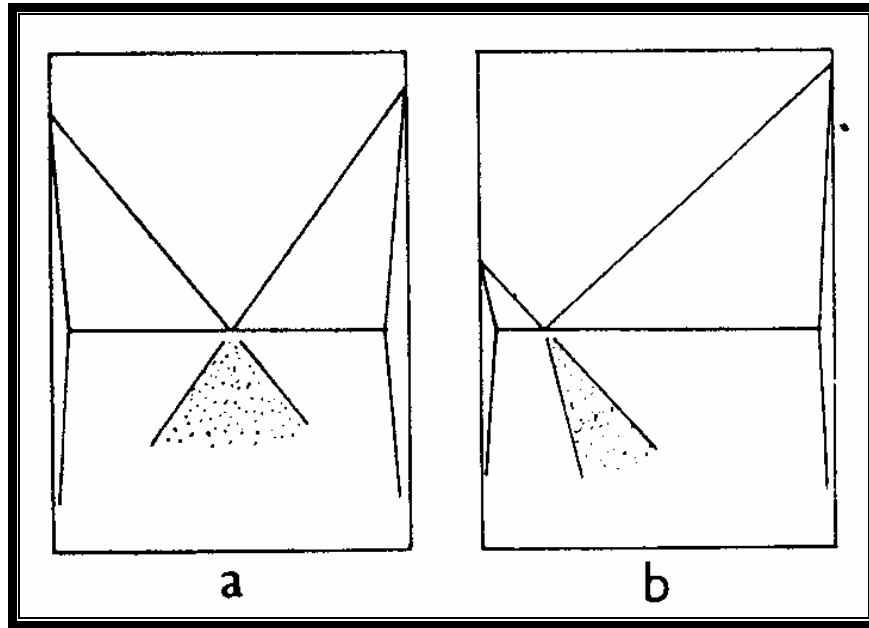


Figure (3.3)
Coupled zone in (a) symmetrical and (b) asymmetrical Phase diagrams [40].

Depression of the eutectic temperature with increased cooling rate may be explained on the basis of the coupled region effect. Coupled regions represent fields within the phase diagram where the two phases of the eutectic are organized in the solid in such a way as to allow diffusion in the liquid to occur effectively at a duplex solid/liquid front. Regions of coupled growth are shown schematically in figure (3.3) for both a symmetric and an asymmetric hypothetical phase diagram. In Al-Si system, silicon is a non-metal, which has directed covalent bonding. Hence silicon phase tends to grow anisotropically to give faceted crystals. Silicon phase needs more under-cooling for its growth than the isotropic aluminum phase. Thus the coupled region in such a system is asymmetric. Apart from cooling rate, addition of some chemical elements like sodium or strontium in minute quantities resulted in shifting the

eutectic point to the right as well as depressing the eutectic temperature [40].

3.3 The Thermal Parameters

In this section, discuss the effect of thermal parameters on solidification of aluminum-silicon alloys. During the solidification of metals, the melt conditions determine the morphology of the solidifying phase. Melt conditions include both thermal conditions and chemical conditions. Thermal conditions during solidification consist of three parameters: cooling rate, thermal gradient ($\hat{G}$) and interface velocity (R). Cooling rate is the rate at which heat is extracted from the melt. Higher cooling rate is known to yield finer structures. The cooling rate is inversely related to the secondary dendrite arm spacing. Thermal gradient ($\hat{G}$) is the change of temperature with distance. Thermal gradient of liquid ahead of the solid/liquid interface determines the constitutional under-cooling of the liquid. Constitutional under-cooling is known to result in cellular and dendritic morphology. Interface velocity (R) is the rate at which the solid/liquid interface moves. High interface velocity implies lesser time for equilibrium growth to take place. Thus, microstructures obtained at higher interface velocities have finer structure and sometimes metastable structures. Cooling rate is the product of thermal gradient and interface velocity. Comprehensive study of the different microstructures possible in a system is done by studying the system at various values of temperature gradient and interface velocity[40].

The summary of tensile and compressive properties of directionally solidified Al-Si eutectic alloy given in table (3.1). Show that the yield and tensile strength increase with increasing growth velocity[24].

Table (3.1)
Tensile and compressive properties of directionally solidified Al-Si eutectic alloy[24].

Structure	Growth velocity $\mu\text{m s}^{-1}$	<u>Tensile properties</u>			<u>Compressive properties</u>		
		0.2% proof stress Nmm^{-2}	UTS Nmm^{-2}	Elongation %	0.2% proof stress Nmm^{-2}	UTS Nmm^{-2}	Elongation %
[100]Angular	1.5	57.8	109	6.8	330	400	0.6
Flake	45	53.8	142	8.5	92.6	—	—
Flake -fiber	450	60.6	155	12.5	—	—	—
Flake -fiber	1300	63.6	157	8.8	104.2	—	—
Chill cast		101.5	220	3.8	150		

CHAPTER FOUR
EXPERIMENTAL PROCEDURE &
COMPUTER MODELING

4.1 Introduction

In this chapter, a set of experiments, conducted to further our understanding of the evolution of aluminum-silicon eutectic will be discussed. Various parameters used in the experiments as well as the modeling along with the materials used to conduct the experiments. It is followed with a step by step description of the procedures used.

A set of experimental approaches were simultaneously undertaken to study the evolution and a unidirectional solidification of the eutectic microstructure. This phase will be very important in the reinforcement process of the matrix which will be very important in the reinforcement process of the Al matrix as an in-situ composite material.

A multi-pronged approach was necessary because of the number of issues that needs to be resolved in order to arrive at a comprehensive understanding of this complex phenomenon. The following is the list of the experiments conducted in this study:-

1. Modeling process using a finite element method by an ANSYS-code (version - 5.4) including a full scale modeling of an unidirectional solidification set up in order to determine an accurate estimation of the temperature distribution with the time under various conditions of thermal insulations of the used molding.
2. Nucleate and growing up of the eutectic phase by melting and solidification the molten alloy in unidirectional manner by using

the solidification unit that designed and produced for this purpose.

The first set of experiments has been done with a reconsidering of the following:-

1. Molten alloy temperature.
2. Pouring temperature.
3. Application of various types of insulation materials to the mold of solidification unit. Then continuous cold water flow through the lower part of the solidification unit, from a suitable reservoir.

The choices of such parameters are adopted according to the results of computer modeling as it is remembered before. The temperature distribution and the heat sink that clearly obvious in the results of modeling part, helping to specify the above parameters.

Eventually, microstructure observations in step by step which give a clear picture on how to control and augmenting the nucleation and growth of the eutectic phase under different solidification conditions.

4.2 Materials Used

(Al-12%Si) alloy was used in the form of ingots. The average chemical composition of this alloy is given in table (4.1) as shown below. The chemical composition analyses i.e. x-ray fluorescence analysis were performed in the Ministry of Scientific and technology /office of water treatment by using the equipment(X – MET 3000 TX, horizon 600 series, model 2004). All the material used ingots were received from the Iraqi local markets.

Table (4.1)

Average chemical composition analysis of the Al-Si alloy in this work.

Element	Si	Fe	Cu	Mn	Ni	Al
wt%	11.9665	0.5532	0.0752	0.0721	0.0101	Bal.

4.3 Procedure

4.3.1 Alloy Preparation for Melting:-

Al-Si alloy ingot was received in (40 x 40 x 150 mm). The alloy small blocks were then ground by using a silicon carbide paper and cleaned in an ethanol to remove any surface impurities. The alloy blocks are now melted by using a graphite crucible with a volume of 1000 gm capacity) by the using of an electric resistance furnace number 2 type (SOLA BASIC 51222), (see figure (4.4)).

4.3.2 Thermal Analysis:-

An approximately 250 grams of the alloy was taken, heated by using an electric resistance furnace number 2 and heated to 750°C. The sample was held at 750°C until the furnace and the melt were in equilibrium. The sample was then cooled slowly beside the furnace on an open door. The temperature was measured by an Infrared thermocouple type (AR 8725S) by subject its light in the center of crucible.

Data of a thermocouple was recorded until the alloy completely solidified then recorded the solidification temperature of alloy.

4.3.3 Experimental Apparatus:-

A schematic and photographic of the apparatus are shown in figures (4.1) and (4.3). Two types of electric resistance furnace have been used to conduct the melting and heating practices (see figure (4.4)). The following is

a list of the apparatus that used in the melting and sampling processes:-

1. Unidirectional solidification unit that including a carbon steel mold with dimensions as shown in figure (4.1).
2. Cold water tank, the flow was done by gravity. The function of the cold water is to work as a heat sink by increasing the heat transfer and dissipation at the bottom side of the mold. The temperature of the cold water was kept at (5°C).
3. Thermocouple (Model TE9-RB10) has been used to monitoring the drop in the molten material temperature. The thermocouple was inserted between the mould and the insulation materials.
4. Mold was made from low carbon steel with the dimensions shown in figure (4.1).

The insulation materials generally defined as a material that retarding of heat energy, the function of such materials are:-

1. Conserve energy by reducing heat loss or gain.
2. Facilitate the temperature control of process.
3. Prevent vapor flow and water condensation on cold surfaces.

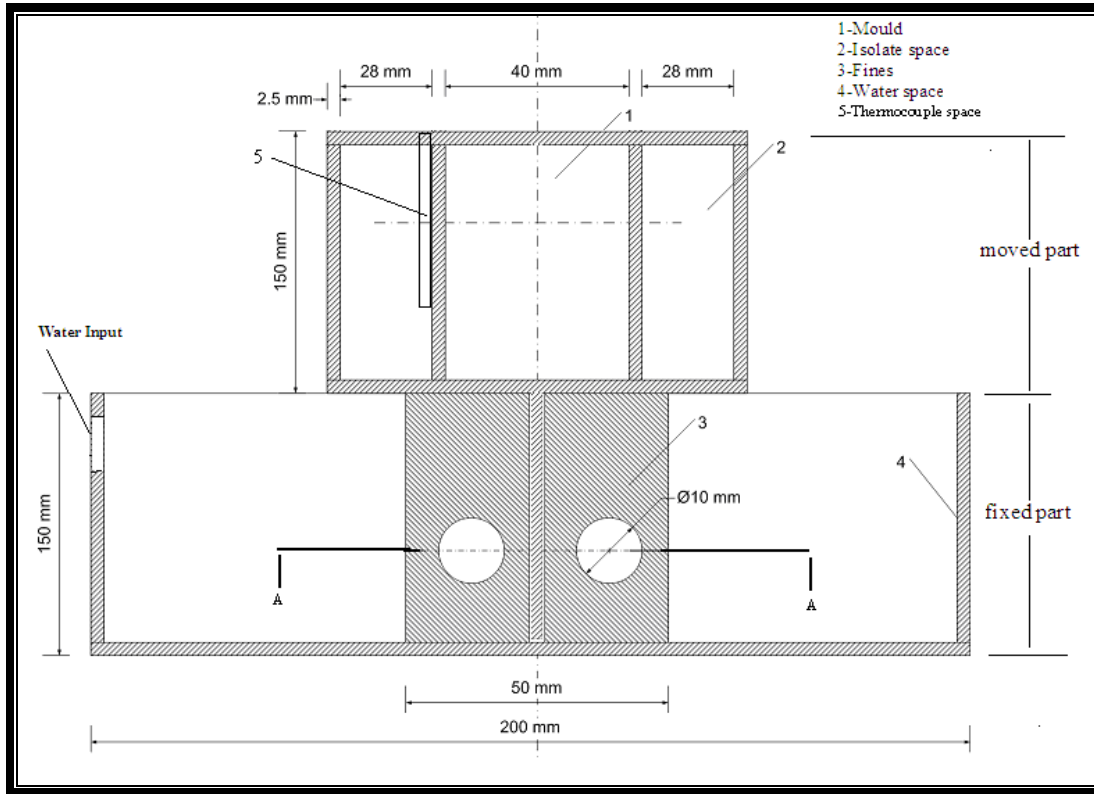


Figure (4.1)
A schematic diagram of the unidirectional solidification unit.

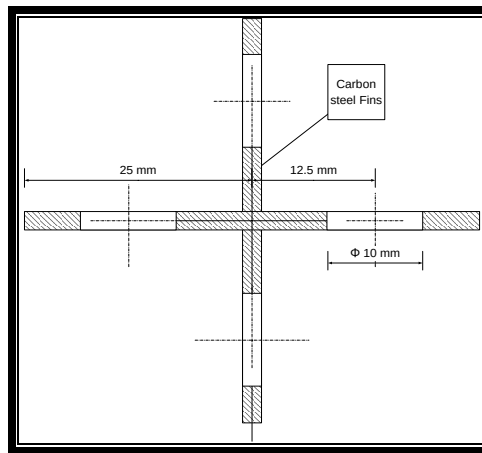


Figure (4.2)
A schematic diagram of the section A-A in the unidirectional solidification unit as labeled above.

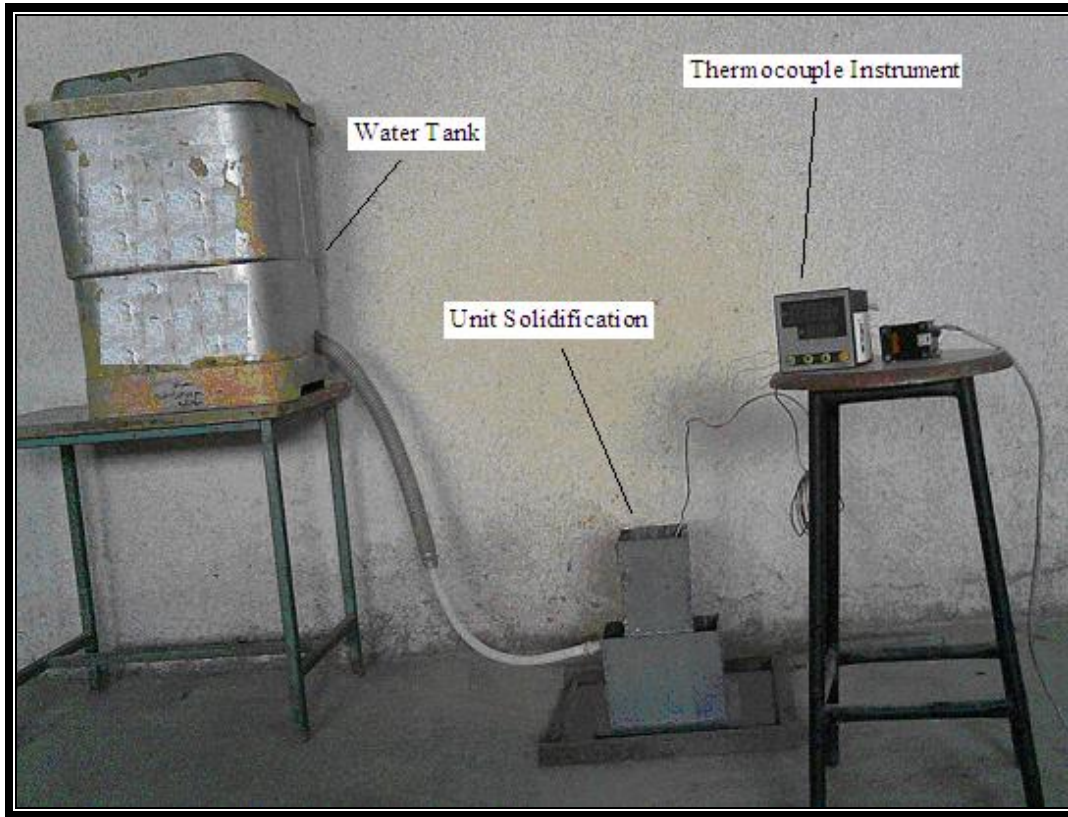


Figure (4.3)

A photographic picture shows the apparatus that used in the solidification practices.

Two types of insulation material have been used in this work as following:-

1. Fibrous insulation (glass wool) which is composed of small diameter fibers that finely divide the air space. The application of the glass wool insulator in this work has been done manually and the fibers material is pressed with the help of tool to ensure a best insulation properties.
2. Sand, it is a granular material which is composed mainly from silica with a particle size ($\approx 0.3\text{mm}$).

