CHAPTER-2

LITERATURE REVIEW

Mold oscillation during solidification of molten metal enhances grain refinement and the quality of cast metals. Mold oscillation of both sonic and ultrasonic nature, when applied during the solidification of molten metals and alloys, modify conventionally obtained macrostructure and microstructure. The most commonly observed effect is the suppression of undesirable dendrite and columnar zones and the development of a fine-grain equiaxed structure. In fact, the effect produced when high intensity sonic or ultrasonic waves are propagated through molten metals can be listed under three headings: grain refinement, dispersive effects and the degassing, with the result that porosity is reduced.

An attempt has been made in this chapter to systematically present some of the significant studies towards the understanding of the above mentioned causes and methods to improve the mechanical properties of aluminum alloys under oscillatory conditions. This chapter ends with a concise summary of the state-of- art of understanding to arrive at the objective of the present research study.

2.1 Solidification process

During the solidification from a melt, chemical thermodynamics and kinetics are generally considered in terms of the enthalpy and Gibbs free energy changes, the solidification path, composition changes, and phase transformations etc.. Chemical thermodynamics describes the most stable phases at equilibrium conditions (i.e. temperature, pressure, compositions etc.) relating to only the initial and final states of a system. Accordingly, the solidification rate in a metallurgical system can be estimated by the enthalpy (H) and heat capacity (Cp), and how these thermodynamic properties reflect the system thermal state and heat energy requirements. Chemical equilibrium is controlled by the Gibbs free energy (G) of the system which is minimized for equilibrium conditions. In contrast, the dynamic system transformation between initial and final states controlled by chemical kinetics indicates the path and phase changes of a chemical reaction in a system when the limited atomic movement (i.e. in solids, low temperatures, etc.) becomes dominant in a short process time. Hence the solidification rate under a real time condition will be greatly influenced by the nucleation efficiency and the atom diffusion between phases **[32].**The solidification rate determines the coarseness of the microstructure including the fraction, size and distribution of intermetallic phases and the segregation profiles of solute in the α-Al phase. Large and brittle intermetallic phases form during slow solidification, and may initiate or link fracture.. Moreover, the defect size such as pore size is also controlled to some extent by the solidification rate. The influence of defects on the elongation to fracture depends on their size, shape, distribution and fraction. Dendrite arms with smaller radius may remelt into the molten liquid along with the decreasing total interfacial energy. The Ostwald ripening effect on the formation of dendrite arm spacing (DAS) is determined by local solidification time, allowing smaller particles to grow and merge into the larger ones due to the reduced total surface energy in the system. DSA, which is proportional to (average cooling rate)-n where n =1/2 and 1/3 for the primary and secondary dendrites respectively generally ranging from 10 to 150 mm and are controlled mainly by the solidification rate **[33].**

2.2 Effects and Mechanisms of Grain Refinement in Aluminum Alloys

Grain refinement plays a vital role in cast and wrought aluminum alloys. There are number of reasons why the control of grain size is important in semi continuously cast alloys. Firstly, reduced mechanical properties have been noted in plate products for structural application when a uniform as cast grain size is not achieved **[23-24].**

Twinned columnar grains **[24]** have been reported to reduce fabricability, yield strength and tensile elongation to fracture. Secondly, a coarse grained structure may result in a variety of surface defects in alloys used in rolled or extruded form for architectural applications **[25].** Thirdly, hot cracking in the shell zone of a D.C. cast ingot is more severe if the grain structure is not equiaxed. An equiaxed structure allows a higher casting rate to be achieved before hot cracking is produced. Apart from wrought alloys grain refinement has several benefits in cast alloys like improved mechanical properties that are uniform throughout the casting, distribution of second phase and micro porosity on a fine scale, better feeding to eliminate shrinkage porosity, improved ability to achieve a uniform anodized surface, better strength and fatigue life **[26-27].**

2.2.1 Nucleation

Grain refinement can be understood to be directly related to the nucleation and growth process of aluminum grains. This is based on the nucleation ideas **[28]**. The theory involves homogeneous and heterogeneous nucleation. In a pure metal solidifying, the critical nucleus size for survival is given by

$$r^{*}_{\text{homogeneous}} = \frac{-2\gamma_{\text{sL}}}{\Delta G_{\text{v}}}. \qquad (1)$$

