SOME STUDIES ON PROCESS PARAMETERS IN CENTRIFUGAL CASTING

Thesis

Submitted in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

by

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by the Ph.D Research Scholar

I hereby declare that the Research Thesis entitled "**SOME STUDIES ON PROCESS PARAMETERS IN CENTRIFUGAL CASTING**" which is being submitted to the **National Institute of Technology Karnataka, Surathkal** in partial fulfillment of the requirements for the award of the degree of **Doctor of Philosophy** in **Department of Mechanical Engineering** *is a bonafide report of the research work carried out by me.* The material contained in this Research Thesis has not been submitted to any University or Institution for the award of any degree.

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(MADHUSUDHAN)

Abstract

In a centrifugal casting process, the fluid behavior of the melt plays an important role in determining the quality of the final products. There are many parameters which influence the centrifugal casting process namely pouring temperature of the melt, initial temperature of the mold, thermal conductivity of the mold material, rotational speed of the mold, size of the mold and time taken for pouring the melt into the mold, etc. Rotational speed of the mold is one such parameter amongst the important process variables which affect the rate of solidification of the molten metal. When the liquid is rotated in partially filled cylindrical mold at different rotational speeds, it exhibits various flow patterns, namely Ekmann flow, Couette flow and Taylor flow; these are disturbing flows inside the cylinder. A brief survey of the earlier literature indicates that many investigations have been carried out to study the behavior of the liquids and its effect on the casting process. The microstructures of the castings are influenced mainly by the behavior of molten metal flow during rotation of the mold. To get a uniform hollow cylinder, the molten metal must spread along the axis after being poured and must slide along the inner surface of the mold. But the factors involved in fluid instabilities that influence the quality of the casting and rate of cooling need to be investigated. The analysis of liquid flow during centrifugal casting is very difficult to comprehend due to the opaque nature of the melt and the mold and the viscosity of the liquid varies with time. The phase change, due to heat transfer also adds to the complexity of the problem. Since the mold and melts are opaque, motion of the melt cannot be visualized and analyzed with conventional measurement techniques. Therefore in order to study the various liquid patterns and the rate of cooling at different rotational speeds, it is necessary to make preliminary examinations about the nature of the liquid flow in a partially filled rotating cylinder at various rotational speeds. Cold modeling experiments have been carried out using liquids with different viscosities to study the fluid behavior. Influence of rotational speed of the mold, its optimization to form a liquid cylinder and regular cooling rates at different rotational speeds have been carried out.

In this research work, an attempt is made to study the process of solidification and the effect of solidification structures on the mechanical properties of centrifugal castings. The three types of solidification processes have been carried out. One being the solidification of pure Tin and the others being the solidification of alloys such as eutectic Al-12wt%Si alloy and a hypereutectic Al-17wt%Si alloy they have a range of temperature to solidify. Tin metal is used to study the metallurgical behavior of pure metal, as it is having low melting temperature of 231°C, Al-12wt%Si alloy of melting temperature 577°C and Al-17wt%Si alloy of melting temperature 577°C to 620°C are used to analyze the metallurgical behavior of the alloys and also to study the particle segregation in the cylinder across the thickness of the casting. Eutectic as we know is a reversible isothermal reaction of a liquid metal which forms two different solid phases in a binary system upon cooling, i.e., $L= \alpha +\beta$. This is an invariant reaction in which liquid phase transforms to two solid phases.

The rate of solidification of any melt during centrifugal castings is of great importance because of its role in determining the microstructure and mechanical properties. The rate of solidification of pure metal in centrifugal casting is measured based on the grain size and for the Al-Si alloys it is measured based on the Secondary Dendrite Arm Spacing (SDAS). In this work properties like grain size, solidification rate, hardness, and specific wear rate are determined. It is found that the regions where rapid solidification occurs, there fine equi-axed grains are observed and coarse grains are observed at regions where slow solidification takes place.

In casting experiments the cooling curves were drawn for the gravity castings which were made initially by monitoring the cooling rate. The microstructures were analyzed using image analyzer. Grain sizes have been measured and a graph is plotted for rate of solidification verses grain size. Using this data the rates of solidification of centrifugal castings are inferred, based on the grain size of the castings. The effect of mold wall thickness on rate of solidification is evaluated by making the castings using molds with varying wall thickness. Experiments have been conducted to study the effect of mold preheating on rate of solidification. As the mold temperature increases the temperature difference between the die and the molten metal decreases and hence

rate of solidification decreases. Fast solidification rate leads to the fine grain formation leading to an increase in hardness and decrease in specific wear rate. For all the cases the variation in hardness along the radial direction is determined. Specific wear rate have been determined at the inner and outer surfaces of the cylindrical castings. For the Al-12wt%Si centrifugal casting by evaluating SDAS the solidification rates have been calculated.

Variation in hardness and specific wear rate were also studied. Fine grains were observed at the outer surface of the cylindrical tin casting which is due to the chilling effect and hence the hardness was found to be higher compared to the hardness at the inner surface. It is also found that hardness is gradually decreasing towards the inner radius of the casting. But in case of Al-12wt%Si at the outer surface the hardness is higher due to chilling effect with the cold mold wall. At the inner surface hardness is higher due to the segregation of Si particles at the inner surface, because of its lower density with the matrix and also due to the centrifugal effect on the Si particles at higher speeds of rotation of the mold. Similar results have been obtained in case of Al-17wt %Si castings with slightly higher hardness at the inner surface of the casting.

Key words: *Centrifugal Casting, Grain Size, Gravity Casting, Hardness, Rate of Solidification, Secondary Dendritic Arm Spacing, Specific Wear Rate*

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NOMENCLATURE

CR	Cooling Rate
CF	Centrifugal Force
GF	Gravitational Force
G	Gravitational Coefficient or G factor
EP	Extra Power
rpm	revolution per minute
BHN	Brinell Hardness Number
FGM	Functionally Graded Materials
Al-Si	Aluminum Silicon alloy
Al-12wt%Si	Aluminum Silicon alloy with 12 weight percent of silicon
Al-17wt%Si	Aluminum Silicon alloy with 17 weight percent of silicon
SWR	Specific Wear Rate
SEM	Scanning Electron Microscope
SDAS	Secondary Dendritic Arm Spacing
EDAX	Energy Dispersive X-ray Analysis

Chapter 1

INTRODUCTION

Centrifugal casting is a process of producing castings by causing the molten metal to solidify inside the rotating molds. This technique is one of the prime methods used in foundry industry to produce cylindrical and symmetrical parts. In centrifugal casting process the rotation of the mold and metal pouring rate vary with the alloy composition, size and shape being cast (Shailesh et al. 2010). Centrifugal casting was invented in 1918 by the Brazilian Dimitri Sensaud deLavaud (Sufei et al. 2008). His invention eliminated the need for the central core in hollow casting and the mold was water cooled and allowing for its continuous use. This technique uses the centrifugal force generated by a rotating cylindrical mold to throw the molten metal against the inner surface of the mold to form a desired shape as shown in the Figure 1.1. It also helps for the rapid solidification and hence strengthens the casting (Pavlovic et al. 2009). The wall thickness of the centrifugal casting can be controlled by the amount of liquid metal poured and by varying the rotational speed of the mold. Centrifugal casting has a greater reliability than static castings as they are relatively free from gas and shrinkage porosity (Sufei et al. 2008). The non metallic inclusions and evolved gasses tend towards the inner surface of the casting and which can be removed by turning operation. Therefore using the outstanding advantage created by the centrifugal force of rotating molds, castings of high quality and integrity can be produced because of their high density and free from oxides, gasses and other nonmetallic inclusions. Sometimes static mold castings require surface treatments such as, case carburizing, flame hardening and nitriding to use as a wear resistant surface combined with a hard exterior surface, which can be eliminated completely by using centrifugal casting process (Campbell. 1961).

Centrifugal casting process is largely used in foundries for the production of axially symmetric components such as tubes, cylinder liners, rolling mill rolls, rings and bushes with main applications on iron and steel production industry. This process allows for obtaining high quality castings and being associated to several advantages with respect to other foundry process.

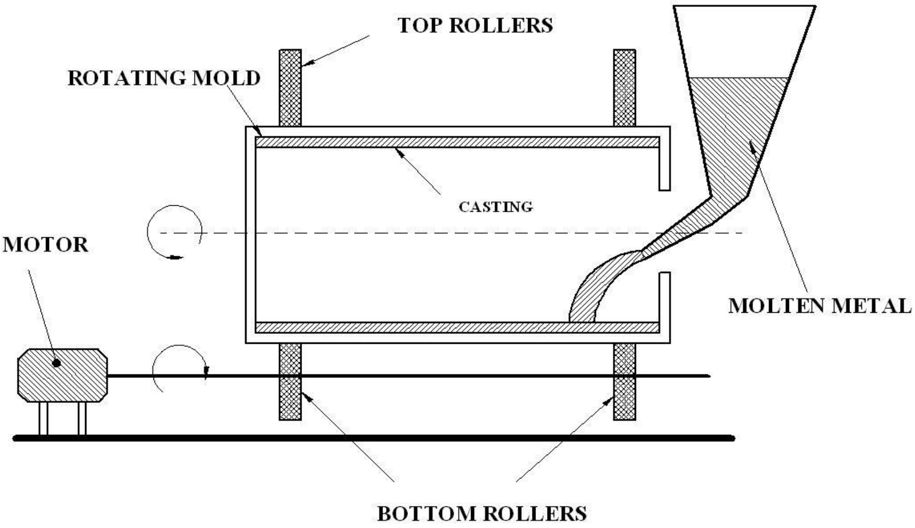


Figure 1.1 Centrifugal Casting Process

The centrifugal casting cools and solidifies from outside to inside towards the axis of rotation, thereby providing conditions which will set up a directional solidification to produce castings free from shrinkage. Therefore the castings produced in metal molds by centrifugal casting method have true directional heat flow facilitating a planar solidification front move from mold inner surface, corresponding to casting outer surface toward the axis of rotation. However it also depends on composition of the alloy. Hence, low melting point impurities are carried by the solidification front to the inner surface of the casting (Sufei et al. 2008).

The quality of the final centrifugal casting is mainly depending upon many parameters such as: pouring temperature of the melt, temperature of the mold, rotational speed of the mold, duration of metal pouring, composition of the melt, diameter and shape of the mold and also thickness of the casting (Zagorski et al. 2007). The mathematical description of centrifugal casting is very difficult because of the above mentioned parameters and the involvement of different processes such as fluid dynamics, heat transfer, rate of solidification, particle segregation and so on. Therefore the above mentioned process variables have a great effect on the rate of solidification of centrifugal casting and in turn the rate of solidification of centrifugal casting process affects the quality of casting in terms of its microstructure and mechanical properties.

During the centrifugal casting process solidification starts at the interface between the mold and melt due to the sudden chilling effect with the metal mold. This happens because the heat within the molten metal flows into the relatively cooler region of the mold. Molding materials transfer heat from the melt into the mold at different rates. If the temperature of the mold is high the temperature difference between the mold and the melt becomes less and hence rate of heat transfer gets decreased. Therefore solidification rate can be controlled by the melt, mold temperature as well as mold wall thickness.

The viscosity is one of the important physical properties of the melt which influences the melt flow behavior and its flow pattern inside the mold (Xu et al. 2002). On the other hand, during the solidification process the melt viscosity may vary by the exponential order of the reciprocal of temperature (Geiger et al. 1973).

Centrifugal casting is one of the casting processes usually associated with obtaining of functionally graded materials mainly metallic materials which have high differences in density and low solubility on different phases or different materials of the same alloy (Suresh, 1997). During mold rotation, the particles suspended in the liquid are subjected to both centrifugal force as well as gravitational force. The centrifugal force (**CF**) acting on a particles along the radial direction is given as $\mathbf{CF = m\omega^2 r}$**,** where **m**-mass (kg), **ω**-angular velocity (rad./s), **r**-radius of rotation (m) and the gravitational force is given as $\mathbf{GF = mg}$**,** where **m**-mass (kg) and **g**-acceleration due to gravity (m/s^2). The ratio of centrifugal force and gravitational force is called the gravitational coefficient (G) or G factor, which is given in equation (1.1).

$$\mathbf{G_{factor}} = \omega^2 r / g \tag{1.1}$$

Since the centrifugal force acting on the particle is G times higher than the gravitational force, the gravitational force is negligible when compared to the centrifugal force. Thus as the rotational speed increases the centrifugal force acting on the particles for their segregation also increases (Kumar et al. 2010). When a higher rotational speed is applied to the mold, it gives rise the different zones across the radial direction in the casting namely, particle rich zone and particle free zones. The thickness of the particle free zones varies with the rotational speed of the mold (Kiran et al. 2010).

Rotational speed of the mold is another important process variable which has an effect on the rate of solidification of the molten metal, because the fluid exhibits different flow patterns like sloshing, Ekmann flow, Couette flow and Taylor's flow which are disturbed flows, when it is rotated at different rotational speeds (Mukunda et al. 2007, Das et al. 2003). As the rotational speed is increased the centrifugal force increases as a square of the speed, which may create a strong convection in the liquid pool and then producing a homogenization of temperature in the bulk liquid. Hence, it leads to the rapid cooling of the liquid. As a result, the growth of equiaxed grains is favored (Wu et al. 2006). Therefore it is required to review and focus on the fluid flow phenomena in the centrifugal casting process.

Therefore the process variables like, rotational speed of the mold, mold wall thickness and mold temperature mentioned above are the important process variables which have great effect on the rate of solidification of the centrifugal casting. Few authors have (Shailesh et al. 2009, Wu et al. 2006, Chirita et al. 2008) used the state of art technology to study the flow and its effects on the centrifugal casting process and the process through analytical, experimental and numerical techniques. But the factors involved in fluid instabilities that influences flow and rate of cooling need to be investigated further. Moreover, the physics of fluid behavior has hardly been understood. It has been also noted that many investigations have been directed at the solution of a particular aspect and no attempts have been made to study the process as a whole. Hence it is necessary to make preliminary examinations of the nature of the flow of liquids in a partially filled rotating cylinder at various rotational speeds to study the various liquid patterns and also the rate of cooling at different rotational speeds. The cold modeling approach aids in finding the flow of the fluid but fails to simulate the complete casting process where other complexities like phase change, variation of viscosity and heat transfer are quite complicated in the process.

In order to study the effect of rotational speed on the solidification rate of the melt, hot liquid can be made to rotate at various rotational speeds in a hollow cylinder by partially filling it with hot liquid and the variation of temperature with respect to the time can be measured. The cooling rate is very slow when the cylinder is static and when the cylinder is rotating, the liquid will be turbulent and hence the cooling rate is high. When the cylinder is rotated above some critical speed the liquid forms a uniform thick layer at which the speed of the liquid layer will be same as the speed of the rotating cylinder which has to be investigated. In this mode centrifugal force dominates and the fluid coats the cylinder surface uniformly and rotates rigidly with it. And due to the minimum relative movement between the fluid layer and the mold wall the rate of cooling will be slower. But during the centrifugal casting process solidification rate of the castings increases with an increase in the rotational speed of the mold (Das et al. 2003). This concept can be studied by conducting the experiments of actual centrifugal casting with varying the mold wall thickness, preheated temperature of the mold and at different rotational speeds of the mold.

Tin metal has been used in this experiment as it has the lower melting temperature of 231^{o}C. As a pure metal, tin has wide industrial applications as it is used in the production of electronic valves, storage tanks for pharmaceutical, chemical solutions, capacitors, electrodes, fuse-wires, ammunitions, tinned iron sheets to protect victuals, sweets or tobacco etc.

Tin melt will solidify at the single temperature which may be termed as the freezing point (F.P) or solidification point as shown in Figure 1.2. The area above the freezing point, the metal is in liquid state and below the freezing point the metal is in solid state. The time versus temperature plot under normal conditions indicates that the liquid metal cools from A to B. This is the liquid shrinkage phase. Here the heat liberated is in the form of super heat. From B to C the melt liberates the heat of fusion, but the temp remains constant.

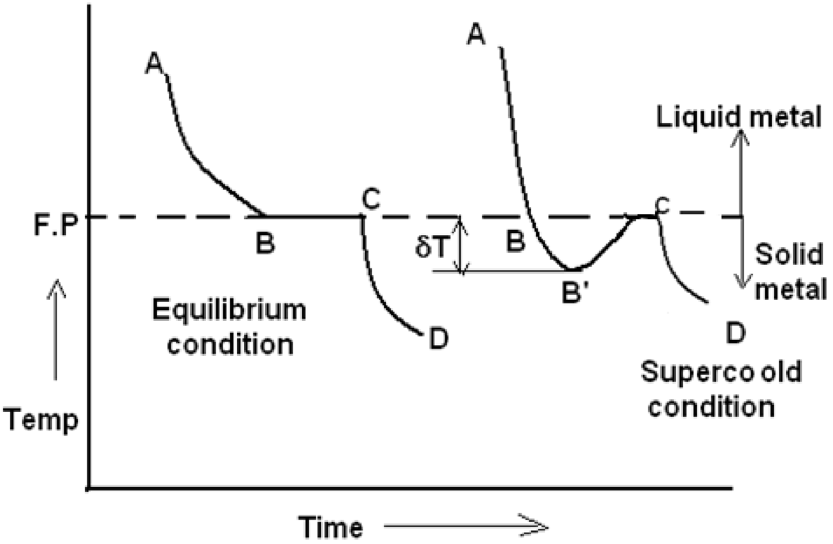


Figure 1.2 Cooling curves for Pure Metals (Raghavan, 1995)

The liquid metal starts solidifying at point B and it is partly liquid and partly solid at any point between B and C and from C to D the solid metal cools and tends to reach room temperature. Practically the liquid metal cools rapidly (super cool condition) nucleation of solid doesn’t start at B, but it starts at B'. That is, after the liquid metal has super cooled (under cooled) by an amount of δT, this metal solidifies in the form of solid skin and then the liquid metal tends to freeze on to it. The successive layers of molten metal are built-up in the form of solid skin. The liquid level in the mold falls because of solidification shrinkage this leads to shrinkage defects and can be compensated by using risers, chills, insulates etc.

In order to study the effect of process variables on solidification of alloys, two types of aluminum alloys Al-12wt%Si (Eutectic) and Al-17wt%Si (Hypereutectic) are used in this study. Eutectic alloy solidifies at a fixed temperature like a pure metal except two solid phases exhibit coupled growth under slow cooling. However aluminum nucleation is faster and how structure formation is affected in this dynamic process is interesting. Al-17wt%Si freezes over a range of temperature with one or the other proeutectic phases followed by eutectic by isothermal freezing; we can study the freezing of an alloy over a range of temperature. Al-Si is an important alloy for many commercial automotive applications like pistons, cylinder liners, etc. due to its unique properties. The Al-Si alloy systems have the advantage of high thermal conductivity and improved mechanical properties for wide temperature range. And the Si having low density of 2.34 g/cm^3 in Al-Si system provides the advantages such as it helps in reducing the overall weight of the component, because of having diamond crystal structure that provides good hardness, since Si has a very low solubility in Al hence it improves the wear characteristics and also Si content imparts fluidity to the melt and low shrinkage resulting in good casting. Figure 1.3 shows the phase equilibrium diagram of solidification for Aluminum-Silicon (Al-Si) alloy. Depending on the Si concentration in weight percentage, the Al-Si alloy system is classified into three major categories:

i. Hypoeutectic (<12 wt % Si)
ii. Eutectic (12-13 wt % Si)
iii. Hypereutectic (14-25 wt % Si).

Aluminum-Silicon system is a simple binary eutectic with limited solubility of silicon in aluminum and increasing the Si content increases the strength but at the expense of ductility (Mondolfo et al. 1976). There is only one invariant reaction in this diagram, namely

$$L_E \rightarrow \alpha_E + \beta_E \text{ (eutectic)}$$

In above equation, L_E is the liquid phase, α_E is predominantly aluminum, and β_E is almost pure silicon. It is now widely accepted that the eutectic reaction takes place at 577°C and at a silicon level of 12.6%. The silicon content in standardized commercial cast Al-Si alloys is in the range of 5 to 23 wt%. The use of Aluminum silicon casting alloys as structural material is determined by their physical and chemical properties.

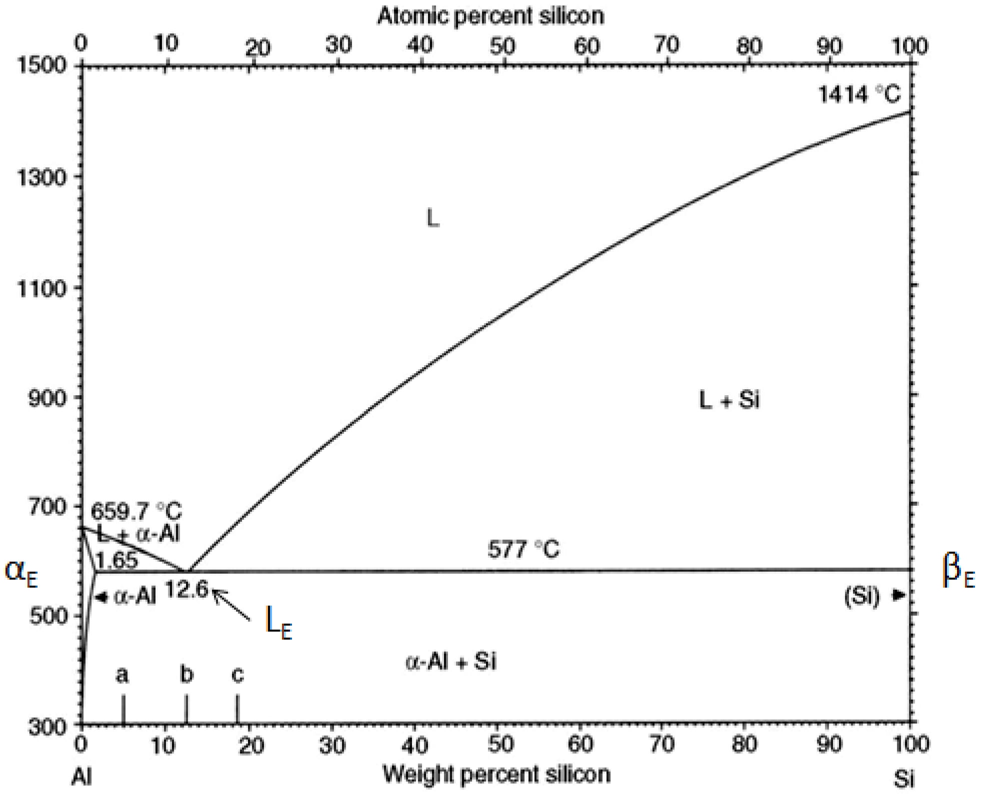


Figure 1.3 Phase Equilibrium Diagram of Aluminum-Silicon (Al-Si) alloy (Mondolfo et al. 1976)

However, mechanical properties of Al–Si casting alloys depend not only on their chemical composition but are also significantly dependent on microstructural features such as the morphologies of the Al-rich α-phase and of the eutectic Si particles. The mechanical properties of the Al-Si alloy are also dependent on the size, shape and distribution of eutectic constituents and primary silicon particles, as small, spherical, uniformly distributed Si particles enhances the mechanical properties of Al-Si alloys.

In aluminum-silicon alloys the specific tensile strength is very strongly influenced by their composed poly-phase microstructure. The properties of specific alloy (Hypoeutectic, eutectic and hypereutectic) are considered as the individual physical properties of its main phase components (α- aluminum solid solution and silicon crystals) and the volume fraction and morphology of these components. The different morphology of silicon particles in Al-Si alloys can be achieved through different casting techniques.

When the eutectic point is reached the eutectic Al-Si phases nucleate and grow until the end of solidification (Haizhi et al. 1994). The primary Aluminum forms in the form of dendrites and eutectic forms at the inter-dendritic region. It may be observed that as the amount of silicon in the alloy increases, the strength properties of Al-Si alloys also increase up to the eutectic composition, after which they show a decline with further increase in the silicon content. However, the hardness increases and the elongation (%) decrease continuously with increasing silicon content (Chirita et al. 2008). This may be largely attributed to the size, shape and distribution of silicon particles in the cast structures up to the eutectic composition. Silicon is present as fine particles and is uniformly distributed in the structure, and hence the strength properties increase. However, when the primary silicon appears as coarse polyhedral particles, the mechanical properties decrease with increase silicon content, but the hardness goes on increasing because of the increase in the volume fraction of silicon particles (Chirita et al. 2008).

From the above discussion it can be observed that several mechanisms and process parameters play very important role in achieving a good, sound and dense casting. And also the centrifugal casting is a very rapid process and the mold being opaque, it is not possible to visualize the flow patterns inside the mold (Suzuki et al. 2004).

Therefore, the main objective of this research work is to:

- Study the effect of process parameters such as rotational speed, wall thickness of the mold and preheated temperature of the mold on microstructure, grain size, hence rate of solidification on the hardness and specific wear rate of the centrifugal castings using Tin metal.

- Effect of rotational speed of the mold on Al-12wt%Si based on microstructure, SDAS, rate of solidification, hardness, tensile strength and specific wear rate.

- Effect of rotational speed of the mold on properties of Al-17wt%Si based on microstructure, hardness, tensile strength, specific wear rate and volume fraction of Si particles.

Above parameters have been experimentally studied and discussed in this research work.

Chapter 2

LITERATURE REVIEW

2.1 INTRODUCTION

Centrifugal casting is termed for a special casting process in which melt fills into the mold and solidifies under a centrifugal force field. The centrifugal casting technique is used primarily for the production of hollow components, but centrifugal casting can also be used to create solid parts (Sufei et al. 2008). All metals that can be cast by static casting can be cast by the centrifugal casting process, including carbon and alloy steels, high alloy corrosion and heat resistant steels, gray iron, ductile and nodular iron, high alloy irons etc.. Non metals can also be cast by centrifugal casting including ceramics, glasses, plastics and virtually any material that can be made into liquid or pourable slurries. Hence a lot of information is available regarding the theoretical study on the various process variables and their effects on properties of centrifugal castings with different alloy compositions but reasonably less experimental results regarding the properties of centrifugal castings at various process variables are available. Therefore more experimental analysis is required to address the influence of process variables on properties of centrifugal casting. The structured literature survey done so far on the above topic will help in planning our research wok. The literature is collected based on the objectives of the present research work and is presented under the following headings.

- Introduction to Centrifugal Casting
- Numerical Simulation of Centrifugal Casting
- Experimental Studies on Effect of Process Variables in Centrifugal Casting
- Mechanical Properties of Centrifugally Cast Alloys

2.2 INTRODUCTION TO CENTRIFUGAL CASTING

The process of centrifugal casting differs from the conventional casting processes, such that in case of centrifugal casting, the mold itself is rotating during the solidification of molten metal. The application of centrifugal force to a metal as it solidifies can be used to feed the molten metal into mold cavities and to achieve a dense sound casting (Janco et al. 1998). The centrifugal casting process uses rotating molds to feed the molten metal uniformly into the mold cavity. And directional solidification of the casting from outer diameter to inner diameter results in clean, dense castings with physical properties that are often superior to those of the static casting processes.

2.2.1 Types of Centrifugal Casting

There are various types of casting methods which are used for the production of centrifugal castings such as:

- Horizontal axis
- Vertical axis

Horizontal axis centrifugal casting is generally used to cast pieces with a high length to diameter ratio and with a uniform internal diameter. In this case molten metal is poured to the mold which is rotating about the horizontal axis. Products like pipe, tubes, bushings; cylinder liners and cylindrical or long hollow castings that are simple in shape are produced using horizontal axis centrifugal casting (Kaufman et al. 2004). Horizontal axis method is used to produce castings having a true cylinder as the inside diameter of the mold (Janco 1998). On the other hand, vertical axis centrifugal casting is mainly for castings with a low length to diameter ratio except vertically cast extra long rolls or with a conical diameter. In a vertical axis casting, the mold is placed vertically and the molten metal is poured from the top. The range of application of vertical axis centrifugal casting is considerably wider, because non-cylindrical or even non symmetrical parts can be made using vertical centrifugal casting. However with a vertical axis mold there is a tendency for the molten metal to form a parabolic shape due to the competing gravitational and centrifugal force. Therefore all the vertical centrifugal castings have more or less taper on their inside diameters, depending on the gravitational (g) force applied to the mold and the casting size (Sufei et al. 2008).

Although both vertical and horizontal methods employ centrifugal force, there are some differences in how the force is applied with respect to the axis of the mold rotation and the speed of the molten metal relative to the rotating mold. With a vertical axis mold, the resultant force on the liquid is constant and this is not the case in a horizontal axis mold (Sufei et al. 2008). The other differences between horizontal and vertical axis mold orientation is the speed obtained by the molten metal as it spins around the mold. When the metal is poured into the horizontally rotating mold considerable slip occurs between the metal and the mold such that the metal does not move as fast as the rotating mold. To overcome this inertia, the metal must be accelerated to reach the mold rotation speed. This is not a problem in the vertical centrifugal casting process, where the molten metal reaches the speed of the mold soon after pouring. The centrifugal force of the rotating mold forces the molten metal against the interior cavity or cavities of the mold under constant pressure until the molten metal has solidified. Cylindrical castings are generally preferred for the centrifugal casting process.

2.2.2 Advantages of Centrifugal Casting Process

Centrifugal castings have many advantages as it is applicable to nearly all compositions with the exception of high carbon steels from 0.40% to 0.85% C. Carbon segregation can be a problem in this composition range (Sufei et al. 2008). Centrifugal castings can be manufactured with a wide range of microstructures tailored to meet the demands of specific applications. Mechanical properties are often superior to those of static castings due to the finer grains resulting from the process, which are of constant size in circumferential and axial directions. And also the centrifugal castings due to cleanliness and finer grain size, good weldability are achieved (Sufei et al. 2008).

Horizontal centrifugal casting allows manufacture the pipes with maximum dimensional flexibility. The centrifugal action removes unwanted inclusions, dross, cleaner casting and material that contain shrinkage, which can be machined away. Hence castings with high density and high quality are obtained by this process (Daming et al. 2002, Campbell. 1961).

The components made from centrifugal casting process exhibit a dense, fine grained structure with vastly improved mechanical properties. The desirable properties are improved up to 30% over those castings produced by conventional, gravity or static casting processes. The process produces castings of good quality, high dimensional accuracy and smooth external surface finish. Centrifugal casting method is used for casting of components that are too difficult to produce satisfactorily by static casting methods because their sections are too thin , e.g. gears, piston ring, impellers and bushings (Kaufman et al. 2004).

Wu Shi-ping explains that the centrifugal casting can improve the flow rate of alloy melt, save raw material, reduce production cost and can also increase casting precision and simultaneously the fluidity of titanium alloy is enhanced by increasing the rotational velocity of the mold (Wu et al. 2006).

Tubular castings produced in permanent molds by centrifugal casting usually have higher yields and higher mechanical properties than castings produced by the static casting process. Centrifugal casting is the most economical method of producing a superior-quality tubular or cylindrical casting with regard to casting yield, cleaning cost, and mold cost. Another advantage of centrifugal casting is the elimination or minimization of gates and risers (Kang et al. 1996).

Researchers by utilizing the outstanding advantages created by the centrifugal force of rotating molds started producing highly engineered functionally graded castings in the form of pipes and tubes (Shailesh et al. 2010). Nowadays by slight modification in the processing technology, castings of solid blocks, circular plates are also produced by centrifugal casting process.

2.3 NUMERICAL SIMULATION OF CENTRIFUGAL CASTING PROCESS

The analysis of fluid flow in centrifugal casting is very complex due to rapid solidification, rotation of the mold, opaque mold and melt and also viscosity of the melt which varies with time. Such complicated mold filling and the coupled heat transfer/solidification behavior is difficult to determine experimentally. Therefore much research efforts have been devoted in developing a numerical simulation technique and computer codes as a tool for achieving a control for the centrifugal casting process. Due to the dramatic variation in the centrifugal forces with rotating speeds and the distance to the spinning axis, the alloy melts will exhibit much more complicated mold filling behavior in comparison with that merely under gravity. Therefore it will be more difficult to design an appropriate technology for centrifugal casting. So some researchers have recently tried to establish various mathematical models for mold filling of alloy melts under centrifugal force field and successfully performed numerical simulations for the centrifugal casting processes considering various process parameters (Vassiliou et al. 2008, Raju et al. 2000, Kang et al. 1996, Panda et al. 2006, Wu et al. 2006, Daming et al. 2002).

2.3.1 Simulation of Heat Transfer in Centrifugal Casting

Casting simulation programs have contributed to the enhancement of the process knowledge of the casting. In order to obtain realistic results from simulation the input parameters like initial conditions, boundary conditions, material properties and the run parameters should be well defined. One of the very crucial parameter is the heat transfer coefficient at the metal-mould interface during solidification of the casting. In practice heat transfer coefficient varies according to the thermo physical properties of the contacting materials such as casting and the mold geometry, the roughness at the mold and melt contacting surface, mold coatings, contact pressure, melt superheat and initial temperature of the mold.

Vassiliou et al. (2008) have worked on the simulation of centrifugal casting process by using the experimental results. So initially they conducted experiments to determine the interfacial heat transfer coefficient. Authors have conducted series of experiments and a large number of simulations for the determination of the heat transfer coefficient using brass during centrifugal casting at different rotational speeds 469 rpm, 391 rpm and 156 rpm. The calculated heat transfer coefficients were used in some typical casting scenarios that were simulated to investigate the effect of some casting parameters.

Table 2.1 Heat transfer coefficients by Forced convection and Radiation heat transfer

Total Heat Transfer Coefficient for Metal/Air and Mold/Air Convection + Radiation	
Metal Temperature (K)	**h_{total} (W/m^{2}K)**
923	107.27
953	107.72
973	108.01
Total Heat Transfer Coefficient for Mold/Air Convection + Radiation	
Mold Temperature (K)	**h_{total} (W/m^{2}K)**
303	82.84
373	84.00
623	87.04
673	88.02

Balout and Bahaa have modeled the cooling rate and the temperature variation across the casting and mold sections through the implicit finite -difference formulation using

FLUENT for a transient unsteady state solidification. The model accounted for the variation of the mold/metal heat transfer coefficient and the contact resistance and the air gap formed between the mold and the metal due to the contraction of the latter during the solidification process. The heat transfer coefficients were calculated based on Poirier D. & Poirier E correlations and are given in the table 2.1(Balout et al. 2010).

Raju and Mehrotra (2000) have presented a more realistic model showing variation in the volume fraction of the particles across the thickness of the casting with time. Their formulation is based on one-dimensional heat-transfer analysis incorporating variations in the thermo physical properties due to particle movement on the matrix. They also considered variations in the heat-transfer coefficient and latent heat release. The effect of process parameters of centrifugal casting of aluminum containing suspended ceramic particles were analyzed to predict: i) particle distribution in the casting region ii) temperature distributions in the casting and mold regions and iii) solidification time. They concluded that the thickness of particle rich region in the composite decreases with increase in rotational speed of the mold, particle size, initial pouring temperature and initial mold temperature. Reduced heat transfer coefficient at the metal mold interface leads to increased solidification time which in turn results in more intensive segregation of solid particles. With increased initial volume fraction of solid particulates, both the solidification rate as well as the final thickness of the particulate rich region increases. The duration of solidification as per their analysis is around 50 seconds but, actually the centrifugal casting gets solidified within 8 seconds.

Kang and Rohatagi (1996) have described the results of a heat transfer analysis of centrifugal casting of metal matrix composites by one-dimensional analysis, considering the thermo-physical properties due to particles moving as a function of temperature. In their investigations, the positions of the dispersed particles at a given instant of time are analyzed as a first step. Then, the temperature distributions in the mold and the solidifying metal are analyzed at different time intervals. Using these temperature distributions, time taken for solidification of casting at different rotational speeds, initial mold temperatures, and pouring temperatures of molten metal are estimated.

Particle segregation pattern in a centrifugally cast product, temperature distribution in the casting and mold and time for complete solidification were predicted using a one-dimensional transient heat-transfer model coupled with an equation for force balance on particles. Panda et al. (2006) have reported that for a given set of operating conditions, the thickness of the particle-rich region in the composite decreases with an increase in rotational speed, particle size, relative density difference between particles and melt, initial pouring temperature and initial mold temperature. With reduced heat-transfer co-efficient at the casting/mold interface, the solidification time increases, which in turn results in more intense segregation of solid particulates. Again, with increased initial volume fraction of the solid particulates in the melt, both the solidification time and the final thickness of the particulates rich region increases. It has been reported that due to the high solidification rate at the beginning, the particles adjacent to the casting/mold interface do not get a chance to move toward this interface to form a cluster. Therefore, the volume fraction of the particulates in the solidified composite is the same as in the initial melt. Thus, with finer particles, the maximum clustering of particles is seen only after a certain distance from the casting/mold interface. However, for melts with coarser particles at higher rotational speeds, maximum segregation is seen at the outer surface itself, because the particle velocity is much higher than the velocity of the solidification front and several particles from the adjoining regions are able to reach there before this layer is solidified.

2.3.2 Simulation of Microstructure Evolution During Solidification Process

The microstructure of castings is an important parameter due to its role on mechanical properties of the casting. Therefore microstructure study is very much essential for the characterization of the castings. Manual method of microstructure evolution is more tedious practice. Therefore, the simulation method of microstructure evolution is of great interest both for theoretical understanding and practical application.

Ping and Rong (2006) have contributed to the study of centrifugal casting process by developing a multi scale model for simulating the microstructure evolution during solidification process of Ti-6Al-4V alloy in vertical centrifugal casting, which combines the 3D finite difference method (FDM) at the macro scale with a 2D cellular automation (CA) model at the micro scale. They concluded that the formation of equiaxed zone increases with increasing mold rotation speed as well as decreasing the melt superheat and by reducing the heat diffusivity of the mould.

Zagórski et al. (2007) have implemented the CFD program to simulate the centrifugal casting of composite. They suggested that the simulation by CFD program (Fluent) can be treated as an attractive and useful tool for modeling centrifugal casting process of metal matrix composite reinforced by ceramic particles. From the simulated results they concluded_that the role of rotational speed of the mold is much greater than that of superheat and mould material. The centrifugal casting sample shows a fine-to-coarse microstructure from inner mold surface towards the center.

With the advent of very powerful computers, advanced numerical methods and better under-standing of the physical phenomena involved in solidification, the applications of computer simulations are becoming increasingly used for the modeling of microstructure formation and associated characteristics or defects such as micro segregation pattern, porosity formation, etc. (Boettinger et al. 1996)

The development of CFD program and other simulation methods allows to study even complicated problems. The created model and procedures can become the basis for more advanced researches. The result of simulations shows that the role of rotational speed of the mold is much greater than that of superheat of the melt and material of the mold.

2.3.3 Mathematical Model for Mold Filling Process

Daming et al. (2002) proposed a mathematical model for mold filling processes under centrifugal force field conditions and the computer codes were tested through the sample simulation of gravity mold filling process for a benchmark plate casting and these were compared with the experimental observations. The model and the developed computer program were then applied to the numerical simulation of centrifugal casting field mold filling processes, for a thin section casting with a titanium alloy melt of assumed viscosity, 1.2 mm^2/s and 12.0 mm^2/s. The computation result shows that the flow behaviors of the melts are basically similar to each other although, the less viscous melt tends to fill into the thin section casting cavity faster. But this process is used to produce thin flat casting and not to make hollow cylindrical casting.

Chang et al. (2006) have conducted a hydraulic simulation of mold filling process of Titanium alloy by using centrifugal governor, high speed camera as well as acryl glass molds including two kinds of filling methods, top filling and bottom filling and also three kinds of rotational velocities, 163 rpm, 245 rpm and 375 rpm of the mold. Photos taken in the experiments have shown that in both top and bottom filling methods, liquids stick to back end wall of cavity or runner due to filling due to the action of centrifugal force and Coriolis force. Filling volume is rising with the increase of the filling time and rotational velocity of the mold. The whole filling process was divided into forward filling, and back filling. During the forward filling liquid cross sectional area decreases with the increase in forward filling length and rotational velocity of the mold. But cross sectional area is unchangeable in the cavity during the back filling. Forward filling is an accelerated velocity process and back filling is a uniform velocity filling process. The experiments showed that the bottom filling method is better than the top one, which can achieve stable filling, minimize turbulence and avoid drastic liquid collision.

2.3.4 Simulation of Composition Gradient in Centrifugal Casting

Prem and Babu (2002) carried out two dimensional dynamics simulations using a developed analytical theory for engineering and a desired composition gradient in centrifugally cast metal-ceramic functionally gradient materials. The simulations are validated with the experimental results. The low temperature and consequent high viscosity of aluminum leave little freedom to the particles which are therefore almost uniformly distributed in the radial direction.

Bonollo et al. (2003) explains from his simulation results that high value of temperature difference between the melt and the mold leads for fast cooling of the liquid because of the efficient heat exchange which hampers the particles' motion.

Zagorski and Sleziona (2007) in their research presented a model to simulate the centrifugal casting of metal matrix composite reinforced with SiC, especially the distribution of the velocity of liquid composite for the initial stage of pouring into the mold up to one second. They considered CFD program Fluent can be treated as an attractive and useful tool for modeling centrifugal casting process of metal matrix composite reinforced by ceramic particles. The simulations shown that the behavior of composite in pouring process depends strongly on the existence of reinforcement and process parameters.

Goa et al. (2000) have conducted numerical investigations on solidification during centrifugal casting of Functionally Graded Materials. They focused on the interplay between the freezing front propagation and particle migration. They have developed a one-dimensional solidification model, with particle transport taken into account, using pure water as the matrix and glass beads as the particle phase. Unidirectional solidification experiments were performed in a rectangular test cell to validate the multiphase model. They identified three factors responsible for creation of the particle concentration gradient: the geometrical nature of particle flow in the cylindrical mold, the angular velocity, and the solidification rate. It was concluded that by optimizing processing conditions, such as the particle size, initial concentration, rotational speed of the mold, cooling rate and superheat, one can engineer a desired gradient in the solidified part.

Gutierrez et al. (2007) have worked on the particle distribution during the manufacturing of Functionally Graded Materials (FGM) by simulation and mathematical formulation of the process. They considered different cases, with each case corresponding to different assumptions up to the more general case that relax the assumptions made. In their work they neglected the effect of gravity during the movement of particles because the radial acceleration is much higher than the gravity acceleration. But previous works done by other researchers (Panda et al. 2006, Watanabe et al. 2001, Kawamoto et al. 2002) have considered the effect of gravity casting. They put the reinforcement particles in to a cylindrical mold and then exposed to a centrifugal action with its central axis along the radial direction. Since the cylinder was rotating about the vertical axis they had considered the effect of gravity.

Simulation of casting process is an important tool in modern manufacturing industries. These technologies will provide the information for a more realistic selection of process parameters and their effect in the centrifugal casting process. From simulation results it has been concluded that by optimizing processing conditions, such as the particle size, initial concentration, rotational speed of the mold, cooling rate and superheat, one can engineer a desired gradient in the solidified part.

2.4 EXPERIMENTAL STUDIES ON EFFECT OF PROCESS VARIABLES IN CENTRIFUGAL CASTING

Centrifugal casting is a casting process where in molten metal crystallizes under the dominant influence of the centrifugal force which occurs during the rotation of the mold. As a result of this action, products of higher densities are produced in comparison to those obtained by the use of standard casting methods (Boris et al. 2010). Jien-Wei et al. (1998) have used a water-cooled centrifugal casting method to cast 7075 Al alloy to generate a much finer cast structure than that produced by conventional ingot casting methods. They studied systematically the effects of casting parameters, i.e., rotation speed, pouring temperature, water flow, and grain refiner, on casting structure so that the optimum casting condition and the solidification mechanism could be established. The typical cast structure divided into four equiaxed zones along the thickness direction of a cast ring including the chill zone which is in contact with the mold wall. All zones have their characteristic grain size, morphology, which are all dependent on the casting condition. They concluded that the optimum casting condition yielding the finest structure was found to be 3000 rpm, teeming temperature of 650 °C with sufficient water cooling of mold wall. A uniform portion occupying 90% of the whole thickness and having a grain size of 17 μm was achieved under such a casting condition. When a grain refiner was added, the whole ring became further concentrated with grains of fine structure (Yeh et al. 1994).

Centrifugal casting consists of a number of processes in which the centrifugal force set up by the rotation of a part of the casting is utilized to shape the casting, fill the mold and helps to solidify and strengthen the metal (Pavlovic et al. 2009). There are various process variables which have effect on the production of good quality sound centrifugal casting. Some of the important process variables of centrifugal casting are discussed below.

2.4.1 Viscosity of the Melt

The flow phenomenon of liquid metal in centrifugal casting is much more complex than in normal liquids, since there is an extra factor of drop in temperature and increase in viscosity during the flow. The melt poured into the mold will have low viscosity and as the molten metal cools, the viscosity will increase. And it is known that fluid flow behavior in the centrifugal casing determines the quality and characteristics of the final product, which depends upon the viscosity of the liquid metal.

Prasad et al. (2010) have proved by their experiment that high viscosity liquids will form uniform layer at very low rotational speeds and low viscous liquids required higher rotational speeds to form uniform layer. For high viscous liquid metal, the rotational speed exceeds 100G, where ‘G’ is the G_{factor} which is the ratio of centrifugal force to gravitational force. This statement seems to be hypothetical because in the case of solids filled in a horizontal rotating cylinder it requires 1G -2 G to form a complete cylinder, since the coefficient of friction is very high between the mold and melt. In the case of liquid, having low viscosity, its coefficient of friction is too small and hence requires a larger drive to form a complete cylinder (Janco et al. 1992).

Daming et al. (2002) observed that the viscosity is an important physical property of alloy melts for mold filling behavior which can influence the melt flow behavior and may vary by order of exponential change with reciprocal of its temperature. They have developed a numerical simulation program for mold filling and verified with the experimental results and proved that less viscous melt tends to fill into the thin section castings cavity faster. Moreover it was observed that when the temperature of the mold and the metal are elevated, the melt becomes less viscous and the desired distribution of the reinforcing particles along the casting section cannot be reached (Bonollo et al. 2004).

Vives et al. (1988) have studied the role of mixed convection, caused by a forced Couette flow, during the directional solidification of tin in a rotating mold. The microstructure of the solidified melt was examined and the metallurgical findings like crystal growth connected with the heat and fluid flow measurements are compared with those obtained by another type of rotating flow, driven by a stationary electromagnetic field and produced by an annular electromagnetic conduction pump. The angle of deflection of the columnar crystals is related to the mean velocity and the shear stress upon the melt-solid interface, as well as to the initial superheat and observed the better results in centrifugal casting.

The viscosity of the melt is an important physical property during the mold filling process which will influence the flow behavior of the melt. Viscosity as the function of temperature also causes variation in the particle distribution in case of solidification of alloys.

2.4.2 Rotational Speed of the Mold

The governing factor in centrifugal casting is retention of the inner circular shape against gravity avoiding, longitudinal tearing and stresses during the accelerated solidification of the molten metal against the mold face. In horizontal mold centrifugal casting the rotational speed of the mold should be sufficiently greater to avoid the melt raining inside the mold due to gravity. The rotational speed of the mold is the dominating process parameter compared to all other parameters which affect the solidification rate and also particle distribution in case of alloys by the action of centrifugal force.

Due to the complexity of the process of centrifugal casting it is difficult to optimize the process parameter; hence some of the researchers have tried with cold modeling experiments to predict the fluid behavior at various rotational speeds of the cylinder. Mukunda et al have made an attempt to understand some aspects of fluid flow which influences the process of centrifugal casting. They observed different flow patterns like Taylor flow, Ekmann flow and sloshing of the liquids at lower rotational speeds of the cylinder. They concluded that Taylor flow patterns also form at low rpm and this pattern formation depends upon thickness of the liquid. At higher rotating speeds, Ekmann flow and Taylor flow get reduced and form a full cylinder. Finally, it is inferred that the formation of liquid cylinder varies linearly with thickness of fluids. It was established that, the speed required to form the full cylinder is directly proportional to the thickness desired (Shailesh et al. 2006).

Prasad et al. (2010) have explained the results by continuing the works of above researchers based on their water modeling experiments conducted to predict the effect of process variables in centrifugal casting. They identified various flow patterns when fluid is rotated in a partially filled rotating cylinder. They considered liquids of different thickness like 2 mm, 4mm and 6 mm and also different viscosity liquids in their experiment. They observed the various flow patterns in aluminum castings produced at lower rotational speeds of the mold. They have also explained in their experimental results that longitudinal cracks are encountered primarily during the early stages of solidification when the high rotational speeds of 1000 rpm are employed. And also excessive speed of rotation produces very high tensile stress in the outer periphery of the casting which results in longitudinal cracks (Janco et al. 1992).

Shrikantha et al. (2010) have concluded from their experiments that the fluid flow behavior of the metal in centrifugal casting always disturbs the quality of the final casting when it is rotated at different speeds of the mold. As can be seen at lower and extremely high rpms, irregular patterns are formed. At an optimized speed of 800 rpm, a uniform cylinder is formed. At the optimized speed, the mechanical properties of the casting improved. Fine equiaxed primary α-Al grains are formed at 800 rpm, which is mainly due to the behavior of the molten metal in the rotating mold. Lee et al. (1994) have conducted experiments to produce centrifugal castings of copper with the speed range of 200 rpm –1000 rpm. And they achieved the better results at higher rotational speeds. Hence the selection of the rotational speeds ranges from 200 rpm to 1000 rpm in this research work.

Ciurea et al. (2003) have conducted the model experiments using rotating vertical cylinder and found that for a rotating liquid in a vessel the distance between the liquid particles and rotation axis is dependent on the rotational speed of the vessel. They concluded that as the rotational speed of the mold increases, the gravity force decreases and the liquid lifts with a force on the inner walls of the vessel. A constant rotation leads to a liquid layer having a formation of parabolic shape in case of vertical centrifugal casting process. Kumar et al. (1997) have concluded that, increasing mold rotational speed leads to high segregation of alloy particles and raising the grain size and secondary dendritic arm spacing (SDAS). Increasing mold cooling rate diminishes the segregation of particles and reduces the grain size and DA. Janco et al. (1998) have reported that the normal spinning speed that would be used for the horizontal centrifugal casting is 20G.

Yanwei et al. (2010) investigated the effect of centrifugal radius and mold rotational speed on microstructure in centrifugal cast Al-Cu alloy. They showed that with increase of the centrifugal radius or mold rotational speed the grain size of centrifugal cast Al-Cu alloy decreases gradually. This is attributed to the reason that the solidification mechanism in centrifugal casting is the combined effect of centrifugal force which is due the rotational speed of the mold, mechanical vibration and convective heat flow (Sui et al. 2010). This experiment is conducted for the solid casting but similar results can be expected in the production of hollow cylindrical casting.