Thermal conductivities of the insulation materials above are mentioned in table (4.2) in order to facilitate the process of understanding and developing the experimental and the modeling part of work. These materials having low thermal conductivity in comparison with the other materials (see reference [42]). This property defined as the amount of heat flux that would pass through a certain material (i.e. insulation) depending on the temperature gradient over that material [42].

Thermal conductivity plays an important role in many heat and mass transport. Phenomena as it are a function of parental number [42] it is denoted by (K).commonly used unit is (W.m/m². °C).

Table (4.2)
Thermal conductivities of insulation materials[42].

Type of insulation material	Thermal conductivity (K)W.m/ m ² . °C
Sand	0.33
Glass wool	0.038

4.4 Melting and Sampling Procedure

Prior to the experiments, a small blocks were cut from the ingots of Al-Si alloy. These blocks were freshly surface ground by the using of 180 and 400 grit silicon carbide papers and then cleaned by using the solution of ethyl alcohol for five minutes and then removed out of alcohol only before the experiment. The following is the list of the procedure steps that adopted for the producing of samples in different conditions of solidification:-

1. The specimens were heated at the rate of approximately 5°C/min till

- the eutectic alloy melted by using a graphite crucible and an electric resistance furnace number 2 that used in the thermal analysis (see 4.3.2).
2. Temperature was monitored with an external thermocouple that equipped with the furnace. The temperature was raised till 700°C.
 3. Three runs were performed representing the three conditions of solidification as follows:-
 - a. Without any insulated mold and no water flow (i.e. free mold insulation).
 - b. With a sand insulation and cold water flow through the unit.
 - c. With a glass wool insulation and cold water flow through the unit.
 4. The moving part of the uni-directional solidification unit is now ready for heating in the second electric resistance furnace type (RECTRADEUAR) that prepared for this purpose (number 1, see figure(4.4)) . The moving part of the solidification unit must be heated to the same molten metal temperature (i.e. 700°C). An elapsed time must be left now to get a homogenization heating of the moving part of solidification unit.
 5. Care must be taken to ensure that, the metal does not overheat. The recommended pouring temperature for alloy under investigation is usually $(700 \pm 10^{\circ}\text{C})$. Note that, the upper part of solidification unit are now ready (i.e. preheated to 700 °C) and out of heating furnace at the right place on the lower part of solidification unit. The measurements of temperature was done by using the thermocouple attached to the mold (see 4.3.3).
 6. The cold water tank valve is now in on- condition and the flow are

now stable with a reasonable flow rate,(ice cubes were added to set the water temperature at 5 °C).

7. Continuous monitoring of the temperature by the data of thermocouple.
8. Using various insulation materials:-
 - a. Sand insulation mold.
 - b. Glass wool insulation mold.



Figure (4.4)
Equipment of electric furnaces.
1. (REC TRADEUAR) type.
2. (SOLA BASIC 51222) type.

4.5 Productions of Samples Ingots

Several sets of ingot samples are now produced according to the steps that proceeded in (section (4.4)), with a high attention during each step of melting and molding practices. These precautions are very important to ensure the uni-directional solidification of the eutectic phase in all samples as the work has aimed.

The following table (4.3) shows, the general plane of ingot samples numbering and the condition that adopted in this work:-

Table (4.3)
General plane of ingot samples production.

Set of sample no.	Solidification condition	
	Mold insulation type	Cold water flow
1	Free	Without
2	Sand	With
3	Glass wool	With

In order to check the uni-directional solidification of ingot samples, sectioning of samples must be done in a direction parallel to the direction of heat sink (i.e. into the bottom direction).

4.6 Modeling Process

4.6.1 Introduction

A numerical modeling of unidirectional solidification (temperature distribution) of (Al-Si) system has been performed in this work. This analysis was implemented by the using of ANSYS-code (version - 5.4). It is based on the finite element method (FEM), and following is the steps of this process:

4.6.2 Model Constitute

FEM model was built in order to simulate the temperature distribution of (Al-Si) eutectic system with varying insulation materials, several assumptions are assumed to conduct the numerical analysis for this process. These assumptions:

1. Two dimensions model was built, to facilitate the problem modeling.
2. Taking the temperature distribution after 3min from pouring alloy (Al-12%Si)
3. Free convection on outer sides, are assumed homogeneously.
4. Just one side (i.e. bottom) is without insulation (i.e. the side were cold by water).
5. Initial condition of melting alloy (Al-Si) is at 700 ° C.
6. Transit solidification was proposed for this case of solidification.
7. One type of element is used to mesh an alloy to be solidified and the insulation materials.
8. Neglected the phase change and assumed only one phase (liquid) and neglect solidified alloy.
9. Neglected heat convection by fins and neglect the speed of any fluid (air, water).

4.6.3 Geometry of Sub. Model

The model was built according to dimensions that adopted in the experimental work that represent the solidification unit (mould and insulation materials). The model geometry of this system is shown in figure (4.5).

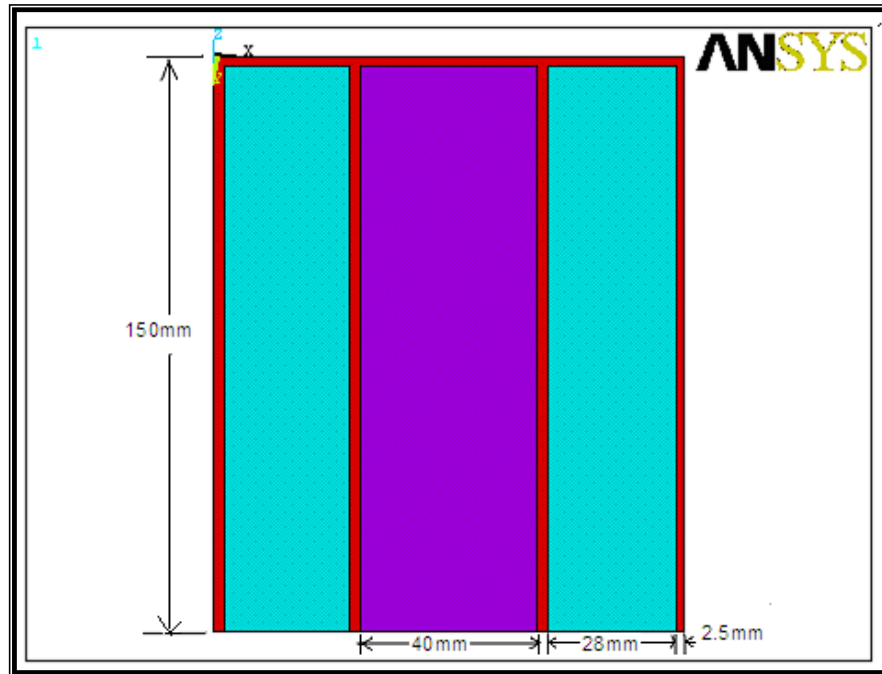


Figure (4.5)
Geometry of sub model adopted for numerical analysis.

4.6.4 Finite Element Model

The geometry of model is meshed now to study the temperature distribution after 3min from pouring alloy. Mash sizes are determined including the scanning for all portion of ingot and mould. Element plane 77 is used to model the ((Al-Si) alloy and insulation of mould) .Finite element model and mesh size are shown in figure (4.6).

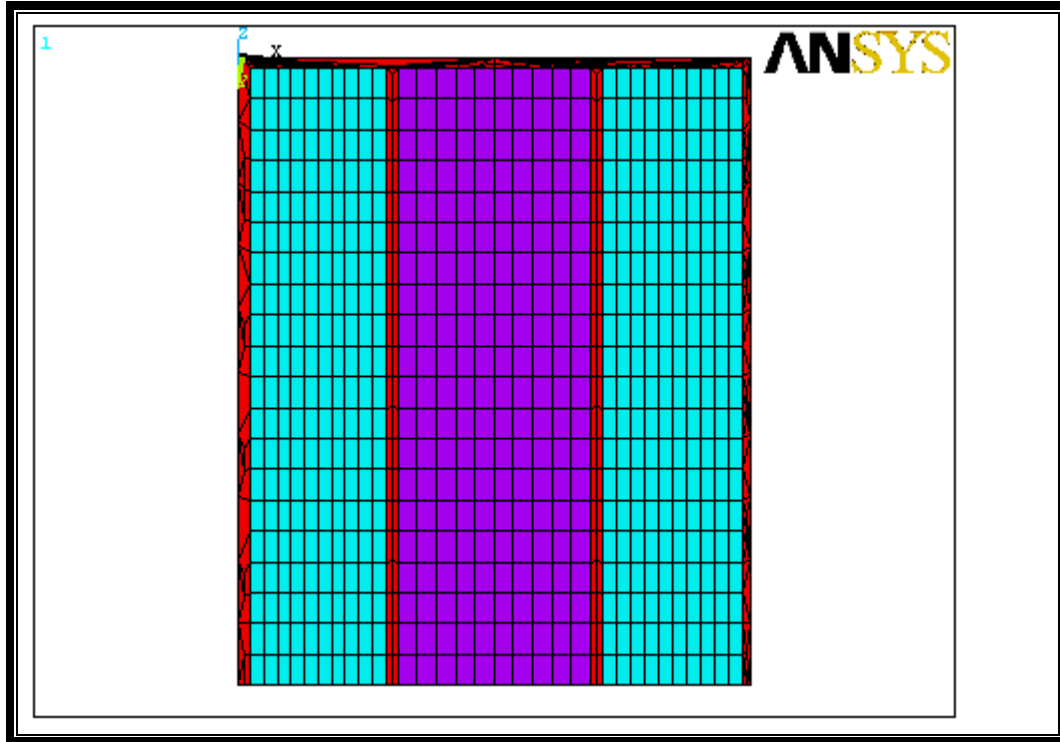


Figure (4.6)
Finite element model assumptions.

4.6.5 Mathematical Formulation

FEM of casting process is based on the classification of heat transfer flow in two dimensions. The conditions of heat transfer during this solidification process of casting alloy are included the following:-

1. Heat conduction within the Al-Si alloy.
2. Heat conduction from ingot (Al-Si) system to the insulation material and mold surfaces.
3. Heat convection (free convection) to the outer surfaces of mold and fluid .

When a temperature gradient exists in a body, we say that the energy is transferred by conduction and that the heat-transfer rate per unit area is proportional to the normal temperature gradient:

$$q/\hat{A} \sim \partial T/\partial x \quad (4.1)$$

When the proportionality constant is inserted,

$$q = -K \hat{A} \partial T/\partial x \quad (4.2)$$

where q is the heat-transfer rate and $\partial T/\partial x$ is the temperature gradient in the direction of the heat flow. The positive constant K is called the thermal conductivity of the material[43].

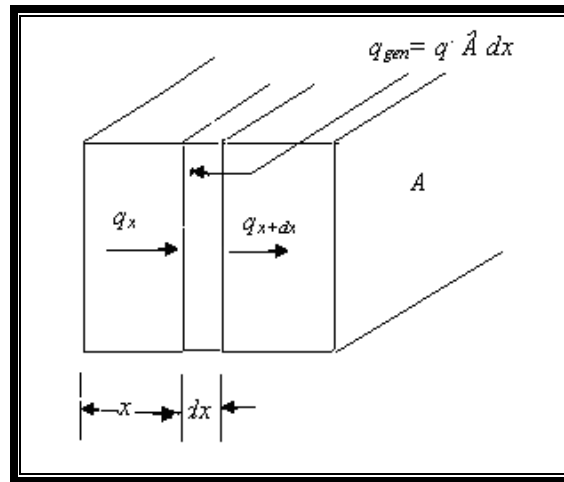


Figure (4.7)

Elemental volume for one-dimensional heat-conduction analysis [43].

Consider the one-dimensional system shown in figure (4.7). If the system is in a steady state, i.e., if the temperature does not change with time, then the problem is a simple one, and we need only integrate equation (4.1) and substitute the appropriate values to solve for the desired quantity. However, if the temperature of the solid is changing with time, or if there are heat sources or sinks within the solid, the situation is more complex. We

consider the general case where the temperature may be changing with time and heat sources may be present within the body. For the element of thickness dx the following energy balance may be made:

Energy conducted in left face + heat generated within element
 = change in internal energy + energy conducted out right face

These energy quantities are given as follows:

$$\text{Energy in left face} = q_x = -K \hat{A} \partial T / \partial x$$

$$\text{Energy generated within element} = \dot{q} \hat{A} dx$$

$$\text{Change in internal energy} = \rho c \hat{A} (\partial T / \partial t) dx$$

$$\text{Energy out right face} = q_{x+dx} = -K \hat{A} \partial T / \partial x \big|_{x+dx}$$

Where $\dot{q}$ = energy generated per unit volume, W/m³.

c = specific heat of material, J/kg. °C.

ρ = density, kg/ m³.

Combining the relations above gives:

$$\partial / \partial x (K (\partial T / \partial x)) + \dot{q} = \rho c (\partial T / \partial t) \quad (4.3)$$

This is the one-dimensional heat-conduction equation[43].

To express the overall effect of convection between:

1. The outer wall of mold and air (in case of free mold insulation conditions).
2. The outer wall of the solidification unit and air (in cases of sand and glass wool mold insulation conditions).
3. The outer wall of the solidification unit and water (in cases of sand and glass wool mold insulation conditions).

used Newton's law of cooling:

$$q = h \hat{A} (T_w - T_\infty) \quad (4.4)$$

Here the heat- transfer rate is related to the overall temperature difference between the wall (T_w) and fluid (T_∞) and the surface area ($\hat{A}$). the quantity h is called the convection heat- transfer coefficient[43].

4.6.6 Material Used in Model

The material behavior is modeled in the simulation process by the using of isotropic thermal transfer in different type of insulation materials and (Al-Si) alloy. This behavior is described by assuming the initial properties of (thermal conducting, specific heat and enthalpy) for each material(Al-Si eutectic alloy, Steel, Sand, Glass wool, air, water) .

4.6.7 Boundary Conditions

The bounding conditions are applied on system are as follows:-

1. Initial temperature (700 ° C) for (Al-Si) alloy.
2. Taking the result after 3 min of pouring of alloy .
3. Film coefficient is (0.014) for free convection.

4.6.8 Paramedic Study

The most paramedics studied in the numerical analysis are the distribution of temperature with varying of insulation materials.

4.6.9 Results Output

Results are recorded as a contour result and query point through any portion of casting system (ingot and mold). These results are followed with time step. The temperature distribution recorded with type of insulation material.

4.7 Sample Preparation for Microscopic Analysis

The samples were prepared in consistent with the standard metallographic techniques. The ultimate objective of such a process was to obtain a flat scratch free, mirror like surface.

From a viewpoint of an ideal sample ready for microstructure examination it must satisfy the following measures [44]:

1. Be representative sample.
2. Have minimum deformation after sectioning, grinding and polishing.
3. Free from grinding and polishing scratches, pits and staining from the etch or subsequent corrosion.
4. A sample polished so that inclusions are presented intact.
5. Enough flatness to allow high magnification.

Such measures are satisfied through a series of subsequent processes as ordered below:

4.7.1 Sectioning

Each sample was cut to a convenient length parallel to the y-axis (i.e. the solidification direction) enables handling during subsequent grinding and polishing. Water was used as a coolant to avoid overheating that may be lead to any phase transformations.

4.7.2 Grinding

This is the process of abrading the sectioned specimen in a sequence of steps using progressively finer abrasive papers (180, 400, 600, 800, 1000, 1200, 2000 grit size).

A series of parallel scratches were introduced and successively removed and replaced by finer scratches. Only light pressure was applied in order to

maintain the specimen flat and eliminate all scratches introduced by the previous paper. Water was used as a coolant and lubricant to facilitate hand grinding.

The specimen had been rinsed between papers to avoid transferring abrasives. The grinding was done on a rotary grinding wheel.

Grinding revealed a flat surface, free of nicks, burrs and all scratches introduced were made invisible. Grinding has done with using of grinding machine type (MP200V).

4.7.3 Polishing

Polishing stage is highly required to ultimately produce a scratch-free, highly polishing and flat surface ready for subsequent etching and microscopy, by using cloth polishing and Alumina liquid.

