1. INTRODUCTION

1.1 General

The Indian foundry industries have been considered as the backbone of the economical growth of India. These industries are not only responsible for fulfilling the need of common man but also able to meet the need of other countries. As a result, large number of industrial components is being exported. This makes the ability of Indian industries to manufacture engineering components with international standards for achieving excellence.

It is reported that ~70% of the components are made of grey cast iron, which is essentially an alloy of iron and carbon (C > 2%) containing silicon, manganese, sulphur and phosphorous as its constituents. The importance of grey cast iron is due to its stiffness rather than its tensile strength. This is responsible for the manufacturing and fabrication of grey cast iron components. The later refers to components such as internal combustion engine cylinder blocks, pump housings, sugar mill rollers etc.

Production of Castings in the World during the years 2007 to 2010 highlights the potential of foundry products in the global market. Around 90 to 95 Million Metric Tons (MMTs) of castings were produced per year during the financial years 2007-08, 2008-09, 2009-10. Top four countries consolidated their major contribution in casting products are China, India, US, and Germany during the year 2010. Other countries like Japan, Russia, Brazil, Korea, Italy and France also contributed in casting products manufacturing with a share of 2 to 5 percent of world market. To understand the world scenario of casted products, 2010 survey with top four contributors are highlighted in further discussion. China contributed around 40 MMTs followed by India, US and Germany share as 9.1 MMTs, 8.3 MMTs, and 4.8 MMTs respectively. The share of top four casting producing countries (internationally) is 43:10:9:5 (approximating ± 0.2 MMTs). European Union (EU) shared around 15% of international market. Germany share among Europe was 5 percent followed by France (2%), Italy (2 %), Spain (1.2 %), Poland (0.95 %), and UK (0.4 %). China leads in casting products in producing every material like grey cast iron, ductile cast iron, steel , non-ferrous (and other materials). China casted the above materials in the ratio of 50: 25: 13: 12. India, US and Germany contributed in casting the said material in the ratios of 68: 12: 12: 8, 32: 34: 12: 12 and 45: 31: 4: 19 respectively.
The above listed countries hold the similar trend in producing grey cast iron. China, India, US, Germany and Japan’s manufactures grey cast iron in the quantity of 19.6 MMTs, 5.8 MMTs, 2.6 MMTs, 2.2 MMTs and 2.2 MMTs respectively. The top six major contributors of ductile cast iron in chronological order are China, US, Germany, Japan, Russia and India. The quantity wise share was 9.9 MMTs, 2.8 MMTs, 1.5 MMTs, 1.4 MMTs, 1.3 MMTs and 1.1 MMTs respectively. In manufacturing of steel related materials, India (1.1 MMTs) still hold the second position after China (9.9 MMTs), followed by US (1.0 MMTs), Russia (0.7 MMTs) and Brazil (0.25 MMTs). Among producers of non-ferrous materials, India’s (0.7 MMTs) position moved to number six after China (4.8 MMTs), US (1.9 MMTs), Japan (1.05 MMTs), Germany (0.93 MMTs) and Italy (0.87 MMTs).

The effect of recession and globalization of economy helps the manufacturing foundry products in the countries other than US and Europe to consolidate in manufacturing the low priced castings. India is one among them to utilize the local skills, labor and other resources to influence its presence globally.

Casting is the process of solidification of metal in a mold cavity or dies. Foundry is the industry where casting is performed. Casting is the process preferred to produce intricate shapes by minimizing the waste compare to other metal working processes like machining, welding etc. Casting simplifies construction and helps in mass production, hence it is economical. Few materials, which are not preferred to manufacture by hot works like rolling, drawing, forging are having option of casting. In spite of various advantages of parts manufactured by other methods like machining, rolling, forging, still Casting process is preferred to manufacture products like valve, pump housing, crushing rollers in power plants and sugar mills, power looms frames, granite polishing arm, cylindrical blocks, machine tool components and flywheels are preferred to manufacture by casting. These products are preferred to manufacture by casting due to their large size, intricate shapes where the products are exposed to compression, heat resistance and wear resistance properties. Selection of various casting methods like sand casting, die or permanent mould casting or centrifugal casting depends up on the few important parameters like shape, size of production, complexity or economical considerations. Sand casting is a simple and economical method of manufacturing casted products. Procedure like pattern making,
moulding, melting, pouring, cleaning and recycling of sand are followed during the process. 4-5 tonnes of sand are prepared to handle one tonne of metal.