Vieira et al have also concluded in their study that functionally graded composites cast at low centrifugal speed of 1500 rpm presented a smooth gradient on SiCp distribution, while FGM cast at higher centrifugal speed of 2000 rpm revealed a sharper gradient on the distribution of reinforcing particles. This gradient was controlled by the movement of the solidification front, blocking the mobility of SiC particles in the melt (Vieira et al. 2009).

Jian et al. (2000) have done a extensive work on influence of the process parameters like rotational speed and cooling rate on formation and gradient distribution of Mg_2Si particles using centrifugal casting technique. They produced Al-Si hypereutectic alloy tubes and studied the graded distribution of Mg_2Si particles in the aluminum alloy matrix. This gave a clear idea on graded distribution of primary Mg_2Si particles in aluminum silicon alloy matrix as a effect of rotational speed of the mold. In these alloy tubes, primary Mg_2Si particles were formed in the tube periphery with graded distribution. It was found that in the outer periphery the particle distribution profile at different rotational speeds is quite different from each other, while it is similar in the inner periphery. Extremely higher cooling rates during centrifugal casting resulted in a better particle distribution gradient and a much finer microstructure in the outer periphery of the tube. As a result, lower rotational speed gave a better gradient distribution of Mg_2Si primary particles, but is also accompanied with higher volume fraction of the casting defect. With an increase in rotational speed an apparent change of the particle distribution profile in the outer periphery has been observed. But, the influence of rotation speed on the particle distribution in the inner periphery is rather small. The extremely high cooling rate achieved by using a copper mold with water-cooling lead to a very fine microstructure in the outer periphery when compared with the same area in the other tubes obtained by using graphite mold. This work indicated optimized process parameters that resulted in better microstructure and the macro segregation in the centrifugal tubes (Zhang et al. 2000).

With the further investigation on the centrifugal casting, the work done by Yoshimi Watanabe on Particle size distributions on functionally graded material showed the better understanding about the centrifugal process and particle distribution. FGM tubes were fabricated from plaster/corundum model materials containing five different particle sizes. The study showed the particle distribution in which the average particle size at the outer region is greater than that at the inner region. The study was on particle distribution by varying the G values i.e. 16, 18 and 45. It was noted that the particle size gradient in the FGM was steeper and the average particle size will be around 87 µm, 102.5 µm, 115 µm, 137 µm and 179.5 µm for the tube dimension of radius of 45mm, length of 30mm and for thickness of 18mm (Watanabe et al. 2002**)**.

Bangsheng et al. (2010) have studied the segregation of mica particles in aluminum / mica composites for centrifugal and static castings. In this work Mica particles were dispersed in molten Al - 4% Cu - 1.5% Mg alloys and then poured into rotating permanent cast iron molds to obtain hollow cylindrical castings. The centrifugally cast hollow cylinders showed two distinct zones, (1) an outer zone free from mica and (2) an inner zone, about 12 mm to 22 mm thick where most of the mica particles had segregated. They were able to segregate up to 9% mica near the inner periphery by centrifuging whereas it is difficult to obtain more than 3% in static castings. In static castings the longitudinal sections of samples made by static casting methods showed that all the particles had floated to the top portion of the casting. This indicates that the segregation due to buoyancy prevails over any effect of rejection of particles by the freezing interface. This may be due to the fact that the freezing fronts under the present experimental conditions are dendritic and the mica particles rejected by the advancing solid front get into the inter-dendritic liquid where they are able to move along the direction of buoyancy force. It was seen that mica could segregate right up to the very top of the casting where the freezing front was moving downwards.

Kim et al. (2000) have concluded from the microstructural observation of centrifugally cast copper alloy C90300, originally containing 13 vol% of graphite particles that a graphite-free zone and a graphite-rich zone (25 vol%) with a unique microstructure are formed near the outer and the inner periphery of the centrifugally cast cylinders, respectively which is depending on the rotational speed of the mold.

Halvaee et al.(2001) had evaluated the effect of process variables on microstructure and segregation in centrifugal casting of C92200 alloy. In this work author has worked on the material Tin_bronze alloy_containing lead and zinc, which has a wide application for valves, taps, gears, bushes and bearings. They concluded that due to elements of having high difference in density and low solubility, tin bronzes are difficult to cast. Segregation normally occurred in centrifugal casting, depending on the density of the material. Lower density material will be segregated at the inner radius and higher density will be segregated at the outer surface of the castings al have found that the displacement of the particles in alloys towards the inner or outer casting surface depends upon their density difference and rotational speed of the mold and particle size. Since determination of solidification time and temperature distribution during the centrifugal process is a complicated problem, they considered the metal to be a liquid, thus obeying Stokes law, constant temperature and viscosity to simplify the analysis (Mehrotra et al. 2000). The movement of the particles in a liquid matrix was studied by Watanabe et al (Watanabe et al. 2001) in order to establish a method for controlling their concentration and distribution in a graded composite. The magnitude of the centrifugal force is regarded as of major importance in this process as it causes segregation by the difference in the densities of the particle and matrix (Murali et al. 2008).

The solidification time of the casting depends upon the rotational speed of the mold, it decreases with an increase in rotational speed of the mold. It causes a significant influence upon metal structure and the most common effect of increased speed being to promote the grain refinement. If the spinning speed is adequate and if the fluidity of the molten metal is satisfactory then the melt will distribute itself uniformly along the length of the mold before the solidification. Segregation normally occurred in centrifugal casting, depending on the density of the material and rotational speed of the mold. The most common effect of increased rotational speed being to promote grain refinement. Although this can also be brought about from turbulence, induced by instability of the liquid mass with constant viscosity at very low speeds of rotation. Excessive speed of rotation produces very high tensile stress in the outer periphery of the casting which results in longitudinal cracks. Furthermore, very high rotational speeds can cause the mold itself to fail. Sometimes due to lower speed of rotation the formation of the metal cylinder will be poor.

2.4.3 Pouring Temperature of the Melt

Pouring temperature exerts a major influence on the mode of solidification as it shows the superheated temperature of the melt. It is the temperature of the melt at which it is poured to the mold cavity. If the temperature of the molten metal is too high or fluidity of the molten metal is too high the metal will not readily accelerate to the speed of the mold. And also increases the solidification time of the melt. Variation in temperature of the melt may cause variation in microstructure and the particle distribution in the casting.

Chen et al. (2010) have studied on the macro segregation of aluminum in centrifugal-cast ZA27 alloy. During the casting process they considered two process variables such as longer pouring time of the molten metal into the mold and reducing the pouring temperature of the molten metal to study the macro segregation in the specimen. So, the casting was done with pouring temperatures as 803K, 833K and 863 K, and the pouring times are 10s, 14s, and 20s, respectively and the mold temperatures were 323K and 423K. The alloy composition was 27.0 wt. % Al, 2.0wt.% Cu, 0.02 wt.% Mg, the remainder is zinc. He observed that the macro segregation of aluminum is caused due to the difference between the density of zinc and aluminum.

Halvaee et al. (2001) explains in his study regarding the effect of process variables on microstructure and segregation in centrifugal casting of C92200 alloy when the thermal gradient between the mold and the liquid metal is very high. The solidification time decreased heat transfer was promoted leading to finer primary alpha dendrites and columnar grains with fewer arms. As solidification continues, the mold became hotter and thermal gradient decreased at solidification front. Hence, solidification rate and time reduced, primary dendrites grow and DAS increases. Fall in DAS adjacent to the internal casting wall was due to primary solidification. As the pouring temperature was increased, the rate of nucleation and solidification time decreased due to slower heat transfer hence in this situation, dendrites grew and DAS increased. At lower pouring temperatures, fine equiaxed grains were formed and at higher pouring temperatures coarse columnar grains were seen. As the pouring temperature was increased, the rate of nucleation and rate of_solidification decreased due to slower heat transfer. In this situation, dendrites grew and DAS increased.

Vassiliou et al. (2008) also suggested that along with the other thermo physical properties of the contacting materials such as casting and the mold geometry, the roughness at the mold and melt contacting surface, mold coatings, contact pressure, and initial temperature of the mold, melt superheat also affects the heat transfer rate from the melt. Zagórski et al. (2007) found from the experimental data that pouring temperature was also one of the process parameters which had an influence on the centrifugal castings along with the other parameters such as, initial temperature of the mould, rotational speed of the mold, time of pouring the mould, composition of the composite, type, diameter and shape of particles and so on.

Bollono et al. (2003) concludes that casting prepared at low melt temperature, low mold temperature and high rate of cooling (ΔT) was having uniform ceramic distribution radially, increasing from inner to outer surface but having low metallurgical quality. At medium melt temperature, high mold temperature and low

ΔT the material exhibited a partition line between the particle free inner zone and the particle rich outer zone with reduced porosity. For medium melt temperature, high mold temperature, when the ΔT was increased to medium level the material yielded the best results in terms of distribution gradient wherein the gradient increased towards the outside with excellent metallurgical quality showing no porosity (Bollono et al. 2003).

Chen et al. (1999) has reported on the various process parameters for centrifugal casting which influenced the macro segregation in ZA27 alloy. The primary phase produced from the melt will float to the inner surface due to the density difference between primary phase and melt. If the pouring time is long or the pouring temperature is low, only a small amount of primary phase could float in the melt. It was concluded that the longer the pouring time or lower the pouring temperature, the less is the degree of the macro segregation. The macro segregation is caused due to the density difference between Zinc and Aluminum.

Variation in temperature of the melt may cause variation in microstructure and also it affects the particle distribution in the casting. Low temperatures of the melt are associated with maximum grain refinement and with equiaxed structures, while higher temperatures promote columnar growth in many alloys, however practical considerations limit the available temperature range. Raising the pouring temperature causes grain size and Dendrite Arm Spacing (DAS) to increase and particle segregation to intensify by delaying the solidification. The pouring temperature must be sufficiently high to ensure satisfactory metal flow and freedom from cold laps while still avoiding coarse structures and the increased risk of hot tearing due to excessive superheat.

2.4.4 Temperature of the Mold

Mold temperature is an important parameter which has an effect on the rate of solidification of centrifugal casting as it will vary the heat transfer rate of the melt. Because of temperature difference is the driving potential for the heat transfer, when variation in temperature difference exists between the mold and the melt, then variation in heat transfer rate occurs.

Vassiliou et al. (2008) have conducted experiments to determine the effect of process variables, mold temperature, pouring temperature and rotational speed of the mold on the quality of the centrifugal casting. They concluded that as the mold temperature increased, solidification time increases and hence rate of solidification decreases. Shrinkage porosity is rather high when solidification concludes fast, while when solidification happens more gradually shrinkage porosity falls. The only restriction in that case is the melt temperature at which brass oxidizes, resulting in a bad surface quality. Generally the speed of rotation in centrifugal casting, the mold temperature and the initial temperature of the liquid metal influence the casting quality.

Velhinho et al. (2003) explains that the principal significance of maintaining the mold at uniform operating temperature will also serve to ensure uniformity of the cyclic pouring operation as well as casting quality. On the other hand under certain conditions the alloy particles close to the outer surface are small in diameter, a phenomenon which is attributable to the solidification front, which tends to prevent large size particles from moving freely toward the outer casting surface. According to Bollono et al when the molten metal at temperature T_{Al} coming in contact with the cast iron mold which is at temperature $T_{mold,}$ due to larger temperature difference between the T_{Al} and T_{mold} solidification takes place quite rapidly. Therefore due to the too low mold temperatures, melt does not have enough time for a complete and homogenous distribution of ceramic particles along the mold length before solidifying. Further molten metal contacting the previously solidified metal which is at higher temperature, due to reduced temperature difference the solidification time increases (Bollono et al. 2003).

Qudong et al. (2005) have investigated the effects of composition, mold temperature, rotating rate and modification on microstructure of centrifugally cast Zn–27Al–*x*Mg–*y*Si alloys and observed that for centrifugally cast Zn–27Al–3.2Mg–1.8Si alloy, the microstructures of inner layer, middle layer and outer layer are almost similar, single layer materials of α (Al) dendrite, $MgZn_2$ phase and eutectic microstructure without primary Mg_2Si and primary Si are obtained. They found that with increase in mold temperature grain size of inner layer, middle layer and outer layer increases apparently, especially in outer layer. Bonollo et al. (2004) also observed that when the temperature of the mold and the metal are elevated, the metal becomes less viscous and the desired distribution of the reinforcing particles along the casting section cannot be reached.

As discussed earlier the variation in rate of solidification causes variation in mechanical properties of the centrifugal castings. Shrinkage porosities are rather high when solidification concludes fast, while when solidification happens more gradually, shrinkage porosity falls. As a general recommendation, molds for centrifugal casting should be maintained at slightly higher temperature range. Preheating of the mold to this temperature range will also facilitate the application of the refractory mold coating.

2.4.5 Mold Wall Thickness

The rate of solidification in centrifugal casting depends on the mold wall thickness, as thickness of the mold wall increases due to the chilling effect from the thermal mass layer the rate of solidification will be increased. As soon as melt enters the metal mold the heat of the melt will the distributed to the mold material hence maximum heat will be taken away by the mold. Once the mold gets heated the rate of heat transfer gets reduced due to decreased temperature gradient.

Ping et al. (2006) observed the fine-to-coarse microstructure from the inner mold surface to the centre of the centrifugal casting. They concluded that the formation of equiaxed zone increases with increasing mold rotation speed as well as decreasing the melt superheat and by reducing the heat diffusivity of the mould. But the role of rotation speed is much greater than that of superheat and mold material.

Wang et al. (2009) during the study on interdependence between cooling rate, microstructure and porosity in Mg alloy AE42 they used graphite plate molds with different wall thickness to produce a wide range of cooling rates for the gravity castings. The microstructure of samples extracted from the regions of measured temperature was then characterized with optical metallography. This concept is adopted in our experimental work to assess the different cooling rates and also to study the effect of mold wall thickness on rate of solidification of the gravity and centrifugal castings.

Zhiliang et al. (2007) in their study regarding the effect of cooling rates on grain size of AZ91 Alloy used a cone-shaped mold to cast samples. They expected different cooling rates correspond to the different locations in the conical sample. Finally they observed that the grain sizes were increasing with the positions from bottom to top. Hence they concluded that cooling rate plays a critical role in determining the final grain size and the cooling rate varies with the thickness of the mold. El-Aini (2010) also concluded by the results of microstructure and hardness that faster cooling rates takes place in mold of thicker section vice versa.

Like other process variable mold wall thickness is also one of the process parameters which have effect on the rate of solidification of centrifugal castings. It known that in order to obtain a fine grain size, either a high cooling rate or a low pouring temperature must be satisfied. If the mold wall is sufficiently thick with good thermal diffusivity will absorb the heat rapidly and rate of solidification will be faster. As thickness of the mold is increased due to the chilling effect the rate of solidification will be higher.

2.5 FEATURES OF CENTRIFUGAL CASTING

The centrifugal casting process is considered to be the optimized process in manufacturing cylindrical components, a few parameters help to maintain the microstructure and segregation of particles as according to the requirement. Parts produced by this process are of high degree of metallurgical cleanliness. Directional solidification provides clean and dense castings with physical properties that are superior to static castings. According to Chirita et al. (2009) the important features of the centrifugal casting process, which affects casting properties are mainly due to three features: centrifugal pressure, fluid dynamics and intrinsic vibrations of the process.

The centrifugal pressure exerted over a casting sample depends on angular speed, the distance from the mold cavity to the rotation axis, the quantity of the melt, viscosity of the melt and the geometry of the sample which was discussed before. The centrifugal pressure is important on the positioning of the densest phases during solidification. It was observed that turbulence is more responsible in centrifugal casting for the uniform distribution of the solidification nuclei and consequently will create a different solidification pattern and faster solidification rate of the casting (Ludmil et al. 2003).

The fluid dynamics, which is responsible for the turbulence in centrifugal casting for the uniform distribution of the solidification nuclei and consequently will create a different solidification pattern and results in faster solidification rate of the casting. Researchers have also concluded that faster solidification rate will lead to a finer micro structure, higher eutectic volume fraction and consequently better mechanical properties (Hengcheng et al. 2002). This is the driving force for utilizing the centrifugal casting process for producing functionally graded materials.

Further Vassiliou et al. (2008) have carried out few investigations to understand the vibration effect which was assessed by introducing a linear vibrating movement to the mold or frame. They reported the that vibration will have influence on the microstructure and under these conditions of solidification observations were made by the author that showed increase in mechanical properties i.e. rupture strength and strain by 20% and 40% respectively. These effects are similar to the one achieved by high solidification rate. It has been explained that higher rate of solidification is due to vibration which causes a strong internal movement of the melt that promotes a quicker heat transfer inside the melt and also to the mold. This attributes to a faster distribution of solidification nuclei inside the melt due to internal melt movement.

2.6 MECHANICAL PROPERTIES OF CENTRIFUGAL CASTING

Centrifugal casting is a process that relies on a centrifugal force to produce hollow and axi-symmetric parts like cylinders, pipes etc. Centrifugally cast parts have a high degree of metallurgical cleanliness and homogenous microstructures and they do not exhibit the anisotropy of mechanical properties evident in rolled/welded or forged parts. The solidification rate is one of the important parameter which has a great influence on the mechanical properties of the centrifugal casting. Many researchers (Vassiliou et al. 2008, Bonollo et al. 2004, Raju et al. 2000) have worked on the centrifugal casting to study the effect of solidification rate on mechanical properties, as the rate at which the heat is extracted determines the strength of the casting.

Mechanical properties of Al-Si cast alloy depend not only on chemical composition but, more important on microstructural features such as morphologies of α –Al dendrite, eutectic Si particles and other intermetalics that are present in microstructure. However the coarse acicular silicon phase morphology adversely affects the properties of these alloy and coarse grained structure responsible for the decrease in mechanical properties mainly tensile strength and rate of elongation (Heng et al. 2002).

The mechanical properties of specific alloys of Ai-Si; hypoeutectic, eutectic or hypereutectic can be attributed to the individual physical properties of its main phase components α-Al solid solution, silicon particles and to the volume fraction and morphology of these components (Kiran et al. 2012). There are different techniques used to control the microstructural features of these alloys. These include casting process, use of grain refiners and modifiers etc. A few researchers have reported the use of modifiers like Serenium or Sodium to obtain finely dispersed eutectic and use of grain refiners AlB_2 to reduce the size of the primary α-Al grains (Basavakumar et al 2008). The use of modifiers and refiners has lead to obtaining of fine equiaxed structure during solidification which resulted in good surface finish during machining (Mitja et al. 2006, Boris et al. 2010). In hypereutectic alloys primary silicon appears in different forms like star, polyhedral and dendrite. The Si morphology is highly dependent on the solidification parameters such as freezing rate, temperature gradient in the liquid and liquid composition. But centrifugal casting is the process which gives fine grains without grain refiners.

Watanabe et al. (2001) have worked exclusively on centrifugal casting of FGMs. They showed that the particle size distribution as well as the volume fraction of particles in composites plays an important role in controlling the mechanical properties. They studied in detail about the particle size distribution to predict the mechanical properties of FGMs. In Al/Al_3Ni FGMs the average particle size of primary Al_3Ni is gradually distributed and found that as the G number becomes larger, the particle size of the ring's outer region becomes smaller. It was concluded that the difference in the particle size distributions is caused due to the variation in cooling rate.

Most of the researchers (Hieu Nguyen et al. 2005, Liang Wang et al. 2009, Mondolfo et al. 1976) used aluminum alloy for their analysis because of aluminum alloy has many uses in the industry due to its excellent strength to weight ratio, high resistance to corrosion, cracking and shrinkage. Though there are many uses for the material, metallurgists and engineers are concerned with gas porosity in the alloy which could decrease its strength.

Nguyen et al. (2005) have worked on the formation of gas porosity in A356 and explained that porosity occurs because, there are traces of hydrogen gas bubbles within the material while it is solidifying after the casting process. These pores do not form while the material is solidifying because the solubility of hydrogen is much lower in the solid state than it is in the liquid state. If the cooling rate is comparatively high, then the pores are small but numerous. If the cooling rate is low, then the pores are large but they are less in volume. Nguyen et al. (2005) has conducted an experiment to study how gas pores and other features of the microstructure formed in relation to the cooling rate and how the mechanical properties of the aluminum alloy A356 were affected with the variation of solidification rate. During the experiment four samples of the alloy were used and those samples are cooled at different cooling rates and metallurgical microscope was used to analyze the microstructure of the material. They finally concluded that there is a relationship between the rate of solidification and the formation of gas porosity and other microstructure features on aluminum alloy A356. The results also showed that high solidification rates enhance the material strength and other mechanical properties, lower solidification rates and are detrimental to the strength of the material and reduce its mechanical properties.

Wang, et al. (2009) also worked on the effect of cooling rate on the formation of porosity which is significant in centrifugal casting process and concluded that smaller size and lower volume fraction of porosity were observed at higher cooling rates. Increasing the Si content increases the strength but at the expense of ductility (Mondolfo et al. 1976). The use of Al-Si system as structural materials is determined by_the physical properties, which are primarily influenced by the chemical composition. Also the mechanical properties are influenced by chemical composition and microstructure.

The high solidification rates of the castings enhance the material strength and other mechanical properties, lower solidification rates will reduce their mechanical properties. There is a relationship between the rate of solidification and the formation of gas porosity and other microstructure features on aluminum alloys. And if the solidification rate is comparatively high, then the small pores will form and if the solidification rate is low, then large pores will form.

2.6.1 Hardness of the Centrifugal Castings or Products

Hardness of the centrifugal castings depends on the grain size, secondary dendritic arm spacing and the particle distribution of alloy elements in the matrix. In case of centrifugal casting due to the rapid solidification of the castings fine grains and also smaller SDAS are the expected characteristics. The variation in mechanical properties is the result of variation in rate of solidification of centrifugal casting. Study of mechanical properties will give the information about the effect of process parameters on solidification of centrifugal castings.

Prasad et al. (2010) have experimented for the determination of grain size as the effect of process variable in centrifugal casting. They found that at lower speed of rotation of the mold grains were coarse and at higher speeds speed of rotation the grains were finer. They also reported that finer grains shows increase in hardness and vice versa. The hardness at the outer surface of the casting is higher compared to the inner surface of the cylindrical casting due to chilling effect at the mold and melt interface. Sui Yanwel, et al. (2010) also explained that rapid cooling rate promotes the formation of a fine grain structure by increasing the degree of constitutional super cooling. Superheat mainly affects the survival of nuclei that originate at the mold wall and consequently affects the grain size.

The silicon content in standardized commercial cast Al-Si alloys is in the range of 5 wt% to 23 wt%. Hypoeutectic alloys are used in many applications such as marine, electrical, automotive and aircraft industries specifically to produce cylinder blocks, cylinder heads and engine body castings. These alloys offer high resistance during machining, which causes tool wear. Hypereutectic alloys are used extensively these days in automotive industries because of their excellent wear resistance and low thermal expansion (Prasad et al. 1998).

Addition of grain modifiers will increase the tensile strength and ductility of the castings. Some of the modifiers such as Sr have increased the thermal stability, lowered the thermal expansion of the hypo Al-Si alloys promoting their application in Internal Combustion Engines. Hardness decreases with increase in thickness of the cylinder cast at the same rotational speed (Keerthiprasad et al. 2010). The hardness of the composite increased along the radial direction and proportionally to the volume fraction of the AlB_2 particles. Appreciable increments in hardness were observed even at lower radial distances as the boron content of the alloy increased. Micro hardness test performed on the composites showed an increase with increasing boron content and this effect is attributed to the higher dislocation density in the matrix due to the higher volume fraction of AlB_2 particles (Basavakumar et al. 2006).

Yan-wei et al. (2007) gave the relationship between Vickers hardness and grain size for Ti-6Al-4V alloy which meets the Hall-Petch equation: $Hv = 353.45+74.17\ d_G^{-1/2}$. They reported that this relationship between microstructure and hardness is used to further optimize the microstructure and property of Ti-6Al-4V alloy.

Vassilion et al. (2008) explains that different heat flow rates across the cast metal and mold surface regions affect the evolution of solidification and the microstructural properties of the casting. Hence variation in microstructure and hardness exhibits across the centrifugal casting along the radial direction. El-Aini et al. (2010) also observed that faster cooling rates exhibits increased hardness and vice versa. They made castings in steel molds with varying thickness and found that a casting at thicker section region of the mold has higher hardness compared to the castings at thinner section of the mold.

The studies have concluded that the hardness of the centrifugally cast metal increases with increase in rotational speed of the mold. The hardness is depending on the rate of solidification of the centrifugal casting. The experimental results have shown that the hardness of centrifugal casting increases with increase in wall thickness of the mold. Xuhong et al proposed that the hardness at the top surface of the centrifugally cast composite piston increases with the increase of the amount of primary Si and primary Mg_2Si particles (Xuhong et al. 2011).

2.6.2 The Tensile Properties of Centrifugal Castings

In pure metals growth of the grain takes place as the growth of the nuclei by addition of atoms during solidification of the metal. The growth of the grain directly depends on the solidification rate and grain size is the measure of the solidification rate of the casting. The grain size will be finer in centrifugal casting due to the rapid solidification because it may end at 4-8 seconds. Therefore these castings will have better mechanical properties. However the characteristic property of aluminum alloys is relatively high in tensile strength in relation to density compared with that of other cast alloys. The tensile properties and fracture behavior of the castings strongly depend on secondary dendrite arm spacing and in particular, the size and shape of eutectic Si particle and Fe-rich intermetalics. Thus by changing the morphology of dendritic α-Al, eutectic Si particles and other intermetalics that are present in the microstructure, the mechanical properties can be changed. Increase in Si content increases the strength but at the expense of ductility. The use of Al-Si system as structural materials is determined by their physical properties, primarily influenced by their chemical composition and their mechanical properties, influenced by chemical composition and microstructure. The characteristic property of aluminum alloys is relatively high in tensile strength in relation to density compared with that of other cast alloys (Mondolfo et al. 1976).

Chirita et al. (2009) have done a study on the mechanical properties of the castings produced by centrifugal and gravity casting process which is made in three different Al-Si alloys: a hypoeutectic, a eutectic, and a hypereutectic alloys. They observed that the centrifugal effect increased to approximately 50% in rupture strength and approximately 300% in rupture strain over the gravity casting. The Young's modulus also increased by 20% and these properties are also gradated within the casting. The higher the distance in relation to rotation centre and the more is the increase in mechanical properties.

Castro et al. (2002) have conducted tensile tests on FGMs at various levels of reinforcement content. They found that the effect of SiC content is significant in the composite cast at 700 rpm. The 1300 rpm cast composite showed no improvement in ultimate strength in the static test. The effect of SiC particulate reinforcement on strengthening of the alloy is limited up to a certain volume fraction. There is a continuous increase in tensile and yield strength at corresponding increments of SiC_P volume fraction in the range of 20-30%. On the contrary there is a reduction in tensile and yield strength for SiC_P concentration in the range of 30-40% volume fractions. Mesquita, R.A et al have studied on Microstructures and mechanical properties of bulk AlFeNd(Cu,Si) alloys obtained through_centrifugal force casting and concluded that the high specific tensile strength of aluminum alloys is very strongly influenced by their poly phase microstructure (Mesquita et al. 2001).

Dobrzanski, et al. (2007) have studied the microstructure and tensile properties of aluminum die cast alloys based on A380 as a function of the iron and manganese content and solidification rate. In this study they analyzed the solidification rate based on the Secondary Dendritic Arm Spacing (SDAS). The microstructure coarseness measured as the distance between the secondary dendritic arm spacing which is the function of rate of solidification. They demonstrated that, smaller the SDAS, finer and more homogeneous is the microstructure and vice versa. They noted that the Al-Si eutectic for the samples with longer SDAS is more of a flake like morphology and not as fibrous as in the case of the samples produced at higher cooling rates even though they are all modified by Sr. And finally they concluded that tensile properties increase with the decrease the SDAS.

2.6.3 Microstructure

Zhiliang et al. (2007) have investigated the effect of cooling rate and superheat on the grain size of AZ91 alloy with Mg-9 Al-1 Zn in %wt. They found that a finer grain size is obtainable at a higher cooling rate and lower superheat. With higher super heat leads to coarse dendrites and for sample cast with decreasing superheat, the grain structure changes from coarse dendritic to fine dendritic and forms globular structure.

Yanwel, et al. (2010) had studied the effect of centrifugal radius and mold rotation speed on microstructure in centrifugal casting of Al-Cu alloy. They concluded that with the increase of the centrifugal radius or mold rotation speed the grain size of centrifugal casting of Al Cu alloy decreases gradually while the content of white phases containing the Al_2Cu precipitated from α–phase divorced eutectic and regular eutectic microstructure increases leading to higher Cu macro segregation. The variation level of microstructure in centrifugal cast Al-Cu alloy at 600 rpm of mold rotation speed is greater than that at 300 rpm.

Dobrzanski et al. (2006) have studied the thermal characteristics of Al-Si-Cu alloy based on the cooling curves. They explained those increased cooling rates will significantly increases the Al nucleate temperature, nucleation under cooling temperature, solidification range and decreases the recalescence under cooling temperature. These phenomena lead to an increased number of nucleus that affects the size of the grains and the Secondary Dendritic Arm Spacing. They have proved that the variation of Secondary Dendrite Arm Spacing (SDAS) is strictly depending on the rate of cooling. In the highest cooling rate the SDAS is fine and easily visible. For the sample which was cooled with lowest cooling rate the SDAS is large. Mechanical properties of the aluminum alloys are strongly dependent on the effect of SDAS (Dobrzanski et al. 2006).

Lipinski et al. (2008) showed that Mechanical properties of the Al-12wt%Si cast alloy with fast cooled Al-12wt%Si alloy mainly depends on the shape, size and distribution of_the α- phase rich on Al, eutectic silicon morphology and other particles elements, in general rich on Fe, Cu and other. The fact that larger amount of a homogenous modifier were required to effectively improve the properties analyzed. This can be explained by the presence of coarse eutectic silicon precipitates in Al-12wt%Si alloy.

Seifeddine and Svensson (2009) have conducted experiments to investigate the microstructure and tensile properties on aluminum die cast alloys at different solidification rates. Solidification rates were determined based on the Secondary Dendritic Arm Spacing (SDAS). These results showed additional insight into commonly discussed microstructure features and their role in the determination of the quality and soundness of Al-Si cast alloys. To quantify microstructural features SEM, EDS and optical microscopy with image processing software were used. Nikanorov et al. (2005) had prepared the Al-Si alloy samples by rapid cooling of levitated melts of various compositions from 11.5 to 35wt%Si and concluded that rapid cooling of the castings have better mechanical properties.

Kumar et al. (1997) in his work observed the effect of cooling rate on the size of the grains, SDAS, size of the β precipitation and thermal characteristic results of AC AlSi9Cu cast alloy. The solidification process was studied using the cooling curve and crystallization curve at solidification rate ranging from 0.16 ºC/s up to 1.04 ºC/s. The analysis of thin foils after the cooling, validated the fact that, the structure of the AC AlSi9Cu cast alloy consists of the solid solution α–Al matrix and an intermatallic secondary phase β–Si in the form large flakes, needle and fibrous precipitations which is depending on the applied cooling rate. Here they concluded that the mechanical properties of the aluminum alloys are strongly dependent on the effect of SDAS. Tensile properties increase with a decrease in SDAS. Increase in cooling rate from 0.16°C/s to 1.04°C/s causes increase in ultimate tensile strength from 252 MPa for lowest cooling rate to 267MPa for highest cooling rate. The cooling curve obtained at the higher cooling rate has a shorter solidification time and larger solidification range. Solidification times is related to the cooling rate according to the equation proposed by Kumar, $t_{SR} = A\,(CR)^{-n}$, where A and n are the constants of the equation CR is the cooling rate (°C/s). The predictions did not involve the adjustment of a fitted parameter.

The solidification rate affects the microstructure formation in centrifugal castings, a finer size grains are obtained at higher cooling rates and lower superheat and coarse grains are formed at lower cooling rate and higher superheat temperature. In case of alloys with higher superheat and slower cooling rate leads to coarse dendrites and for castings with decreasing superheat and higher cooling rate, the grain structure changes from coarse dendrites to fine dendrites. The SDAS decreases with increasing cooling rate and the variation of the SDAS with cooling rate is in excellent agreement with the predictions of the micro segregation models (Halvaee et al. 2001). Solidification rates were determined based on the Secondary Dendritic Arm Spacing (SDAS) for alloys. An increase of the cooling rate provided to refine the size of the secondary phase intermetalics and also alter their morphology towards equiaxed by reducing the aspect ratio. This is attributed to the process of repeated nucleation of the intermetalics phases during eutectic solidification.

The studies have suggested that the centrifugal casting technique being the best casting process by which the castings will have better mechanical properties along the whole of the casting length as compared to the gravity casting (Chirita et al. 2006). The centrifugal casting process may be effective even for materials with similar phase densities or metal densities in the same alloy. The rapid cooling gives a fine eutectic structure, small α-Al dendrite arm spacing and reduced grain size. Slower cooling rates result in randomly oriented coarse eutectic Si needles and coarse columnar α-Al dendrites. The higher the distance in relation to the rotation centre, higher will be the centrifugal force and hence increase in mechanical properties.

2.6.4 Wear

Wear is related to the interactions between the surfaces and more specifically the removal and deformation of material on a surface as a result of mechanical action of the opposite surfaces (Rabinowicz et al. 1995). The need for relative motion between two surfaces and initial mechanical contact between asperities is an important distinction between the mechanical wear compared to other processes with similar outcomes. Some commonly referred wear mechanisms or processes include:

- **Adhesive wear -** Adhesive wear can be found between surfaces during frictional contact and generally refers to unwanted displacement and attachment of wear debris and material compounds from one surface to another. Two separate mechanisms operate between the surfaces.
- **Abrasive wear -** Abrasive wear occurs when a hard rough surface slides across a softer surface (Rabinowicz et al. 1995). It is the loss of material due to hard particles or hard protuberances that are forced against and move along a solid surface (ASTM, 1987). The two modes of abrasive wear are known as two-body and three-body abrasive wear. Two-body wear occurs when the grits or hard particles remove material from the opposite surface. The common analogy is that of material being removed or displaced by a cutting or plowing operation. Three-body wear occurs when the particles are not constrained, and are free to roll and slide down a surface.

Three commonly identified mechanisms of abrasive wear are: Plowing, Cutting and Fragmentation. Plowing occurs when material is displaced to the side, away from the wear particles, resulting in the formation of grooves that do not involve direct material removal. The displaced material forms ridges adjacent to grooves, which may be removed by subsequent passage of abrasive particles. Cutting occurs when material is separated from the surface in the form of primary debris, or microchips, with little or no material displaced to the sides of the grooves. This mechanism closely resembles conventional machining. Fragmentation occurs when material is separated from a surface by a cutting process and the indenting abrasive causes localized fracture of the wear material. These cracks then freely propagate locally around the wear groove, resulting in additional material removal by spalling (ASM Handbook Committee, 2002).

- **Erosive wear-** Erosive wear can be described as an extremely short sliding motion and is executed within a short time interval. Erosive wear is caused by the impact of particles of solid or liquid against the surface of an object.
- **Fretting wear** - Fretting wear is the repeated cyclical rubbing between two surfaces, which is known as fretting, over a period of time which will remove material from one or both surfaces in contact. It occurs typically in bearings, although most bearings have their surfaces hardened to resist the problem.

The wear is a complex phenomenon which depends on different parameters viz., type of the matrix material, type of the reinforcement, surface roughness, processing technique, pressure, temperature, environment, sliding speed, type of friction etc. (Bialo et al. 2000). The complex nature of wear has delayed its investigations and resulted in isolated studies towards specific wear mechanisms or processes (Jones, M., H. and Scott, Eds. 1983).

Vieira et al have conducted the research on influence of processing variables on dry sliding wear of Al alloy/SiCp, functionally graded composites produced by centrifugal casting method. During their study the unlubricated sliding wear of centrifuged Al alloy and Al–SiCpFGMMC's processed with different centrifugal speeds was studied by ball-on-ring tests using high-carbon chromium steel (AISI52100) as counter body. They concluded that Centrifugal casting process promotes a gradient in the microstructure and in hardness of the centrifuged unreinforced Al alloy due to differences of solidification rates. This material was characterized by severe wear assisted by an adhesive wear mechanism. For the aluminum-based FGM composites considered in this study, two-body abrasion wear, oxidative wear, adhesion and delamination were the main wear mechanisms identified. Formation of a mechanically mixed layer (MML*)* was also reported, mainly constituted by iron, aluminum oxide, iron oxide and inter metallic compounds of Al–Fe and Al–Fe–O (Vieira et al. 2009).

Shrikantha et al. (2010) have observed in their study regarding the wear rate of aluminum centrifugal casting that the wear rate decreased at the optimized speed of 800 rpm and increased at other mold speeds. Moreover, the wear rate was reduced with increase in sliding velocity due to the decreased contact of asperity of the two surfaces in contact during rotation. The higher the applied load, the higher the wear loss also higher the wear velocity, the lower the wear intensity (Leon-Patino et al. 2013).

Kim et al. (2000) have used Centrifugal casting technique to impart better tribological properties to the inner periphery of centrifugal castings of a C90300 copper alloy originally containing 13vol% of graphite particles. They observed that the wear rate and the temperature at the counter face for the pins from the graphite-rich zone of the centrifugal castings were lower than the wear rate and the temperature at the counter face for the pins from the graphite free zone of the same centrifugal casting under similar conditions. A greater transfer of the copper phases from the pin to the cast-iron counter face was observed visually from the pin of the graphite free zone than from the pin of the graphite-rich zone, which was confirmed by EDX analysis also. This leads to an increase in the weight of the counter face running against the pin from the graphite free zone with an increase in the applied load. Despite the presence of graphite in cast iron, the presence of graphite in the matrix of mating copper alloys lead to improved tribological properties. The effect of graphite particles on tribological properties of the composites was discussed in terms of the transfer of iron and copper phases, the inter particle distance between graphite.

Alam et al. (1996) investigated aluminum bronze bushes fabricated using centrifugal casting process. The microstructural examination revealed that the distribution of alpha phase was not uniform and in homogeneity was due to centrifugal action on the solidification melt. The tribological behavior showed that the centrifugally cast specimens experienced boundary lubrication conditions at the start of the test. It was also found that the wear loss of the centrifugally cast specimen was less compared to that of the forged cast specimen. Siddhartha et al have concluded from the steady-state wear study that centrifugally cast graded composites revealed better wear resistance than their homogeneous components (Siddhartha et al. 2011).

2.7 SUMMARY

From the literature survey it is understood that various process parameters have great affect on the rate of solidification in centrifugal casting and this rate of solidification of centrifugal casting affects its microstructure, quality and mechanical properties. Even flow phenomenon of liquid metals in centrifugal casting is much more complex than normal liquids of constant viscosity. Numerical investigations and process modeling have helped in predicting the behavior of the casting produced by varying the process variables. The input parameters for the solidification modeling system are solidification range and solidification time where total solidification time, is the time interval between the start and end of solidification. Some authors have assumed as constant solidification rate of the melt during their analysis. The assumptions of constant solidification rate are valid in a small number of real objects and for short time intervals.

In case of alloys with higher superheat and slower cooling rate leads to coarse dendrites and for castings carried out with decreasing superheat and higher cooling rate, the grain structure changes from coarse dendrites to fine dendrites. The microstructure coarseness in alloys can be measured as the distance between the secondary dendritic arm spacing (SDAS) which is the function of cooling rate. The SDAS decreases with increasing cooling rate and the variation of the SDAS with cooling rate is in excellent agreement with the predictions of the micro segregation models. It is demonstrated that, smaller the SDAS, finer and more homogeneous is the microstructure and vice versa. Hence in case of alloy solidification rates can be determined based on the Secondary Dendritic Arm Spacing. In case of pure metals, since the rate of solidification controls the grain size, the rate of solidification can be determined based on the grain size. It has been observed that the centrifugal effect leads to increased tensile strength, strain and also the Young's modulus over the gravity casting of the same metal. Further these properties are gradated within the casting. The studies have concluded that the hardness of the centrifugally cast metal increases with increase in rate of solidification of centrifugal casting hence the reduction in the wear.

The solidification time of the casting depends upon the speed of rotation of the mold. It decreases with an increase in the speed of rotation. If the spinning speed and melt temperature are adequate the teemed melt will distribute itself uniformly along the length of the mold before solidifying. It was noted that the solidification rate in centrifugal casting can be controlled by the heat transfer between the casting and the mold. Therefore by preheating the mold heat transfer through the mold can be varied. The particle size distribution plays an important role in controlling the mechanical properties of the metal centrifugal castings. The magnitude of the centrifugal force is regarded as the major factor in centrifugal casting process as segregation of particles occur due to centrifugal force, either at the inner or the outer periphery of the casting depending on the relative densities of the particles and the melt, resulting in functionally gradient composites. Lower density material will be segregated at the inner radius and higher density will be segregated at the outer surface of the castings. Thus it is expected that in alloys where there are phases or metals with different densities the densest ones will concentrate on the outer part of the casting. Thus as the rotational speed increases, the force acting on the particles to segregate will also increases. The extent of segregation depends also on various process parameters including casting geometry, melt poring temperature, solidification time, density difference between matrix and reinforcement particles and rotational scheme.

It has been suggested that the centrifugal casting technique being the best casting process by which the castings will have better mechanical properties along the whole of the casting length as compared to the gravity casting. But from the literature survey it is also seen that the information regarding the experimental methods of determining of rate of solidification of centrifugal casting is limited. But the final quality of the castings depends on some of the critical process parameters of centrifugal castings. Hence a detailed study on the evaluation of solidification rate and its effect on the mechanical properties, effective process parameters in designing the castings and their effects on the microstructure and mechanical properties of the castings need to be studied.

Chapter 3

EXPERIMENTAL DETAILS

3.1 INTRODUCTION

Centrifugal casting is a process of producing cylindrical castings by pouring the molten metal into a rotating mold. From the literature review it has been observed that the quality of the final centrifugal casting is mainly depends on many process parameters such as pouring temperature, initial temperature of the mold, rotational speed and wall thickness of the mold, melt composition, shape and size of the Si particles and so on. So the following discussions are to study the effects of various process variables on the solidification of centrifugal casting.

There are various difficulties in the study of centrifugal casting and few of them are listed below

- The process is very rapid due to sudden solidification of the liquid metal
- Difficult to visualize the fluid behavior
- Opaque nature of the mold and melt
- High Temperature of the melt
- Change in viscosity during solidification of the casting.
- Phase change during solidification that leads to change in the fluid flow and microstructure of the casting.

Therefore motion of the liquid during centrifugal casting cannot be visualized and studied with conventional techniques. It is necessary to make preliminary examinations on the nature of the liquid flow in a partially filled cylinder rotating at various speeds to study the formation of different liquid flow pattern formations and also the rate of cooling at different rotational speeds. Hence the cold modeling experiment has been adopted to study the liquid flow behavior at various rotational speeds of the mold using liquids of different viscosities. The liquids of different viscosities such as water, glycerin, 90 EP oil and 140 EP oil are used in this study to visualize the behavior of melt as it cools to freeze with increased viscosity. Visual observations of different fluids inside a rotating cylinder indicate the existence of certain critical magnitude of angular velocity for the formation of liquid cylinders. These results are compared with the solidification behavior of centrifugally cast Tin.

Centrifugal casting facility was designed and fabricated in the laboratory has been employed to assess the solidification characteristics of Tin, Al-12wt%Si (eutectic) and Al-17wt%Si (hypereutectic). The casting test samples as influenced by the magnitudes of the processing parameters are discussed in the present work.

The rate of solidification of centrifugal castings produced by varying the process variables are determined based on the grain size, since grain size is proportional to the rate of solidification in pure metals and for the alloys it is based on the Secondary Dendrite Arm Spacing (SDAS).

3.2 SCOPE OF WORK AND PROBLEM STATEMENT

Based on the literature study, scope for research in the area of centrifugal casting is proposed as below:

1. Cold modeling experiment to determine the optimum speed of rotation for liquids of different viscosities using partially filled rotating horizontal cylinder.

2. Study on cooling rates of liquids with different viscosities rotating in a cylinder rotated at different speeds.

3. Preparation of gravity castings of Tin metal subjected to different solidification rates and measurement of their grain sizes. The relationship between the rate of solidification and grain size is used to estimate the rate of solidification of centrifugal casting of Tin.

4. Producing the centrifugal castings of Tin metal at different rotational speeds of the mold, preheated to different temperatures and using the molds of different wall thickness. The different centrifugal castings are characterized based on microstructural changes, hardness, grain size and specific wear rates.

5. Preparation of gravity castings of Al-12wt%Si metal at different solidification rates and measurement of SDAS. The relationship between the rate of solidification and SDAS is used to analyze the rate of solidification of centrifugal castings of Al-12wt%Si.

6. Experimental study on the effect of rotational speed of the mold on the solidification behavior of Al-12wt%Si is based on microstructural changes, SDAS, hardness, specific wear rate and tensile strength are measured.

7. Experimental study to determine the effect of rotational speed of the mold on the hardness, specific wear rate, tensile strength and the Si particle distribution in centrifugal casting of Al-17wt%Si to be carried over.

This chapter gives an insight of the centrifugal casting process for producing cylindrical objects and the effect of process parameters on the quality of the castings. An overview of the materials used to produce the castings, microstructural studies, determination of rate of solidification, hardness; tensile strength and wear test are presented. The sequence of operations carried out for the processing and characterizing the centrifugal casting are depicted in Figure 3.1.

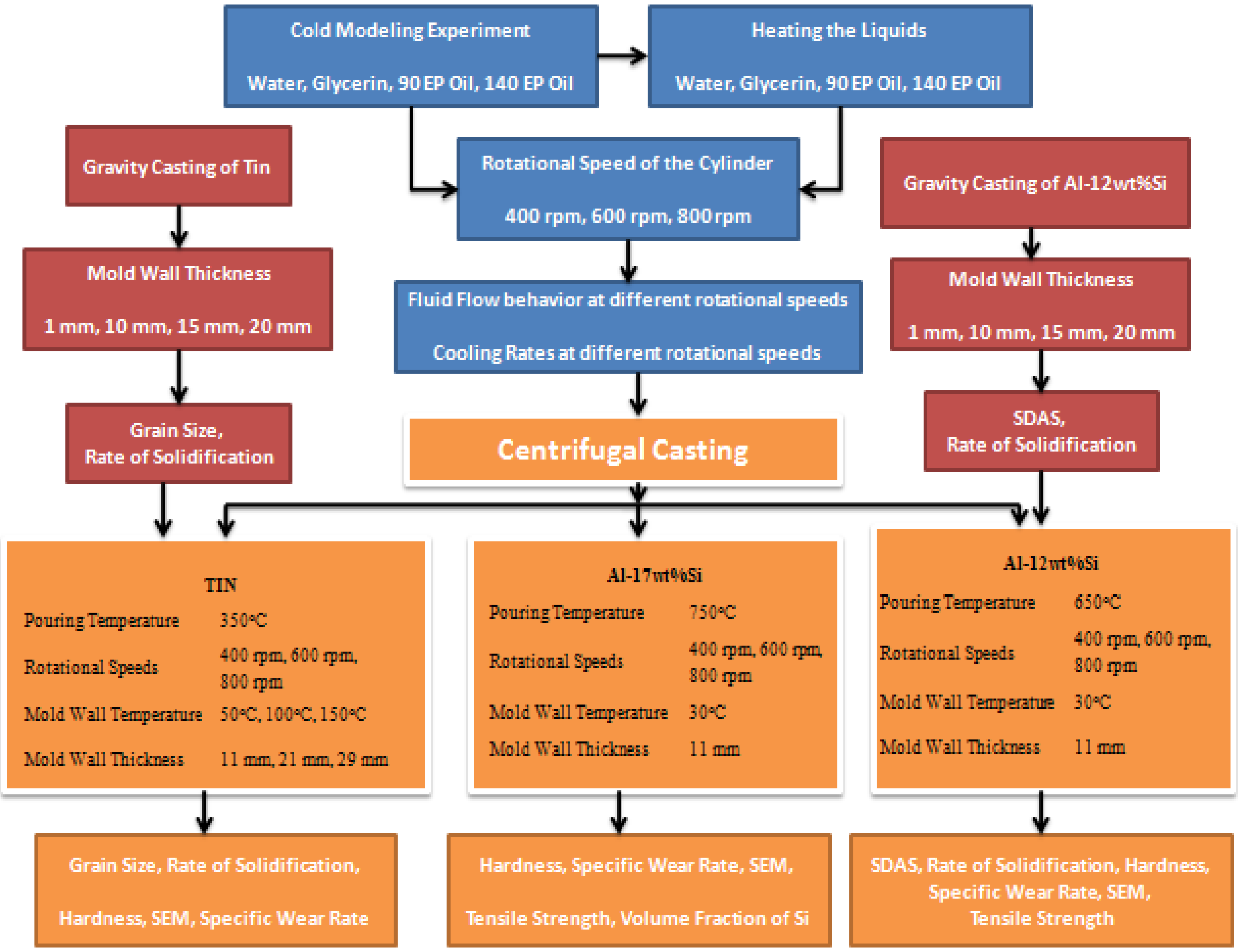


Figure 3.1 Flow Chart Showing the Sequence of Processes and Experiments

In view of the above the problem statement for the present research work is defined as '**SOME STUDIES ON PROCESS PARAMETERS IN CENTRIFUGAL CASTING**'.

3.3 STUDY OF COLD MODELING

Cold modeling experiments were conducted to establish the optimum processing conditions to obtain a uniform thick cylindrical casting. Optimum process parameters were established based on the visual observations of the cylinder rotated with different fluids having different viscosities. The relationship between the critical speeds of rotation for different liquids such as water, glycerin, 90 grade EP oil and

140 grade EP oil when thickness of the liquid layer were varied for 4 mm to 8 mm in steps of 2 mm.

Experimental setup to carry out the cold modeling experiments for the study of liquid behavior in partially filled rotating cylinder is as shown in the Figure 3.2. It consists of a horizontal transparent polymer cylinder of 107 mm diameter and 140 mm length fixed to the motor shaft. Initially calculated volume of water to form 4 mm wall thickness cylinder and is poured to the horizontal cylinder. The machine is switched on and as the speed of rotation increases gradually, the formation of various flow patterns are observed. The process is continued till the formation of liquid cylinder with uniform wall thickness. The speed of the cylinder or mold at which the liquid forms a uniformly thick layer is called critical speed of rotation. Similar experiments are conducted for 6 mm and 8 mm thick layers of water and during each case critical speed of rotation is determined. In order to study the liquid behavior and critical speed of rotations for different viscosity fluids such as glycerin, 90 EP Oil and 140 EP oil are used for conducting the similar experiments. The liquids are selected according to their increasing viscosities from water which is having lower viscosity to 140 EP oil, which has higher viscosity. Table 3.1 shows the viscosities of the liquids considered for the experiment.