4.7.4 Etching

This was the last step before visual inspection. It involved a short treatment for 15 sec in an etchant solution prepared as:

0.5%HF+99.5%H₂O (distilled) [44, 45]

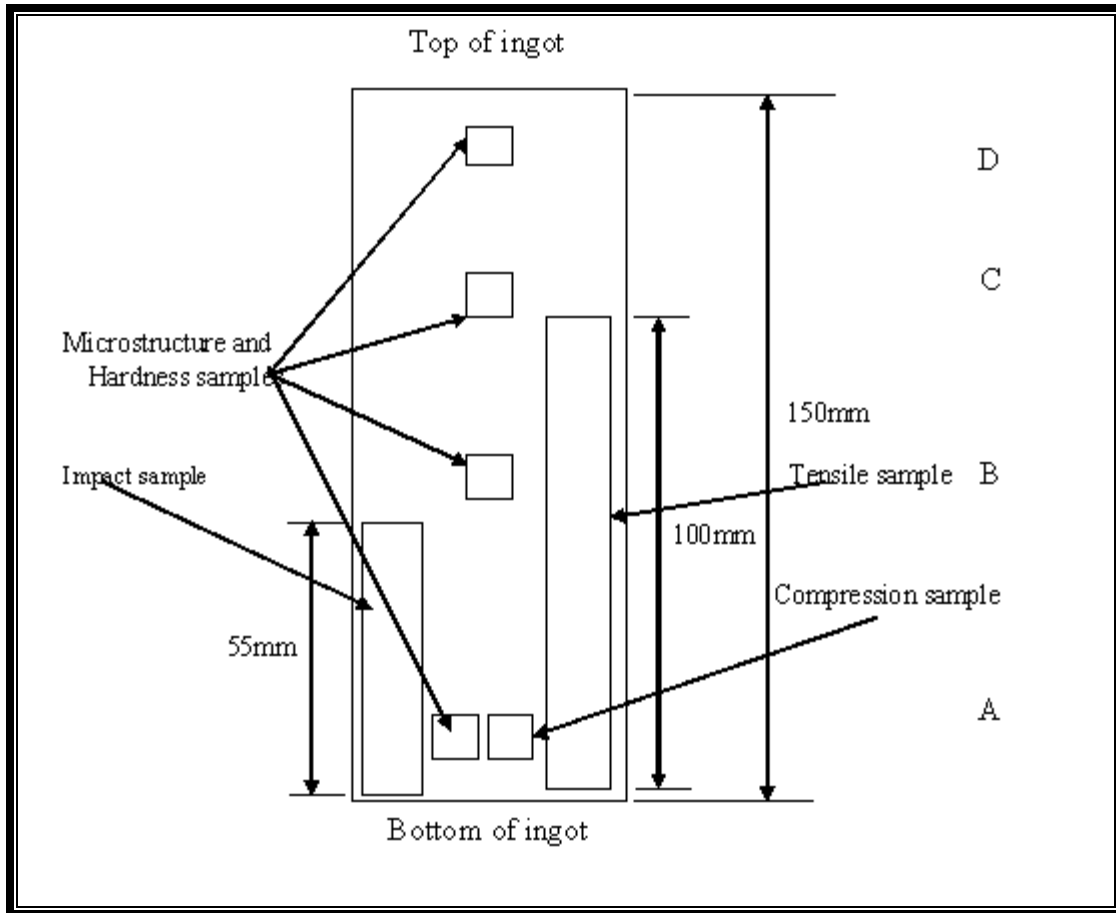
It revealed various structural characteristics of the samples by the preferential attack of the constituents and grain boundaries.

Etching was performed by repeated dipping of the sample in the reagent. It would be stopped by immediate washing with distilled water, rinsed with ethylalcohol and dried by air.

Standard metallographic examinations using optical microscopy (Union / ME-3154) type was used to reveal the samples structures.

4.8 Mechanical Testing

Many mechanical testing have been done . The samples of testing were cutting from bottom part of ingot in the direction of heat sink, see figure (4.8).



Figure(4.8)
The places that have been cutting from it the samples.

4.8.1 Hardness Test

Hardness is a measure of a materials' resistance to localized plastic deformation (e.g., a small dent or a scratch).Early hardness tests were based on natural minerals with a scale constructed solely on the ability of one material to scratch another that was softer [46].

Appropriate grinding and polishing was done before subject specimens to hardness tests[44].

In Brinell tests, a hard, spherical indenter is forced into the surface of the metal to be tested [34]. A Brinell hardness testing machine was used to conduct the test with a load of 500 Kg for 30 sec. using a steel ball with a 10 mm diameter [44, 46].

This is expressed by the formula

$$\text{BHN} = P / ((\pi D/2) (D - \sqrt{D^2 - d^2})) \quad (4.5)$$

Where P = applied load, kg

D = diameter of ball, mm

d = diameter of indentation, mm

It will be noticed that the units of the BHN are kilograms per square millimeter [9]. In this test used the "Material Testing Unit" that shown in figure (4.10).

4.8.2 Tensile Test

The engineering tension test is widely used to provide basic design information on the strength of materials and as acceptance test for the specification of materials. In the tension test, a specimen is to a continually increasing uniaxial tensile force while simultaneous observations are made of the elongation of the specimen. An engineering stress-strain curve is constructed from the load-elongation measurements [9].

The sample dimensions that used was (Lt=100, Lc=30, Lo=14, b=6, r=12) as shown in figure (4.9) [47].

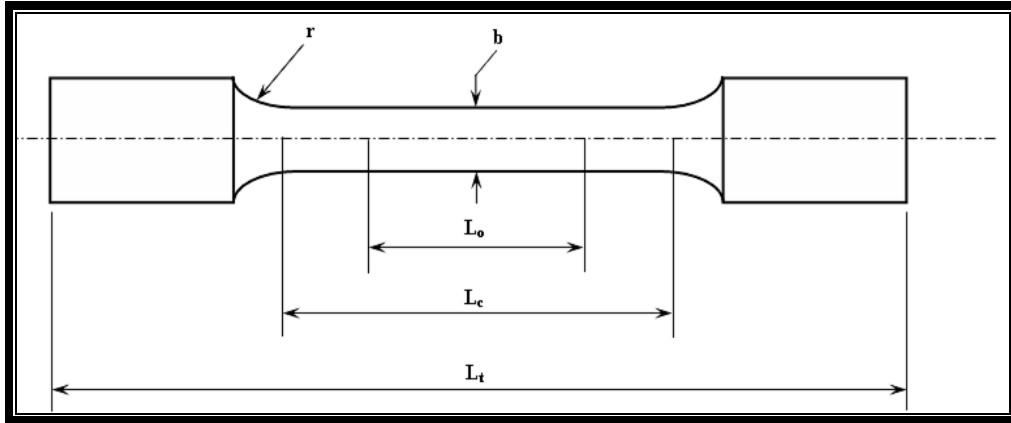


Figure (4.9)
Tensile test specimen [47].

Since both the stress and the strain are obtained by dividing the load and elongation by constant factors, the load-elongation curve will have the same shape as the engineering stress-strain curve. The two curves are frequently used interchangeably[9].

At low speed and room temperature were measured tensile properties. Used the (Material Testing Unit), see figure (4.10).



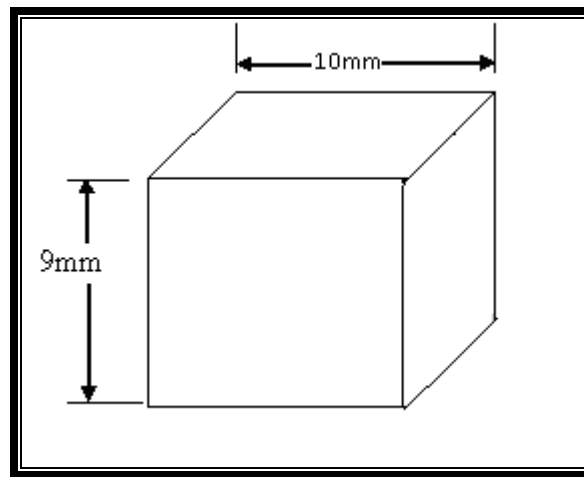
Figure (4.10)
Equipment of Material Testing Unit.

4.8.3 Compression Test

It consists of compressing a sample between parallel platens; the height / diameter ratio has to be lower than a critical value in order to eliminate the possibility of instability (buckling).

In compression testing, a cylinder or a parallelepiped cube (with one side- the parallel to the loading direction-longer than the other two) is subjected to compression between two parallel plates. The plates should have a self-alignment system. And they often ride on one or two hemispherical caps.

The specimen that used in this test was the cube short sample ($d^* \cdot 0.9 = h$), where ' d^* ' the length of top section = 10mm, ' h ' the height of sample, [47], as shown in figure (4.11).



Figure(4.11)
Comparison test specimen.

In this test, the samples subject to the same magnitude of the load to study the behavior of them through compression load.

4.8.4 Impact Test

Various types of impact tests are used to determine the tendency of a material to behave in a brittle manner. This type of test will detect differences between materials which are not observable in a tension test. The results obtained from impact tests are not readily expressed in terms of design requirements, since it is not possible to measure the components of the triaxial stress condition at the notch.

The notch is located in the center of the test specimen, which is supported horizontally at two points. The specimen receives an impact from a pendulum of a specific weight on the side opposite to that of the notch. The specimen fails in flexure under impact [48].

1Degree=2Joule

Impact testing was performed on Charpy testing machine using 55mm length with 45° V notch, 2mm deep with 0.25 mm root radius as Shown in figure (4.12).

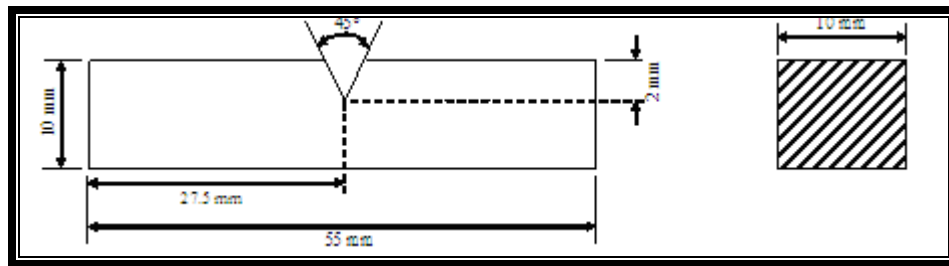


Figure (4.12)
Impact test specimen.

The equipment that used in this test was (FIT-300(N)) type, shown in figure (4.13).



Figure(3.13)
Equipment of Impact.

4.9 X-Ray Diffraction Analysis

The X-ray diffraction analysis is a vital tool in which the constituent phases can be monitored. This analysis covered a selected sample from the three conditions of solidifications. The analysis has been done for all selected samples in the Ministry of Sciences and technology /office of materials sciences by using Equipment (Lab XRD-6000 Shim ADZU x-Ray Diffract meter). The measure conditions are (Target: Cu, length wave: $1.54060 \text{ \AA}$).

From "Bragg law", " d_{hkl} " the radius of the sphere can be calculated describing the locus of the reciprocal lattice point (hkl), as shown:

$$(2/\lambda') \sin\Theta = 1/d_{hkl} \quad (4.6)$$

Where λ' is the length wave.

Θ is the angle of deviation of the diffracted beam [14].

CHAPTER FIVE

RESULTS & DISCUSSION

5.1 Introduction

In this chapter, the results obtained in each parts of work that including the computer model of temperature distribution and experimental will be presented and followed by the discussion of results. Since the results of the computer modeling are interrelated with the experiments, the discussion will be combined i.e. for modeling and experiments.

The results are presented and discussed under various aspects such as thermal analysis, effect of insulation material on the nucleation, growth of eutectic system and mechanical properties such as (impact, tensile, compression and hardness properties) and also the microstructure evolution of eutectic system.

First, can see the microstructure of alloy before any processes of pouring, see figure(5.1).

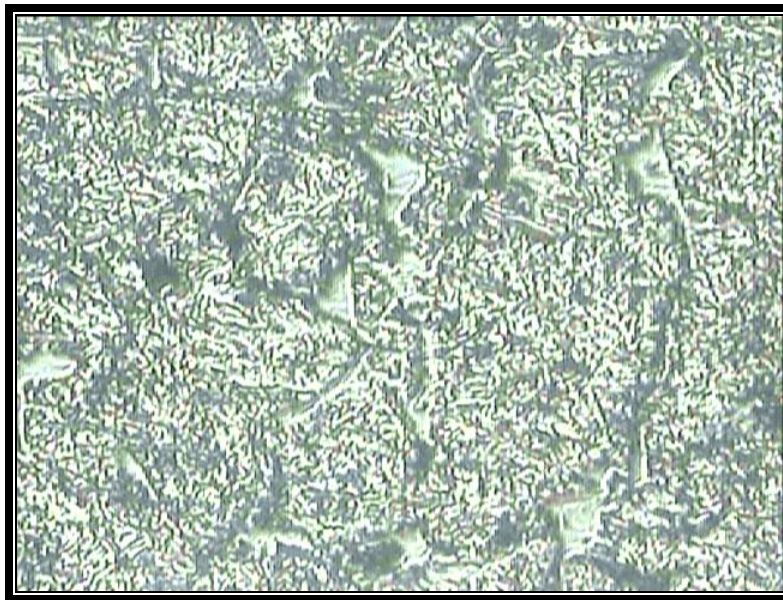


Figure (5.1)
Microstructure of alloy before any process of pouring 200X.

The thermal analysis of the alloy under investigation was performed at section (4.3.2). The solidification temperature was 550 °C. The eutectic temperature in this work supposes to still constant (the values are identical to some extent with the standards) since there is no additions of modifiers like Sr or Na but the other elements also effect on the solidification temperature and other properties.

The technique that used during the production and improvement of the grown eutectic system during the solidification process has been proposed, designed and manufactured according to many assumptions that adopted in this work such as:-

1. The molten alloy should be kept in its pouring temperature as much as possible at the mold.
2. Preventing any heat dissipations through the walls and keeping only one direction as a heat sink.
3. The heat sink direction promoted the direction and growing the β -phase.

The examinations of the produced in-situ composite materials at different conditions are discussed in details. These discussions are parallel for each type of results which are computer modeling and experimental.

5.2 Discussion of Modeling & Experimental Results

5.2.1 Discussion of Microstructure Evolution and Mechanical Properties in Free Mold Insulation Conditions :-

Figure (5.2) shows the temperature gradient distribution contour across the solidification system in the case of mold free of insulation (i.e. free solidification) after 3 min. of pouring.

The numerical model shows a logical distribution of temperature across the system (alloy, steel, air) and the difference of temperature between the alloy and outer surface of wall shows the no high (626-595)°C because escape the heat in the direction of sides. The predicted and measured temperature monitoring is in good agreement. Taking into consideration that the thermocouple (was put at the side of mold) reading in every 30 seconds until the solidification is completed. The decrease in the temperature with the time is clear in the figure (5.3) that recorded from the thermocouple that put beside the outer surface of the mould.

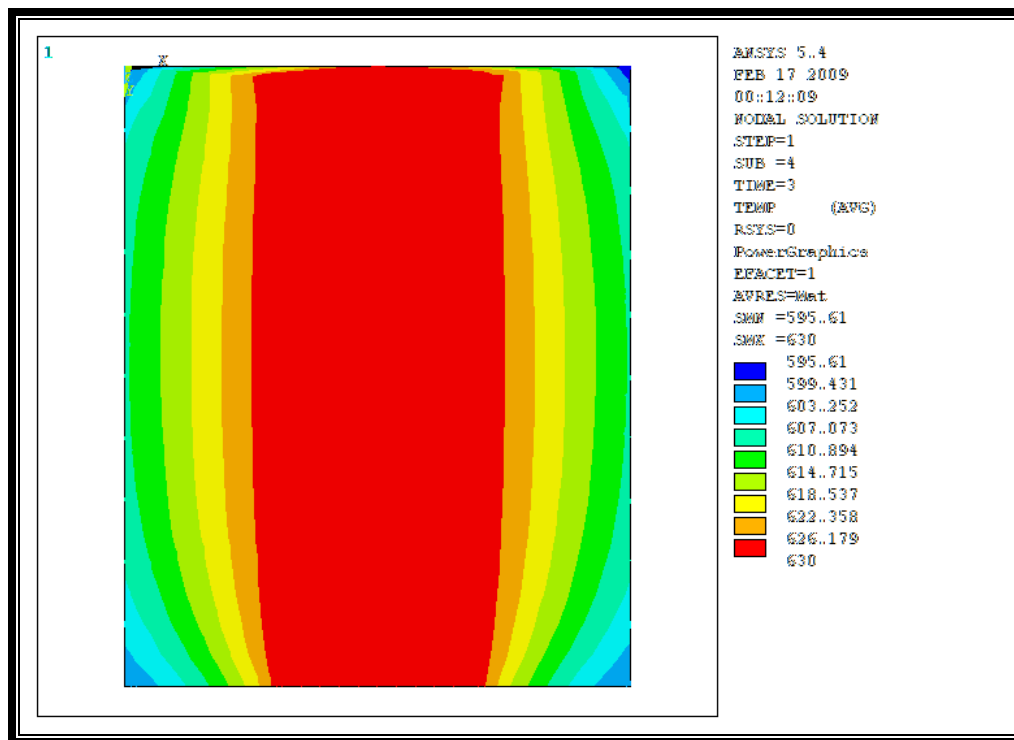


Figure (5.2)
 Temperature distribution gradient across the solidification system at the free mold insulation conditions after 3 min. of pouring (results in °C).

