FE EVALUATION OF THERMAL PROPERTY OF MOULD WALL MATERIAL FOR INVESTMENT CASTING AND THE EFFECT OF LAYERS ON THE HARDNESS OF THE CASTING PRODUCT

PHUAN YOONG JIANN

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(TANDATANGAN PENULIS)

(TANDATANGAN PENYELIA 1)
Dr. Nazri Bin Kamsah

Alamat Tetap : 98B, Kampung Raja,
39010 Tanah Rata,
Cameron Highlands, Pahang

(TANDATANGAN PENYELIA 2)
Dr. Mohd. Hasbullah Idris

Tarikh : **8 April 2005**

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Sesi Pengajian : 2004/2005

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(Tandatangan Penyelia 1 Sebagai Saksi)

(Tandatangan Pelajar)

(Tandatangan Penyelia 2 Sebagai Saksi)

Alamat Tetap:
98B,Kampung Raja,
39010 Tanah Rata,
Cameron Highlands, Pahang.

Nama Penyelia 1: Dr. Nazri Bin Kamsah
Nama Penyelia 2: Dr. Mohd. Hasbullah Idris

Tarikh: 8 APRIL 2005

Tarikh: 8 APRIL 2005

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Date : ……………………………….

Signature : …………………………………
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For my beloved parents, sisters, brother and friends……

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ABSTRACT

This thesis is aimed to investigate and establish a correlation between the mold wall thickness and the mechanical properties of the non-ferrous alloy in investment casting. Mold material of the fine stucco system is investigated. For the investigation proposes, four molds with different thicknesses are established: 5, 7, 9, and 11 layers. Pouring temperature is set to 660°C. After pouring, the temperatures of the outer and inner wall of the mold materials is recorded until the temperature reach the steady state condition. Finite element analysis based on a plane strain assumption is employed to evaluate the thermal conductivity *k*, of the mold material with different thicknesses, based on the experimental steady state temperature of the inner and outer surface of the mold material. The mechanical properties of the casting materials are investigated by observing the microstructure and performed Vickers Hardness Test on the casting specimens. In the findings, the thermal conductivity *k*, of the mold materials is almost the same. The percentage of the silicon flakes for the cast product is decreased with the increasing of mold wall thickness. The Vickers Hardness also decreased with the increasing of mold wall thickness.

ABSTRAK

Thesis ini bertujuan untuk mengkaji dan membina hubungan antara ketebalan acuan dan sifat mekanikal bagi aloi bukan ferrous dalam tuangan invesmen. Bahan acuan bagi system perlaburan halus yang dikaji. Untuk tujuan kajian, empat acuan dengan ketebalan yang berbeza dibina iaitu dengan 5, 7, 9, 11 lapisan. Suhu tuangan untuk kajian ini adalah 660°C. Selepas tuangan, suhu untuk dinding luaran dan dalaman acuan dicatat sehingga suhu mencapai peringkat kestabilan. Thermal konduktiviti k bagi bahan acuan akan ditentukan dengan menggunakan analisis kaedah unsur terhingga. Ini dapat dilakukan dengan menggunakan suhu peringkat kestabilan sebagai unsur boundari. Sifat mekanikal untuk hasil tuangan dapat dikaji dengan melihat mikrostruktur and Vickers Hardness untuk specimen tuangan. Dalam kajian ini, thermal konductiviti k, untuk bahan acuan adalah lebih kurang sama. Peratusan untuk silicon dalam hasil tuangan berkurangan dengan bertambahnya ketebalan acuan. Vickers Hardness juga berkurangan dengan bertambahnya ketebalan acuan.

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LIST OF SYMBOLS

Al	Aluminium
k	Thermal conductivity
Si	Silicon
Mg	Magnesium
MN/m^2	Mega Newton per meter square
RTV	Room Temperature Vulcanizing
HCl	Acid hydrochloride
Ti	Titanium
Al-Si	Aluminium Silicon alloys
H	Hydrogen
O	Oxygen
C	Carbon
P	Phosphorus
N	Nitrogen
B	Boron
LM25	Aluminium-Silicon alloys with 0.7% Silicon and 0.35% Magnesium
Cr	Chromium
Zr	Zircon
Hv	Vickers Harness unit

CHAPTER I

INTRODUCTION

The investment casting or lost wax process has been utilized through history for some 5000 years, principally for the production of ornamental objects, statues and jewelry. It is considered the most ancient of metal casting arts. Technological advances have also made it the most modern and versatile of all metal casting processes. Investment casting is originally used to cast sculptures and other “works of art”, it is now used to cast some of the most complex castings for some of the most critical application.

History of the "lost wax" process dates back several thousands of years, even beyond Egypt's pyramids. Around 500 B.C. started the era of religious upheavals, and metals began to be used for statues of gods and goddesses. It was at this time that lost wax process made its impact. This casting process also traces its roots to the Sang Dynasty in China from 1766 B.C to 1122 B.C.

The Aztec gold-smiths of pre-Columbian Mexico used the lost wax process to create much of their elaborate jewelry, and some very nice examples of these works are from the tribe of Quimbaya, who lived in a little area between the Cauca River and the Micos and Gauiaya rivers. The few castings which survived the plunder of treasur hunters show complete mastery of a difficult and involved technique that must have taken years of trial and error to develop.

1.1 The Renaissance of The Investment Casting

In Europe, this technology can be seen during the sixteenth century, when Benvenuto Cellini describes in his autobiography the method he used to create the Perseo, a great masterwork of Italian renaissance sculpture. To cast this 3 tons statue, Cellini indeed uses the lost wax process. Only at the beginning of 1900 people start using this technology for industrial application.

Dr. Taggart of Chicago was wrote a detailed study on the investment casting process in 1907. Dr. Taggart not only developed and described a technique, he also formulated a wax pattern compound of excellent properties, developed an investment material and invented an air pressure casting machine. [3]

The technology had a great evolution in the United States during World War II, due to the need of precision components with complex geometry such as turbine blades for aircraft engines. At this stage, investment casting became necessary to fill an urgent demand for finished components for the machining tool industry. During World War II, traditional tooling processes were unable to meet the increased demand caused by the war so alternative routes were required. Investment casting became one of those alternatives. Investment casting was the solution for many complexes, undercut parts with smooth surfaces, accurate dimensions and fine detail. Since that time, and particularly in the last decade, the industry has continued to expand due to the advantages it offers not only as a casting process, but to manufacturing on varies products.

During the fifties the lost wax process started to spread over Europe, especially in those fields where complex shaped components and tight tolerances are required. The very first industrial applications of the investment casting process in Italy took place in Gardone Val Trompia, for the production of firearms components.

By 1953, the investment casting industry saw the need for standardization and a need for publishing realistic information regarding the benefits and what customers can expect when specifying investment castings. The industry knew it was imperative for companies producing investment castings to turn out a high quality product which would meet and exceed claims for the new process.

1.2 Recent Researches In Investment Casting

In view of the renewed interest in platinum jewelry it has now become desirable to increase the efficiency of the investment casting process. The effect of the very much higher temperatures involved introduces many difficulties into the casting of platinum. The investments used for casting lower melting point materials are generally based on crystobalite / gypsum mixes; for platinum a more refractory material is required and composition based on silica with additions of phosphate based bonding agents are at present used. A more refractory investment material that may be capable of withstanding higher preheat temperatures, and be more durable at the metal / investment interface, is currently under development in the United States of America. If successful this material will alleviate to some extent a number of the problems faced by the platinum faced by the platinum investment caster. [21]

Another research was carried out by E. K. H. Ho and B. W. Darvell. The purpose of that study was to develop a method for determining casting discrepancy free of interference form oxide, slag and surface defects, working under realistic conditions. In addition, a variable was sought that could be used for calibrating the casting process to allow for local errors. During the study, a crown pattern was designed to incorporate circular V-grooves on the margin and the inside surface of the occlusal part for determination of the 'groove foot diameter' (GRD) with a measuring microscope. Castings using a phosphate-bonded investment were made to test the effects of 'hygroscopic' expansion, burn-out temperature, powder/liquid ratio and groove location. [22]

The tested investment variables showed the expected effects, but the distortion between marginal and pulpal region was clearly shown, as were interactions between some variables. 'Special liquid' proportion appears to be a good candidate variable for process calibration. The GRD method was shown to be sensitive and reproducible. [22]

Mohd Hasbullah Idris, Ali Ourdjini and Esah Hamsah were worked together to investigate the mould cracking during investment casting of magnesium alloy. The investigation focuses on the control of slurry viscosity, shell drying time and dewaxing temperature. According to the paper, several combination of the viscosity of the slurry, stucco system and the dewaxing temperature were developed and are very useful to the current investment casting industrial sector. [23]

1.3 Problem Statement

In investment casting, the parameters and factors which are influence the mechanical properties of the products are Pouring temperature, $T_{pouring}$ and Heat flux, $\dot{Q}_{out}$

The heat transfer equation is:

$$\dot{Q}_{out} = -k\, dT/dx$$

Where $\dot{Q}_{out}$ = Heat flux

k = Thermal conductivity

dT/dx = Temperature gradient

The minus sign is a consequence of the fact that heat is transferred in the direction of decreasing temperature.

$\dot{Q}_{out}$ is depends on the thermal conductivity of the stucco system used during the mould are established. There are two types of stucco system usually used in producing the moulds, fine stucco and coarse stucco. Besides, $\dot{Q}_{out}$ is also influence by the mould wall thickness dx and the temperature gradient dT. Thus, it is useful to investigate the effect of the mould wall thickness on the hardness of the cast products.

The hardness of the casting products is influenced by the heat transfer rate, $\dot{Q}_{out}$. The higher the $\dot{Q}_{out}$, the faster the casting product solidifies. Thus harder and brittle microstructure will be formed.

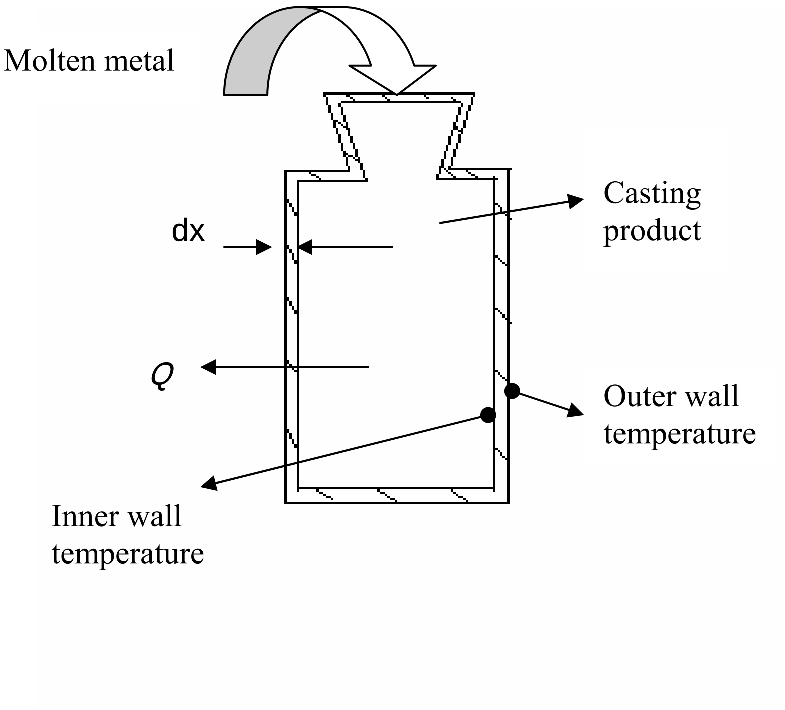


Figure 1.1 Cross section of the mould material

1.4 Objectives

1) To estimate thermal conductivity (*k* value) of the investment casting mould material using Finite Element technique, for four fine stucco system for a given pouring temperature of 660°C.

2) To investigate the effect of number of layers or the thickness of the mould material on the hardness of the cast aluminium alloy products.

1.5 Scopes

For this thesis work, couple of scopes are defined to achieve the objectives of the project and are shown as below:

a) Material to be investigated is LM25 (Al-Si-Mg) alloy.

b) A fixed pouring temperature of 660°C.

c) Steady-state heat transfer analysis to evaluate the *k* value.

d) Mould materials with fine stucco system for 5, 7, 9, 11 layers are studied.

1.6 Methodology

The methodologies of this thesis work are shown as follow:

1) Construct the mould material with fine stucco for 5, 7, 9, 11 layers.

2) Pour molten metal at 660 °C.

3) Temperature of the inner and outer wall of the mould material is measured and recorded until the temperature reached the steady-state condition.

4) Estimate the thermal conductivity (*k* value) of the mould materials by using Finite Element analysis, using the temperature of the inner and outer surfaces, at steady state.

5) Perform the hardness test and inspect the microstructure of the casting product.

CHAPTER II

LITERATURE REVIEW

2.1 Investment Casting

Investment casting is well known variously by the terms lost wax, lost pattern, hot investment and precision or cire-perdue (French – literally, wax – lost). Investment denotes the mechanical manner of obtaining a mould rather than the material used. It is the process of completely investing a three – dimensional pattern in all of its dimensions to produce a one piece destructible mould into which molten metal will be poured. This process uses a pattern of an expendable material, such as wax or polystyrene. Investment casting gives high standard of dimensional accuracy, surface finish, complex geometry and design flexibility without the necessity of extensive machining or other fabrication/ finishing work required to provide a usable end item. The general expendable processes maybe summarized as follows: (1) Construction of a die containing an impression of the expandable patterns, (2) Production and assembly of expendable patterns, (3) Investment of the patterns to form a one piece refractory mould, (4) Pattern elimination and high temperature firing, (5) Casting and finishing [3].

2.2 Procedures for Investment Casting

There are two types of process for the investment casting depends on the desired mould type.

2.2.1 Moulds

a) Block moulds:

Metal die is used to produce the pattern. In this process an expendable pattern of wax, plastic, tin or frozen mercury is used. The pattern (pattern, if several castings are to be made at once) is prepared by attaching suitable gates and risers, and assembly or tree, is place inside a container, usually a stainless-steel cylinder open at each end.

The slurry of suitable binder plus alumina, silica gypsium, zirconium silicate or mixtures of these and other refractories are then poured into a container surrounding the pattern. The container is vibrated in the whole pouring process to remove air bubbles. After the refractory has taken an initial set, the container is placed in an oven at low heat, the refractory becomes harder and as the temperature of the furnace is raised steadily the pattern either melts and flow from the mould, or volatilizes if made of a plastic such as polystyrene.

The mould now contains a cavity in the identical form of the original pattern, the temperature is raised to 600 to 1000°C and molten metal is poured into the hot mould. Any alloy that can be melted is amenable to investment casting by adapting refractory and mould temperature to the requirements of the metal being poured [1].

b) Shell mould:

In a new technique, refractory costs are minimized by forming only a thin shell of the refractory around the pattern: This is accomplished by dipping the wax assembly or tree into a ceramic slurry followed immediately by a coating (stucco) of dry grain. (The composition of the slurry and refractory grain is selected primarily based upon the alloys cast).The coated assembly is then allowed to dry in a controlled environment. The dip, stucco and dry are repeated until a shell of sufficient thickness has been formed.

When the shell is complete, it is necessary to remove the wax invested within. This is accomplished by either placing the shell into a steam autoclave or directly into a preheated furnace. To minimize shell cracks from wax expansion, it absolutely necessary to reach de-wax temperature in a very few seconds. As the wax melts it exits the shell through the runner or sprue system of the assembly. After dewax, the shells can be stored in an uncontrolled environment until scheduled to cast.

Prior to casting the shell is fired primarily to develop the fired strength of the ceramic (green or unfired shells have insufficient strength to contain the metal), and secondarily to remove any traces of the wax. After proper firing, the shells are removed from the furnace and immediately cast unsupported. The metal enters the shell through the runner or sprue system, which must be of proper design to prevent metallurgical defects due to improper gating.

2.2.2 Dies

The die contains an accurate impression and shape of the casting and is used to form the expendable patterns. Dies can be manufactured either in strong alloys such as steel and Duralumin or in softer fusible alloys, while epoxy resins or vulcanized rubber are suitable where accuracy and permanence are less important. Plaster or ‘stone’ dies can be used for short life purposes. Steel dies are most satisfactory for long production runs and are machined from the solid by die sinking and assembly in the tool room: this technique gives the highest standard of accuracy [5].

Dies in fusible alloys are formed by casting and require the preliminary production of a master pattern or metal replica of the final casting. This master pattern requires an allowance for subsequent contractions of pattern and metal, partly offset by expansion of the mould: the net allowance used may be up to 2 %. The master is embedded to a selected joint line in plaster of Paris and the fusible alloy cast directly against the combined surface after drying [5].

For the production of a small number of patterns and where wax is not injected at very high pressure (not higher than 20 kg/cm^2), low melting point alloys, such as tin-bismuth alloy (Cerro-alloy) and zinc alloy, which can be quickly melted and used in as-cast form without any finishing, are most suitable. Silicon-rubber dies are also used for small quantities and intricate shapes [2].

Many dies can be produced in two sections but more complex designs require multiple construction and loose segments to enable the pattern to be extracted by dismantling. Gates for injection of the pattern material are usually machined separately. During production die faces are coated with a parting agent or lubricant, for example a silicone based fluid, to assist pattern extraction [3].

2.2.3 Patterns

The most common pattern material in the investment casting is wax, the term ‘lost wax’ being widely used to describe this version of the process. Wax patterns are excellent for the investment casting process. The materials generally used are blends of several types of waxes and other additives, which act as polymerizing agents and stabilizers. The waxes commonly chosen are paraffin wax, carnauba wax, shellac wax, ceracin wax, and microcrystalline wax [2].

The properties desired in a good wax pattern include [4]:

a) Low ash content (up to 0.05 %, this pattern waxes are compound of strength, contraction characteristic and dimensional stability).
b) Resistance to the primary coat material used for investment.
c) High tensile strength and hardness so that it can retain its shape while being machine and investing.
d) Good wettability.
e) Resistance to oxidation, this makes the waxes can be reused for many times.
f) Low shrinkage so that the cast products with high accuracy in the dimension can be produced.
g) It should have be adhesiveness (weldability) so that the different components part pattern can be joined together to form a complex pattern.
h) Solubility in specific solvents.
i) Resistance to chemical action when binders are used in the investment process.
j) It should be chemically resistant to primary cast and to other binders used in the preparation of investment mould.
k) It should be strong and hard, when solid.

The materials usually melt within the range 55-90 °C. Since reproducible contraction values are essential a single blend of waxes is normally maintained; operating temperatures too must be closely controlled because of the high coefficient of expansion of the pattern material [5].

Pattern can be produced by gravity pouring by hand operated injection gun, or by the use of low pressure injection equipment, most quantity production is based on automatic injection machines offering close control of temperature, pressure and speed of injection. Pressure ranging up to about 2.8 MN/m^2; enable the wax to be injected at lower temperatures, in the pasty rather than the fully molten state. Pressure is maintained for a short and constant dwell time after injection to counteract the high solidification shrinkage and provide better strength. This prevents surface sinks and loss of accuracy [5].

As the patterns are generally small in size, a number of pattern are welded (two ends to be joined by a hot spatula are heated and pressed lightly together) to a common runner or sprue through in-gates. The whole assembly of patterns complete with runner, sprue, etc., which is often termed as “tree”, is then invested to prepare the investment mould [2].

Below are some blends of waxes commonly used in investment casting [5]:

- Paraffin wax 50% and stearine 50% - suitable for small, relatively complex castings as the mixture has low softening temperature low strength and large shrinkage.
- Paraffin wax 60%, Carnauba wax 25%, Cerasin wax 10% and bees wax 5% - suitable for small sized, thin-walled patterns.

- Paraffin wax 30%, Carnauba wax 30%, Cerasin wax 10%, bee wax 10% and dammar resin 10% - suitable for thin-walled, medium to large size casting requiring close dimensions.
- Cerasin wax 20%, resin 20% and polystyrene 30% - suitable for the production o thin-walled and large sized castings requiring tight dimensions and enhanced surface finish but has low fluidity.

Besides the wax, there are also several types of pattern materials used as alternatives in the investment casting. These materials have their own characteristic. Polystyrene, RTV (Room Temperature Vulcanizing), Mercury and some low-melting-point metallic alloys are some of the alternative materials.

Polystyrene of the thermoplastic has been developed as expendable pattern materials. Such patterns are less fragile than wax and can be handled more readily without deterioration. A further advantage is the lower coefficient of expansion, pattern dimensions being consequently less sensitive to temperature variation. It is also less expensive compare to the wax pattern [5].

Polystyrene also tend to become soft and subsequently gasify on heating, the most common is polystyrene foam. This material is available in different densities in foamed (expanded) form. It can be easily shaped, machined and fabricated by gluing to form the pattern Polystyrene behaves as a viscous liquid in the temperature range 200-350°C and required higher injection pressures than those used for wax, up to about 140 MN/m^2 being normal. Polystyrene patterns are eliminated during high temperature firing of the mould. Preliminary drying is carried out below 70 °C to avoid mould cracking associated with a sudden expansion encountered in polystyrene at approximately 82 °C [2].

Polyurethane foam too has been used like polystyrene but to a much smaller extent. Urethane elastomers are applied on a limited scale for forming dies for investment casting. This material has low thermal conductivity, high strength and no shrinkage. Certain types of rubber, such as silicon rubber, are favoured for forming intricate types of dies for investment casting. This material is available in two parts, binder and hardener. When the two parts, originally in liquid form, are mixed together, pour over a master pattern of into a die, and cured, a solid shape is produced [2].

RTV (Room Temperature Vulcanizing) – is often used for the construction of flexible moulds. A catalyst is mixed with liquid rubber and in a few hours vulcanizing takes place at room temperature. RTV offers an easily castable mould material with nonsticking properties and excellent duplication of detail. It is flexible enough to allow it to be stripped from shapes that will not draw [7].

The bubbles from the mix before and after pouring can only be removed by using a vacuum chamber. A salvaged automobile air-conditioner compressor can become a suitable inexpensive vacuum pump. After curing, the RTV mould can be removed from the flask and stripped from the pattern. An irregular incision roughly following the parting line will help provide a match when the RTV mould is closed and reinstalled in the jacket [8].

A further version of precision investment casting is the Mercast process, in which the expendable patterns are produced by casting liquid mercury into the die, which have been cooled to -56°C or even lower, and allowing the mercury to solidify. Exposure to a temperature below -39 °C produces a solid pattern which is high density and good wetting properties, gives faithful reproduction of the die surface [7]. Besides, the pattern provides highest dimensional accuracy because the pattern material does not expand or shrink during change of state from liquid to solid and vice versa. When the investment is brought out at room temperature, the mercury melts by itself and is drained and the moulds are then fired and poured. No injection equipment is required as mercury is merely poured by gravity [2].

The Mercast process face some problems while producing the shell mould because the need to maintain the dip slurry under refrigeration. This can be achieved by using the low freezing point media [7]. The main drawbacks are the expansive equipment required for creating low temperature conditions, the high cost of mercury itself, its handling problems, and its poisonous nature [2].

2.2.4 Investment

Investment castings moulds are of two types – block moulds and shell moulds. Thus, there are two methods of investment to form the moulds – solid investment (block moulds) and shell investment (shell moulds). The process was originally developed using block moulds, produced by slip casting a grog or slurry into a container surrounding the patterns, followed by consolidation and pattern removal. But, there has been increasing use of ceramic shell moulds produced by alternate dip coating of the pattern assembly in refractory slip and stucco finishing with coarse or fine particles. Drying and pattern elimination leaves a permeable shell using only a fraction of the materials required for a block mould. Besides the lower material costs the shell process lends itself more readily to mass production because of the shorter drying times and the possibilities for dip automation [6].

In solid investment, a primary coat (pre-coating) of binder mixed with fine refractory, such as silica flour and zircon flour, is applied to the pattern which is then placed, complete with gating in a metal flask and is surrounded by refractory slurry. The method is speedy but a large quantity of expansive ceramic materials is necessary for preparing the slurry. The pre-coating is not essential for non-ferrous metals. The binder used in preparing the primary coat and investment slurry is ethyl silicate. The following shows the chemical reaction gives rise to the formation of silica gel in a hydrolyzed solution of water, which imparts a permanent siliceous bond [2]:

$$\underset{\text{(Ethyl silicate)}}{Si(OC_2H_5)_4} \quad + \quad \underset{\text{(Water)}}{4H_2O} \quad \longrightarrow \quad \underset{\text{(Ethyl alcohol)}}{4C_2H_5OH} \quad + \quad \underset{\text{(Silicic acid)}}{Si(OH)_4}$$

As water is insoluble in ethyl silicate, methylated spirit is used as a mutual solvent. Dilute 10% HCl also serves as a catalyst. Hydrolysis is catalyzed and the solution held stable by the presence of a small amount of hydrochloric acid, permanent gelation can then be induced by further addition of water and by neutralizing with an alkali to pH > 3. Close control of the pH value in the range 3-6 enables gelation to be timed to suit production requirements [5]. Silicic acid produced by the foregoing reaction gets converted, when heated during the firing stage, into silica gel, which is hard, strong, and permeable mass. This process can also be accelerated in the investment by addition of an alkali or by keeping the investment in an ammonia chamber [2].

