CHAPTER 1

INTRODUCTION

1.1 CASTING AND SOLIDIFICATION

Casting is one of the ancient processes in the metal working industry which is used for making components in large quantity, yet economically. It is the practice of converting the liquid metal, poured into a die / mold designed suitable to the required product, in to solid with the release of latent heat. It is followed by cooling till the cast reaches the ambient temperature. Casting technique has many inherent advantages that have long been acknowledged by design engineers and manufacturers. Casting is principally an ingenious process accomplished in mass production, particularly for making components with intricate shapes and outstanding properties, which are almost impractical to produce by any other methods. Although casting is one of the oldest known production techniques, contemporary advances in casting technology have led to an expansive array of specialized casting methods.

The components which are produced by casting process may vary in size and weight from about a gram up to few tonnes. Castings are made by placing the exact quantity of molten metal into a mold, thereby reducing wastage of raw materials. This can actually lead to economical product development and decreased product cost in the manufacturing sector. Castings exhibit distinct advantages over other manufacturing processes such as design flexibility, high production rate and practicability. The cast components are stronger and lighter than those produced with other manufacturing methods, because castings are not subjected to any deformation or strain of the raw material and does not consist of individual parts welded or fastened together.

In the entire casting process, the solidification phase is considered important since it directly influences the establishment of microstructure in the cast product. The properties of cast materials especially the mechanical properties are largely governed by their microstructural characteristics. It can be appreciated that production of almost every engineering component involves solidification at some stage (Kurz 1984). Solidification of cast metal is fundamentally the process of crystallization, i.e. nucleation and growth of crystals (Mikhailov 1989). It incorporates significant metallurgical and mechanical properties in the cast product. It is a well-known fact that the microstructural features of castings like segregation of alloying elements, formation of microporosity, and size of the grains are more sensitive to conditions that prevail during solidification. The solidification microstructure and its accompanying defects (if any) stay with the castings, even after subsequent forming and product finishing operations.

1.2 CASTING OF METALS

The metals which are difficult to shape by plastic working can be produced by casting process for a variety of applications. Metal casting typically involves the following four stages:

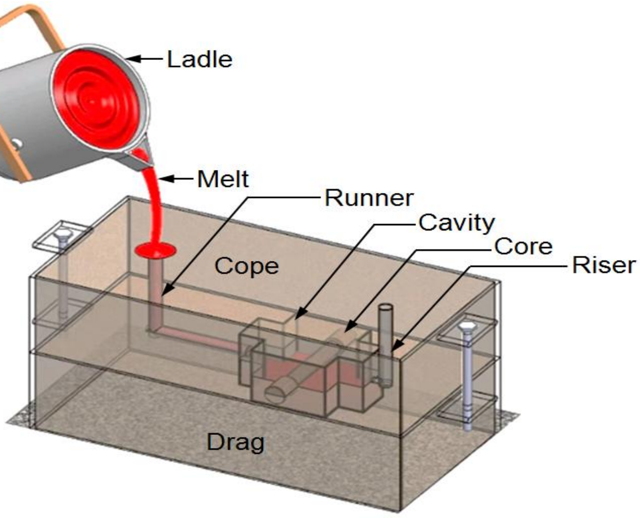
1. Design and manufacture of mold
2. Melting the raw material and superheating it
3. Pouring the required amount of molten metal into the mold cavity
4. Solidifying the melt with appropriate solidification or cooling rate

The precise control of the above mentioned stages are of foremost importance to obtain defect free castings. The molten metal is directly transferred to a shaped mold to get the finished product. All other techniques to obtain a finished product involve many stages (Mukherjee 1988). Using the appropriate casting technique, practically all types of engineering materials can be cast into required shape and size with a close dimensional tolerance and surface finish.

Expendable mold casting techniques such as sand casting and investment casting are illustrated in Figure 1.1. The sand casting method as shown in Figure 1.1(a) is preferred for producing large sized products with a lesser quantity requirement. The investment casting method as shown in Figure 1.1(b) is typically used for the production of components requiring complex, often with thin-walled castings.