The free energy barrier is given by

$$\Delta G^*_{\text{homogeneous}} = \frac{16\pi\gamma^3_{\text{sL}}}{3\Delta G^2_{\text{v}}}, \qquad (2)$$

Where, $\boldsymbol{\gamma}_{\textbf{sL}}$ is the interface surface energy of a solid–liquid interface in J/m^2, Assuming the specific heats of liquid and solid as same ΔG_{v} is the driving force for solidification

$$\cong \Delta T \Delta S = \frac{\Delta H_f \Delta T}{T_m}, \qquad (3)$$

DT is the under cooling below the liquidus temperature K,ΔS the entropy change for liquid to solid phase transformation, J/K/m^3, ΔH_{f} the enthalpy of solidification and T_{m} the melting temperature. If the embryo of the solid is greater than critical radius, $r^*_{\text{homogeneous}}$, the embryo will survive and become a nucleus.

In heterogeneous nucleation, the critical nucleus size is

$$r^*_{\text{heterogeneous}} = \frac{-2\gamma_{\text{sL}}}{\Delta G_{\text{v}}}, \qquad (4)$$

(1) and (3) are identical for both homogeneous and heterogeneous nucleation and the free energy barrier is

$$\Delta G^*_{\text{heterogeneous}} = \frac{16\pi\gamma^3_{\text{sL}}}{3\Delta G^2_{\text{v}}} f(\theta), \qquad (5)$$

Where f (θ) is a function of the contact angle, θ on the substrate on which nucleation takes place. **Figure 2.1** shows the solid nucleating on a substrate in a liquid. **Figure 2.2** shows the variation of f (θ) with θ and since f (θ) is always ≤ 1, the critical free energy for heterogeneous nucleation is always less than or equal to that for homogeneous nucleation. However, it is clear that strong heterogeneous substrates are those with θ close to zero. The values of under cooling, ΔT is of the order 1–2 K for observable nucleation rates in commercial aluminium alloys with grain refiners. Therefore, clearly heterogeneous nucleation is taking place. The following simplified expression for heterogeneous nucleation rate per unit volume in $m^{-3}\ s^{-1}$ is

$$I^{\mathrm{V}}_{\mathrm{heterogeneous}} = 10^{18} N^{\mathrm{p}}_{\mathrm{v}} \exp\left[\frac{-16\pi\gamma^{3}_{\mathrm{sL}} f(\theta)}{3K_{\mathrm{B}}\Delta S^{2}\Delta T^{2}}\right], \quad (6)$$

Where, K_B is the Boltzmann's constant, J/K, N^p_V is the number of nuclei/m^3, and $I^V_{Vheterogeneous}$ is the heterogeneous nucleation rate of nuclei/m^3.sec.

Therefore, it can be seen that if contact angle is close to zero, wetting of the substrate for nucleation is promoted and nucleation rate increases.

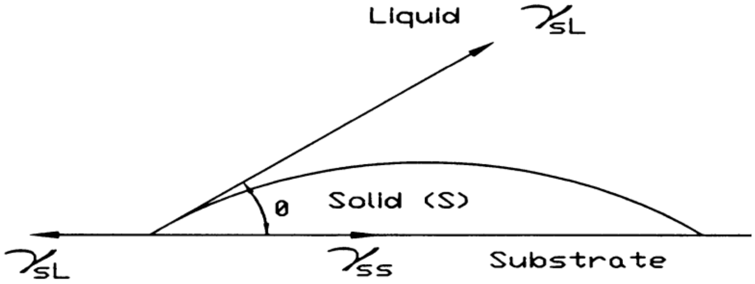


Figure 2.1 Schematic representations showing the formation of spherical cap of solid (s) on a substrate, contact angle and surface tension forces [27]

2.2.2 Growth of nuclei

Once nucleation takes place, more importantly heterogeneous nucleation, the growth front of the nuclei is seldom planar. The well known constitutional super cooling occurs as solute is rejected at the interface and the criterion is given by [30].