Other bonding materials that have been used are (i) Colloidal silica, (ii) Sodium silicate, (iii) A mixture of ethyl silicate and sodium silicate, (iv) Phosphate-bonded materials such as gypsum phosphate, ammonium dehydrogenate phosphate, mono-ammonium phosphate, and mono-magnesium phosphate [2]. In these compounds the bond is developed in aqueous solution without the need for organic solvents. Phosphate bonding, for example, can be represented as follow [5]:

$$MgO + NH_4H_2PO_4 = MgNH_4PO_4 + H_2O$$

In sodium silicate, bonding is brought about by treatment with dilute acids, resulting in a siliceous bond similar to that developed in the carbon dioxide process.

For production of castings in highly reactive metals and alloys interest has been shown in the development of binders free from silica and phosphorus. The objective is to form a refractory oxide bond by dissociation of a suitable salt in reactions analogous to the formation of silica from the silicate binders. This system is based on treatment of aluminium nitrate to form a colloidal aqueous solution of aluminium hydroxide. Setting is affected by treatment with magnesia or ammonia and decomposition on firing produces alumina. Using this binder in conjunction with a corundum base, a highly refractory all-alumina mould can be produced [5].

To form a block mould the main investment is poured as a thick suspension into a container surrounding the inverted pattern assembly. The mould is then vibrated to accelerate settling of the solids and to eliminate air bubbles. In some cases, air is exhausted by vacuum treatment applied to the mixed grog or to the mould container or both. For consolidation of silicate bonded block moulds, excess liquid which separates on settling of the solids needs to be removed, first by decanting and subsequently by evaporation and drying. Moulds are normally held for 12-27 hours before pattern removal and firing.

In the shell investment process, after applying a pre-coating as in the case of solid investment, the pattern assembly is alternately dipped in a coating slurry and stucco with granulated refractory, either by sprinkling or by immersion in a fluidized bed. The grain size of refractory particles varies from 20 to 100 meshes. A fine grain size is used for the initial coat is air-dried before applying the next coat. Refractory grains of high refractoriness, such as zircon, are better suited for high melting points metals, like steels and alloy steel [2].

The shell is built up in successive layers to a total thickness of up to 5mm, each layer being allowed to set initially before application of the next. This intermediate setting may require up to 2 hours but can be accelerated chemically by exposure to ammonia gas or force drying in an air current. The completed investment is air dried for 20-150 minutes before pattern removal and firing [5].

Whether producing block or ceramic shell moulds, the pattern assembly is usually given a preliminary dip or spray coating containing a fine (<200 mesh) suspension of refractory particles in bonding solution. This governs the finish on the casting and enables cheaper grog to be used in the main investment. The primary coating is air dried before application of the main investment but may first be stuccoed with granular material to act as a key and prevent local spilling. The dried assembly may be given a waterproof coating to avoid dissolution in the investment medium. In certain cases the primary coating is used to produce finer and more reproducible microstructures in the castings.

2.2.5 Stucco System

Fused silica, zircon flour, siliminite flour are used as refractory materials for pre-coat and backup coat slurries. Stuccoing these pre-coat and backup coats is carried out using coarser refractory materials such as zircon sand, kyanite sand and high alumina sand.

The investment casting process uses moulds from refractory materials which completely surrounded a wax pattern which then melted out or burned out without leaving any residue. The thickness is made up alternate strata of 6 to 8 mm. This thickness is made up of alternate strata of fine and coarse refractory aggregates. The required thickness of the coating cannot be obtained in a single coating.

The function of the primary coating is to serve as an interface between the main body of the investment and smooth surface of the pattern. Thus, the surface finish of the coating depends on the quality of the primary coating. While the primary coating still wet, coarse or fine refractory particles are applied on to it as stucco. The purpose of the stucco is to minimize the drying stresses in the coatings by presenting a number of stress concentration centers which distribute and hence lower the magnitude of drying stresses. The second main purpose of the stucco is to present a rough surface thus facilitating a mechanical bond between the primary and the secondary investment [6].

Rounded grain shape is recommended for primary stucco as it influences the surface finish of the mould wall. Good surface finish, smoother yield and capability to sustain good film thickness can be acquired by using the rounded grains. A satisfactory distribution of grain sizes the value of degree of uniformity is usually between 60 to 70%. The specific gravity of the aggregates governs the mould weight as well as the coverage power of the slurry. The advisable surface area of the fine aggregates varies from 1616.9 to 5067.1cm^2/gm [6].

The refractory for coarser aggregates may be rounded or angular or sub-angular in shape. Rounded grains are preferred to other shape because they possess more contact area, good packing characteristics and uniform backup for primary coat. Finer and well-rounded grains of the primary stucco will show the effects of the primary slurry. A satisfactory distribution for stucco sands varies from 0.15 mm to 0.830 mm. The degree of uniformity is in the range of 70 to 90%. The criteria of the selection for the primary stucco sands are permeability, strength, cost and availability [6].

According to Bidwell, the most commonly used refractory aggregates are the following [6]:

(1) Silica (SiO_2), (2) Alumina (Al_2O_3), (3) Chromic oxide (Cr_2O_3), (4) Magnesia (MgO), (5) Zircon $(ZrSiO_2)$, (6) Calsines China Clay (42-44% Alumina), (7) Siliminite $(Al_2O_3.2SiO_2)$(42-44% Alumina), (8) Mullite $(3Al_2O_3.2SiO_2)$ (56-79% Alumina), (9) Fire Clay Grog.

The following show some examples of the fine and coarse aggregates [6]:

Fine aggregate: (1) Zircon flour, (2) Siliminite, (3) Fuses silica grade Fw, (4) Fused silica grade Fp.

Coarse aggregate: (1) Zircon, (2) Kyanite, (3) Bauxite, (4) High Alumina.

2.2.6 Dewaxing and Mould Firing

After the initial setting and air drying of the mould, the next stage is pattern elimination or ‘dewaxing’ and then pre-heating. Pre-heating is done to remove all residues of wax or plastic or other pattern materials. The actually time and temperature cycle fir dewaxing and pre-heating depends on the type of binder and refractory materials used, the metal composition and the method of investment [2].

The early drying stage has been emphasized because it is a critical stage to avoid cracking of the investment. A further factor in cracking is expansion of the pattern on heating, especially in the case if thin walled ceramic shell moulds. For the block mould, the method of dewaxing is to heat the mould to a temperature slightly above the melting point of the wax, which is allowed the wax to be drained out. The residue is volatilized and burn out during further heating to the firing temperature.

For shell mould, there is one technique to drain the wax out, called flash dewaxing, in which the temperature is raised rapidly to approximately 1000°C by placing the cold assembly directly into the furnace. Under these conditions a steep temperature gradient produces superficial melting of the wax before it undergoes appreciable expansion. In this technique, dewaxing and firing are completed in a single operation of about 2 hours [5].

Besides, there is another way to dewax the shell mould. It can be achieved by using steam pressure at lower temperatures. By using this technique, shell moulds can be dewaxed without cracking. The steam pressure is developed and dewaxing completed in a few minutes with high wax recovery, thus can reduce the cost on wax. Thermal shock is much less than in high temperature burnout.

There is a further method on dewaxing by using trichloroethylene solvent in a vapour degreasing installation. Other techniques include support of the ceramic shell in hot refractory granules so as to maintain the mould under compression during the critical stage of heating to the dewaxing temperature [5].

In the Mercast process, the danger and possibility of shell cracking is diminished because of the lower volume expansion of mercury. Melt out of the pattern assembly is assisted by a jet of liquid mercury directed against the sprue.

Firing of moulds other than plasters based moulds is normally completed at temperatures around 1000°C. Firing of the moulds brings about final dehydration and full development of dry strength, elimination of organic material and preheats the mould to the casting temperature. Preheat the mould will facilitate metal flow and reproduction of mould detail. For the mould with less refractory plaster investments which is used to cast non-ferrous alloys are fired at lower temperatures in the range 550-650°C, and higher temperatures during the firing is avoided because the binder partly decomposes above 650°C. Ignition of the wax is also avoided so that volatilization prevents carbonaceous residues [5].

2.2.7 Casting / Pouring

Besides the simplest method by using hands in pouring the molten metal into the mould, there are several others techniques can be used to achieve the same goal. These techniques included using air pressure, vacuum (suck the air from the mould), gravity cast and centrifugally cast.

Gravity casting is frequently used for ceramic shell moulds, because the shell moulds provide high permeability. Pressure casting is widely used with Merrick furnace, in which a single charge of metal is melted by indirect carbon arc, after which the heated mould is inverted and clamped over the furnace outlet. The compressed air at a pressure of up to about $70 kN/m^2$ is admitted above the metal [5].

There is one technique where metal is displaced upwards into the inverted mould. This can be done by pressure exerted on the surface of an enclosed bath. In the

U.S.A, Chandly and Lamb have introduced a casting process called C.L.A process which is similar to this system. In this process, the procedures are [2]: (i) place the ceramic shell mould upside down in a closed chamber, (ii) submerging the sprue portion of the mould, protruding out of the chamber, in a molten metal bath, (iii) creating a vacuum in the chamber using the vacuum pump to suck the molten metal into the mould, this can make sure the mould is fully filled by the molten metal, (iv) release the vacuum when the casting is solidified, this step will release most of the molten metal in the sprue to return to the bath.

Mould filling is achieved fast and it can be precisely controlled. There is practically no turbulence and castings as thin as 0.3mm have been easily produced in this process. Castings also free from dross and inclusions. Casting yield as high as 90.92% can be achieved and rejection can be largely eliminated. Since no ladle is employed for transporting the molten metal, much less superheating of the metal is required and lower casting temperatures are possible, enabling fine as-cast structure of the metal [2].

Centrifugal casting is usually carried out on vertical axis machines with provision for clamping mould assembly to the turntable. Very small moulds such as those used in dental casting are cast on special machines rotating about either a horizontal or a vertical axis. These provide for melting small charges which are then centrifuged directly from the crucible into the mould [5].

To cast the high temperature alloys, vacuum melting and casting are increasingly used. This is because casting under vacuum not only improves metallurgical quality but facilitates the running of thin sections by eliminating back pressure of air. Ceramic shell moulds can be cast cold if it given rapid pouring. By using the vacuum cast, some installation incorporate vacuum locks through which preheated moulds can be successively loaded into the vacuum chamber, without pumping down from atmospheric pressure during each cycle [5]. Thus, save a lot of time and energy on each cycle. The basic steps in the investment casting are illustrated in **Figure 2.1**.

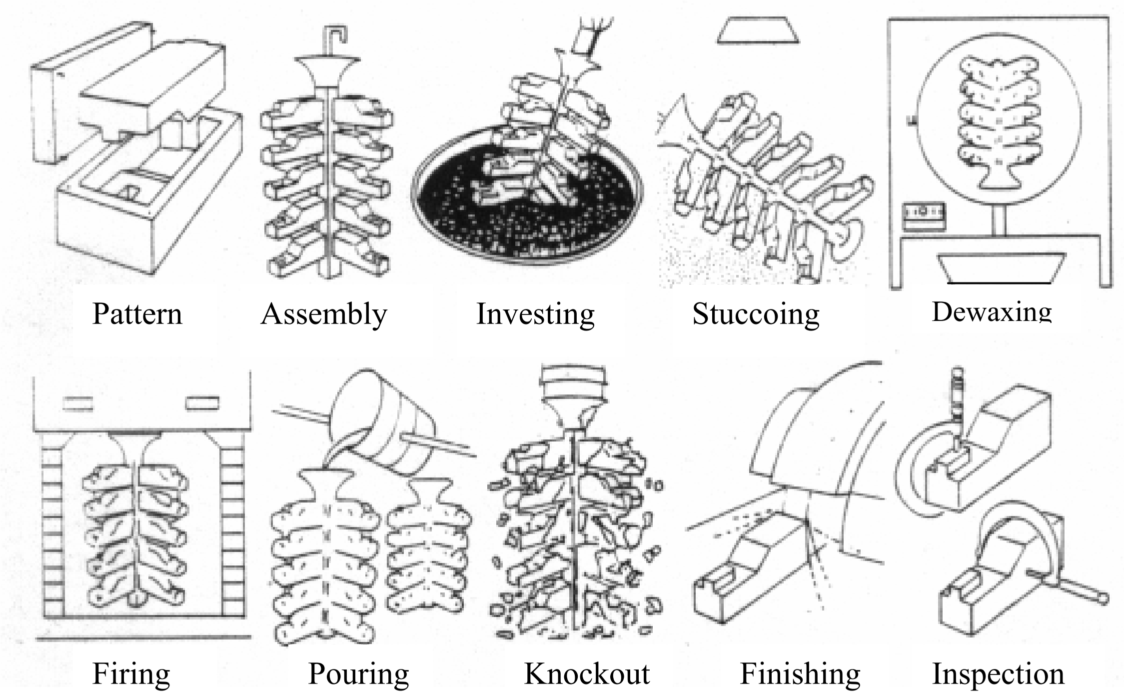


Figure 2.1 Steps in the investment casting process [8].

2.3 General Investment Casting Procedures for Shell Mould

1) Form the desire patterns by using wax or plastic.
2) Patterns are gated to the center sprue and this is also called assembly.
3) Investing or dip the pattern clusters in the ceramic slurry.
4) Sift refractory grain onto coated pattern and this process is called stuccoing.

5) Repeat steps 3 and 4 until the desired thickness is achieved.
6) Dewaxing or melt patterns out from the moulds.
7) Firing or pre-heating of the moulds.
8) Pour the hot moulds with molten metal.
9) Break the mould material away from the castings.
10) Finishing.

2.4 Application of Investment Casting

Applications for investment castings exist in most manufacturing industries. The largest applications are in the aircraft and aerospace industries, especially turbine blades and vanes cast in cobalt and nickel-base superalloys as well as structural components cast in superalloys, titanium and 17-4-PH stainless steel. A partial list of the applications for investment casting is given as below:

- Dentistry and dental tools
- Electrical equipments
- Electronics, radar
- Guns and small armaments
- Hand tools
- Jewelry
- Machine tools
- Materials handling equipments
- Metalworking equipments
- Oil well drilling and auxiliary equipments
- Aircraft engines, air frames, fuel systems
- Agriculture equipments

- Baling and strapping equipment
- Cameras
- Communications
- Optical equipments
- Packaging equipments
- Pneumatic and hydraulic systems
- Prosthetic appliances
- Pumps
- Sports gear and recreational equipments
- Stationary turbines
- Textile equipments
- Transportation, diesel engines
- Valves
- Aerospace, missiles, ground support systems
- Automotive
- Bicycles and motorcycles
- Computers and data processing
- Construction equipment

Piston engines used in older aircraft and on some small general aviation planes also benefited from investment casting. Investment casting is used in the production of these engines particularly for the same reason it is used in the gas turbine engines.

2.5 Advantages and Disadvantages of Investment Casting

Since the investment casting process is widely in use to manufacture the products in many fields like aerospace, automobile, communication and so on. Thus, this process surely has it own advantages. But in contrast, there are also disadvantages in this process. Some advantages and disadvantages are listed below.

2.5.1 Advantages of Investment Casting

- In general, investment casting produces high accuracy and fine surface finish. Tolerances close to ± 0.1mm can be achieved on small components [2].
- Extremely smooth surfaces are easily produced in investment-cast parts.
- The surface finish around 1-5 microns (Ra value, IS: 3073-1967) are possible to be achieved. Thus, investment casting makes possible the elimination of most machining operation including thread cutting and gear-tooth forming.
- This process generally provides for an increased yield [7].
- Investment casting is adaptable to more complex and smaller designs in both limited and production lots [7].
- Investment casting is adaptable to all metallic alloys.

2.5.2 Disadvantages of Investment Casting

- The limitation of size and weight by physical and economic considerations render the process best applicable to castings weighing from a few grams to 5 kg. Thus, the large objects are impractical owing to equipment-size limits [7].
- Precise control is required at all stages of production. Special equipment is required for preparing patterns making investment, etc. for efficient use of the process [7].
- The raw materials, special tooling, equipment, and technology required are expensive.
- There is a slower production cycle that makes the process less applicable where the smooth surfaces and fine details are not essential [2].

2.6 Non-ferrous Alloys

Metals are designated as either ferrous or nonferrous. Iron and steel are ferrous metals, and any metal other than iron or steel is called nonferrous. Nonferrous metals such as gold, silver, copper and tin were in use hundreds of years before the smelting of iron; yet some nonferrous metals have appeared relatively recently in common industrial use. For example, aluminium was first commercially extracted from ore in 1886 by the Hall-Heroult process, and titanium is a space-age metal that has been produced in commercial quantities only since World War II. Cadmium, chromium, cobalt, brass, bronze, lead, magnesium, manganese, nickel and zinc are some examples for nonferrous.

2.7 Aluminium

Aluminium is white (or white-gray if the surface is oxidized) and can have any surface finish from dull to shiny and polished. Aluminium has a density (or weight) of 2700kg/m³ as compared to 7800kg/m³ for steel, and pure aluminium has a melting point of 660°C. Aluminium alloys have a specific gravity of 2.55 to 2.77. **Table 2.1** shows the general properties of aluminium [10]. The outstanding characteristics of aluminium and its alloys are their strength-weight ratio, their resistance to corrosion and their high thermal and electrical conductivity; they are non toxic and can be wrought and cast by all conventional, and a few less usual, methods and can be profitably recycled.

Table 2.1 Properties of aluminium [13].

Property	Value
Density	2.7 g/cm³
Melting point	660°C (1220°F)
Tensile strength	10000 – 80000 psi
Yield strength	5000 – 68000 psi
Modulus of elasticity	10.6×10^{6} psi
Maximum percent elongation	14 – 15%
Poisson's ratio	0.33
Electricity resistivity	$3 \times 10^{-6}\ \Omega/\text{cm}^{3}$
Thermal conductivity	130 Btu/hr/ft²/°F
Coefficient of thermal expansion	13×10^{-6} in./in./°F
Heat capacity	0.23 Btu/ib/°F
Tensile strength/density	100000 – 800000in.

2.7.1 Classification of Aluminium

There are several numerical systems used to identify aluminium, such as federal specifications, military specifications, the American Society for Testing & Materials (ASTM) specifications, and the Society of Automotive Engineers (SAE) specifications. The system most used by manufacturers, is one that was adopted by the Aluminium Association in 1954 [11].

Table 2.2 Designation of wrought aluminium alloys [11].

Code Number	Major Alloying Element
1xxx	None
2xxx	Copper
3xxx	Manganese
4xxx	Silicon
5xxx	Magnesium
6xxx	Magnesium and silicon
7xxx	Zinc
8xxx	Other elements
9xxx	Unused (not yet assigned)

From **Table 2.2**, the first digit of a number in the aluminium alloy series indicates the alloy type. The second digit, represented by an x in the table, indicates any modifications that were made to the original alloy. The last two digits identify either the specific alloy or aluminium impurity. For an example, an aluminium alloy number 5056 is an aluminium-silicon alloy, where the first 5 represents the silicon, the second digit represents modifications to the alloy, and the last 5 and 6 are numbers of a similar aluminium alloy of an older marking system.

Aluminium and its alloys are produced as castings or as wrought (cold-worked) shapes such as sheets, bars and tubing. Some of the aluminium alloys can not be heat-treated. Thus they can only be hardened by cold working. These temper (hardness) designations are made by a letter that follows by the four-digit alloy series number.

- F	As fabricated. No special control over strain hardening or temper designation is noted.
- O	Annealed, recrystallized wrought products only. Softest temper.
- H	Strain hardened, wrought products only. Strength is increased by work hardening.

The letter ‘H’ is always followed by two or more digits. The first digit, 1, 2 or 3, denotes the final degree of strain hardening.

- H1	Strain hardened only.
- H2	Strain hardened and partially annealed.
- H3	Strain hardened and stabilized.

The second digit denotes higher strength tempers.

2	¼ hard
4	½ hard
6	¾ hard
8	Full hard
9	Extra hard

For example, 5056-H18 is an aluminium-magnesium alloy, strain hardened to a full hard temper.

For the heat-treatable aluminium alloys, the letter ‘T’ follows the four-digit series number. Numbers 2 to 10 follow this letter to indicate the sequence of treatment.

- T2 Annealed (cast products only).
-T3 Solution heat treated and cold worked.
-T4 Solution heat treated but naturally aged.
-T5 Artificially aged only.
-T6 Solution heat treated and artificially aged.
-T7 Solution heat treated and stabilized.
-T8 Solution heat treated, cold worked, and artificially aged.
-T9 Solution heat treated artificially aged, and cold worked.
-T10 Artificially aged and then cold worked.

For example, 2024-T6 is an aluminium-copper alloy, solution heat treated and artificially aged.

The Aluminium Association designation system attempts alloys family recognition by the following scheme [10]:

- 1*xx.x*: Controlled unalloyed compositions
- 2*xx.x*: Aluminium alloys containing copper as the major alloying element
- 3*xx.x*: Aluminium-silicon alloys also containing magnesium and/or copper
- 4*xx.x*: Binary aluminium-silicon alloys
- 5*xx.x*: aluminium alloys containing magnesium as the major alloying element
- 6*xx.x*: Currently unused
- 7*xx.x*: Aluminium alloys containing zinc as the major alloying element, usually also containing additions of either copper, magnesium, chromium, manganese, or combination of these elements
- 8*xx.x*: Aluminium alloys containing tin as the major alloying element
- 9*xx.x*: Currently unused

2.8 Aluminium-Silicon Alloys

Aluminium casting alloys must contain, in addition to strengthening elements, sufficient amounts of eutectic-forming elements (usually silicon) in order to have adequate fluidity to feed the shrinkage that occurs in all castings processes. These required amounts of eutectic formers depend in part on casting process. The range of cooling rates characteristic of the casting process being used controls to some extent the distribution of alloying and impurity elements [9].

Most aluminium foundry alloys can be cast by all processes, and choice of casting technique usually is controlled by factors other than alloy composition. A large number of aluminium alloys has been developed for casting, but most of them are varieties of six basic types: aliminium-copper, aluminium-copper-silicon, aluminium-silicon, aluminium-magnesium, aluminium-zinc-magnesium and aluminium-tin alloys [9].

Aluminium-silicon alloys that do not contain copper additions are used when good castability and good corrosion resistance are needed. If high strength is also needed, magnesium additions make these alloys heat treatable. Alloys with silicon contents as low as 2% have been used for casting, but silicon content usually is between 5 and 13%. A portion of the equilibrium diagram is shown in **Figure 2.2**. An eutectic is formed at approximately 11.7% silicon, and below this amount the structure consists of primary aluminium plus eutectic while above it is composed of eutectic with amounts of free silicon according to the percentage present [10].

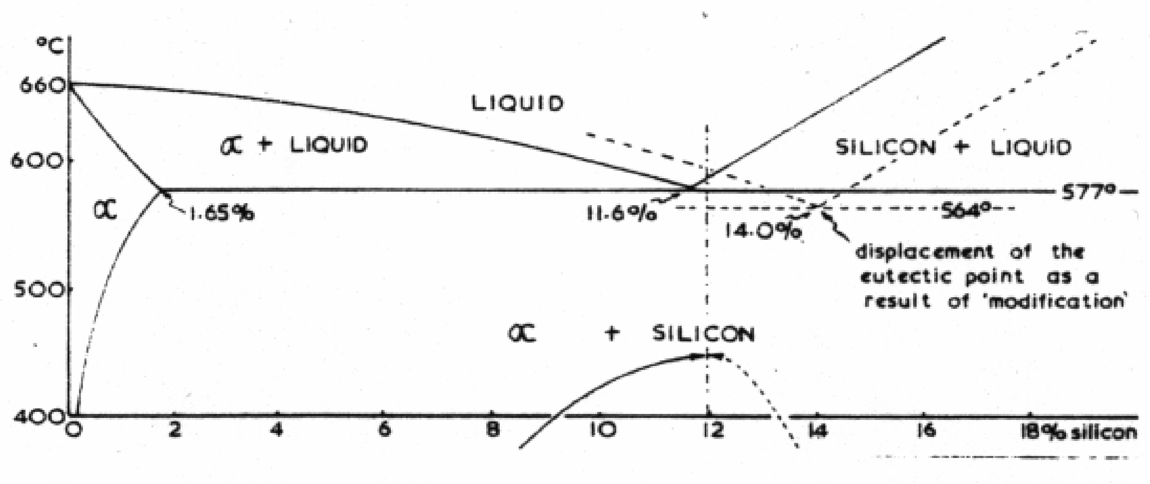


Figure 2.2 Phase diagram of Al-Si alloys.