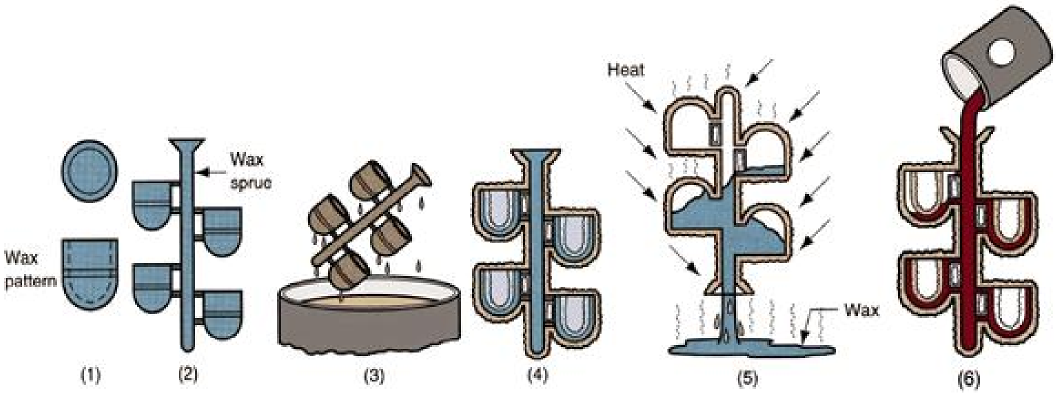
Whereas in the case of mass production, especially for smaller size components, the permanent mold (die) casting technique is considered as an economically feasible and technically suitable method. This method can be used to produce the alloy components with near perfect shape, which would else be challenging and/or inefficient to make, by other manufacturing methods. In general, the mold cavity is formed by placing two die halves together with fixtures.

Gravity die casting is the simplest and one of the earliest methods to produce cast products where the gravitational force alone was utilized, without any external force as shown in Figure 1.2 (a). In gravity die casting, molten metal is poured under gravity into a mold, where it remains until it solidifies. Figure 1.2(b) shows the pressure die casting method which is preferred for producing large number of parts with good surface finish and dimensional accuracy. In this method a measured amount of metal is poured into the shot sleeve and then introduced into the mold cavity with desired pressure using a hydraulically-driven piston. Once the metal gets solidified, die is opened and the cast will be removed.



(Courtesy: E-Foundry IIT Bombay)

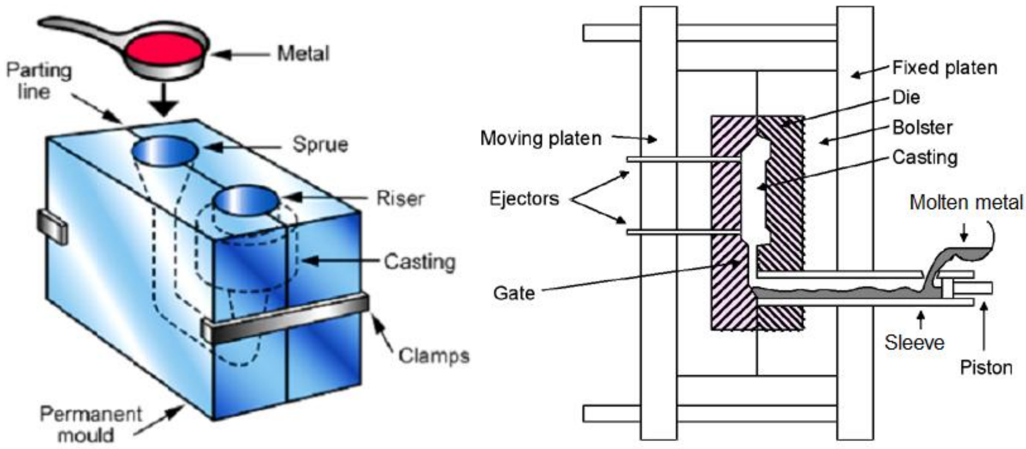
(a) Sand casting



(Courtesy: www.green-mechanic.com)

(b) Investment casting

Figure 1.1 Expendable mold casting techniques



(a) Gravity die casting **(b) Pressure die casting**

(Courtesy: www.expertsmind.com)

Figure 1.2 Permanent mold casting methods

1.2.1 Sand Casting Vs Die Casting

In case of sand casting, mold is sacrificed when removing the cast part. This method is preferred for large size castings with more complex shapes. Production rate is often restricted by time required to prepare the mold rather than the casting itself. The mold prepared using foundry sand such as silica (SiO_2) or silica mixed with other minerals like Plaster, granulated Zircon and Mullite have poor thermal conductivity and hence offer higher resistance to heat flow within itself.