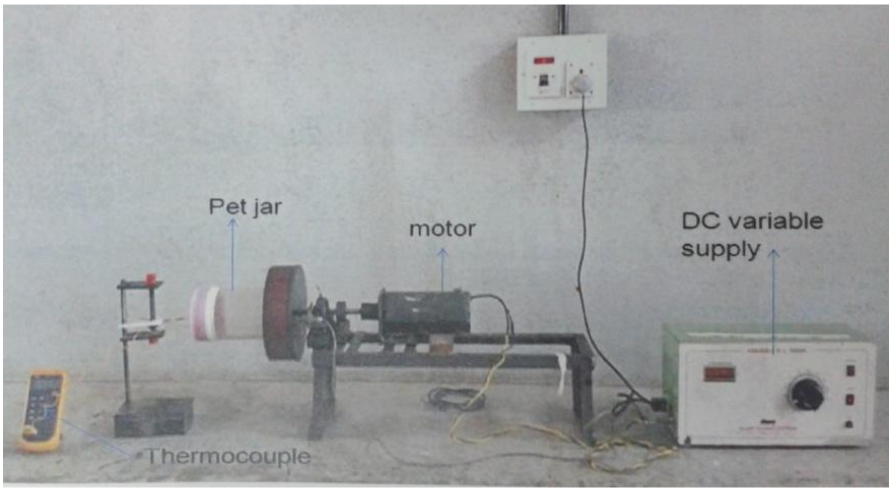


Figure 3.2 Cold Modeling Experimental Setup

Table 3.1 Physical Properties of the Fluids at Room Temperature

Liquid	**Kinematic viscosity (m^2 /s)**	**Dynamic Viscosity (N-s/m^2)**
Water	0.817×10^{-6}	8.146×10^{-4}
Glycerin	132.35×10^{-6}	319×10^{-4}
90 EP Oil	278.74×10^{-6}	2430×10^{-4}
140 EP Oil	576.55×10^{-6}	5160×10^{-4}

3.4 STUDY ON COOLING RATE OF LIQUID IN A PARTIALLY FILLED ROTATING CYLINDER

To study the cooling rates of liquids of different viscosities at different rotational speeds of the mold, liquids are heated and poured into the rotating mold. Glycerin, 90 EP oil and 140 EP oil are poured at 100^oC but water is heated to 70^oC, since water boils at 97^oC in Bangalore. Temperature of liquid is noted for every 10 seconds. The objective of the experiment is to measure the variation of the temperature of the melt with time as a function of rotational speed of the mold and viscosity of the liquid.

The experimental set up consists of a rotating cylinder which is coupled to the motor and a digital thermocouple as shown in Figure 3.2. Thermocouple is attached to the arm of the stand and can be moved up and down in the liquid. The mold axis is aligned with the axis of motor shaft to avoid wobbling of the mold during rotation.

Measured quantity of water required to form particular thickness is heated to about 70^oC in a pan and is poured to the stationary mold. As the water starts getting cooled the decrease in temperature is noted for every 10 seconds. The readings are noted starting from 60^o C. The graph of variation of temperature with respect to time is plotted and is represented as cooling curves of water. Again water is heated to a temperature of 70^oC and poured to the mold which is rotating at a speed of 400 rpm. Decrease in temperature is noted and cooling curve of temperature versus time has been plotted. Similar experiments were conducted and cooling curves have been plotted for the speeds of 600 rpm and 800 rpm. In order to study the effect of viscosity on rate of cooling, same liquids which were used in earlier experiments such as glycerin, 90 EP oil and 140 EP oil are used to conduct the similar type of experiments.

3.5 INDUCTION FURNACE

To get melt of Tin, Al-12wt%Si and Al-17wt%Si alloy the resistance furnace is used which is shown in Figure 3.3. The unit consists of a 3 kW resistance furnace placed on a stand. The furnace constitutes a closed muffle box made with Kanthol Al heating element. A ceramic fiber blanket of grade 128 surrounds the furnace to minimize heat loss. The clay graphite crucibles of diameter 110 mm is used to melt the materials.

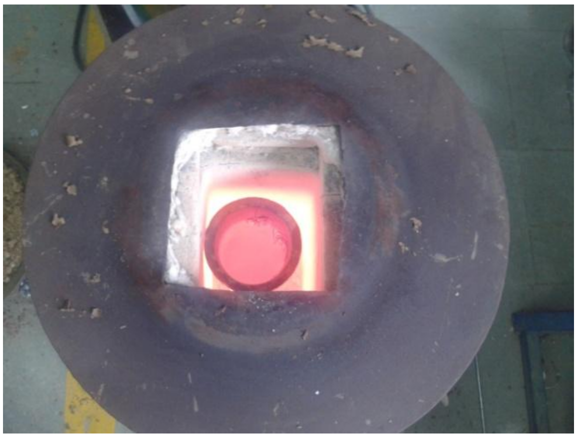


Figure 3.3 Melting Muffle Furnace

3.6 RATE OF SOLIDIFICATION BASED ON GRAIN SIZE OF GRAVITY CASTING OF TIN

In centrifugal casting the solidification rate is the important parameter which has a great influence on the mechanical properties of the casting. But during the centrifugal casting process the determination of rate of solidification is very difficult as discussed earlier. From the literature it has been learnt that formation of grain size directly depends on the rate of solidification. Therefore based on the grain size the solidification rate of the centrifugal casting can be determined. Initially gravity castings are made where it is possible to measure the solidification rate by plotting their cooling curves using a thermocouple to measure the temperature at different intervals of time. For the gravity castings which are produced at different solidification rates the grain size has to be determined. By using the relationship between the grain size and the solidification rates of gravity castings produced at different solidification rates, the rate of solidification in centrifugal castings can be determined.

The four types of gravity castings are produced at four different cooling rates. It is expected that the molds with different wall thickness causes different cooling rate, hence four mild steel molds are used with wall thickness of 1 mm, 5 mm, 10 mm and 20 mm and height 70 mm as shown in Figure 3.4 and Table 3.2. These molds are expected to have different cooling rates; cooling rate 1, cooling rate 2, cooling rate 3 and cooling rate 4. A digital thermocouple made of chromel-alumel of 32 gauge junction is inserted approximately at the centre of the die cavity and the mold was maintained at room temperature. Tin metal is melt in the graphite crucible in an electric induction furnace which is shown in the Figure 3.3 where temperature is set at 350^{o}C using thermostat setting. Molten Tin is maintained at 350^{o}C at about 5 minutes is taken out from the furnace and is poured into the mold directly from the crucible to minimize the temperature drop during pouring. The temperature reading in the thermocouple which is in contact with the melt is noted for every 10 seconds and the relationship between the temperature and time of the cast samples for different cooling rates is plotted which the cooling curves of the solidified tin metal. The slope of the cooling curves gives the rate of solidification in ^{o}C/s.

The test samples are prepared by cutting the gravity castings near the location of the thermocouple for the analysis of the microstructure. The sectioned surface obtained is prepared for a metallographic study by grinding, using a series of abrasive papers starting from mesh size 600, 220, 4/4, …, 1/4. Later polished in polishing machine with velvet cloth using water for tin and lavigated alumina in water for Al-12wt%Si and Al-17wt%Si alloys. The Specimens so obtained were etched with an etchant 4%

nital for tin and kellers for Al-Si alloys. The grain size of the tin microstructures has been measured by using Image Analyzer.

The relationship between the average grain size and the rate of solidification obtained by the measurement of temperature at known short periodic time intervals for the Tin gravity test samples have been plotted for the four gravity castings which are produced at different solidification rates. This graph of correlation between the grain size and rate of solidification is used to infer the solidification rates of centrifugal castings produced by varying the process parameters.

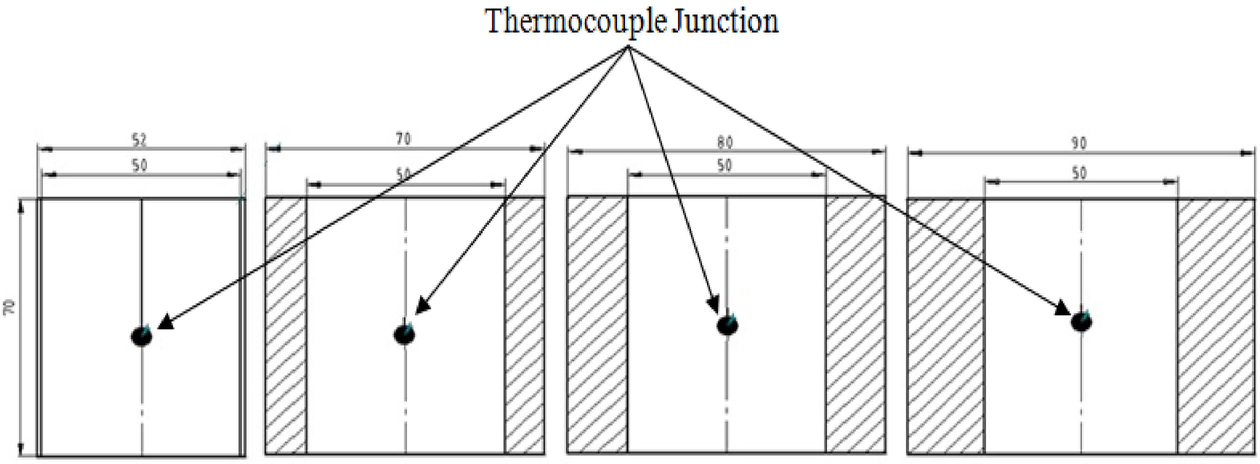


Figure 3.4 Molds of Different Wall Thickness Used for the Gravity Castings

Table 3.2 Specifications of the Mold Used for the Production of Gravity Castings

	Mold 1	Mold 2	Mold 3	Mold 4
Inner Diameter (mm)	50	50	50	50
Outer Diameter (mm)	52	70	80	90
Wall Thickness (mm)	01	10	15	20
Length (mm)	70	70	70	70

3.7 MATERIAL SELECTION AND PROCESS PARAMETERS OF CENTRIFUGAL CASTING

As discussed in the literature there are several process parameters that have great effect on the microstructure, mechanical properties and particle distribution in centrifugal castings. These parameters include rotational speed of the mold, wall thickness of the mold and initial temperature of the mold etc..The process parameters selected for this study are given in the Table 3.3. In this experiment only for tin the effect of all the three process parameters are considered. Since all these process parameters have the influence on the rate of solidification of the castings, in case of Al-12wt%Si and Al-17wt%Si only the effect of rotational speed is considered. And our main aim of the present study is to determine the rate of solidification of centrifugal casting, for Tin metal which is analyzed based on grain size and in case of Al-12wt%Si alloy it is based on the SDAS. Since the Al-17wt%Si alloy is having more weight percent of Si content, it is used to study the segregation of Si particles as an effect of rotational speed of the mold. Tensile test for tin metal is not performed as it is difficult to machine the specimen since it is a soft material. The studies have been limited to metals and alloys which freeze at a fixed temperature and results are compared with the alloy which freezes over a range of temperature.

Table 3.3 Process Parameters for the Centrifugal Casting

Process Parameters	**Tin(Sn)**	**Al-12wt%Si**	**Al-17wt%Si**
Pouring Temperature (^oC)	350	650	750
Rotational Speed of the Mold (rpm)	400, 600, 800	400, 600, 800	400, 600, 800
Temperature of the Mold (^oC)	30	30	30
Preheated Temperature of the Mold (^oC)	50, 100, 150	NA	NA
Wall Thickness of the Mold (mm)	11, 21, 29	11	11
Wear Load (N)	5, 10, 15, 20	10, 20, 30, 40	10, 20, 30, 40

A commercial grade of Tin metal is used for the analysis of pure metal. And in Al-Si system eutectic Al-12wt%Si and hyper eutectic Al-17wt%Si alloys which forms two different solid phases upon cooling are used as test materials in this investigation. The compositions of tin, eutectic Al-12wt%Si and Al-17wt%Si alloys are given in Table 3.4. The test samples were produced by melting the test materials in a temperature controlled furnace and pouring them into the stationary molds in the case of gravity die casting and rotating molds in the case of centrifugal casting process by following the standard procedures available for the purpose.

The detailed experimental procedures have been employed to carry out the experiments to establish the influence of process parameters on solidification rate and its effect on the microstructure, mechanical properties and the particle distribution have been discussed in this chapter.

Table 3.4 Composition of Tin, Al-12wt%Si and Al-17wt%Si Alloys Used for the Centrifugal Casting

Metal	**Composition (wt %)**	
Tin	Impurities	Sn - 99.9%
Al-12wt%Si	Si- 12.7	Al - Balance
Al-17wt%Si	Si- 17.0	Al - Balance

3.8 EFFECT OF ROTATIONAL SPEED AND WALL TEMPERATURE OF THE MOLD ON RATE OF SOLIDIFICATION OF TIN CENTRIFUGAL CASTING

From the literature it has been observed that the mold temperature plays an important role on the solidification behavior of centrifugal casting. This is because during the solidification of the casting the heat transferred from the casting through the mold wall. Therefore the heat dissipation rate from the melt depends on the temperature of the mold.

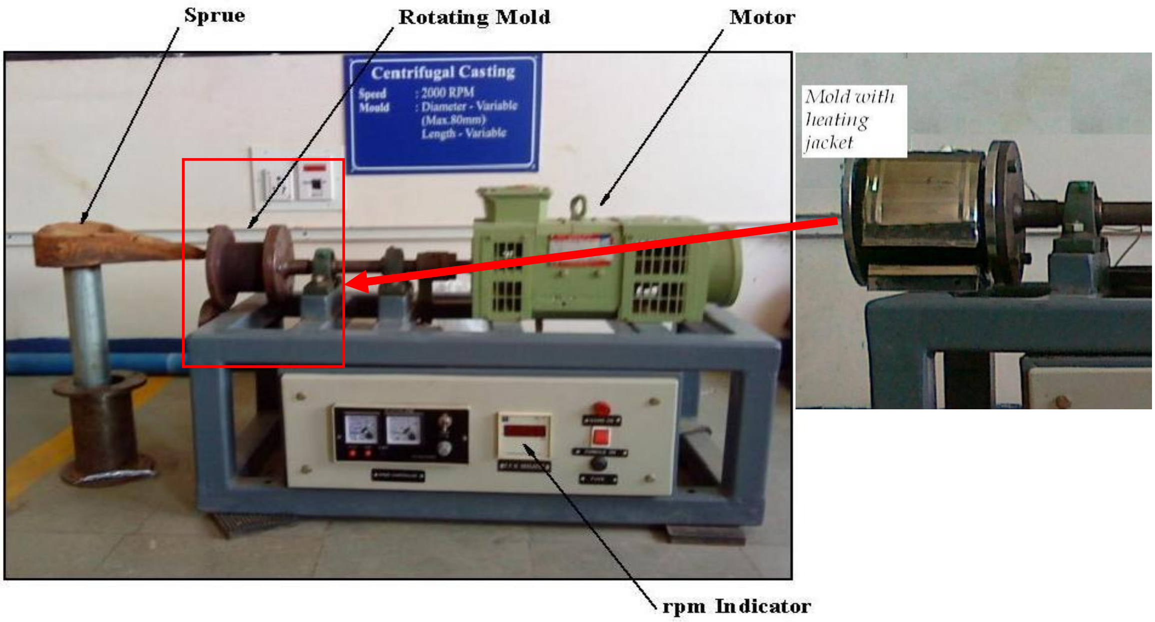


Figure 3.5 Centrifugal Casting Setup

In actual practice due to continuous production of castings, the temperature of the mold will increase hence the temperature difference between the mold and the molten metal will decrease due to this the rate of cooling will be decreased. Therefore solidification rate of the centrifugal casting can be controlled by the heat transfer between the casting and the mild steel mold. By preheating the mold the heat transfer between the mold and the casting can be altered. In this work by varying the temperature of the mold wall to 50°C, 100°C and 150°C the effect of mold wall temperature on the rate of solidification of tin centrifugal casting has been studied.

The Figure 3.5 shows the centrifugal casting set up consisting of a mild steel cylindrical mold which is fixed to a driving flange. The driving flange is connected to a shaft of a 1 HP DC shunt motor, wherein the speed can be varied from 20 rpm to 2000 rpm using an accurate speed controller. The flow of liquid metal into the mold is confined in the horizontally oriented, axially rotating cylindrical mold. The mold has a length of 80mm and inner diameter of 72 mm. Initially three tin castings are produced at three rotational speeds of the mold of 11 mm wall thickness and at room temperature. These castings are used to study the effect of rotational speeds of the mold on rate of solidification and mechanical properties of tin centrifugal casting.

In order to study the effect of mold wall temperature on rate of solidification of tin centrifugal castings heating jacket is mounted around the mold and temperature of the mold is increased to 50^{o}C. The molten Tin at 350^{o}C is poured to the rotating mold immediately after removing the heating jacket. Similarly castings are produced by rotating the molds at 400 rpm, 600 rpm and 800 rpm respectively. In this analysis, microstructures have been considered at three locations in the casting along the radial direction namely inner, middle and outer as shown in the Figure 3.6. The grain size has been measured for the obtained microstructures and further rate of solidifications have been determined. Similar experiments have been repeated by heating the mold to 100^{o}C and 150^{0}C. The hardness, specific wear rates are also determined for the test samples. The results have been compared for different cases of mold wall temperature and at different rotational speeds of the mold.

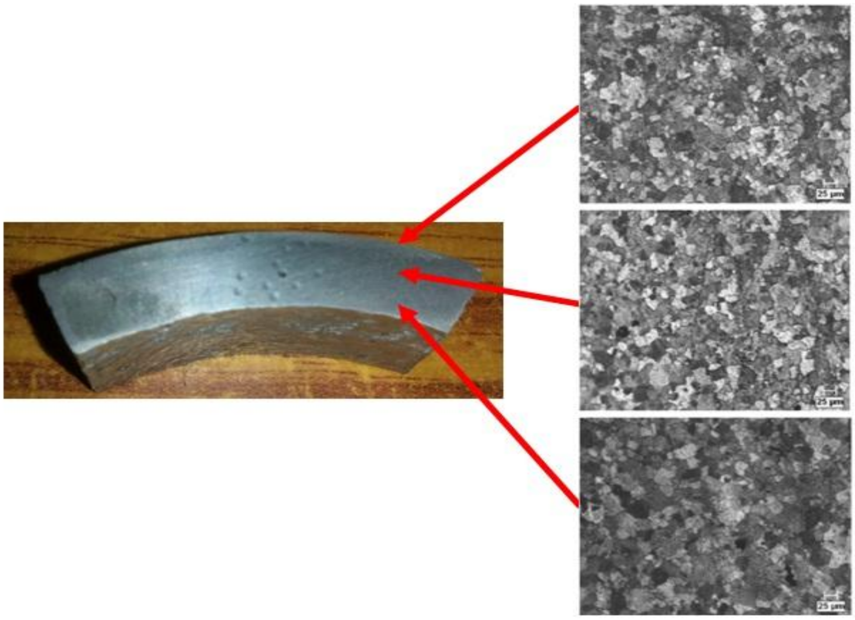


Figure 3.6 Microstructure along the Radial Direction of Centrifugal Casting of Tin

3.9 EFFECT OF MOLD WALL THICKNESS ON RATE OF SOLIDIFICATION OF CENTRIFUGAL CASTING

As discussed earlier wall thickness of the mold is also one of the prominent process parameters which have an influence on the rate of solidification of centrifugal casting. As wall thickness of the mold is increased the chilling effect will be more and hence more heat will be dissipated to the mold wall. To study the effect of mold wall thickness on rate of solidification of centrifugal casting, experiments were conducted by using three sets of molds with different wall thickness namely 11 mm, 21 mm and 29 mm which will provide different cooling rates. Microstructures of the castings have been analyzed and grain size has been measured using the image analyzer. This will give the rate of solidification of centrifugal castings produced using the molds with varying wall thickness. The Brinell hardness number and specific wear rate are determined by using Brinell Hardness Tester and Pin on Disc wear tester respectively.

3.10 CENTRIFUGAL CASTING OF Al-12wt%Si (EUTECTIC) AND Al-17wt%Si (HYPEREUTECTIC)

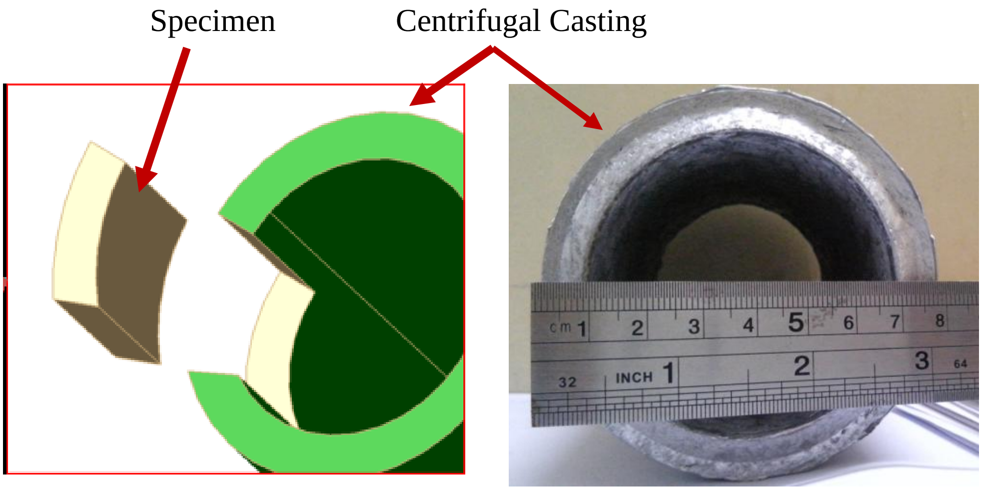
In the casting industry an improvement of component quality depends mainly on the better control over the process parameters. As discussed earlier the variation in process parameters will cause variation in solidification rates of the castings. Also the solidification rate of the casting is proportional to the rate of heat extraction from the melt during solidification of the castings. Therefore at a lower rate of solidification the rate of heat extraction from the sample is slower and the slope of the cooling curve is small, but at higher rate of solidification, the rate of heat extraction from the sample is faster, the slope of the cooling curve will be steeper and it exhibits a narrow cooling curve. In case of Al-12wt%Si alloys, the variation of Secondary Dendrite Arm Spacing (SDAS) is strictly depending on the rate of solidification of the casting. Hence the microstructure coarseness has been measured as the distance between the secondary dendrite arm spacing (SDAS), which is the function of solidification rate. Therefore SDAS can be used as the measure of solidification rates of the Al-Si alloy castings. With the highest cooling rates the SDAS will be finer and easily visible and the melt which is cooled with lowest cooling rate, the SDAS will be larger. And it is also known that the mechanical properties of the aluminum alloys are strongly dependent on the structure of the SDAS, e.g. the tensile properties will increases with decrease in SDAS.

Initially gravity castings of Al-12wt%Si have been made at four different cooling rates similar to the experiments conducted for Tin. The graph of SDAS versus cooling rate has been plotted for these gravity castings. The curve drawn has been used to measure the cooling rates of the centrifugal castings of Al-12wt%Si.

The centrifugal castings of Al-12wt%Si and Al-17wt%Si are made at different rotational speeds of mold. The required volume of Al-12wt%Si and Al-17wt%Si alloys needed to produce castings of outer diameter Ø 80, 120mm long, and 8 mm wall thickness are melted in an electric furnace by setting the temperature of 650^{o}C for Al-12wt%Si and 750^{o}C for Al-17wt%Si. Melt is maintained at set temperature for about 5 minutes and is poured to the rotating mold which was set for a speed of 400 rpm. Similar procedure is adopted to produce castings at 600 rpm and 800 rpm of the mold. Test samples are prepared from the castings to study the microstructure, specific wear rate, hardness and tensile strength. Secondary Dendrite Arm Spacing (SDAS) measurements were carried out for the Al-12wt%Si castings using Image Analyzer and tensile strength has been tested using electronic extensometer. The hardness and wear tests have been conducted using Brinell hardness tester and Pin on Disc wear testing machine. The results obtained have been compared with the other results obtained at different rotational speeds of the mold. The percentage segregation or volume fraction of Si particles for Al-17wt%Si alloy castings have been determined and compared with the results obtained for samples formed at different rotational speeds of the mold.

3.11 CHARACTERIZATION

The centrifugal castings produced by varying the process parameters have been cut horizontally through the centre to prepare the test specimen as shown in Figure 3.7. Three samples have been prepared of which one is used for metallographic observations, second sample used for the hardness test and third sample is used for testing the tensile strength. Meta-lite image analyzer software is used to capture and analyze the microstructure. The hardness is measured along the radial direction of the specimen using Brinell hardness tester with the load of 15.623kg. At least five readings are taken and the final BHN value for each specimen is arrived considering the statistical variation. In this study Wear tests were performed on a Pin-on-Disc type wear testing machine (model TR-20LE, Ducom make). Tensile testing has been done using KUDALE Electronic Tensometer for the specimen prepared as per the ASTM E8M-09 standard. The subsequent explanation gives an insight into the detailed procedure of characterization of centrifugal casting.



(a) (b)

Figure 3.7 Test samples a) Specimen considered from the centrifugal casting
b) Centrifugal Casting (Ø80 outer diameter, 120 mm long and 8 mm wall thickness)

3.11.1 Image Analyzer

Samples for micro structural observations were prepared by following the standard metallographic procedure for optical microscopy as discussed earlier. The optical microscope used for the microstructure characterization is shown in Figure 3.8. An inverted optical microscope of Dewinter make interfaced with Metalite image analyzer software is used to capture and analyze the microstructures of centrifugally cast test specimens produced by varying the process variables like rotational speeds, mold wall thickness, mold wall temperature for Tin test samples and microstructures for Al-12wt%Si and Al-17wt%Si test samples produced at different rotational speeds of the mold. The microstructure and grain size have been observed in case of tin samples produced by both gravity casting and centrifugal casting methods while secondary Dendritic Arm Spacing as per ASTM-E562 in case of Al-12wt%Si alloy and volume fraction of Si particles in Al-17wt%Si alloy. The grain size measurement and SDAS calculations of the test sample were made at magnifications 100X. Grain sizes were determined by intercept counting method from ASTM standard as shown in the Figure 3.9.

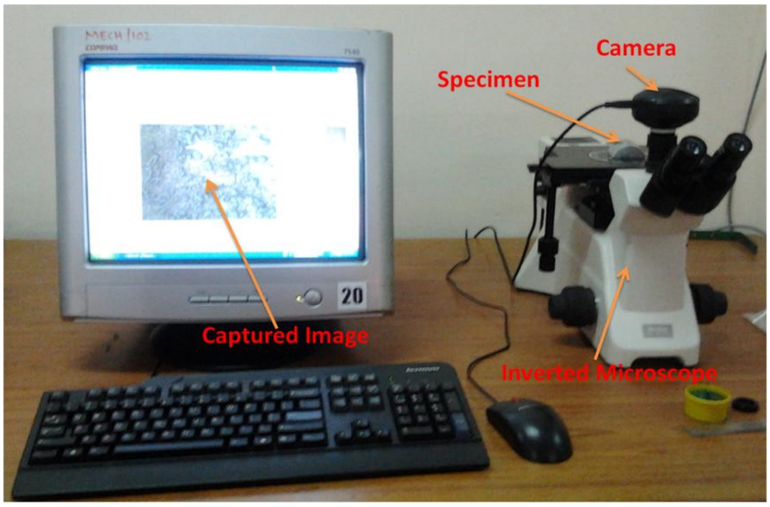
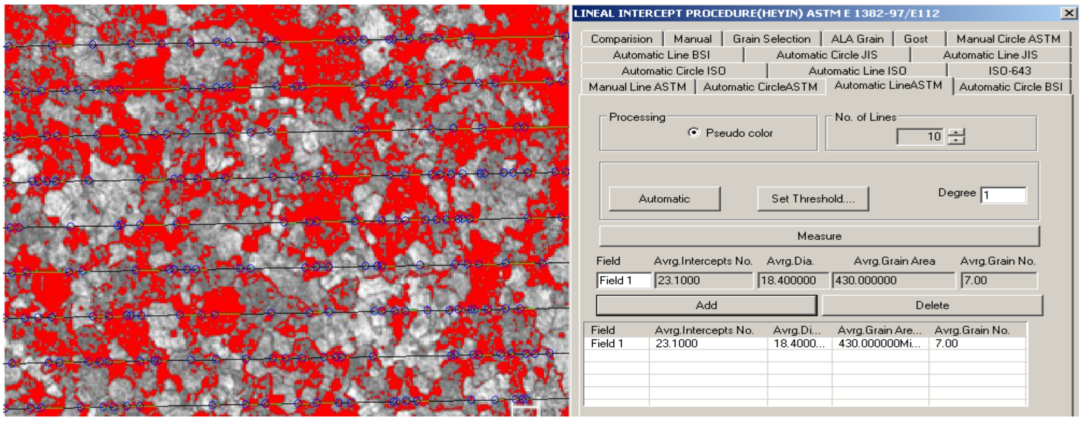


Figure 3.8 An Inverted Microscope Interfaced with Metalite Software


LINEAL INTERCEPT PROCEDURE(HEYIN) ASTM E 1382-97/E112

Processing ● Pseudo color

No. of Lines 10

Degree 1

Field	Avrg.Intercepts No.	Avrg.Dia.	Avrg.Grain Area	Avrg.Grain No.
Field 1	23.1000	18.400000	430.000000	7.00

Field	Avrg.Intercepts No.	Avrg.Di...	Avrg.Grain Are...	Avrg.Grain No.
Field 1	23.1000	18.4000...	430.000000Mi...	7.00

Figure 3.9 Linear Intercept Procedures (HEYIN) of Grain Size Measurement for Tin (ASTM E 1382-97/E112)

The Secondary Dendritic Arm Spacing is measured at different locations in the microstructure and average value has been measured as shown in the Figure 3.10.

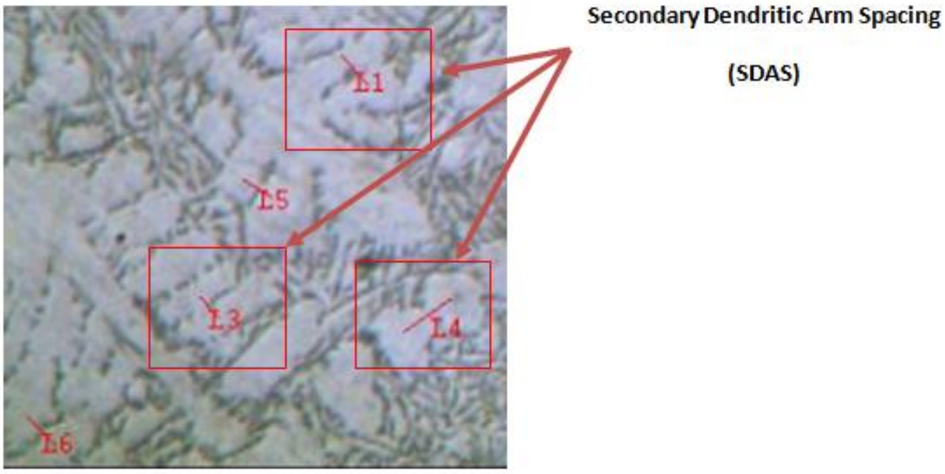


Figure 3.10 Measurement of Secondary Dendritic Arm Spacing (SDAS) for Al-Si alloys

3.11.2 Brinell Hardness Tester

As discussed earlier it has been known that the castings having fine grains are harder than the casting with coarse grains. In order to correlate the solidification rate with the microstructure, hardness measurement also carried out on all the test samples of centrifugal castings produced by varying various process parameters. Brinell hardness tester has been employed to examine the hardness characteristics of the test samples produced by employing various processing conditions in order to analyze the solidification characteristics of the test samples.

Hardness is defined as the ability of a material to resist permanent indentation when in contact with an indenter under load. Since the indenter is pressed into the material during testing, hardness is also viewed as the ability of a material to resist compressive loads (Revankar et al. 2000). Hardness testing is perhaps the simplest and the least expensive method of mechanically characterizing a material since it does not require an elaborate specimen preparation, it involves rather inexpensive testing equipment and is relatively quick. Many times hardness testing is the only nondestructive test alternative available to qualify and release finished components for end application. In the Brinell hardness test, a hard spherical indenter is pressed under a fixed normal load onto the smooth surface of a material. When the equilibrium is reached, the load and the indenter are withdrawn, and the diameter of the indentation formed on the surface is measured using a microscope with a built-in millimeter scale. The Brinell hardness is expressed as the ratio of the indenter load to the area of the concave (i.e., contact) surface of the spherical indentation that is assumed to support the load and is given as Brinell Hardness Number (BHN) as shown in Eq 3.1

$$BHN = \frac{2F}{\pi D\left[D - \sqrt{\left(D^2 - d^2\right)}\right]} \qquad 3.1$$

Where F is the Constant load in kilograms, D is the diameter of the indenter millimeters and d is the diameter of the indentation in millimeters which is the average value of d_1 and d_2 respectively. The schematic representation of the hardness test is shown in Figure 3.11.

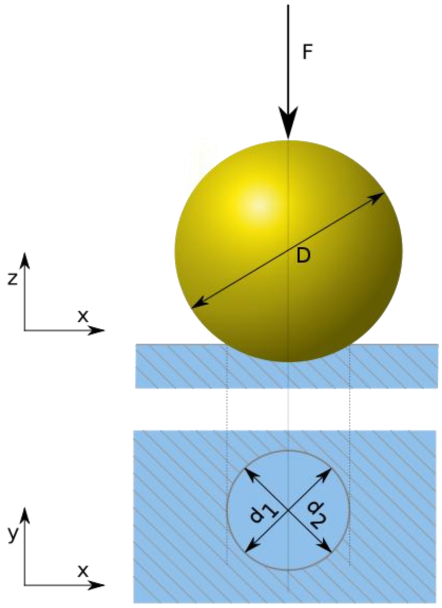


Figure 3.11 Schematic representation of Indentation process for Brinell Hardness Test

In the present work Brinell Hardness Tester (model BV-120) is used which confirms to IS-Specification 1754. The specimen is cleaned to remove dirt and oil on the surface. In this test a ball indenter of diameter 5mm and a normal load of 15.625 kg are selected in accordance with ASTM E-10. Once the load actuation button is pushed the indenter swings due to its own weight and penetrates into the specimen. The load adjusted by means of push button becomes effective and produces the impression. The produced impression is lighted and displayed on the focusing screen. The impression is magnified depending on the objective used.

The hardness is measured along the radial direction leaving 1mm from both sides of the casting at inside and outside of the casting. Therefore measurements have been done at radial thickness of 1mm, 3mm, 5mm and 7mm. At each radius minimum of 5 readings have been taken and the final BHN value for each specimen is arrived at considering the statistical variation. Hardness is calculated for all the castings of Tin, Al-12wt%Si and Al-17wt%Si alloys.

3.11.3 Pin on Disc Wear Tester

Wear tests have been performed for the samples using Pin on Disc wear tester (Model TR -20LE, Ducom Make). The tests were conducted as per ASTM standards (A57MG-99, 1995). Scientifically designed and commercially fabricated Pin on disc wear testing facility shown in the Figure 3.12. It is employed to assess the magnitudes of specific wear rate of the test samples used in this investigation. The specific wear rate were determined based on the normal wear loss of the test samples subjected to wear with varying load conditions and rotating at constant sliding speed of 300 rpm with track diameter 90 mm. The disc is made of En-32 steel (0.45%, 0.18%Si, 0.52% S, 0.019% P, 0.13% N, 0.005% G, 0.06%Mo balance Fe) having dimensions of 160mm diameter and 8 mm thickness with a hardness value HRC 65. The processing parameters for carrying out wear test on the test sample were based on the information available in published literature. The data acquired in the Pin on Disc wear testing processed is transmitted to the PC using the software Winducom 200b. The wear characteristic of the test sample Tin produced by varying the process variables rotational speed, mold wall thickness and mold wall temperature; Al-12wt%Si and Al-17wt%Si produced by varying the rotational speed of the mold are carried on Pin on Disc wear testing machine. The normal load between 5N to 20 N in steps of 5 N are used for tin test samples and between 10 N to 40 N in steps of 10 N are used for

Al-12wt%Si and Al-17wt%Si samples during the wear test. The tests are carried out at a constant rotational speed of the disc at 300 rpm. Hence the specific wear characteristic of the test samples as influenced by the process parameters of centrifugal casting are examined here.

$$\text{Specific wear rate (SWR)} = \frac{\text{(Volume of layer removed)}}{\text{(Normal load x sliding distance)}} \quad \mathbf{mm^3/N\text{-}m}$$

The measurement in reduction of length of the specimen due to wear is measured continuously by electronic sensors. The LVDT used is capable of measuring a maximum displacement of ±2 mm and the measuring range of wear is ± 2000 micron with an accuracy of ±1 micron. The wear rate was measured as reduction in specimen (pin) length in microns. The tests were conducted under dry conditions and at room temperature according to ASTMG99-95a standards. The specimen 5 mm×5 mm cross section and 8 mm thick were prepared and was attached to a cylindrical pin for testing. The wear test has been performed for inside and outside surface of the casts. This is to determine the specific wear rates at the inner surface and outer surface of the cylindrical centrifugal casting. The mating surfaces of the pin and the disc were polished using 600 mesh emery paper before the start of the wear test. The wear and wear rate were calculated from the collected data.

Figure 3.12 Pin-on-Disc Wear Testing Machine (Model TR-20LE, Ducom make)

3.11.4 KUDALE Electronic Extensometer

The tensile test specimens were prepared from the cast samples of Al-12wt%Si and Al-17wt%Si produced at three rotational speeds of the mold such as 400 rpm, 600 rpm and 800 rpm. Three specimens were obtained along the longitudinal directions from every casting. The specimens were machined to the dimensions as per ASTM E8M-91 standard shown in the Figure 3.13 and the tensile test was carried out by using a computerized tensometer model PC-2000 shown in the Figure 3.14, which is fully automatic consisting of a servomotor. Load cells have been provided for high precision load measurements. The strain rate of the tensile test was 0.2 mm/s. All the tests were recorded and results were extracted through the built in software which automatically generates peak load, ultimate tensile strength.

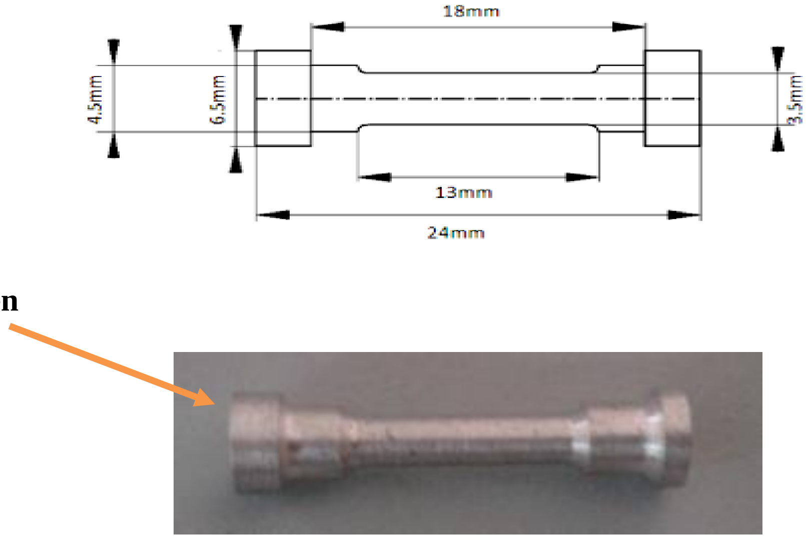


Figure 3.13 Specimen used for Testing the Tensile Strength using Electronic Tensometer

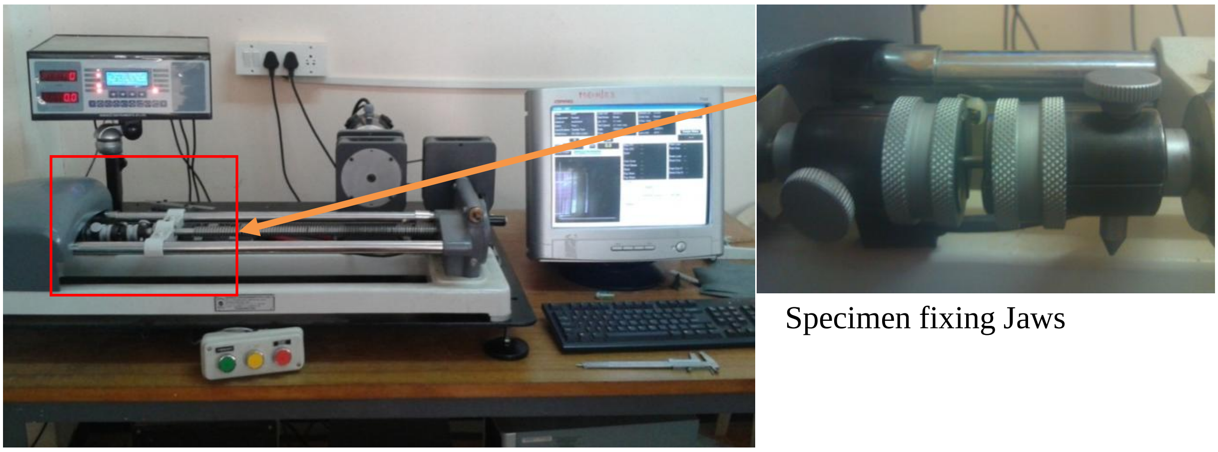


Figure 3.14 Electronic Tensometer used to Measure the Tensile Strength of the Test Samples

3.11.5 Volume Fraction of Si

During the centrifugal casting, segregation of primary Si particles takes place in the melt due to the movement of particles resulting from the difference in densities of the particles and the melt driven by the centrifugal force. In the present work, the effect of rotational speed of the mold as one of the process parameters, on volume fraction of Si particles in Al-17wt%Si (hypereutectic) alloy produced by using centrifugal casting has been studied.

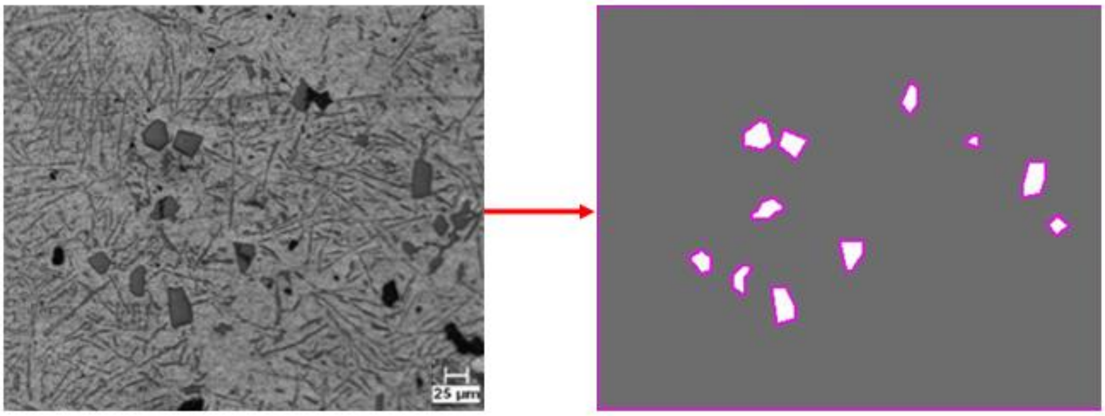


Figure 3.15 Measurement of Volume Fraction of Si Particles Based on Area Measurement

Initially the microstructure has been imported in Solid Edge mechanical software work sheet. The primary silicon particles are identified and their boundaries are marked in the microstructure as shown in the Figure 3.15. The total area occupied by these silicon boundaries and also the total area of the microstructure are measured. Hence the percentage area occupied by the silicon particles is evaluated using the following relation and this is the measure of the volume fraction of Si particle in the alloy.

$$Percentage\ area = \frac{(Area\ occupied\ by\ the\ Primary\ Si\ particles)}{Total\ area}\ X100\ \%$$

3.11.6 SEM Analysis

The microstructures of the worn surfaces of the centrifugal casting specimens were captured using Scanning Electron Microscope (SEM). Figure 3.16 shows the SEM instrument which is having the resolution of 3nm at 30KV. The instrument has secondary electron and back-scattered electron detectors. The samples were loaded in the proper sequence inside the chamber and SEM pictures at suitable magnifications were taken. Electron Dispersive X-ray Analysis was also carried out in the same instrument along with the microstructures to get an idea regarding the amount of elements present in the samples.

Figure 3.16 Scanning Electron Microscope (Make Jeol)

3.12 CONCLUSION

As per the discussions from the literature there are many process parameters that affect the characteristics of centrifugal castings. By this work an attempt has been made to study the effects of three important process parameters which will influence the rate of solidification in centrifugal castings. The experimental procedure described has been used to study the effect of process parameters such as rotational speed of the mold, initial temperature of the mold and mold wall thickness on the microstructure and mechanical properties of tin, Al-12wt%Si and Al-17wt%Si alloys and also volume fraction of Si particles in case of Al-17wt%Si. The results obtained from the above experiment have been discussed in the next chapter.

Chapter 4

RESULTS AND DISCUSSION

4.1 INTRODUCTION

In centrifugal casting, the molten metal is poured into a rapidly rotating mold and centrifugal force generated from the rotation of a cylindrical mold forces the metal against the inner wall of the metal mold, resulting in rapid solidification of the molten metal. The rate of solidification of centrifugal casting affects its microstructure, quality and also its mechanical properties. The quality of the final centrifugal casting depends on many parameters such as: pouring temperature, initial temperature of the mold, rotational speed of the mold and wall thickness of the mold, size, shape and weight percentage of alloy particles and so on (Zagorski et al. 2007). In order to analyze the fluid behavior and cooling rates at different magnitudes of process variables, initially cold modeling experiments with fluids those undergo no phase transformation have been considered. By producing gravity casting samples of Tin at different cooling rates, the relationship between grain size and cooling rates has been established. This relationship is used to determine the cooling rates of the Tin test samples produced by centrifugal casting technique.

Centrifugal casting is one of the cast technologies usually associated with obtaining of functionally graded materials mainly composite materials or metallic materials which have high differences of density and low solubility in different phases or composition differences in the same alloy (Suresh et al. 1998). They are characterized by the variation in distribution of ceramic particles along the radial direction as a consequence of centrifugal effect. The higher density constituent migrates to outer zones and vice versa. The migration speed is controlled by the size of the particles. The solidification of aluminum-silicon alloys, the morphology and distribution of silicon particles formed as the primary or eutectic constituents determine the mechanical properties of the castings. Generally, during solidification the silicon content of the melt and cooling rate are the process parameters that control the volume fraction and size of the silicon particles. Thus, mechanical properties of Al–Si cast alloys depend not only on chemical composition but, also on the micro structural features such as morphology of dendritic α-Al, eutectic Si particles and other intermetallics that are present in the microstructure. The microstructure coarseness can be measured, as the distance between the secondary dendrite arm spacing, (SDAS) which is a function of the cooling rate, but often preferred to the solidification time as an indicator of the solidification conditions in the castings (Kumar et al. 1997)

The centrifugally cast alloys show increasing tensile or compressive strength, with increasing volume fraction and decreasing size of the silicon particles. As for the shape of silicon particles is concerned, spherical shapes are better compared to angular shapes from a viewpoint of stress concentration (Matsuura et al. 2004).

The flow of liquid metal in centrifugal casting is much more complex phenomenon than any other liquid flow since there is an extra factor of drop in temperature during the flow that leads to variation in density of the melt. Due to change in density during cooling, viscosity will increase and the melt will stick to the mold surface due to increased friction between melt layers.

Since at different rotational speeds of the cylinder the liquid exhibits various flow patterns which disturb the rate of cooling or rate of solidification of the casting. So the fluid flow pattern that arises in centrifugal casting process is critical in determining the quality and characteristics of the final product. From the literature (Mukunda et al. 2007) it is evident that most of the work has been carried out on the behavior of fluids in rotating cylinders, however information regarding optimum speed of rotation for the formation of hollow liquid cylinder and cooling rates at various speeds are not much focused.

The present investigation is to analyze the relationship between process parameters and specific metallurgical parameters such as grain size, solidification rate, hardness gradient along the thickness of the cylindrical centrifugal casting and specific wear rates of commercial grade Tin, eutectic Al-12wt%Si and hypereutectic Al-17wt%Si alloys, produced through centrifugal casting technique. Cold modeling technique has been employed to optimize the magnitudes of the processing parameters to obtain a uniform wall thickness samples in Centrifugal Casting techniques.

The experiments have been conducted by altering the mold geometry in case of gravity die casting to determine relationship between cooling rate and grain size. These results have been used to estimate the cooling rate of centrifugal castings of tin produced by varying the rotational speed of the mold, wall temperature of the mold and thickness of the mold wall are summarized in this section. The cooling rates of tin castings have been determined based on grain size and for Al-12wt%Si has been determined based on the SDAS. The specific wear rates for Tin, Al-12wt%Si and Al-17wt%Si is determined by conducting the wear test using pin on disc wear testing apparatus. SEM analysis also been performed for the worn out surfaces of Tin, Al-12wt%Si and Al-17wt%Si. In addition to this the effect of rotational speed of the mold on the volume fraction of the primary Si particles in Al-17wt%Si are also determined.

4.2 COLD MODELING EXPERIMENT FOR WATER, GLYCERIN, 90 EP OIL AND 140 EP OIL

The effect of rotational speeds of the mold for the formation of complete hollow liquid cylinder has been investigated by conducting the cold modeling experiments. This has been performed by rotating a horizontal transparent cylinder partially filled with fluids of different viscosities whose properties are given in the previous chapter. Visual observations were used to analyze the effect of rotational speed on the formation of flow patterns of fluids in a rotating cylindrical mold. The specific purpose of this exercise is to ascertain the magnitude of the processing parameters which ensure a uniform thickness, a prerequisite to the formation of a good hollow casting.