2.8.1 Modification of Aluminium-Silicon Alloys

Strength and ductility of the aluminium alloys, especially the ones with higher silicon, can be substantially improved by “modification”. This can be effectively achieved through the addition of a controlled amount of sodium or strontium, which refines the silicon eutectic. Calcium, antimony and phosphorus additions are also used. These additional elements to hypoeutectic aluminium-silicon alloys results in a finer lamellar or fibrous eutectic network [9]. Various degrees of eutectic modification are shown in **Figure 2.3**.

The reason for low mechanical properties in unmodified Al-Si alloys is caused by the existence of coarse silicon plates that act as internal stress raisers in the microstructure and create more paths for fracture. With modification, the structure becomes finer and the silicon more rounded, both of which contribute to higher values of ultimate tensile strength and greatly increased the value of ductility.

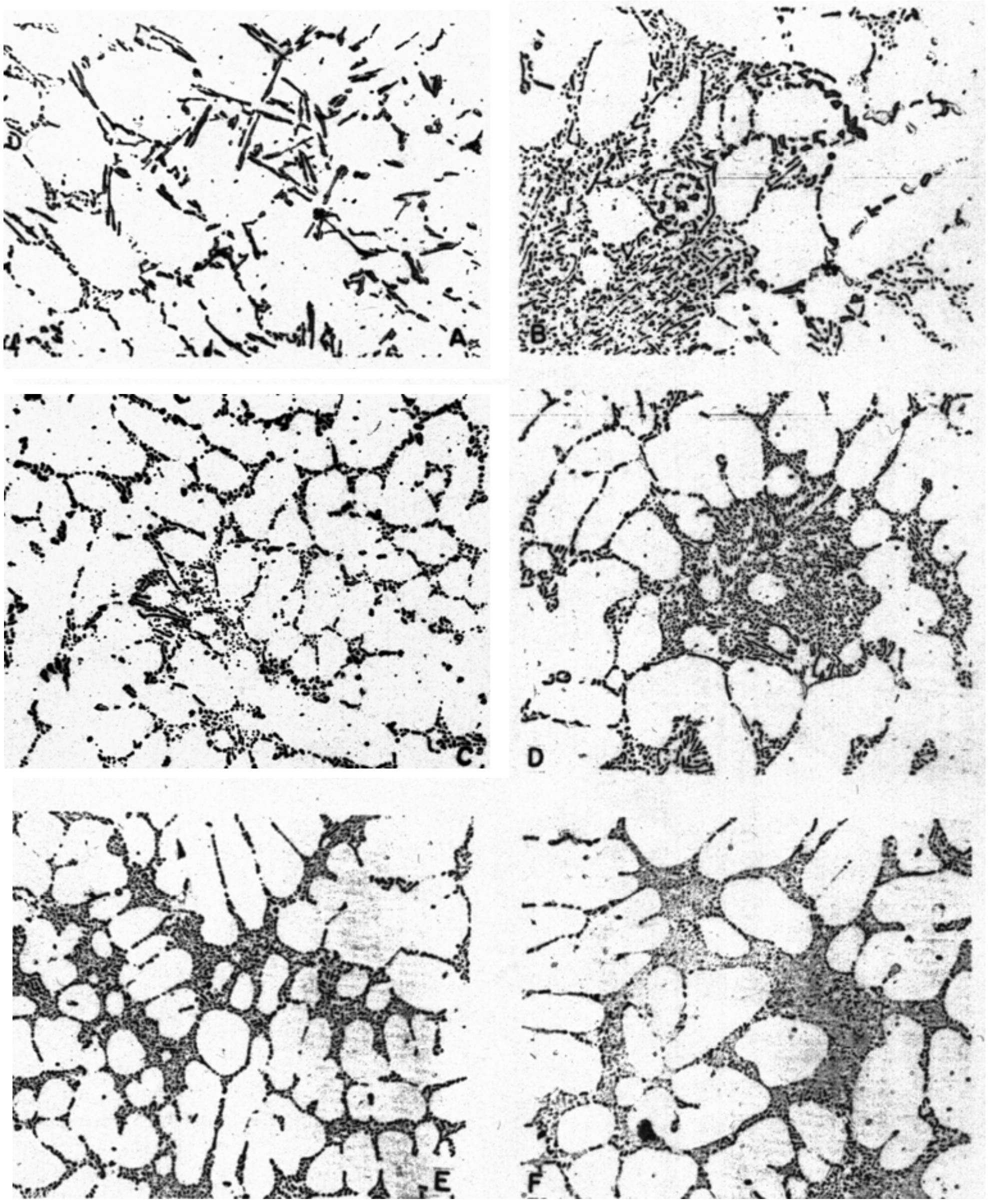


Figure 2.3 Varying degrees of aluminium-silicon eutectic modification ranging from unmodified (A) to well modified (F) [8].

The results of modification by strontium, sodium and calcium are similar. Sodium has been shown to be the superior modifier, followed by strontium and calcium, respectively. Each of these elements is mutually compatible so that combinations of modification additions can be made without adverse effects.

Very low sodium concentrations (~0.001%) are required for effective modification. More typically, additions are made to obtain sodium content in the melt of 0.005 to 0.015%. A much wider range of strontium concentrations are in use. A range of 0.0015 to 0.050% is standard industry practice. Normally, good modification is achievable in the range in the range of 0.008 to 0.015% Sr. To be effective in modification, antimony must be alloyed to approximately 0.06%. In practice, antimony is employed in the much higher range of 0.10 to 0.50% [8].

It has been well established that phosphorus interferes with the modification mechanism. Phosphorus reacts with the sodium and probably with strontium and calcium to form phosphates that nullify the intended modification additions. It is therefore desirable to use low-phosphorus metal when modification is a process objective and to make larger modifier additions to compensate for phosphorus-related losses. Primary producers may control phosphorus contents in smelting and processing to provide less than 5 ppm of phosphorus in alloyed ingot.

Typically, modified structures display somewhat higher tensile properties and appreciably improved ductility when compared to similar but unmodified structures. **Figure 2.4** illustrates the desirable effects on mechanical properties that can be achieved by modification.

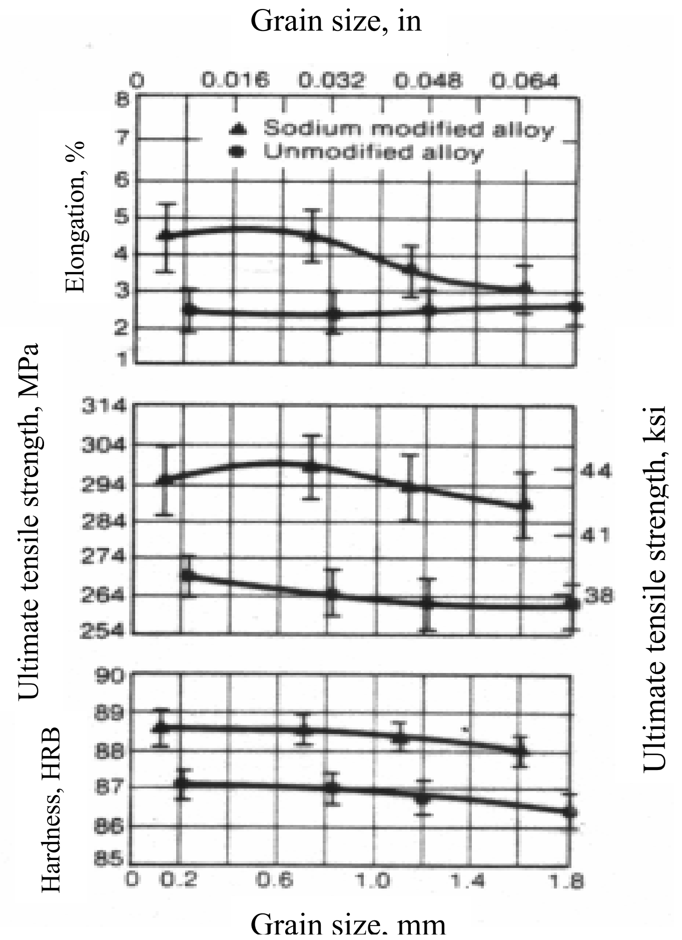


Figure 2.4 Mechanical properties of as-cast A356 alloy as a function of modification and grain size. [9]

2.8.2 Grain Refinement of Aluminium-Silicon Alloys

All aluminium alloys can be made to solidify with a fine grain structure through the use of suitable grain-refining additions. The most widely used grain refiners are master alloys of titanium or of titanium and boron, in aluminium. Aluminium-titanium refiners generally contain from 3 to 10 % Ti. The same range of titanium concentrations is used in Al-Ti-B refiners with boron contents from 0.2 to 1% and titanium-to-boron ratios ranging from about 5 to 50. Although grain refiners of these types can be considered conventional hardeners or master alloys, they differ from master alloys added to the melt for alloying purpose alone. To be effective, grain refiners must introduce controlled, predictable and operative quantities of aluminides (and borides) in the correct form, size and distribution for grain nucleation.

Additions of titanium in the form of master alloys to aluminium casting compositions normally result in significantly finer grain structure. The period of effectiveness following grain-refiner addition and the potency of grain-refining action are enhanced by the presence of TiB_2.

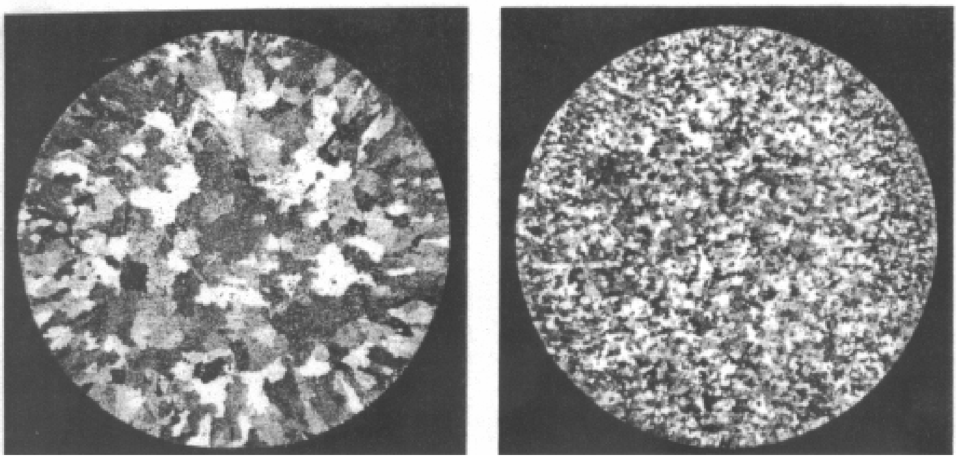
The role of boride in enhancing grain refinement effectiveness and extending its useful duration is observed in both casting and wrought alloys, forming the basis for its use. However, when the boride is present in the form of large, agglomerated particles, it assumes the character of a highly objectionable inclusion with especially damaging effects in machining. Particle agglomeration is found in master alloys of poor quality or it may occur as a result of long quiescent holding periods.

A finer grain size promotes improved casting soundness by minimizing shrinkage, hot cracking and hydrogen porosity. The advantages of effective grain refinement are:

- Improved feeding characteristics
- Increased tear resistance
- Improved mechanical properties
- Increased pressure tightness
- Improved response to thermal treatment

- Improved appearance following chemical, electrochemical and mechanical finishing

The coarse columnar grain structure (**Figure 2.5 a**) is less resistant to cracking during solidification and post solidification cooling than the well-refined grain structure of the same alloy shown in **Figure 2.5 (b)**. This is because reduced resistance to tension force at elevated temperature may be expected as a result of increased sensitivity to grain-boundary formations in coarse-grain structures.



(a) **(b)**

Figure 2.5 As-cast Al-7Si ingots showing the effects of grain refinement. (a) No grain refiner. (b) Grained refined.

CHAPTER III

EXPERIMENTAL PROCEDURES

3.1 Mould Preparation and Casting

Mould with the desire shape need to be formed before casting. The procedures of the mould making and the casting is describes in the following sections.

3.1.1 Production of the Patterns

To produce the patterns, PVC pipes with 9cm height and 5.8cm in diameter have been used as the dies. The wax patterns used for preparation of investment casting moulds consist of a mixture of 70% paraffin wax and 30% bees wax.

First of all, the die was placed on a brick. The wax is then heated up to 80°C which is slightly above the melting point of the wax by using an electrical resistance heater inside a small container. The molten wax is then poured into the die. After that, the patterns are left to cool in room temperature for an approximately 1 hour. This is to ensure that the wax is completely solidified. After that, the pattern is removed from the brick and the die.

All the patterns were sand blasted to make the patterns' surface stick able to the investment slurry. **Figure 3.1** and **Figure 3.2** show one of the patterns before and after sand blast.

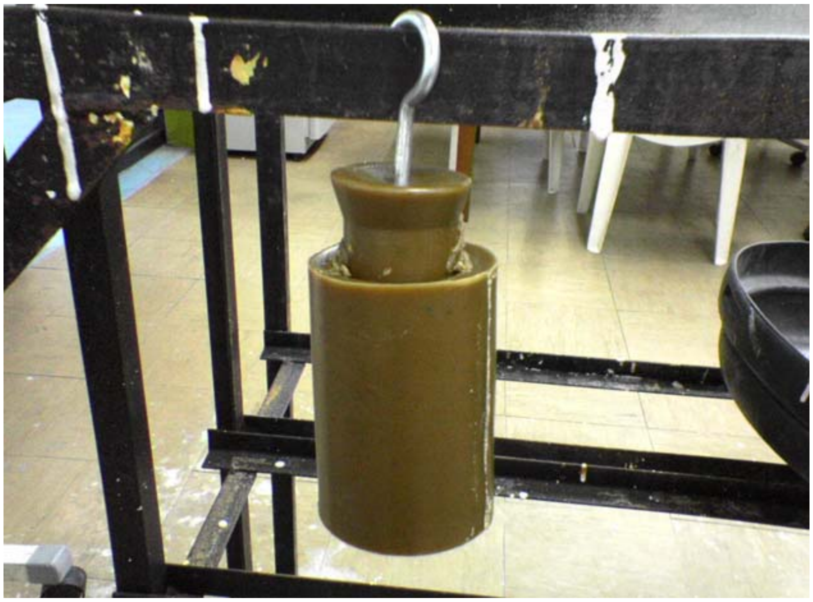


Figure 3.1: Cylinder-shaped pattern

Figure 3.2: Pattern after sand blasted.

3.1.2 Mixture of the Slurry

The slurry is being mixed by using the zircon sand and colloidal silica as the binder. Zircon sand is famous of its dimensional stability, less effect of mould metal reaction and good rheology property. While the colloidal silica is chosen as the binder because it is water based material and does no emit harmful gases during dewaxing and pouring stage.

The first stage in mixing the slurry is to add the zircon slowly into a container that is contains 1000ml of colloidal silica. The mixture is being stirred by using the mixer which is operating at 30 rpm. The zircon is added until the desired viscosity of the slurry is obtained. **Figure 3.3** shows the mixture of the slurry being stirred by the mixer.

Figure 3.3 The mixture of the slurry

3.1.3 Mould Making

When the slurry is ready, the pattern is dipped into the slurry. Just after the dipping, the pattern is then coated with the refractory material by sprinkling the refractory on the dipped pattern. This process is called stuccoing. **Figure 3.4** shows the stucco system for 5 layers. The refractory material used to form the stucco system is Mollochite, and the grade of the Mollochite used is fine.

The pattern is then left to dry in the room temperature for about two hours. This is to ensure that the mould is completely dry before the next dipping process. The dipping and stuccoing process is repeated until the desired layers of the mould are achieved. The desired layers are 5, 7, 9 and 11 layers. **Figure 3.5** shows the mould with 5 layers. When the last coat is applied, the moulds are then let to dry in room temperature for bout 16 to 48 hours. This is to ensure that the mould is completely dry to reduce or avoid cracking of the mould during dewaxing.

Figure 3.4 Stucco systems for the mould with 5 layers

Figure 3.5 Mould with 5 layers

A hole is then drilled by hands around the center of the moulds. The hole about 6 mm in diameter is drilled before dewax is used to insert the thermocouple's probe in order to measure the inner wall temperature during the pouring stage.

The last stage before the metal pouring process is dewaxing. The dewaxing temperature is about 200°C to 300°C. And the dewaxing time is about an hour. This is a critical stage in the mould making procedures because the wax will expand during melting and there is possibility of the moulds to crack. This is follow by the mould firing to remove all the wax residues inside the moulds. The mould firing temperature for this experiment is around 400°C.

3.1.4 Casting

After all, the moulds are ready for pouring. In this experiment, thermocouple is used to obtain the inner and outer wall temperature of the moulds. Thus, before pouring, one of the thermocouple probes is inserts into the hole drilled before dewaxing, and one more thermocouple probe is attached to the outer wall of the mould.

The last stage is to pour the melting metal into the mould. The non-ferrous metal use for the casting is aluminium LM-25. The metal is melted in an induction furnace, and the pouring temperature is 660°C. Once the metal filled into the mould, the temperature is recorded for each 2 minutes for the first 40 minutes, and is then recorded for each 5 minutes. The whole process takes 3 hours.

3.2 Calibration of Thermocouple

Calibration is done to make sure the thermocouple can provide the correct and precise measurement.

To accomplish the calibration of the thermocouple, first of all, water is boiled in a container. This is followed by inserted the thermocouple’s wires and a lab thermometer into that container with boiled water. The water in the container is then left to cool naturally in room temperature. The temperature is recorded whenever the calibration data was changed until it fell to about 50°C. The temperatures obtained are shown in **Table 3.1**.

Table 3.1 Recorded temperature.

Channel	Temperature (°C)										
1	99	96	92	87	81	76	71	66	61	56	50
2	99	97	93	87	82	77	72	66	61	56	51
3	99	97	92	87	83	77	72	67	61	57	52
4	100	97	92	87	83	78	73	68	62	57	51
5	100	97	93	87	83	78	73	68	62	57	51
6	100	97	93	87	83	78	71	68	62	57	51
Thermometer	Temperature (°C)										
	100	95	90	85	80	75	70	65	60	55	50

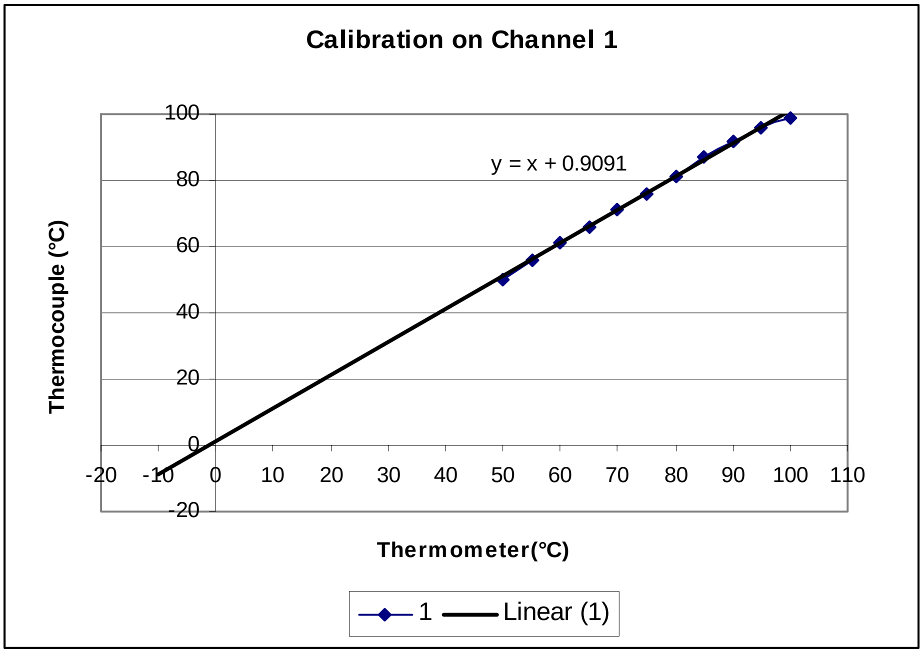


Figure 3.6 Temperature correction graph for channel 1.

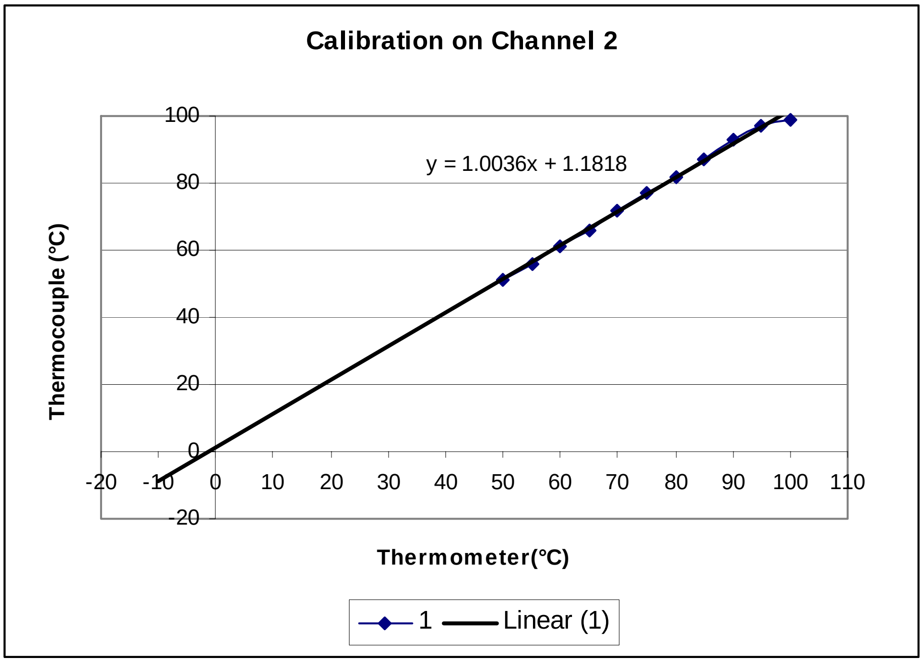


Figure 3.7 Temperature correction graph for channel 2.

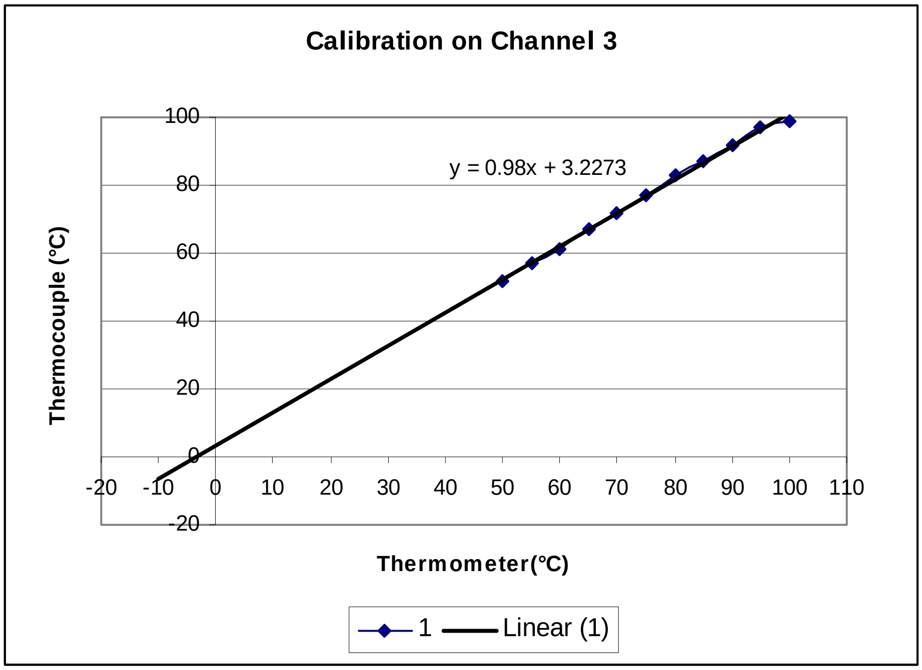


Figure 3.8 Temperature correction graph for channel 3.