Whereas die casting is a competent and inexpensive practice offering a wider range of shapes and components with closer tolerances than any other casting techniques. No further machining is required and thousands of identical castings can be produced without any additional tooling and machining. Die casting produces parts that are consistent and dimensionally stable. Die castings can be made with smooth or textured surfaces, and they are easily finished with least surface preparation. Generally in die casting, the die materials have high thermal conductivity. This gives rise to extremely high thermal gradient, which promotes rapid solidification of the molten metal. As a consequence of the rapid solidification, a variety of fascinating metallurgical microstructures can be developed in die casting.

1.3 ALUMINIUM ALLOYS AND THEIR APPLICATIONS

Virtually in every instance, aluminium based alloys have replaced other materials in numerous existing applications. Casting aluminium alloys are quite widespread and find more and more applications in modern industry. Earlier it was hypothesized that the general level of properties required of cast aluminium parts were lower, and they were mostly used for producing non-critical (e.g., not heavily loaded) parts. However, during the last two decades this situation has started to change. Due to significant improvements in casting technologies, now it is possible to produce high-quality castings with outstanding properties.

A unique combination of properties makes Aluminium a very versatile metal that is used for a great many aerospace, automobile, ship building, medical, defence and commercial applications. Today almost certainly the automotive industry is the most important consumer of Aluminium alloy castings. Every year the overall volume of cast Aluminium in automotive technologies grows gradually. This is particularly true during the last 10 years, when the production of “Aluminium” vehicles started and the number of aluminium-intensive components grew rapidly. Such details as cylinder blocks, pistons, other engine parts, frames, and covers of different devices are traditionally cast from Aluminium. Figure 1.3(a) shows the cylinder blocks of BMW N52 (6-cylinder engine) series which was made by Al casting (Cylinder, Water-Jacket and Crankshaft journal bearing) and Mg casting (Outer surface). Figure 1.3(b) shows the images of pistons used for Automotive, Stationary Engines, and Compressors etc.

Owing to their exceptional specific strength, corrosion resistance, and relatively less labour intensity of manufactures, cast aluminium alloys are also extensively used in other transportation sectors of the economy such as aerospace, marine, and railroad transportation. The structural components of a typical modern commercial transport aircraft is 50 percent aluminium by weight. Aluminium alloys are the overwhelming choice for the stabilizers, fuselage and supporting structures of aircraft. Structural components of current United States Navy aircraft are made of wrought aluminium (forged, machined and assembled parts). Figure 1.4 shows Boeing 787 and 777 aircrafts that use 20% and 50% aluminium by weight respectively.

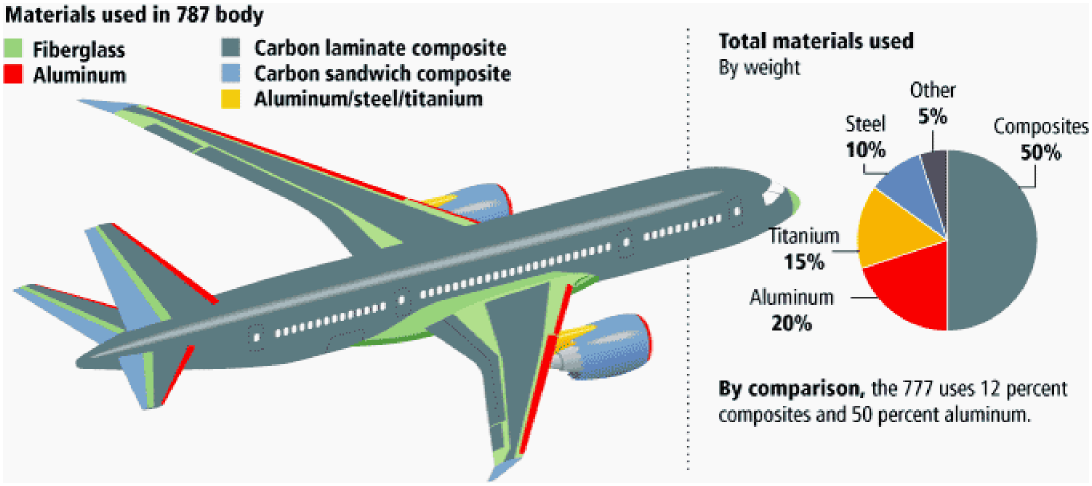
(Courtesy: www.commons.wikimedia.org)

(a) Aluminium engine block

(Courtesy: www.cast-alloys.com)

(b) Aluminium pistons

Figure 1.3 Automotive components



Courtesy: www.modernairliners.com

Figure 1.4 Aluminium usages in Aerospace Industry

Aircraft industries are now focusing on aluminium casting technology, which offers lesser manufacturing costs, the ability to form intricate shapes and the flexibility to incorporate inventive design perceptions.