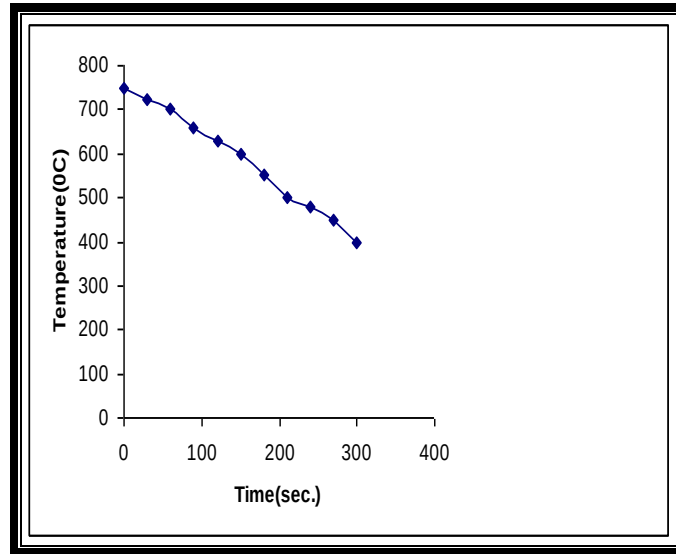


Figure (5.3)

The relation between the temperature and the time in case of free mold insulation condition that recorded from the thermocouple that used in experimental procedure.

These temperature distributions are reflected directly on the experimental part of work (i.e. during the experiments of samples production by using the unidirectional solidification unit without any insulation material and also no cold water flow through the unit. The molten metal (i.e. Al –Si alloy) is in thermodynamic instability during solidification;[22] the β - phase nuclei can nucleate and grow due to the crystallization driving force, the solidified interface between the growing β -phase and the solidified matrix would become unstable under the following conditions:-

1. solute fluctuations.
2. heat disturbances.

The solute fluctuations are no longer working especially at the progress of solidification (i.e. %Si constant), while the heat disturbances still the main parameter that affecting the process of second phase (i.e. β -

phase) nucleation and growth. The microstructure observations as shown in figure (5.4) in the case (free mold of insulation conditions).

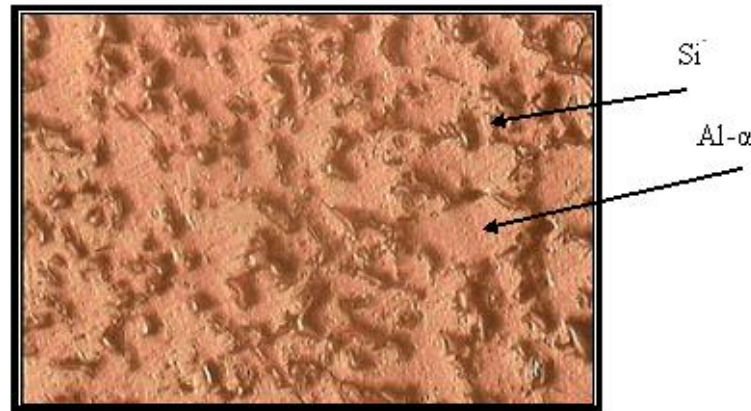


Figure (5.4)
Optical microscopy of alloy at (free mold of insulation) conditions(200X).

The irregular orientation and distribution of eutectic phase in figure above are coming as a result of irregular little growth of individual phase (i.e. the β -phase). The β -phase appears in the microstructure above could be seen in most commercial Al-Si eutectic alloy casting that solidified in this regime (i.e. free mold insulation condition) or free solidification with no modifiers addition to the molten material such as sodium or strontium.

5.2.1.1 Discussion of Mechanical Properties of Produced Alloy at Free Mold Insulation Conditions

According to the experimented procedure adopted to produce the samples in this case (i.e. free mold insulation condition). The mechanical properties evaluation includes:-

1. Hardness Results Discussion:-

Brinell hardness testing survey on all the outside area of solidified Al-Si eutectic alloy supporting the results that obtained from the

microstructure observations above. The hardness results are almost equal or homogeneous at all the outside area of material under investigation as can be seen in figure (5.5).

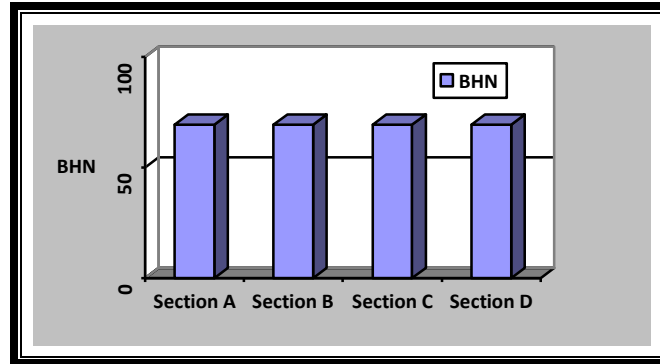


Figure (5.5)

Brinell harness survey at the four specified sections of the alloy under free mold insulation conditions.

As it was stated above, the reason behind such equal or homogeneous results of hardness is the homogeneous grain size distribution along the material under these conditions of solidification. The little grown β -phase and its heterogeneous orientation did not improve the hardness results. That will give an idea about the effect of β -phase orientation and its growth on the subsequent conditions of solidification.

2. Tensile & Compression Strength Properties:-

Figure (5.6) shows the stress- strain curve of the samples produced at (free mold insulation condition). These tests coming to evaluate the effect and the role of the β -phase in the reinforcement process of the Al- matrix and also to see the effect of cooling rate on the grain size of the matrix and its role in the direction of second phase. The behavior seems to be very close to the brittle material in behavior each type of loading (i.e. tension and compression).

The reasons behind such behavior are the effect of the following:-

1. Much micro-segregation in solid solution state.
2. Irregular distribution of primary Silicon due to the escape the heat from the material by air during the solidification process.
3. At, this conditions of solidification, where the cooling rate is low, the gas porosity nucleates and grows as expected (i.e. no degasser added).
Taking into consideration that the material is not homogenized or heat treated (i.e. as cast condition).

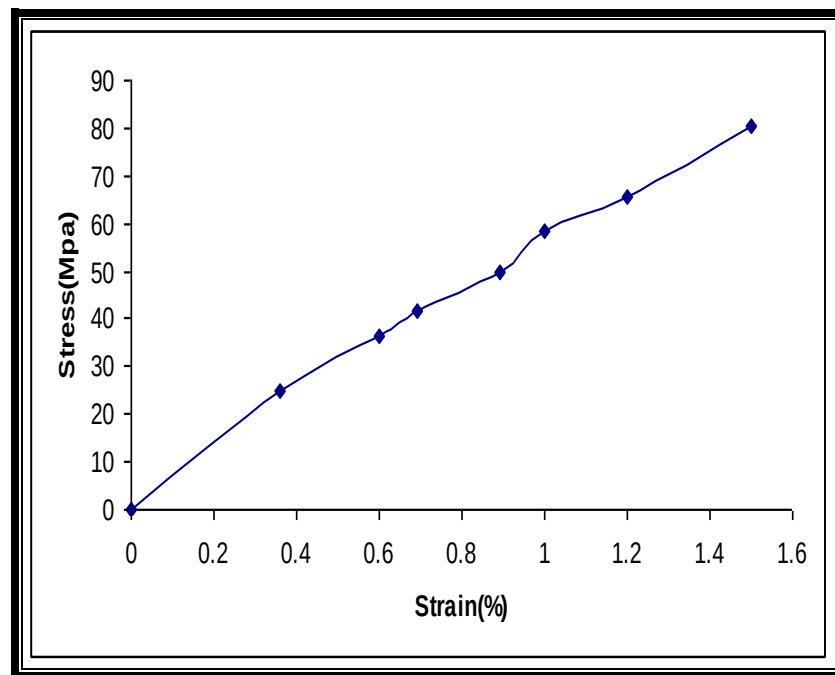


Figure (5.6)
Stress-strain curve of the Al-Si eutectic alloy under tension load at (free mold insulation conditions).

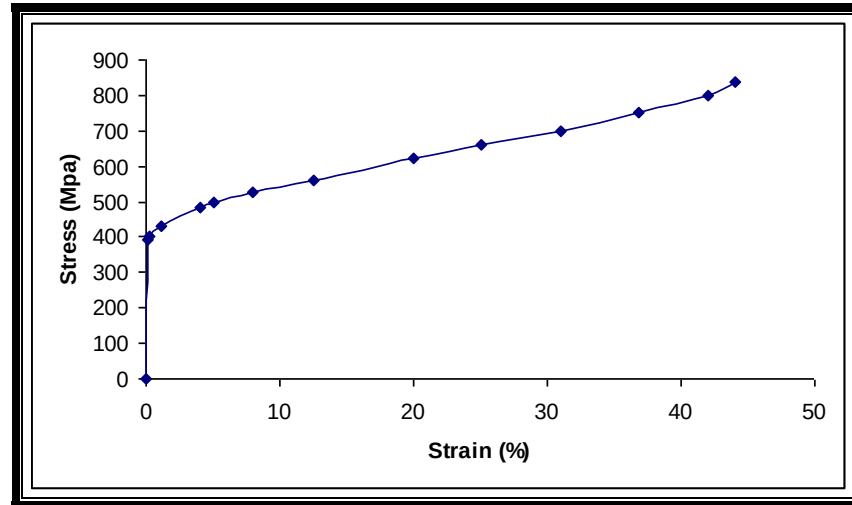


Figure (5.7)

Stress-strain curve of the Al-Si eutectic alloy under compression load at (free mold insulation conditions).

Compression results as shown in figure (5.7), shows the beginning or starting of material yielding at lower stresses (i.e. 392 Mpa), and when the applied stresses reach the value of (838 Mpa), the strain becomes (44%). These values give an indication that the material is weak under such loading that because of the irregular of orientation β -phase in the α -matrix.

3. Impact Toughness Results Discussion:-

Impact toughness of Al-Si eutectic alloy mainly depends on shape, size and distribution of α -Al grains and silicon morphology.

The absorbed energy of the samples of free mold insulation conditions is (1.8 Joule). This value is characterized to be very low (i.e. the material is classified as a brittle material).

The irregularity of the little grown β -phase with the large grain size of matrix induces poor ductility to the cast material.

5.2.2 Discussion of Microstructure Evolution and Mechanical Properties in Sand Mold Insulation Conditions :-

The possibility of monitoring in details, the evolution of eutectic structure and its orientation in specific direction in order to use as an in- situ reinforcement phase of aluminum matrix is fundamental in this work. In order to have the correct understanding of the final microstructure and metallurgical behavior of the produced casting alloy under the conditions of using an efficient insulation material (i.e. dry sand).

A liquid alloy, placed into the unit solidification (i.e. unidirectional solidification unit) (see experimental procedure), the temperature now falling down starting from the bottom end of mold, this falling in temperature coming as a result of cooling by cold water flow at the end bottom of mold that exposed to cooling directly. The efficiency of end cooling is augmented by connecting a large scale double fin (i.e. in order to increase the surface area of the mold end). The heat transfer now is increased in this direction while it is seized in other directions of mold where it is insulated by dry sand. The amount of heat transfer is dependent on various factors [49]:-

- 1- Geometry of the mold and the type of mold material used (which is constant along the experiments types).
- 2- The insulation conditions (i.e. thermal properties and physical properties of the material used as an insulator).
- 3- The presence of cooling devices.

Figure (5.8) shows the temperature distribution modeling of the solidification system in the mold that insulated from four sides with dry sand after 3 min. of pouring as it was stated in the experimental part. It can be seen from the temperature distribution that, the difference of temperature

between the alloy and outer surface of wall was (623-571)°C. The difference is higher from the first case (free mold insulation conditions) because preventing escape the heat in the direction of sides.

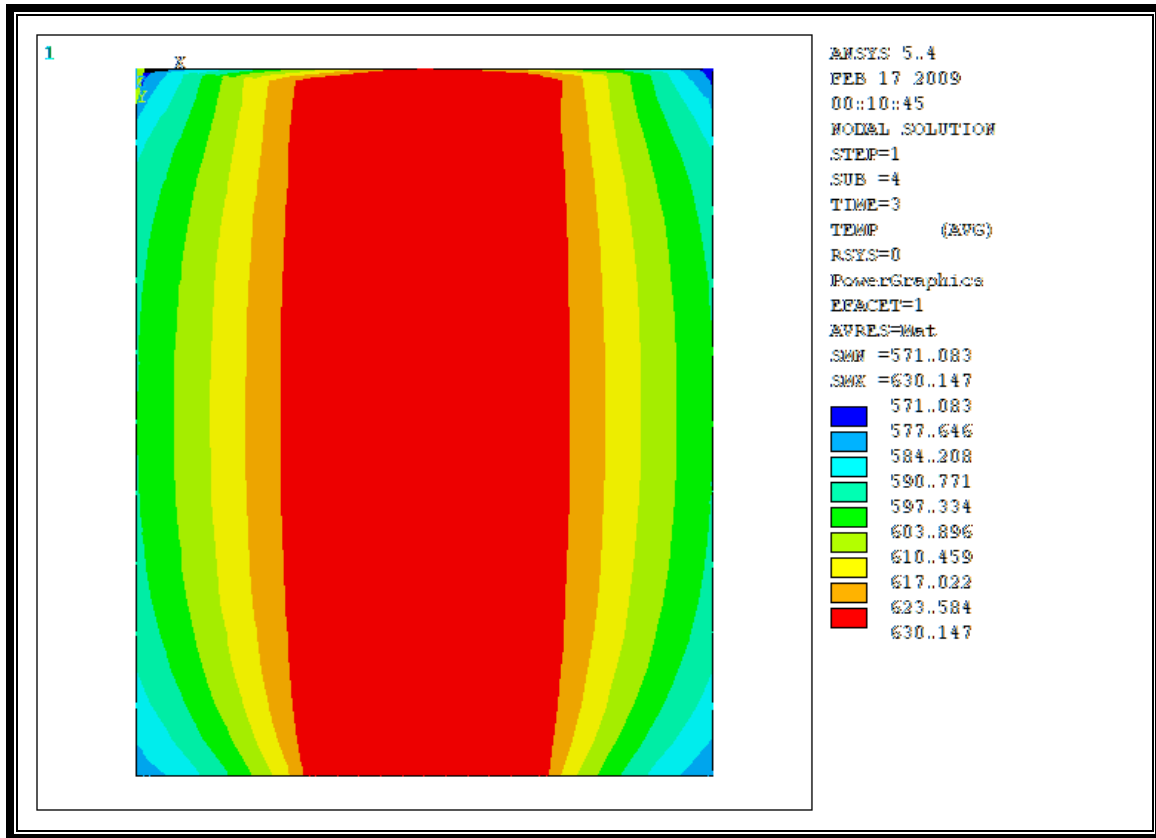


Figure (5.8)

Temperature distribution gradient across the solidification system at the sand mold insulation conditions after 3 min. after pouring(results in °C).

Figure (5.9) shows the relation between the temperature and the time for solidification that recorded from the thermocouple that inserted between the mould and the insulation material(in the solidification unit).