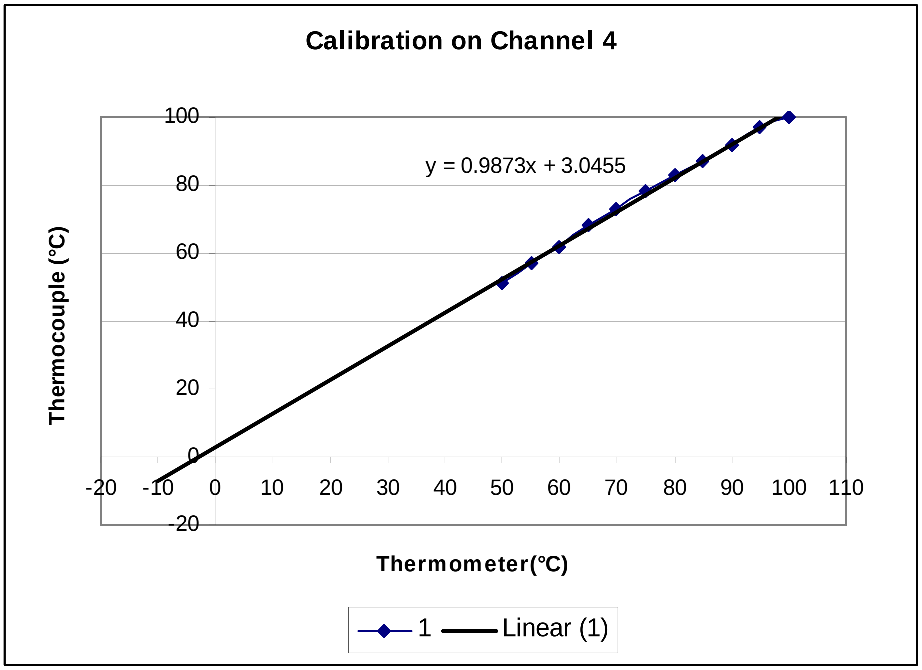


Figure 3.9 Temperature correction graph for channel 4.

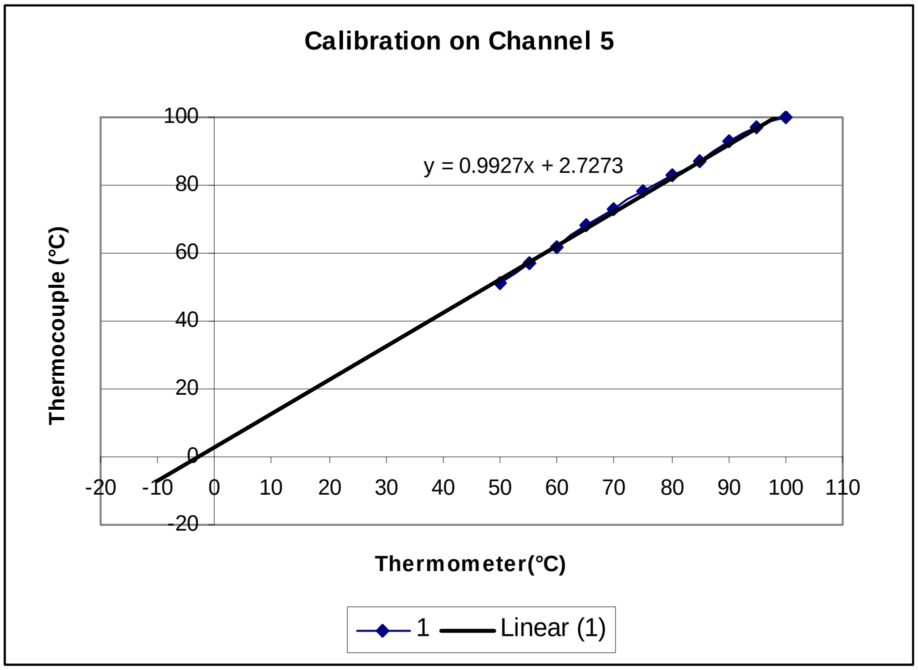


Figure 3.10 Temperature correction graph for channel 5.

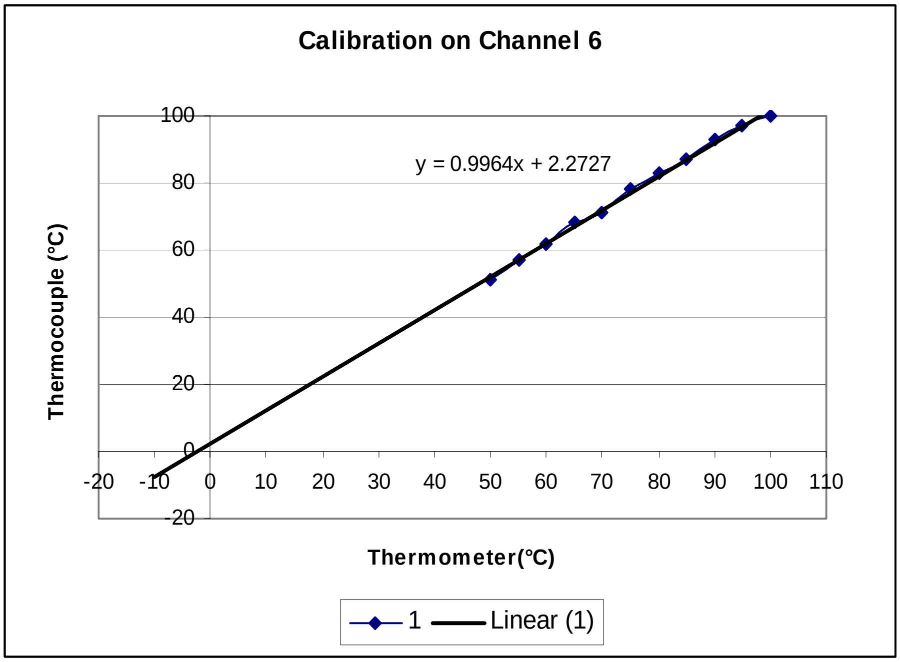


Figure 3.11 Temperature correction graph for channel 6.

From the graphs temperatures of the thermocouple versus temperatures of the thermometer, the curve is a straight line and almost cross the origin. Thus, the thermocouple is said to function correctly and precisely. For channel 3, if the temperature of the thermometer is 40°C, the temperature measured by the thermocouple is to be 42.4273°C, since the function of the graph is

$$y \text{ (thermocouple)} = 0.98\, x \text{ (thermometer)} + 3.2273.$$

The temperatures measured by the other channels can be calculated according to the function for each graph.

3.3 Microstructure Observation and Vickers Hardness Test

The cast aluminium is then sent to undergo Vickers hardness test and the microstructure of the aluminium is observed. In order to view the microstructure of the cast aluminium, metallographic specimen of the cast metal had to be prepared. Vickers Hardness test is conducted on the same specimens after the microstructure of the specimens is observed. The steps to produce specimen is described as follows.

A piece of the aluminium is cut from the cylinder shape cast material by using the bend saw, the sawing method used is cold sawing.

Before starting the grinding process, the specimens are mounted in a plastic medium. This is done by putting the specimen in the BUEHLER SIMPLEMET 1000 AUTOMATIC MOUNTING MAHCHINE follows by adding the phenolic hot mounting resin which is black in color into the machine and start the mounting process. The process takes about 15 minutes. Specimens are embedded in epoxy to facilitate their handling and to improve the results from the preparation. **Figure 3.12** shows the mounting equipment.

To view the microstructure, the surface of the specimen must be in minimum damage. Thus, the surface is grinded and polished to achieve this goal. This is done by grinding the specimen surface on the paper of abrasive compounds. The starting grade of the paper is 600 and follows by 800, 1000 and 4000 (the higher the grade, the smaller the abrasive compound). The specimens are turned though 90° before shift to the paper with higher grade.

Figure 3.12 The mounting equipment

The following step is to polish the specimens, it is done on a rotating disc with cotton cloth followed by slevyt cloth. The slevyt cloth is used together with a suspension solution consists of SiO_2 particles to provide a presentable results without etching. The polishing proposes is to remove all the deformation and the scratches from the specimens. **Table 3.2** shows some examples of the polishing cloth. All the specimens are soaked into a chemical solution before the microstructure inspection; the example of the solution is the Keller Solution which consists of hydrofluoric acid. This step is to differentiate clearly the boundary and the microstructure of the specimens before analysis is carried out.

After the specimens are prepared, observation of the microstructure is done by using the image analyzer system, as shown in **Figure 3.13**. And the Vickers Hardness Test is performed using the tester as shown in **Figure 3.14.**

Table 3.2 Examples of polishing cloths and their application

Polishing Cloths	Application
DP – Net	A very hard, woven steel cloth for fine diamond grinding and pre-polishing of hard materials.
DP – Dur	A hard, woven, silk cloth for diamond pre-polishing.
DP – Mol	A medium hard, woven, wool cloth for diamond polishing.
DP – Nap	A soft, short-napped cloth for final diamond polishing.
OP – Nap	A soft, short-napped cloth for final oxide polishing.

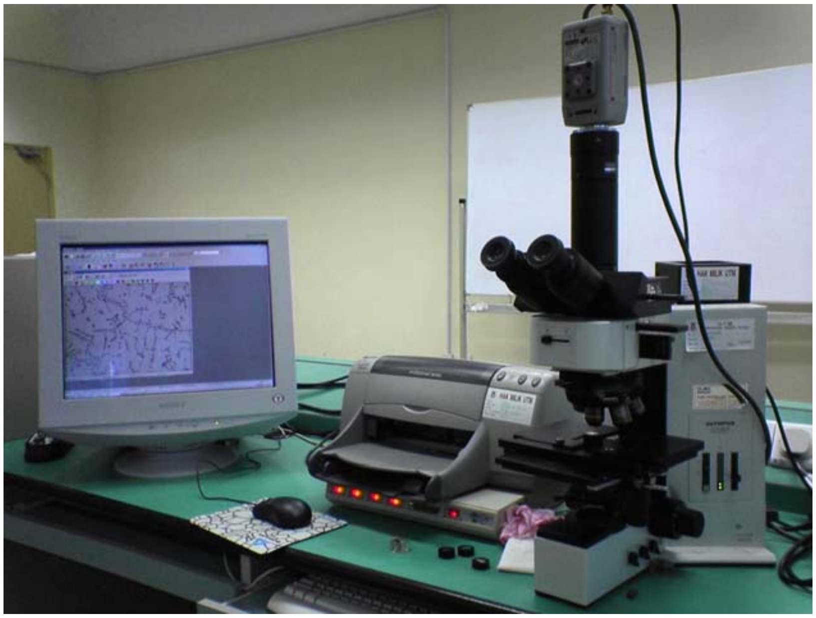


Figure 3.13 Image analyzer system

Figure 3.14 Vickers Hardness Tester

CHAPTER IV

FINITE ELEMENT SIMULATION PROCEDURES

4.1 Introduction

Finite element simulation is performed to estimate the thermal conductivity (*k* value) of the investment casting mould material by using trial and error. A finite element model was built to represent the whole investment casting mould. In this case, the inner and outer surface temperature of the investment casting mould material is considered to be equal for the whole mould material during the metal pouring was being conducted until the temperature reached the steady-state condition. Thus, the finite element model of the mould material was created, using a plane-strain assumption. Due to the geometrical symmetry, only a quarter section of the actual geometry was considered.

4.2 The Finite Element Technique

The finite element analysis was carried out as followed:

1) A finite element model is first created by drawing the plan view of the investment casting mould. As mentioned, only a quarter section of the actual geometry was considered. This is shown in **Figure 4.1** by using the 5 layers mould material as the example.

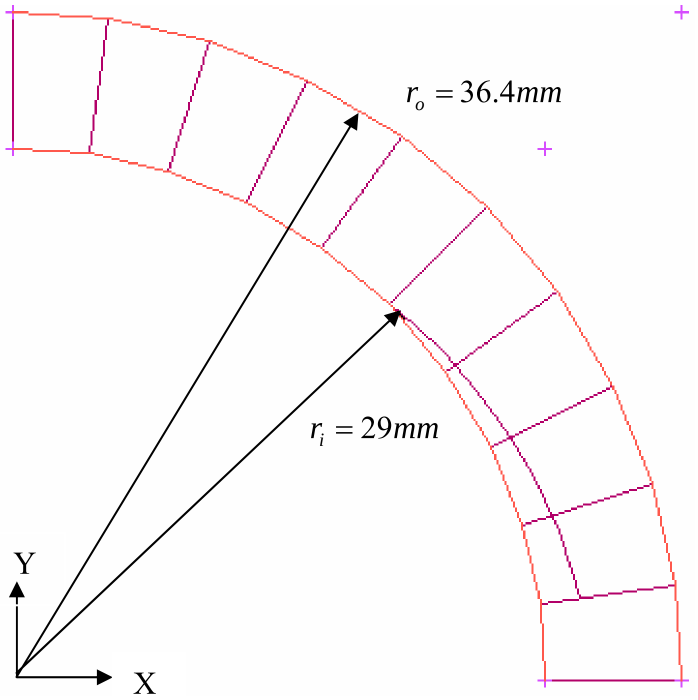


Figure 4.1: Geometry of the Model.

2) The line geometry was then converted into ruled surface.

3) The ruled surface just created is converted into 200 quadrilateral (QUAD 4) elements. This is shows in **Figure 4.2**.

4) Boundary conditions are applied on the model. Inner surface steady-state temperature of the mould material obtained during the pouring stage is applied on the nodes along the curve representing the inner surface of the mould.

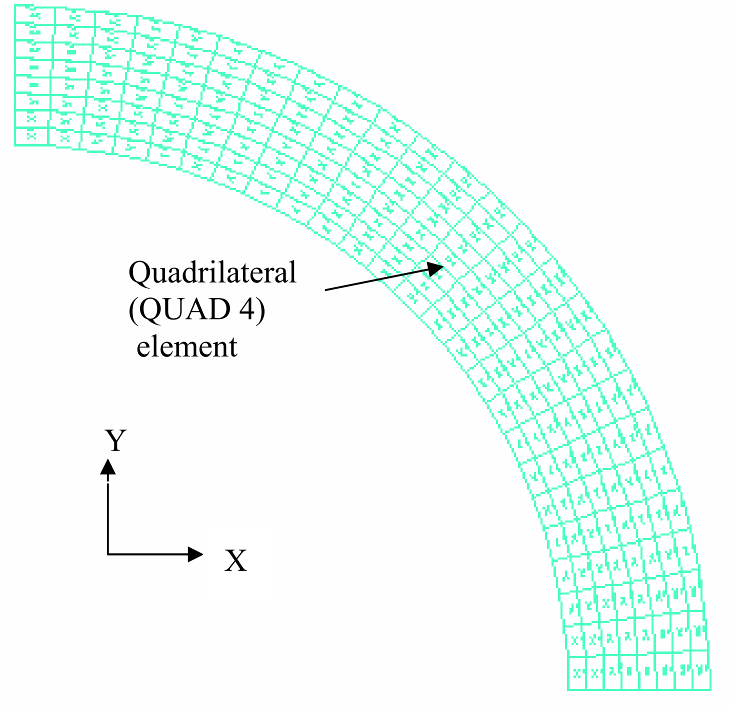


Figure 4.2 Model after converted into quadrilateral element

5) Another boundary condition is applied at the edges of the outer surface of the model as convection with the convection coefficient as 10 W/m^{2}K and the room temperature as 25°C. **Figure 4.3** shows all the loads and boundary conditions of the finite element model.

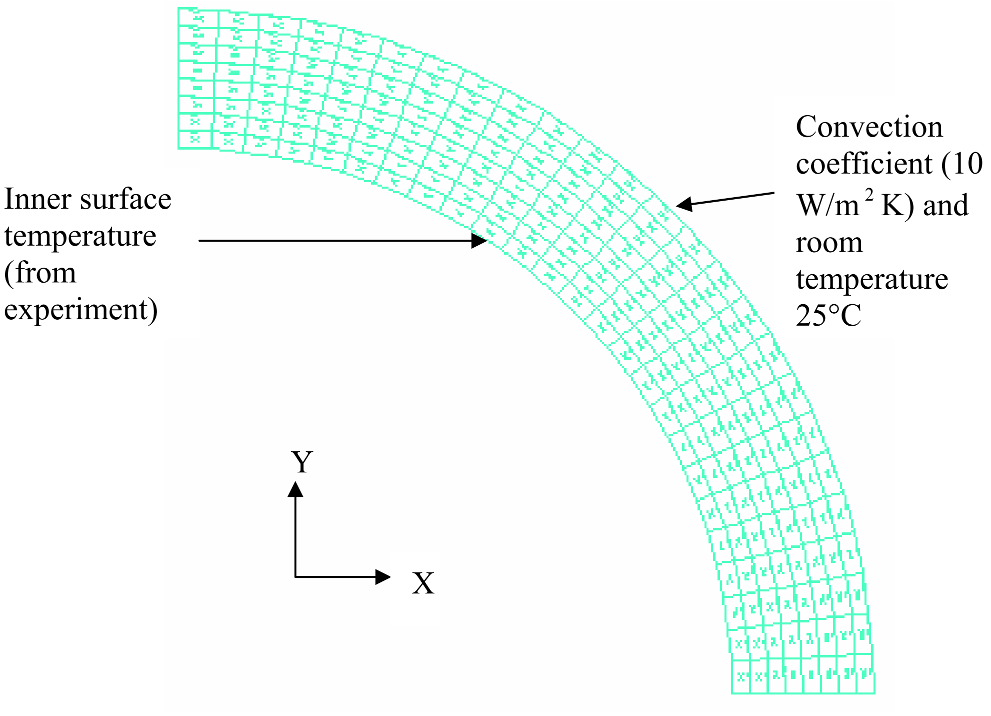


Figure 4.3 Load and boundary condition of the finite element model.

6) The material property of the mould material is assigned to the model. In this case, only a guess value of the thermal conductivity, *k* of the mould material is specified.

7) The element property of the investment casting mould material is assigned to the model by choosing plain strain properties and the thickness normal to the plane is assigned to be 1 unit.

8) A steady-state heat transfer analysis is carried out to obtain the distribution of the temperature within the mould wall.

9) The temperature of the nodes at the outer surface is then compared to the temperature of the outer surface obtained from experiment. If the different of both the temperature for the nodes and the outer surface is obvious, the analysis is repeated by using others guess value of the thermal conductivity, *k*. The guess *k* value is assumed as the approximately *k* value of the mould material once the temperature for the nodes is equal or almost equal to the temperature for the outer surface obtained from the experiment.

CHAPTER V

RESULT AND DISCUSSION

5.1 Temperature Plot from the Casting Results

The temperatures of the inner and outer wall of the mould materials obtained from the casting process are plotted in the graph form. **Figure 5.1** to **Figure 5.4** show the graphs with temperature versus time for 4 mould materials with different wall thickness.

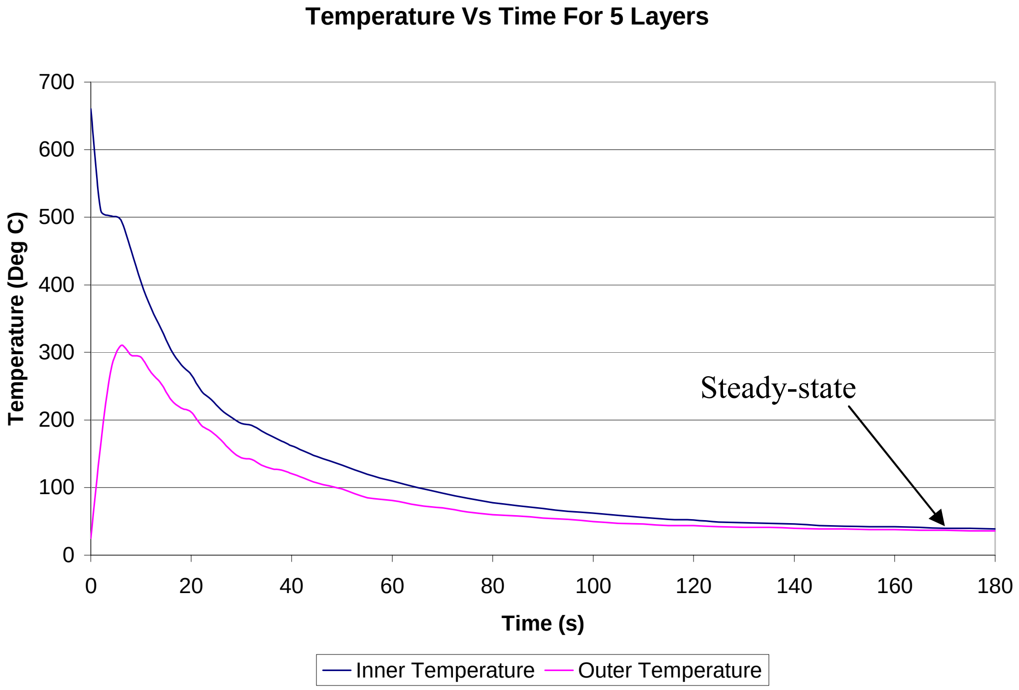


Figure 5.1 Temperatures versus time for 5 layers

From the graph of the **Figure 5.1**, the slope of the inner wall temperature drops rapidly within the first 2 minutes. The temperature remains flat for the following 4 minutes, this is due to the solidification of the cast metal. After that, the temperature starts dropping until it reached the steady-state condition at the 180 minutes. For the outer wall, temperature increased rapidly after pouring due to the sudden heat transfer from the inner wall. After 6 minutes, until it reached the maximum temperature of 310°C, the temperature of the outer wall begins to drop and reached the steady-state condition after 180 minutes.

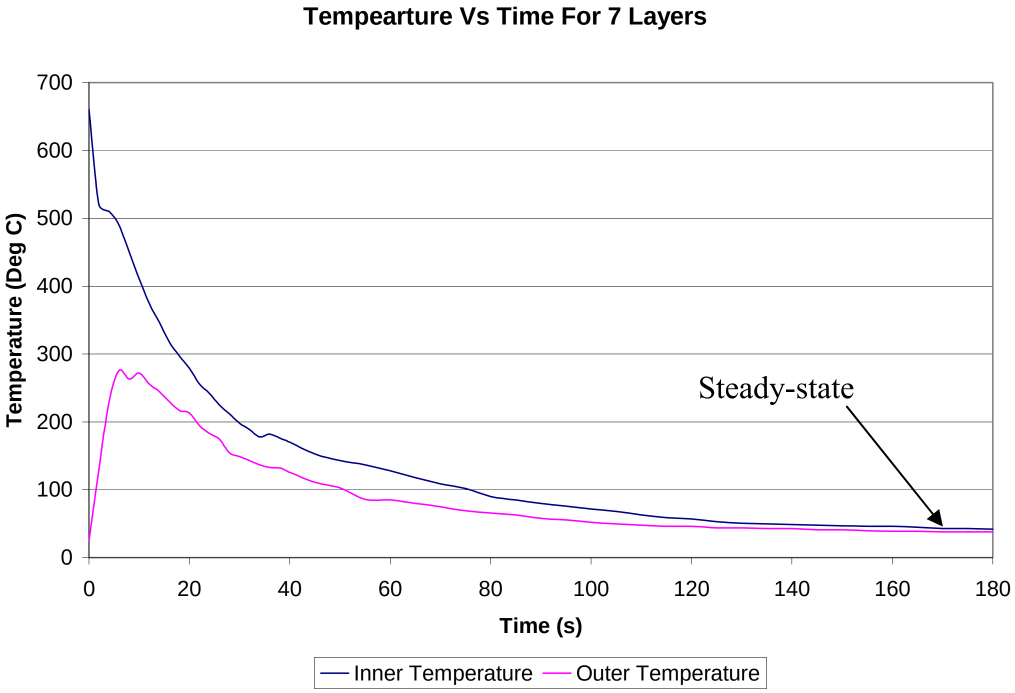


Figure 5.2 Temperatures versus time for 7 layers

Figure 5.2 shows the cooling process of the mould recorded for 180 minutes until the steady-state condition is achieved. From the graph, the temperature of the inner wall dropped rapidly after the pouring at the 660°C for the first 2 minutes. This is followed by the slowly drop of temperature between the 4 and 6 minutes. The temperature started to drop again gradually until it reached the steady-state condition. The outer temperature increased rapidly once the molten metal is pour into the mould material for the first 6 minutes, and is then dropped gradually until the steady-state condition is achieved.