Use of aluminium alloys in marine water applications is of foremost and continuous interest because of the need for light-weight structural materials with good corrosion resistance. Aluminium boats constructed from 5000-series alloys were already in use in 1930s with recorded lifetimes exceeding 40 years (Feron 2007). Since then, areas of application have augmented considerably. The main applications include outboard motors, propellers, masts, ladders, floating bridges, desalting equipment, buoys, etc. Figure 1.5 shows photographic view of VS1680 Ranger boat, in which the major components are made of cast and forged aluminium alloy. With more quality and more all-out performance, these multi-species boats not only take along affordable excitement to the world of fishing but even more prospect for great times with family and friends.

Courtesy: www.rangeraluminum.com

Figure 1.5 Aluminium usages in Marine applications

1.3.1 Aluminium-Silicon Alloys

In early days alloys were developed when characteristics of pure Aluminium were inadequate to meet all of the requirements of the prospective applications. Several types of Aluminium alloys are frequently developed to enrich their mechanical and metallurgical properties. According to Zolotorevsdy et al. (2007) the first and foremost function of the alloying elements is to increase alloy strength, since pure Aluminium has very low strength ($\sigma < 60$MPa). In most of the cases only four alloying elements are majorly used: Silicon, Copper, Magnesium and Zinc. These elements are "*basic*" or "*principal*" alloying elements because they are introduced into Aluminium alloys in (relatively) large amounts and define their microstructure and properties.

Among these alloys, Aluminium-Silicon (Al-Si) alloys were found to be more advantageous in many engineering applications and considered to be suitable alternates for steel components. Owing to commercial and eco-friendly necessities, it is becoming more and more important to reduce vehicle weight. For such an intention, Al-Si alloys are widely preferred and have been commercially used for engineering applications in automobile, air-conditioning, electrical, aerospace and fluid power systems because of their higher strength to weight ratio, good wear resistance, excellent corrosion resistance, and minimal coefficient of thermal expansion, outstanding castability and the solubility of Si in α-Al. Their application as structural materials is to be determined by their physical and mechanical properties (depends on chemical composition and microstructure).

Warmuzek (2004) stated that the typical property of aluminium alloys is relatively high tensile strength in relation to density compared with that of other cast alloys, such as cast steel and ductile cast iron. The high specific tensile strength of aluminium silicon alloys is highly influenced by their composed poly-phase microstructure. The weight percentage of the silicon in commercial cast aluminium silicon alloys is in the range of 5 to 19 wt. %. Figure 1.6 (a) illustrates the phase composition of Al-Si alloy. The solubility of silicon in aluminium reaches a maximum of 1.65 wt. % at the eutectic temperature. The weight percentage of silicon is around 12.6% for eutectic composition. These alloys can be characterized as hypoeutectic, eutectic and hypereutectic and are denoted as 1, 2 and 3.

The microstructures of Al-5 Si, Al-12.6 Si and Al-19 Si cast alloys are illustrated in Figures 1.6 (b), (c) and (d) respectively. The major phases in as-cast microstructure of hypoeutectic alloy consist of large size primary α-Al and acicular eutectic Si. On the other hand for eutectic alloy due to eutectic shift toward higher silicon content the volume fraction of eutectic silicon particles increases and with refined primary α-Al dendrites. In the case of hypereutectic alloy, presence of primary silicon (Si) and eutectic silicon phases are visualized clearly. The primary Si exhibited the blocky morphology while the eutectic silicon revealed needle shape morphology. The size of the eutectic silicon was, however, found to be larger when compared to the hypoeutectic and eutectic alloys. LM2, LM6, LM24 and LM25 are few of commercially available Al-Si alloys.