Moulding sands are preferred due to its hot strength, permeability (porosity), thermal stability, refractoriness, flowability, collapsibility and its recycling or reusability. Moulds are prepared by applying a pressure of 20-150 Psi through mechanical, pneumatic or other advanced systems. In die or permanent mould casting, metal is injected under high pressures (1000 to 100000/ 300000 Psi). Die-castings are widely used or preferred for low melting temperature alloys such as aluminium which offers dimensional accuracy and aesthetics. Die-castings are superior to sand mould castings. Maintenance of dies is the major hurdle as the mould surfaces are having high tendency to erode due to temperature and pressures applied.

In centrifugal casting, metal is poured through the sprue and gates are designed in such a way that the molten metal is poured to the centre of the axis. Other moulding methods like ceramic moulding, plaster moulding, vacuum moulding, investment casting etc. are various ways to prepare the moulds and produce castings.

Design of gating system plays a major and important role in manufacturing sound castings. Pouring basins, sprue, gates and runners designs are the parts of gating system, which are important to fill the mould cavity. Various gating systems like top gates, bottom gates or parting gates are designed and selected to fill the mould cavity to minimise the casting defects. Effective selection and designing of gating system will promote directional solidification. Various techniques were adopted to filter the molten metal by incorporating skim bobs and slag traps to filter the foreign material and separate out the slag mixing with the molten metal. Gating system design helps to control the turbulence of material flow, which may leads to erode the mould surfaces. Hence, proper gating ratio will be maintained according to the desired product to be manufactured.

Selection of melting furnaces is depending upon the quality and quantity of the products to be manufactured. Various furnaces used for metal melting are cupola, electric arc furnace, induction furnace, rotary furnace, crucible furnace, open hearth furnace, air furnace and direct arc furnace are also used to melt the ferrous and nonferrous metals. Cupola is widely used and preferred for cast iron melting in high volume. High frequency induction furnace and open-hearth furnaces are used to melt heavy metals like cast iron and steel (higher melting point metals). In the present study cupola and induction furnace are used for melting cast
iron. Hence cupola and induction furnace are discussed further. In stage-1, cast iron was melted using core type induction furnace having a capacity of 100 Kg /h. In stage-2 and stage-3, cast iron was melted in a cupola furnace having a capacity of 1-3 tons per heat.

Cupola furnace is commonly used for melting iron scrap and refining pig iron. Cupola is having advantages over other types of furnaces due to its simplicity of operation, efficient, continuous and economical production.

![Fig.1.1 Inner lining of cupola after melting](https://via.placeholder.com/150)

**Fig.1.1 Inner lining of cupola after melting (Courtesy: Manikantan Foundries, Bangalore)**

During cupola preparation slag and other impurities adhere to the shell lining will be removed. The refuse and slag will be rammed from the bottom and top of the cupola through man hole and charging door respectively. Refuse/ slag deposition on the inner lining of the cupola furnace is shown in Fig.1.1. Lining will be repaired or remade. Bottom plates are supported by the prop. Sand bottom is prepared sloping towards the tap hole. Kindling wood is ignited and soaking of charge is allowed for 45 to 60 min. As a thumb rule, 150 Kg coke is required to melt 1 ton of metal. Around 8 m$^3$ of air will burn 1 Kg of coke. Lime stone is added in range of 30-40 kg /ton as a flux material.

Induction furnace of a frequency of 1000 cycles/sec or higher is supplied through the motor generator set. By induction, secondary currents (eddy currents) are produced in the crucible. The heat energy dissipated in the process leads to melt the metal.

Microstructural features of grey cast iron plays significant role in altering various mechanical and tribological wear properties. Cast iron is an alloy of iron with major constituents as carbon (2 to 4%), silicon (1 to 3%), and manganese (0.2 to 1%). Other
constituents discussed in standard reference books and literature is sulphur (0.05 to 0.25%) and phosphorous (0.05 to 0.2 %). Moreover, the chemical elements present in the cast iron are responsible for various microstructural changes. Some of the microstructural features of various types of cast iron is listed below:

**Austenite:** Austenite was originally used to describe an iron-carbon alloy, in which the iron was in the face-centered-cubic (gamma-iron) form. It is now a term used for all iron alloys with a basis of gamma-iron. Austenite in iron-carbon alloys is evident for FCC structure above 723 °C and below 1500 °C, depending on carbon content. However, it can be retained to room temperature by alloy additions such as nickel or manganese.