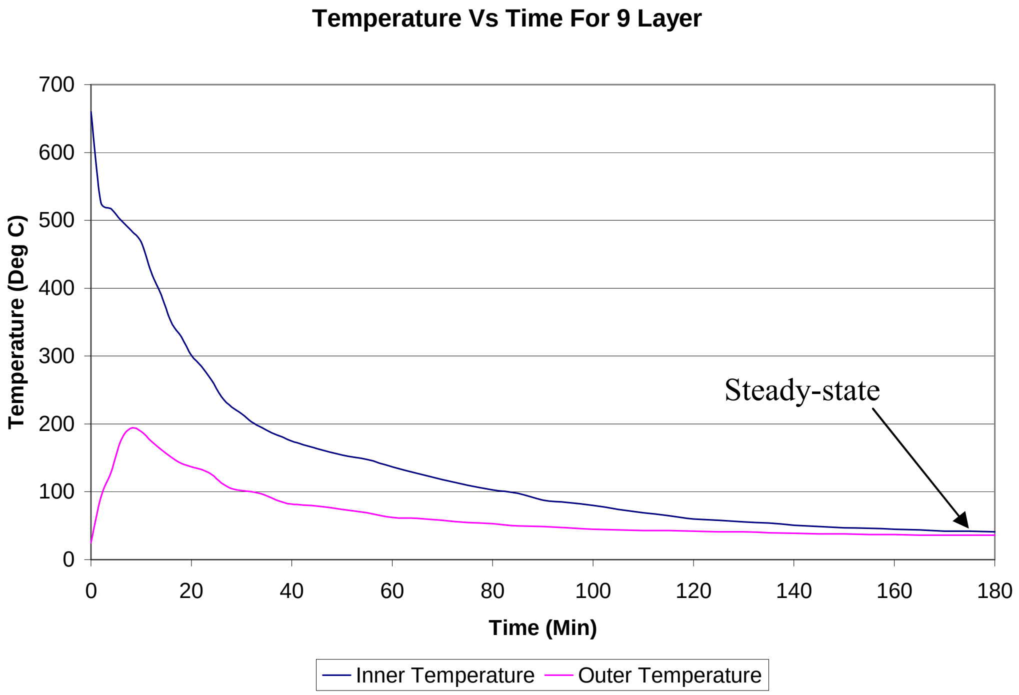


Figure 5.3 Temperatures versus time for 9 layers

As shown in the graph of **Figure 5.3**, after pouring at 660°C the temperature of the outer wall increased rapidly for the first 10 minutes. Then temperature is dropped gradually until it reached the steady-state condition at the 180 minutes. For the temperature of the inner, it dropped rapidly at the first 2 minutes and remained flat for 2 minutes. This is due to the solidification of the cast metal. After that, the temperature dropped gradually until the steady-state condition is achieved.

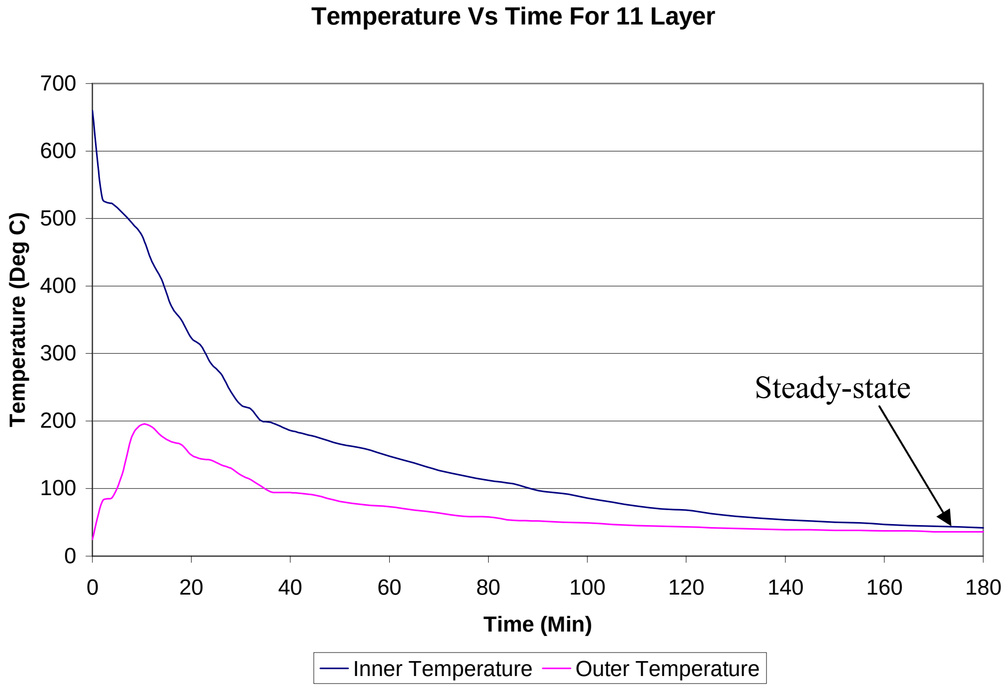


Figure 5.4 Temperatures versus time for 11 layers

Figure 5.4 shows the graph of the cooling process of the mould material with 11 layers after pouring at 660°C. The inner wall temperature dropped rapidly after pouring and the cast metal is solidified. The outer wall temperature increased rapidly in the early stage of the pouring process and dropped gradually until it reached the steady-state condition at 180 minutes.

5.2 Finite Element Simulation Results

The finite element analysis gives the thermal conductivity, *k* value for the mould material with fine stucco system. Besides that, the finite element simulation also gives the temperature distribution through the mould wall at the steady-state heat transfer condition. The finite element simulation results are shown in **Figure 5.5** to **Figure 5.8**.

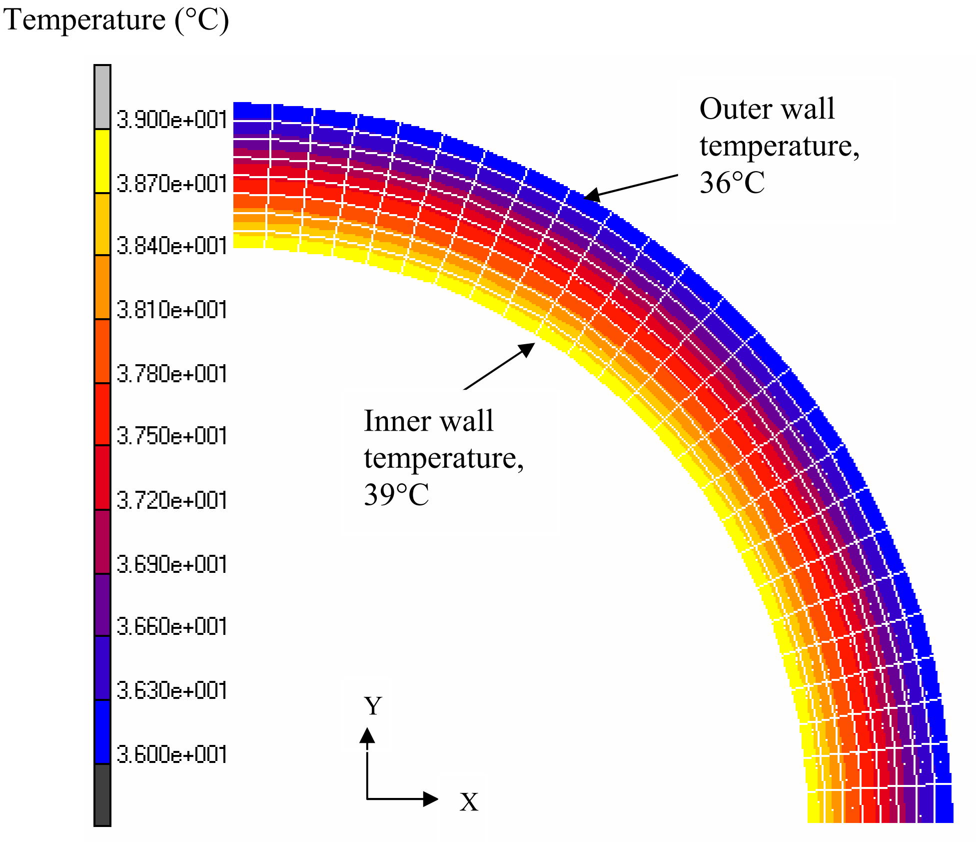


Figure 5.5 Temperature distributions for 5 layers

The thickness for the 5 layers mould material is 7.41mm. The inner wall temperature used as the boundary condition is 39°C which is obtained from the experiment. And the outer wall temperature obtained from the experiment is 36°C.

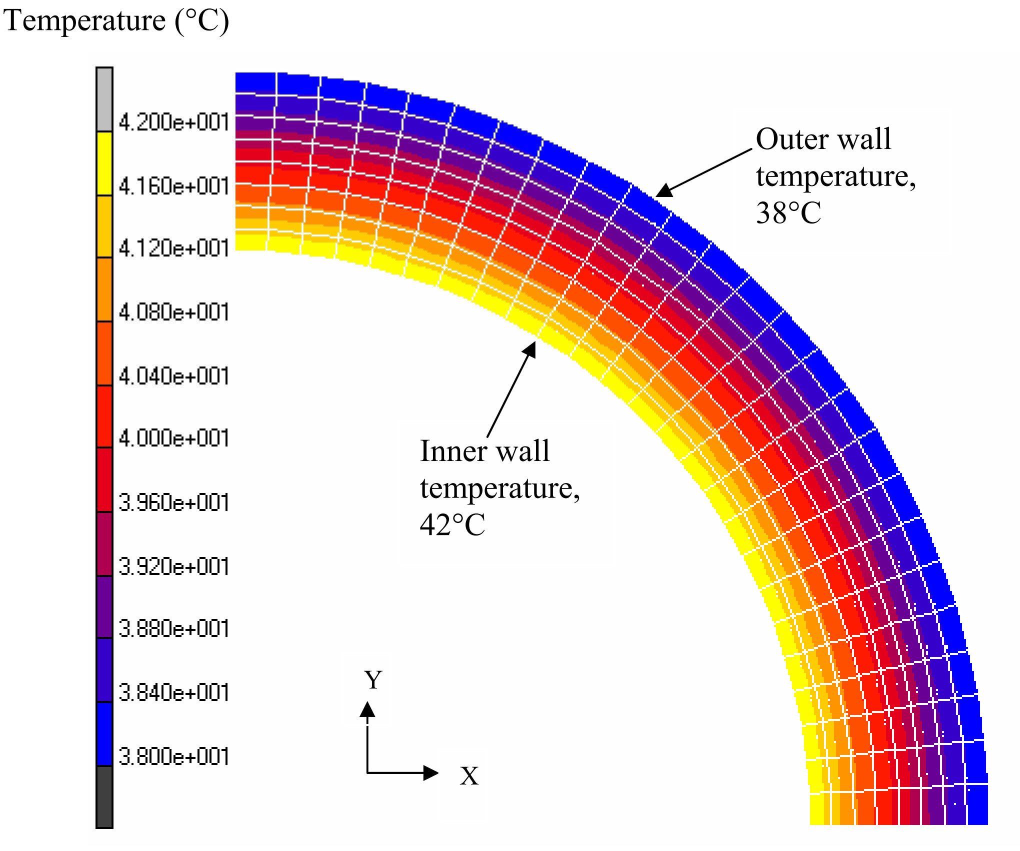
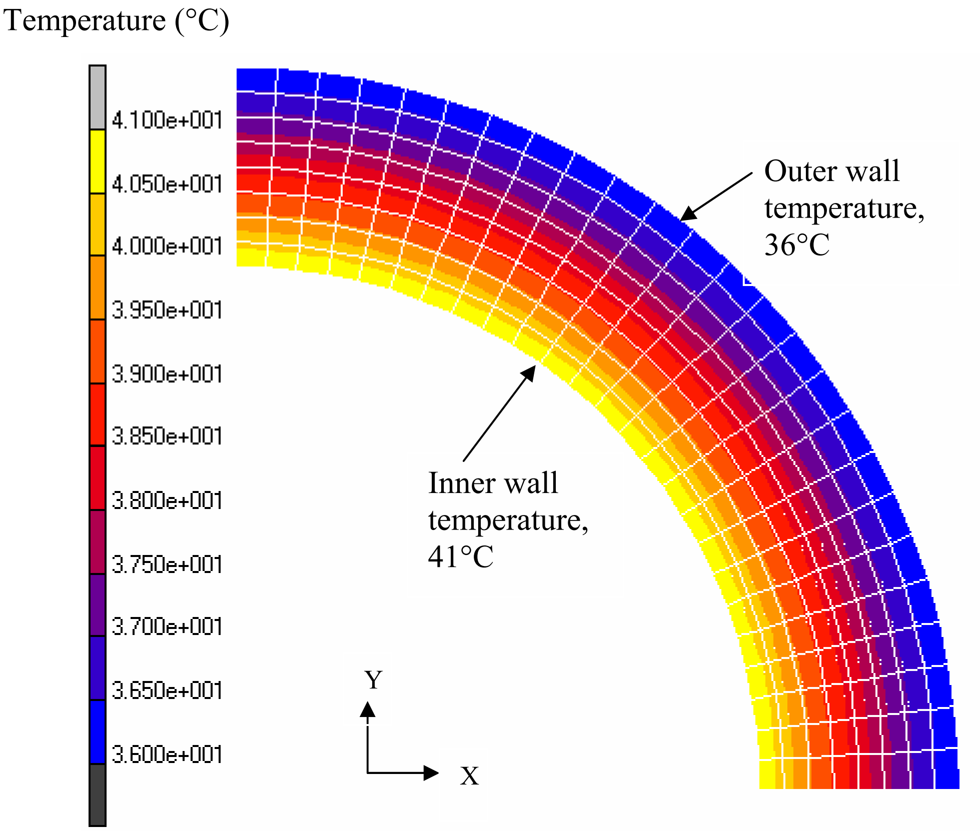


Figure 5.6 Temperature distributions for 7 layers

The thickness for the 7 layers mould material is 9.1mm. The inner wall temperature used as the boundary condition is 42°C which is obtained from the experiment. And the outer wall temperature obtained from the experiment is 38°C.



Outer wall temperature, 36°C

Inner wall temperature, 41°C

Figure 5.7 Temperature distributions for 9 layers

The mould material with 9 layers has thickness of 11.12mm. The inner wall temperature used as the boundary condition is 41°C which is obtained from the experiment. And the outer wall temperature is 36°C.

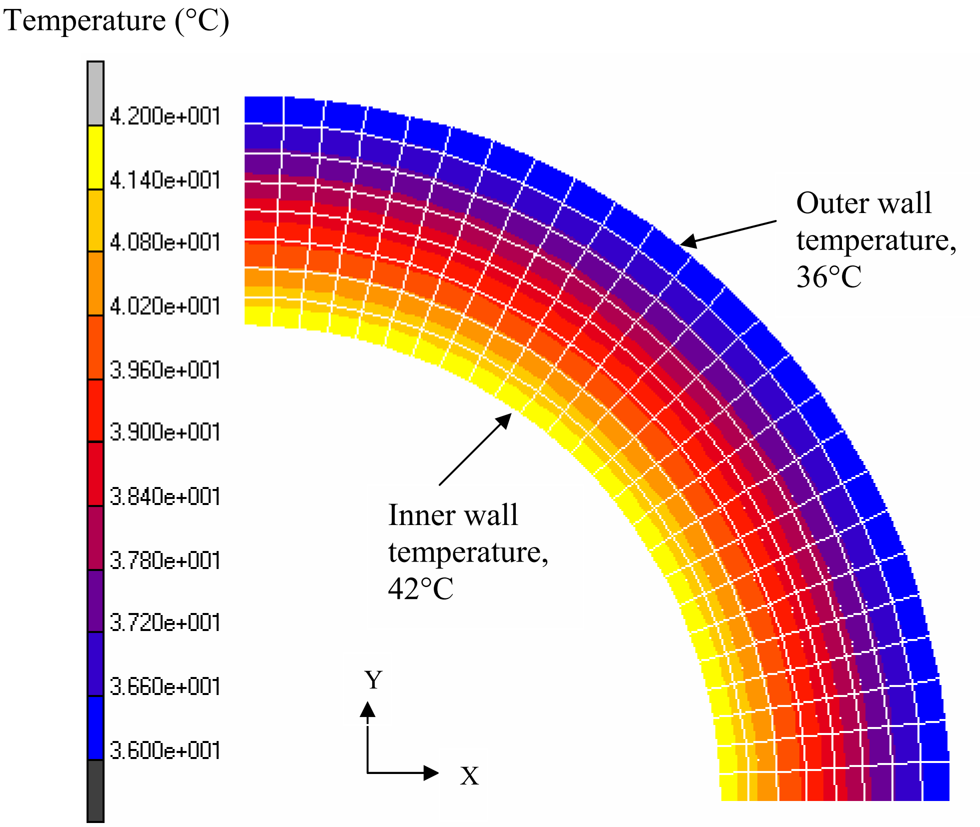


Figure 5.8 Temperature distributions for 11 layers

The mould material with 11 layers has thickness of 14.1mm. The inner wall temperature used as the boundary condition is 42°C which is obtained from the experiment. And the outer wall temperature from the experiment is 36°C.

The thermal conductivity, *k* value for the mould material with the different thickness is summarized in the **Table 5.1**.

From the finite element analysis, the thermal conductivity, *k* for the different thickness is able to be estimated. From the **Table 5.1**, the *k* value is different with the different mould wall thickness. However, the values of the *k* are close. This is because of the mould was established by the same material and stucco system. Since the mould materials are same, thus the *k* value should be the same, but it is difficult to construct the mould using the exact viscosity and the investment shell building process can not be fully controlled. Air gap between layers may form during dipping and stuccoing which will affect the heat transfer rate of the mould materials. Besides, the pouring temperature is also not consistent.

Table 5.1 The thermal conductivity, *k* for different mould wall thickness

Thickness	5 layers	7 layers	9 layers	11 layers
Thermal conductivity, *k* (W/mK)	0.303	0.338	0.286	0.313

5.3 Microstructure Observation

To achieve the goal of the thesis work, the mechanical properties of the cast products are need to be evaluated. Thus, the microstructures of the cast products are observed.

By using the image analyzer system, the microstructure of the cast products can be seen. Besides, the percentage of the silicon flakes can also be determined.

For the cast product from the mould material with 5 layers, the microstructure of the cast metal is shown in **Figure 5.9**. **Figure 5.10** shows the silicon flakes highlighted in red contrast to the aluminium which is in light blue. The percentage of the silicon flakes is 18.4% and is shown in **Figure 5.11**.

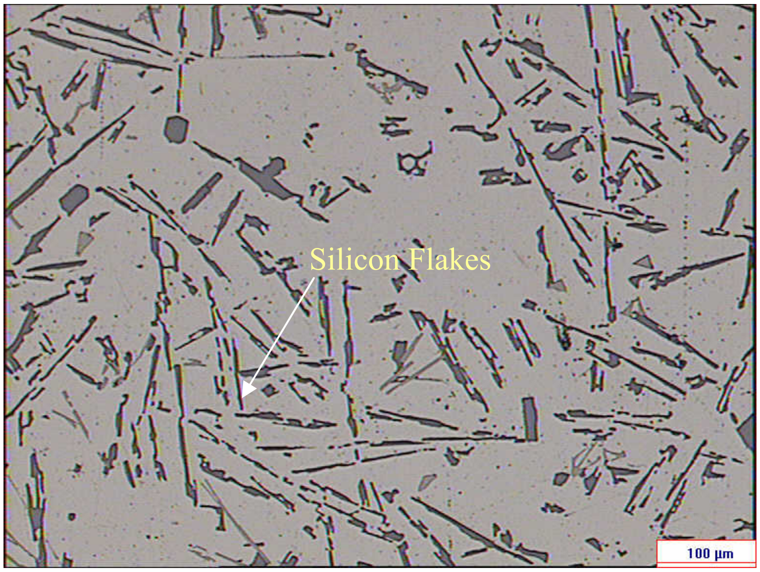


Figure 5.9 Microstructure for the cast product of 5 layers mould material (100X magnification)

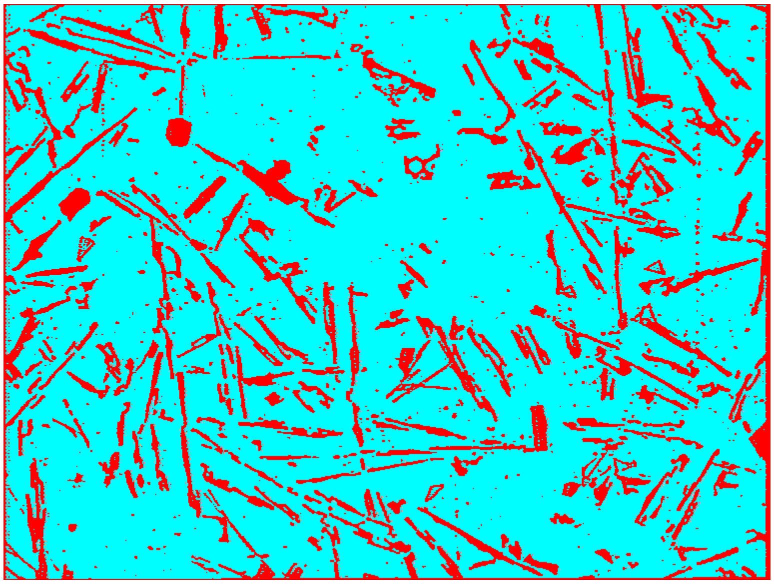
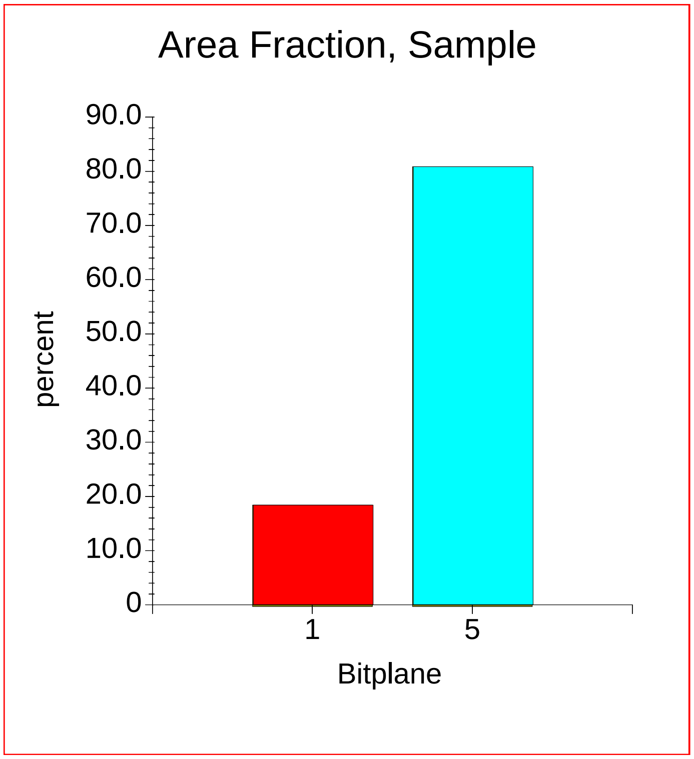


Figure 5.10 Silicon flakes in red for 5 layers cast product (100X magnification)



Field Summary

1: Bitplane 1	18.4026 %
5: Bitplane 5	80.8413 %
Fld Area:	170660 µm²
Tot Area:	170660 µm²
Fld Count:	1 ##

Figure 5.11 Percentages of the silicon flakes for 5 layers cast product

For 7 layers mould material, the microstructure of the cast metal is shown in **Figure 5.12**. **Figure 5.13** shows the silicon flakes highlighted in red. The percentage of the silicon flakes is 17.61% and is shown in **Figure 5.14**.