$$\frac{G_{\mathrm{L}}}{R} \geq \frac{-m_{\mathrm{L}} C_{0}(1-k)}{kD_{\mathrm{L}}}, \quad (1)$$

where, G_L is the temperature gradient in the liquid ahead of the solid–liquid interface (K/m), R the growth rate of solid liquid interface (m/sec), m_L the liquidus slope of phase diagram (K/wt%), C_0 the bulk alloy composition in the liquid (wt%), k the partition coefficient between solid and liquid, and D_L the diffusion coefficient of the solute in the liquid (m^2/sec).Normally in a casting we have a columnar zone and a central portion of equiaxed crystals [**29**].The columnar dendrites grow in [1 0 0] directions in the cubic system and growth direction is anti-parallel to the heat flow direction. The equiaxed dendrites grow in the same direction of heat flow i.e. radially outward. The formation of equiaxed crystals is due to dendrite arm melt off [**30**], which provides nuclei for equiaxed crystals.

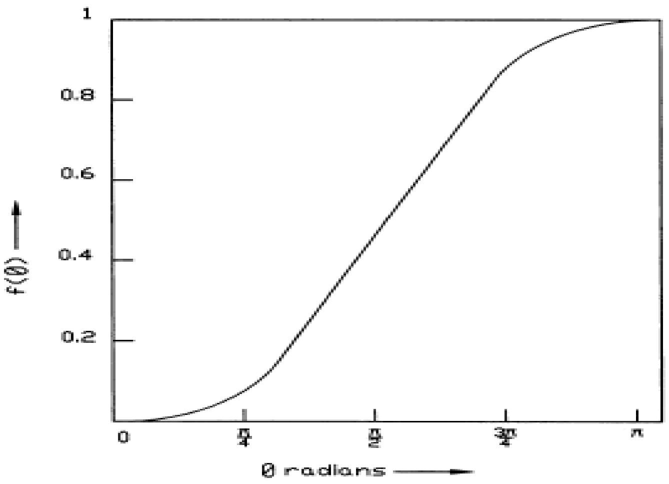
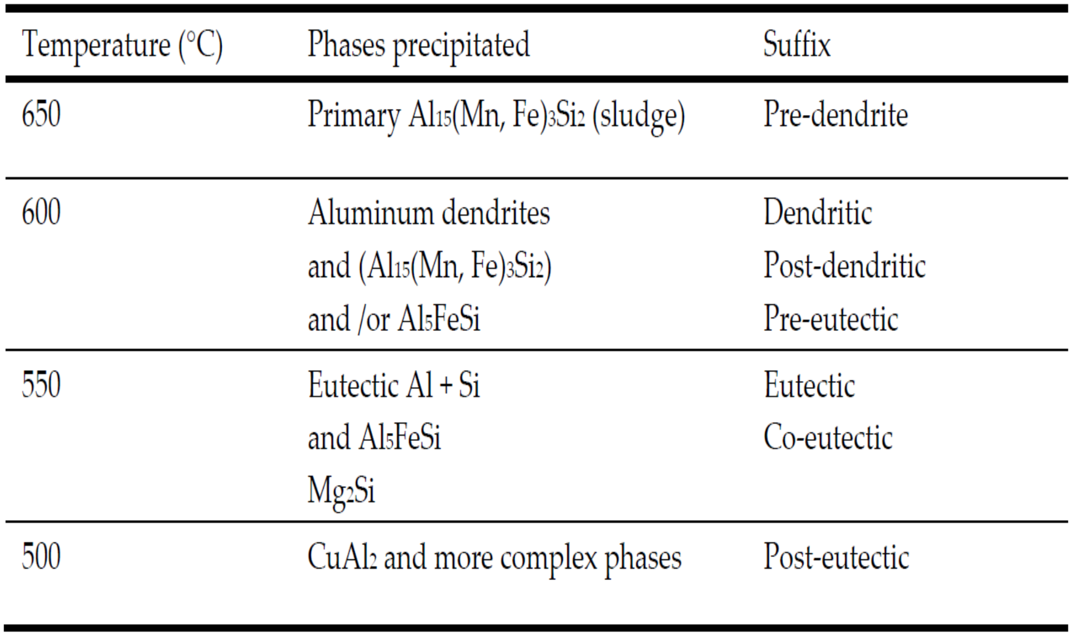


Figure 2.2 Showing the variation of $f(\theta)$ with θ where $f(\theta)$ is equal to $(2 - 3\cos\theta + \cos^3\theta)/4$ [27]