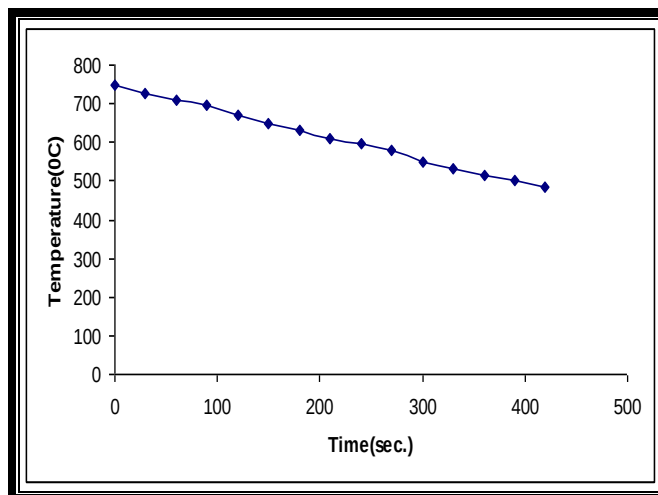


Figure (5.9)

The relation between the temperature and the time in case of sand mold insulation condition that recorded from the thermocouple that used in experimental procedure.

Figure (5.10) represents a schematic representation of the ingot obtained from the casting or solidification process, this figure shows the four sections that specified along the height or y-axis of ingot at almost equally distance. These sections are generalized to all the conditions of solidification that adopted in this work. Micro-structural observations have been conducted at each specific section as shown in figure (5.10), where the samples are cut under careful conditions and parallel to the y-axis (i.e. solidification direction).

The microstructures are taken parallel to the Y-axis at specific locations across the ingot. Figure (5.10) shows four of micrographs obtained under the solidification conditions adopted in this step. These samples at those locations represent four different cooling rates regimes according to its location distance from the cooled bottom end.

From figure (5.10) described above, microstructure micrograph at section (D) , where the cooling rate is very low. Now since the cooling rate

is low at this section, a so expected gas porosity and microporosity nucleates and grows with the formation of primary Si due to the high alloy content of silicon.

At, section (C) where a moderate cooling rate could be achieved at this condition of solidification process, a truly and obvious flaky structure forms without any microporosity or primary Si formation. The microstructure shows a clear growing of flaky β -phase that growing discontinuously as shown in section (C) still uncompleted and mis-oriented to the right wanted direction.

Sections(A,B) microstructure is different to some extent from the above sections microstructure. This microstructure is attributed by the following:-

1. Microstructure of the ingot generally consists of a α -phase aluminum and a second phase consists of a flake-shape β -phase(Si).
2. A little elongated grain structure could be seen clearly at this section, the reason behind such elongated structure is the pulling process of solidification by the active cooling at the bottom end of solidification unit.
3. The orientation of β -phase becomes more aligned with the y-axis approximately (60%) as the material solidifying close to bottom end of mold.
4. The orientation now step by step becomes less oriented in the y-axis due to the decrease in cooling rate with the height of ingot and also due to the efficiency of insulation material.

It is clear from above discussion, which, the growth of β -phase need a sufficient time. Preferential segregation of Al & Si occurs at high cooling rates due to shorter time available for diffusion.

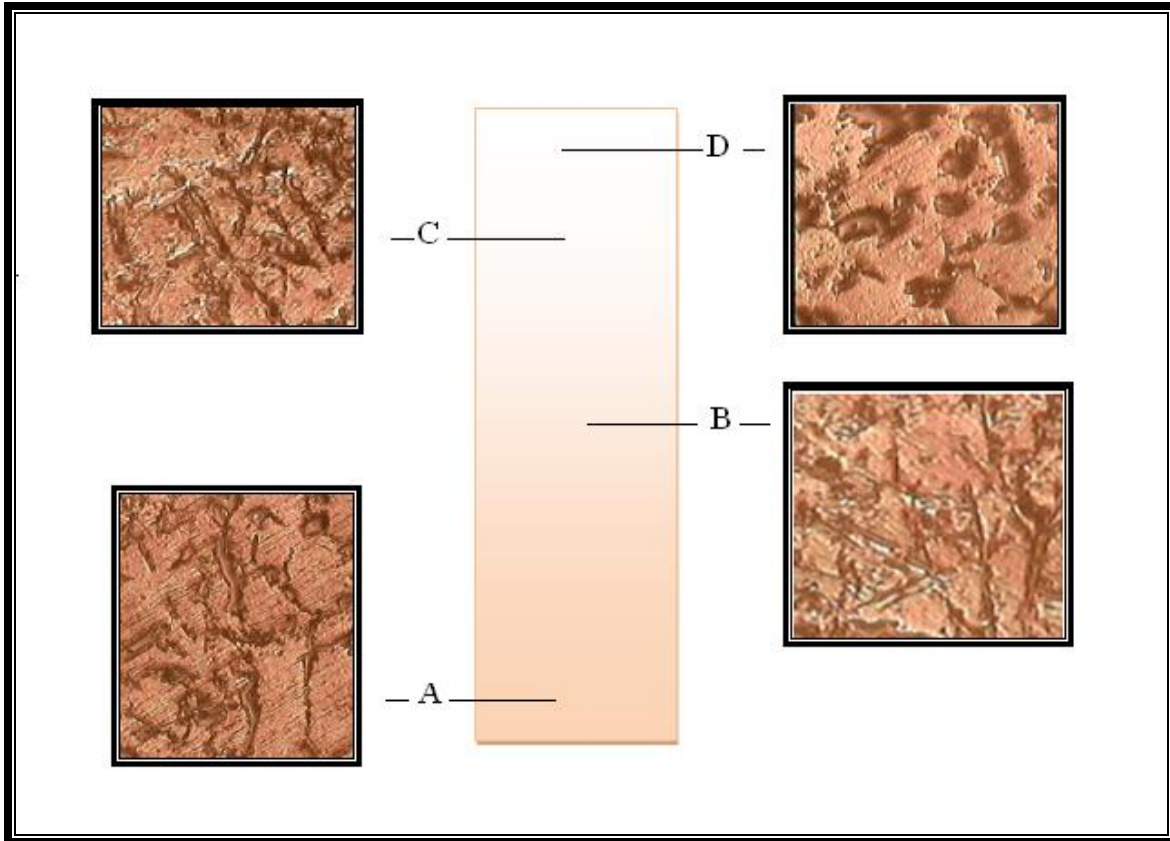


Figure (5.10)

A schematic representation of the ingot and the microstructure evolution at each section in case of sand mold insulation conditions (200X).

5.2.2.2 Discussion of Mechanical Properties of Produced Alloy at Sand Mold Insulation Conditions

1. Hardness Testing Results Discussion:-

The Brinell hardness testing survey on all the outside area of solidified Al-Si eutectic alloy in these conditions can make a supporting of the results obtained from the microstructure observations above. The hardness results are now different from that obtained in condition number one. The bar chart

shown in figure (5.11) shows the Brinell hardness number variations at the pre-specified sections that indicated in figure (5.10).

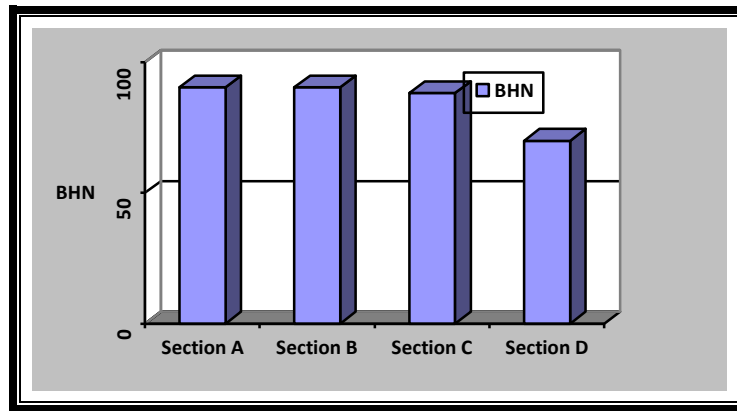


Figure (5.11)

Brinell hardness survey at the four specified sections of the alloy surface under the conditions of sand mold insulation.

The reasons behind such variation in results of hardness are the non homogeneous grain size distribution along the material under these conditions of solidification, the clear growth of β -phase and its better orientation in the required direction of solidification. That will augment the idea about the role of β -phase orientation and growth on the improvement of mechanical properties of the material that reinforced with this phase.

2. Tensile and Compression Test Properties:-

Figure (5.10) as it was stated above shows, the key of how the microstructure has changed along the y-axis of solidified ingot. This microstructure affects directly the mechanical behavior of material produced according to this condition.

Tensile tests has been conducted only in section (A) according to figure (5.10), keeping in mind that the tensile specimen needs at least (100 mm) long of ingot(i.e. multi-microstructure). The tensile test results show a clear improvement in comparison with the case of free mold insulation

conditions, the ultimate tensile strength has been improved, comparing will be done according to the fracture strength that required for each specimen(see figure (5.12)).

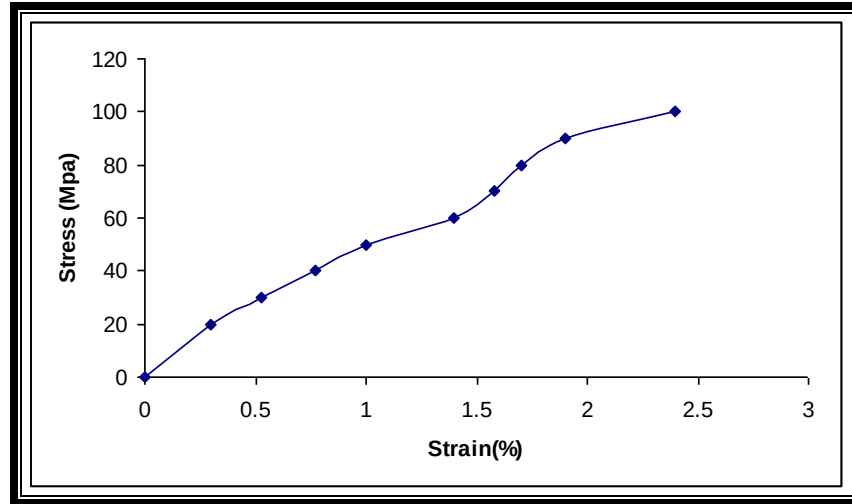


Figure (5.12)

Stress-strain curve of the Al-Si eutectic alloy under tension load at (sand mold insulation conditions).

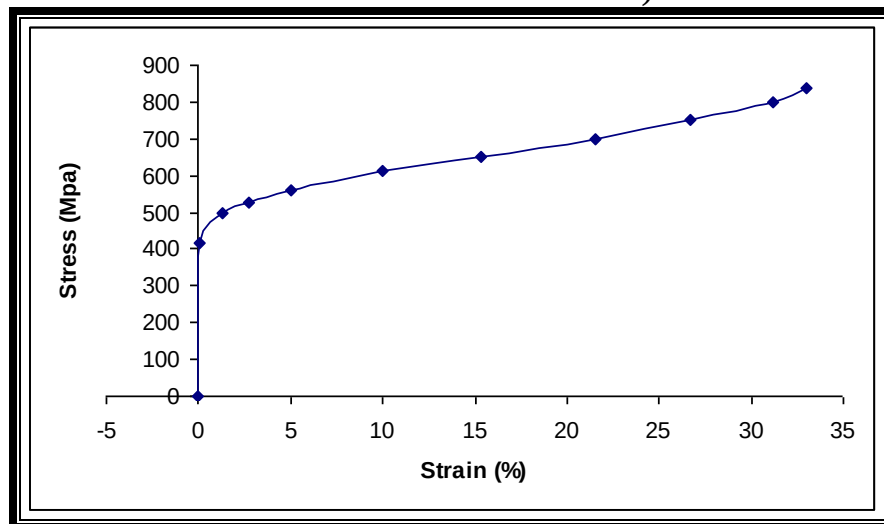


Figure (5.13)

Stress-strain curve of the Al-Si eutectic alloy under compression load at (sand mold insulation conditions).

From figure (5.13), compression results shows the beginning of material yielding at higher stresses (i.e. 415 Mpa), and when the applied

stresses reach the value of (838 Mpa), the strain becomes (33%). These values give an indication that the material becomes stronger under such loading comparing with the material produced under the conditions of free mold insulation solidification.

1. It is known that, the behaviors of the investigated alloy under the conditions of free mold insulation are almost brittle behavior (see 5.2.2).
2. Figure (5.12) shows a clear improvement in tensile properties. The reason behind such improvement is the development of grown β -phase firstly (i.e. it becomes flaky-shape with an improved length) and secondly its better orientation in the direction of y-axis (i.e. solidification axis).
3. This behavior is so expected due to the high cooling rate at the bottom end of the mold and also due to the grain refinement of fast cooling part of ingot at the area close to the bottom end.
4. Now, as the solidified ingots have sectioned away from the bottom, the tensile properties have decreased continuously until it reaches a very close values of the case of free mold isolation conditions.
5. The better grown and unidirected β -phase plays as an in-situ fiber which is the reason behind such indicated reinforcement in the alloy under investigation.

3. Impact Toughness Properties :-

In order to assess the toughness of the produced ingots or samples, impact tests are conducted according to the specified section that indicated previously in section (A).

Now, if a comparison has been made between the impact toughness data at section (A) of the conditions above and the results obtained from the impact test of the conditions of free mold insulation, one can conclude that a noticeable development has occurred at this conditions of solidification. The energy absorbed by the sample at section (A) in figure (5.9) jumped from (1.8 Joule) in the case of free mold insulation conditions to be (2 Joule) in case of sand mold insulations.

The reasons behind such improvement could be summarized as follows:

1. Noticeable elongation in the grain structure at the section (A), where the cooling rate is high.
2. Better orientation of grown β -phase in the direction parallel to the required solidification axis.

Less interfacial energy between the β -phase and the α -matrix.

The flaky shapes β -phase concentrate the stresses at the tips of the phase that enhancing the fracture of specimens, so that the efforts have been directed to get continuous fiber phase instead of discontinuous.

5.2.3 Discussion of Microstructure Evolution and Mechanical Properties in Glass Wool Mold Insulation Conditions :-

The third condition adopted in this work in order to produce a directed grown β -phase is the use of a glass wool insulation material around the mold (i.e. high density glass wool). The mold now insulated from above and four sides, except the bottom end which is free to cool by the cold water flow and the large surface fins area that equipped at this point.

The very low thermal conductivity of the high density glass wool ($0.038 \text{ W.m/m}^2 \cdot ^\circ\text{C}$) helps to prevent almost all the heat energy that transfer across the mold walls to the atmosphere and then it can help to maintain the molten material at the pouring temperature at sufficient time more than the two above cases (i.e. free mold insulation and dry sand mold isolation cases) as can be seen in the following figure (5.14) that shows a relation between the time and temperature for a three cases of mold insulation that recorded from the thermocouple that used in experimental procedure.

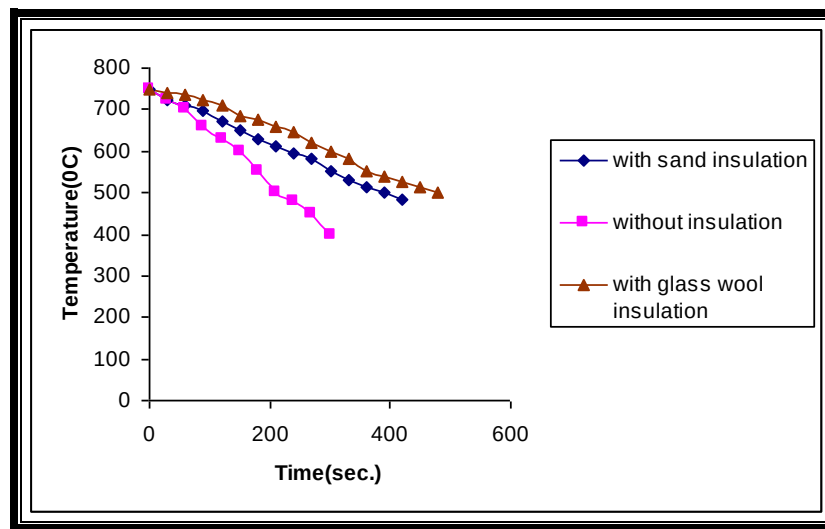


Figure (5.14)

The relation between the time and temperature for a three cases of mold insulation that recorded from the thermocouple that used in experimental procedure.