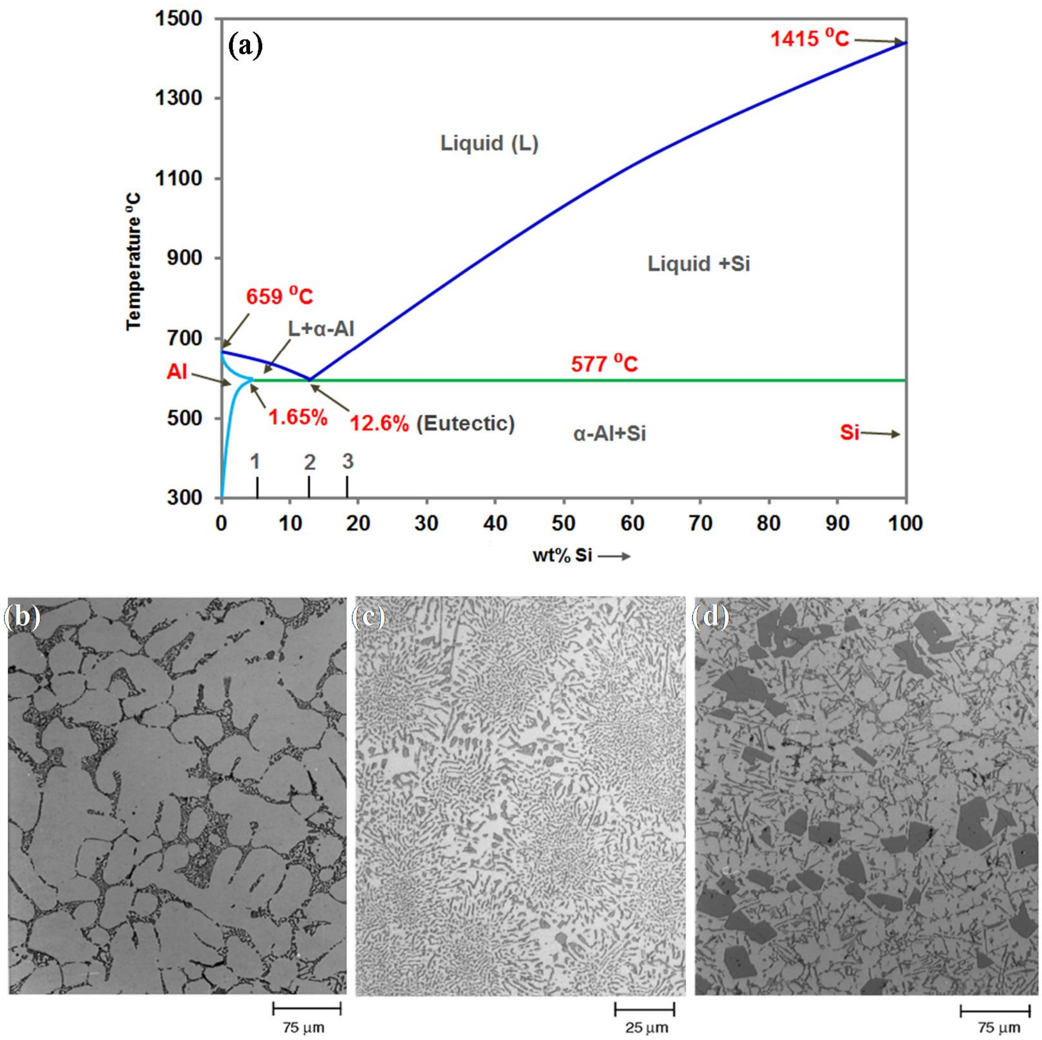


Figure 1.6 Metallurgical Features of Al-Si Alloy (Warmuzek 2004) (a) Al-Si alloy phase diagram (b) Microstructure of hypoeutectic alloy (c) Microstructure of eutectic alloy (d) Microstructure of hypereutectic alloy

1.4 FACTORS GOVERNING CASTING PROCESS

Many factors have a pronounced effect on achievable microstructure and therefore, on the quality of the cast product. When applied to metal castings, the term quality denotes the soundness (pores and crack free) of the cast and magnitude of mechanical properties exhibited by the cast product. Basically the quality of metal castings depend on the castability of the metal being used.

The phenomena like fluidity, viscosity, freezing temperature, shrinkage, impurities, inclusions and surface tension etc., determines the castability of metals. Factors like pouring temperature of the molten metal, pouring rate, mold design, mold material, cooling conditions such as air gap formation and cooling medium, solidification rate etc., influences the quality of cast products. Some of the most important factors and their influences on the castings are discussed in detail below.