To gain an optimum property of an alloy, the DAS therefore must be minimized and distributed homogeneously. The major phases in as-cast microstructure of Al-Si alloys are large size grains and primary α-Al, acicular eutectic Si, coarse primary Si, and also other harmful inter-metallic phases such as needle like β-Al_5FeSi, with uncontrolled and unevenly distributed porosities etc. **[35]**. Table 1 summarizes the sequence of phase precipitation in hypoeutectic Al-Si alloys **[37].** Al in the eutectic has been reported to have mainly the same crystallographic features as the primary α-Al dendrites in unmodified alloys **[38]**. **Figure 2.3.a** indicates a basic structure of hypoeutectic Al-Si alloys consisting of grains (sizes at1~10 mm in general), dendrites (typical DAS - 10~150 μ m), and eutectic Si which can be in acicular shapes as long as 2 mm or round particle as small as 1 μm. The acicular Si might have heterogeneous nucleation which is the major approach to refine the grains. They nucleate on some of the foreign nuclei sites and grow slowly in the melt. Effective grain refiners, such as $TiAl_3$ and TiB_2, must match their lattice coherently to the Al matrix with their lattice coherencies **(Figure 2.3.b)**. In contrast, particles with a poor lattice matching have little influence on increasing the nucleation of grains **(Figure 2.3.c)**, resulting in an unrefined grain structure **[37]**. Typical examples of the microstructure of unmodified, Sr-modified, and Sb-modified alloys are shown in **Figure 2.4**.



Temperature (°C)	Phases precipitated	Suffix
650	Primary $Al_{15}(Mn, Fe)_3Si_2$ (sludge)	Pre-dendrite
600	Aluminum dendrites and ($Al_{15}(Mn, Fe)_3Si_2$) and /or Al_5FeSi	Dendritic Post-dendritic Pre-eutectic
550	Eutectic Al + Si and Al_5FeSi Mg_2Si	Eutectic Co-eutectic
500	$CuAl_2$ and more complex phases	Post-eutectic

Table 2.1 Sequence of phase precipitation in hypoeutectic Al-Si alloys [35]

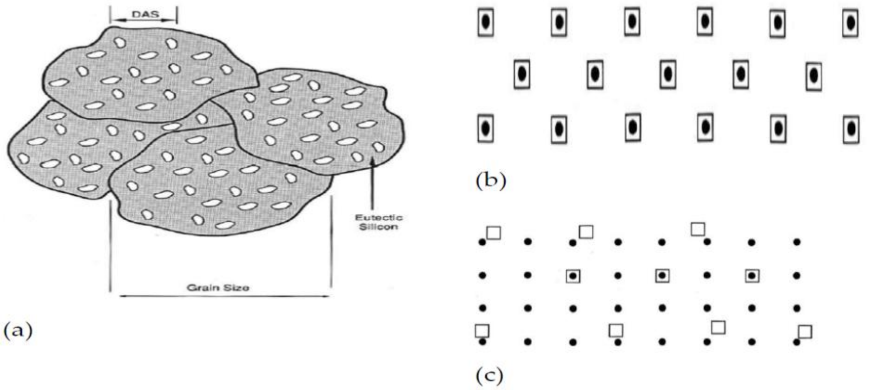


Figure 2.3 Schematics of a) Three essential elements (grains, Al dendrites, DAS, and eutectic Si in a basic hypoeutectic Al-Si microstructure; b) Perfect grain refiner particles (squares) with one to one lattice matching to Al atoms (points); c) Poor lattice matching [35].