The long time maintaining of molten material at the pouring temperature at this condition in compared with the other two conditions and the continuity of cold water flow through the lower part of the unidirectional solidification unit allows the heat energy to escape in only in one direction and then it works to drawing the growth process of the β -phase in the specified direction(i.e. required direction).

The computer modeling as shown in figure down (5.15), shows the temperature gradient distribution along the solidification system at the conditions where the mold is insulated by the high density glass wool. From the figure shown the difference of temperature between the alloy and outer surface of wall was (622-559)°C. The difference is higher from the other cases (free mold insulation conditions, sand mold insulation conditions) because preventing escape the heat in the direction of sides, using glass wool as insulation material to maintaining temperature of melting alloy .

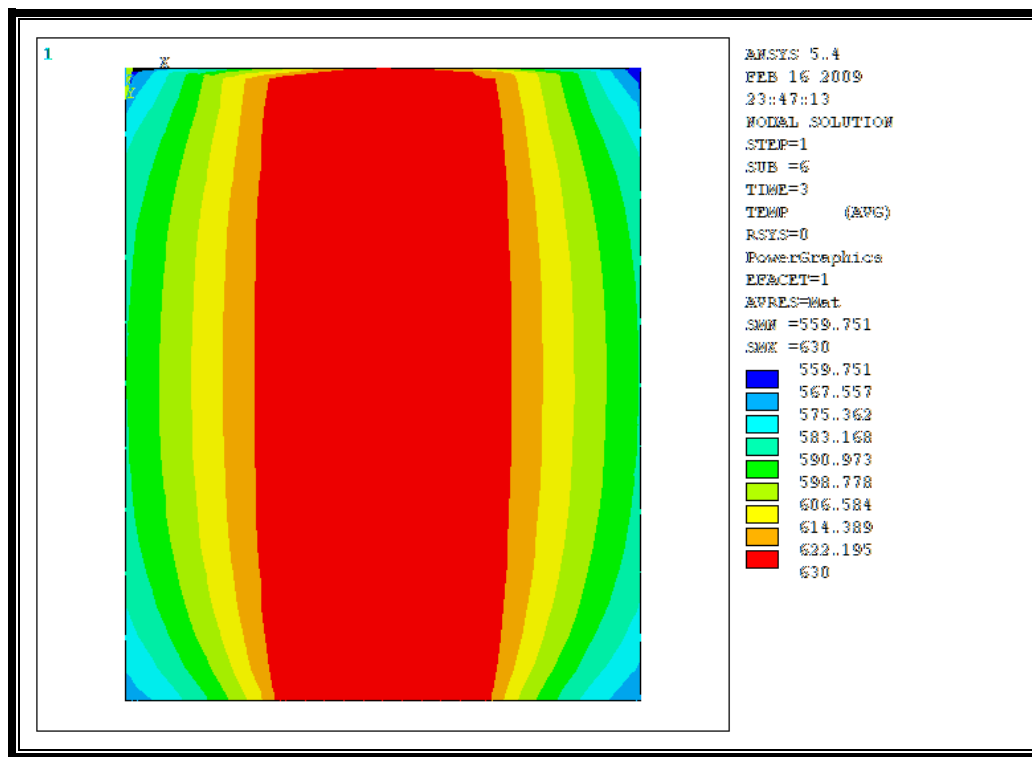


Figure (5.15)

Temperature distribution gradient across the solidification system at the glass wool mold insulation conditions after 3 min. after pouring(results in °C).

A large time now available under conditions (i.e. glass wool insulation mold), and this time allows more diffusion activities which is the reason behind the nucleation and growth of second phase (i.e. β -phase).

The microstructure observations show an extinct improvement in the processes of β -phase growing, along the y-axis. Four sections also taken to monitor the microstructure variations along the material. The microstructure consists mainly from α -grains of aluminum and flaky shapes β -phase as can be seen in figure (5.16) .

Sections (A,B) shown the increasing of β -phase length which is directed in good percentage in the direction of heat sink. The other benefits of the solidification in this manner are the elongation of grain at the first sections along the y-axis and that because the prevent the heat escape from the wall by the glass wool material. That will reflected directly on the mechanical properties evaluations.

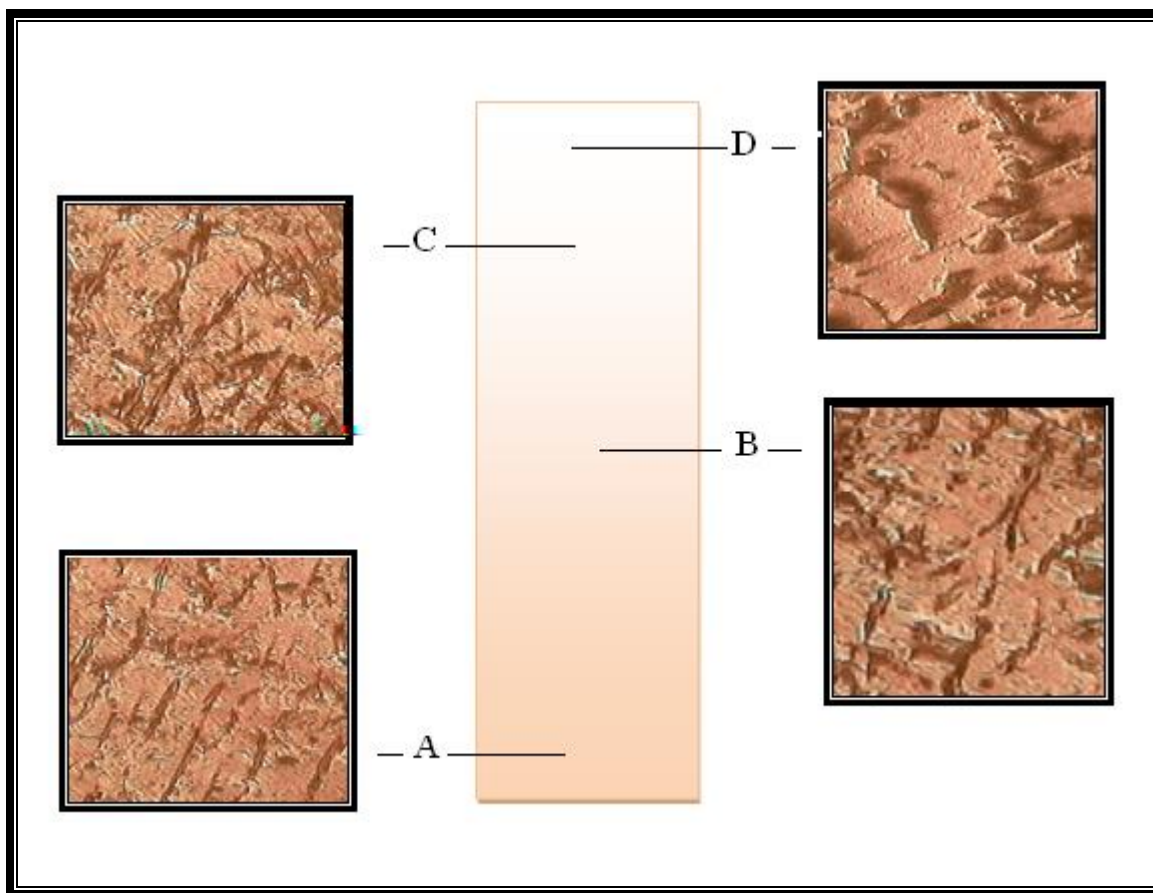


Figure (5.16)

A schematic representation of the ingot and the microstructure evolution at each section in case of glass wool mold insulation conditions(200X).

5.2.3.1 Discussion of Mechanical Properties of Produced Alloy at Glass Wool Mold Insulation Conditions

1.Hardness Testing Results Discussion:-

The final Brinell hardness testing survey is conducted to evaluate how much progresses have been done by using this conditions of solidification (i.e. high density glass wool insulation material). The test covers all the outside area of solidified Al-Si eutectic alloy in this conditions. This survey is very important as a first indication of how much the microstructure has changed. The hardness results are now different from that obtained in two conditions above. The bar chart shown in figure (5.17), shows the Brinell

harness number variations at the pre-specified sections that indicated in figure as shown.

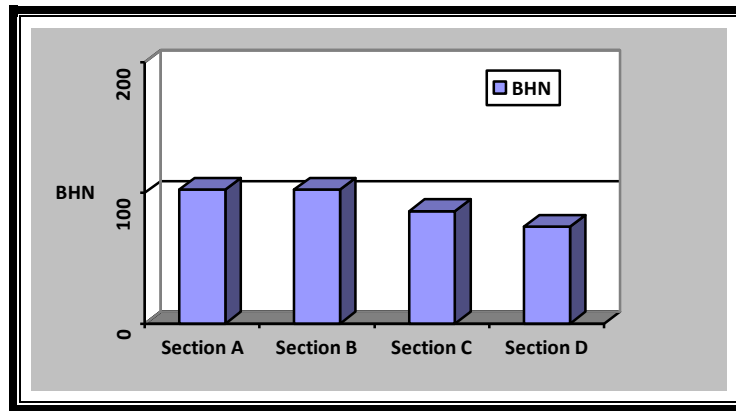


Figure (5.17)

Brinell hardness survey at the four specified sections of the alloy surface under the conditions of glass wool mold insulation conditions.

The reasons behind such improvement in hardness number especially at sections (A,B) are the change of the microstructure near the end bottom of the mold. This change in microstructure is due to the high cooling rate at this sections (i.e. section A,B) where the heat transfer is seized in efficient manner except from the bottom end of mold.

According to the figure (5.14), a long time resulted until the complete solidification of ingots at this condition (i.e. glass wool insulation mold). It is clear that, the diffusion kinetics now found sufficient time to work properly in this condition, but the better mold insulation (i.e. keeping or maintaining pouring temperature) leading to lower the cooling rate , that means a compromising now working between the reinforcement of α - grains with the directional eutectic growing and the grain coarsening resulted from a long time of solidification.

As a result, the activities of diffusion contributions take the priority in growth and enhancing also the grain refinement of the resulted

microstructure to some extent. The orientation are now more easy to gided due to the long time maintaining at the liquid state and the concentration of heat flow in unidirectional (i.e. Y-axis)

2. Tensile and Compression Test Properties:-

The response of produced composite material now reinforced by this manner to the multi-types of loading through the mechanical properties testing is different now. Key of how the microstructure has changed along the y-axis of solidified ingot. This microstructure reflects directly the mechanical behavior of material produced according to these conditions.

Tensile test has been conducted in multi-sections in interference manner, keep in mind that the tensile specimen need at least (100 mm) long of ingot. The tensile test results show a clear improvement in comparison with the other cases of insulation conditions, see figure (5.18).

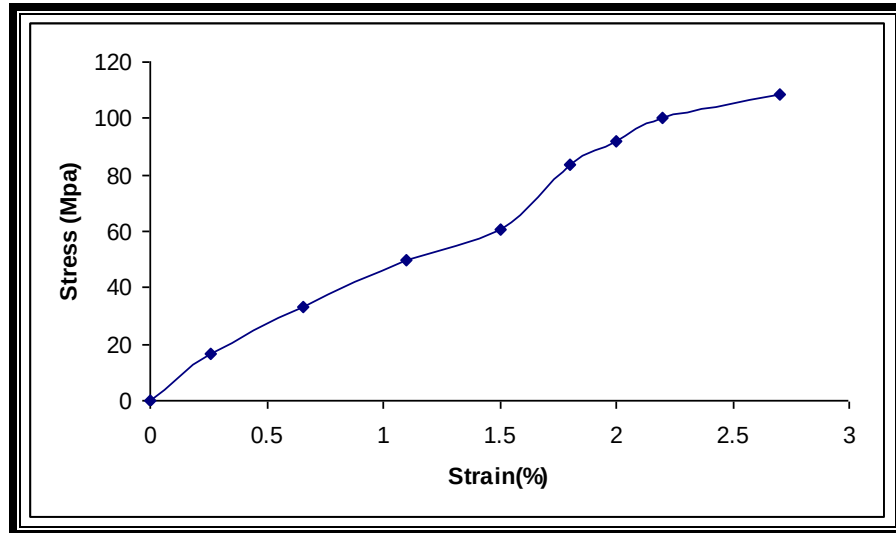


Figure (5.18)

Stress-strain curve of the Al-Si eutectic alloy under tension load at (glass wool mold insulation conditions).

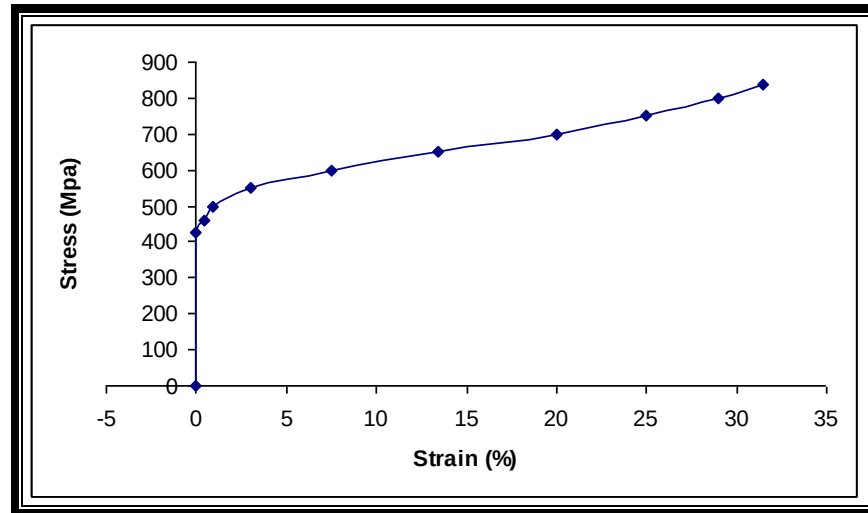


Figure (5.19)

Stress-strain curve of the Al-Si eutectic alloy under compression load at (glass wool mold insulation conditions).

Compression results show the beginning of material yielding at higher stresses (i.e. 426 Mpa), and when the applied stresses reach the value of (838 Mpa), the strain becomes (31.5%), see figure(5.19). These values give an indication that the material becomes stronger under such loading comparing with the material produced under the conditions of free mold insulation solidification.

1. It is known that, the behavior of the investigated alloy under the conditions of free mold insulation is almost brittle behavior (see 5.2.2).
2. Figure (5.18) shows a clear improvement in tensile properties. The reason behind such improvement is the development of grown β -phase firstly (i.e. it becomes flaky-shape with an improved length) and secondly its better orientation in the direction of y-axis (i.e. solidification axis).

3. This behavior is so expected due to the high cooling rate at the bottom end of the mold and also due to the grain refinement of fast cooling part of ingot at the area close to the bottom end.
4. Now, as the solidified ingots have sectioned away from the bottom, the tensile properties have decreased continuously until it reaches a very close value of the case of free mold insulation conditions.
5. The better grown and unidirectional β -phase plays as an in-situ fiber which is the reason behind such indicated reinforcement.

3. Impact Toughness Properties :-

In order to assess the toughness of the produced ingots or samples, impact tests are conducted according to the specified section that indicated previously in section (A).

The tests show a noticeable improvement have documented in the case of (glass wool mold insulation conditions) rather than the cases of free mold insulation conditions and sand mold insulation conditions., one can conclude that a noticeable development have occurred at this conditions of solidification. The energy absorbed by the sample at section (A) in this case (i.e. glass wool mold insulation condition) is jumped to be (2.5 Joule).

The reasons behind such improvement could be summarized as follows:

1. Noticeable grain elongation at the section (A), where prevent escape the heat from the wall was perfect from the sand mold insulation conditions because of the less of thermal conductivity.
2. Very better orientation of grown β -phase in the direction parallel to the required solidification axis.

3. The interfacial energy between the grown phase and the matrix in this case is less from the above two cases.

figure (5.20) can show the accumulative impact properties of all solidification conditions.