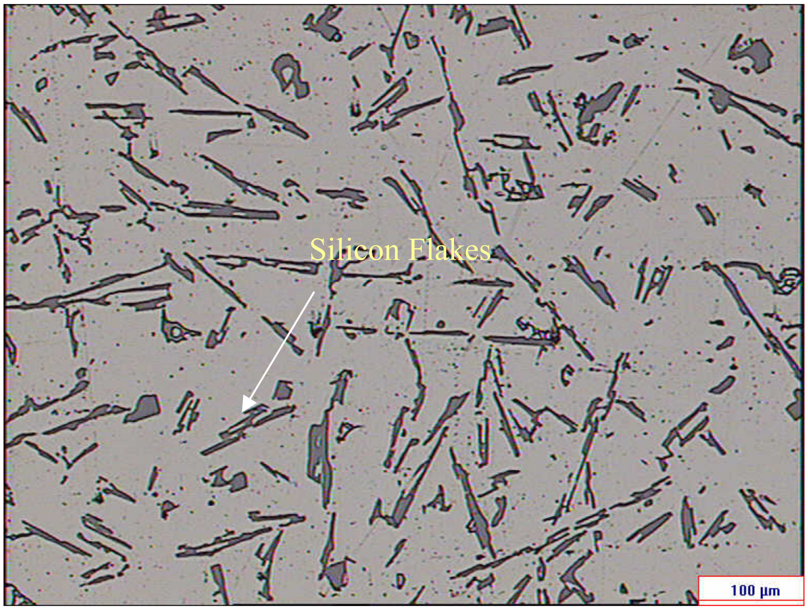


Figure 5.12 Microstructure for the cast product of 7 layers mould material (100X magnification)

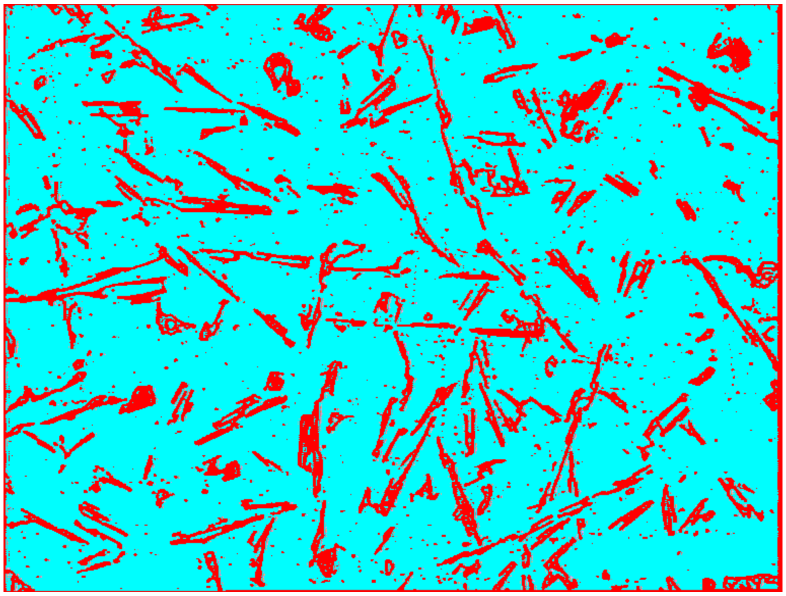
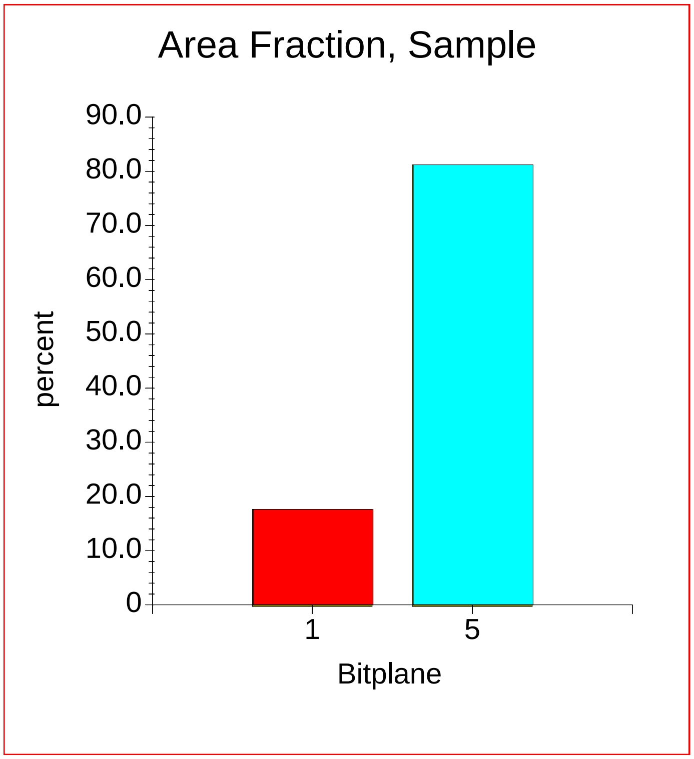


Figure 5.13 Silicon flakes in red for 7 layers cast product (100X magnification)



Field Summary

1: Bitplane 1	17.6089 %
5: Bitplane 5	81.1937 %
Fld Area:	170660 µm²
Tot Area:	170660 µm²
Fld Count:	1 ##

Figure 5.14 Percentages of the silicon flakes for 7 layers cast products

For 9 layers mould material, the microstructure of the cast metal is shown in **Figure 5.15**. Silicon flakes highlighted in red is shown in **Figure 5.16**. The percentage of the silicon flakes is 16.26% and is shown in **Figure 5.17**.

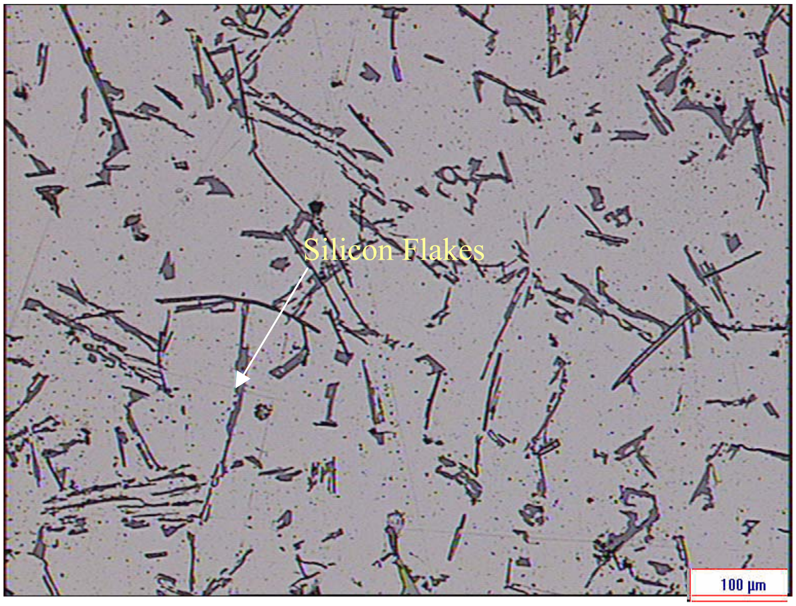


Figure 5.15 Microstructure for the cast product of 9 layers mould material (100X magnification) *µm*

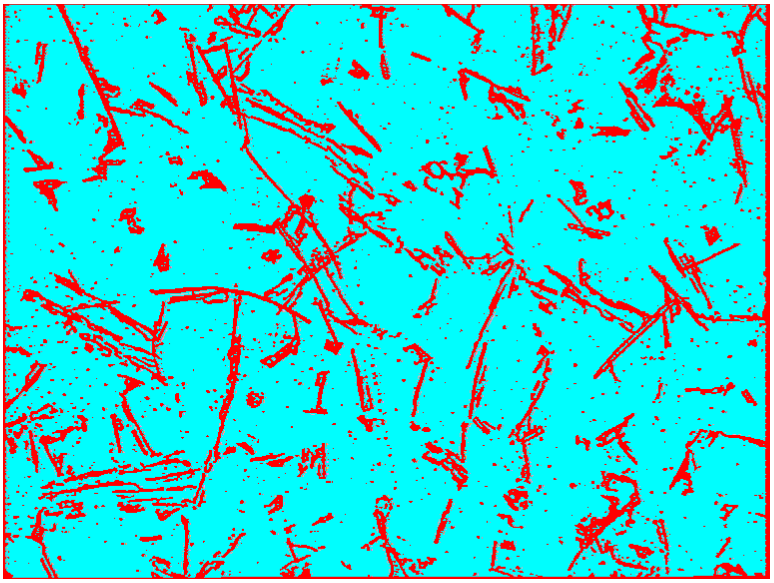
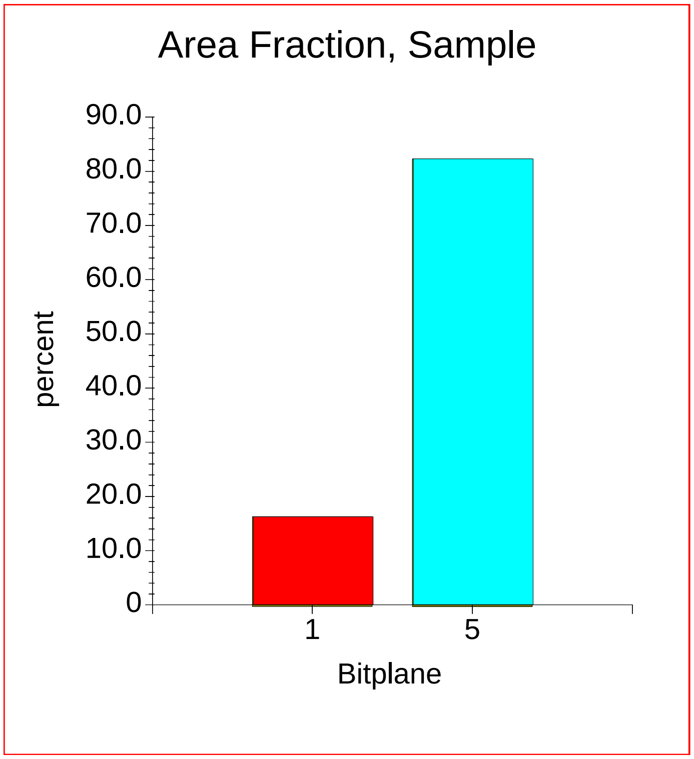


Figure 5.16 Silicon flakes in red 9 layers cast product (100X magnification)



Field Summary

1: Bitplane 1	16.2593 %
5: Bitplane 5	82.2842 %
Fld Area:	170660 µm²
Tot Area:	170660 µm²
Fld Count:	1 ##

Figure 5.17 Percentages of the silicon flakes for 9 layers cast product

Microstructure of the cast metal for 11 layers mould material is shown in **Figure 5.18**. Silicon flakes highlighted in red is shown in **Figure 5.19**. **Figure 5.20** shows the percentage of the silicon flakes is 15.38%.

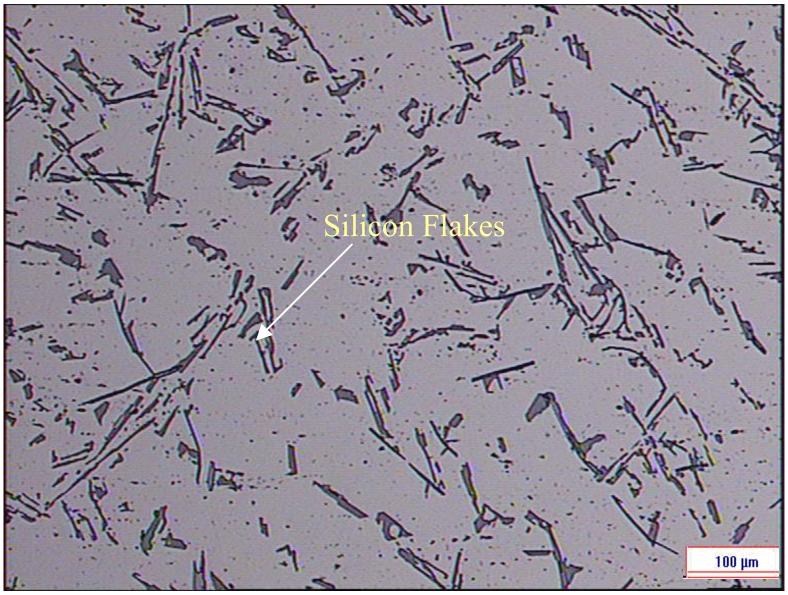


Figure 5.18 Microstructure for the cast product of 11 layers mould material (100X magnification)

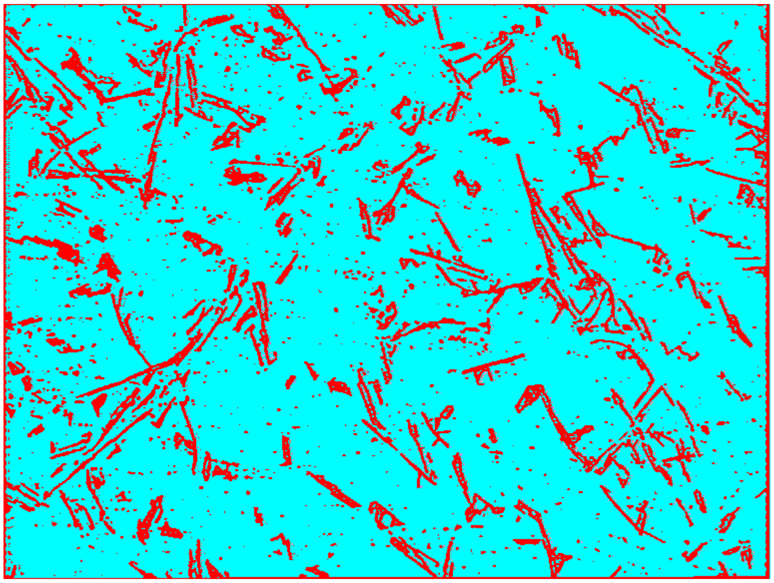
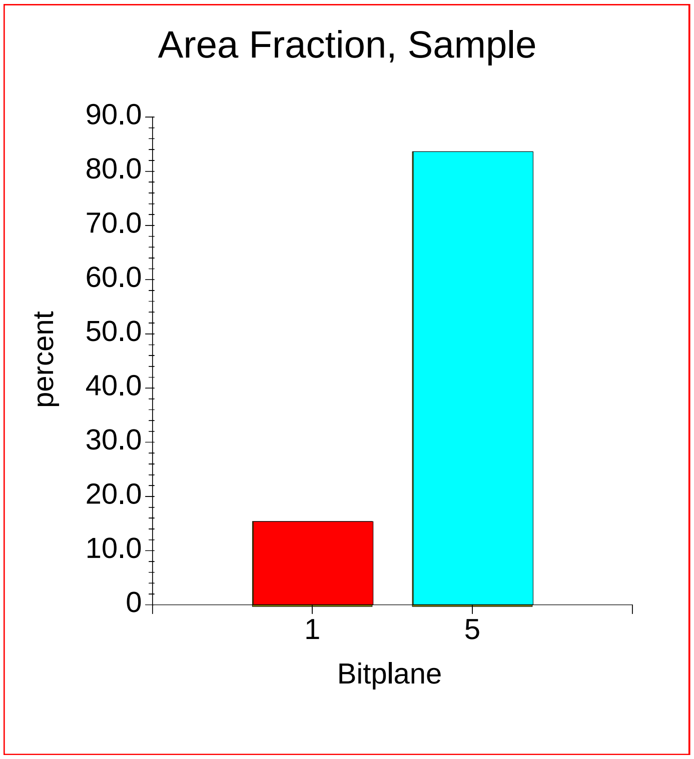


Figure 5.19 Silicon flakes in red 11 layers cast product (100X magnification)



Field Summary

1: Bitplane 1	15.3797 %
5: Bitplane 5	83.6084 %
Fld Area:	43200 µm²
Tot Area:	43200 µm²
Fld Count:	1 ##

Figure 5.20 Percentages of the silicon flakes for 11 layers cast product

The data is simplified in the **Table 5.2.**

Table 5.2 Percentage of the silicon flakes in the cast product for different layer

Thickness	Silicon Flakes Area (%)
5 layers	18.40
7 layers	17.61
9 layers	16.26
11 layers	15.38

5.4 Vickers Hardness Test

The hardness of the cast aluminium alloys are tested by using Vickers Hardness Method. The findings are discussed in this section.

Load	: 5 kg	Loading speed	: 50 μ m/s
Load time	: 10s		

Table 5.3 Results of Vickers Hardness Test for the cast aluminium alloys

Specimen	5 layers	7 layers	9 layers	11 layers
1st reading (Hv)	50.6	50	45.4	46.7
2nd reading (Hv)	49.5	49.1	44.1	46.3
3rd reading (Hv)	50.5	48.8	44.1	47.9
4th reading (Hv)	48.3	48.1	46	45.1
5th reading (Hv)	48.4	49.8	47	46.1
Mean	49.46	49.16	45.32	46.42

The graph Vickers Hardness versus number of layers is plotted and shown in **Figure 5.21.** From the graph, the hardness of the cast products shows a declined with the increasing number of layer. This might be caused by the heat transfer rate is higher for the mould material with thinner wall, and theoretically the faster the molten metal solidified the harder and more brittle the metal will be in the solid stage. However, the Vickers hardness for the cast product by using the 9 layers mould material is smaller than the Vickers hardness for the product by using 11 layers. This might be cause by the cracked on the 11 layers mould material during the pouring stage. As a result, the cast product solidified faster.

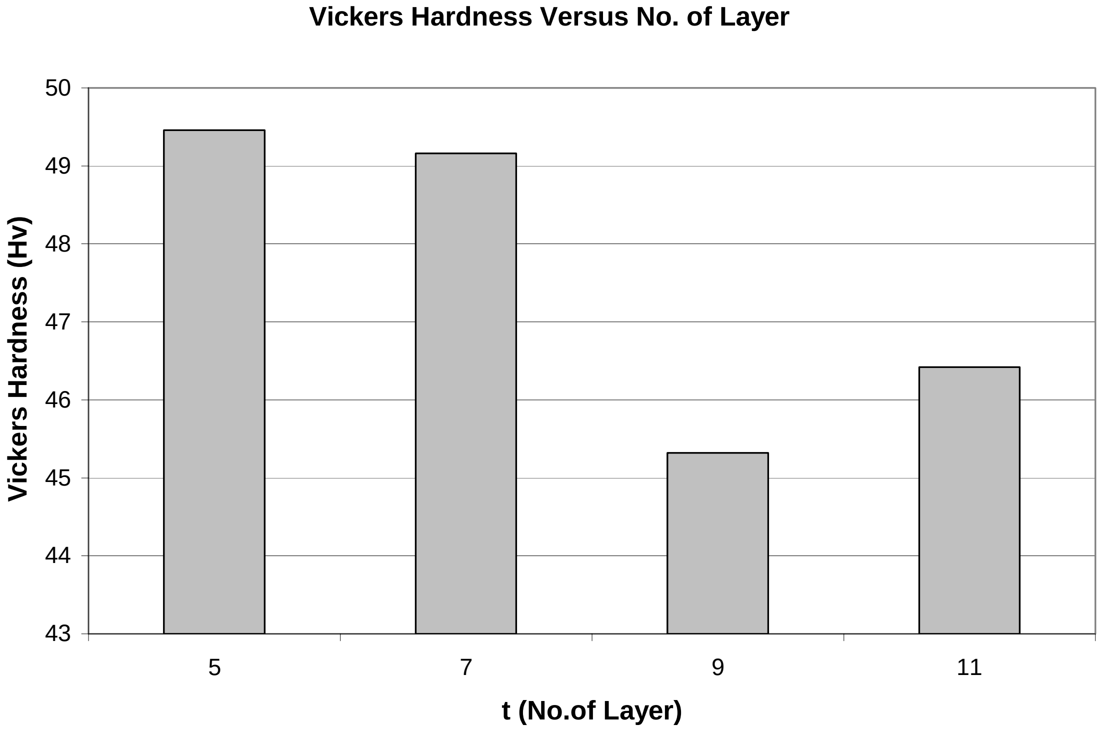


Figure 5.21 Graph Vickers Hardness vs. No. of Layer

CHAPTER VI

CONCLUSION AND RECOMMENDATION

6.1 Conclusion

In this thesis, the mould materials with the desired mould wall thickness are established successfully without crack and defect. The finite element technique is capable to be used to estimate the thermal conductivity, *k* of the mould materials. For a pouring temperature of 660°C, it can be concluded that the thermal conductivity, *k* value for all the mould materials is almost the same. This is true because the mould materials are formed by using the same slurry and stucco system. The cooling trends of the inner and outer wall temperatures are also almost alike for all mould materials and the steady-state temperatures are not much different.

The microstructure of the cast products is somewhat affected by the number of layers of the mould material. The percentage of the silicon flakes for the cast product decreased with the increasing mould wall thickness. This is due to the different heat transfer rate when the molten metal solidified. The microstructure of the cast products is the type of unmodified as shown in the **Figure 2.3**. The cast products content of coarse silicon plates that act as internal stress raisers in the microstructure and thus create more paths for fracture.

From the results of the Vickers Hardness Test, it shows that the hardness of the cast products cast by the mould materials with fewer layers is higher. Thus it can be concluded that the hardness of the cast products is quite significantly affected by the number of layers of the mould materials. But the different in the Vickers hardness of the cast products are not significant.

As the conclusion, the result of this study indicates that for a pouring temperature of 660°C, the thermal conductivity, *k* value of the mould materials is almost the same. The Vickers hardness of the cast products show a decrease with the increasing of the number of layers of the investment casting shell for fine stucco system.

6.2 Recommendation

This thesis work can be repeated by using the different pouring temperature, e.g. 680°C and 700°C. Then the correlation between the pouring temperature, number of layers or thickness of the mould material and the hardness of the casting products can be established. Besides, the effects of the slurry’s viscosity to the thermal conductivity, *k* value can also be studied and investigated.

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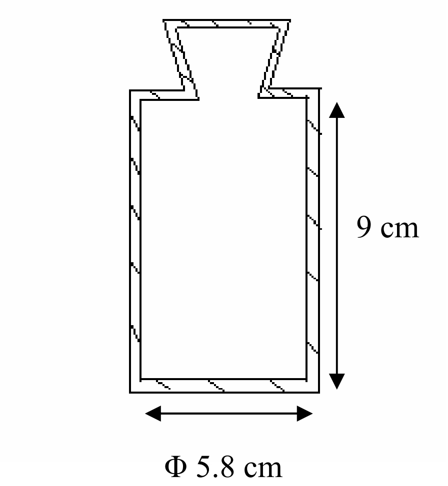
APPENDIX A



Dimension of the cast product

Wax pattern for the experiment

Mold material (1 layer)

Mold material (2 layers)

Mold material (3 layers)

Mold material (4 layers)

Mold material (5 layers)

Mold material (6 layers)

Mold material (7 layers)

Mold material (8 layers)

Mold material (9 layers)

Mold material (10 layers)

Mold material (11 layers)

A hole is drilled to locate the thermocouple in order to measure the inner wall temperature

Wax melted out from the mold material in the dewaxing stage

Set-up of the mold material before pouring the molten aluminium alloy

Mold material with solidified aluminium alloy

Cast aluminium alloy

Specimens for the microstructure observation and Vickers Hardness Test

APPENDIX B

Designation: E 92 – 82 (Reapproved 2003)$^{\epsilon 1}$

An American National Standard

Standard Test Method for Vickers Hardness of Metallic Materials[1]

This standard is issued under the fixed designation E 92; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

This standard has been approved for use by agencies of the Department of Defense.

ϵ^1 NOTE—Section 3.2 was editorially updated in June 2003.

1. Scope

1.1 This test method covers the determination of the Vickers hardness of metallic materials, using applied forces of 1 kgf to 120 kgf,[2] the verification of Vickers hardness testing machines (Part B), and the calibration of standardized hardness test blocks (Part C). Two general classes of standard tests are recognized:

1.1.1 *Verification, Laboratory, or Referee Tests*, where a high degree of accuracy is required.

1.1.2 *Routine Tests*, where a somewhat lower degree of accuracy is permissible.

1.2 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

E 4 Practices for Force Verification of Testing Machines[3]

E 140 Hardness Conversion Tables for Metals (Relationship Among Brinell Hardness, Vickers Hardness, Rockwell Hardness, Rockwell Superficial Hardness, Knoop Hardness, and Scleroscope Hardness)[3]

E 384 Test Method for Microindentation Hardness of Materials[3]

3. Terminology

3.1 *calibration*—determination of the values of the significant parameters by comparison with values indicated by a reference instrument or by a set of reference standards.

3.2 *verification*—confirmation by examination and provision of evidence that an instrument, material, reference, or standard is in conformance with a specification.

3.3 *Vickers hardness number, HV*—a number related to the applied force and the surface area of the permanent impression made by a square-based pyramidal diamond indenter having included face angles of 136° (see Fig. 1 and Table 1), computed from the equation:

$$\text{HV} = 2P\sin(\alpha/2)/d^2 = 1.8544P/d^2 \qquad (1)$$

where:

P = force, kgf,
d = mean diagonal of impression, mm, and
α = face angle of diamond = 136°.