1.4.1 Pouring Temperature

The pouring temperature of melt has a significant effect on the quality of the casting. Pouring of melt with lower temperature can lead to improper filling of die cavity. Generally the higher temperature improves the castability of metals and alloys, since the fluidity of the melt increases with the increase in temperature. At the same time too high pouring temperature will increase the mold temperature, which in consequence decreases the temperature gradient between the cast and the mold, thus decreasing the rate of heat transfer.

1.4.2 Pouring Rate

Pouring rate of melt is an important criterion in metal casting. Slower pouring rate requires a higher pouring temperature to avoid premature solidification. Also it helps in back filling the space created by the shrinkage of the cast when getting solidified, in the case of die casting where provision of risers is not possible. A rapid pouring would create turbulence and results in entrapment of air and gases.

1.4.3 Die Material

Thermal properties of the die material like thermal conductivity and specific heat influences the rate of heat transfer from the mold to the ambient. The properties and quality of cast products are considered as the best with the formation of well refined grains, controlled profile of solute segregation and the uniformity in the distribution of secondary phases. The way in which the casting solidifies (solidification rate) defines the quality, influences the interior soundness and the number of viable castings obtained. Higher solidification rate, due to higher heat transfer through the mold, offers superior strength which is required for components of high-strength alloys for service at elevated temperatures. To achieve higher heat transfer rate, metallic molds (die) are widely used than sand molds, especially for Al-Si alloy castings. Lower values of Dendrite Arm Spacing (DAS) formed during higher heat removal rates, increases the hardness value and tensile strength of the cast, which can be achieved by using metallic molds.

1.4.4 Formation of Air Gap

In die casting, the heat transfer through the interfaces between metal-mold and mold-ambient directly influences the solidification rate. While pouring the molten metal in to the mold, initially the liquid metal will have good contact with the mold. Consequently, an air gap forms between the metal and mold interface. This gap gets widened, as the cast shrinks during its solidification and the mold which enlarges due to its thermal expansion. This air gap actually acts as a thermal barrier due to its relatively low thermal conductivity and affects the subsequent heat transfer from cast to mold. The Interfacial Heat Flux (IHF), which is the heat transfer per unit area of the mold surface through the cast-to-mold interfaces, can be considered as one of the critical parameter to assess the solidification rate of the cast.

1.4.5 Solidification Rate

In the recent years, research works relating to solidification of cast alloys with high cooling rate have come progressively more important. Compared with conventional casting techniques, rapidly solidified cast products have a very good amalgamation of strength and elongation, which is due to the formation of finer grains and homogenous microstructure across the cast. By refining the microstructure of cast aluminium alloys, mechanical performance of the cast product at elevated operating temperatures would be improved. The solidification rate can be varied by controlling the rate of cooling in the die. The cooling rate can be varied by having a cooling medium outside the die / mold, with better thermal properties such as thermal conductivity and specific heat.

1.5 RESEARCH MOTIVATION

Extensive studies have been reported on casting of Al-Si alloys with an objective to enhance the microstructure and thus the properties exhibited by the components produced with these alloys. However, the mechanism involved in the formation of the microstructure, for different cast materials in combination with alloying elements, as a function of cooling / solidification rate are currently not well defined. The reason is that the solidification rate is a lumped parameter which cannot be simply related to the observed microstructure and needs a detailed experimental and/or computational investigation. This formed the motivation of the present work which aims at quantifying the solidification/heat transfer rate in terms of IHF.

Among several die casting processes available, gravity die casting was chosen for the present research work, as it will be simple in construction, the cost of operation will be minimal and has least influencing process parameters. The present research work was focussed on assessing the heat transfer at the metal/mold interface during gravity die casting of chosen Al-Si alloys with two different cooling conditions. This was addressed with the help of estimated multiple IHF components along the vertical length of the mold wall. Apart from cooling conditions, other parameters which might have influence on the solidification rate are considered '*out of scope*' for the present work.

1.6 UNIQUENESS OF THE PRESENT WORK

The uniqueness of the present research work is that it aims at the quantification of the differences in the solidification rate, due to differences in the cooling rate by using different cooling media, in terms of spatially varying IHF in a gravity die casting of Al-Si alloys. The influence of spatially varying IHF on the microstructure formation of the castings at different strategic locations were evaluated and reported. The effect due to the introduction of cooling medium with higher thermal conductivity on the spatial variation of IHF and the resultant microstructural features and mechanical properties were also reported.