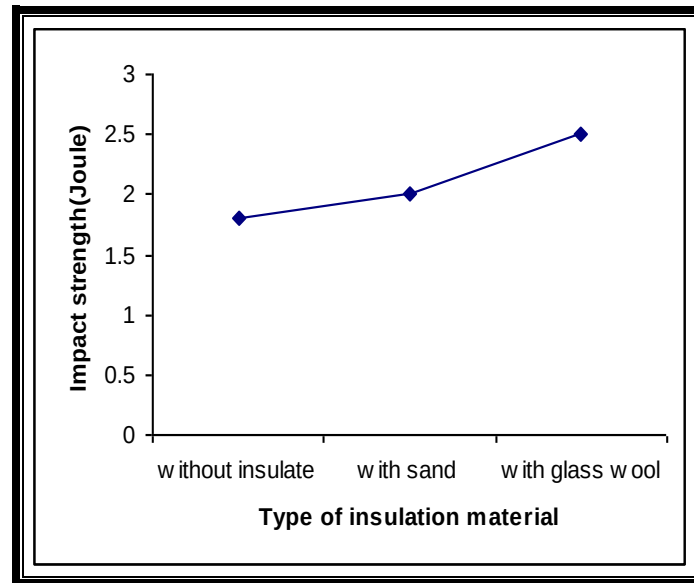


Figure (5.20)

The accumulative impact strength of all solidification conditions.

5.3 The Results of X-Ray Diffraction Analysis

From the charts of X-ray diffraction for samples appeared that there are no any new phases in the structure. And also appeared that the only the Al- and Si-phases. The figures(5.21),(5.22) and(5.23) ,and from the tables (5.1) ,(5.2) and (5.3)shown the X-ray diffraction charts and data for the three types of insulation.

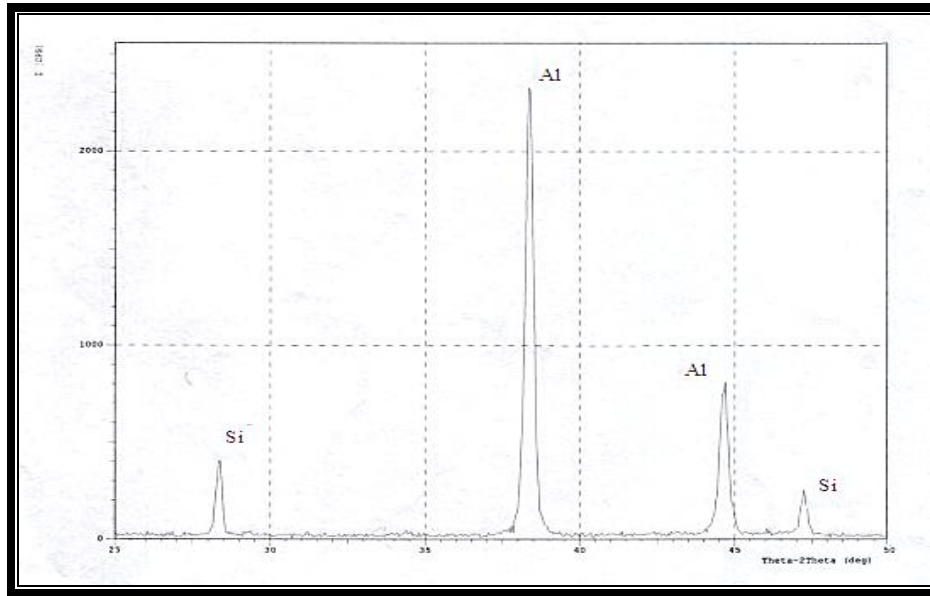


Figure (5.21)

Result of X-ray diffraction analysis for the ingot without insulation.

Table (5.1)

Result of X-ray diffraction analysis for the ingot with free mold insulation conditions.

2Θ	$d_{hkl}(A^0)$	phase
28.4	3.140	Si
38.4	2.342	Al
44.75	2.023	Al
47.3	1.920	Si

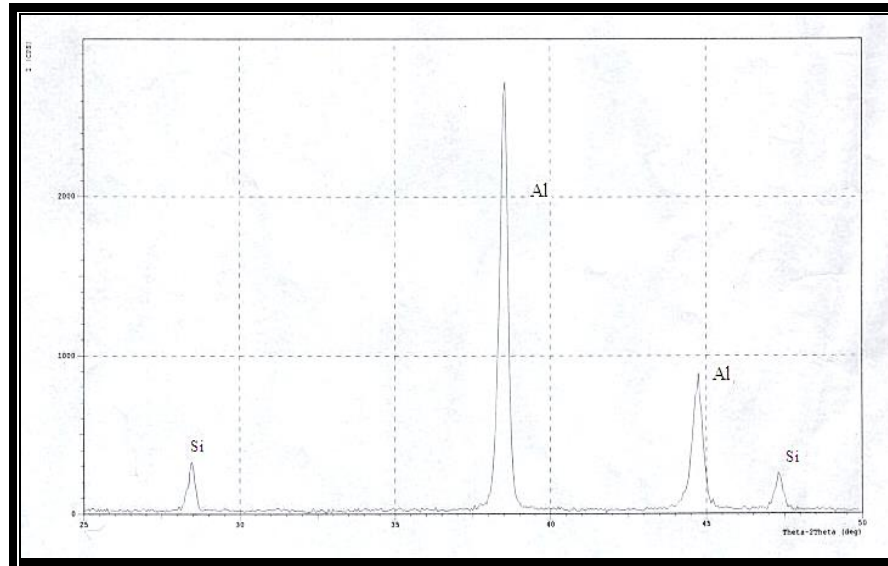


Figure (5.22)
Result of X-ray diffraction analysis for the ingot with sand insulation.

Table (5.2)
Result of X-ray diffraction analysis for the ingot with sand mold insulation condition.

2θ	$d_{hkl}(A^0)$	phase
28.4	3.140	Si
38.6	2.330	Al
44.7	2.023	Al
47.4	1.916	Si

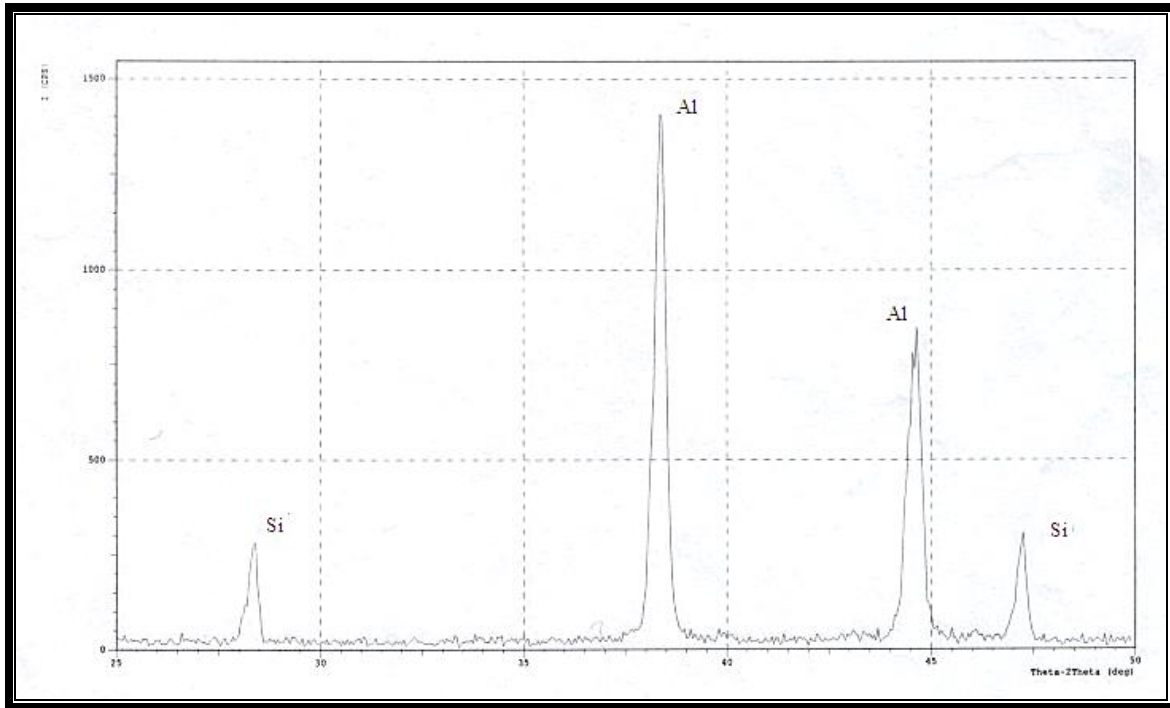


Figure (5.23)

Result of X-ray diffraction analysis for the ingot with glass wool insulation.

Table (5.3)

Result of X-ray diffraction analysis for the ingot with glass wool mold insulation conditions.

2θ	$d_{hkl}(A^{\circ})$	phase
28.4	3.161	Si
38.4	2.342	Al
44.6	2.029	Al
47.25	1.922	Si

CHAPTER SIX

CONCLUSIONS & SUGGESTIONS FOR FUTURE WORKS

6.1 Conclusions

According to results of present work, the following can be concluded:-

1. The microstructure of Al-Si eutectic alloy is affected directly by the method by which the alloy can solidify.
2. It is possible to improve hardness, tension, compression and impact properties by making the molten eutectic alloy solidifying in one direction.
3. The unidirectional solidification of eutectic alloy can assist the nucleation and growth of the second eutectic phase in one direction.
4. Better insulation of mold adopted in this work is by the using of high density glass wool around the mold , with keeping the bottom side free to cool fast by cold water flow and large surface area of equipped fin.
5. The numerical model is agreed with the experimental practices that recommend using the glass wool with the bottom mold cooling by cold water flow.
6. Some elongation in the grains near the mold bottom end resulted from a pulling solidification or cooling in one direction.

6.2 Suggestions for Future Works

The following recommendations for further works:-

1. Using a modified Al-Si eutectic alloy with Na or Sr.
2. Using of grain refinement to investigate the effects on the unidirectional solidifications.
3. Studying the other properties such as creep or fatigue of investigated alloy under the adopted three conditions of solidifications.
4. Simulate the produced microstructure numerically and studying the interfacial energy effects between the grown phase and matrix.

Examining committee approval sheet

We certify that have read this thesis entitled (*Experimental Analysis of In- situ Composite Al-Si Eutectic Alloy*) and as an examining committee,we have examined the student (*Awham Jumea Salman*) in contents and that is related to it, and that in our opinion it meets the standard of a thesis for the degree of Master of science in Material Engineering.

Signature

Ass. Prof. Dr. Ali H. Atewi

Committee Chair

Date: / /2009

Signature

Ass. Prof. Dr. Fadl A. Hashm

Committee Member

Date : / / 2009

Signature

Lecture Dr. Ahmed O. Jasm

Committee Member

Date : / / 2009

Signature

Ass. Prof. Dr.Najim A. Saad

supervisor

Date : / / 2009

Signature

Lecture Dr.Alaa A. Ateia

supervisor

Date : / / 2009

Approval of the Department of

Material Engineering

Head of Material Engineering Department.

approval of the College

of Engineerng

Dean of the College of Engineering.

Signature

Lecture Dr. Ahmed O. Jasm

Date : / / 2009

Signature

Ass. Prof. Dr. Salah T. Ali

Date : / / 2009

List of contents

No.	Title	Page
	Abstract	I
	List of figures	II
	List of tables	V
	List of symbols	VI
	List of contents	VIII
	CHAPTER ONE: GENERAL INTRODUCTION	
1.1	Introduction	2
1.2	Definition of Composite Materials	3
1.3	Classification of Composite Materials	3
1.4	In-situ Composite Materials	4
1.4.1	Types of In-situ Composite Materials	5
1	Particle In-situ Composite Materials: - (Precipitation Hardening)	5
2	Fiber In-situ Composite Materials: - (Unidirectional Eutectic Solidification)	6
1.4.2	Applications of Fiber In-situ Composite Materials	8
1.5	Literature Review	9
1.6	Aim of the Work	14
	CHAPTER TWO : DIRECTIONAL EUTECTIC SOLIDIFICATION	
2.1	Eutectic	16
2.1.1	Metallic Eutectics	17
2.2	Eutectic Solidification	19
2.2.1	Nucleation in Eutectic Solidification	20
2.2.2	Growth of Lamellar Eutectics	20
2.3	Eutectic Leading Phase	26
2.4	Nonequilibrium Crystallization	27
2.5	Unidirectional Solidification of Eutectic	28
2.5.1	Mechanical Behavior	29
	CHAPTER THREE: ALUMINUM –SILICON EUTECTIC ALLOY	
3.1	Introduction	33
3.2	The Aluminum-Silicon Phase Diagram and Equilibrium Cooling	34
3.3	The Thermal Parameters	38
	CHAPTER FOUR: EXPERIMENTAL PROCEDURE& COMPUTER MODELING	
4.1	Introduction	41

4.2	Materials Used	42
4.3	Procedure	43
4.3.1	Alloy Preparation for Melting	43
4.3.2	Thermal Analysis	43
4.3.3	Experimental Apparatus	43
4.4	Melting and Sampling Procedure	47
4.5	Productions of Samples Ingots	49
4.6	Modeling Process	50
4.6.1	Introduction	50
4.6.2	Model Constitute	50
4.6.3	Geometry Sub. Model	51
4.6.4	Finite Element Model	52
4.6.5	Mathematical Formulation	53
4.6.6	Material Used in Model	56
4.6.7	Boundary Conditions	56
4.6.8	Paramedic Study	56
4.6.9	Results Output	56
4.7	Sample Preparation for Microscopic Analysis	57
4.7.1	Sectioning	57
4.7.2	Grinding	57
4.7.3	Polishing	58
4.7.4	Etching	58
4.8	Mechanical Testing	59
4.8.1	Hardness Test	59
4.8.2	Tensile Test	60
4.8.3	Compression Test	62
4.8.4	Impact Test	63
4.9	X-Ray Diffraction Analysis	64
	CHAPTER FIVE: RESULTS & DISCUSSION	
5.1	Introduction	67
5.2	Discussion of Modeling & Experimental Results	68
5.2.1	Discussion of Microstructure Evolution and Mechanical Properties in Free Mold Insulation Conditions	68
5.2.1.1	Discussion of Mechanical Properties of Produced Alloy at Free Mold Insulation Conditions	71
5.2.2	Discussion of Microstructure Evolution and Mechanical Properties in Sand Mold Insulation Conditions	75
5.2.2.1	Discussion of Mechanical Properties of Produced Alloy at Sand Mold Insulation Conditions	79
5.2.3	Discussion of Microstructure Evolution and Mechanical	83

	Properties in Glass Wool Mold Insulation Conditions	
5.2.3.1	Discussion of Mechanical Properties of Produced Alloy at Glass Wool Mold Insulation Conditions	87
5.3	The Results of X-Ray Diffraction Analysis	92
	CHAPTER SIX : CONCLUSIONS & SUGGESTIONS FOR FUTURE WORKS	
6.1	Conclusions	97
6.2	Suggestions for Future Works	98
	References	99

List of figures

No.	Title	Page
1.1	Unidirectional solidification of a eutectic alloy, the solid contains microstructure constituents aligned parallel to the growth direction	7
1.2	Turbine blades manufactured by three different processes	9
2.1	A simple binary system	16
2.2	(a) Phase diagram typical of a system showing a normal eutectic structure. (b) Phase diagram typical of a system showing an anomalous eutectic structure	18
2.3	Interdiffusion in the liquid ahead of a eutectic front	21
2.4	Molar free energy diagram at a temperature ΔT_o below the eutectic temperature, for the case $\lambda = \lambda^*$	22
2.5	(a) Molar free energy diagram at $(T_E - \Delta T_o)$ for the case $\lambda^* < \lambda < \infty$, showing the composition difference available to drive diffusion through the liquid. (b) Model used to calculate the growth rate	42
2.6	Eutectic phase diagram showing the relationship between ΔX and ΔX_o	25
2.7	Formation of a lamellar structure (α and β phases) in an unidirectional solidification of a eutectic. The solidification front is perpendicular to the direction of growth (direction of arrows). T_L , T_E and T_S are the temperature of the liquid (L), the solidification front and the solid, respectively	28
3.1	depicts the contemporary aluminum-silicon phase diagram.(a) Hypoeutectic alloy, (b) eutectic alloy,(c) Hypereutectic alloy.	34
3.2	Al-12.5wt% Si alloy (a) Slowly cooled 200X (b) Chill Cast 500X	36
3.3	Coupled zone in (a) symmetrical and (b) asymmetrical phase diagrams	37
4.1	A schematic diagram of the unidirectional solidification unit	45
4.2	A schematic diagram of the section A-A in the unidirectional solidification unit as labeled above	45
4.3	A photographic picture shows the apparatus that used in the solidification practices	46
4.4	Equipment of electric furnaces	49
4.5	Geometry of sub model adopted for numerical analysis	52