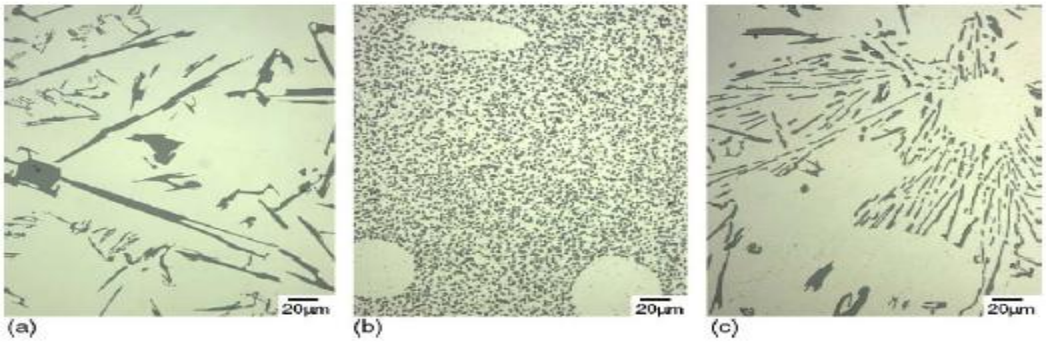


Figure 2.4 Comparison of the silicon morphology in: (a) unmodified; (b) Sr-modified (300 ppm Sr); and(c) Sb-modified (2400 ppm Sb), hypoeutectic aluminum-silicon alloys [38].

Copper forms an intermetallic phase with Al that precipitates during solidification either as blocky $CuAl_2$ or as alternating lamellae of α-Al + $CuAl_2$ **[39].** During solidification, in the presence of iron, other copper containing phases form, such as Cu_2FeAl_7 or Q-$Al_5Cu_2Mg_8Si_6$ [44]. The $CuAl_2$ phase can be blocky shape or finely dispersed α-Al and $CuAl_2$ particles within the interdendritic regions, as shown in **Figure 2.5**. The presence of nucleation sites,such as $FeSiAl_5$ platelets or high cooling rates during solidification can result in fine $CuAl_2$ particles [**39**]. The blocky $CuAl_2$ phase particles are difficult to dissolve during solid solution heat treatment, unlike the fine $CuAl_2$ phase particles that can dissolve within 2 hrs by solid solution heat treatment **[41]**. Magnesium is present as Mg_2Si in Al-Si-Mg alloys if Mg is not in solution. Mg can also form a true quaternary compound $Cu_2Mg_8Si_6Al_5$ with other alloy elements in Al-319 alloy. In the absence of Cu, high Fe and Mg result in the appearance of π-$FeMg_3Si_6Al_8$. The π phase is difficult to dissolve during solid solution heat treatment **[42].**

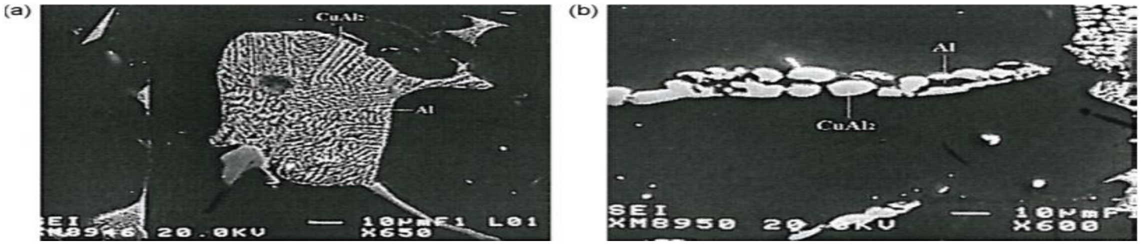


Figure 2.5 Cu-rich phases in as-cast 319 alloys
(a) Eutectic Al_2Cu and (b) blocky Al_2Cu [44].

A comparative study of the mechanical properties of Al-Si-Cu-Mg alloys was carried out by **Cáceres et al. [43]** to investigate the effects of Si, Cu, Mg, Fe, and Mn, as well as solidification rate. The authors observed that increasing the Cu and Mg content generally resulted in an increase in strength and a decrease in ductility, whereas an increased Fe content (at an Fe/Mn ratio of 0.5) dramatically lowered the ductility and strength of low-Si alloys. They also reported that the Cu + Mg content of the alloys determine the precipitation strengthening and the volume fraction of the Cu-rich and Mg-rich intermetallics obtained.

Yi F. [44] adopt the enhanced solid diffusion coefficient of Cu in his model. The diffusion coefficient of Cu in α-Al phase is increased by 4-fold. The presence of Si-phase also has great influence on the diffusion of Cu in the matrix. It is assumed that the diffusion coefficient of Cu increases by 20-fold due to the presence of Si-phase. The distribution of Mg and Si across the dendrite arm spacing also changes due to the increase of Cu diffusion in the matrix. This is attributed to the change of solidification path.