**Ferrite:** The term used for iron-carbon alloys, in which the iron was in the body-centered cubic (alpha or delta iron) morphology, but is now used for the constituent in iron alloys, which contains iron in the alpha or delta iron form. Alpha ferrite forms by the slow cooling of austenite, with the associated rejection of carbon by diffusion. This can begin within a temperature range of 900 °C to 723 °C, and alpha-ferrite is evident to room temperature. Delta ferrite is the high temperature form of iron, formed on cooling low carbon concentrations in iron-carbon alloys from the liquid state before transforming to austenite. In highly alloyed steels, delta ferrite can be retained to room temperature. In cast iron, ferrite contains the silicon present in the iron. Silicon hardens and strengthens the ferrite. Free ferrite dominates in nodular malleable iron resulting in increasing ductility. In grey iron, ferrite occurs as a constituent of pearlite. When incomplete graphitization is encouraged, the structure of iron consists of graphite and pearlite (or a mixture of pearlite and free ferrite or pearlite and free cementite).

**Pearlite:** Pearlite formed during the slow cooling of iron alloys, and can begin at a temperature of 1150 °C to 723 °C, depending on the composition of the alloy. It is usually a lamellar (alternate plate) combination of ferrite and cementite (Fe₃C). It is formed by eutectoid decomposition of austenite upon cooling by diffusion of carbon atoms, when ferrite and cementite grow closely. Carbon precipitates as Fe₃C between strips of ferrite, resulting in parallel layers of iron and iron carbide, which is pearlite. Pearlite in cast iron is strong and hard with some ductility.
**Martensite:** Martensite is formed in steels when the cooling rate from austenite is very fast. It is a very hard constituent, where carbon is trapped in solid solution. Unlike decomposition to ferrite and pearlite, the transformation to martensite does not involve atomic diffusion, but rather occurs by a sudden diffusion less shear process.

**Graphite:** Carbon in cast iron occurs in free form is called graphite. In grey iron, graphite flakes are developed during solidification. Due to its low density, it occupies ~6 to 17 percent of total volume. Several forms of graphite are formed other than flake form due to heat treatment (malleable iron - graphite aggregates) and alloy additions like magnesium and cerium (spheroidal graphite).

**Cementite:** Carbon in steel or cast iron formed partly or entirely in the chemically combined form as Fe₃C (cementite). Free cementite develops during freezing of white or chilled cast irons. Carbon in iron carbide (Fe₃C) form contains around 15 times its weight in the iron, i.e. White iron with 3% carbon contains about 45% of iron carbide and hence very hard and brittle. Cementite is also present as part of pearlite.

**Ledeburite:** Ledeburite is a mixture of 4.3% carbon in iron and is a eutectic mixture of austenite and cementite. Ledeburite is found with cementite or pearlite in a range of CIs.

**Bainite:** Bainite is a eutectoid product and a mixture of ferrite and cementite. Eutectoid point is a solidification point at 0.8% carbon at 723 °C and forms ferrite and cementite.

Carbon equivalent (CE) is another important aspect for determining the quality of grey cast iron components. In general carbon equivalent in cast iron are as follows.

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CE = % C + 0.33 (% Si) + 0.027 (% Mn) + 0.33 (% P) + 0.4 (% S)
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CE = % C + 0.33 (% Si)
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CE = % C + 0.33 (% Si + % P)
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Mechanical properties of cast iron are very much dependent upon the morphology of its carbon content. Carbon is present in the form of flakes in grey cast iron, where as it is incorporated in the form of compound Fe₃C (cementite) in white cast iron. Nodular cast iron,
which shows improved tensile strength than grey iron carry carbon in the form of sphere shape granules. Addition of silicon helps to reduce shrinkage and density. Addition of sulphur prevents formation of graphite, thus increases hardness and promotes short run defects. Addition of manganese with sulphur minimizes short run defects and gives chilling effect, which assist to increase hardness. Nickel refines the pearlite and graphite structure and improves toughness. Addition of Copper decrease chilling effect, refine graphite and increases fluidity. Titanium is added as a degasser and deoxidizer, but it also increases fluidity. Vanadium is added to cast iron to stabilize cementite, increase resistance to wear and heat. Zirconium helps to form graphite, deoxidize and increase fluidity. Vanadium, Niobium, or titanium is added to white iron to increase the ductility. Chromium is added to cast iron as carbide stabilizer, and to increase wear resistance, fracture toughness, and hardness. Molybdenum is a weak carbide stabilizer and added to increase the hardness. By adding graphite and rare earth metals, the graphite can be spheriodized, thereby increasing the wear resistance and retains reasonably good machinability.

Chills are used to increase the quality of casting. Internal chills will melt along with the molten metal and act as an integral part of casting. External chills are used repeatedly and placed to enhance mechanical properties and tribological effect. Property of grey cast iron is enhanced by using copper chills. Higher percentage addition of chromium leads to have chilling effect resulting in increased wear resistance and mechanical properties.