4.6	Finite element model assumptions	53
4.7	Elemental volume for one-dimensional heat-conduction analysis	54
4.8	The places that have been cutting from it the samples	59
4.9	Tensile test specimen	61
4.10	Equipment of Material Testing Unit	61
4.11	Comparison test specimen	62
4.12	Impact test specimen	63
4.13	Equipment of Impact	64
5.1	Microstructure of alloy before any process of pouring 200X	67
5.2	Temperature distribution gradient across the solidification system at the free mold insulation conditions after 3 min. of pouring (results in °C)	69
5.3	The relation between the temperature and the time in case of free mold insulation condition that recorded from the thermocouple that used in experimental procedure	70
5.4	Optical microscopy of alloy at (free mold of insulation) conditions(200X)	71
5.5	Brinell harness survey at the four specified sections of the alloy under free mold insulation conditions	72
5.6	Stress-strain curve of the Al-Si eutectic alloy under tension load at (free mold insulation conditions)	74
5.7	Stress-strain curve of the Al-Si eutectic alloy under compression load at (free mold insulation conditions)	74
5.8	Temperature distribution gradient across the solidification system at the sand mold insulation conditions after 3 min. after pouring(results in °C)	76
5.9	The relation between the temperature and the time in case of sand mold insulation condition that recorded from the thermocouple that used in experimental procedure	77
5.10	A schematic representation of the ingot and the microstructure evolution at each section in case of sand mold insulation conditions (200X)	79
5.11	Brinell hardness survey at the four specified sections of the alloy surface under the conditions of sand mold insulation	80
5.12	Stress-strain curve of the Al-Si eutectic alloy under tension load at (sand mold insulation conditions)	81
5.13	Stress-strain curve of the Al-Si eutectic alloy under compression load at (sand mold insulation conditions)	81

5.14	The relation between the time and temperature for a three cases of mold insulation that recorded from the thermocouple that used in experimental procedure	84
5.15	Temperature distribution gradient across the solidification system at the glass wool mold insulation conditions after 3 min. after pouring(results in °C)	85
5.16	A schematic representation of the ingot and the microstructure evolution at each section in case of glass wool mold insulation conditions(200X)	87
5.17	Brinell hardness survey at the four specified sections of the alloy surface under the conditions of glass wool mold insulation conditions	88
5.18	Stress-strain curve of the Al-Si eutectic alloy under tension load at (glass wool mold insulation conditions)	89
5.19	Stress-strain curve of the Al-Si eutectic alloy under compression load at (glass wool mold insulation conditions)	90
5.20	The accumulative impact strength of all solidification conditions	92
5.21	Result of X-ray diffraction analysis for the ingot without insulation	93
5.22	Result of X-ray diffraction analysis for the ingot with sand insulation	94
5.23	Result of X-ray diffraction analysis for the ingot with glass wool insulation	95

List of tables

No.	Titles	Page
2.1	Leading phase of eutectic alloys	27
3.1	Tensile and compressive properties of directionally solidified Al-Si eutectic alloy	39
4.1	Average chemical composition analysis of the material used	43
4.2	Thermal conductivities of insulation materials	47
4.3	General plane of ingot samples production	50
5.1	Result of X-ray diffraction analysis for the ingot with free mold insulation conditions	93
5.2	Result of X-ray diffraction analysis for the ingot with sand mold insulation conditions	94
5.3	Result of X-ray diffraction analysis for the ingot with glass wool mold insulation conditions	95

References

- (1) A. K. Bhargava, "Engineering materials polymers, ceramics and composite " , 2005 , Prentice-Hall of India.
- (2) R. S. Khurmi, R. S. Sedha, "Material science", 1989, Second Edition, S. Chand & Company Ltd.
- (3) M. M. Schwartz, "Composite materials handbook", 1984, McGraw-Hill Book Company, USA.
- (4) Mathew phlip & Bill Bolton, "Technology of engineering materials", 2002, First published, Butterworth-Heinemann, Britain.
- (5) Valery V. Vasiliev& Evgeny V. Morozov, "Mechanics and analysis of composite materials", 2001, First edition , Elsevier Science Ltd, Netherlands.
- (6) R.M.A.Aikin,Jr., "The Mechanical properties of In-Situ Composites",1997, The journal *JOM*,49(8), pp. 35-39, The Minerals, Metals & Materials Society.
- (7) Fishman, S.G., Lewis, D., Singh, M , "In situ composite materials", 1995, Advanced Materials & Processes, <http://www.highbeem.com/> .
- (8) Kwai S .Chan, Robert E. Beissner, David L.Davidson, "Development of a computational material science-based methodology for alloy/composite design", 1999, Southwest Research Institute, <http://www.swri.org>.
- (9) George E. Dieter, "Mechanical metallurgy", 1976, Second edition, McGraw-Hill series, USA.
- (10) Abdulhaqq A. Hamid, P.K.Ghosh, SC.Jain,and Subrata Ray, "Processing, microstructure, and mechanical properties of cast in-situ Al(Mg,Mn)- Al₂O₃(MnO₂) composite",2005,Indian Institute of Technology Rookee,surayfmt@iitr.ernet,in.

- (11) "In Situ Fibers ",1989, CRC Press LLC, About.com, <http://www.about.com>.
- (12) Peter A. Thornton and Vito J. Colangelo, "Fundamentals of Engineering Materials", 1985, Prentice-Hall, U.S.
- (13) G.Piatti, "Advances in composite materials", 1987, Applied Science Publishers Ltd, London.
- (14) R.E.Smallman and R.J.Bishop,"Modern physical metallurgy and materials engineering science, process, applications"1999, Sixth edition, Butterworth-Heinemann, Britain.
- (15) Michael F.Ashby and David R.Jones, "Engineering materials 1 an introduction to microstructures processing and design" , 2005, Third edition, Cambridge university.
- (16) M.A. Martorano, C. Beckermann, and Ch.-A. Gandin, "A solutal interaction mechanism for the columnar to-equiaxed transition in alloy solidification",2003, Metallurgical and materials transactions, VOL. 34A, pp.1657-1674.
- (17) K. Ohsasa, H. Shirosawa, and T .Narita ,"Prediction of the solidification structure of casting and heterogeneous nucleation",2003, Journal of University of Science and Technology Beijing, Vol.10, No.3, pp.43-47.
- (18) R.E. Napolitano, H. Meco, and C. Jung ,"Faceted solidification morphologies in low-growth-rate Al-Si eutectics", JOM • April 2004, Smart ImagingTechnologies,pp.16-21.
- (19) Taylor A. Groll ,"Effect of solidification rate on cast microstructure ",2004, Padnos College of Engineering and Computing Grand Valley State University.
- (20) K.Nogita, S.D. McDonald, A.K. Dahle, "Modification of Al-Si alloys",

2004, Institute of Materials Engineering Australasia Ltd, Materials forum, Vol.28, pp.945-950.

(21) M.F. Zhu, C.P. Hong, "Modeling of dendritic and eutectic microstructures in solidification of aluminum alloys",2004, Institute of Materials Engineering Australasia Ltd, Materials forum, Vol.28, pp.895-900.

(22) Yuhong Zhao, Hua Hou , "Simulation for microstructure evolution of Al-Si alloys in solidification process",2006, Institute of Physics Publishing, Journal of Physics: Conference Series 29 ,pp. 210–219.

(23) M. Jeyakumar, Suresh Sundarraj, S. Vijayalakshmi, G. S. Vinodhkumar, "Cooling rate effect on microporosity and primary silicon formation in eutectic aluminum-silicon alloy",2007, International Conference on Advanced Materials and Composites, Oct 24-26, pp.150-157.

(24) Roy Elliott BSc,PhD, "Eutectic solidification processing crystalline and glassy alloys",1983, First published, University of Manchester, England.

(25) "Eutectic point" , From Wikipedia , the free encyclopedia,2007, [http://en.wikipedia.org/wiki/Eutectic point](http://en.wikipedia.org/wiki/Eutectic_point).

(26) Prof. Stephen Nelson , "Two component(Binary) Phase Diagrams", 2004, Tulane University.

(27) D.A.Porter and K.E.Esterling, "phase transformations in metals and alloys",1981, First published, Van Nostrand Reinhold Co. Ltd, England.

(28) G Phanikumar and K Chattopadhyay, "Solidification microstructure development ", 2001, Indian Institute of Science, *Sadhana*, Vol. 26, Parts 1 & 2, pp. 25–34.

(29) J.N.DPuont, "Mathematical modeling of solidification paths in ternary alloys: limiting of cases of solute redistribution",2005, *Sadhana*, Vol. 26, Parts 1 & 2, February–April 2001, pp. 25–34..

- (30) Ludo Froyen and Fabienne Lemoisson, "Solidification of intermetallics in space", 2003, Katholieke Universiteit Leuven, <http://www.kuleuven.ac.be/>.
- (31) José Eduardo Spinellia, Otávio Fernandes Lima Rochab, Amauri Garciaa, "The influence of melt convection on dendritic spacing of downward unsteady-state directionally solidified Sn-Pb alloys", 2006, Materials Research, Vol. 9, No. 1, pp.51-57.
- (32) Atsumi Ohno, "Solidification the separation theory and its practical applications", 1987, Springer-Verlag Berlin Heidelberg, Germany.
- (33) Albert G. Guy and John J. Hren, "Elements of physical metallurgy", 1974, Third Edition, Addison-Wesley Publishing Company, USA.
- (34) Yu. M. Lakhtin, "Engineering physical metallurgy and heat treatment", 1977, MIR publishers, Moscow, Translated from the Russian by Nicholas Weinstein.
- (35) Nikolas Provatas, Quanyong Wang, Mikko Haataja, and Martin Grant, "Seaweed to Dendrite Transition in Directional Solidification", 2003, The American Physical Society, Physical review letters, VOL. 91, No. 15, pp. 155502-1 – 155502-4.
- (36) Rajiv Sampath and Nicholas Zabaras, "A finite variable method for the thermal design of eutectic directional solidification processes in an open-boat configuration", 2001, Taylor & Francis, Numerical Heat Transfer, Part A, 39, pp. 655-683.
- (37) J. Kajornchaiyakul, R. Sirichaivejakul, N. Moonrin, "Solidification characteristics and mechanical properties of hypoeutectic aluminum-silicon alloy containing sulfur", 2005, National Metal and Materials Technology Center, Bangkok, Thailand.
- (38) R. Cornell and H. K. D. H. Bhadeshia, "Aluminum-silicon casting

- alloys", 1999, Materials Word, University of Cambridge.
- (39) E. Paul DeGarmo, J. T. Black, Ronald A. Kohser, "Materials and processes in manufacturing", 2005, Eighth edition, Prentice, Hall of India.
- (40) Hema V. Guthy, "Evolution of the eutectic microstructure in chemically modified and unmodified aluminum silicon alloys", Master thesis, 2002, Worcester Polytechnic Institute.
- (41) Matgorzata Warmuzek, "Aluminum-silicon casting alloys atlas of microfractographs", 2004, ASM International.
- (42) الدكتور خالد احمد الجودي, "مبادئ تكييف الهواء و التثليج", 1986, جامعة البصرة, كليه الهندسة.
- (43) J.P Holman, "Heat transfer", 1976, Fourth edition, McGraw-Hill, USA.
- (44) Mohamed A. Ahmed AL-Said, "Production and mechanical properties of leaded aluminum bearing alloys", 1998, Master thesis, Baghdad.
- (45) John E. Hatch, "Aluminum: properties and physical metallurgy", 1984, First edition, Metals Park, Ohio, American Society for Metals.
- (46) William D. Allister, JR., "Materials science and engineering an introduction 2000, Fifth edition, University of Utah.
- (47) الدكتور قحطان الخزرجي, عادل محمود حسن, "المواد الهندسية و اختباراتها", 1987, جامعة بغداد.
- (48) Marc Andre´ Meyers, "Mechanical behavior of materials", 1999, USA.
- (49) M. Rappaz, "solidification processes :constitutive equations and microstructures", proc conf. modeling of casting welding and advanced solidification processes VI TMS(1993), pp.67-91.

Supervisors Certificate

We certify that this thesis entitled, "*Modeling and experimental analyses of in situ –grown composite to improve the mechanical and physical properties in eutectic system*". Prepared by (*Awham Jumea Salman*) under our supervision at the Department of Materials Engineering/ College of Engineering/ University of Babylon in partial fulfillment of the requirements for the degree of Master of Science in Materials Engineering.

Signature

Name : Dr.Najim A. Saad

(supervisor)

Date : / / 2009

Signature

Name :Dr.Alaa A. Ateia

(supervisor)

Date : / / 2009

Table of symbol

Symbol	Definition	Unit
MMCs	Metal-matrix composites	/
CMCs	Ceramic-matrix composites	/
PMCs	Polymer-matrix composites	/
α	Alpha phase	/
β	Beta phase	/
v	The rate of solidification	$\mu\text{m/s}$
$\hat{G}$	Temperature gradients	$^{\circ}\text{C/mm}$
C	Composition	/
T_n	The nucleation temperature	$^{\circ}\text{C}$
λ	The interlamellar spacing	mm
$\gamma_{\alpha\beta}$	The α/β interfacial energy	J/m^2
$G(\lambda)$	The free energy change associated with the solidification of 1 mol of liquid	J/mol
$\Delta G(\infty)$	The free energy decrease for very large values of λ	J/mol
V_m	The molar volume of the eutectic	m^3
T_E	The equilibrium eutectic temperature	$^{\circ}\text{C}$
ΔT_o	The total undercooling	$^{\circ}\text{C}$
ΔH	Enthalpy term	J/mol
λ^*	The minimum possible spacing	mm
G^{α}	The free energy of the α	J/mol
G^{β}	The free energy of the β	J/mol
$X_B^{L/\alpha}$	The composition of liquid in local equilibrium with the α	wt%
$X_B^{L/\beta}$	The composition of liquid in local equilibrium with the β	wt%
D	The liquid diffusivity	m^2/s
dC/dl	The concentration gradient driving the diffusion	atoms/m^3
k_1	Proportionality constant	/
k_2	Proportionality constant	/
k_3	Proportionality constant	/
k_4	Proportionality constant	/
ΔX	The composition difference	wt%
ΔX_o	The composition difference at ΔT_o	wt%
m	The slope of the liquidus curve	/
C_E	The eutectic composition	/
C_O	The alloy composition	/

A	Constant	/
a	Constant	/
b	Constant	/
R	Interface velocity	$\mu\text{m/s}$
FEM	Finite element method	/
q	The heat-transfer rate	W
K	The thermal conductivity	$\text{W.m/m}^2.\text{°C}$
$\hat{A}$	Area	m^2
$\partial T/\partial x$	The temperature gradient in the direction of the heat flow	°C/m
$\partial T/\partial t$	The temperature gradient with time	°C/sec
$\dot{q}$	Energy generated per unit volume	W/m^3
c	Specific heat of material	J/kg. °C
ρ	Density	kg/ m^3
h	the convection heat- transfer coefficient	$\text{W /m}^2.\text{°C}$
T_w	The wall temperature	°C
T_∞	The fluid temperature	°C
BHN	Brinell hardness number	Kg/mm^2
P	Applied load	kg
D	Diameter of ball	mm
d	Diameter of indentation	mm
t	Depth of the impression	mm
Π	22/7	/
Lt	Total length for tensile sample	mm
Lc	length of reduced section for tensile sample	mm
Lo	Gauge length for tensile sample	mm
b	Width of tensile sample	mm
r	Radius of curvature for tensile sample	mm
d^*	The length of top section for compression sample	mm
h^*	The height of sample	mm
λ'	the length wav	$\text{\AA}^0$
d_{hkl}	the radius of the sphere describing the locus of the reciprocal lattice point (hkl)	$\text{\AA}^0$
Θ	the angle of deviation of the diffracted beam	degree