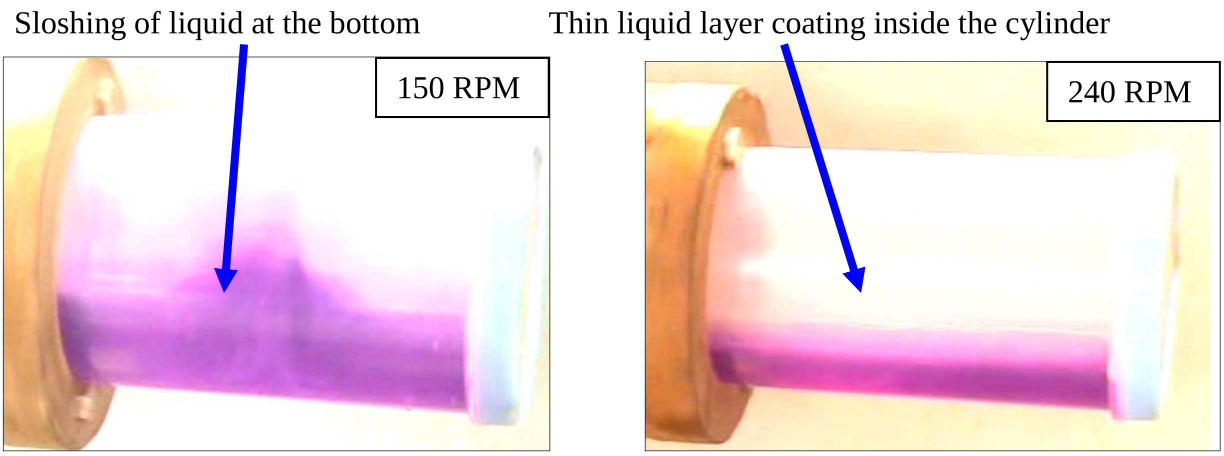
4.2.1 Effect of Rotational Speed of the Mold for the Formation of Complete Hollow Liquid Cylinder

Visual observations of different fluid patterns inside a partially filled rotating cylinder indicate the existence of a certain critical value of the angular velocity for the formation of liquid cylinder. It has also been referenced in the published literature that the characteristics of the flow pattern are critical in establishing the quality as well as metallurgical and mechanical characteristics of the final finished components.

Earlier investigations (Keerthiprasad et al. 2010) have shown that at lower rotational speeds the liquid exhibits different types of flow patterns such as Sloshing of liquid, Couette flow, Ekmann flow and Taylor flow, each one of them playing a significant role in contributing flow instabilities during the process. But clear definitions of these flow patterns are not given. At very low rotational speed of the cylinder just sloshing of liquid takes place and at a slightly higher speed a thin film is found to adhere to the inner wall of the cylinder. This pattern is referred to as Couette flow. On further increase in the rotational speed, the formation of fluid rings in the medium takes place which is referred to as Taylor flow. Further increase in the rotational speed, would ensure the formation of a uniform thickness of the hollow cylinder and the speed at which this happens is referred to as critical speed of rotation for the formation of uniform hollow cylinder pattern (Moffatt et al. 1997). The various flow patterns formed when the water rotated in a cylinder are shown in the Figure 4.1 a, b, c, d and e. And for the remaining liquids also similar flow patterns were observed.

The formation of different types of flow patterns as discussed previously, at low rotational speeds are also found to depend upon the thickness of the liquid layer as well as its viscosity. It has also been observed that Ekmann flow and Taylor flow patterns disappear at higher rotational speeds of rotation. These experiments have been conducted by varying the quantity of the liquids like 4 mm, 6 mm and 8 mm thick liquid cylinder. The speed at which the liquid forms a uniform layer is found to vary linearly with the thickness of the fluid as per the information available in the published literature (Shailesh et al. 2010**).** Cold modeling experiments have also revealed the existence of sloshing of the liquid as well as Couette flow at lower rotational speeds of mold which are less than 200 rpm (1.6G) for all the liquids. The fluid tries to form a cylinder but not of uniform thickness at rotational speeds of 400 rpm (6.62G), whereas formation of liquid rings has been observed at rotational speeds of the liquid above 400 rpm (6.62G) which are referred to as Taylors flow. The uniformly thickness hollow cylinder are found to form at rotational speed greater than 600 rpm (14.9G) and the pattern remains unaltered with further increment in rotational speeds (Thoroddsen et al. 1999).

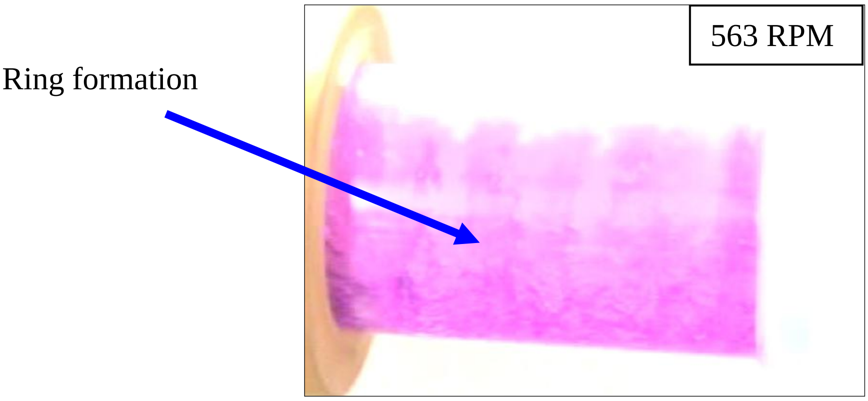
It has also been observed that when water is poured directly to the mold which is rotating at 400 rpm (6.62G), it forms different types of flow patterns, which are mentioned earlier and the trend remains similar when it is poured into a mold which is rotating at 600 rpm (14.9G) though it forms a uniform thick cylinder. However when water is poured into a mold which is rotating at 800 rpm (26.5G) it directly forms a continuous cylinder layer without exhibiting any flow transitions, mentioned earlier. Therefore this speed is called the critical speed of rotation, because at this speed a uniform thickness hollow cylinder of water is formed. So it is clear that at higher rotating speeds, the different flow patterns discussed earlier gets disappeared and a uniform thick liquid cylinder is formed. The results of this model have been employed to examine the melt behavior characteristics of the test materials used in this investigation. Based on this optimization of rotational speeds to obtain uniformly thick hollow cylinder with different fluids experimented in this investigation.


Sloshing of liquid at the bottom

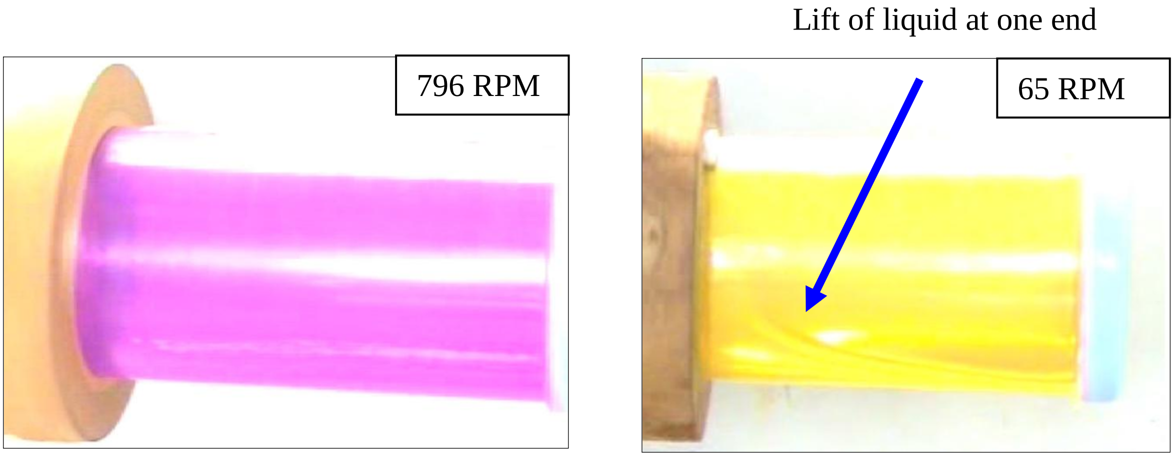
Thin liquid layer coating inside the cylinder

a. Sloshing of Water

b. Couette Flow of Water


Ring formation

c. Taylor Flow of Water


Lift of liquid at one end

d. Liquid cylinder of uniform thickness

e. Ekmann Flow of 140 EP Oil

Figure 4.1 Flow Patterns of Water Formed at Various Rotational Speeds of the Cylinder

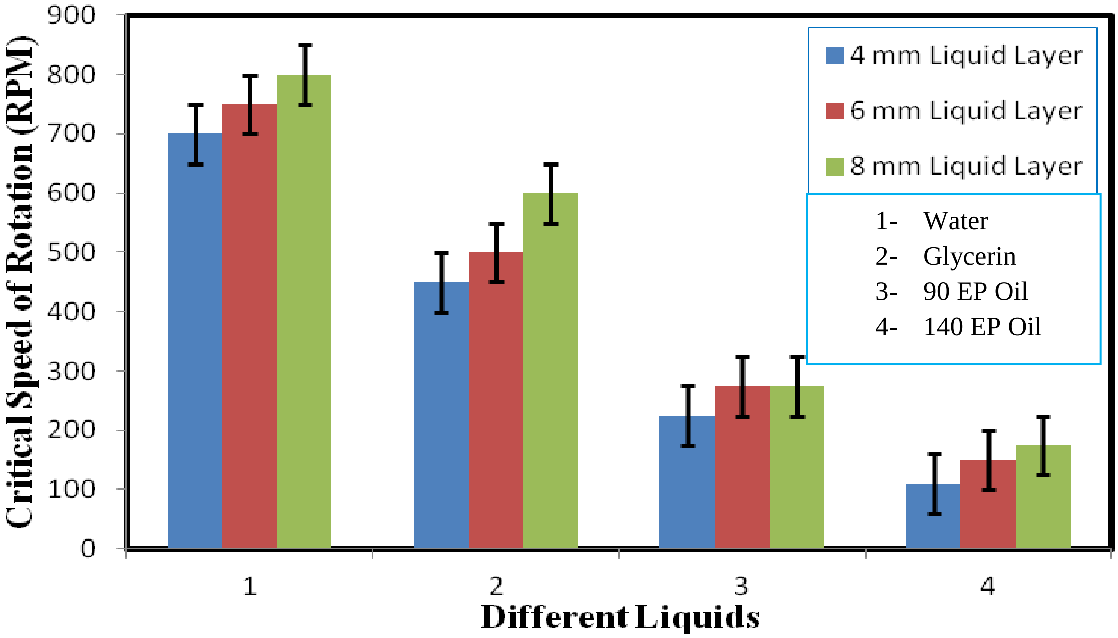


Figure 4.2 Rotational Speeds Required to Form Liquid Cylinders for different viscosity Liquids

The results were also noted when water was replaced by glycerin, 90 EP oil and 140 EP oil to understand the influence of viscosity in this process. But high viscous fluids like 90 EP oil and 140 EP oil exhibits the Ekmann flow pattern, lifting of the liquid at the ends of the rotating cylinder.

The relationship between the critical speeds of rotation for different liquid medium employed in this investigation such as water, glycerin, 90EP oil and 140 EP oils with thickness of the of the liquid layers varying from 4 mm to 8 mm in steps of 2 mm is shown in Figure 4.2.

In order to correlate the fluid behavior with the melt behavior at different rotational speeds Tin metal is used, since its melting point is very low 231^{o}C, less difficult to handle. The melt is centrifugally cast in a cold mild steel mold at different rotational speeds of 400 rpm (6.62G), 600 rpm (14.9G) and 800 rpm (26.5G). The temperature of liquid metal is maintained at 300^{0}C.

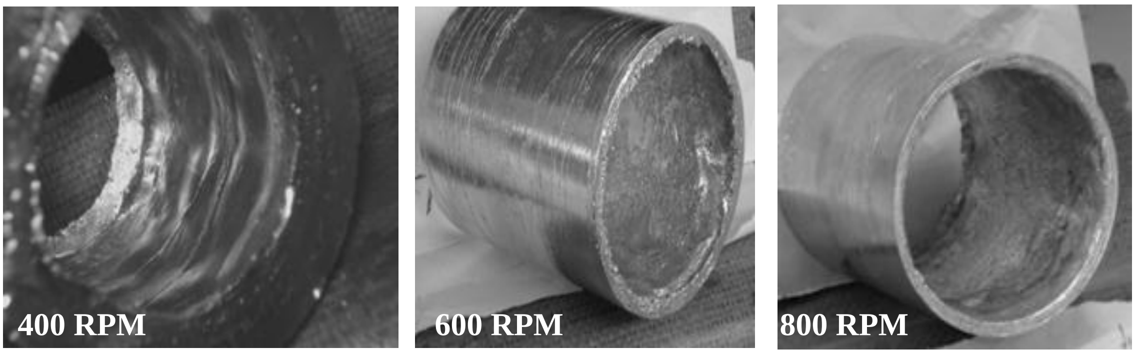


Figure 4.3 Centrifugal Castings of Tin produced at Different Rotational Speeds of the Mold

In all the experiments, the rotating mold is adjusted to a set rotational speed before the process and the mold is rotated at least for a minute after that liquid metal is poured into it, to ensure complete solidification. Figure 4.3 shows the Tin castings produced by Centrifugal casting process at three different rotational speeds of the mold. The casting produced at 400 rpm (6.62G) shows waviness at the inner surface which is similar to the Taylor flow patterns exhibited by regular liquids rotated at lower rpm. This phenomenon is also obtained during the cold modeling experiment. At higher rpm, the centrifugal force is dominant and at about 600 rpm (14.9G) the casting produced shows uniformly thick cylindrical castings without any waviness on the inner surface, but as soon as liquid metal is poured it flows along the axial direction towards the other end of the mold because of its high fluidity and low rotational speed which is not sufficient to lift the metal to form a hollow cylinder. And as viscosity of the melt increases due to solidification of the melt tries to lift from the inner wall of the mold. But at higher speed of 800 rpm (26.5G) the melt spreads along the axis it also moves along the circumferential direction of the mold, hence fast cooling takes place. Hence at 800 rpm (26.5G), a uniform cylinder is formed with good distribution of molten metal along the length of the mold. These castings are used for the further investigation like solidification rate, microstructure, grain size, hardness specific wear rate etc. Here based on the grain size the solidification rate has been determined as discussed by Kumar et al. (1997). So mold rotational speed 800 rpm (26.5G) is the optimum speed for the preparation of centrifugal casting for the mold size discussed before. That’s why for the future discussions regarding the effect of process parameters on the solidification of centrifugal castings three speeds 400 rpm (6.62G), 600 rpm (14.9G) and 800 rpm(26.5G) are selected.

It has been observed from the above discussion that the low viscosity liquids like water requires higher value of critical speed of rotation and the liquids with higher viscosity require lesser value of critical speed of rotation to form a uniform thick cylinder. This is due to the reason that a large centrifugal force dominates over gravity leading to the formation of a liquid cylinder. Since the water is having low viscosity, the liquid layers will slip during rotation and falls down due to the gravity effect due to this water becomes turbulent. As the viscosity of fluid increases, the liquid cylinder forms at lower rotational speed of the cylinder (Janco et al. 1992)

As the rotational speed of the mold increases, the centrifugal force also increases and hence the liquid will stick to the inner surface of the rotating cylinder. The fluids having high viscosity there is no separation of liquid layers takes place, hence liquid does not slip. Therefore at lower rotational speeds also the liquid layers stick to the inner surface of the rotating cylinder and with slight increase in rotational speed the centrifugal force is sufficient to form the uniformly thick liquid cylinder. And at higher speeds like 800 rpm (26.5G) all the liquids suddenly get lifted and take the shape of the inner surface of the rotating cylinder.

4.2.2 Cooling Rate of the Liquid in a Partially Filled Rotating Cylinder

As discussed earlier the liquids of various viscosities exhibits different types of flow patterns as influenced by the rotational speeds of the cylinder in a partially filled cylinder, but this in turn influences the cooling rates of the hot liquids during rotation and also solidification rates of the melt during castings process. Therefore the cold modeling technique was extended to establish the cooling rates encountered during the formation of uniform thick hollow cylinder with different fluid medium used in this investigation.

The major objective of this study is to visualize and study the influence of rotational speeds of the cylinder on the characteristics of the liquid flow and cooling rates of the liquids at different rotational speeds of the cylinder using liquids of different viscosities.

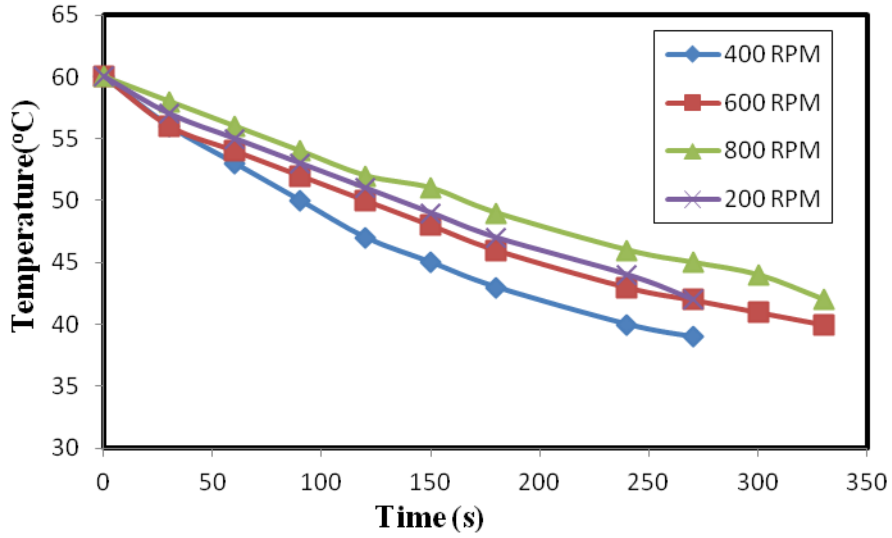


Figure 4.4 Cooling Rate of Water at Different Rotational Speeds of the Cylinder

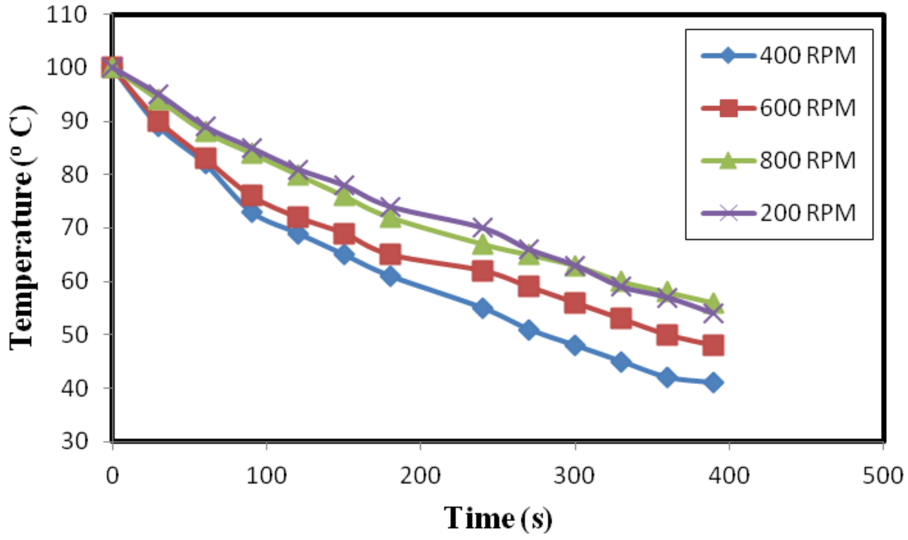


Figure 4.5 Cooling Rate of Glycerin at Different Rotational Speeds of the Cylinder

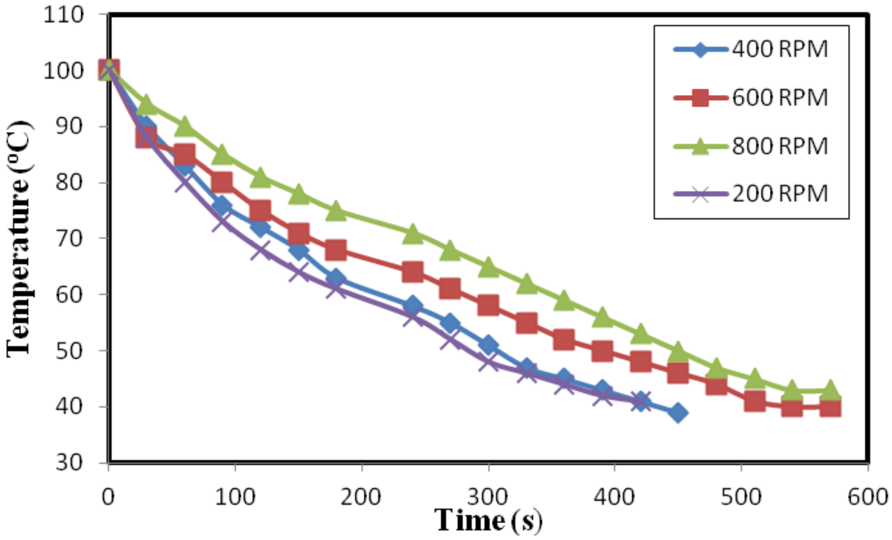


Figure 4.6 Cooling Rate of 90 EP Oil at Different Rotational Speeds of the Cylinder

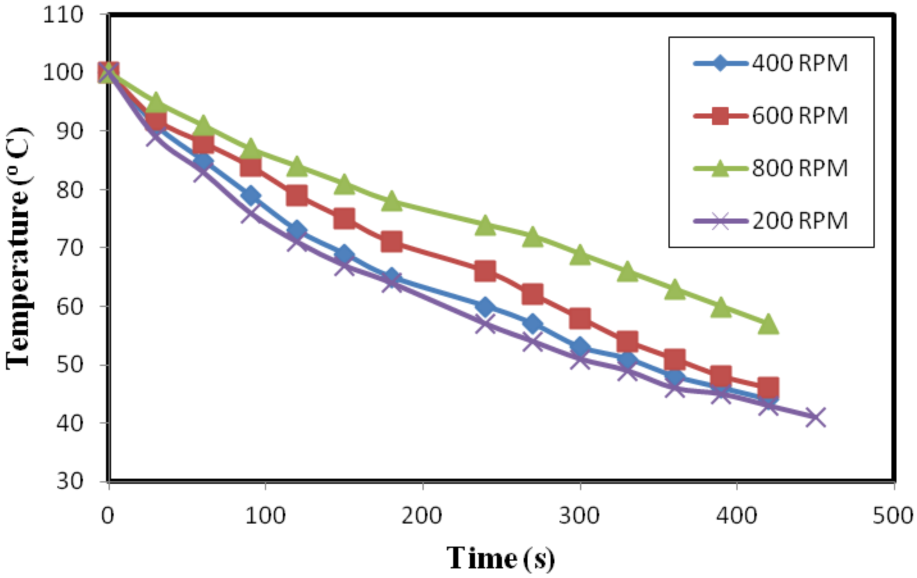


Figure 4.7 Cooling Rate of 140 EP Oil at Different Rotational Speeds of the Cylinder

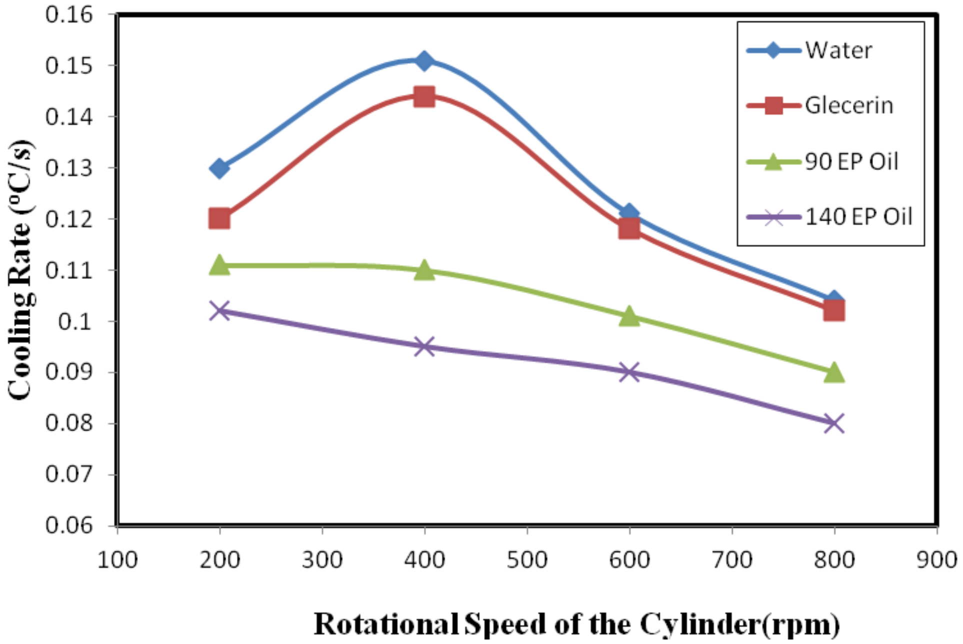


Figure 4.8 Cooling Rates of Liquids at Different Rotational Speeds of the Cylinder

The rotational speeds varied as 200 rpm (1.6G), 400 rpm (6.62G), 600 rpm (14.9G) and 800 rpm (26.5G) and the relationship between temperature and time to determine the cooling rates have been drawn and are shown in Figure 4.4 - Figure 4.7. The slopes of the curves give the cooling rates for the corresponding liquids of different viscosities rotated at various rotational speed of the cylinder.

The Figure 4.8 shows the relationship between the cooling rate and rotational speeds of the cylinder as experimented with different liquid mediums employed in this investigation. It is evident from the graphs that the cooling rate is maximum for water and glycerin when the rotational speed is 400 rpm (6.62G) in comparison with 800 rpm (26.5G) which is optimum speed of rotation for the above liquids. Therefore it is clear that rate of cooling is faster at 400 rpm (6.62G) for low viscous liquids like water and glycerin. Since slopes of the graph representing the ratio of temperature of the liquid to time which is greater for 400 rpm (6.62G) compared to the speeds like 600 rpm (14.9G) and 800 rpm (26.5G). This is due to the reason that at 400 rpm (6.62G) the fluid experiences turbulence hence due to fluid mixing and forced convection heat transfer effect, the rate of cooling is faster. This concept is also explained by Barrow et al. (1996). This also explain the reason for the occurrence of turbulence at rotational speeds of 400 rpm (6.62G) which is attributed to possibility of mixing of fluids as well as the effect of forced convective heat transfer phenomenon leading to faster cooling rates at lower rotational speeds of the liquids. When the cylinder is stationary as well as rotating at 200 rpm (1.6 G), the rate of solidification is found to be very low. And also as rotational speed of the cylinder increases the turbulence reduces and relative movement between the cylinder and the liquid reduces and around 800 rpm (26.5G) the speed of the liquid inside the cylinder is almost same as the speed of the cylinder and hence rate of cooling decreases. Therefore liquid speed and the rotational speeds of the mold are found to be more or less the same at a rotational speed of 800 rpm (26.5G), leading to reduction in cooling rates. The liquids having higher viscosity forms full cylinder at below 400 rpm, hence there is no turbulence at 400 rpm (6.62G) and there will be no large variation in cooling rate of the liquids with higher viscosity. And there is no variation in cooling rates with further increase in rotational speed of the cylinder. Therefore it is observed that the curves corresponding to the cooling rates are converging at 800 rpm (26.5G) of the mold.

Therefore from the previous discussion it is found that the centrifugal force increases with the increase in the rotational speed, leading to the occurrence of strong levels of convection in the liquid pool and hence rapid cooling of the liquid. The cooling rate is maximum at 400 rpm (6.62G) for water and glycerin, which is less than the critical speed for water rotated in a partially filled cylinder. Cooling rate is minimum when the mold is stationary which is due to the lack of relative movement between the mold and the hot liquid and heat dissipated by natural convection. Also at higher rotational speeds like above 800 rpm (26.5G), the relative movement is again minimum if not negligible resulting in reduced cooling rate. It is also observed that at speeds below the optimum levels the flow exhibit different flow patterns and can become turbulent leading to higher cooling rate of the medium. However, further observations revealed that with the low viscosity media such as water the liquid layers try to disintegrate during rotation leading to turbulent flow situation. This clearly reasons the requirement of higher rotational speeds in case of water to achieve the same results.

For higher viscosity liquids like 90 EP oil and 140 EP oils the critical speed of rotation is lower than 400 rpm (6.62G) and hence cooling rate is less compared to low viscosity liquids at 400 rpm (6.62G). It is observed that even though with the negligible relative movement between the liquid and rotating cylinder the increase in speed, increase in centrifugal force and there is a slight decrease in cooling rate, this is due to the higher magnitude of rotational speed that leads to forced convection heat transfer. This explains the reason for experiencing faster cooling rates in case of high viscosity liquids at higher rotational speeds of the mold.

From the above discussions it has been observed that, as the rotational speed increases the centrifugal force also increases which create a strong convection in the liquid pool, this leads to rapid cooling of the liquid. But minimum rate of cooling is observed for the stationary mold which is due to the reason that, in case of stationary cylinder there will be no turbulence of liquids, hence no mixing of liquids takes place and also due to free convection heat transfer the liquid cools down slowly. In case of rotational speed above optimum value, the relative movement between the cylinder and the liquid is minimum, hence once again the cooling rate decreases. The liquids at below optimum speed shows different flow patterns and the flow becomes turbulent, hence the cooling rate of the liquid is high. It is clear from the above discussion that the rotational speed of the mold is very critical to decide the formation of full cylindrical casting because the variation in the rotational speed causes variation in the quality of the casting. In order to make a good quality casting it is required to decide the optimum speed of rotation of the mold. Therefore the aim of the future work is to study the metallurgical properties of the castings which are produced at different rotational speeds of the mold and also produced at other process variables such as different wall thickness of the mold and at different mold wall temperatures.

4.3 GRAVITY CASTING OF TIN

In centrifugal casting process due to the mold rotation and due to the opacity of both the metallic melt and the mold materials, analysis of the complicated mold filling and the coupled heat transfer / solididification behaviour is difficult. It can be observed from the earlier literature, the size and shape of the grain structures in pure metal castings depend on the rate of solidification of centrifugal casting (Keerthi et al. 2010). Therefore rate of solidiifcation is the very important parameter in understanding of centrifugal casting. In rotating mold it is difficult to monitor the temperature of the freezing mass. Hence to study the solidification rate of the centrifugal casitng initially, gravity castings are made and the results obtained during the gravity casting are used to detremine the solidification rates of the centrifugal casting.

It is known that rapid cooling of the casting causes fine grains and slow cooling of casting causes coarse grains (Mukunda et al. 2010). So the grain size is a measure of cooling rate of the castings. By producing the gravity castings at different cooling rates and measuring the grain size, the relationship between the grain size and cooling rates can be established for the metal tin. This relation is used to measure the cooling rates of the centrifugal castings of tin produced by varying the process parameters such as rotational speed of the mold, initial temperature of the mold and wall thickness of the mold .

4.3.1 Cooling Curves for Gravity Castings of Tin

In order to correlate between the rate of solidification and grain size initially cooling curves, temperature versus time has been plotted for gravity casting. Four different solidification rates have been experimented to establish the relationship between solidification rate and grain size of the Tin gravity casting using the molds with different wall thickness. The rate of solidifications is the slope of the cooling curve. And the relationship between the rate of solidification and the grain size is obtained from a plot of the rate of solidification versus grain size.

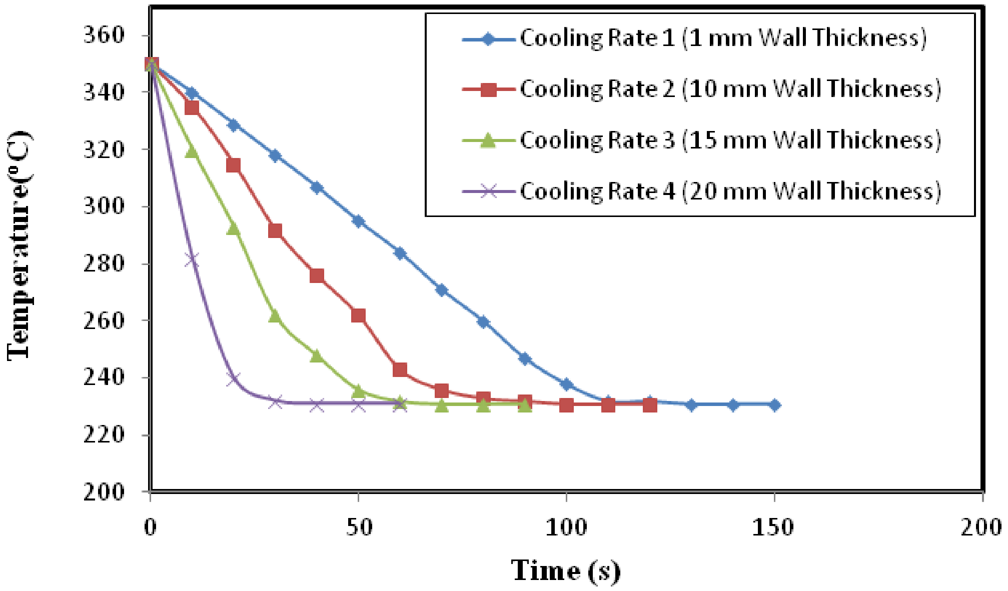


Figure 4.9 Cooling Curves for the Gravity Castings at Different Cooling Rates.

Figure 4.9 shows the decrease in temperatures of the castings at different intervals of time during various cooling rates of the casting samples. At the beginning, the temperature of the metal decreases rapidly with time and during solidification the temperature remains constant until the casting is entirely to become solid. These curves are called cooling curves of the metal and the slopes of the initial part of these curves represents the solidification rates (^{o}C/s). Later stage of cooling is the cooling of solid metal to attain the room temperature, but this decrease in temperature does not have any effect on grains structure. Therefore slopes of initial parts alone are considered to determine the cooling rates of the gravity cast samples.

Curve corresponding to Cooling rate 1 represents solidification rate of 1.44 $^{\mathbf{o}}$C/s, Cooling rate 2 represents 5.9 $^{\mathbf{o}}$C/s, Cooling rate 3 represents 7.9 ^{o}C/s and cooling rate 4 represents 14.4 ^{o}C/s. The sample corresponding to the cooling rate 1 is made in a mold of wall thickness of 1mm; the cooling rate is slower compared with others. The cooling rate 2 is made in mold with wall thickness of 10 mm. The cooling rate 2 is slightly faster than the previous, due to the increased chilling effect. The cooling rate 3 is corresponding to the casting made in a mold of wall thickness of 15 mm. The cooling rate 4 is corresponding to the casting produced in the mold wall thickness of 20 mm.

4.3.2 Microstructure, Rate of Solidification and Grain Size of Gravity Casting of Tin

Four different solidification rates 1.44^{o}C/s, 5.9^{o}C/s, 7.9^{o}C/s and 14.4^{o}C/s have been experimented by using the molds with different wall thickness to establish the relationship between temperature and time using the gravity cast process of Tin test samples. The test samples are cut along the location of the thermocouple and polished to analyze the microstructure. The grain sizes of the test samples are measured using Image Analyzer at the location of the thermocouple. Different heat flow rates across the cast metal and mold surface regions affect the evolution of solidification and the microstructures of the casting.

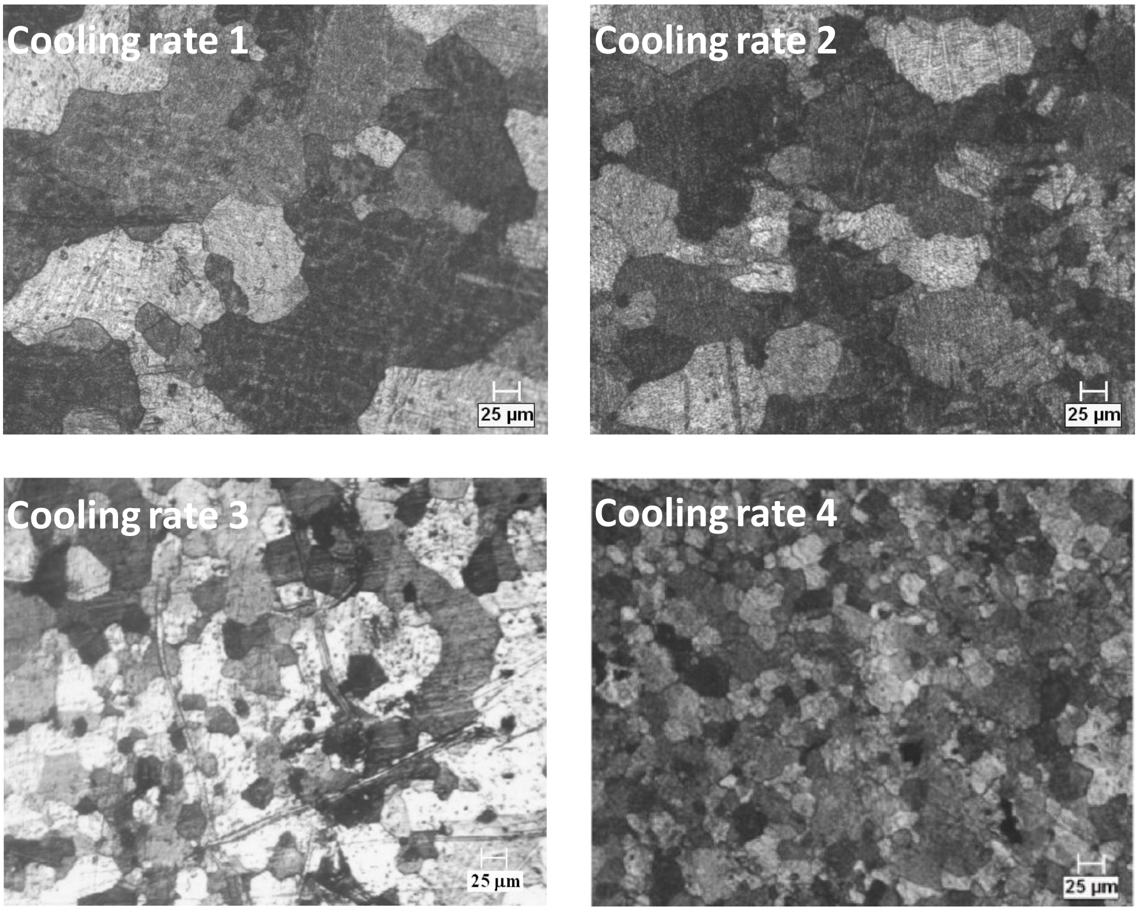


Figure 4.10 Microstructures of Gravity Castings of Tin Produced at Different Cooling Rates

The Figure 4.10 showing the microstructures of four gravity castings produced at four different solidification rates. It has been found that the average grain size is found to be 243µm when the solidification rate is 1.44^{o}C/s, it is 112 µm at 5.9^{o}C/s, 86 µm at 7.9 ^{o}C/s and 32 µm at 14.4^{o}C/s. Out of four cooling rates the cooling rate 1 is the slowest rate of cooling compared to other three, hence the formation of grain size is the biggest and cooling rate 4 is the fastest cooling rate compared to other cooling rates and cooling rate 2 and 3 lies in between the cooling rate 1 and cooling rate 4. The casting corresponding to the Cooling rate 1 produced using thin walled mold which causes slower cooling rate, hence coarse grains are formed. And Cooling rate 4 is corresponding to the casting produced using the thickest walled mold hence due to rapid solidification rate fine grains are observed. Thick walled mold extracts heat from the melt at faster rate compared to thin walled mold (Liang et al. 2009). Due to the chilling effect of the metal mold the rapid solidification takes place in thick walled mold. The temperature of the mold is maintained at room temperature during the casting process in this investigation.

It is evident from the measurements of grain size and the analysis of microstructure of the samples produced at different solidification rates that, fine grains are associated with higher or faster solidification rates and coarse grains are the resultant of slower or lower cooling rates.

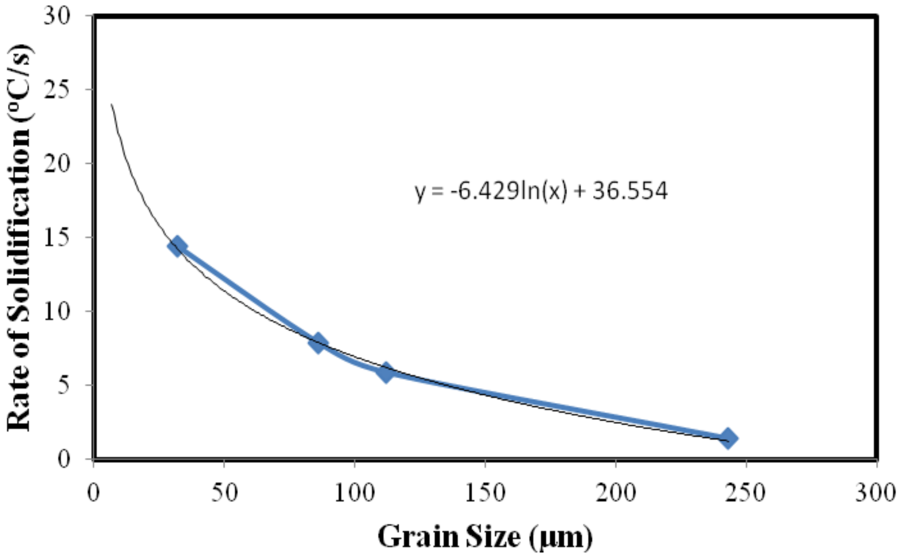


Figure 4.11 Relationship between Rate of Solidification and Grain size of Gravity Castings of Tin

Figure 4.11 shows the relationship between solidification rate and grain size for gravity casting of tin samples and fitted exponential curve. It shows that the decrease in rate of solidification causes increase in grain size. Halvaee et al. (2001) also explains that solidification rate affects the microstructure formation in centrifugal castings, a finer grains are obtained at a higher cooling rates and coarse grains are formed at slower cooling rate. The logarithmic curve trend is assumed for the graph and this graph can be used to determine the rate of solidification of centrifugal castings which are obtained by varying the various process variables like rotational speed of the mold, preheated temperature of the mold, mold wall thickness and so on, based on the grain size. It is also reported from the earlier studies that fine grains are associated with samples produced through centrifugal casting process (Keerthiprasad et al. 2010). Accordingly the regions lying to the left in Figure 4.11 can be gainfully employed to examine the relationship between the grain size and solidification rates of test sample produced through centrifugal casting technique.

The relationship between the grain size and the rate of solidification is obtained from the curve by means of equation **$Y = -6.429\ln(x) + 36.554$,** where Y= Solidification rate in ^{o}C/s and x = grain size in µm. This equation is further used to calculate the solidification rate of the tin centrifugal castings based on the grain size of the castings.

4.4 CENTRIFUGAL CASTING OF TIN

Centrifugal casting process is used for the production of axisymmetric objects such as tubes, cylindrical sleeves, rolling mill roles, bushes etc. And due to high rotational speed of the mold the solidification is quite rapid and a good metallurgical quality will be achieved. From the literatures it can be seen that there are many researchers working on the theoretical and experimental analysis of the centrifugal casting process (Watababe et al. 2002, Raju et al. 2000, Emila et al. 2006, Sufei et al. 2008, Vassiliou et al. 2008). Since there are many process parameters which have influence the final quality of the castings, it is required to do further investigation on the effect of these process parameters. In this work an attempt has been made to study the effects of process variable like rotational speeds of the mold, wall thickness of the mold and preheated temperature of the mold on the quality of the tin centrifugal castings.

4.4.1 Effect of Rotational Speed of the Mold in Centrifugal Casting of Tin

It has been observed from the experiments that when the molten metal is poured into the rotating mold the molten metal gets lifted up immediately by the virtue of friction between the liquid metal and the mold, subsequently due to the friction between the melt and already solidified metal layers and finally solidified cylindrical casting will be obtained. With increase in rotational speeds of the rotating mold, the molten metal gets wavy structure and disturbed at the interfaces between the molten metal layers, which may result in poor castings, which was also explained by Shailesh et al. (2009). Since melt solidifies layer by layer, at high rotational speeds such as 600 rpm (14.9G) and 800 rpm (26.5G) there will be an increased surface friction which results in the higher rate of solidification which is further explained in this chapter. Photographs of Tin test samples produced by centrifugal casting route at rotational speeds of 400 rpm (6.62 G), 600 rpm (14.9G) and 800 rpm (26.5G) is shown Figure 4.3. It has been observed that the melt starts solidifying by covering the entire circumference along the length of the mold to form a thin strip of metal at the initial rotations of the mold. This is attributed to the rapid cooling of the molten metal coming in contact with the cold mold (Zagorski et al. 2007, Wu et al. 2006). The subsequent layers of the molten metal will be formed at a slower solidification rate when they come in contact with the hot metal layers which are already solidified. In this case rate of solidification rate is slower due to the lower temperature difference between the solidified metal and the fresh molten metal. Metal layers continue to form one over the other until pouring is stopped and molten metal completely solidifies based on the optimum speed of the rotating mold. The cast cylinders which are produced below the optimum speed show a poor inside surface.

It has been observed that the molten metal poured into the mold starts rapidly lifted up at a rotational speed of 600 rpm (14.9G) which results in the formation of continuous metal layers leading to the formation of fine grains compared to those obtained at lower rotational speeds of 400 rpm (6.62G). On the other hand, at the critical rotational speed i.e. 800 rpm (26.5G), the moment molten metal is poured, the metal gets directly lifted up without moving along the length of the mold, which leads to rapid solidification of the metal compared to those obtained at 400 rpm (6.62G) and 600 rpm (14.9G) of the mold. But at higher speeds namely 1000 rpm the metal does not flow along the length of the mold, instead all the melt gets lifted at the poured point itself of the mold, as seen by the earlier researchers (Shailesh et al. 2009). As the speed of rotation increased further, above 1200 rpm the casting quality deteriorates because of the failure of molten metal flow along the length of the mold which is also explained by Murali et al. (2010). This clearly shows higher speeds of the mold are not of much significant value in producing castings by centrifugal casting. It is always the optimum speed results in better castings. It has been observed that the solidification rate is slower at mold rotational speed of 400 rpm (6.62G) in comparison with those at 600 rpm and 800 rpm.

From the above discussion it is seen that the flow behavior of molten metal under unstable conditions plays an important role in the formation of good hollow cylinders with uniform thickness. At lower rotational speeds the castings are of poor quality because of their wavy structure at the inner surface of the casting which is mainly due to the insufficient centrifugal force on the molten metal during rotation of the mold. But it is seen that as the rotational speed of the mold increases to 600 rpm (14.9G) to 800 rpm (26.5G) the quality of the castings improved drastically which can be attributed to the layer by layer solidification of the molten metal which led to enhanced surface friction between the molten metal layer and already solidified layer leading to a faster rate of solidification. This clearly shows in centrifugal casting process an optimum speed has to be identified to obtain a quality casting which is dependent on the rotational speed of the mold.

4.4.1.1 Microstructure, Rate of Solidification and Grain Size of Tin Centrifugal Casting

Figure 4.12- Figure 4.14 shows the microstructures of the cast Tin test samples produced through centrifugal casting process at different rotational speeds of the mold. These microstructures are taken along the radial direction in the cast sample at inner, middle and outer of the casting. It has been known from the earlier literatures that the rotational speeds of the mold play a very strong role in the microstructure formation of the specimen (Halvaee et al. 2001). At higher rotational speed of the mold the rate of solidification will be faster compared to the lower rotational speeds of the mold. The molten metal gets lifted up immediately after it is poured to the rotating mold, due to high forced convection between atmosphere and the outer mold surface; between inside liquid metal and the air present inside the mold cavity, conduction heat transfer through the mold and through already solidified cylindrical metal layers resulting in higher cooling rates. But in case of liquids at higher rotational speeds like 800 rpm (26.5G) of the mold due to negligible relative movement between the rotating mold and the melt the rate of cooling is decreased as discussed earlier. In case of centrifugal casting it is observed that rate of solidification increases at higher rotational speeds (Chirita et al. 2009). This is due to the reason that at higher rotational speeds of the mold the metal gets solidified continuously at faster

rate until the pouring stopped and also the increased viscosity of the melt during solidification.

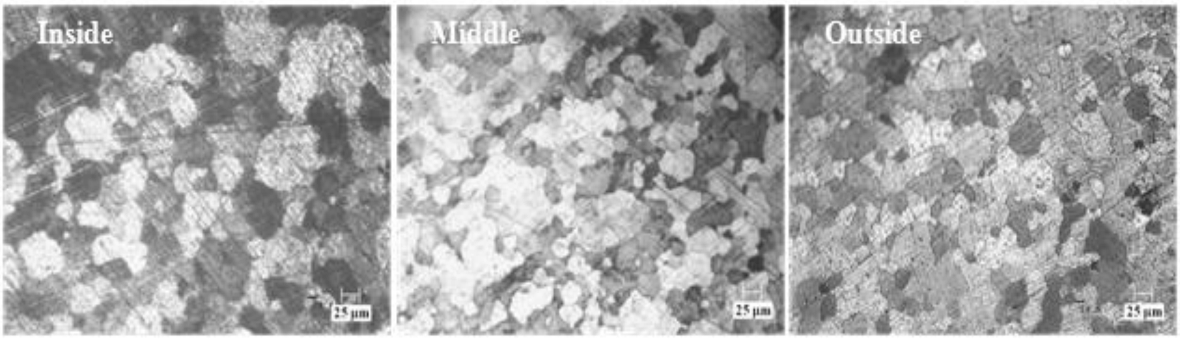


Figure 4.12 Microstructures of Tin Casting Produced at Mold Rotational Speed of 400 rpm (6.62G)

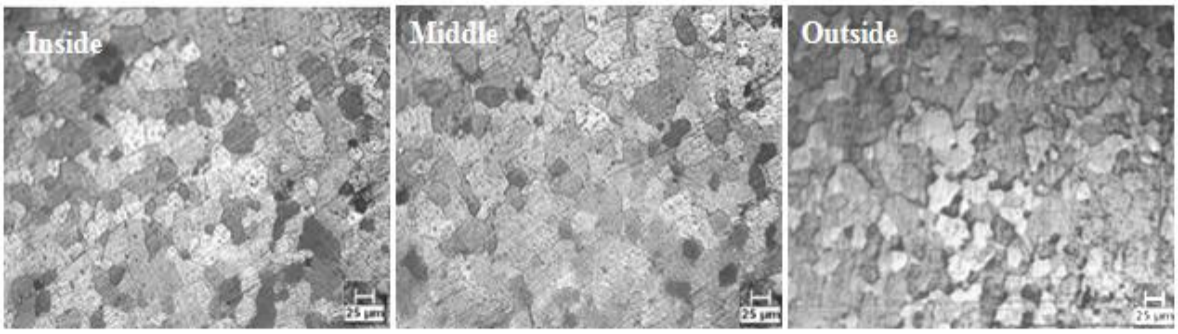


Figure 4.13 Microstructures of Tin Casting Produced at Mold Rotational Speed of 600 rpm (14.9G)

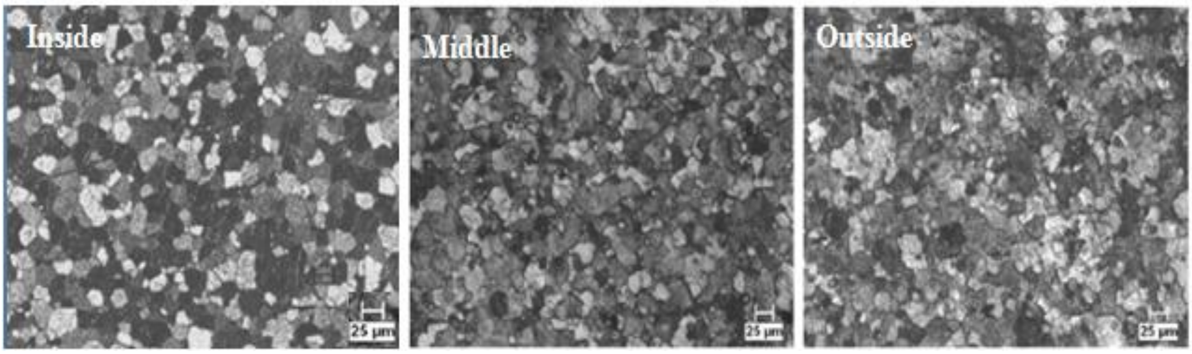


Figure 4.14 Microstructures of Tin Casting Produced at Mold Rotational Speed of 800 rpm (26.5G)

The microstructures showed in the above figures exhibit fine equiaxed grains along the radial direction in all the three rotational speeds of the mold. It is also observed that grain size decreases in size gradient from inner to outer diameter of the casting produced at three rotational speeds of the mold due to decreasing cooling rate from outer to inner layer.