The cast irons are classified depends on its physical appearance, solidification process, chemical combination of carbon in iron, heat treatment and their mechanical behavior. Various types of cast irons discussed are grey, white, mottled, chilled, malleable and nodular cast irons.

In grey cast iron, large portion of its carbon is distributed throughout the casting as free graphite in the form of flakes. Grey cast iron always presents a grey sooty surface when fractured. Grey cast iron is most common form of cast iron and softer than white cast irons. The graphite flakes have low density and hence compensate during freezing (contraction) which leads to produce sound casting (minimising porosity). Because of graphite flakes, grey cast iron has excellent damping characteristics and machinability. Graphite acts as a chip breaker and lubricant during machining and wear. Graphite flakes acts as stress concentrators, which leads to poor toughness. The fluidity of grey cast iron and expansion during
solidification due to the formation of graphite makes grey cast iron ideal for production of shrinkage free intricate castings. Grey cast iron exhibits high damping characteristics with negligible elastic behavior, hence fails in tension without significant plastic deformation.

In white cast iron, carbon is present in combined form as cementite (iron carbide). Due to less silicon content and faster cooling, the carbon in cast iron precipitates out of the melt, leads to formation of cementite (Fe₃C). White cast iron is extremely hard, high wear resistant, very brittle and difficult to machine. It has wide applications such as slurry pumps, shell liners, crushing roller surface and similar applications, where sliding or abrasive wear resistance is important. The microstructure of white cast iron contains dominance of cementite (white) and pearlite.

In ductile iron or spheroidal irons, inoculants like cerium and magnesium (with low sulphur content) are added. The structure of carbon formed as spherical or nodular shape in the iron. Ductile cast iron has superior mechanical properties with high ductility and strength. Ductile cast irons are used for many structural applications, particularly those requiring strength and toughness combined with good machinability and low cost.

Malleable cast iron is formed by heat treatment of white cast iron at about 900 °C (1650 °F) for a long period (decomposes cementite into ferrite and free carbon). Upon cooling, it further decomposes into small compact particles of graphite or free carbon. This free carbon is referred to as tempered carbon, and the process is called malleabilising. Malleable cast iron has good machinability with fair amount of ductility and shock resistance. Mottled iron is an intermediate cast iron, which solidifies partly as a white iron and partly as a grey iron.

Chilled iron solidifies rapidly, as iron of such composition normally freeze as grey cast iron, but caused to freeze as white iron in few portions by rapid cooling during solidification. Fractured surfaces of chilled irons show areas of white iron where freezing was rapid and other areas of grey iron where the cooling rate was normal.

The above information clearly demonstrates that under various conditions, cast iron exhibits different mechanical properties. However, little information is available on using
mild steel chills, its position and its influence on varying mechanical properties. The work presented in this thesis is focused with the following aims.

1.2 Objectives of the present work

- Preparation of grey cast iron samples with and without addition of alloying elements.
- Use of mild steel chills in the mould at room temperature and cryogenic temperature.
- Effect of Mild Steel chill thickness on mechanical and tribological properties.
- Position of mild steel chill and its influence on mechanical properties.
- Microstructural details of as cast and rapidly solidifies cast iron.
- Tribological wear performance of chilled and alloyed cast irons.
- Mechanical properties of chilled and alloyed cast irons.

1.3 Scope of the work

The present work is aimed to study the influence of mild steel chills on grey cast iron with different possible combinations of position of chill and percentage of alloying elements. Moreover, alloy elements are added to cast iron and its solidification effect using mild steel chills have been addressed. The complete work has been divided into 6 chapters.

Chapter-1, concentrates in giving introduction of grey cast iron and foundry practices and its importance of manufacturing industrial components are discussed. It also covers the objective of the present Research work and scope of present work.

The detailed literature review is covered in Chapter 2, in which various aspects of grey cast iron are discussed. The research work carried out by large number of researchers connected to the present research topic is discussed in detail.

Chapter-3 depicts the experimental details. The casting procedures and types of furnaces used, chemical composition of grey cast iron are discussed. Various specimens used for different investigations on different characteristics are detailed. Mechanical and tribological
experimentation and microstructural studies using various test equipment’s and procedures are discussed.

The crucial and important Chapter-4 is focused on the results obtained from the present investigation. It is also discussed in detail about the solidification effect due to chills, influence of aligned elements on hardness, compression strength and sliding wear properties. Micro structural analysis, mechanical and tribological properties are also evaluated for all the combinations.

The conclusions drawn from the above investigation work is mentioned in Chapter-5 in a tabular form which is highly useful for comparison.

Chapter-6 emphasizes on the scope for future work, followed by references.