3.4 *Vickers hardness test*—an indentation hardness test using calibrated machines to force a square-based pyramidal diamond indenter having specified face angles, under a predetermined force, into the surface of the material under test and to measure the diagonals of the resulting impression after removal of the force.

3.4.1 Vickers hardness tests are made at test forces of 1 kgf to 120 kgf.

3.4.2 For practical purposes the Vickers hardness number is constant when a square-based diamond pyramid with a face angle of 136° is used with applied forces of 5 kgf and higher.

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[1] This test method is under the jurisdiction of ASTM Committee E28 on Mechanical Testing and is the direct responsibility of Subcommittee E28.06 on Indentation Hardness Testing.

Current edition approved Jan. 10, 2003. Published April 2003. Originally approved in 1952. Last previous edition approved in 1997 as E 92 – 82 (1997)$^{\epsilon 3}$.

[2] A procedure covering Vickers tests using applied forces of 1 gf to 1000 gf (1 kgf) may be found in Test Method E 384, Test Method for Microindentation Hardness of Materials, appearing in the *Annual Book of ASTM Standards*, Vol 03.01.

[3] *Annual Book of ASTM Standards*, Vol 03.01.

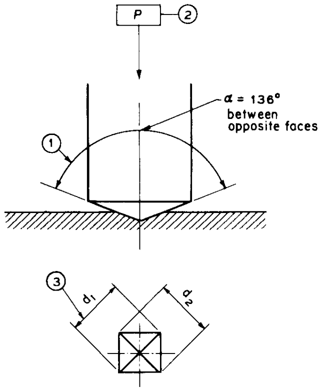

FIG. 1 Vickers Hardness Test (see Table 1)

TABLE 1 Symbols and Designations Associated with Fig. 1

Number	Symbol	Designation
1	...	Angle at the vertex of the pyramidal indenter (136°)
2	*P*	Test force in kilograms-force
3	*d*	Arithmetic mean of the two diagonals d^1 and d^2

TABLE 2 Vickers Hardness Numbers
(Diamond, 136° Face Angle, force of 1 kgf)

Diagonal of Impression, mm	Vickers Hardness Number for Diagonal Measured to 0.0001 mm									
	0.0000	0.0001	0.0002	0.0003	0.0004	0.0005	0.0006	0.0007	0.0008	0.0009
0.005	74 170	71 290	68 580	66 020	63 590	61 300	59 130	57 080	55 120	53 270
0.006	51 510	49 840	48 240	46 720	45 270	43 890	42 570	41 310	40 100	38 950
0.007	37 840	36 790	35 770	34 800	33 860	32 970	32 100	31 280	30 480	29 710
0.008	28 970	28 260	27 580	26 920	26 280	25 670	25 070	24 500	23 950	23 410
0.009	22 890	22 390	21 910	21 440	20 990	20 550	20 120	19 710	19 310	18 920
0.010	18 540	18 180	17 820	17 480	17 140	16 820	16 500	16 200	15 900	15 610
0.011	15 330	15 050	14 780	14 520	14 270	14 020	13 780	13 550	13 320	13 090
0.012	12 880	12 670	12 460	12 260	12 060	11 870	11 680	11 500	11 320	11 140
0.013	10 970	10 810	10 640	10 480	10 330	10 170	10 030	9 880	9 737	9 598
0.014	9 461	9 327	9 196	9 068	8 943	8 820	8 699	8 581	8 466	8 353
0.015	8 242	8 133	8 026	7 922	7 819	7 718	7 620	7 523	7 428	7 335
0.016	7 244	7 154	7 066	6 979	6 895	6 811	6 729	6 649	6 570	6 493
0.017	6 416	6 342	6 268	6 196	6 125	6 055	5 986	5 919	5 853	5 787
0.018	5 723	5 660	5 598	5 537	5 477	5 418	5 360	5 303	5 247	5 191
0.019	5 137	5 083	5 030	4 978	4 927	4 877	4 827	4 778	4 730	4 683
0.020	4 636	4 590	4 545	4 500	4 456	4 413	4 370	4 328	4 286	4 245
0.021	4 205	4 165	4 126	4 087	4 049	4 012	3 975	3 938	3 902	3 866
0.022	3 831	3 797	3 763	3 729	3 696	3 663	3 631	3 599	3 567	3 536
0.023	3 505	3 475	3 445	3 416	3 387	3 358	3 329	3 301	3 274	3 246
0.024	3 219	3 193	3 166	3 140	3 115	3 089	3 064	3 039	3 015	2 991
0.025	2 967	2 943	2 920	2 897	2 874	2 852	2 830	2 808	2 786	2 764
0.026	2 743	2 722	2 701	2 681	2 661	2 641	2 621	2 601	2 582	2 563
0.027	2 544	2 525	2 506	2 488	2 470	2 452	2 434	2 417	2 399	2 382
0.028	2 365	2 348	2 332	2 315	2 299	2 283	2 267	2 251	2 236	2 220
0.029	2 205	2 190	2 175	2 160	2 145	2 131	2 116	2 102	2 088	2 074
0.030	2 060	2 047	2 033	2 020	2 007	1 993	1 980	1 968	1 955	1 942
0.031	1 930	1 917	1 905	1 893	1 881	1 869	1 857	1 845	1 834	1 822
0.032	1 811	1 800	1 788	1 777	1 766	1 756	1 745	1 734	1 724	1 713
0.033	1 703	1 693	1 682	1 672	1 662	1 652	1 643	1 633	1 623	1 614

TABLE 2 *Continued*

Diagonal of Impression, mm	Vickers Hardness Number for Diagonal Measured to 0.0001 mm									
	0.0000	0.0001	0.0002	0.0003	0.0004	0.0005	0.0006	0.0007	0.0008	0.0009
0.034	1 604	1 595	1 585	1 576	1 567	1 558	1 549	1 540	1 531	1 522
0.035	1 514	1 505	1 497	1 488	1 480	1 471	1 463	1 455	1 447	1 439
0.036	1 431	1 423	1 415	1 407	1 400	1 392	1 384	1 377	1 369	1 362
0.037	1 355	1 347	1 340	1 333	1 326	1 319	1 312	1 305	1 298	1 291
0.038	1 284	1 277	1 271	1 264	1 258	1 251	1 245	1 238	1 232	1 225
0.039	1 219	1 213	1 207	1 201	1 195	1 189	1 183	1 177	1 171	1 165
0.040	1 159	1 153	1 147	1 142	1 136	1 131	1 125	1 119	1 114	1 109
0.041	1 103	1 098	1 092	1 087	1 082	1 077	1 072	1 066	1 061	1 056
0.042	1 051	1 046	1 041	1 036	1 031	1 027	1 022	1 017	1 012	1 008
0.043	1 003	998	994	989	985	980	975	971	967	962
0.044	958	953	949	945	941	936	932	928	924	920
0.045	916	912	908	904	900	896	892	888	884	880
0.046	876	873	869	865	861	858	854	850	847	843
0.047	839	836	832	829	825	822	818	815	812	808
0.048	805	802	798	795	792	788	785	782	779	775
0.049	772	769	766	763	760	757	754	751	748	745
0.050	742	739	736	733	730	727	724	721	719	716
0.051	713	710	707	705	702	699	696	694	691	688
0.052	686	683	681	678	675	673	670	668	665	663
0.053	660	658	655	653	650	648	645	643	641	638
0.054	636	634	631	629	627	624	622	620	617	615
0.055	613	611	609	606	604	602	600	598	596	593
0.056	591	589	587	585	583	581	579	577	575	573
0.057	571	569	567	565	563	561	559	557	555	553
0.058	551	549	547	546	544	542	540	538	536	535
0.059	533	531	529	527	526	524	522	520	519	516.8
0.060	515.1	513.4	511.7	510.0	508.3	506.6	505.0	503.3	501.6	500.0
0.061	498.4	496.7	495.1	493.5	491.9	490.3	488.7	487.1	485.5	484.0
0.062	482.4	480.9	479.3	477.8	476.2	474.7	473.2	471.7	470.2	468.7
0.063	467.2	465.7	464.3	462.8	461.3	459.9	458.4	457.0	455.6	454.1
0.064	452.7	451.3	449.9	448.5	447.1	445.7	444.4	443.0	441.6	440.3
0.065	438.9	437.6	436.2	434.9	433.6	432.2	430.9	429.6	428.3	427.0
0.066	425.7	424.4	423.1	421.9	420.6	419.3	418.1	416.8	415.6	414.3
0.067	413.1	411.9	410.6	409.4	408.2	407.0	405.8	404.6	403.4	402.2
0.068	401.0	399.9	398.7	397.5	396.6	395.2	394.0	392.9	391.8	390.6
0.069	389.5	388.4	387.2	386.1	385.0	383.9	382.8	381.7	380.6	379.5
0.070	378.4	377.4	376.3	375.2	374.2	373.1	372.0	371.0	369.9	368.9
0.071	367.9	366.8	365.8	364.8	363.7	362.7	361.7	360.7	359.7	358.7
0.072	357.7	356.7	355.7	354.7	353.8	352.8	351.8	350.9	349.9	348.9
0.073	348.0	347.0	346.1	345.1	344.2	343.3	342.3	341.4	340.5	339.6
0.074	338.6	337.7	336.8	335.9	335.0	334.1	333.2	332.3	331.4	330.5
0.075	329.7	328.8	327.9	327.0	326.2	325.3	324.5	323.6	322.7	321.9
0.076	321.0	320.2	319.4	318.5	317.7	316.9	316.0	315.2	314.4	313.6
0.077	312.8	312.0	311.1	310.3	309.5	308.7	307.9	307.2	306.4	305.6
0.078	304.8	304.0	303.2	302.5	301.7	300.9	300.2	299.4	298.6	297.9
0.079	297.1	296.4	295.6	294.9	294.1	293.4	292.7	291.9	291.2	290.5
0.080	289.7	289.0	288.3	287.6	286.9	286.2	285.4	284.7	284.0	283.3
0.081	282.6	281.9	281.2	280.6	279.9	279.2	278.5	277.8	277.1	276.5
0.082	275.8	275.1	274.4	273.8	273.1	272.4	271.8	271.1	270.5	269.8
0.083	269.2	268.5	267.9	267.2	266.6	266.0	265.3	264.7	264.1	263.4
0.084	262.8	262.2	261.6	260.9	260.3	259.7	259.1	258.5	257.9	257.3
0.085	256.7	256.1	255.5	254.9	254.3	253.7	253.1	252.5	251.9	251.3
0.086	250.7	250.1	249.6	249.0	248.4	247.8	247.3	246.7	246.1	245.6
0.087	245.0	244.4	243.9	243.3	242.8	242.2	241.6	241.1	240.6	240.0
0.088	239.5	238.9	238.4	237.8	237.3	236.8	236.2	235.7	235.2	234.6
0.089	234.1	233.6	233.1	232.5	232.0	231.5	231.0	230.5	230.0	229.4
0.090	228.9	228.4	227.9	227.4	226.9	226.4	225.9	225.4	224.9	224.4
0.091	223.9	223.4	222.9	222.5	222.0	221.5	221.0	220.5	220.0	219.6
0.092	219.1	218.6	218.1	217.7	217.1	216.7	216.3	215.8	215.3	214.9
0.093	214.4	213.9	213.5	213.0	212.6	212.1	211.7	211.2	210.8	210.3

TABLE 2 *Continued*

Diagonal of Impression, mm	Vickers Hardness Number for Diagonal Measured to 0.0001 mm									
	0.0000	0.0001	0.0002	0.0003	0.0004	0.0005	0.0006	0.0007	0.0008	0.0009
0.094	209.9	209.4	209.0	208.5	208.1	207.6	207.2	206.8	206.3	205.9
0.095	205.5	205.0	204.6	204.2	203.8	203.3	202.9	202.5	202.1	201.6
0.096	201.2	200.8	200.4	200.0	199.5	199.1	198.7	198.3	197.9	197.5
0.097	197.1	196.7	196.3	195.9	195.5	195.1	194.7	194.3	193.9	193.5
0.098	193.1	192.7	192.3	191.9	191.5	191.1	190.7	190.4	190.0	189.6
0.099	189.2	188.8	188.4	188.1	187.7	187.3	186.9	186.6	186.2	185.5

At lower test forces the Vickers hardness may be force-dependent. In Table 2 are given the Vickers hardness numbers for a test force of 1 kgf. For obtaining hardness numbers when other test forces are used, the Vickers hardness number obtained from Table 2 is multiplied by the test force in kilograms-force (Table 3).

NOTE 1—The Vickers hardness number is followed by the symbol HV with a suffix number denoting the force and second suffix number indicating the duration of forceing when the latter differs from 10 to 15 s, which is the normal force time. *Example:*

440 HV 30 = Vickers hardness of 440 measured under a force of 30 kgf applied for 10 to 15 s.

440 HV 30/20 = Vickers hardness of 440 measured under a force of 30 kgf applied for 20 s.

TABLE 3 Decimal Point Finder for Use with Table 2

An example of determination of hardness numbers follows the table.

Diagonal Length, mm	Vickers Hardness (HV), 1-kgf Force
0.005	74 200
0.006	51 500
0.007	37 800
0.008	29 000
0.009	22 900
0.010	18 540
0.020	4 640
0.030	2 060
0.040	1 159
0.050	742
0.060	515
0.070	378
0.080	290
0.090	229
0.100	185.4
0.200	46.4
0.300	20.6
0.400	11.6
0.500	7.42
0.600	5.15
0.700	3.78
0.800	2.90
0.900	2.29
1.000	1.85
1.100	1.53
1.200	1.29
1.300	0.10
1.400	0.946
1.500	0.824
1.600	0.724
1.700	0.642
1.800	0.572
1.900	0.514
2.000	0.464

Example—Using a 50-kgf test force, the average measured diagonal length = 0.644 mm.
In Table 2 read:

HV = 447 at 0.0644-mm diagonal length at 1-kgf force.

Using Table 3 determine:

HV = 4.47 at 0.644-mm diagonal length at 1-kgf force.

50 × 4.47 = 224 HV for 50-kg test force.

A. GENERAL DESCRIPTION AND TEST PROCEDURE FOR VICKERS HARDNESS TESTS

4. Apparatus

4.1 *Testing Machine*—Equipment for Vickers hardness testing usually consists of a testing machine which supports the specimen and permits the indenter and the specimen to be brought into contact gradually and smoothly under a predetermined force, which is applied for a fixed period of time. The design of the machine should be such that no rocking or lateral movement of the indenter or specimen is permitted while the force is being applied or removed. A measuring microscope is usually mounted on the machine in such a manner that the impression in the specimen may be readily located in the optical field.

4.2 *Indenter*:

4.2.1 The indenter shall be a highly polished, pointed, square-based pyramidal diamond with face angles of 136° ± 30 min.

4.2.2 All four faces of the indenter shall be equally inclined to the axis of the indenter (within ±30 min) and meet at a sharp point, that is, the line of junction between opposite faces shall not be more than 0.001 mm in length as shown in Fig. 2.

4.2.3 The diamond should be examined periodically and if it is loose in the mounting material, chipped, or cracked, it should be discarded or reconditioned.

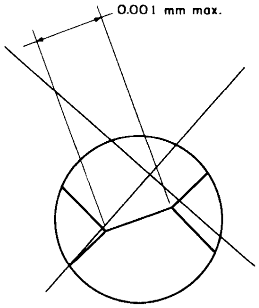

FIG. 2 Junction of Indenter Faces

NOTE 2—The condition of the point of the indenter is of considerable importance where the test force is light and the impression is small. It is recommended that the point be periodically checked by examining an impression made in a polished steel block. Under a magnification of 600× or more, using a vertical illuminator, any chipping or rounding of the point can be detected and the extent of the defect measured with a filar micrometer. It is recommended that a diamond pyramid indenter should not be used for tests in which the maximum length of such a defect exceeds 5 % of the length of the impression diagonal.

4.3 *Measuring Microscope*—The divisions of the micrometer scale of the measuring microscope or other measuring device shall be so constructed that the length of the diagonals of an impression in a properly surface-finished specimen (see section 5.1.2) can be measured to within ±0.0005 mm or ±0.5 %, whichever is larger.

5. Test Specimen

5.1 The Vickers hardness test is adaptable to a wide variety of test specimens ranging from large bars and rolled sections to minute pieces in metallographic mounts. In general the backs of the specimens shall be so finished or the specimens shall be so clamped that there is no possibility of their rocking or shifting under the test force. The specimens shall also conform to the requirements given in the following 5.1.1, 5.1.2, and 5.1.3.

5.1.1 *Thickness*—The thickness of the test specimen shall be such that no bulge or marking showing the effect of the force appears on the side of the specimen opposite the impression. In any event the thickness of the specimen shall be at least one and one half times the length of the diagonal. When laminated material is tested, the thickness of the individual component being tested shall be used for the thickness-diagonal length relationship.

5.1.2 *Finish*—The surface of the specimen should be so prepared that the ends of the diagonals are clearly defined and can be read with precision of ±0.0005 mm or ±0.5 % of the length of the diagonals, whichever is larger. Care should be taken in specimen preparation to avoid tempering during grinding, or work-hardening the surface during polishing.

5.1.3 *Alignment*—The specimen should be so prepared or mounted that the surface is normal to the axis of the indenter within ±1° of angle. This can readily be accomplished by surface grinding (or otherwise machining) the opposite side of the specimen to parallelism with the side to be tested.

5.1.4 *Radius of Curvature*—Until further investigative work is accomplished to determine the effect of the radius of curvature on readings, due caution should be used in interpreting or accepting the results of tests made on cylindrical surfaces.

NOTE 3—A method recommended by the International Organization for Standardization for correcting Vickers hardness readings taken on spherical or cylindrical surfaces is given in Table 4, Table 5, and Table 6.

NOTE 4—These tables give correction factors to be applied to Vickers hardness values obtained when tests are made on spherical or cylindrical surfaces. The correction factors are tabulated in terms of the ratio of the mean diagonal *d* of the indentation to the diameter *D* of the sphere or cylinder. Examples of the use of these tables are:

TABLE 4 Correction Factors for Use in Vickers Hardness Tests Made on Spherical Surfaces

Convex Surface		Concave Surface	
d/D[A]	Correction Factor	d/D[A]	Correction Factor
0.004	0.995	0.004	1.005
0.009	0.990	0.008	1.010
0.013	0.985	0.012	1.015
0.018	0.980	0.016	1.020
0.023	0.975	0.020	1.025
0.028	0.970	0.024	1.030
0.033	0.965	0.028	1.035
0.038	0.960	0.031	1.040
0.043	0.955	0.035	1.045
0.049	0.950	0.038	1.050
0.055	0.945	0.041	1.055
0.061	0.940	0.045	1.060
0.067	0.935	0.048	1.065
0.073	0.930	0.051	1.070
0.079	0.925	0.054	1.075
0.086	0.920	0.057	1.080
0.093	0.915	0.060	1.085
0.100	0.910	0.063	1.090
0.107	0.905	0.066	1.095
0.114	0.900	0.069	1.100
0.122	0.895	0.071	1.105
0.130	0.890	0.074	1.110
0.139	0.885	0.077	1.115
0.147	0.880	0.079	1.200
0.156	0.875	0.082	1.125
0.165	0.870	0.084	1.130
0.175	0.865	0.087	1.135
0.185	0.860	0.089	1.140
0.195	0.855	0.091	1.145
0.206	0.850	0.094	1.150

[A] D = diameter of sphere.
d = mean diagonal of impression in millimeters.

Example 1. Convex Sphere:
Diameter of sphere, *D* = 10 mm
Load = 10 kgf
Mean diagonal of impression, *d* = 0.150 mm
d/D = 0.150/10 = 0.015
From Tables 2 and 3, HV = 824
From Table 4, by interpolation, correction factor = 0.983
Hardness of sphere = 824 × 0.983 = 810 HV 10

Example 2. Concave Cylinder, One Diagonal Parallel to Axis:
Diameter of cylinder, D = 5 mm
Load = 30 kgf
Mean diagonal of impression, *d* = 0.415 mm
d/D = 0.415/5 = 0.083
From Tables 2 and 3, HV = 323
From Table 6, correction factor = 1.075
Hardness of cylinder = 323 × 1.075 = 347 HV 30.

6. Verification of Apparatus

6.1 The hardness testing machine shall be verified as specified in Part B.

6.1.1 Two acceptable methods of verifying Vickers hardness testing machines are given in Part B.

TABLE 5 Correction Factors for Use in Vickers Hardness Tests Made on Cylindrical Surfaces
(Diagonals at 45° to the axis)

Convex Surface		Concave Surface	
d/D^A	Correction Factor	d/D^A	Correction Factor
0.009	0.995	0.009	1.005
0.017	0.990	0.017	1.020
0.026	0.985	0.025	1.015
0.035	0.980	0.034	1.020
0.044	0.975	0.042	1.025
0.053	0.970	0.050	1.030
0.062	0.965	0.058	1.035
0.071	0.960	0.066	1.040
0.081	0.955	0.074	1.045
0.090	0.950	0.082	1.050
0.100	0.945	0.089	1.055
0.109	0.940	0.097	1.060
0.119	0.935	0.104	1.065
0.129	0.930	0.112	1.070
0.139	0.925	0.119	1.075
0.149	0.920	0.127	1.080
0.159	0.915	0.134	1.085
0.169	0.910	0.141	1.090
0.179	0.905	0.148	1.095
0.189	0.900	0.155	1.100
0.200	0.895	0.162	1.105
		0.169	1.110
		0.176	1.115
		0.183	1.120
		0.189	1.125
		0.196	1.130
		0.203	1.135
		0.209	1.140
		0.216	1.140
		0.222	1.150

$^A D$ = diameter of cylinder.
d = mean diagonal of impression in millimeters.

TABLE 6 Correction Factors for Use in Vickers Hardness Tests Made on Cylindrical Surfaces
(One diagonal parallel to axis)

Convex Surface		Concave Surface	
d/D^A	Correction Factor	d/D^A	Correction Factor
0.009	0.995	0.048	1.035
0.019	0.990	0.053	1.040
0.029	0.985	0.058	1.045
0.041	0.980	0.063	1.050
0.054	0.975	0.067	1.055
0.068	0.970	0.071	1.060
0.085	0.965	0.076	1.065
0.104	0.960	0.079	1.070
0.126	0.955	0.083	1.075
0.153	0.950	0.087	1.080
0.189	0.945	0.090	1.085
0.243	0.940	0.093	1.090
		0.097	1.095
Concave Surface		0.100	1.100
		0.103	1.105
		0.105	1.110
d/D^A	Correction Factor	0.108	1.115
		0.111	1.120
0.008	1.005	0.113	1.125
0.016	1.020	0.116	1.130
0.023	1.015	0.118	1.135
0.030	1.020	0.120	1.140
0.036	1.025	0.123	1.145
0.042	1.030	0.125	1.150

$^A D$ = diameter of cylinder.
d = mean diagonal of impression in millimeters.

7. Procedure

7.1 *Magnitude of Test Force*—Test forces of 1 kgf to 120 kgf may be used, depending on the requirements of the test. Although tests on homogeneous materials indicate that the Vickers hardness number is nearly independent of the test force, this condition will not be present in cases where there is a hardness gradient from the specimen surface to the interior of the specimen. The magnitude of the test force should therefore be stated in the test report (Section 11).

7.2 *Application of Test Force*—Apply the test force and release smoothly without shock or vibration. The time of application of the full test force shall be 10 to 15 s, unless otherwise specified.

7.3 *Spacing of Indentations*—The center of the impression shall not be closer to any edge of the test specimen or to another impression than a distance equal to two and one half times the length of diagonal of the impression. When laminated material is tested, a bond surface shall be considered as an edge for spacing of indentation calculations.

8. Measurement of Impression

8.1 Both diagonals of the impression shall be measured and their mean value used as a basis for calculation of the Vickers hardness number. It is recommended that the measurement be made with the impression centered as nearly as possible in the field of the microscope.

8.2 In the case of anisotropic materials, for example materials that have been heavily cold worked, there may be a difference between the lengths of the two diagonals of the impression. In such cases, the test specimen should be reoriented so that the diagonals of a new impression are approximately of equal length.