Figure 4.15 shows the grain size of the Tin castings measured from inner radius to outer radius, produced at different rotational speeds of the mold. As the rotational speed of the mold increases rate of solidification increases, this leads to a variation in the grain size from inside surface of the casting to the outside surface of the casting. Here grain size observed as large at the inner surface and decreases towards the outer surface of the casting. This is because the direction of solidification is from outer to inner surface of the casting. And also at higher speeds like 800 rpm (26.5G) the rate of solidification is faster as discussed earlier. Therefore the average value of grain size of the castings produced at 800 rpm (26.5G) was found to be 14µm at the inside and at the middle and at the outer radii the average grain size is measuring 12 µm. The average value of grain size of the castings produced at 600 rpm (14.9G) was found to be 20µm at the inside, 16µm at the middle and 15µm at the outer radius. And also the average grain size of the castings produced at 400 rpm (6.62G) is 25µm at the inside, 21µm at the middle and 19µm at the outer radius. This is due to the reason that the rate of solidification is slower during the lower rotational speeds like 400 rpm (6.62G) and 600 rpm (14.9G) of the mold compared to that at higher rotational speed like 800 rpm (26.5G). The castings produced at 600 rpm (14.9G) and 400 rpm (6.62G) shows a higher gradient in grain size from inside to outside of the casting. There is a slight variation in grain size from inside to outside of the castings produced at 800 rpm (26.5G) of the mold. The solidification times have been determined by referring the relationship shown in Figure 4.11.

From the above results and discussions it has been noted that the grain size is dependent on the solidification rate which is in turn depends on the mold rotational speed. Similar techniques have been used to find the solidification rate at middle and outer radius of the casting. The Figure 4.16 shows the variation of solidification rate of the castings produced at different rotational speeds of the mold from inner radius to outer radius of the castings. As discussed before the rate of solidification increases with the magnitude of rotational speed of the mold, this was also seen by many authors (Janco et al. 1992, Yoshini et al. 2002, Vieira et al. 2009)

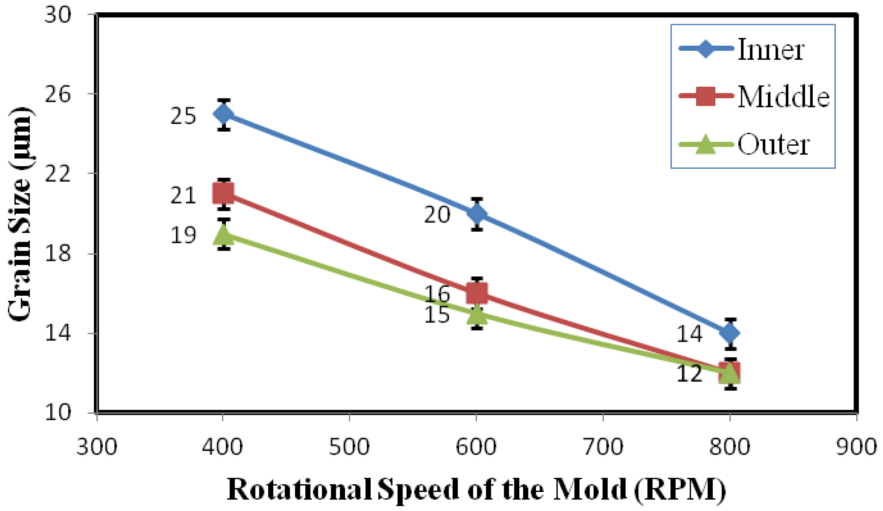


Figure 4.15 Grain Size of Tin Centrifugal Casting at Different Rotational Speeds of the Mold

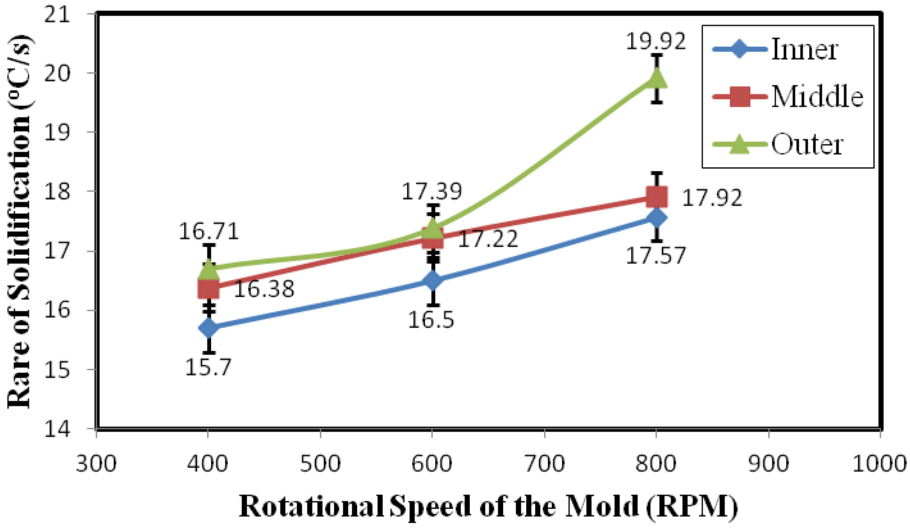


Figure 4.16 Rate of Solidification of Tin Centrifugal Casting at Different Rotational Speed of the mold.

From the above discussion we can see that the grain size in the casting varies along the radial direction. At all the three rotational speeds it is found that the grain size at the inner surface is larger compared to outer. This is due to the fact that when the molten metal is poured onto the cold wall of the mold due to the chilling effect the molten metal solidifies faster with finer grain size. But as we go on pouring the molten metal the cylinder formation takes place layer by layer. During this process the layers away from the chilling layer solidify slowly giving rise to bigger grain size.

4.4.1.2 Hardness of Tin Centrifugal Casting

It is clear from the previous discussion that the rate of solidification varies with rotational speed of the mold, which causes variation in heat dissipation from the melt. As the melt enters the mold it forms a continuously metal layers and the melt layer which contacts first to the cold metallic mold gets chilled and solidifies rapidly. Therefore the outer surface of the casting is harder compared to the inner surface. The solidification front advances from the outer casting surface to inner surface of the melt. Hence direction of solidification is from outer casting surface to inner surface. Since solidification is a layer by layer process the columnar grain does not form along the direction of solidification from outer wall to inner wall of the casting, instead it appears as broken grains. Figure 4.17 shows the variation of hardness along the radial direction of the casting from inner to outer surface across the casting at various rotational speed of the mold. At 400 rpm (6.62G) the Brinell Hardness Number (BHN) varies from 6 BHN from inside to 8 BHN at the outside.

At 600 rpm (14.9G) it is varying from 6 BHN at inside to 9 BHN at outside. But at 800 rpm (26.5G), its variation shows slightly higher values ranging from 8 BHN to 10 BHN. From the above discussion it is seen that due to the rapid cooling at the outer surface the hardness number is higher and it decreases towards the inner surface. The hardness values obtained from the experiments clearly shows that there is an effect of mold rotational speed.

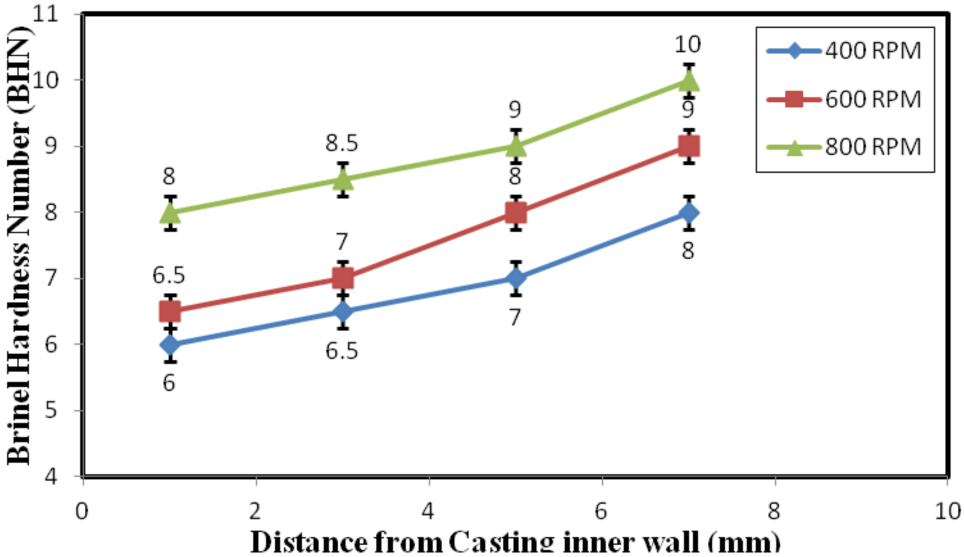


Figure 4.17 Hardness along the Radial Direction of the Tin Centrifugal Casting

At higher rotational speed the hardness values obtained are higher compared to those of low rotational speeds. These hardness values are in good relationship with the microstructures discussed earlier with respect to the minimum variations in grain size. This is due to the reason that at lower rotational speeds of the mold, solidification rate of the melt is slower. It is also been observed that, there is a variation in hardness along the radial direction of the casting. The hardness at the outer surface of the casting will be a greater compared to the inner surface of the casting because of the chilling effect of the molten metal at the mold wall. Hence melt gets solidified rapidly and the solidification front moves from outside to inside of the casting. The temperature difference towards the centre gradually decreases with adjacent layers. Hence heat dissipation rate decreases and rate of solidification also decreases. This shows the direction of solidification of centrifugal castings towards the inner surface of the casting.

4.4.2 Effect of Mold Wall Temperature on Centrifugal Casting of Tin

The rate of heat transfer will be maximum when there is a maximum temperature difference which is the driving force for the heat transfer. As the temperature difference reduces the rate of heat transfer will decrease. Due to slower heat transfer rate the solidification time increases and grain size will be coarse compared to faster cooling rate. It shows that as the temperature of the die increases there will be increase in the grain size of the cast.

This reduces the rate of solidification of the centrifugal casting at increased mold temperature. This leads to the increased grain size. During initial casting the temperature of the mold is less and hence due to large temperature difference between the mold and the melt cooling will be very rapid and later stages due to heated mold wall the temperature difference will decreases and cooling rate also decreases. This study will provide information for a realistic selection of these parameters via experiment and to highlight this effect of process variables in the centrifugal casting process.

In centrifugal casting, the maximum amount of heat is absorbed by the mold wall during the solidification of the casting. Therefore temperature of the mold is also one of the important process variables which affect the solidification rate of the casting. Different heat flow rates across the cast metal and mold surface regions affect the evolution of solidification and the micro structures of the casting, which in turn affects the other mechanical properties such as wear and tensile strength of the casting.

To understand the effect of mold wall temperature the experiments were conducted by preheating the mold with a heating MANTLE wound around the mold and by slowly increasing the temperature of the coil. The experiments were conducted for 50^{o}C, 100^{o} C and 150^{o}C mold temperature.

4.4.2.1 Microstructure, Rate of Solidification and Grain Size of Tin Centrifugal Casting

Centrifugal cast samples of Tin have been produced by the centrifugal casting process at three different rotational speeds of the molds such as 400 rpm (6.62G), 600 rpm (14.9G) and 800 rpm (26.5G). At every specified rpm three castings are produced at three different mold temperatures of 50^{o}C, 100^{o}C and 150^{o}C respectively. It has been reported in the literatures that the initial temperature of the mold influences the solidification rate (Vassiliou et al. 2008) of the melt. The mold temperature at the beginning will be at room temperature and when the melt is poured at a teeming temperature of 300°C the difference between mold temperature and melt temperature will be large resulting in rapid solidification due to maximum heat dissipation and hence the size of the grains would be finer. When the casting process is continuous the difference in temperature between the melt and mold progressively reduces resulting in decreased solidification rate towards the inner surface of the casting resulting in larger grain size.

Microstructures of the Tin samples produced by centrifugal casting process at different rotational speeds of 400 rpm (6.62G), 600 rpm (14.9G) and 800 rpm (26.5G) of the mold and also by varying the temperature of the mold from 50°C to 100°C and 150°C are shown in Figure 4.18- Figure 4.20, which clearly establishes the variations in grain size as a function of both rotational speeds of the mold as well as temperature of the mold.

It shows that at higher temperature of the mold the grain size is coarse compared to the grain size when the mold is at lower temperature. This is due to reason that at higher temperature of the mold due to the reduced temperature difference between the mold and the melt the heat transfer rate is less, hence grains will grow bigger. But at lower temperature of the mold, due to the large temperature difference between the mold and the melt, rate of heat transfer is faster hence, solidification rate will be rapid and also grain size becomes finer. Also at lower speed of rotation of the mold the grain size is bigger. By comparing the castings produced with preheating the mold and without preheating the mold it is observed that there is a slight variation in the grain size which is not so dominant as compared to increase in the rotational speed of the mold. So it is confirmed that the effect of rotational speed of the mold is more dominant than the effect of preheated mold temperature for casting of low melting point metals. This is in agreement with the results reported earlier (Sui et al. 2010). At lower speeds like 400 rpm (6.62G) the rate of solidification is slower and also at high temperature like 150°C of the mold the rate of solidification is slower. Hence coarse grains are formed as compared to microstructure of the casting obtained at higher rotational speeds.

Figure 4.21 - Figure 4.23 shows the grain size along the radial direction of the castings produced at different rotational speeds of the mold and different preheated temperature of the mold. It has been observed that at lower temperature of mold like 50^{o}C the fine grains are formed and as the speed increases to higher value of 800 rpm (26.5G) the rate of solidification also increases and the grain size become further refined. But at higher pre heated temperature of the mold and lower speed of rotation the coarse grains are formed. This is because of the lower temperature difference between the mold and the melt which causes a decrease in rate of heat dissipation hence rate of solidification also decreases (Bonollo et al. 2003).

At 400 rpm (6.62G) of the mold speed the size of the grain obtained is 30 µm at 150^{o}C and at inner radius. At 600 rpm (14.9G) of the mold speed, the maximum size of the grain at inside is 26 µm at 150 ^{o}C temperature of the mold. Again at 800 rpm (26.5G) of the mold speed the maximum size of the grain is 20 µm at 150 ^{o}C. This shows grain size of the casting is depending on the temperature of the mold as well as rotational speed of the mold. As the temperature increases grain size also increases and as the speed increases the grain size decreases. It has been observed that the grain size is increasing along the radial direction from outside to inside. The direction of solidification is towards the inside of the casting.

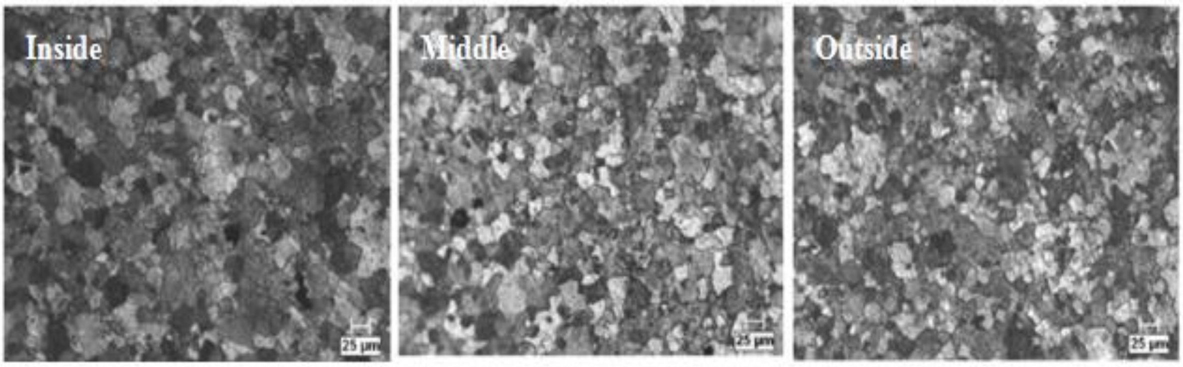


Figure 4.18 Microstructures of the Castings along the Radial Direction, Produced at Mold Wall Temperature of 50^{0}C and Rotational Speed of 800 rpm (26.5G)

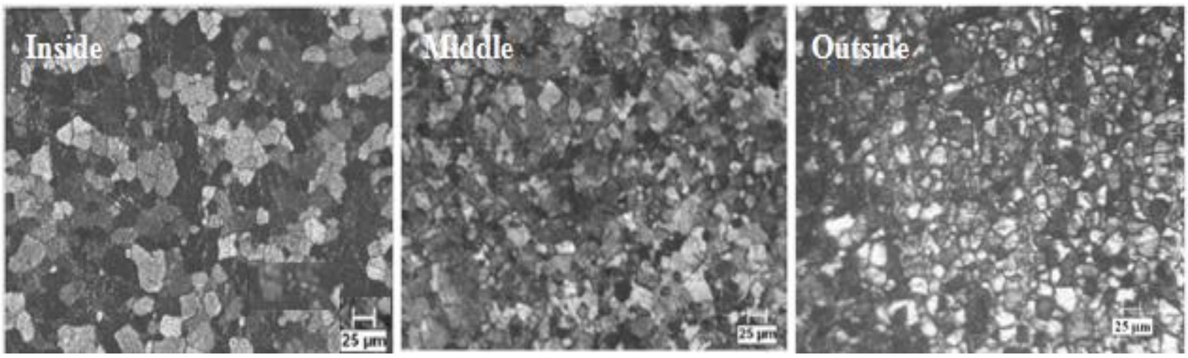


Figure 4.19 Microstructures of the Castings Along the Radial Direction, Produced at Mold Wall Temperature of 100^0C and Rotational Speed of 800 rpm (26.5G)

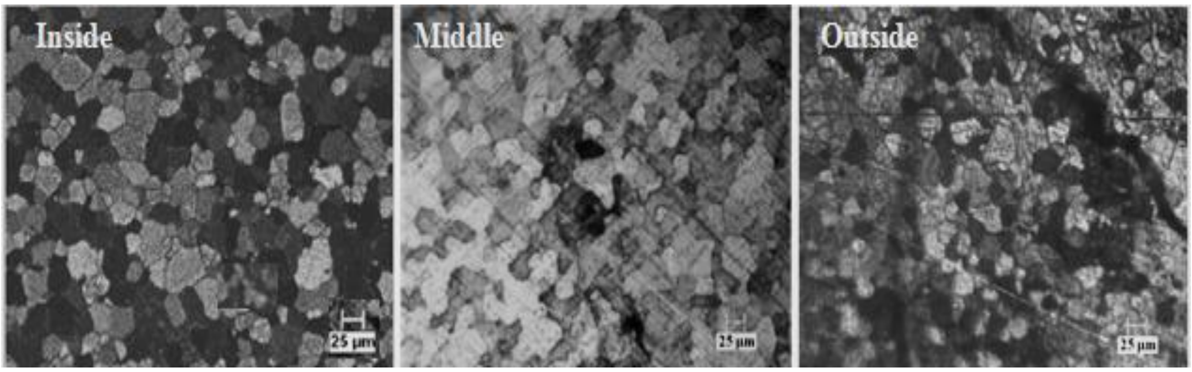


Figure 4.20 Microstructures of the Castings along the Radial Direction, Produced at Mold Wall Temperature of 150^0C and Rotational Speed of 800 rpm(26.5G)

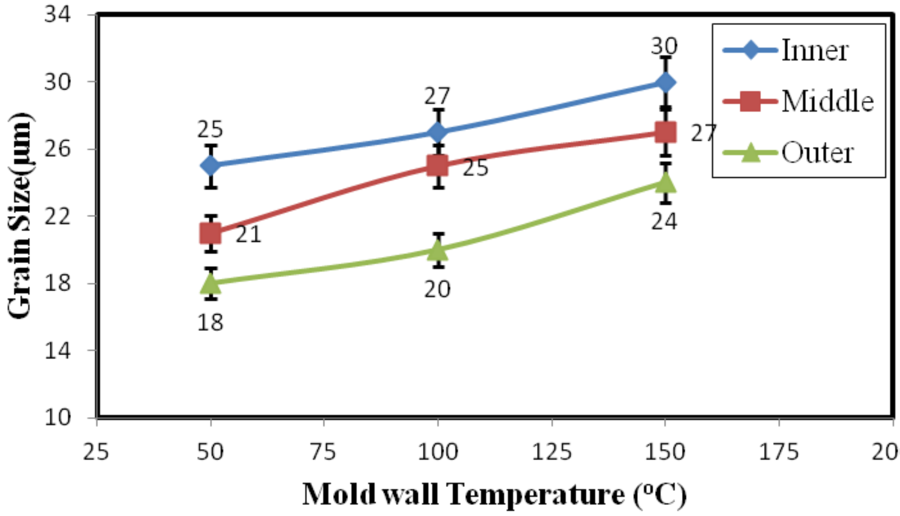


Figure 4.21 Grain Size of the Centrifugal Castings at 400 rpm (6.62G) Rotational Speed of the Mold

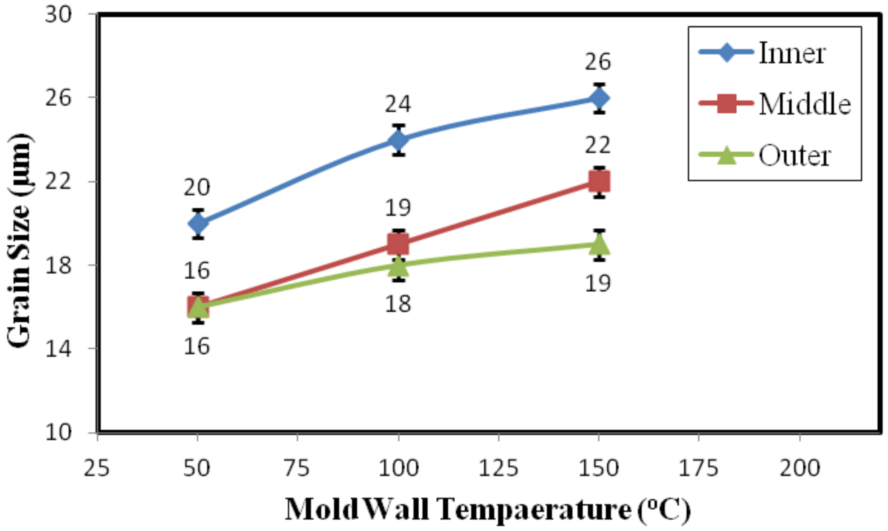


Figure 4.22 Grain size of the centrifugal castings at 600 rpm (14.9G) Rotational Speed of the mold

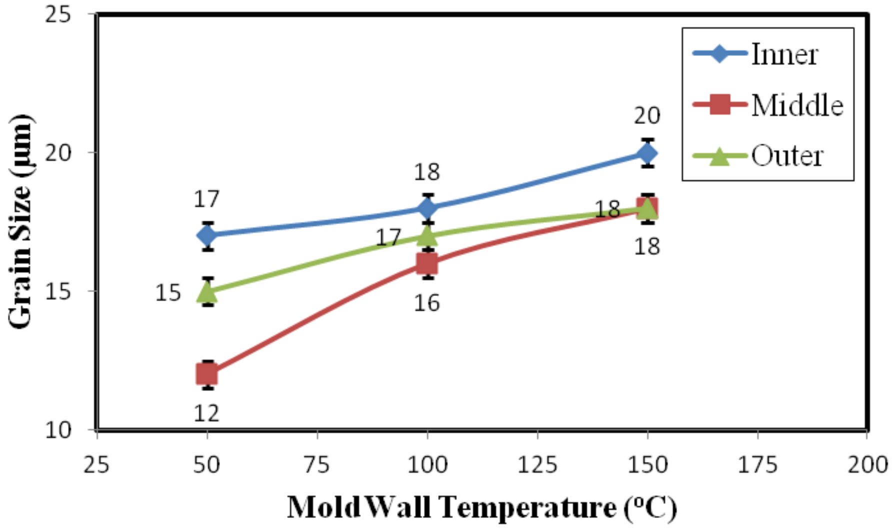


Figure 4.23 Grain Size of the Centrifugal Castings at 800 rpm (26.5G) Rotational Speed of the mold

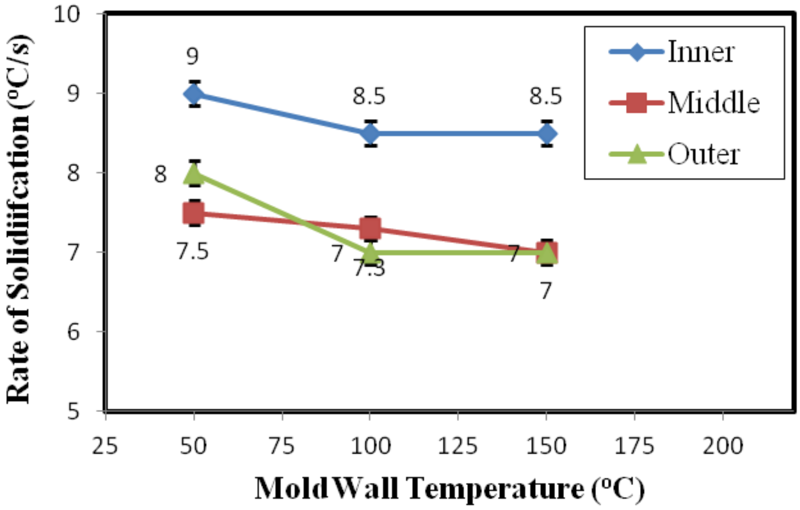


Figure 4.24 Rate of Solidification at Different Wall Temperature of the Mold and at 400 rpm (6.62G) Rotational Speed of the Mold

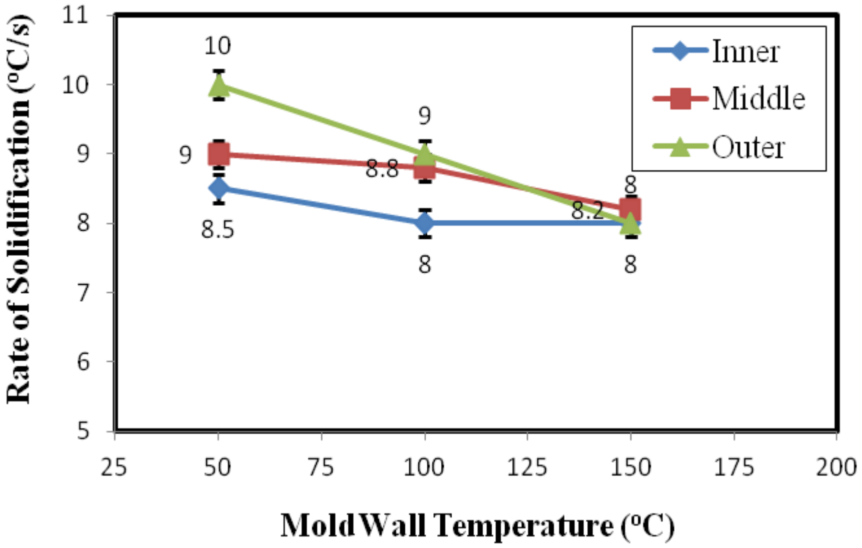


Figure 4.25 Rate of Solidification at Different Wall Temperature of the Mold and at 600 rpm (14.9G) Rotational Speed of the Mold

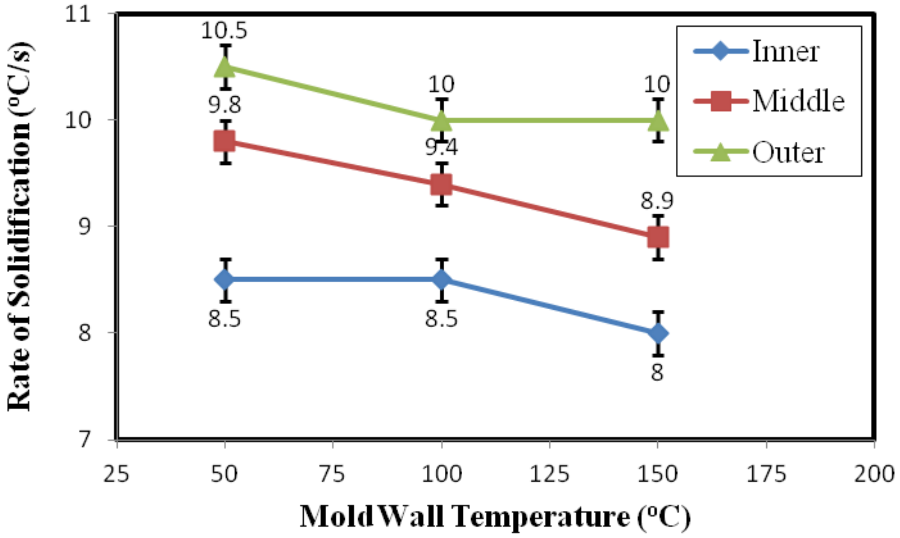


Figure 4.26 Rate of Solidification at Different Wall Temperature of the Mold and at 800 rpm (26.5G) Rotational Speed of the Mold

Figure 4.24- Figure 4.26 shows the relationship between rate of solidification and mold wall temperature of the cast tin test sample produced at three different rotational speeds and also by varying the mold temperature from 50^{o} C to 150^{o}C in steps of 50^{o}C. The values of rates of solidification are obtained from the gravity casting data. Solidification rate is higher for the samples produced at a rotational speed of 800 rpm in comparison to those produced at 400 rpm (6.62G). Similar conclusions are obtained from the previous discussions regarding the grain size versus mold temperature. And it is observed that the rate of solidification decreases with increase in temperature of the mold.

From the above discussion it appears that solidification rate significantly influenced by the mold wall temperature. By increasing the mold wall temperature (preheat temperature of the mold) it is clearly established that the mechanical properties are influenced due to variation in the solidification rate. It can be see that mold wall temperature plays an important role in defining the solidification rate which intern influences the optimum process parameters.

4.4.2.2 Hardness

In centrifugal castings it is expected that the properties vary with respect to the direction of solidification. Further from the literature it has been seen that mechanical properties of centrifugal casing are affected by process variables like mold rotational speed, mold material and also temperature of the mold.

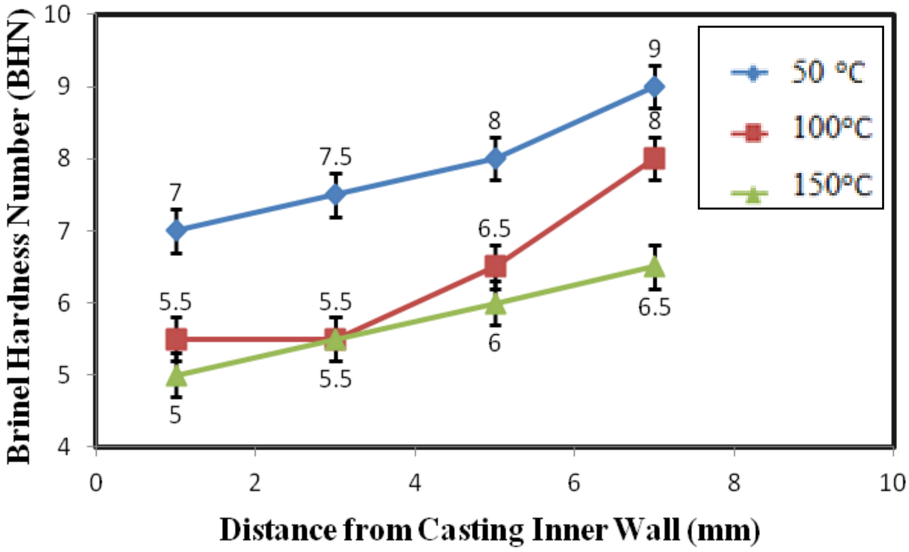


Figure 4.27 Hardness along the Radial Direction of the Tin Centrifugal Castings at 400 rpm (6.62G) Rotational Speed of the Mold

Hardness values are determined by using Brinell hardness tester. The hardness values are determined from inner radius to outside radius at three locations. At least five readings are obtained at each radius and average values are used for the analysis. Figure 4.27- Figure 4.29 shows the hardness gradient of the tin centrifugal casting samples produced at different rotational speeds of 400 rpm (6.62G), 600 rpm (14.9G) and 800 rpm (26.5G), when the mold temperature varies from 50^{o}C to 150^{o} C , with steps of 50^{o} C at three levels.

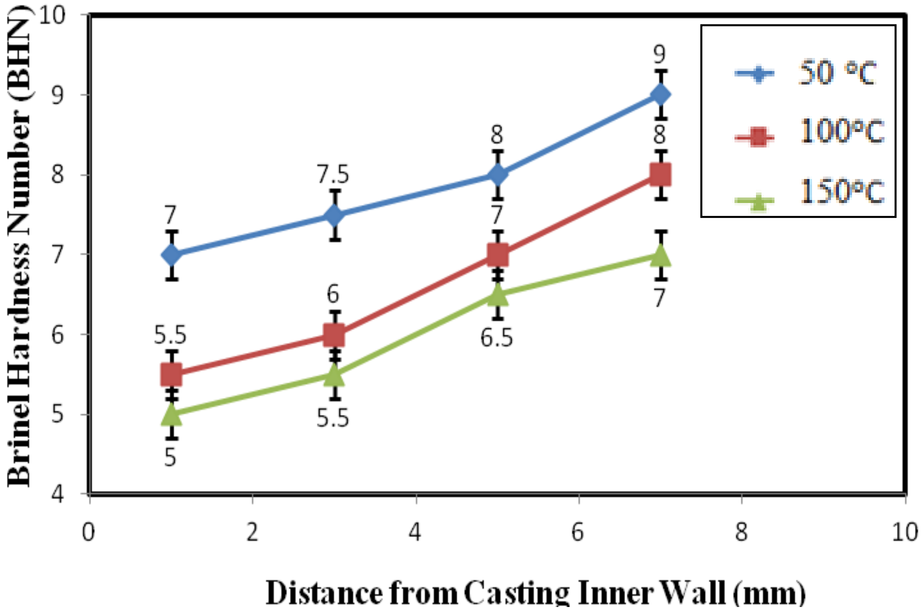


Figure 4.28 Hardness along the Radial Direction of the Tin Centrifugal Castings at 600 rpm (14.9G) Rotational Speed of the Mold

At inner radius it can be seen that hardness values are 6 BHN, 7 BHN and 8 BHN for 150°C 100°C and 50°C respectively at 400 rpm (6.62G). For the same speed at outer radius for 50°C, 100°C and 150°C mold temperature, the hardness values were found to be 6 BHN, 6 BHN and 5 BHN respectively. This trend continues for 600 rpm (14.9G) and 800 rpm (26.5G) casts also. Where there is a significant variation of hardness at inner radius for all the three mold temperatures. But at outer radius there is a distinct value of hardness at 50°C but as the mold temperature is increased hardness doesn’t vary much and it is seen that for all the three cases of mold rotational speeds, the hardness remains the same at 100°C and 150°C. This clearly indicates that the effect of mold temperature is not much significant as the mold rotational speeds affect the hardness at the outer radius.

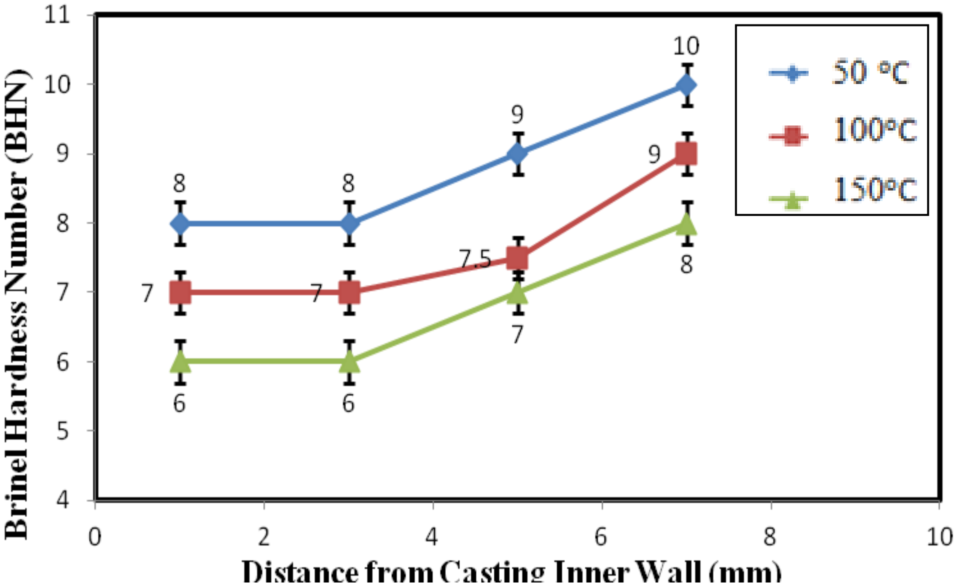


Figure 4.29 Hardness along the Radial Direction of the Tin Centrifugal Casting at 800 rpm (26.5G) Rotational Speed of the Mold

Hardness at the outer surface is higher when the mold temperature is at minimum and gradually decreases towards the interior surface of the casting because rate of solidification decreases in the radial direction. Similar trends have been obtained when the mold temperatures are varied at 100°C and 150°C for the reasons stated earlier. Further the hardness at the surface increases with the increase in rotational speeds. These results are in well agreement with results of microstructure shown in Figure 4.18-Figure 4.20, fine grained structure exhibits higher hardness than the coarse grained ones. This was also observed by Wu et al. (2006).

Grain sizes are coarser at lower rotational speeds due to lower solidification rates. Further, the grain size variation for a given test sample produced at a constant mold rotational speed but by varying the mold wall temperature appears to be more or less linear possibly due to not so significant temperature variations attempted in this investigation.

With higher initial mold temperature, the rate of heat withdrawal from the melt to the mold is reduced because of the reduced thermal gradient. As a result the solidification time is increased. Hardness is decreasing along the radial inward direction, this shows direction of solidification is towards the centre of the casting. The analysis of hardness values indicated that increasing the temperature of the mold reduces the rate of solidification.

It has been established that the heat transfer coefficient at the melt mold interface increases with an increase in the rotational speed and at a higher rotational speed liquid metal exerts a larger pressure on the solidified layer which in turn results in a better physical contact between the solidified layer and the mold wall, improving the heat transfer coefficient at their interface (Shamsi et al. 1993).

4.4.3 Effect of Mold Wall Thickness on Centrifugal Casting of Tin

The properties of a casting significantly depend on the rate of solidification. This is controlled by controlling the various process variables which were discussed in the previous sections. Thickness of the mold wall is one of the process variables not only in centrifugal casting but also in gravity casting process which affects the rate of solidification of the castings. When the molten metal is poured into the mold, the solidification begins, the heat within the molten metal starts dissipating into the relatively cooler part of the mold, probably explains the reason for rapid solidification of the melt. Hence the cooling rate is largely controlled by the mold material used for making the mold. It has also been established that different mold materials employed for making the mold transfer the heat at different rates. Metallic molds are found to transfer the heat very fast in comparison with non-conducting molding mediums. Mild steel is used as the molding media in the present investigation to cast test samples of the Tin.

By increasing the mold wall thickness the melt close to the wall gets solidified at faster rate due to larger thermal mass of mold and the subsequent layers of the melt gets cooled continuously by dissipating heat to the previously cooled metal layers (Liang et al. 2009, Zhiliang et al. 2007). Initially the molten metal comes directly in contact with the inner surface of the mold, since the thermal contact resistance is very less due to the direct contact of the molten metal with the mold wall surface, hence fast cooling is expected. After solidification the thermal contact resistance increases because of the contraction of the casting during solidification hence the cooling rate decreases. Therefore it clearly shows that the rate of solidification rate can be controlled by varying the thickness of the mold.

4.4.3.1 Microstructure, Rate of Solidification and Grain Size of the Centrifugally Cast Tin for Different Wall Thickness of the Mold

Mild Steel molds with different wall thicknesses stated in earlier sections are used for casting tin samples used in the investigation. The thickness of the mold wall indicates the variation in the thermal mass and hence it causes variation in cooling rates of the castings. Solidification rate of centrifugally cast tin are faster than those produced from normal gravity die casting process. This is due to the forced convection heat transfer happening between the melt and air inside surfaces as well as between the mold wall and outside environment at the outer surfaces of the mold experienced with the former processes and also during rotation the melt flow will be turbulent. The metal layer very close to the mold wall gets solidified faster and metal which is away from the mold wall cools slightly slow. As soon as the melt enters the mold the heat will be carried to the mold which acts as a heat sink and heat is distributed to the mold wall. Hence if the thickness of the mold is more with good diffusivity the melt cools rapidly. In the later stages the heat transfer will takes place by conduction through the metal and through the mold wall. It is also found that due to the rotation of the mold during solidification the columnar grains will break and forms fine grains.

The microstructure of the Tin cast samples produced through the centrifugal casting process by varying the thickness of the mold wall at 11 mm, 21 mm and 29 mm and at a rotational speed of 800 rpm is shown in the Figure 4.30 - Figure 4.32.

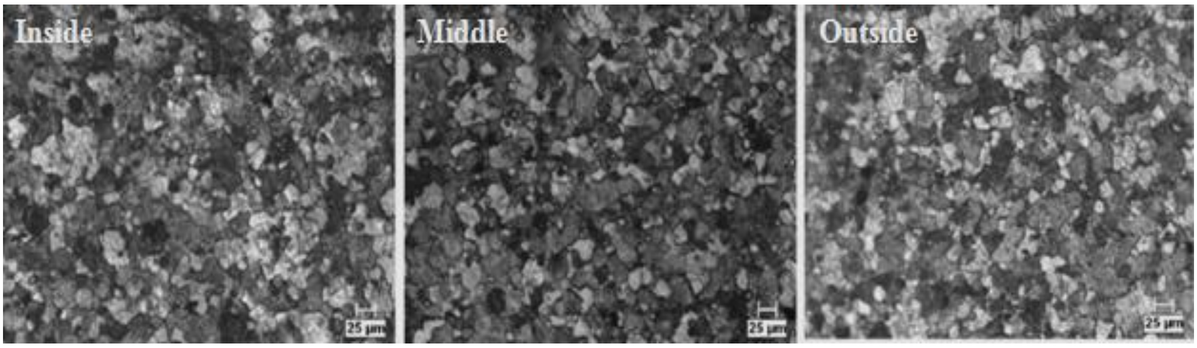


Figure 4.30 Microstructures of the Castings Produced using Mold of 11 mm Wall Thickness and 800 rpm (26.5G) Rotational Speed of the Mold

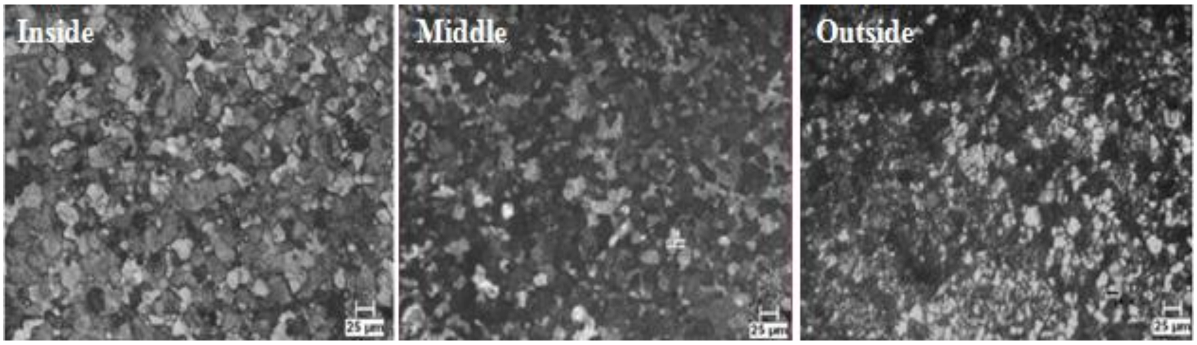


Figure 4.31 Microstructures of the Castings Produced Using Mold of 21 mm Wall Thickness and 800 rpm (26.5G) Rotational Speed of the Mold

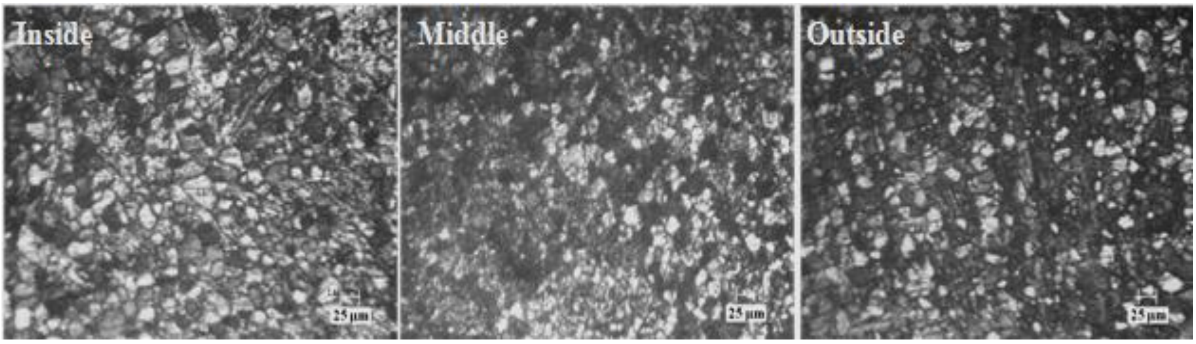


Figure 4.32 Microstructures of the Castings Produced Using Mold of 29 mm Wall Thickness and 800 rpm (26.5G) Rotational Speed of the Mold

The average grain size is measured using metallurgical microscope and plotted against the wall thickness of the mold. The microstructure shows variation in grain size from outer casting surface to inner surface of the casting. This is confirmed with the earlier studies (Wu et al. 2006).

As discussed in the previous sections the microstructure obtained at 800 rpm (26.5G) mold are observed to be finer compared to the microstructure obtained at 400 rpm (6.62G) due to the rapid cooling of the casting at speed of 800 rpm (26.5G). The microstructure of the casting obtained at 800 rpm (26.5G) using molds of different wall thickness shows lesser variation in grain size.

Lesser variation in grain size is observed because the heat within the molten metal flows into the relatively cooler parts of the mold. Molding materials transfer heat from the casting into the mold at different rates. The mold which is made entirely of metal would transfer the heat very fast. The material of mold used in this experiment is of mild steel with various wall thicknesses. When the liquid metal is poured in to the mild steel mold at temperature T_{Tin} coming in contact with the mold with temperature T_{mold} which is at very low temperature so solidification takes place quite quickly as the temperature gradient will be the difference between T_{Tin} and T_{mold}, so first solidified layer is formed and further the liquid melt enters in a second time and comes in contact with this layer whose temperature is higher than that of the mold. This molten metal does not solidify soon but is thrown with a helicoidal path and a turbulent flow towards the zones sited on the opposite side with respect to the pouring area (Bollono et al. 2003). The micro structures with minimum mold wall thickness exhibits larger grain size due to slow cooling rates and casting obtained from thick mold wall thickness shows fine grains, this is due to rapid cooling rates of the casting. The chilling effect on the casting depends on thermal mass of liquid metal and relative movement between the liquid metal and inner surface of the mold.