1.7 OBJECTIVE AND SCOPE OF THE PRESENT WORK

The present research work is formulated as an experimental investigation, numerical computation of IHF, metallurgical and mechanical characterization of Al-Si alloy castings. In order to carry out the above mentioned research works, the following objectives are formed:

- To conduct casting experiments for the chosen Al-Si alloys, with different cooling medium to vary the rate of solidification of the cast, in a gravity die casting setup and to measure die temperatures at different spatial locations.

- To numerically estimate the transient variation of IHF at the interfaces by using an inverse solver, with inputs from the experimentally measured temperature values.

- To conduct various mechanical and metallurgical tests, at chosen regions in the cast, to arrive at an understanding of the relationship between the estimated IHF and properties.

Based on the objectives, the scope of the present research work is detailed below:

- The present research work is intended to study the effect of cooling conditions on the microstructure and mechanical properties of chosen Al-Si alloy castings and hence devising and creating the appropriate casting setup is very much essential. Developing the simple Gravity Die Casting setup with two different cooling methods is desired, since it has least influencing process parameters. Wide varieties of automotive components are made of Al-Si alloys, which are preferably produced by die casting methods.

- The defect free castings can be produced by conducting the experiments with optimized process parameters with the implementation of appropriate design of experiment technique. The variation in cooling conditions will show the influence on the microstructure and mechanical properties of castings. Conducting the casting experiments with optimized process parameters and improved cooling conditions will dramatically enhance the metallurgical and mechanical characteristics of alloy castings.

- The overall thermal history of the casting process can be demonstrated by accurately capturing the temperature variations of both the casting and mold with modern data acquisition system.

- The heat transfer during the solidification process can be quantified in terms of Interfacial Heat Flux values, computed with the help of Inverse Heat Conduction Problem based solver.

- The metallurgical and mechanical characterization of the castings using appropriate techniques and methods and comparing the same with the IHF values will establish the good correlation between them. Hence in future the properties of the castings will be predicted easily.

1.8 ORGANISATION OF THE THESIS

Chapter 1 introduces the casting and solidification processes in general and highlights applications that are relevant to the Al-Si alloys. The different casting processes followed in the industry were touched and the methods that are specific to the casting of Aluminium alloys were discussed in detail. The primary factors that govern the casting processes were discussed. The motivation of the present research work and the uniqueness of the present work are discussed. The outline of the objectives and scope of the present research work is highlighted.

Chapter 2 summarizes the survey of literature that focuses on the enhancement of mechanical properties of the Al-Si alloy castings. Methodology adopted for the measurement and computation of interfacial properties used by researchers were reviewed in detail. At the end, the summary of the literature review and need for the present study were presented.

Chapter 3 describes the experimental investigations carried out in the present research work, catering to the objectives outlined earlier. The details of the experimental setup, equipments and instruments used were discussed in detail. The experimental procedure adopted in arriving at the design of experiments for identification of the critical parameters of the gravity die casting presently considered for the research work was discussed in detail. The metallurgical and mechanical characterizations of the castings of Al-Si alloys chosen for the present study were described in detail.

Chapter 4 explains the computational investigation methods adopted presently to estimate the interfacial heat flux. The detail of a commercially available numerical tool TmmFE which was used in the present research work was discussed. The computational methodology adopted, assumptions made, boundary conditions and the process to estimate the heat flux using the inverse heat conduction problem approach were discussed in detail in this chapter.

Chapter 5 discusses the results of investigations in detail. The temperature variations of the mold and Al-Si alloy castings were described. The interfacial heat flux computed using the inverse solver was also discussed. Later the metallurgical characterisation and mechanical characterization of the castings of Al-Si alloys prepared with optimal combinations of influencing parameters were carried out. The mechanical behaviours of any metallic casts such as tensile, compressive, impact and wear characteristics were discussed.

Chapter 6 summarizes the conclusions arrived from the experimental and computational results obtained. The summary clearly identifies the underlying physics behind the mechanical behaviour of the given cast alloys, with the help of the numerical computation results and the metallurgical characteristics. Recommendations for the future work were also suggested so that research aspirants can take hint for their research work.