9. Accuracy

9.1 The accuracy of the Vickers hardness method is a function of the accuracies of the test force, indenter, and measuring device. The condition of the test and support surfaces and support of the test piece during application of the test force also affect accuracy. Under optimum conditions of these factors the accuracy that can be expected is the equivalent of 4 % of the Vickers hardness number of the standardized reference hardness test blocks (see section 18.2). Under less than ideal conditions the reduction in accuracy, when required, can be established empirically by employing statistical methods.

10. Conversion to Other Hardness Scales or Tensile Strength Values

10.1 There is no general method for converting accurately Vickers hardness numbers to other hardness scales or tensile strength values. Such conversions are, at best, approximations and therefore should be avoided, except for special cases where a reliable basis for the approximate conversions has been obtained by comparison tests.

NOTE 5—Standard E 140 gives approximate conversion values for specific materials such as steel, nickel and high-nickel alloys, and cartridge brass.

11. Report

11.1 The report shall include the following information:

11.1.1 The Vickers hardness number,

11.1.2 The test force used (see 3.4.2, Note 1), and

11.1.3 The force application time, if other than 10 to 15 s (see 3.4.2, Note 1).

12. Precision and Bias

12.1 Due to the wide variety of materials tested by this method and the possible variations in test specimens, the precision of this method has not been established. The accepted practice is to utilize the information in 9.1 when establishing hardness tolerances for specific applications. The precision of this method, whether involving a single operator, multiple operators, or multiple laboratories, can be established by employing statistical methods.

B. VERIFICATION OF VICKERS HARDNESS TESTING MACHINES

13. Scope

13.1 Part B covers two procedures for the verification of Vickers hardness testing machines and a procedure that is recommended for use to confirm that the machine has not become maladjusted in the intervals between the periodical routine checks. The two methods of verification are:

13.1.1 Separate verification of force application, indenter, and measuring microscope.

13.1.2 Vertification by standardized test block method.

13.2 The first procedure (13.1.1) is mandatory for new and rebuilt machines.

13.3 The second procedure (13.1.2) shall be used for verifying machines in service.

14. General Requirements

14.1 Before a Vickers hardness testing machine is verified the machine shall be examined to ensure that:

14.1.1 The machine is properly set up.

14.1.2 The indenter holder is mounted normally in the plunger.

14.1.3 The force can be applied and removed without shock or vibration in such a manner that the readings are not influenced.

14.2 If the measuring device is integral with the machine, the machine shall be examined to ensure that:

14.2.1 The change from forceing to measuring does not influence the readings.

14.2.2 The method of illumination does not affect the readings.

14.2.3 The center of the impression is in the center of the field of view.

15. Verification

15.1 *Separate Verification of Force Application, Indenter, and Measuring Microscope*:

15.1.1 *force Application*—The applied force shall be checked by the use of dead weights and proving levers, or by an elastic calibration device or springs in the manner described in Practices E 4. Such dead weights or other forceing devices shall be accurate to ±0.2 %. Vickers hardness testing machines shall be verified at a minimum of three applied forces including the test force specified. A minimum of three readings should be taken at each force. A Vickers hardness testing machine is acceptable for use over a forceing range within which the machine error does not exceed ±1 %.

15.1.2 *Indenter*—The form of the diamond indenter shall be verified by direct measurement of its shape or by measurements of its projection on a screen. The angle between opposite faces of the pyramid shall be 136° ± 30 min. All four faces shall be equally inclined to the axis of the pyramid within ±30 min. The four faces of indenters used for laboratory, or routine tests, shall meet at a point no more than 0.001 mm in length (see Fig. 2). The four faces of indenters used in calibrating standardized hardness test blocks, shall meet at a point in which the line of junction between opposite faces is no more than 0.0005 mm in length (see Fig. 3). The quadrilateral that would be formed by the intersection of the four faces with a plane perpendicular to the axis of the indenter shall have angles of 90° ± 12 min.

15.1.3 *Measuring Microscope*—The measuring microscope or other device for measuring the diagonals of the impression shall be calibrated against an accurately ruled line scale (stage micrometer). The errors of the line scale shall not exceed 0.05 µm (0.00005 mm) or 0.05 % of any interval, whichever is greater. The measuring microscope shall be calibrated throughout its range of use and a calibration factor chosen such that the error shall not exceed ±0.5 %. It may be necessary to divide the complete range of the micrometer microscope into several subranges, each having its own factor.

15.2 *Verification by Standardized Test Block Method*:

15.2.1 A Vickers hardness testing machine used only for routine testing may be checked by making a series of impressions on standardized hardness test blocks (Part C).

15.2.2 A minimum of five Vickers hardness readings shall be taken on at least three blocks having different levels of

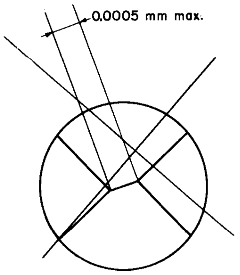

FIG. 3 Junction of Indenter Faces

hardness using a test force or forces as specified by the user with the test force applied for 12 s.

15.2.3 Vickers hardness testing machines shall be considered verified if the mean diagonal for five hardness impressions meets the requirements of 17.2.

16. Procedure for Periodic Checks by the User

16.1 Verification by the standardized test block method (15.2.2) is too lengthy for daily use. Instead the following is recommended:

16.1.1 Make at least one routine check each day that the testing machine is used.

16.1.2 Before making the check, verify that the zero reading of the measuring apparatus is correctly adjusted.

16.1.3 Make at least five hardness readings on a standardized hardness test block on the scale and at the hardness level at which the machine is being used. If the values fall within the range of the standardized hardness test block the machine may be regarded as satisfactory; if not the machine should be verified as described in 15.2.2.

17. Repeatability and Error

17.1 *Repeatability*:

17.1.1 For each standardized block, let d_1, d_2, $\cdots$ d_5 be the arithmetic means of the two diagonals of the indentations, arranged in increasing order of magnitude.

17.1.2 The repeatability of the machine under the particular verification conditions is expressed by the quantity $d_5 - d_1$.

17.2 *Error*:

17.2.1 The error of the machine under the particular verification conditions is expressed by the quantity $\bar{d} - d$, where $\bar{d} = (d_1 + d_2 + \cdots d_5)/5$, and d is the reported mean diagonal of impressions on the standardized hardness test block.

18. Assessment of Verification

18.1 *Repeatability*—The repeatability of the machine verified is considered satisfactory if it satisfies the conditions given in Table 7.

18.2 *Error*—The mean diagonal for five impressions should not differ from the mean diagonal corresponding to the Vickers hardness of the standardized test block by more than 2 % or 0.5 µm (0.0005 mm), whichever is greater.

C. CALIBRATION OF STANDARD HARDNESS TEST BLOCKS FOR VICKERS HARDNESS MACHINES

19. Scope

19.1 Part C covers the calibration of standardized hardness test blocks for the verification of Vickers hardness testing machines as described in Part B.

TABLE 7 Repeatability of Machines

Range of Standardized Hardness of Test Blocks	The Repeatability of the Machine Should be Less Than:	Examples of Equivalents in Hardness Units
100 to 240, incl	4 % of $d^{A,B}$	8 at 100 HV; 16 at 200 HV
Over 240 to 600, incl	3 % of $d^{A,B}$	18 at 300 HV; 36 at 600 HV
Over 600	2 % of $d^{A,B}$	28 at 700 HV

[A] $d = (d_1 + d_2 + ... + d_5)/5$.

[B] In all cases the repeatability is the percentage given or 1 µm (0.001 mm), whichever is the greater.

20. Manufacture

20.1 Each metal block to be standardized shall be not less than ¼ in. (6 mm) in thickness.

20.2 Each block shall be specially prepared and heat treated to give the necessary homogeneity and stability of structure.

20.3 Each block, if of steel, shall be demagnetized by the manufacturer and maintained demagnetized by the user.

20.4 The lower surface of the test block shall have a fine ground finish.

20.5 The test (upper) surface shall be polished and free of scratches which would interfere with measurements of the diagonals of the impression.

20.5.1 The mean surface roughness height rating shall not exceed 4 µin. (0.0001 mm) center line average.

20.6 To ensure that no material is subsequently removed from the test surface of the standardized test block, an official mark or the thickness at the time of calibration shall be marked on the test surface to an accuracy of ±0.005 in.(±0.1 mm).

21. Standardizing Procedure

21.1 The standardized hardness test blocks shall be calibrated on a Vickers hardness testing machine verified in accordance with the requirements of 13.1.1.

21.2 The mechanism that controls the application of force should either:

21.2.1 Employ a device such as a spring to reduce the velocity of indentation of the indenter during the period of indentation, or

21.2.2 Employ a device to maintain a constant velocity of indentation of the indenter.

21.3 The full test force shall be applied for 12 s.

22. Number of Indentations

22.1 At least five and preferably ten randomly distributed indentations shall be made on each test block.

23. Measurement of the Diagonals of the Indentation

23.1 The illuminating system of the measuring microscope shall be adjusted to give uniform intensity over the field of view and maximum contrast between the indentation and the undistributed surface of the block.

23.2 The measuring microscope shall be graduated to read 0.001 mm with estimates made to the nearest ±0.0002 mm.

23.3 The measuring microscope shall be checked by a stage micrometer, or by other suitable means, to ensure that the difference between readings corresponding to any two divisions of the instrument is correct within ± 0.0005 mm.

23.4 It is recommended that each indentation be measured by two observers.

24. Repeatability

24.1 Let d_1, d_2, $\cdots$ d_n be the mean values of the measured diagonals as determined by one observer, arranged in increasing order of magnitude.

24.2 The repeatability of the hardness readings on the block is defined as $(d_{10} - d_1)$, when ten readings have been made or 1.32 $(d_5 - d_1)$ when five readings are taken on the block.

25. Uniformity of Hardness

25.1 Unless the repeatability of hardness readings as measured by the mean diagonals of five or ten impressions is within the limits given in Table 8, the block cannot be regarded as sufficiently uniform for standardization purposes.

TABLE 8 Repeatability of Hardness Readings

Range of Standardized Hardness of Test Block	The Repeatability of the Test Block Readings Shall be Less Than:
100 to 240, incl	3 % of $d^{A,B}$
Over 240 to 600, incl	2 % of $d^{A,B}$
Over 600	1.5 % of $d^{A,B}$

[A] $d = (d_1 + d_2 + ... + d_n)/n$.

[B] In all cases the repeatability is the percentage given or 1 µm (0.001 mm), whichever is the greater.

26. Marking

26.1 Each block shall be marked with the following:

26.1.1 Arithmetic mean of the hardness values found in the standardization test (see also 3.4.2, Note 1).

26.1.2 The name or mark of the supplier,

26.1.3 The serial number of the block, and

26.1.4 The thickness of the test block or an official mark on the top surface (see section 19.6).

NOTE 6—All of the markings except the official mark or thickness should be placed on the side of the block, the markings being upright when the test surface is the upper face.

27. Keywords

27.1 metallic; Vickers hardness

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Objective: B_10X
Calibration: 0.62112 µm/Pixel

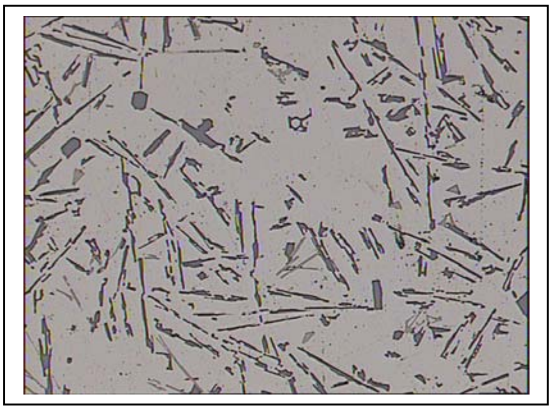


Fig. 1 Captured image

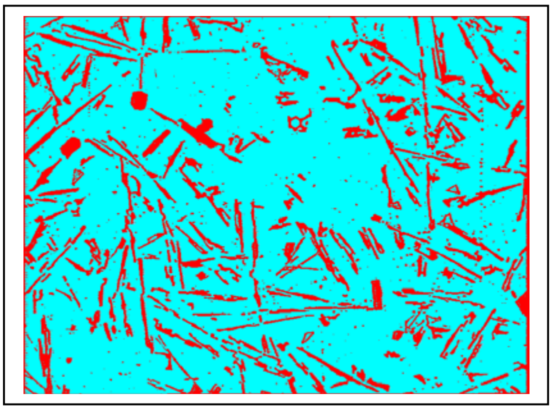
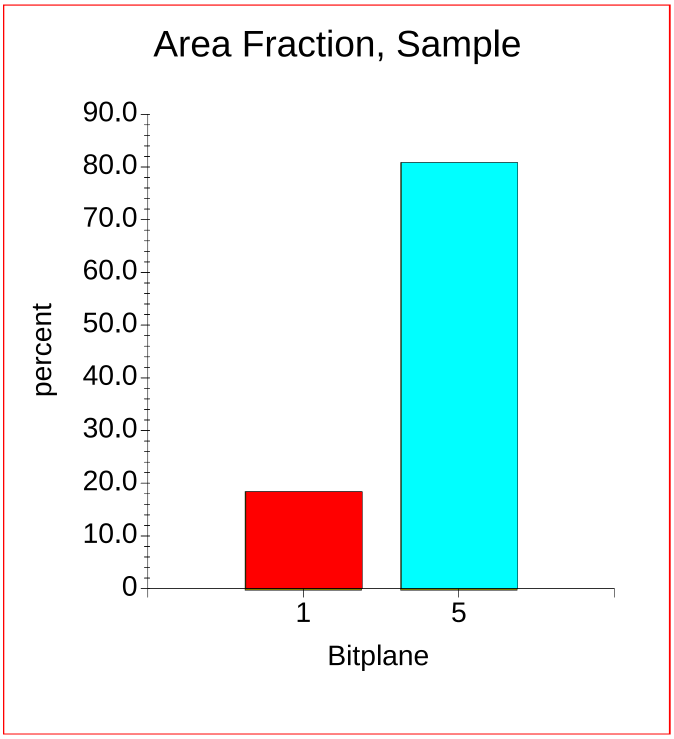


Fig. 2 Detected image



Field Summary

1: Bitplane 1	18.4026 %
5: Bitplane 5	80.8413 %
Fld Area:	170660 µm²
Tot Area:	170660 µm²
Fld Count:	1 ##

Fig. 3 Image Analysis Measurements

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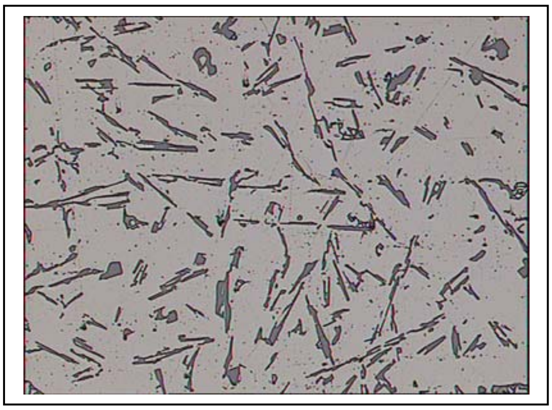
Calibration: 0.62112 µm/Pixel



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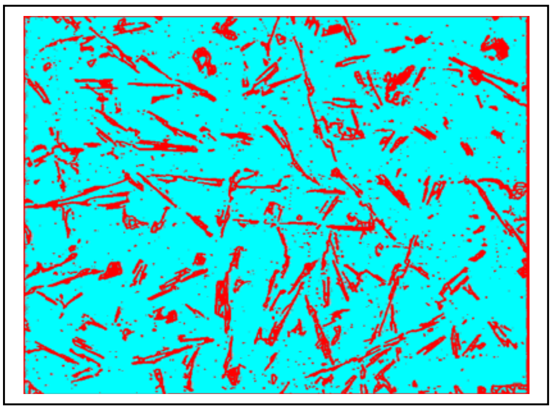
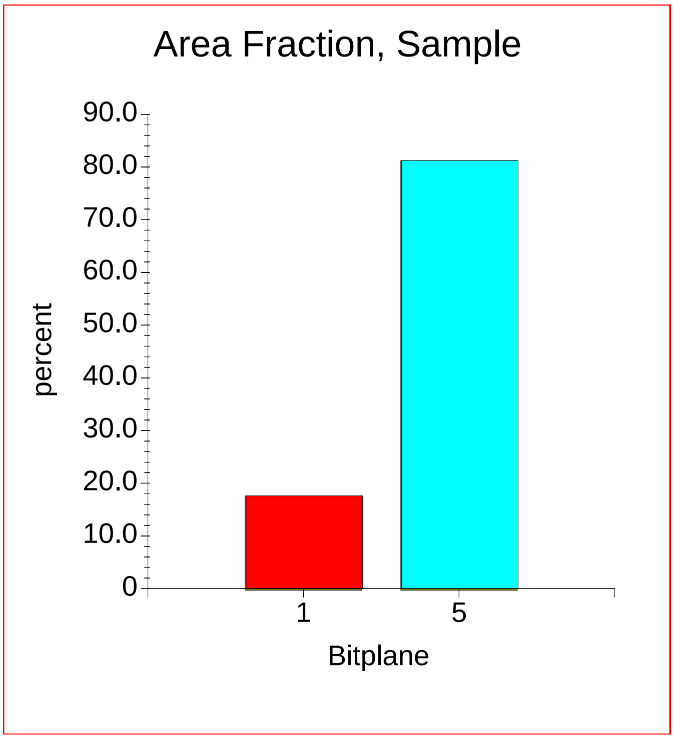


Fig. 2 Detected image



Field Summary

1: Bitplane 1	17.6089 %
5: Bitplane 5	81.1937 %
Fld Area:	170660 μm^2
Tot Area:	170660 μm^2
Fld Count:	1 ##

Fig. 3 Image Analysis Measurements

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Report :
Objective: B_10X
Calibration: 0.62112 µm/Pixel

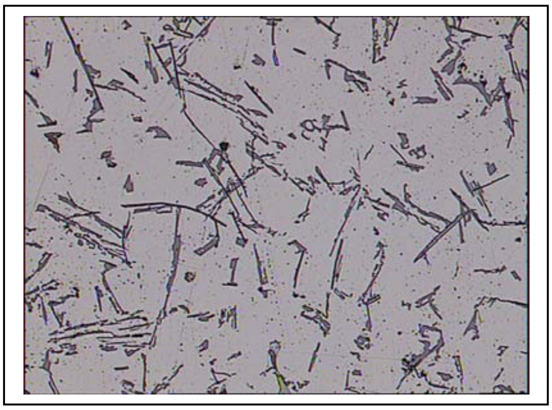


Fig. 1 Captured image

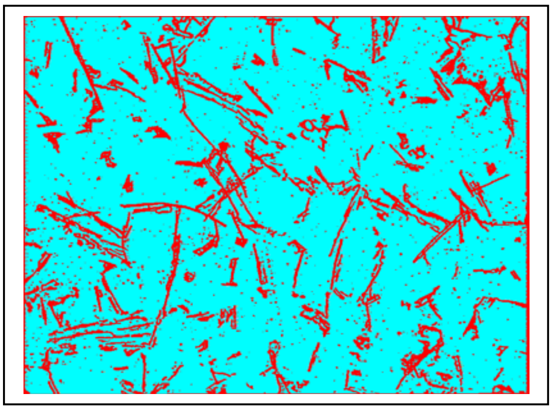
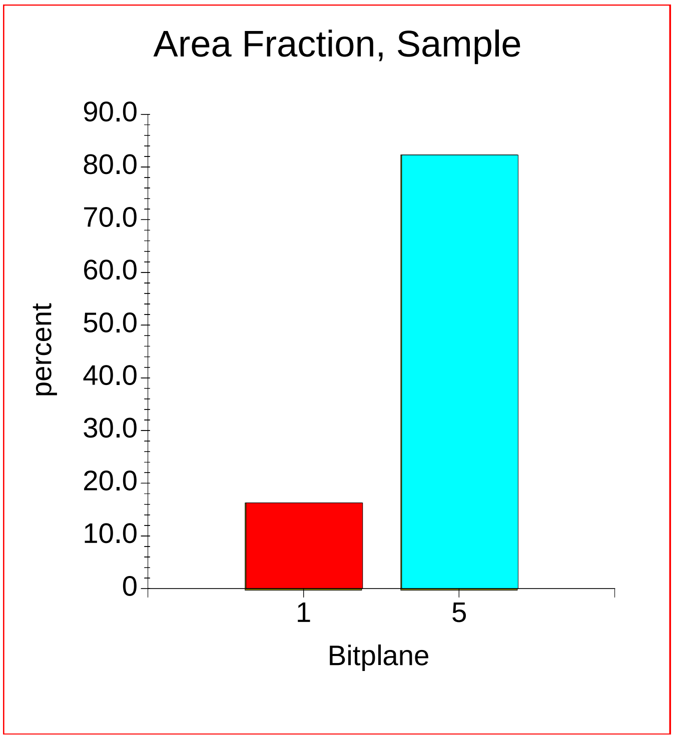


Fig. 2 Detected image



Field Summary

1: Bitplane 1	16.2593 %
5: Bitplane 5	82.2842 %
Fld Area:	170660 µm²
Tot Area:	170660 µm²
Fld Count:	1 ##

Fig. 3 Image Analysis Measurements

<u>Comments</u>

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Heat No:

Report :
Objective: C_20X
Calibration: 0.31250 µm/Pixel

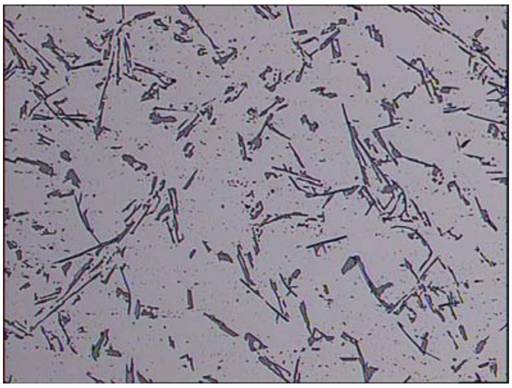


Fig. 1 Captured image

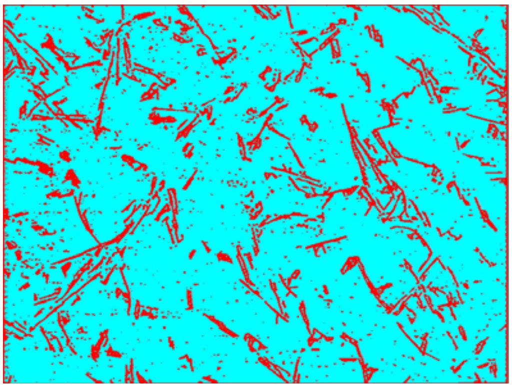
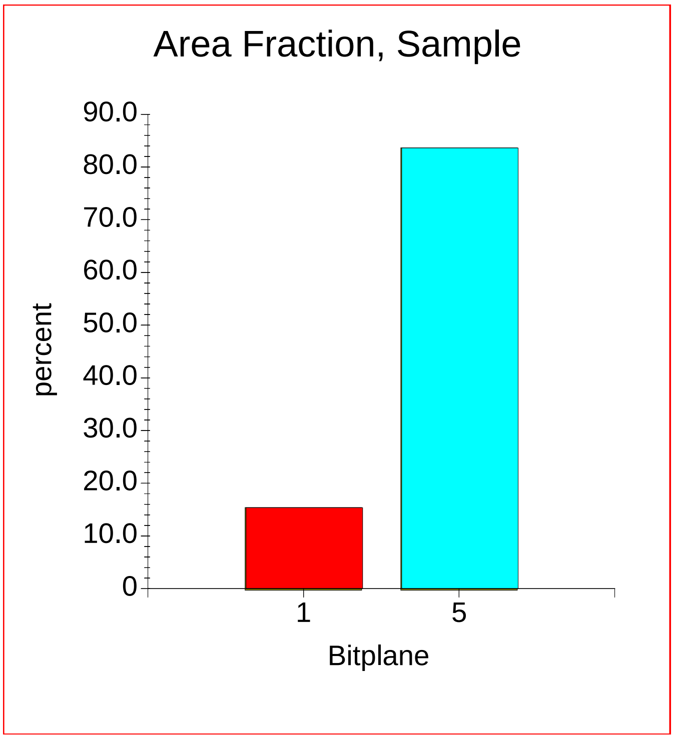


Fig. 2 Detected image



Field Summary

1: Bitplane 1	15.3797 %
5: Bitplane 5	83.6084 %
Fld Area:	43200 µm²
Tot Area:	43200 µm²
Fld Count:	1 ##

Fig. 3 Image Analysis Measurements

Comments

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