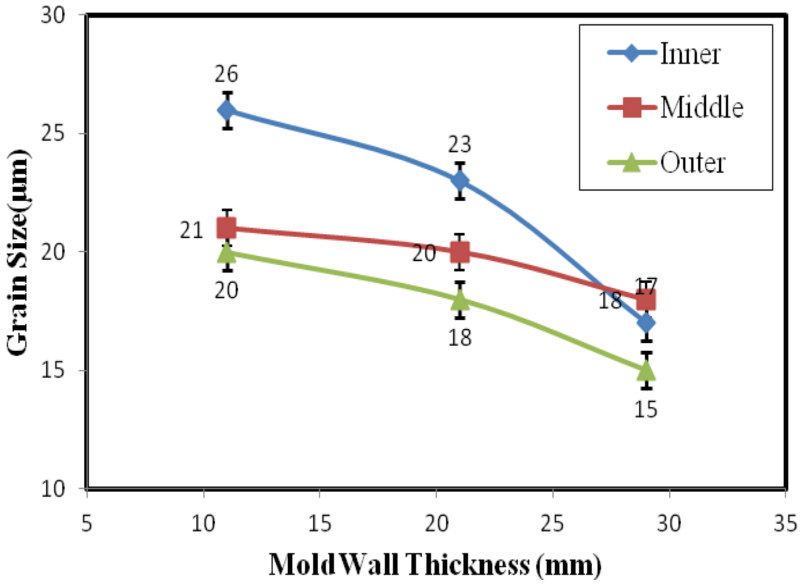


Figure 4.33 Grain Size at Different Mold Wall Thickness and at 400 rpm (6.62G) Rotational Speed of the Mold

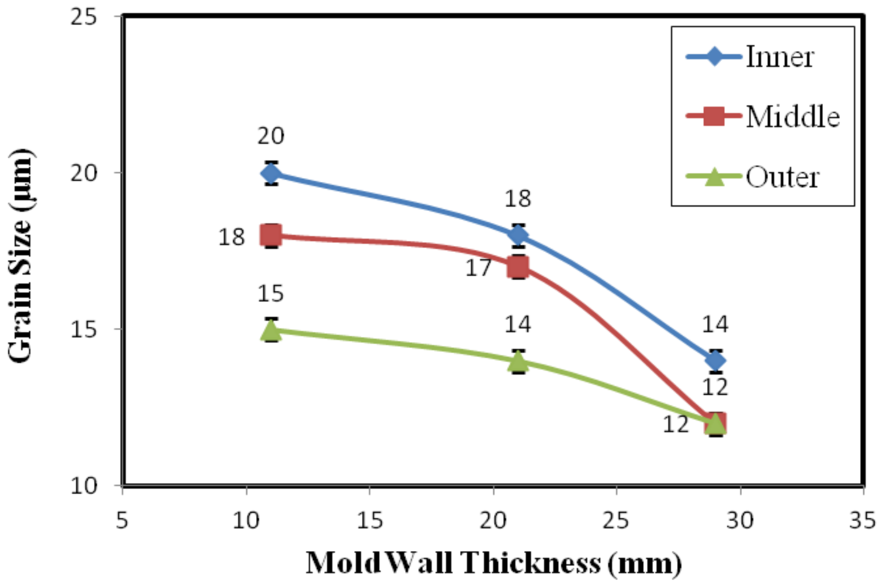


Figure 4.34 Grain Size at Different Mold Wall Thickness and at 600 rpm (14.9G) Rotational Speed of the Mold

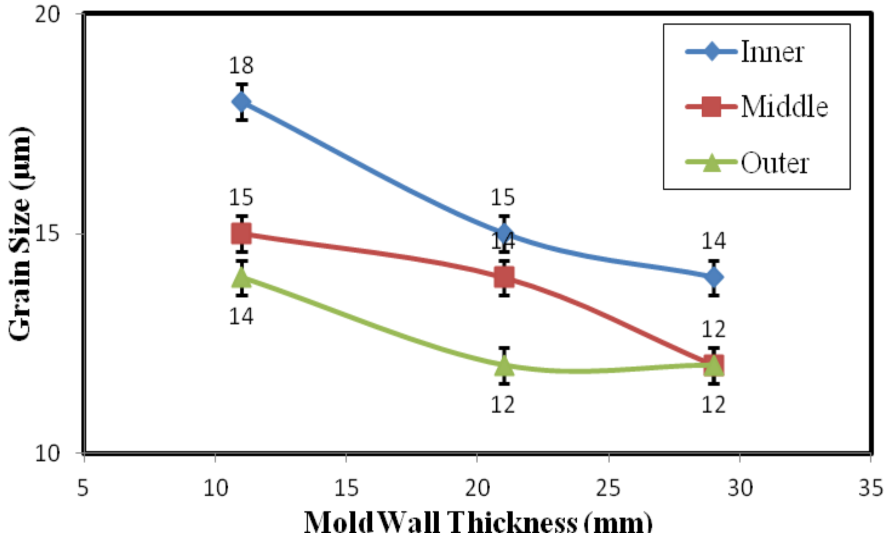


Figure 4.35 Grain Size at Different Mold Wall Thickness and at 800 rpm (26.5G) Rotational Speed of the Mold

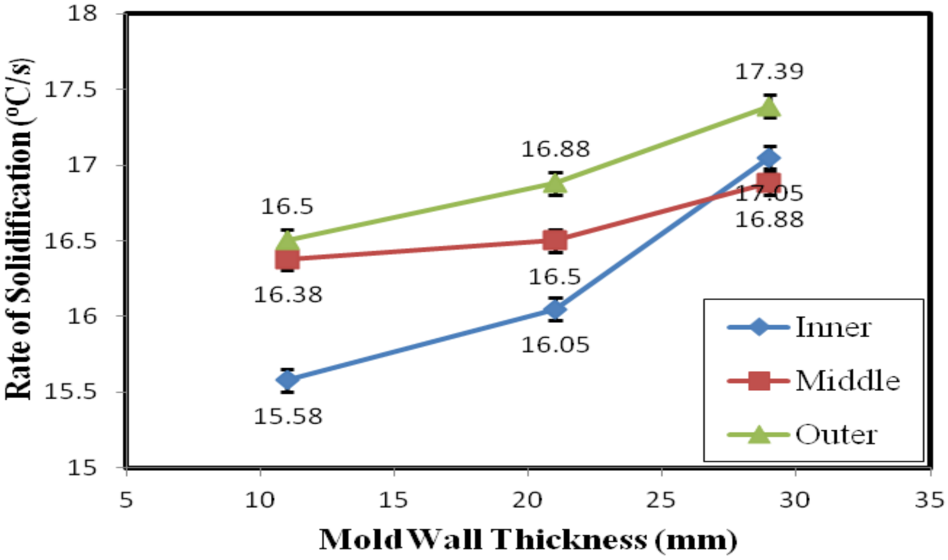


Figure 4.36 Rate of Solidification at Different Mold Temperatures and at 400 rpm (6.62G) Rotational Speed of the mold

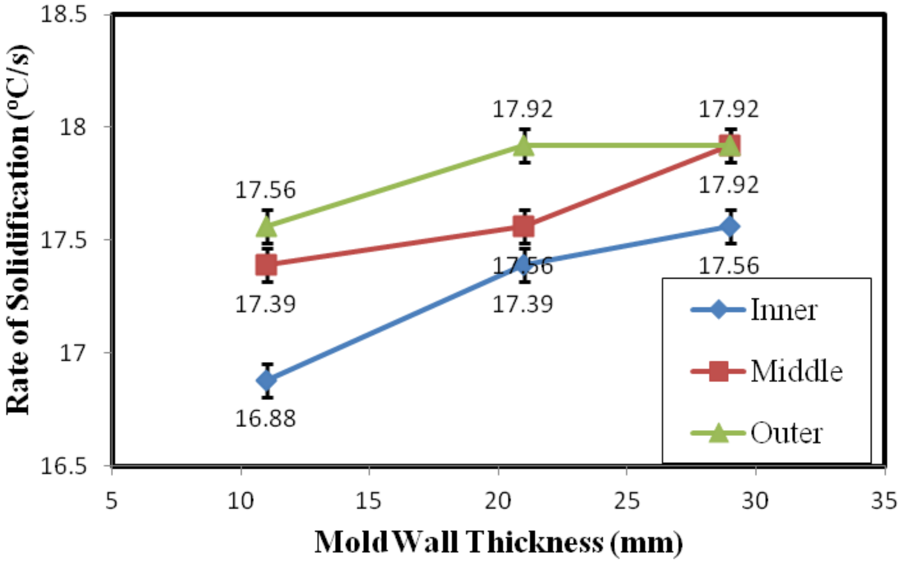


Figure 4.37 Rate of Solidification at Different Mold Temperatures and at 600 rpm (14.9G) Rotational Speed of the mold

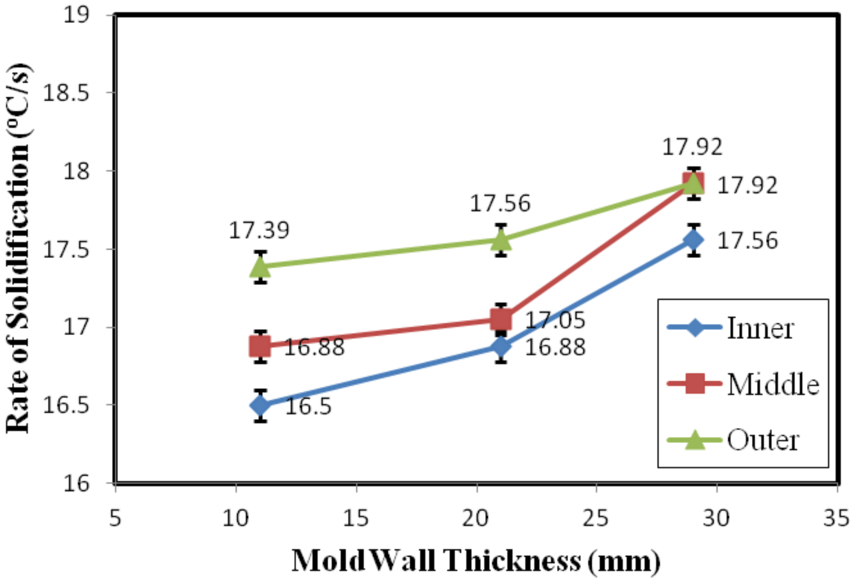


Figure 4.38 Rate of Solidification at Different Mold Temperatures and at 800 rpm (26.5G) Rotational Speed of the mold

The relationship between the grain size and the mold wall thickness of the cast Tin test sample at different rotational speeds of the mold is shown in Figure 4.33 - Figure 4.35. It shows that at 400 rpm (6.62 G) mold rotational speed, there is a prominent gradient in grain size from outer to inner surface of the cylinder for different mold wall thicknesses.

The relationship between the rate of solidification and mold wall thickness of the cast Tin test samples at different rotational speeds of the mold for a given preheated temperature of the mold are shown in Figure 4.36- Figure 4.38.

The grain size of the test samples produced with minimum wall thickness larger due to the slower cooling rates encountered in comparison with those produced with molds with higher wall thickness which possesses fine grains due to rapid cooling process. Rapid cooling is attributable to the chilling effect of the mold and the effect is influenced by both thermal mass of the liquid metal and relative movement between the molten metal and inner surface of the mold as well.

Rate of solidification is highest at higher rotational speed of the mold and it keeps decreasing with the decrease in rotational speeds of the mold for a given wall thickness of the mold experimented in this work. Further solidification rate increases with the increase in thickness of the mold wall and proportional trend is observed with the different rotational speeds of the molds experimented in this work. Higher rotational speed with maximum wall thickness resulted highest cooling rates.

4.4.3.2 Hardness

The hardness gradient of Tin centrifugal casting samples produced at 400 rpm (6.62G), 600 rpm (14.9G) and 800 rpm (26.5G) rotational speed of the mold as a function of variations in the mold wall thickness are shown in Figure 4.39- Figure 4.41. It is observed that there is an increase in hardness from inside of the casting to outer surface. This is attributed to the reason that the solidification front starting from the outer surface due to chilling effect moves towards the inner surface. The magnitudes of the hardness are the lowest when the mold wall thickness is the least and it keeps increasing with the increase in thickness of the mold. The highest hardness of 12 BHN is observed for the casting produced at 800 rpm (26.5G) of the mold with 29 mm thick. Further the hardness decrease from the surface to the interior of the casting due to the reduction in cooling rate. Similar results were confirmed from the microstructural study discussed in 4.3.2.1.

Larger grains sizes are associated with lower rotational speeds of mold and they become finer with increase in rotational speed of the mold. Further the grain size becomes finer with the increase in wall thickness in case of test samples produced at a rotational speed of 400 rpm (6.62G) of the mold whereas this variation are insignificant with reference to the variation in die wall thicknesses when they are produced at 600 rpm (14.9G) and 800 rpm (26.5G) rotational speed s of the mold. One of the significant results revealed during these experiments that higher hardness are observed for the castings produced using 29 mm wall thickness mold compared to the other two. This shows that, as the wall thickness of the mold increases there are chances that the castings which are produced can be identified as functionally graded material where in properties varies significantly from one end of the casting to the other end.

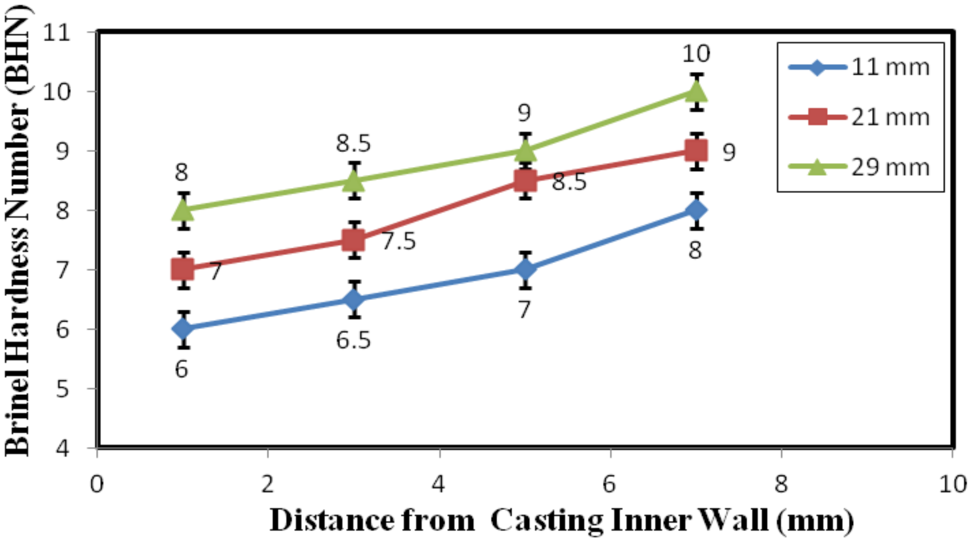


Figure 4.39 Hardness of the Castings for Different Wall Thickness of the Mold and at 400 rpm (6.62G) Rotational Speed of the mold

The hardness of the castings produced using molds with different wall thickness increases with increased mold wall thickness. This is because the hardness of the castings increases with increase in rate of solidification (Samarasekara et al. 1984).

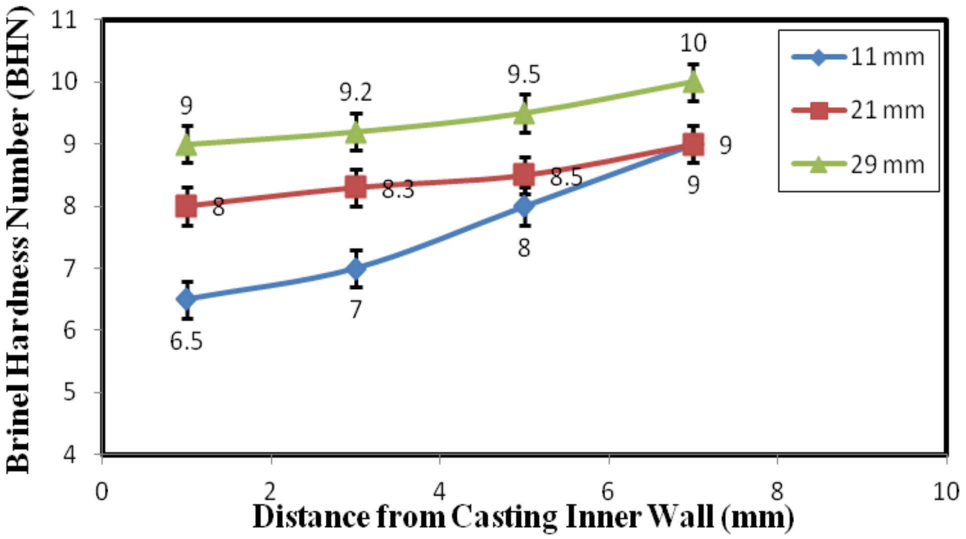


Figure 4.40 Hardness of the Castings for Different Wall Thickness of the Mold and at 600 rpm (14.9G) Rotational Speed of the mold

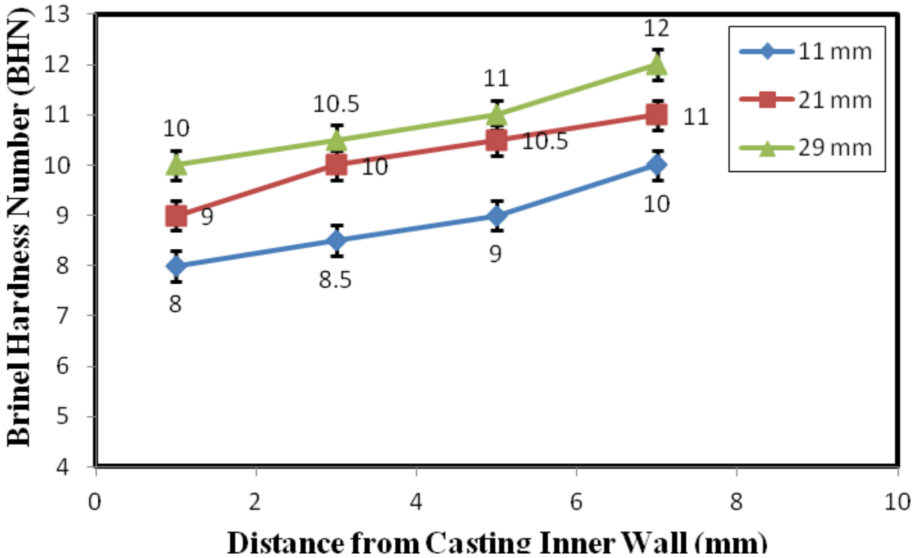


Figure 4.41 Hardness of the Castings for Different Wall Thickness of the Mold at 800 rpm (26.5G) Rotational Speed of the mold

4.4.4 Wear Analysis of Tin Centrifugal Castings

Wear involves the process of abrading particles penetrating into the metal and causing tearing of the surface which may introduce surface stress cracks leading to surface breakdown. The process of wear is complex in its nature as it involves many factors which influences the abrasion and friction. Some of the parameters which influence are hardness, toughness, microstructure and its constituents. Similarly considering the service factors which influence wear behavior are contact pressure, applied pressure, sliding speed and environment in which the test is conducted and the temperature between the two mating surfaces (Bialo et al. 2000). Another important feature which influences the wear is lubrication and corrosion (Vieira et al. 2009).

As known from the literature that wear resistance is one of the important parameters which describe the wear process quantitatively. Three process parameters were considered while producing the cylindrical castings for tin material. In this work an effort has been made to find the influence of mold rotational speed, mold wall temperature and wall thickness of the mold on wear. The wear is quantified through the specific wear rate which is a function of volume loss, sliding distance and normal load. In this work the wear is quantified based on the linear measure that is measuring the amount of wear as dimensional change by length in terms of specific wear rate using pin on disc sliding wear methodology according to ASTM G99 Standards.

4.4.4.1 Effect of Rotational Speed of the Mold on Specific Wear Rate of Tin Centrifugal Castings

The inner and outer surfaces of the cast samples were subjected to wear test at ambient temperature under dry sliding condition. The aim of this study is to find the volume loss under different loads for the test samples produced at various rotational speeds of the mold.

Specific wear rates are found to be highest at lower normal test loads and decreases for the casts produced at higher mold speeds. Figure 4.42 - Figure 4.44 shows the specific wear rates of tin centrifugally cast at the inner surface and at the outer surfaces produced at different wall temperature of the mold and for different rotational speeds of the mold. Normal load for the specific wear rate associated with tin samples produced at mold rotational speeds of 800 rpm (26.5G) appears to be lower in comparison with those test samples produced at 400 rpm (6.62G) and 600 rpm (14.9G) attributable to fine grains and enhanced hardness. From the results of the wear tests, it can be realized that the decrease in specific wear rate is dominant at lower loads compared to that at higher loads. Rotational speed of the mold is one of the process variables in centrifugal casting which has a significant effect on the specific wear rate. At higher rotational speeds of the mold due to the formation of equi-axed fine grains the hardness is increased which leads to the decrease in specific wear rate. Inner surface as well as outer surfaces of the test samples was used to measure the specific wear rate. Since outer surface is harder than the inner surface specific wear rate was found to be lesser than that of the inner surface, due to hardness variation, which was discussed in the earlier section.

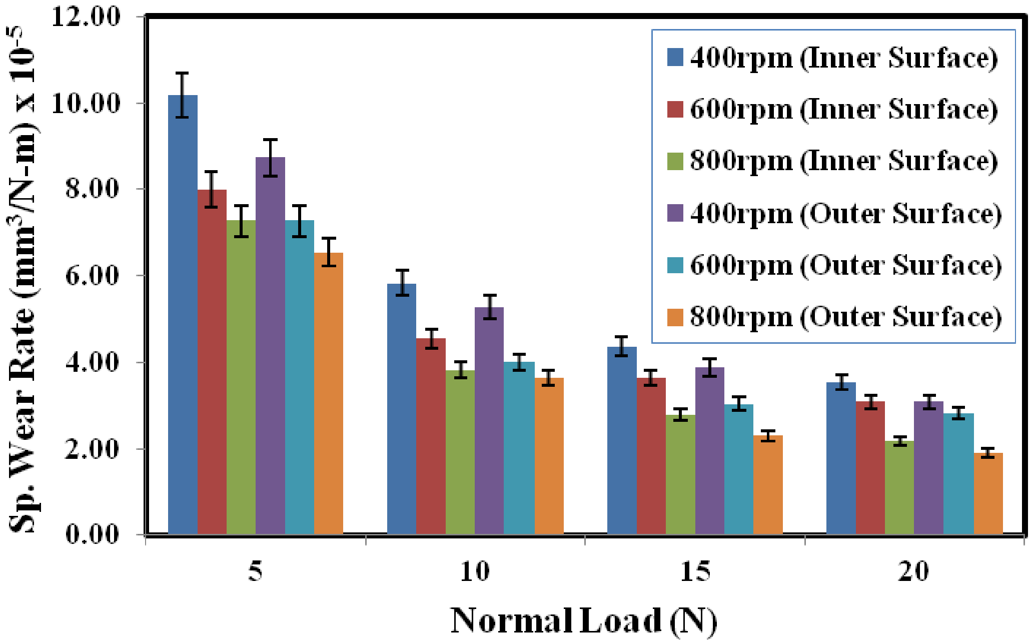


Fig 4.42 Specific Wear Rate of the Tin at Inner Surface and Outer Surfaces for Different Rotational Speeds of the Mold and 50°C Initial Mold Temperature

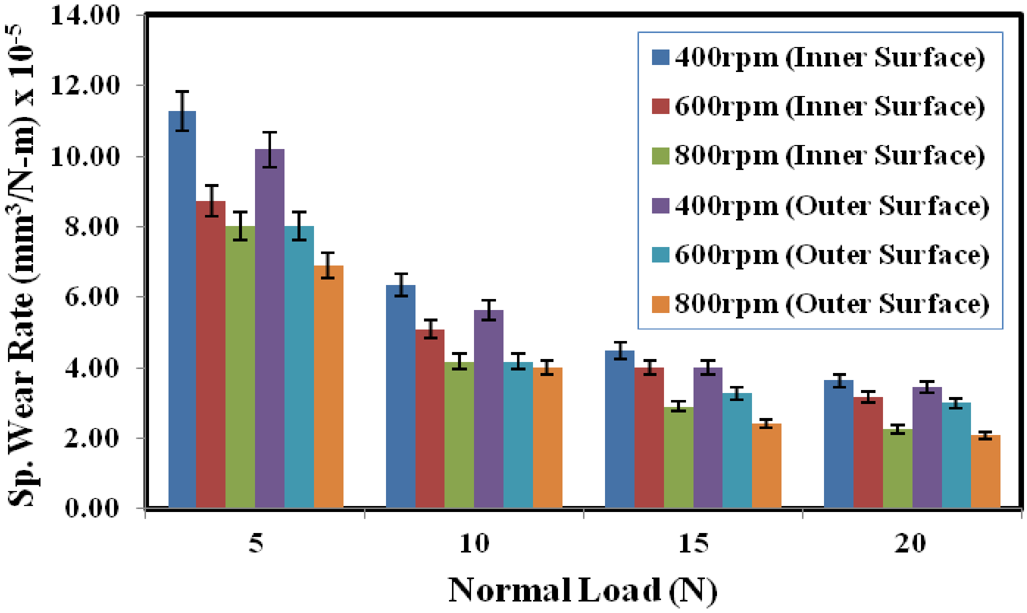


Figure 4.43 Specific Wear Rate of the Tin at Inner Surface and Outer Surfaces for Different Rotational Speeds of the Mold and 100°C initial Mold Temperature

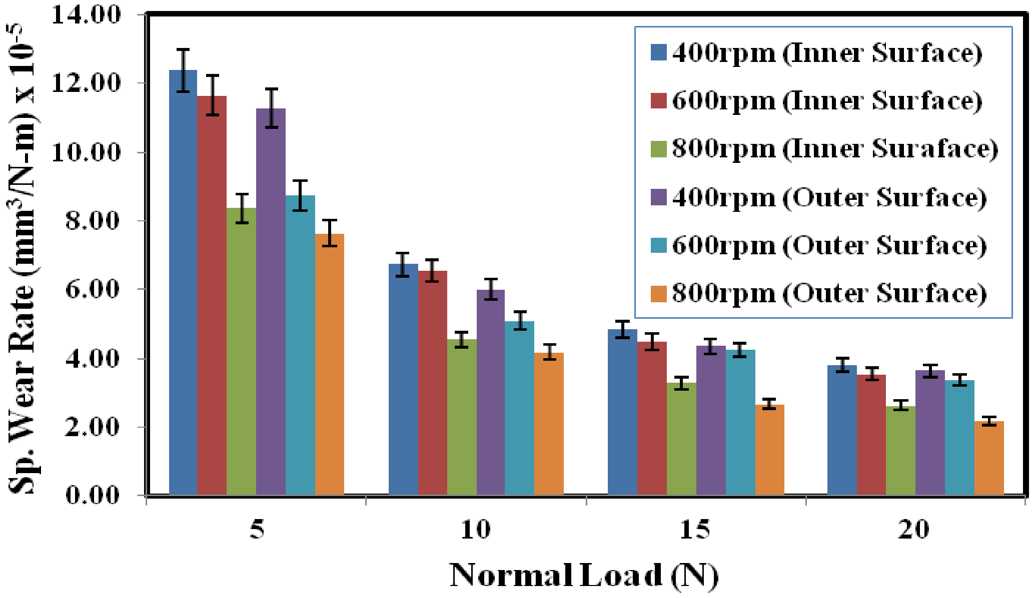


Figure 4.44 Specific Wear Rate of the Tin at Inner Surface and Outer Surface for Different Rotational Speeds of the Mold and 150°C Initial Mold Temperature

4.4.4.2 Influence of Initial Temperature of the Mold on Specific Wear Rate of Tin Centrifugal Castings

Figure 4.45- Figure 4.47 shows the variation of specific wear rate for different mold rotational speeds at a particular mold temperature. It can be observed that there is a strong influence of mold speed on specific wear resistance. At 50^{o}C mold wall temperature for a normal load of 5 N and mold rotational speed of 400 rpm (6.62G,) the specific wear rate is found to be 12.37 x 10^{-5} mm^{3}/N-m, whereas at 800 rpm (26.5G) it decreases to 6.55 x 10^{-5} mm^{3}/N-m. This shows a percentage decrease of 47% in specific wear rate. This trend is continued even for 10N, 15N and 20N normal applied load. But the influence of speed on specific wear resistance decreases at the higher normal loads. At 10 N the specific wear rate decreases by 40% for 800 rpm (26.5G) compared to 400 rpm (6.62G) similarly 37.5% for 15 N and 38.2% for 20 N. At 100^{o}C mold temperature a similar trend is observed as above with 45.2%, 42.8% 43.3% 37.63% for 5N, 10N, 15N and 20 N respectively. Even at higher temperature of the mold the same trend is continued with 42.8 % for 5 N and 38.6% for 20 N normal loads.

For a given mold wall temperature, the mold rotational speed influences the microstructure of the cast. The grain size is refined at higher rotational speed of the mold and shows higher hardness, which can be attributed to the faster cooling rate which decreases the grain size. When two surfaces are in contact the actual area is far less than the nominal area. The real contact area starts increasing with the increase in the applied load and the seizure of the surfaces is found to take place when the real area of contact becomes equal to the normal area of that surface. Since for tin recrystallization temperature is close to room temperature, increase in load offers same wear resistance due to recrystallization.

Wear resistance is found to be better in the presence of fine and equiaxed primary grains. From the above results we can see that the rotational speed of the mold is found to influence the quality of the microstructure which in turn influences the wear. At higher rotational speed due to the fast cooling effect fine equiaxed grains are formed enabling them to exhibit higher wear resistance even at higher applied loads. The wear patterns clearly indicate the absence of steady state wear even with the increase in the applied load on the test samples. From the graphs we can see that as the mold temperature is increased the wear resistance is decreased. The results shows that for 400 rpm(6.62G) and 5N normal load the specific wear resistances $10.19x10^{-5}mm^{3}$/N-m,$11.28x10^{-55}mm^{3}$/N-m, $12.35x10^{-5}mm^{3}$/N-m for a mold temperature 50^{o}C, 100^{o}C 1nd 150^{o}C respectively. This variation is seen for all the normal loads and continues to be similar. So it can be categorically said that casts produced with preheating the mold has a lesser wear resistant when compared to others. The results are compatible with the results of microstructure and hardness.

As seen from the graphs increase in mold temperature essentially means longer time to solidify. The rate of heat withdrawal from the melt to the mold is reduced because of the reduced thermal gradient due to which the solidification time is increased. This in turn effects the formation of the grains size during solidification. For higher solidification rate smaller the grain size and for the lower solidification rate the grain size will be higher. The higher cooling rate gives rise to a finer cast microstructure. From the literature survey it has been discussed that finer microstructure will increase the wear resistance where as for coarse structure wear resistance will be reduced.

Specific wear rates are highest at lower normal loads and keep decreasing with the increase in normal load. The magnitude of the specific wear rate correspondingly decreases when the rotational speeds of the mold are increased to 600 rpm (14.9G) and to 800 rpm (26.5G). Further the specific wear rate is also found to increase with the increase in temperature of the mold wall for obvious reasons.

The relationship between the specific wear rate and the normal load when plotted for a given rotational speed of the casting and also as the function of variation in mold temperature are plotted. Similar trends with specific wear rate decreasing with the increase in rotational speeds as well as lowest temperature of the mold wall attributable to variations in the cooling rates influencing the grain size and hence hardness.

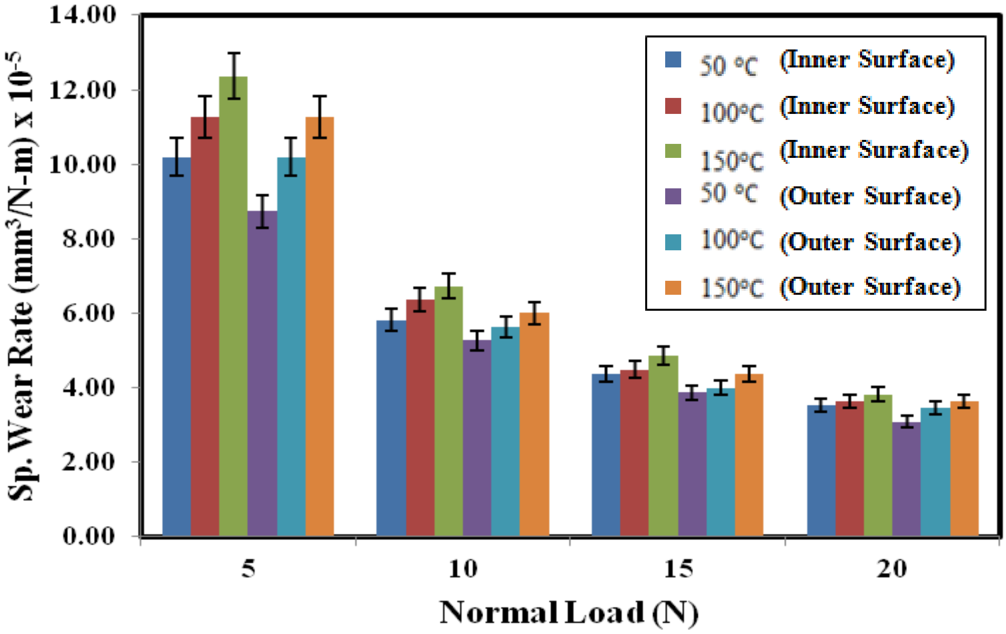


Figure 4.45 Specific Wear Rate of Tin at 400 rpm (6.62G) Rotational Speeds of the Mold with 11mm Wall Thickness

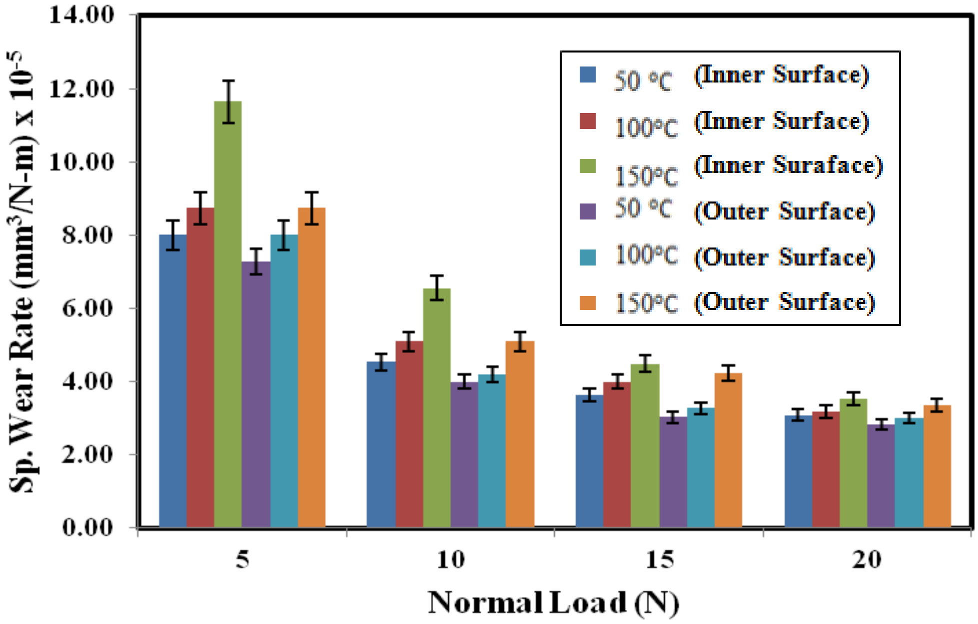


Figure 4.46 Specific Wear Rate of Tin at 600 rpm (14.9G) Rotational Speeds of the Mold with 11 mm wall Thickness

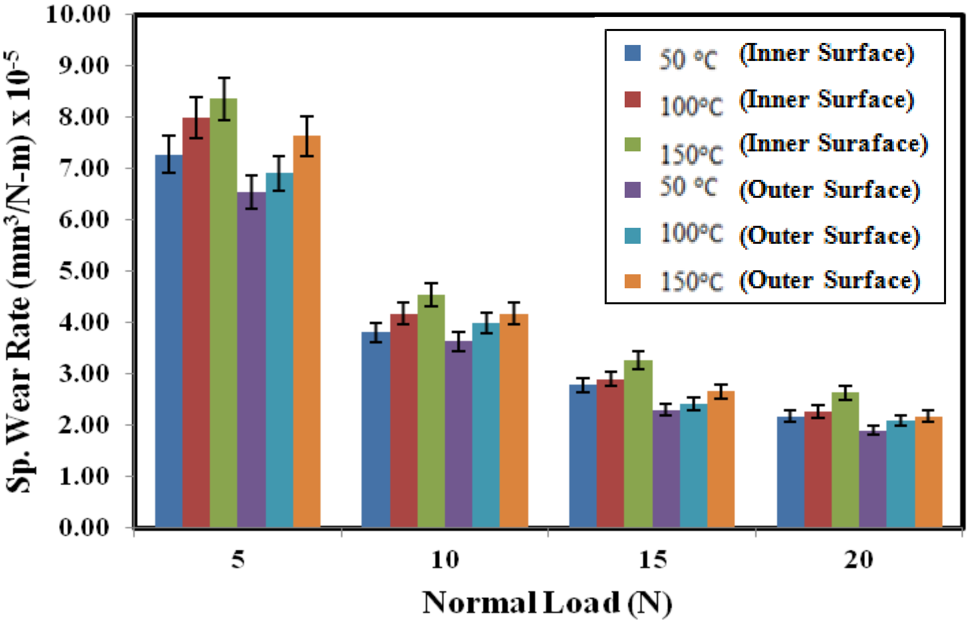


Figure 4.47 Specific Wear Rate of Tin at 800 rpm (26.5G) Rotational Speeds of the Mold with 11 mm Thick Wall Thickness

At maximum temperature the difference of the rate of heat transfer will be maximum, which is the driving potential for the heat transfer. As the temperature difference reduces the rate of heat transfer will decrease. Due to slower heat transfer rate the solidification time decreases and grain size will be coarse compared to faster cooling rate. Due to the reduction in rate of solidification of the centrifugal castings at increased mold temperature there will be an increase in the grain size and this leads to the decrease of hardness of the castings.

At higher testing load the specific wear rate is higher. But centrifugal castings produced at different mold temperature showed a slight variation in rate of solidification and also marginal increase in wear loss is observed. The reduced or no difference in specific wear rates in samples of Tin tested at higher loads can be ascribed to dynamic recrystallization that sets in metals like Pb, Sn etc.

4.4.4.3 Effect of Mold Wall Thickness

Figure 4.48 - Figure 4.50 shows the effect of speed on specific wear rate for different wall thickness of the casting. In this section the combined effect of wall thickness and mold rotational speed have been presented. From the graphs it has been seen that for a specific wall thickness at lower rpm the wear resistance is less as compared to higher mold rotational speeds. And the trends are very much similar to the previous section for all the wall thickness. And it is also seen that, at a particular speed and for a particular load, the specific wear rate decreased with increase in mold wall thickness. For 11 mm thickness at 400 rpm (6.62G) the specific wear rate $10.19\text{x}10^{-5}$ mm^3/N-m whereas for 21mm and 29 mm thick it is 9.46x 10^{-5} mm^3/N-m and $8.73\text{x}10^{-5}$ mm^3/N-m respectively. Similarly for 800 rpm (26.5G) and 20N normal load there is an increase of 12.9% for 21 mm wall thickness compared to that of 11 mm. Similarly an increase of 26.53 % for 29 mm wall thickness compared to that of 11 mm. This clearly indicates the wear resistance increased as the mold wall thickness increased.

From the theory of solidification for the material we know that solidification time is influenced by heat transfer coefficient, latent heat of solidification temperature difference across interface, cooling surface areas and volume of the casting. It has been well established that interaction between solidification front constituents as well as size of the constituent of the structure are responsible for the final distribution / grain size of a casting. In centrifugal casting where high centrifugal force is involved the structure becomes finer and equi-axed with higher angular velocities. The solidification front on the other hand moves in the opposite direction with a variable speed towards the inner surface of the casting. The cooling rate is increased by increasing the wall thickness which in turn affects the grain size. From the data obtained it is clearly evident that the increase in the thickness in wall increases the mechanical and tribological properties of the casting.

Specific wear rate as influenced by normal load for cast Tin test samples produced at different rotational speeds of the mold. Specific wear rate is highest when the normal load as well as mold wall thickness are minimum and keeps decreasing with the increase in the magnitude of the normal load as well as increase in the thickness of the mold wall for reasons associated with cooling rates and hardness. Further proportionate decrement in the trend in the magnitudes of specific wear rate is found when the rotational speeds of the mold are increased from 600 rpm (14.9G) to 800 rpm (26.5G) for the earlier cited reasons. Specific wear rate is directly proportional to the hardness, but at higher loads not seen in Tin, due to dynamic recrystallization that occurs when test load is higher.

Tin specimen produced at different mold speeds 400 rpm (6.62G), 600 rpm (14.9G) and 800 rpm (26.5G). As the mold wall thickness increases the hardness of the casting increases due to the rapid solidification rate. This is due to the reason that as the mold thickness increases the chilling effect of casting will increase.

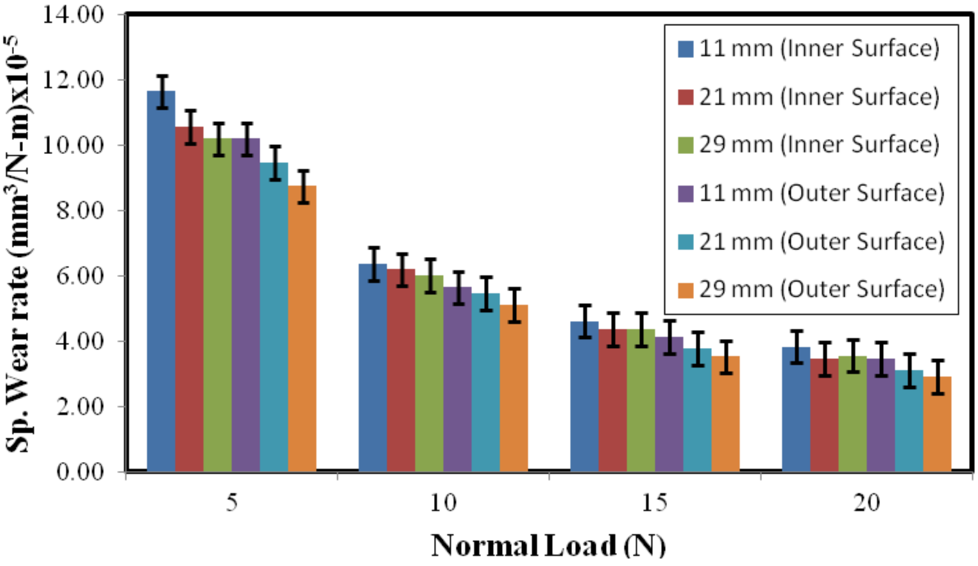


Figure 4.48 Specific Wear Rates at Different Mold Wall Thickness at 400 rpm (6.62G) of the mold

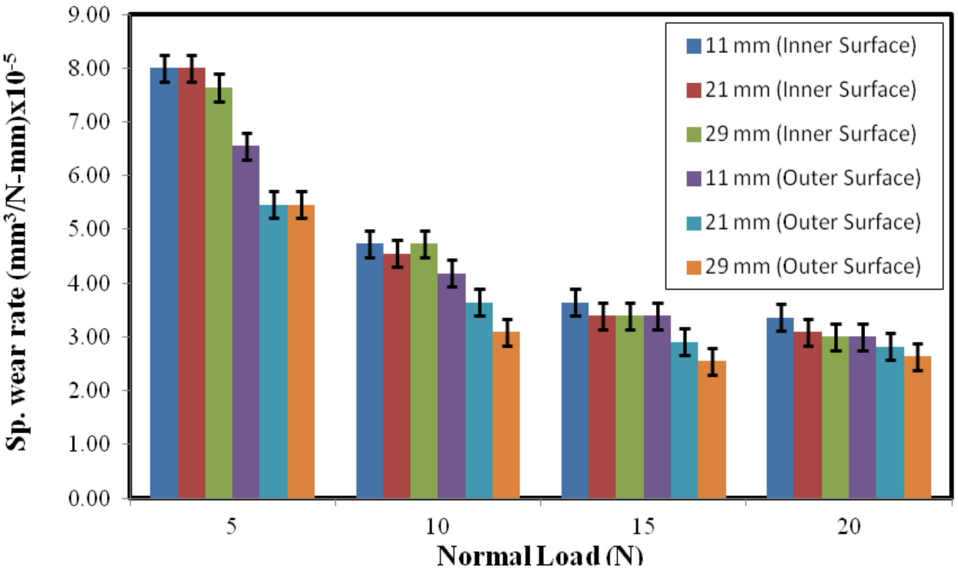


Figure 4.49 Specific Wear Rates at Different Mold Wall Thickness at 600 rpm (14.9G) of the mold

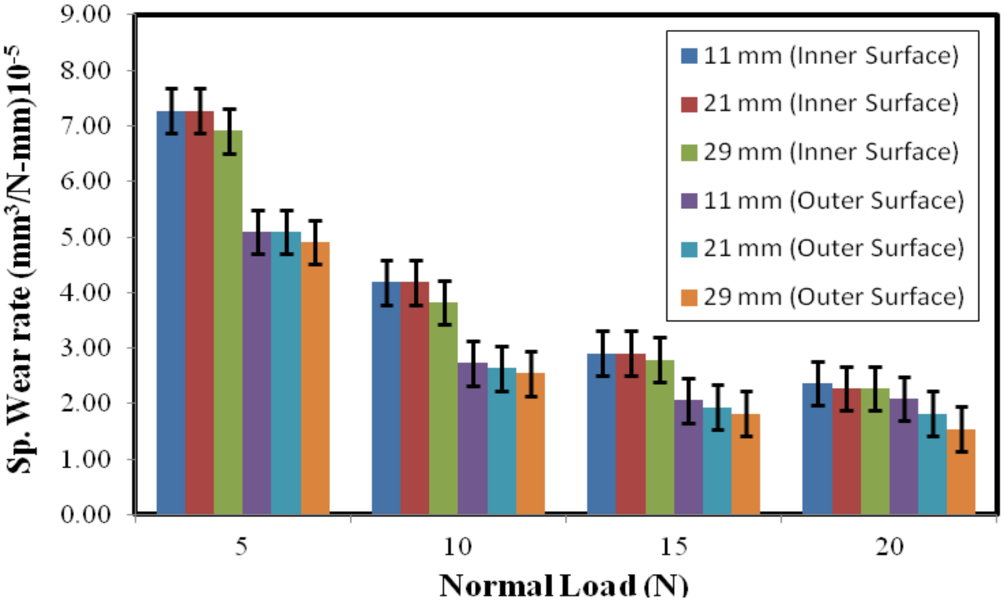
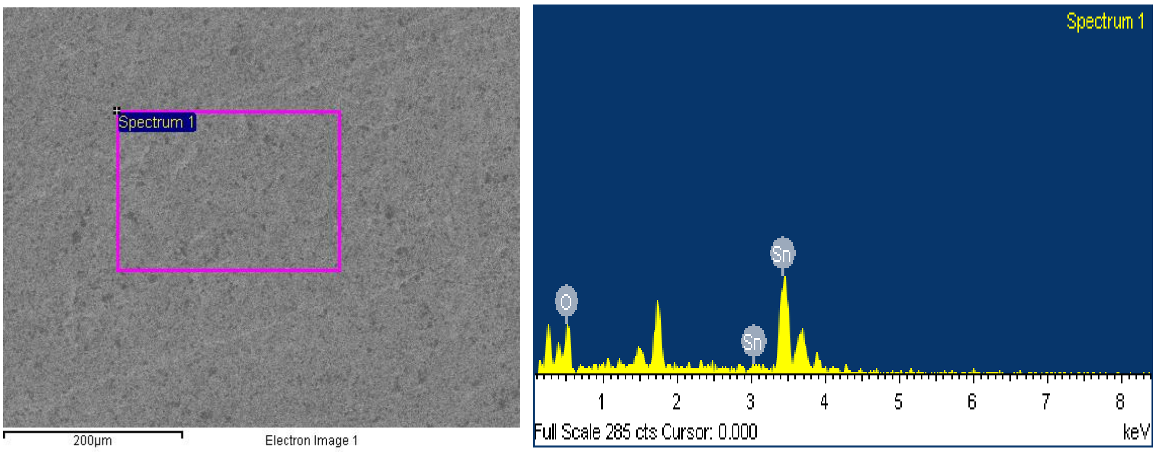


Figure4.50 Specific Wear Rates at Different Mold Wall Thickness and at 800 rpm (26.5G) Rotational Speed of the mold

4.4.5 SEM analysis of Centrifugal Casting of Tin

Tin is the softest materials available hence in comparison with Al-Si alloys the Tin wear out more. Based on these criteria the normal load selected for the wear test on

Tin is varying from 5N to 20N. The Figure 4.51 shows the SEM with EDAX of the unworn surfaces of Tin specimen which will undergo wear. The images clearly show the surface without any scratches, grooves and cracks.



Element	**Weight%**	**Atomic%**
O K	17.44	61.05
Sn L	82.56	38.95
Totals	100.00	

Figure 4.51 EDS Images of Tin Test Sample before Wear Test

SEM examinations of the worn pin surfaces after the wear test under dry sliding wear conditions have shown, different wear mechanisms like abrasion, delamination, adhesion and thermal softening and melting are operating either individually or in combination.

Figure 4.52 and Figure 4.53 shows the SEM image of inner and outer worn surfaces of the tin centrifugal casting produced at 400 rpm (6.62G) after wear test at lower normal load of 10 N. At lower loads the pin surface is having numerous ploughing grooves at inner surface and abrasion marks at the outer surface of the casting. Grooving and scratching are characteristics features of abrasion, in which hard asperities on the steel counter face or hard particles in between the contacting surfaces, plough or cut into the pin, causing wear by the removal of small fragments or ribbon like strips or small flakes of the material. This occurrence suggests that abrasion takes place primarily via ploughing, in which the material is displaced on either side of the abrasion groove. At higher load condition such as 20 N normal load condition the pin surfaces exhibited series of short cracks roughly perpendicular to the sliding direction. The intersection of these cracks result in the detachment of sheet like wear particles, causing shallow craters. This is a kind of fatigue wear mechanism in which repeated sliding induces subsurface cracks that gradually grow and eventually shear to the surface, forming wear sheets, this is known as delamination wear and is shown in Figure 4.54 and Figure 4.55. This is observed to be more extensive under the higher load. Since the delamination involves subsurface deformation, crack nucleation and crack propagation, an increase in load will hasten these processes and produce greater wear. The magnitude of this strain depends on the wear load and sliding speed and this tends to multiply the dislocations. Then the subsurface region is fragmented and redistributed near the surface region. This leads to a hardened layer.

The Figure 4.56 and Figure 4.57 shows the worn surface formed at 800 rpm of the mold speed at higher load condition with 20 N normal load. It shows only scratches at the inner and outer surfaces of the castings. This is due to the reason that at 800 rpm rotational speed the casting will be having harder surface due to the rapid cooling. These results are comparable with the earlier results of microstructure and the hardness study.

The Figure 4.58 (a) and (b) shows the EDS spectrum at the worn surface which exhibits some iron and fragmentation in this layer. This iron originated from the steel disc and is caused by metal transfer to the pin. Repeated sliding between the pin and the disc results in the formation of cracks and subsequent delamination on the wear surfaces of the pin. The various wear mechanisms and their regions of dominance show that transitions of wear from one group of mechanism to another are found to be dependent on Si content and the load.

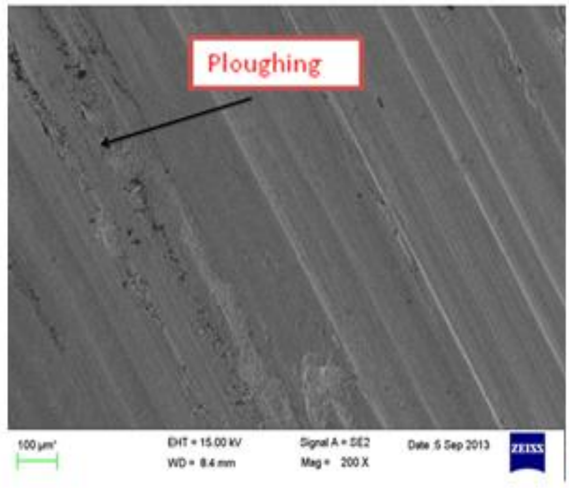


Figure 4.52 Ploughing at Outer Surface the Casting Produced at 400 rpm (6.62G) and Tested at 10 N Normal Load

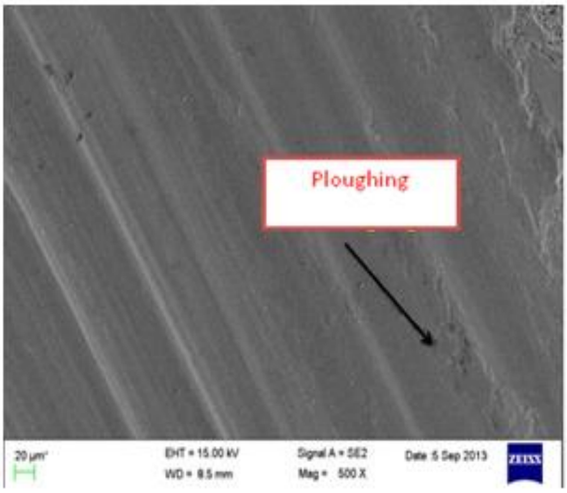


Figure 4.53 Ploughing at Inner Surface of of the Casting Produced 400 rpm(6.62G) and tested at 10 N Normal Load

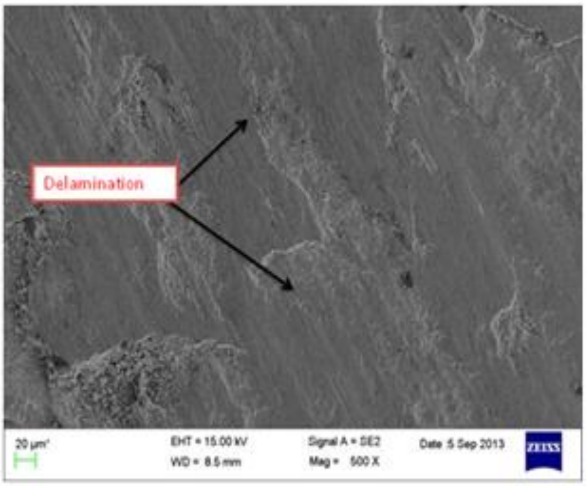


Figure 4.54 Delamination at Outer Surface of the Casting Produced at 400 rpm and Tested at 20 N Normal Load

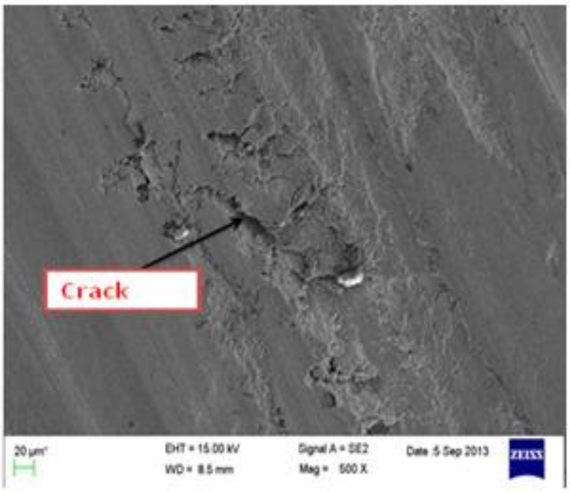


Figure 4.55 Crack Formation at Inner Surface of the Casting Produced 400 rpm (6.62G) and Tested at 20 N Normal Load

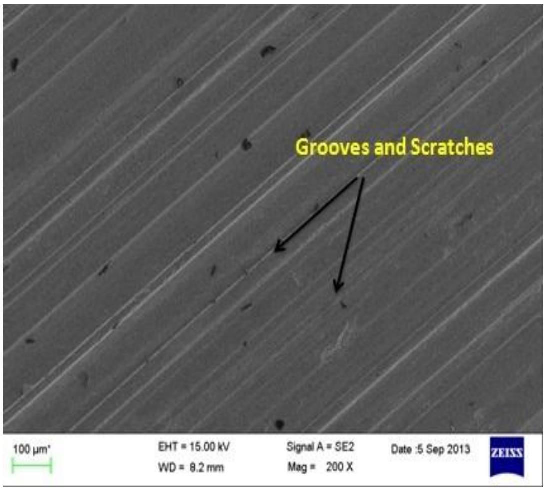


Figure 4.56 Grooves and Scratches at Outer Surface of the Casting Produced at 800 rpm and Tested at 20 N Normal Load

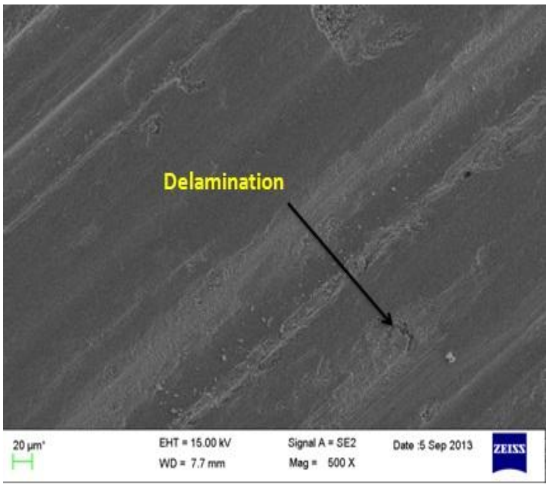
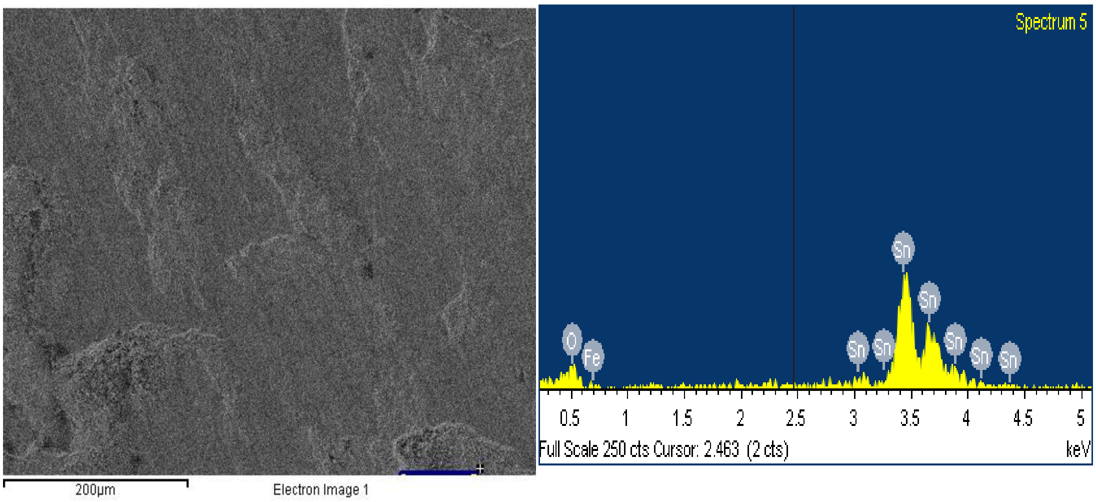


Figure 4.57 Delamination Wear at Inner Surface of the Casting Produced at 800 rpm and Tested at 20 N Normal Load



Element	Weight%	Atomic%
O K	22.64	67.49
Fe K	3.15	2.69
Sn L	74.21	29.82
Totals	100.00	

Figure 4.58 EDS Images Showing Traces of Fe on the Worn Surface

Under lower load, the effects of these are mitigated by the presence of oxide film which forms the stable protective layer. Under the higher loads the rate of removal of the oxide film exceeds that of its formation and a transition from oxidation to delamination and abrasion occurs. Therefore at higher loads a gradual transition occurs from delamination to adhesion.

4.5 CENTRIFUGAL CASTING OF Al-12wt%Si

In Centrifugal castings several parameters influence the microstructure, mechanical properties and distribution of phases inside the casting. The parameters include the centrifugal force, G force (Watanabe et al. 2001), cooling rate and heat transfer between the mold and the melt which are controlled by rotational speed of the mold, mold temperature, pouring temperature of melt, size and initial concentration of alloying element or particulate addition. All these parameter have influence on rate of solidification of the centrifugal casting. Therefore in the previous section the effect of these parameters on the solidification of tin has been discussed. Based on the grain size, the rate of solidification has been determined. In the next sections will focus on the effect of rate of solidification of the centrifugal casting on the quality of the Al-Si alloys. The rate of solidification is determined based on the Secondary Dendritic Arm Spacing. Since the process parameters affect the rate of solidification of the centrifugal castings, only effect of the rotational speed has been discussed in this study. And it is also known that the centrifugal casting of alloys show increasing tensile strength an additional phenomenon in case of alloys is the particle segregation (Matsuura et al. 2004). Therefore study has been extended to analyze the effect of rotational speed on the tensile properties in centrifugal castings of Al-12wt%Si and Al-17wt%Si alloys.

4.5.1 Effect of Rotational Speed of the Mold on Centrifugal Casting of Al-12wt%Si

The effect of process variables like rotational speed of the mold, mold wall thickness and temperature of the mold and its significance on the mechanical properties of a pure metal have been discussed in the previous part of this chapter. In case of alloys there are several other effects of process parameters on the microstructure are distribution of phases and their constituents in centrifugal castings. From the previous discussions it has been concluded that, variations in the above mentioned process variable affect the rate of solidification of centrifugal castings. Therefore in order to study the rate of solidification of alloys, only effect of rotational speed of the mold has been considered. In this work Al-12wt%Si (eutectic) alloy has been considered to understand the effect of process parameters on solidification and its effect on mechanical properties. Eutectic alloy of Al-12wt%Si has been considered because its solidification takes place at a fixed temperature and solidifies into two solid phases. Generally during solidification the silicon content of the melt and cooling rate are the process parameters that control the volume fraction and size of the silicon particles.

The mechanical properties of Al-Si cast alloys depend not only on the chemical composition but also on micro structural features such as size of dendritic α-Al, eutectic Si particles and other intermetallics that are present in the microstructures. The eutectic compositions of the binary Al-Si alloy are having close to 12% of Si. The concentration below this forms primary aluminum phases in the form of dendrites from the liquid. Silicon reduces the thermal expansion coefficient, increases corrosion & wear resistance and also improves the casting and machining characteristics of the alloy. When noneutectic Al-Si alloys solidify, the primary aluminum forms and grows into dendrites and silicon phase forms and grows as angular primary particles. When the eutectic point is reached the eutectic Al-Si phases nucleate and grow until the end of solidification (Haizhi Ye, 2002). The Si in eutectic of Al-Si forms as needles with random orientation.

In this work cylindrical castings of eutectic Al-12wt%Si are produced at three different rotational speeds of the mold, 400 rpm (6.62G), 600 rpm (14.9G) and 800 rpm (26.5G) as considered in the analysis of tin. The pouring temperature of the melt is maintained at 850^{o}C. The microstructures at three regions from inside to outside of the casting are considered for the analysis. The microstructure, secondary dendrite arm spacing (SDAS) for the determination of rate of solidification, hardness, specific wear rate for eutectic alloy under varying speed have been discussed. The distance of the secondary dendrite arm spacing (SDAS) has been measured, which is the function of rate of solidification. As demonstrated in the earlier literature that the smaller the SDAS the finer and more homogenous is the microstructure (Seifeddine et al. 2009).

From the previous discussions it is known that the microstructure in radial direction of the centrifugal casting changes from inner periphery to the outer periphery due to variation in rate of solidification, and also it is very difficult to find the solidification rate experimentally in centrifugal casting as the whole process of casting completes in a few seconds and at the same time it is a system wherein the mold and melt are all rotating. Therefore initially gravity castings of Al-12wt%Si alloy are made at four different cooling rates by conducting the experiments similar to that conducted for the gravity castings of Tin. The measured values of SDAS at the location of the thermocouple are plotted against the solidification rate which is obtained from four different cooling rates of the gravity castings of Al-12wt%Si. The reason of using this curve is to know the solidification rates in centrifugal casting of Al-12wt%Si.

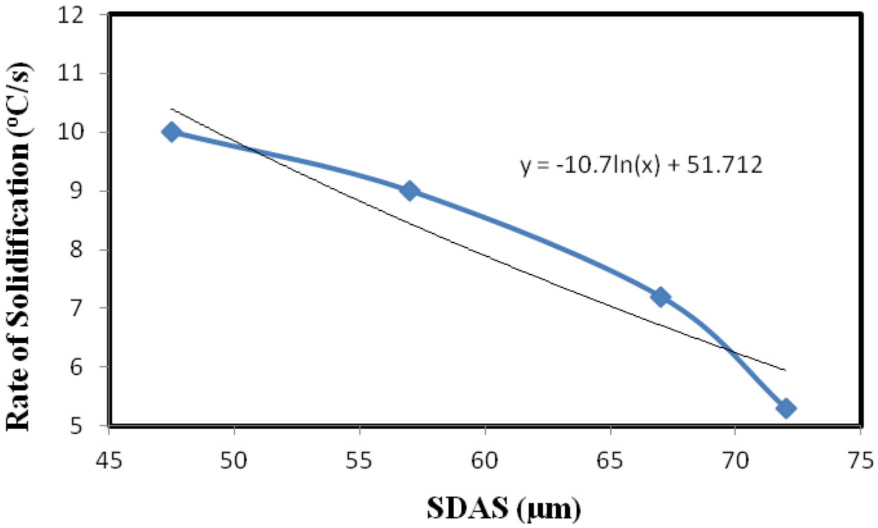


Figure 4.59 Relationship between SDAS and Solidification Rates of Al-12wt%Si

The Figure 4.59 shows the relationship between the SDAS and solidification rates obtained by four different cooling rates of Al-12wt%Si alloy gravity castings and the fitted logarithmic curve shows the expression, **Y = -10.7ln(x) + 51.712** which is used to measure the cooling rates of the centrifugal casting of Al-12wt%Si produced by varying the rotational speed of the mold which is one of the process parameters that affects the rate of solidification of centrifugal casting.

4.5.1.1 Microstructure, SDAS and Rate of Solidification of Centrifugal Casting of Al-12wt%Si

Figure 4.60-Figure 4.62 shows the variation in microstructure from inside of the cast sample to the outside along the radial direction at three different locations 2 mm apart in the centrifugally cast test samples of Al-12wt%Si. In this experiment castings are produced at three different speeds of the mold 400 rpm (6.62G), 600 rpm (14.9G) and 800 rpm (26.5G).

Microstructures of Al-12wt%Si alloy are composed of the dendrites of α_{Al} and eutectic $(\alpha_{Al}+\beta_{Si})$ in the inter-dendritic regions. The Silicon particles can be identified by its dark color and tendency to group together with other silicon particles. When solidified at a high cooling rate, these particles improve the mechanical properties of the alloy castings. When it is cooled slowly the eutectic particles become needle like layer, hence weakening the metal (Kammer et al. 1999).

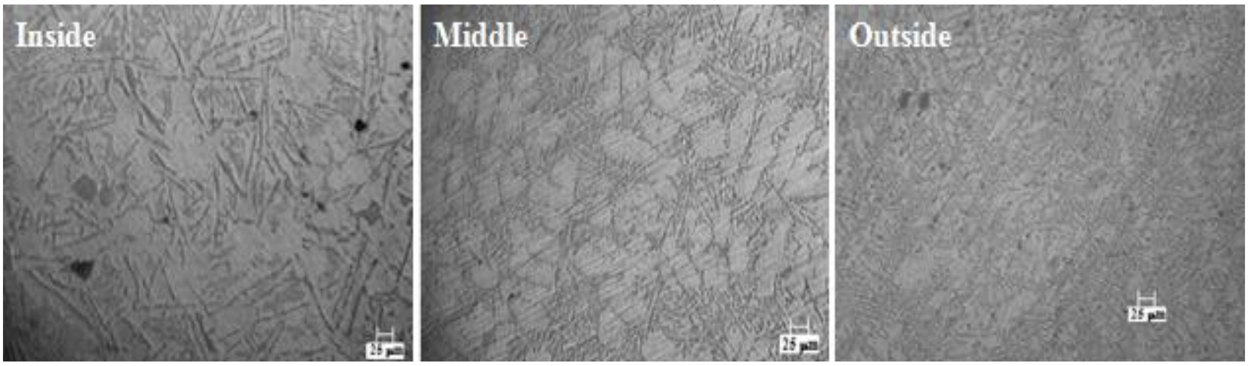


Figure 4.60 Microstructure of Al-12wt%Si Alloy Cast at 400 rpm (6.62G)

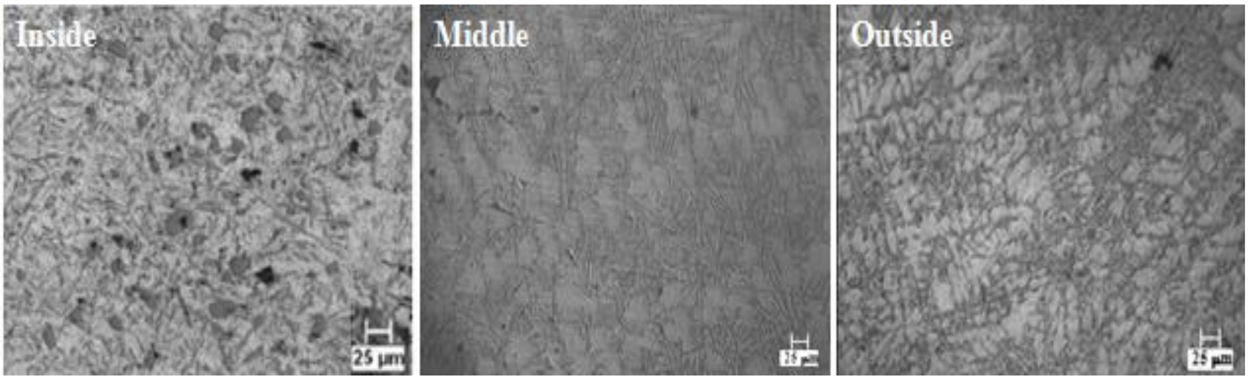


Figure 4.61 Microstructure of Al-12wt%Si Alloy cast at 600 rpm (14.9G)

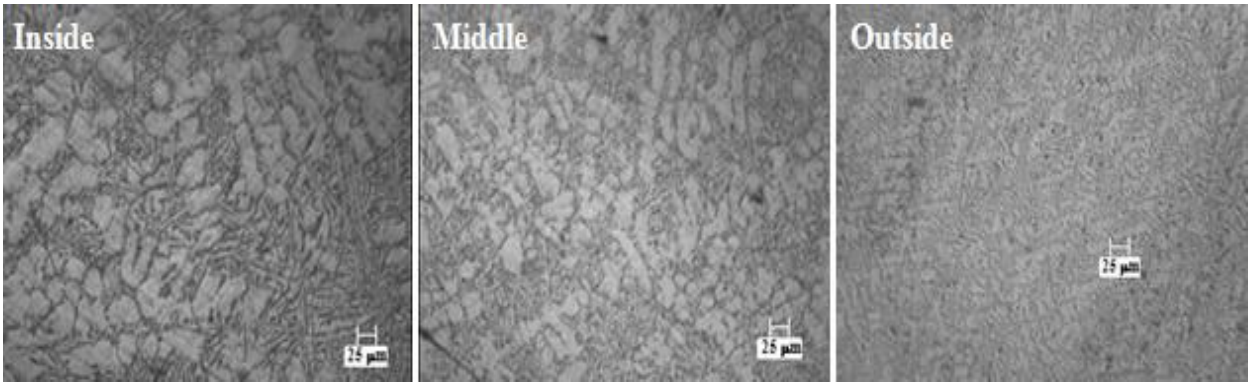


Figure 4.62 Microstructure of Al-12% wt Si Alloy cast at 800 rpm (26.5G)

Microstructure corresponding to 400 rpm (6.62G) shows coarse α_{Al} dendrites from inside to outside along the radial direction and dendrite size gradually increases towards inner radius. This is due to slower solidification rate at lower rotational speeds of the mold as discussed for the tin castings. The lower speed like 400 rpm (6.62G) does not provide enough centrifugal force to precipitate the particles before solidification and therefore there is no significant precipitation of primary Si particles (Mondolfo et al. 1976).

At slightly higher rotational speed of 600 rpm (14.9G) the microstructure shows finer dendrites and also shows small particles of primary Si near the inner surface. This is due to the centrifugal effect on the Si particles getting pushed towards the inner casting surface due to lower density of the particles. Fine α_{Al} dendrites are observed in the casting of Al-12wt%Si produced at 800 rpm (26.5G) of the mold rotational speed at the outer periphery. This occurs due to higher rotational speeds of the mold, where the melt solidifies rapidly giving rise to fine dendrites. At the same time increasing the speed increases the G force which in turn influences the precipitation of Si at the inner periphery. It is seen that the precipitation of Si is more for 800 rpm compared to 400 rpm and 600 rpm (14.9G) for the above said reason.

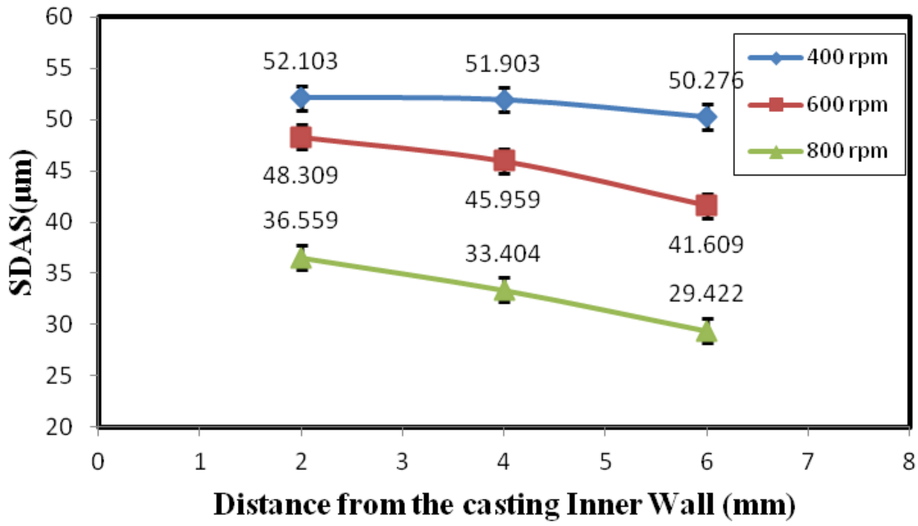


Figure 4.63 SDAS along the Thickness of the Centrifugal Casting of Al-12wt%Si

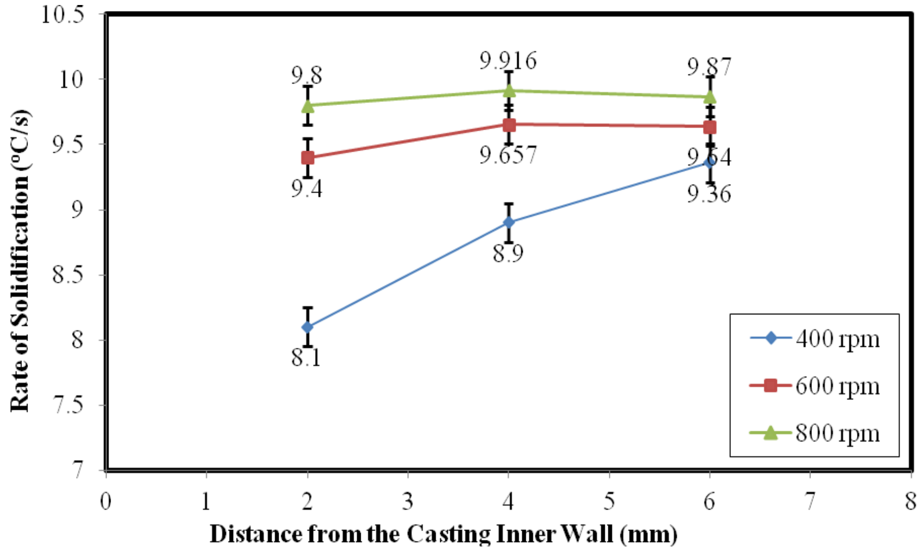


Figure 4.64 Rate of Solidification along the Thickness of the Casting

Figure 4.63 shows the values of SDAS (µm) measured along the radial direction of the casting from inner to the outer periphery of the cylindrical casting. From the graph it can be seen that the value of SDAS is more at the inner surface of the casting compared to outer. This is due to the reason that the direction of solidification is towards the inner surface from the mold surface as discussed under tin castings.

The calculated values of rate of solidification corresponding to the measured values of SDAS of centrifugal castings produced at different rotational speeds of the mold have been plotted. Figure 4.64 shows the rate of solidification along the radial direction from inside to outside of the casting for different rotational speeds of the mold. For the castings produced at 400 rpm (6.62G), the measured SDAS are 50.276 µm, 51.903 µm, 52.103 µm from outside to the inside of the casting. And the corresponding rates of solidifications are found to be 6.3 °C/s, 6.1 °C/s and 5.9°C/s, respectively. Also for the casting produced at 600 rpm (14.9G) of the mold speed are observed to be 5.4 °C/s, 5.0 °C/s and 4.2°C/s corresponding to the SDAS of 41.609 µm, 45.959 µm and 48.309 µm. Similarly for the casting produced at 800 rpm of the mold rotational speeds are 3.1°C/s, 2.4°C/s, 1.2°C/s corresponding to the SDAS of 29.422 µm, 33.404 µm and 36.559 µm respectively.

The decrease in rate of solidification towards the inner surface of the casting is due to the reason that, when the metal enters the mold cavity it is always in contact with the previously solidified hot metal. Therefore temperature difference will be very small between the solidified metal and fresh melt, hence heat dissipation rate is reduced hence rate of solidification also decreases.

From the above discussion it is seen that in centrifugal casting it becomes very vital to know the solidification rate. The solidification rate plays an important role in defining the structure and segregation of Si. The segregation of Si towards the inner periphery increases as the mold rotational speed increases. The segregation of few Si particles at the inner portion of the casting is attributed to the lower density of the silicon particles in comparison with that of the liquid alloy. Similarly it is also seen that the structure at the outer periphery which is of dendritic in structure also depends on the solidification rate which is defined by SDAS. The middle region consists of rich α-Al solid solution.

4.5.1.2 Hardness

The hardness is measured in the radial direction at four locations such as 1 mm, 3 mm, 5 mm and 7 mm distance along the radial direction in the casting. At least five readings at each radius have been measured and average of closest three has been considered. It has been known that during solidification of the alloy castings low density particles are segregated towards the inside which in turn significantly improves mechanical properties such as hardness and tribological properties such as wear. It is also known from the previous discussion that the presence of Si at the inner surface is influenced by the dominant process parameter which is the mold rotational speed of the mold.

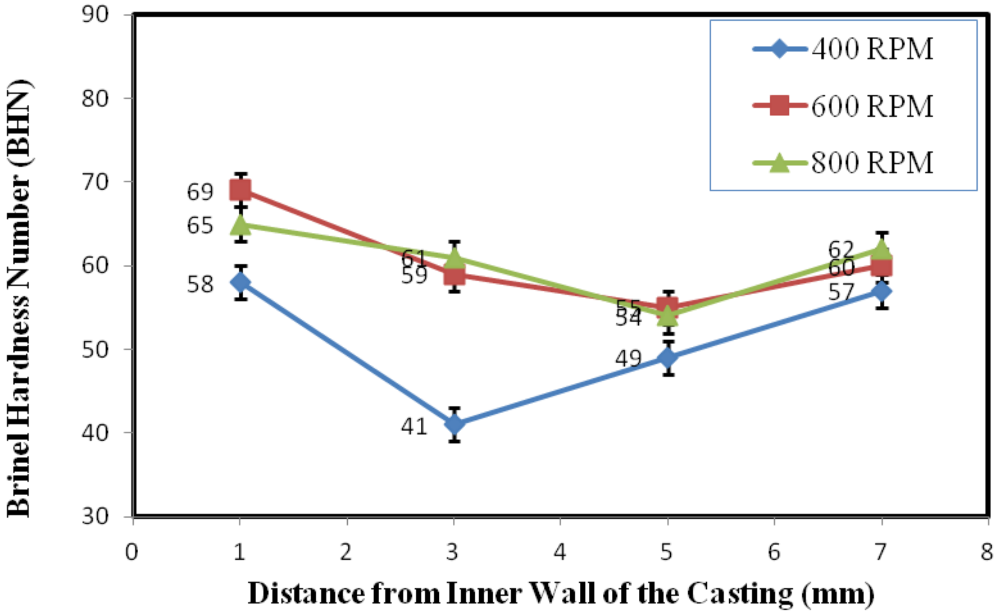


Figure 4.65 Hardness of Al-12wt%Si along the Radial Direction

From the Figure 4.65 it is seen that the hardness are more at the inner surface compared to the outer surface of the casting, but the difference between the two is very small. The hardness at the intermediate region is very small compared to outer and inner. Castings produced at 800 rpm (26.5G) show the hardness of 89 BHN at inner and 82 BHN at outer having intermediate values of 81 BHN and 75 BHN at a distance of 3 mm and 5 mm from the inner. This trend is followed for other two castings also which are produced at 400 rpm (6.62G) and 600 rpm (14.9G). Low hardness are obtained at rotational speed of the mold is 400 rpm (6.62G) and these results are in agreement with the microstructures.

The variation in the hardness is dependent on the rate and direction of solidification and also on particle distribution (volume fraction) due to centrifugal action. As the rotational speed is increased the variation in the hardness also varies which corresponds to the microstructures obtained. It has been discussed in the previous chapter that as the speed increases from 400 rpm (6.62G) to 800 rpm (26.5G), the hardness value increases due to the rapid solidification. Increase in hardness value at the inner surface is due to the reason that the primary silicon particles are concentrating at the inner radius because of the density difference between reinforcement and melt and also due to centrifugal force. Higher values of hardness are seen at the inner radius and outer radius of the casting (Prasad et al. 1998). At the inner surface due to the chilling effect, the hardness will be high and at the inner surface hardness increases due to the concentration of primary Si particles which are forced towards the inner radius. When the mold is rotating, due to the centrifugal effect the Si particles being lesser density will move towards the inside, i.e towards the axis of rotation. If the mold rotation speed rises, the centrifugal force acting on heavy particles intensifies segregating more of Si in casting section. Severe segregation of Si at higher rotation speeds is due to rejection of the liquid metal rich in Si from α_{Al} dendrites.

4.5.1.3 Specific Wear Rate of Centrifugal Casting of Al-12wt%Si

Previous sections indicated that the centrifugal castings of Al-12wt%Si produced have two structures at the outer and inner diameter of the casting that are totally different in their nature. The wear volume is directly proportional to applied load and sliding distance and inversely proportional to the hardness. Thus wear resistance can be related to the hardness specific wear rate which is defined as the wear rate per unit load and unit sliding distance. Wear tests are conducted to determine the specific wear rate under different normal loads with constant sliding distance of 90 mm track diameter and at a constant sliding speed of 300 rpm.

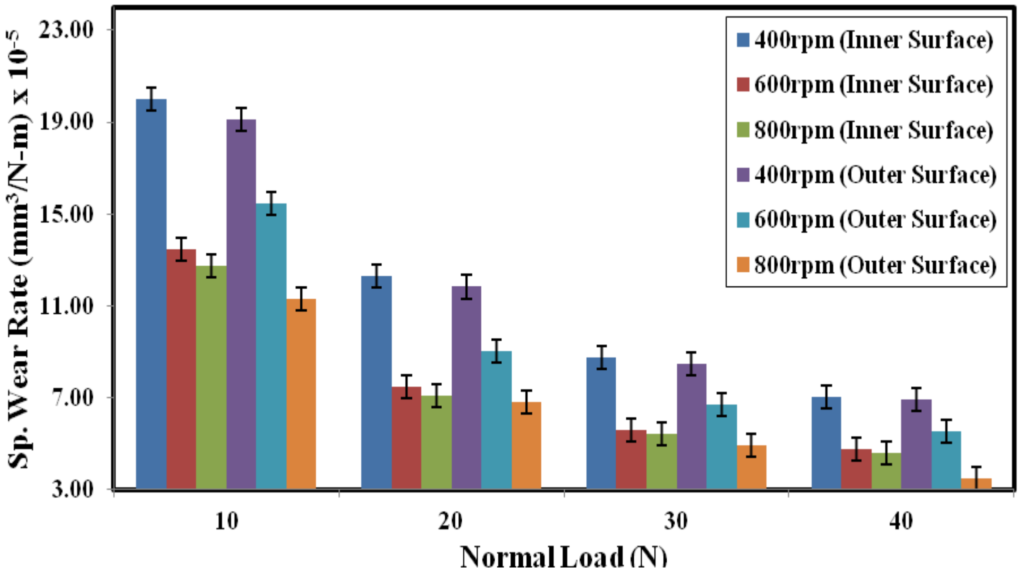


Figure 4.66 Specific Wear Rates at Inner Surface and Outer Surface of Al-12wt%Si Alloy at Different Rotational Speeds of the Mold

It is clearly observed that the specific wear rate for a sample is more at the outer surface of the casting than at the inner surface of the casting as shown in Figure 4.66. It has been observed that the mold rotational speed has a very significant effect on the specific wear rate. At a constant teeming temperature and mold temperature it is found that the specific wear rate of the specimen cast at different mold speeds decreased towards the inner surface of the casting. And values of specific wear rates were found to be lower for the castings produced at higher rotational speeds of 800 rpm (26.5G) which is due to the higher hardness values of the castings produced at higher rotational speeds of the mold. Also the values of specific wear rate are higher at the outer surface of the casting. The decrease in the specific wear rate at the inner can be attributed to the presence of more amounts of Si particles at the inner surface of the centrifugal casting which has been revealed through microstructure in Figure 4.60- Figure 4.62 and hardness in Figure 4.65 studies. Primary Si particles are found to be concentrated at the inner radius hence showing decrease in specific wear rate at the inner portion of the casting (Shailesh et al. 2010).

The major mechanism responsible for the wear of aluminum silicon alloy is the delamination of surface material. The breaking of silicon particles or silicon and matrix interfaces can initiate micro cracks. These micro cracks propagate along the subsurface until they reach the surface where the whole piece of material is removed. Simultaneously external abrasives can cut off the soft aluminum matrix by local plastic deformations if there is no protection from the secondary hard phase.

From the Figure 4.66 it is seen that there is an increase in wear resistance at the inner surface of the casting by 40% for 10N load and 400 rpm (6.62G) of the mold. A similar trend is observed for increasing loads 20 and 30N. From the graph it is also noticed that as the speed is increased the wear resistance increased at the inner surface. An increase of 36.36% wear resistance is found for 800 rpm (26.5G) mold speed compared to 400 rpm (6.62G) at 10N load. This trend is continued for all other loads. Therefore the mold rotational speed shows a very significant effect on the specific wear rate. At the constant teeming temperature and mold temperature it is found that the specific wear rate of the specimen cast decreased in case of specimens cast mold rotational speeds. It is also seen that there is no significant effect of mold rotational speed for the outer portion of the casting. At outer region, it is found that on an average the specific wear rate remains constant for all samples for different process parameters. The decrease in the specific rate at the inner surface can be attributed to the more amount of Si present at the inner surface of the casting which has been revealed through microstructure and hardness studies. This leads to a decrease in specific wear rate. Crack nucleation generally occurs at some depth below the surface rather very near to the surface, owing to the very high hydrostatic compressive pressure acting near the asperity contact. Thus, once a crack is nucleated, its propagation is slow and seizure does not occur, owing to the presence of well distributed particles in the matrix (Jahanmir et al. 1977).

The specific wear rate is distinctly different for the inner and outer surfaces. The toughness and strength of the alloy increases with the presence of primary Si which leads to decreased wear rate as compared to the outer region where primary Si is absent. This could be due to the fact that at lower silicon content dislodging of material was more when compared to the higher silicon content.

From the previous discussion we can see that the there is a segregation of hard particles to the inner radius of the cylinder compared to the outer. This attributed to the fact that the Si is lighter in density compared to the matrix aluminum wherein, the Si is forced to segregate through the process of precipitation at the inner radius of the cylinder. It is also seen that the Si segregation increased as the speed of the mold is increased. Another important feature noted from the Figure 4.65 is that at the outer surface of the casting the hardness remained nearly same for all the speeds of rotation.

4.6 CENTRIFUGAL CASTING OF Al-17wt%Si

The basis of material science involves, relating the desired properties and relative performance of a material in a certain application is due to the phase structure in that material (Kiran et al. 2011). The major determinants of the structure of a material and thus of its properties are its constituent chemical elements and the way in which it has been processed into its final form.

Several parameters determine the microstructure and distribution of phases inside the casting. These parameters are the size and initial concentration of alloying element or particulate addition, which are depends on the centrifugal force and solidification rates of the casting which are controlled by the heat transfer between the mold and the melt and G force (rpm).

From the literature survey it is seen that the mechanical properties of Al-Si alloy not only depends on chemical composition but also more on micro structural aspects. Thus the centrifugal casting technique helps in changing the morphology of dendritic α-aluminum eutectic phase and primary Si particles in hyper eutectic region. From the literature survey it is also seen that by changing the micro structural morphology of Al-Si alloy the wear characteristics of a particular material can also be changed. It has been reported that the different phases in an Al-Si alloy acts differently when it is subjected to wear.

In this present work centrifugal castings of Al-17wt%Si alloy are produced at three different rotational speeds of the mold such as 400 rpm (6.62G), 600 rpm (14.9G) and 800 rpm (26.5G). The mechanical properties such as hardness along the radial direction, specific wear rate and tensile strength are discussed. And volume fraction of Si particles is analyzed for the three castings.

While producing the hollow cylindrical castings using centrifugal casting process for Al-Si alloy it is seen that Si particles are radially distributed towards the axis of rotation. This segregation of Si is basically due to the density difference between melt and reinforcement. It is seen that since the density of the reinforcement Si is lower than the density of the matrix Al the Si particles are segregated towards the axis of rotation. So it can be clearly understood that centrifugal force i.e. the rotational speed of the mold plays an important role in redistributing the particles radially in centrifugal casting. The size of the silicon particles in Al-Si alloys depend on the solidification range and chemical composition and can be controlled by the cooling rate variation. So during solidification of Al-17wt%Si alloys, the morphology and distribution of silicon particles formed as the primary or eutectic constitutes determine the mechanical properties of the casting. In case of alloys it becomes necessary to know the effect of process variables on the particle segregation during the solidification of centrifugal casting.

4.6.1 Effect of Rotational Speed of the Mold on Particle Distribution of Si in Centrifugal Casting of Al-17 wt % Si

During the rotation of the mold in centrifugal casting the particle suspended in the melt subjected to both centrifugal force and gravitational force. As the rotational speed increases the force acting on the particles increases which leading to the segregation to increase and same has been observed in this investigation. The volume fraction of the Pro-eutectic Si obtained at the inner surface also increases with increase in the rotational speed of the mold (Panda et al. 2006). In the Al-Si system, the primary aluminum rich phase grows dendritically, where as the silicon grows in a facetted manner. The segregation and precipitation of Si to the inner radius of the casting during centrifugal casting is attributed to the density difference between the Si and the melt. The Si particles are pushed to the inner diameter by the centrifugal force. The thickness of particle free zone decreases with increasing particle volume fraction, while the gradient region increases (Bonollo et al. 2003).

An image analyzer is used to measure the concentration of the Si particles across the casting section and also to analyze the microstructure and Si distribution along the radial direction of the cast samples of Al-Si. The area occupied by the primary Si in the whole matrix has been calculated and concentration of the Si Particles is determined in terms of percentage occupied in total area of the microstructure.

4.6.1.1 Microstructure, Volume Fraction of Primary Si in Centrifugal Casting of Al-17wt % Si alloy

The rotational speed of the mold has strongly influenced the structure development and the distribution of the primary silicon. Figure 4.67 to Figure 4.69 shows the microstructure of Al-17wt%Si casting produced at three different rotational speeds of the mold such as 400 rpm (6.62G), 600 rpm (14.9G) and 800 rpm (26.5G). Microstructural examinations revealed that the structure of the specimens cast by centrifugal casting was quite different from that of the normal gravity casting. The microstructure shows primary α_{Al} dendritic solid solution from inside surface of the casting to outside surface, which is due to the rapid solidification of the centrifugal casting and also leads to the presence of primary Si particle distribution across the casting. Due to the centrifugal effect on the particles there is a gradient of Si particle distribution exists across the thickness of the casting. Near the outer surface of the casting chilling effect suppresses primary silicon nucleation and results in near hypoeutectic structure. The optical micrographs of specimens show microstructures with a non uniform distribution of needle-like Si particles in the matrix of α-Al (eutectic) at the outer surface of the casting. As observed towards the inner region, micrographs showed similar microstructure, except with increasing primary Si concentration. At the inner region of the casting, the Al-17wt%Si alloy exhibits not only needle-like eutectic Si phase but also large faceted massive primary Si crystals that signify a high silicon hypereutectic microstructure.

Under equilibrium condition, Al-17wt%Si should have shown primary Si and eutectic only. Due to difficulties in nucleation growth of nonmetallic Si primary aluminum dendrites and some primary silicon along with eutectic are seen in the microstructure. Hence the differences in the microstructure across the thickness of the castings. Relative high under cooling application on an alloy of a given composition causes dendritic growth in which metallic phases grow rapidly and the other phase or micro constituent solidifies between dendrites while lower under cooling leads to cellular growth. The difference between microstructures across the thickness resulted from different cooling rates are also under the influence of high G forces.

During mold rotation, the particle suspended in the liquid is subjected to centrifugal force acting on a particle is given as $\boldsymbol{mr\omega^2}$ and the gravitational force is given by $\boldsymbol{mg}$. The ratio of the centrifugal force to the gravitational force is called the gravitational coefficient (G) or G number. The thickness of the Si rich (primary) layer which indicates the extent to which Si particles have segregated along the radial direction of the specimen is called the rim thickness. The rim thickness decreased with increased mold speed for a given mold. This is attributed to the increase in cooling rates of the casting at higher rotational speed of the mold. It can be noted that, as the angular velocity increases, the G factor increases (Watanabe et al. 2001). Since the centrifugal force acting on the particle is G times higher than the gravitational force, the role of gravitational force can be ignored. Thus as the rotational speed increases, the force acting on the particles to segregate is expected to increase, as observed in the study.

For the Al-17wt%Si alloys cast at 850^{o} C pouring temperature, the influence of the rotational speed of the mold for evaluations of the percentage of Si segregated at three different thicknesses of the casting have been studied. The three locations are considered at steps of 2 mm from inside to outside of the casting such as 2 mm, 4 mm and 6 mm.

For the casting produced at lower rotational speed of 400 rpm (6.62G) of the mold, coarse primary α_{Al} are formed due to slower cooling rate. The casting produced at 600 rpm (14.9G) of mold speed, the microstructure showed a gradation of primary silicon along the radial direction. This is due to the higher rotational speed of the mold and due to higher cooling rate, the Si particles are pushed towards the inner surface. But the casting produced at 800 rpm shows fine primary Silicon particles throughout the cross section of the casting which is shown in Figure 4.69. This is due to the rapid solidification of the casting at around 800 rpm, continuously metal gets solidified as long as the metal is poured to the rotating mold. The primary Si particles formed are segregated as a graded layer near the inner surface of the casting leading to a better hardness and improved wear resistance of the inner surface.

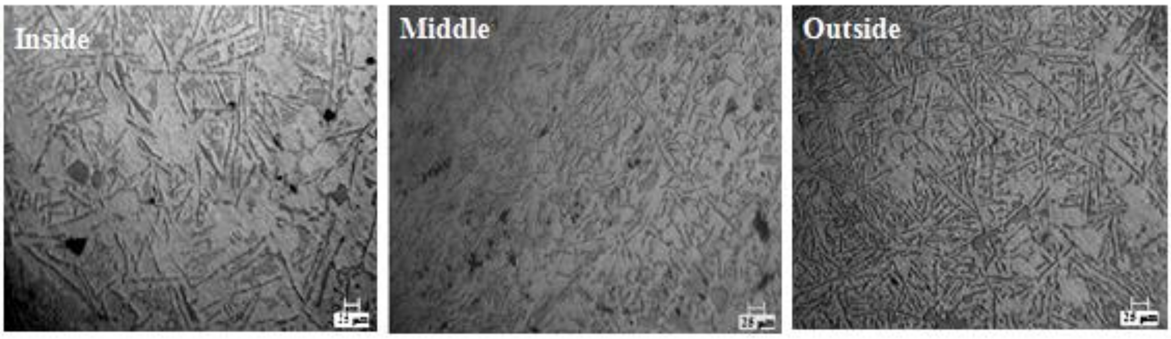


Figure 4.67 Microstructure of Al-17 wt % Si at 400 rpm (6.62G) of Rotational Speed of the mold

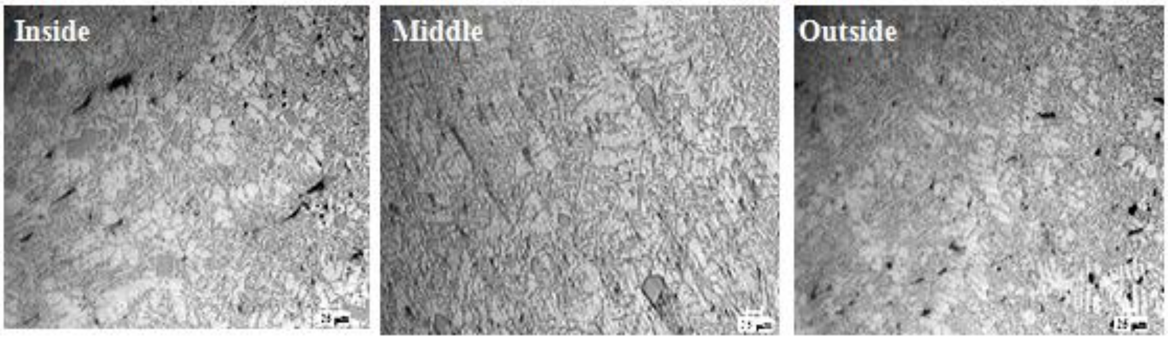


Figure 4.68 Microstructure of Al-17 wt % Si at 600 rpm (14.9G) of Rotational Speed of the Mold

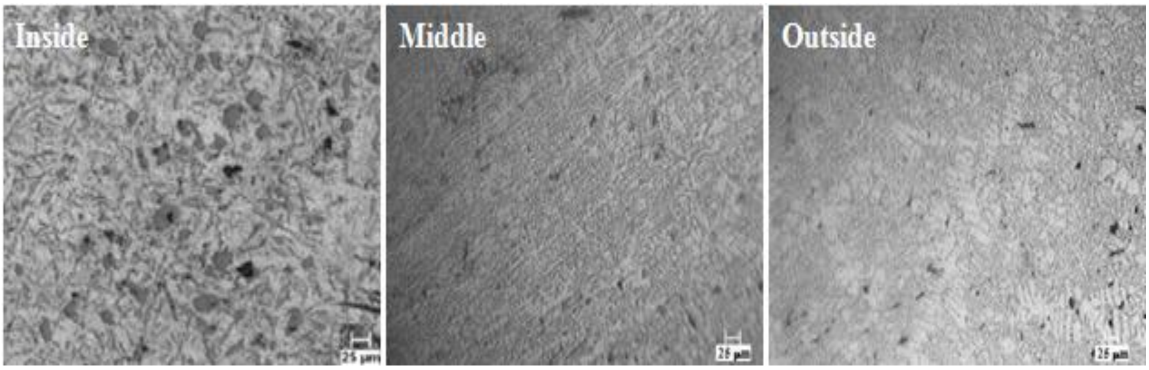


Figure 4.69 Microstructure of Al-17 wt % Si at 800 rpm (26.5G) of Rotational Speed of the Mold

The origin of the graded structure is due to the density difference between the melt and Si, wherein the density of the Si is much less and the centrifugal force enables stratification resulting from sedimentation, a floatation of solids from liquids. Further seperation of aluminum and Si in the melt occurred during the early stage of the centrifuging, resulting in the formation of a melt with compositional gradient prior to the crystallization of primary crystals (Watanabe et al. 2005).

The region near the outer surface of the centrifugal casting of Al-17wt%Si shows a very fine primary Al dendrites structure with minimum spacing between them. This shows the rapid solidification of the casting at the outer surface. And inner surface of the casting shows Al dendrites with bigger spacing with primary Si particles shows slow cooling rate of the casting. This is in agreement with observations made by earlier similar works (Kumar et al. 2010, Rajan et al. 2009).

Figure 4.70 shows the percentage of primary silicon concentration across the thickness of the casting at different rotational speeds of the mold. The centrifugal casting produced at 600 rpm (14.9G) shows maximum percentage of Si particles at the inner diameter. This is because at 600 rpm (14.9G) rotational speed causes maximum centrifugal force on the Si particles and also due to lower rate of solidification compared to 800 rpm (26.5G) the Si particles are pushed towards the centre. But at 800 rpm (26.5G) the centrifugal force may be maximum, but the casting solidifies rapidly and Si particles will be trapped in due to rapid solidification of the casting. But compared to casting produced at 400 rpm (6.62G) the Si particles are concentrated more at the inner surface in case of 800 rpm rotational speed. The Si particles are pushed towards the inner diameter due to its lower density compared to Al matrix and also due to the centrifugal force caused due to rotation of the mold.

Maximum of 10% of Si was observed at the inner radius and 2% at the outer radius of the casting produced at 600 rpm (14.9G). The casting produced at 400 rpm (6.62G) shows 4% of primary silicon at the inner radius and 5% at the outer radius. Similarly 7% of primary silicon at the inner radius and 4 % silicon at outer radius of the casting produced at 800 rpm (26.5G). Fine particles of primary silicon were observed at 800 rpm (26.5G) due to the rapid solidification. The average size of the silicon particles is 26µm, 20µm and 10µm were observed for the casting produced at 400 rpm (6.62G), 600 rpm (14.9G) and 800 rpm (26.5G) respectively.

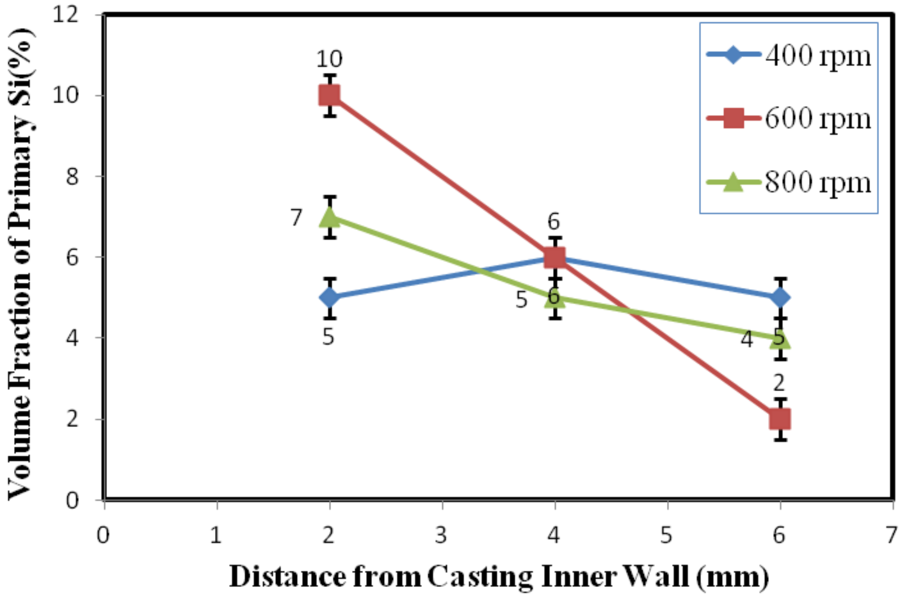


Figure 4.70 Volume Fraction of Primary Silicon of Al-17%wt Si Casting at Different Rotational Speeds of the Mold

4.6.1.2 Hardness

Hardness values are determined by following the method used in case of Al-12wt%Si. Figure 4.71 shows the Brinell Hardness Number (BHN) along the radial direction of the Al-17wt%Si produced at three different rotational speeds of the mold. The hardness number is directly related to the microstructure formation. At the outer surface of the casting it is found to be higher values of hardness and also at the inner surface of the centrifugal casting of Al-17wt%Si. Higher values of the hardness at the outer surface are due to the chilling effect of the mold. As soon as metal touches the mold surface immediately melt gets solidified and hence hardness is found to be slightly a higher value. At the inner surface of the casting the hardness value is varying depending upon the primary silicon concentration. Casting produced at 600 rpm (14.9G) shows highest value of the hardness at the inner surface due to the maximum concentration of the primary silicon at the inner surface. And also due high centrifugal force Si particles will be pushed towards the inner surface separating from the aluminum.

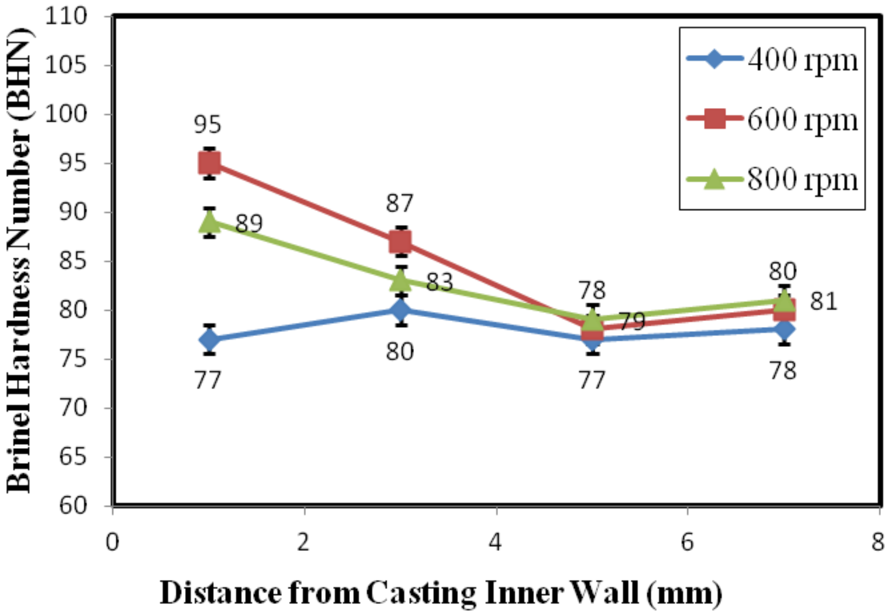


Figure 4.71 Hardness at Different Locations Along the Radial Direction in Centrifugal Casting of Al-17wt% Si at Different Rotational Speeds of the Mold

4.6.1.3 Specific Wear Rate of Centrifugal Casting of Al-17wt%Si

Wear test was conducted to investigate specific wear rate under 4 different normal loads and at a constant sliding speed of 300 rpm. Specific wear rate is a function of volume loss, sliding distance and normal load. Specific wear rate is inversely proportional to the normal load for a constant sliding distance. The actual area of contact becomes equivalent to the normal area with an increase in the normal load on the pin resulting in an increase in the magnitude of the frictional force between pin and the disc which increases the magnitude of wear. By study of wear surface of the counter surface we can quantitatively describe the wear process.

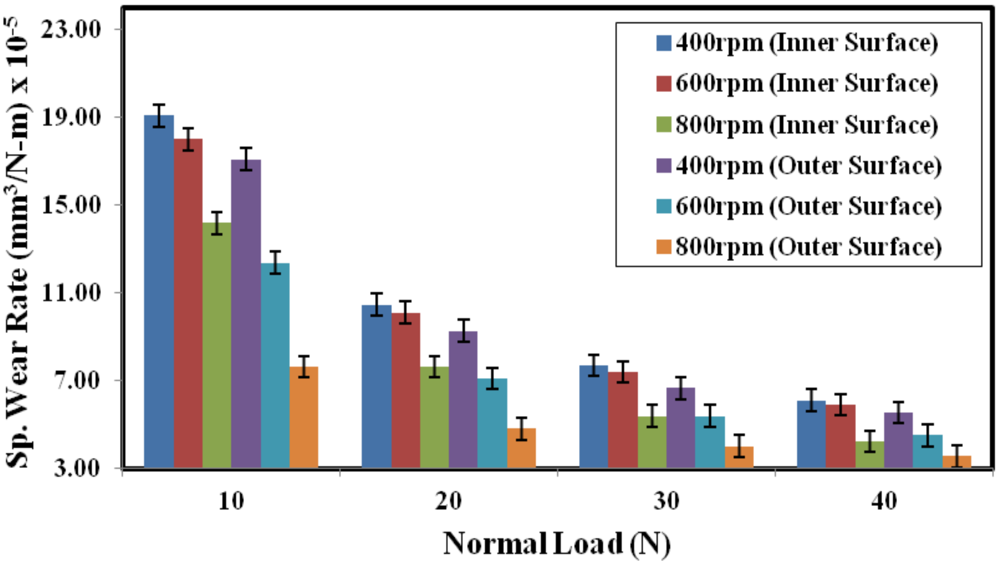


Figure 4.72 Specific Wear Rates at Inner Surface and Outer Surface of Al-17wt% Si Alloy at Different Rotational Speeds of the Mold

Figure 4.72 shows the specific wear rate of centrifugal casting of Al-17wt% Si alloy produced at different rotational speeds of the mold. It is noted from the graph that at 5N normal load there is a decrease of 5.4% in specific wear rate for 600 rpm (14.9G) compared to 400 rpm (6.62G). Similarly, 13.6% for 800 rpm compared to 400 rpm (6.62G). However, there is not much significant improvement between 10 N and 20N normal loads. The difference of only 6.7% improvement for 600 rpm (14.9G) and 5.4% for 800 rpm (26.5G) improvement is achieved. From this, we can clearly establish the significant effect of mold rotational speed on specific wear rate of the casting. From the results, we can see that for a particular teeming temperature the specific wear rate decreased significantly as the speed increased. The decrease in the specific wear rate at the inner surface of the casting is achieved because more amount of Si presence in the specimen as the mold rotational speed is increased. This follows the results of microstructure and hardness discussed before. The toughness and the strength of the alloy increases with presence of primary Si, which leads to a decreased specific wear rate.

From the above graphs it is also seen that as the pouring temperature is increased the specific wear rate decreased. This also prevents scratch and cut from the hard counter face. From the results of microstructure, hardness and wear, comparing all the three it is found that wear resistance is better in the presence of fine and equi axed primary α grains and uniform distribution of second phase particles. This is influenced by mold rotational speed. At higher speeds of 800 rpm (26.5G) the large primary α-grains are converted into fine equi axed and that of eutectic Si needles into fine particles enabling them to exhibit higher wear resistance similar to grain refined modified structures.

From the wear analysis it is seen that at lower loads they appears as smooth worn surface with continuous grooves with smaller width. With increasing load the width of the groove increases. Further it is seen that a transition occurs from mild wear to severe wear when the load or speed exceeds a certain value. This creates maximum surface damage and metal transfer takes place to the counterpart. This is confirmed by the EDS spectrum.

At lower loads, the load is supported because of the resistance offered by the structure but the wear rate increases as the load is increased. At the end of this severe wear takes place which is dominant. Here the wear debris collected shows fine powders which clearly indicates of this type of wear mechanism which is called as adhesive wear which involves delamination. As we know the wear is influenced by the sliding speed, applied load, counterpart surface, environmental temperature and atmosphere.

Here further rotating the disc beyond the critical value of severe wear, wear debris in the form of flakes are collected which clearly indicates the abrasive wear which involves the fracture of the worn surface which is caused due to the deep grooves in which perpendicular cracks are produced with respect to the grooves. Further there will be a plastic deformation and shear fracture which is of dominant and found to be different in different regions.

4.7 TENSILE STRENGTH OF CENTRIFUGAL CASTINGS OF Al-12 wt%Si AND Al-17 wt%Si

The high specific tensile strength of aluminum alloys is very strongly influenced by their composed poly-phase microstructure (Chirita et al. 2006). The properties of a specific alloy (hypoeutectic, eutectic or hypereutectic) can be attributed to the individual physical properties of its main phase components (α-aluminum solid solution and silicon particles) and to the volume fraction and morphology of these components. Mechanical properties of the aluminum alloys are strongly dependent on the effect of SDAS and grain size. Tensile properties increase with a decrease in the SDAS and vice versa (L A Dobrzanski et al. 2007). The increase in grain size increases the Yield stress as per Hall-Petch equation (2).

i.e. $$\sigma y = \sigma i + kd^{-1/2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(2)$$

σy=Yield Stress, σi=Yield Stress for a crystal of the same material where there are no grain boundaries, k= Constant & d = average grain diameter). Also it is known that increasing the Si content results in an increase of the strength of hypoeutectic alloys and a decrease of the strength of hypereutectic alloys (Stroganov, et at., 1977).

The mechanical properties of cast aluminum – silicon alloys can be improved by centrifugal casting. In this section the effect of process variable on the tensile properties of Al-12wt%Si and Al-17wt%Si have been discussed. For each speed three samples are made and tested using an electronic extensometer as discussed earlier.

Figure 4.73 shows the combined Ultimate tensile stress - strain diagram for the Al-12wt%Si and Al-17wt%Si castings produced at three different rotational speeds of the mold 400 rpm (6.62G), 600 rpm (14.9G) and 800 rpm (26.5G). From the analysis of tensile strength it can see that there is continuous improvement in the tensile strength of the centrifugal castings with the increased rotational speeds of the mold. The greatest benefits were achieved for the Al-12wt%Si and Al-17wt%Si cast samples which were produced at 800 rpm. The maximum value of Tensile strength at 800 rpm (26.5G) for is 120.3N/mm^2**.** This shows there is a substantially improvement in the alloy properties of centrifugal casting samples of Al-12wt%Si produced at 800 rpm (26.5G). The value of Tensile strength at 400 rpm (6.62G) is found to be lower than the castings produced at 800 rpm (26.5G) and the value is 107.8N/mm^2. This is due to the reason that at lower the speeds of rotation the rate of solidification is lower. Even the tensile strength of the casting produced at 600 rpm (14.9G) lies between the values of tensile strength of the castings produced at 400 rpm (6.62G) and 800 rpm (26.5G). Therefore there is a good correlation between the mechanical properties and microstructure which was discussed earlier.

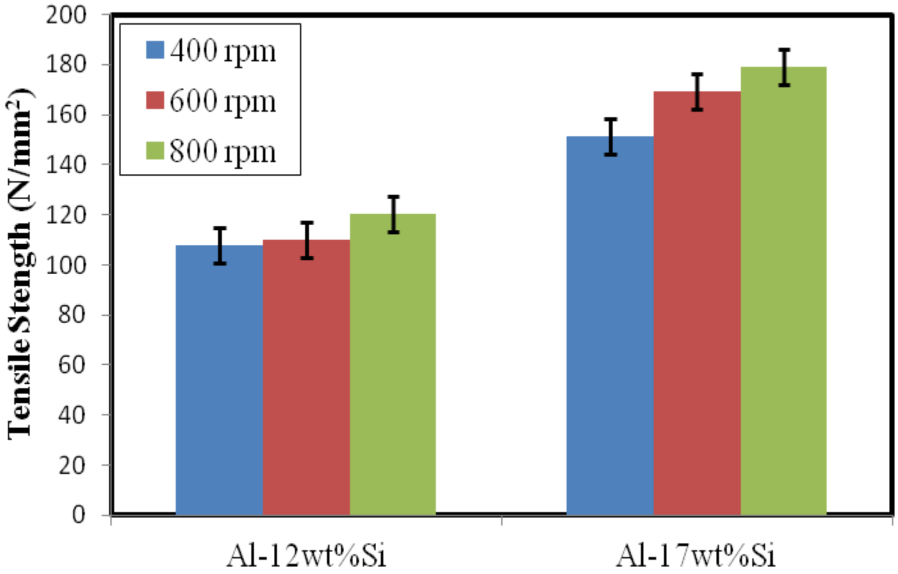
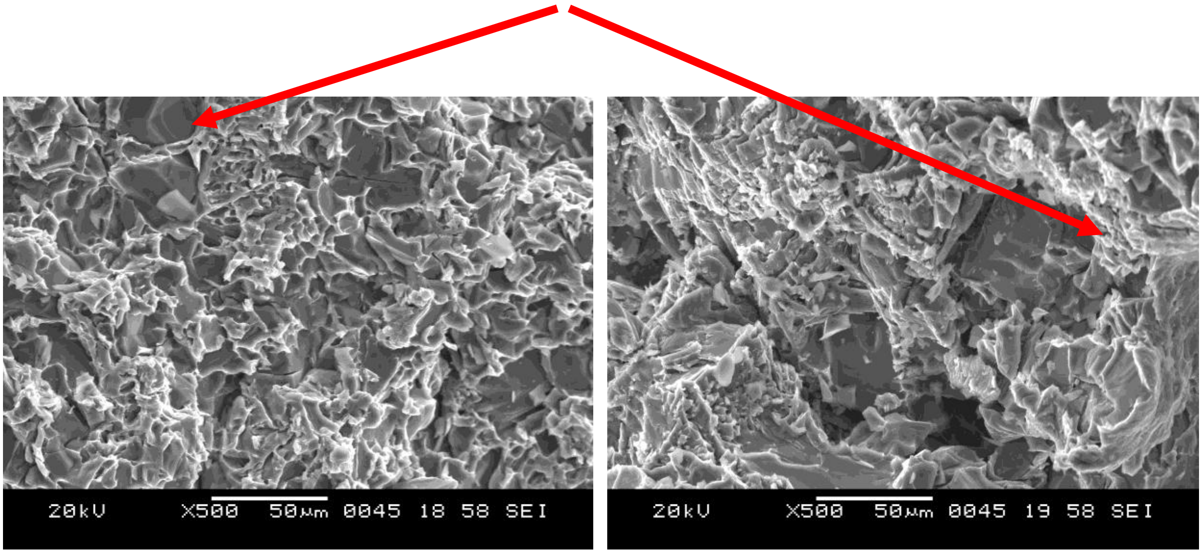


Figure 4.73 Tensile Strength of Al-12 wt % Si and Al-12 wt % Si Castings Produced at Different Rotational Speeds of the Mold

From the above results, it can be seen that as the magnitude of rotational speed of the mold is increased the tensile strength is also increased. The microstructures are progressively improved with the rotational speed. The common defects in aluminum castings like pin holes, porosities, inclusions are eliminated. Further, it is also noted that as the speed is increased the refinement of Si increases which in turn will increase the tensile strength.

The analysis of tensile strength shows the greatest improvement in tensile strength of the Al-17 wt % Si test samples at higher speed of 800 rpm (26.5G) compared to the casting produced at 400 rpm (6.62G) and 600 rpm (14.9G) of the mold. At 800 rpm the fine globular primary Si are formed which will provide higher strength to the metal. The average value of tensile strength results from the casting which is produced at 400 rpm (6.62G) is 151.2 N/mm², 600 rpm (14.9G) is 169.2N/mm² and at 800 rpm (26.5G) it is 178.9N/mm². This is due to the rapid cooling of the casting obtained at 800 rpm and also due to the refinement of primary silicon particle shape and size.



Void formation and concoidal fracture during tensile test

a b

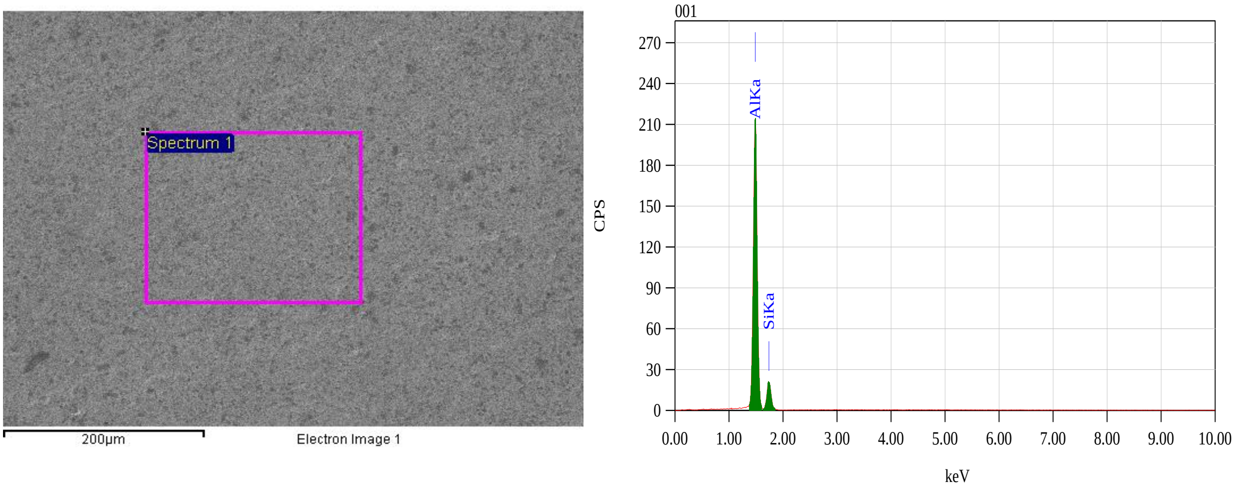
Figure 4.74 The Fractured Surfaces of the Tensile Specimens under SEM of Centrifugal castings: a) Al-12 wt % Si and b) Al-17 wt % Si Produced at 800 rpm (26.5G) of the Mold

Figure 4.74 a) and b) shows the fracture surfaces of the tensile specimens under SEM of centrifugal castings of Al-12wt%Si and Al-17wt%Si alloys. It is seen that the surface obtained at lower rpm is rough in nature because of the larger grains present in the alloy. But as speed increases it is known that the grain size becomes finer. The SEM at 800 rpm shows a finer fractured surface with some dimples as compared to the lower rotational speeds. In case of Al-17wt%Si the fractured surface shows the mixed modes like brittle and ductile fractures and Al-12wt%Si shows homogeneous modes of fracture. It clearly shows that the increases in properties are mainly due to structural difference of the castings which is mainly due to solidification rate which is controlled by mold rotational speed. It can be seen that at higher speed the particles are formed with rounded corners throughout the matrix and has formed along the inter-dendritic region. This is also one of the reasons for improving the strength of the matrix. It also reveals a fine equiaxed α–Al grains with rounded silicon. This increases the energy absorption of the material remarkably.

Examinations of the fractured surfaces revealed a dimpled morphology in the material, this is a characteristic of ductile process of nucleation, growth and coalescence of micro voids. The voids are concave micro regions of the material de-cohesion usually around the hard particles i.e. Si. The first type dimples are of rounded hallows on the fracture surface. The Second types are smaller dimples which are neighboring the Si particles and these small dimples are a variety of potential nuclei sites within the ductile matrix due to inter metallic inclusion and Si particles. The growth extensions of this type of dimple were less when the Si concentration was higher.

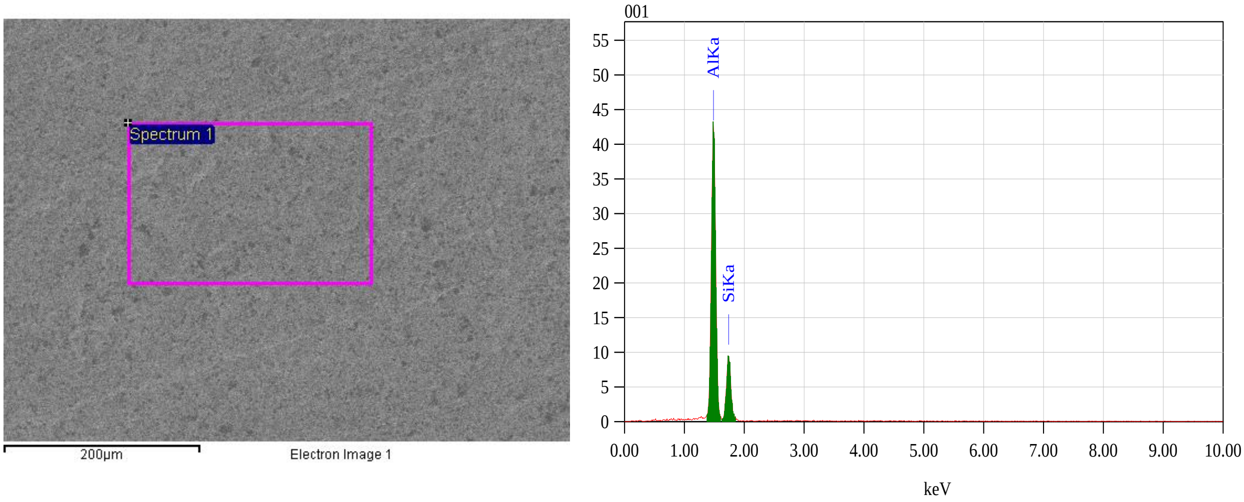
4.8 SEM ANALYSIS OF Al-12%wt Si AND Al-17%wt Si SPECIMENS

The Figure 4.75 and Figure 4.76 shows the SEM with EDS for the Al-Si alloy specimens Al-12wt%Si and Al-17wt%Si without wear. The image clearly shows the surface of the specimen without any scratches, grooves and cracks. Similarly the EDS of the alloy surface don’t show any Fe content, this confirms without wear of the surface.



Element	Weight%	Atomic%
Al K	89.7551	90.23
Si K	10.2449	9.77
Totals	100.00	

Figure 4.75 EDS Images of Al-12wt%Si before Wear Test



Element	Weight%	Atomic%
Al K	80.39	81.02
Si K	19.61	18.98
Totals	100.00	

Figure 4.76 EDS Images of Al-17wt%Si before Wear Test

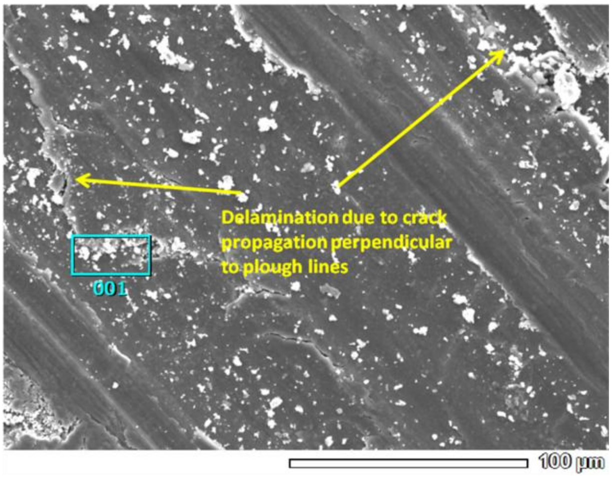


Figure 4.77 Delamination Due to Cracks at the Inner surface of the Al-12wt% Si

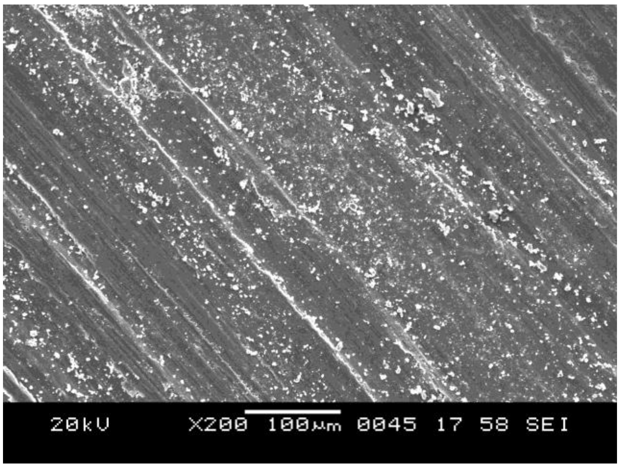


Figure 4.78 Long, Shallow grooves of Varying sizes Caused by Abrasion at the Inner Surface of Al-17wt % Si Casting

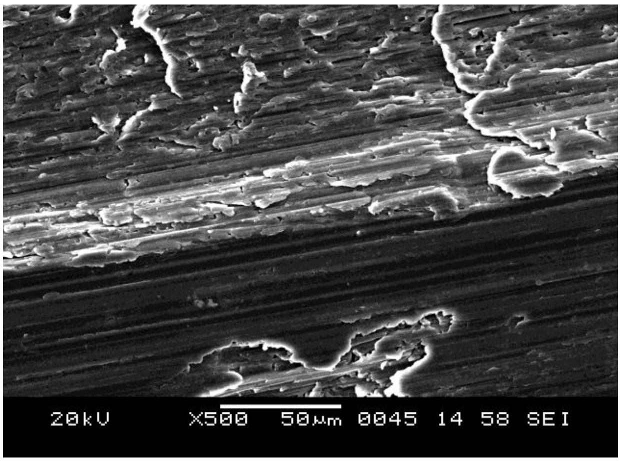


Figure 4.79 Cracks and holes caused by Delamination at the outer region of the Al-12wt %Si

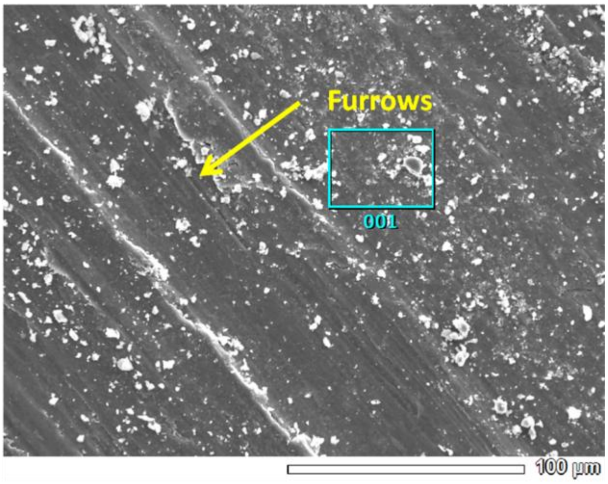
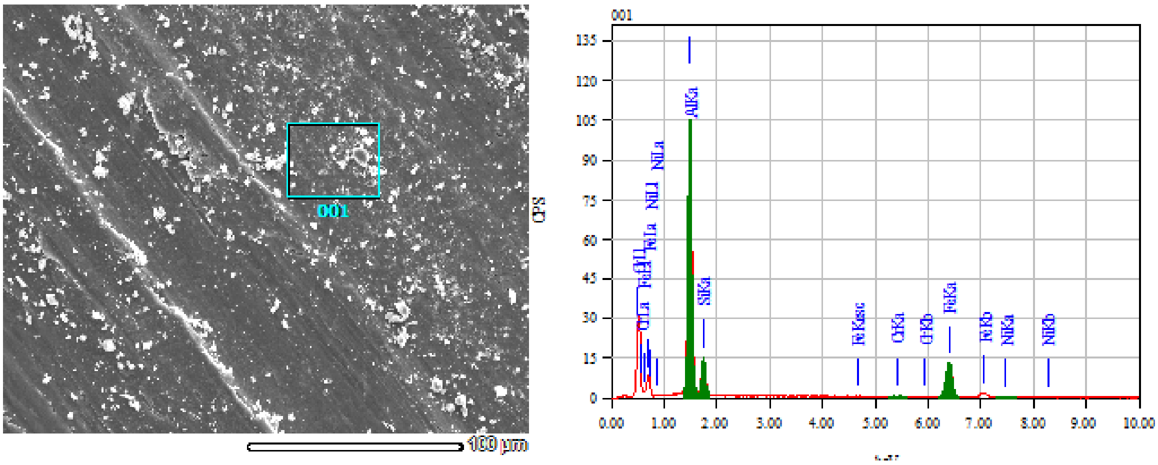
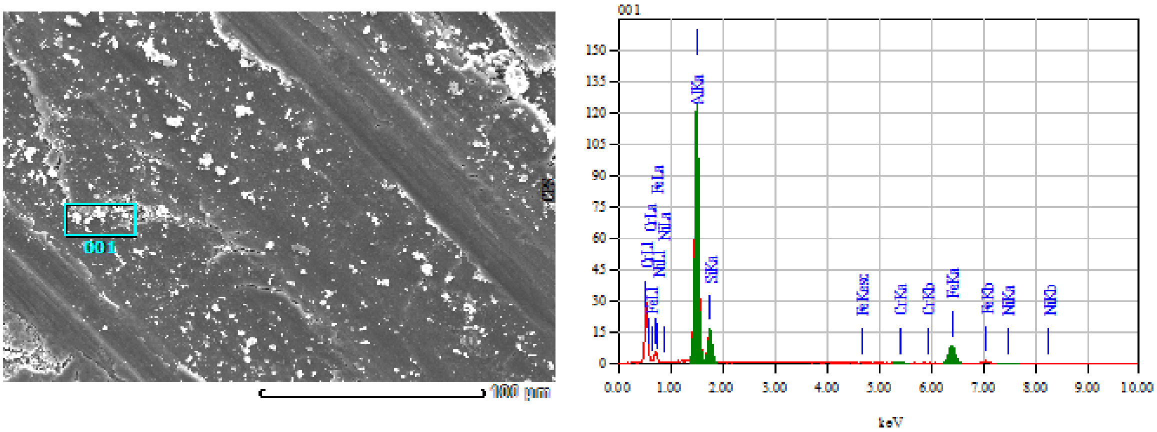


Figure 4.80 Adhesion and Furrow formation at the outer surface in the casting of Al-17wt% Si



Element	mass%	At%
Al K	64.18	72.67
Si K	14.31	15.57
Cr K	0.19	0.11
Fe K	21.18	11.59
Ni K	0.14	0.07
Total	100.00	100.00

Figure 4.81 EDS images Showing the Adhesion of Fe at the Outer Surface of the Al-17 wt % Si Specimen



Element	mass%	At%
Al K	56.22	67.54
Si K	12.25	14.14
Cr K	0.36	0.22
Fe K	31.09	18.05
Ni K	0.08	0.04
Total	100.00	00.00

Figure 4.82 EDS Images Showing the Adhesion of Fe at the Inner Surface of the Al-12wt % Si Specimen

It was expected from the hardness study that the specimen would show different wear characteristics and this was confirmed by the wear test results. It showed different wear rates for sample taken for different mold rotational speeds. The wear mechanisms observed are abrasive wear, delamination wear and adhesive wear.

SEM examination of the worn surfaces of the Al-12wt%Si produced at 800 rpm (26.5G) shown in the Figure 4.77 exhibits scratches at the inner surface this is due to the segregation of Si particles. But outer surface is dominated by abrasive and delamination wear, which is also shown in Figure 4.78. Similarly the outer worn surface of the Al-17wt% Si shows scratches and grooves with lesser wear compared to Al-12wt% Si due to the presence of higher percentage of Si particles at the outer surface also which is shown in Figure 4.79. Inner worn surface also shows slight scratches in cast of Al-17wt% Si castings due to maximum percentage of Si particles settled at the inner surface of the casting as shown in Figure 4. 80. The Figure 4.81 and Figure 4.82 shows the SEM images and EDS results of Al-12wt%Si and Al-17wt% Si worn surfaces. At low magnification, the worn surface of specimen from the outer surface characterized by long ploughing lines that run parallel to the direction of sliding. Such features suggest abrasive wear during sliding against the steel counter face. The scouring seen in the micrographs may be due to abrasion by tapped debris or due to work hardened deposits on the counter face or by hard asperities on the hardened steel counter face. Furthermore, upon closer examination, shallow craters as well as cracks perpendicular to the sliding direction were commonly observed and extensive plastic flow and cracking was observed. These are the two likely modes of crack initiation and propagation. Cracks may initiate in the highly work hardened layer, particularly in the sub surfaces region. When cracks grow and get interconnected, a layer of metal is removed. This is delamination of wear. The presence of these cracks and formation of such holes and craters during sliding of the specimens has been associated with the process of delamination on several occasions by other researchers (Dwivedi et al. 2009, Reddy et al. 2009).

Delamination is the propagation of cracks preferentially along the sliding direction, which gives rise to the detachment of wear debris in the form of sheets. In case of inner surface of the casting of Al-Si cylinder, delamination wear was observed to be the dominant wear mechanism. This was confirmed by the presence of abundant flake-like wear debris collected from the wear of inner region. It is also seen from the photographs that long and continuous grooves are seen at lower loads but these grooves get wider and fine cracks starts appearing as the load is increased. But at the same time the inner region has a tendency to flake. The EDS spectrum of these wear specimen shows the presence of iron, indicating that the material transfer occurs across the interface during the wear tests. At high loads high interface temperature may increase the back transfer of Fe, which may diffuse into the near sliding surface and change the composition.

The outer worn surface after dry sliding shows the deep well separated grooves. Cracks are also observed which are spread perpendicular to the sliding direction. Comparing it with the SEM of inner worn surface it is found that the grooves are along the sliding direction, but not many cracks are seen. However, crack propagation is seen along the same direction as sliding. With increase in load it can be observed that although deeper grooves/abrasive tracks are observed but are smooth in dry condition; and the separation of groove line is reduced. This may be due to the fact that at dry condition the wear debris (of the material) might have flown off, but in high loaded condition some particles are embedded in the matrix which is the reason for deeper grooves.

In case of increased mold rotational speed hardness of the material has increased. Deeper grooves in dry sliding condition may be assigned to the abrasion of Si particles that have forced into the grain boundaries in platelet form, for which deeper grooves are produced. This can also be clarified at higher load and speed condition that debris and silicon platelets (i.e. pro-eutectic silicon) are observed along the direction of sliding and are obligated to deep crack lines.

4.9 COMPARISON OF HARDNESS VALUES FOR TIN, Al-12wt%Si AND Al-17wt%Si

Figure 4.83 to Figure 4.85 shows the hardness values at different rotational speeds of the mold for tin, Al-12wt%Si and Al-17wt%Si. The hardness is measured across the casting at four locations in the radial direction. It is seen that since tin metal is a soft metal its hardness values are very low compared to alloys Al-12wt%Si and Al-17wt%Si. And Al-17wt%Si alloy shows higher hardness values compared to Al-12wt%Si. Tin shows highest hardness value of 10 BHN at 800 rpm (26.5G) rotational speed of the mold and 6 BHN at 400 rpm (6.62G) rotational speed of the mold. Al-17wt%Si shows highest hardness value of 95 BHN near the inner wall of the casting for the 600 rpm (14.9G) rotational speed of the mold.

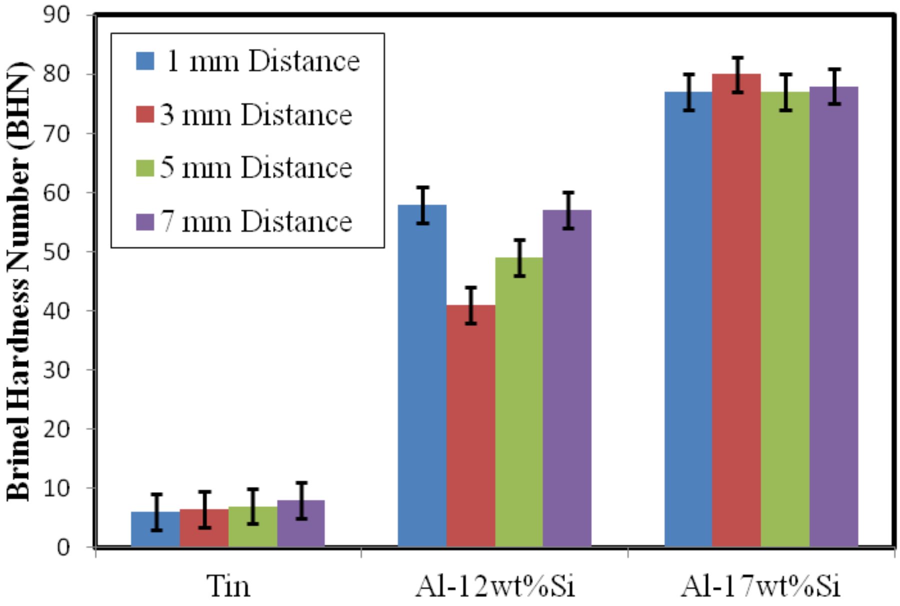


Figure 4.83 Hardness Values for Tin, Al-12wt%Si and Al-17wt%Si across the Wall Thickness at 400 rpm (6.62G) of the Mold Speed

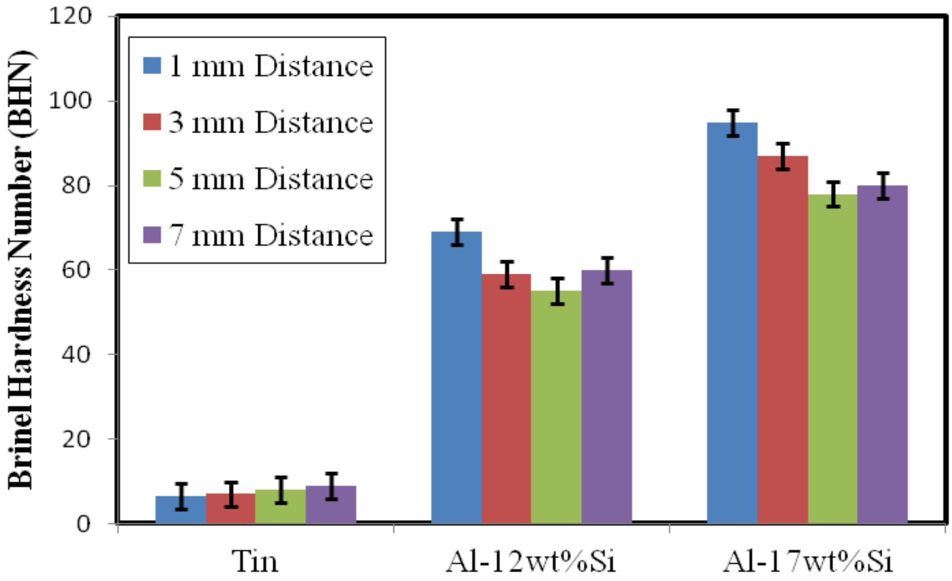


Figure 4.84 Hardness of Tin, Al-12wt%Si and Al-17wt%Si Across the Wall Thickness at 600 rpm (14.9G) of the Mold Speed

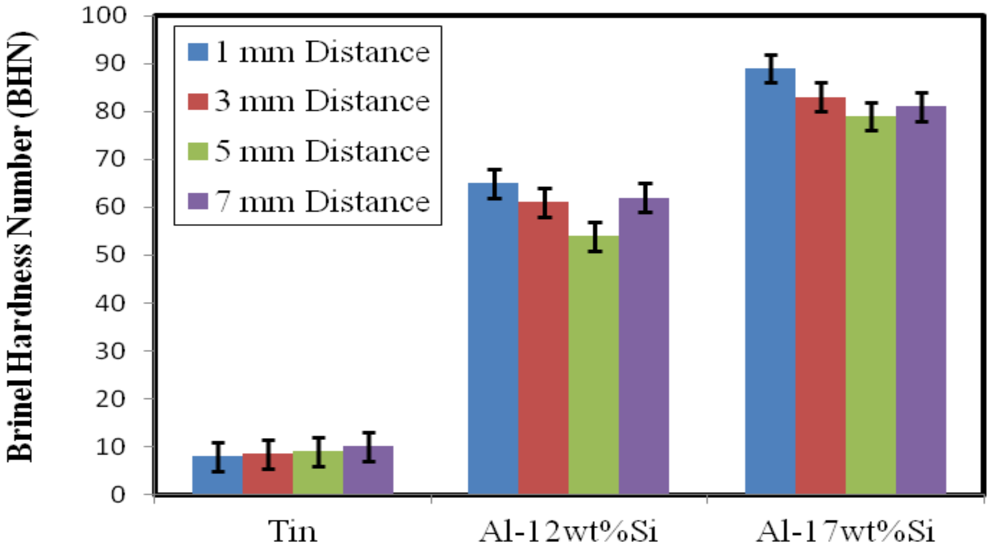


Figure 4.85 Hardness of Tin, Al-12wt%Si and Al-17wt%Si Across the Wall Thickness at 800 rpm (26.5G) of the Mold Speed

It has been observed that the hardness for tin is increasing from inner casting surface to outer surface as direction of solidification is from outer surface to inner surface. Due to rapid solidification at the outer surface of the casting the hardness will be higher and the inner surface of the casting is the last melt layer to solidify and hence the hardness value is lower. But in case of Al-12wt%Si and Al-17wt%Si alloys the direction of solidification is from outer casting surface to inner surface but due to the Si particles segregation effect in aluminum alloys the variation in hardness values are not in one direction. For both the alloys at higher rotational speeds of the mold the hardness values are higher at the inner surface due to higher volume segregation of Si particles at the inner surface. This segregation of Si particles due to their lower density compared to the Al matrix, Si particles will be pushed towards the inner wall. From the previous discussions it was seen that the microstructure property has varied from hypo to hyper eutectic through eutectic from outer diameter to inner diameter. And it is seen that hard particles has been segregated at the inner diameter which in turn significantly improves mechanical properties such as hardness and tribological properties such as wear. It is also seen from the discussion that the precipitation of Si at the inner surface is influenced by process parameters such as mold rotational speed. It also seen that there is an effect of speed on the hardness values along the radial direction of the castings which is agreement with the earlier researcher (Vassilion et al. 2008). For castings produced at rotational speed of 400 rpm (6.62G) there is no much difference in hardness along the radial direction. But maximum variation of hardness is observed for the alloys Al-12wt%Si and Al-17wt%Si at rotational speed of 600 rpm (14.9G). The reason for increase in the hardness at the inner surface of the casting is the amount of primary Si, which is a hard ceramic component, has segregated more when compared to outer surface.

The hardness values vary from 80 BHN to 95 BHN for alloy Al-17wt%Si and 60 BHN to 65 BHN for alloy Al-12wt%Si produced at 600 rpm (14.9G) rotational speed of the mold. The castings are having very low variation in hardness values from inner surface to outer surface of the castings produced at 800 rpm (26.5G) rotational speed of the mold the rate of solidification is very fast and particles have no time to segregate.

But there is a significant improvement in hardness values for the castings produced at 800 rpm rotational speed of the mold. Another important result which has been noticed during the measurement of hardness is that the value of hardness at the outer surface remains same for all the speed. This can be attributed to the fact that when the metal is poured into the mold the metal is exposed to the mold walls and gets chilled. This gives clear indication of no effect of mold rotational speed or centrifugal force at the outer surface because of very high solidification rate.

Chapter 5

CONCLUSIONS AND SCOPE FOR FUTURE WORK

5.1 CONCLUSIONS

In the centrifugal casting process the turbulence in the liquid becomes more intense in the mold, disturbing the melt and mushy metal or first crystals break into small fragments. These fragments move outside along the centrifugal radius direction and accumulate at farther position. These fragments act as new nuclei and consequently increase the number of solidification sites in the casting, resulting in the finer equi-axed grains. The cooling rate is mainly depending upon the transient heat transfer mechanism produced between the metal and the mold. But a direct study of rate of solidification of centrifugal casting is highly impossible due to the complexity of the process.

- A fluid flow pattern that arises in centrifugal casting process is critical in determining the quality and characteristics of the final product. At lower rotational speeds fluid exhibits patterns like sloshing of liquid and various disturbed flows like Couette flow, Ekmann flow and Taylor flow. At higher rotating speeds, Ekmann flow and Taylor flow get reduced and form a uniformly thick liquid cylinder.

- Above 800 rpm (26.5 G) all the liquids directly form cylinder with uniform thickness without undergoing various flow patterns for observable time. Therefore 800 rpm (26.5 G) is accepted as the critical speed of rotation of the mold in centrifugal casting. By analyzing the cooling rates of the liquids it is clear that minimum rate of cooling is observed for the stationary cylinder. This is due to the reason that in case of stationary cylinder the relative movement between the cylinder and the hot liquid is approximately zero and also heat dissipation is due to conduction through the mold wall and through the liquid and convection between the mold and the stationary liquid, But as the speed increases due to the turbulence, forced convection rate of cooling is increased. Up to 600 rpm (14.9 G) cooling rate is maximum and above 600 rpm (14.9 G) again cooling rate decreases. And also in case of rotational speed above optimum, the relative movement is minimum hence again the cooling rate decreases.

- In case of centrifugal casting of Tin, the formation of full cylinder takes place at higher rotational speed of 600 rpm (14.9 G). And also at lower rotational speeds it exhibits flow pattern like Taylor flow.

- The rate of solidification of the Centrifugal casting is determined on the basis of grain size measurement for Tin and by Secondary Dendrite Arm Spacing (SDAS) in case of alloys Al-12wt% Si & Al-17wt %Si.

- At around 400 rpm (6.62 G) the rate of solidification of Tin is slower unlike in the case of liquids wherein viscosity remains constant and hence the coarse grains are formed in Tin and at around 800 rpm (26.5 G) the rate of solidification is slightly faster due to high speed of rotation, continuously melt layers solidifies which results in fine grain structures.

- Mold wall thickness is one of the parameters which affect the rate of solidification in casting. Effect of mold wall thickness on rate of solidification of centrifugal casting has been studied based on the grain size measurement principle. The centrifugal cast sample shows a fine to coarse microstructure from outer to inner casting surface. This is due to the chilling effect of the mold. The chilling effect on the casting depends on thermal mass of mold and also the thermal contact resistance between the melt and inner surface of the mold.

- Rapid solidification shows the well distributed fine grains and slow solidification rate shows coarse grain size. The experimental details can be the basis for the more advanced researchers. As the thickness of the mold wall increases, cast grains become finer, hardness of the casting increases and specific wear rate decreases.

- Effect of preheat temperature on rate of solidification of centrifugal casting is based on the grain size or SDAS measurement principle. As the mold temperature increases the solidification rate decreases since the temperature difference between the die and the molten metal decreases. The casting hardness decreases and specific wear rate of the casting increases.

- Al-12%wt Si & Al-17%wt Si were produced at three different rotational speeds of the mold 400 rpm (6.62 G), 600 rpm (14.9 G) and 800 rpm (26.5 G). In case of Al-12%wt Si the formation of α_{Al} dendrites becomes finer from inside surface of the casting to outside surface. Outside surface showing finer dendrites due to the chilling effect of the mold wall and by measuring the SDAS the solidification rate has been determined. The Brinell Hardness Number shown higher hardness at the inner surface and outer surface. Outer surface harder due to the chilling effect and inner surface due to the formation of primary Si particles and also due to the formation of fine dendrites. At 800 rpm (26.5 G) the hardness values are higher than those at other speeds like 400 rpm (6.62 G) and 600 rpm (14.9 G). In relation with the hardness the specific wear rate also found to be decreasing towards the inner surface.

- Unlike Al-12%wt Si, Al-17%wt Si castings shows maximum fraction of primary Si particles and distribution of these particles are depending on the speed of rotation of the mold. At lower speeds like 400 rpm (6.62 G) coarse dendrites are formed and also centrifugal force caused due to the rotational speed is not sufficient to move the Si particles to the extreme. Maximum fractions of coarse Si particles were found at the middle radius of the casting. With increase in rotational speed of the mold the segregation of primary Silicon particles are found near the inner surface. At 600 rpm (14.9 G) of the mold maximum fraction of the Si particles were found near the inner surface due to the increased centrifugal force on the particles and slower speed compared to 800 rpm (26.5 G). Due to slower cooling rate maximum volume of the Si particles were pushed towards inner surface. But at higher speeds of 800 rpm cooling rate is faster, more or less equal volume fractions were observed with finer Silicon particles.

- In both the cases of Al-12%wt Si & Al-17%wt Si castings the tensile strength was found to be maximum at 800 rpm (26.5 G) compared to lower speeds of 400 rpm (6.62 G) and 600 rpm (14.9 G) of mold rotational speeds.

- Brinell hardness number variation along the radial direction of the Al-17%wt Si cast samples is not similar to Al-12%wt Si. BHN depends upon the solidification rate and also depends on the particle distribution within the casting.

5.2 SCOPE FOR FUTURE WORK

The quality of the centrifugal castings are depend on various process parameters such as rotational speed of the mold, pouring temperature of the melt and initial temperature of the mold etc. The centrifugal casting is a complex process wherein it involves moving boundary phenomenon varying viscosity and rapid solidification. This work explains the experimental results regarding the effect of these process parameters on the solidification of centrifugal casting and also the optimization of these parameters. But still more experimental studies are required to understand the actual process of centrifugal casting mainly fluid flow behavior and its affect on the rate of solidification. Therefore detailed study is required for the further optimization of these parameters. One of the theoretical approaches is the use of simulation software like CFD, Fluent etc. Since these tools are already in use for the analysis of gravity castings, the tools can be used for the analysis of centrifugal castings. And these experimental results can be used for the validation of results obtained by the software simulations. By obtaining the temperature plot from outside of the mold to the inner surface of the casting the rate of solidification can be determined.

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TECHNICAL PAPERS PUBLISHED

Sl. No.	Title of the Paper	Authors (in the same order as in the paper. Underline the Research Scholar's name)	Name of the Journal / Conference / Symposium, Vol., No., Pages	Month & Year of Publication
1	Effect of Mould wall thickness on rate of solidification of centrifugal casting	Madhusudhan, Narendranath S, Mohankumar G C, Mukunda P G	International Journal of Engineering Science and Technology (IJEST), Vol.2 (10), 6090-6094.	2010
2	Experimental study on rate of solidification of centrifugal casting	Madhusudhan, Narendranath S, G. C. M. Kumar, P G Mukunda	International Journal of Mechanical and Materials Engineering (IJMME), Vol. 5, No 1, 101-105.	2010
3	Experimental study on cooling rate of centrifugal casting based on grain size	Madhusudhan, Narendranath S, G C Mohankumar	International Journal of Scientific & Engineering Research (IJSER), Volume 3, Issue 1, 1-3.	2012
4	Effect of Mould wall Temperature on rate of solidification of centrifugal casting	Madhusudhan, Mukunda P G, Narendranath S, G C Mohan Kumar	International Journal of Advanced Materials Science(IJAM), Research India Publications, Volume 4, Number 1, 37-42	2013
5	Properties of centrifugal casting at different rotational speeds of the die	Madhusudhan, Narendranath S, Mohankumar G C	International Journal of Emerging Technology and Advanced Engineering (IJETAE), Certified Journal, Volume 3, Issue1, 727- 731	2013
6	Understanding of fluid behavior in partially filled rotating cylinder	Madhusudhan, Narendranath S, Mohankumar G C, Shailesh Rao	National Conference on New Advances in Thermal, Design, Materials and Manufacturing Engineering-(NATDMME 09)	2009

7	Experimental study on effect of mould wall thickness on rate of solidification of Centrifugal casting	Madhusudhan, Narendranath S, Mohankumar G C	International conference (FIME 2010) held at NITK, Surathkal	2010

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10. Work Experience

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I declare that above information is true and correct to best of my knowledge.

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