2.3 Heat Treatment

The mechanical properties of cast Al–Si–Cu–Mg alloys depend mainly on the alloy composition and the parameters of the casting process. In order to further improve the mechanical properties of cast components these alloys can be heat treated. Various heat treatment cycles, e.g. different combinations of temperatures and times, are used depending on the casting process, the alloy composition and the desired mechanical properties. The Aluminum Association has standardized the definitions and nomenclature for heat treatment. A typical heat treatment applied to sand and gravity die-cast Al–Si alloys is the T6 heat treatment.

2.4 Casting Metallurgy

Die castings are produced from alloys composed of two or more metals. The predominant metal is usually aluminum, magnesium, zinc, or, in some cases, lead or tin. Die castings must satisfy a wide range of requirements from cosmetic to structural and the performance depends upon the properties of the chemistry of the alloy from which the casting is made. These properties are a function of the alloy constituents, contaminants, solidification patterns, and treatments performed after casting. Each pure metal has a characteristic cooling pattern as it transforms from the liquid state to the solid state and the reverse when it is melted. As time passes, heat is removed, and the temperature drops. While the metal solidifies, however, the temperature does not change, even though heat is being removed. Metals that lend themselves to rapid solidification and still maintain desirable physical properties are most commonly used in the die casting process. For these pure metals, this phenomenon is graphically illustrated in the time, temperature, transformation plot. The flat portion of the curves describes the phase when the metals give up the heat of fusion, which is called the eutectic of the metal.

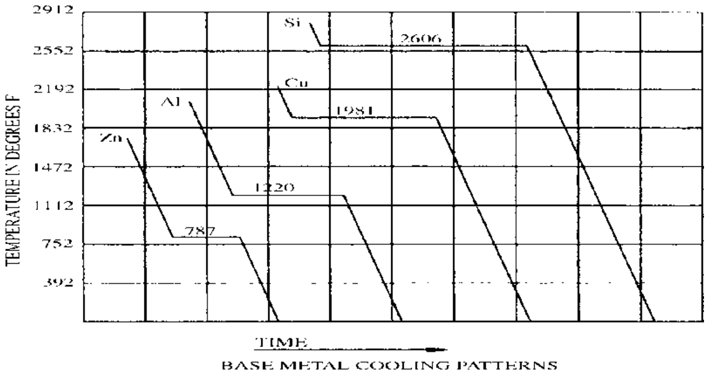


Figure 2.6 Base Metals Cooling Pattern [45]

The perfect flat condition shown in the chart will not be found in the real world where base metals are alloyed with other elements. A typical TTT curve will describe the flat line of a die casting alloy at a down sloping angle because the perfect metallurgical condition is compromised.

Two critical temperatures for these metals are the melt convenient reference. These data will help to visualize the thermal behavior of the base metals used in die casting. Note that the steep pitch of the TTT curves describes rapid solidification. The table tells us that it takes more than four times as long for aluminum to solidify than for zinc because the heat of fusion is greater. It must be understood, however, that this is very basic and fundamental casting alloy information that is presented in a simple form here for purposes of brevity. The rapid

		Heat of Fusion	
Metal	**Melting Point (^{o}F)**	**Cal/g**	**BTU/lb**
Aluminum	**1220.4**	**94.6**	**170.0**
Copper(brass)	**1981.4**	**50.6**	**91.1**
Magnesium	**1202.0**	**89.0**	**160.0**
Silicon	**2605.0**	**337.0**	**607.0**
Zink	**787.03**	**24.09**	**43.36**

Table: 2.2 Melting point and heat of fusion of some common die casting alloy base metals [45]

solidification rate of all die casting alloys distinguishes high pressure die casting from the other foundry processes. When the alloys change from the liquid to the solid state, the quick freezing rate is important to crystallization. Thus, die castings have a fine grain size, dense structure, and superior mechanical properties that make this process superior to other casting processes. The structural properties of the castings produced are affected by the environment in which solidification occurs. It is defined by the combination of metals in the casting alloys and their atomic composition. During solidification, atoms form crystals that become relatively dormant. Atoms of each metal are oriented into specific relationships within the crystals. The arrangement of atoms for each metal displays certain identifiable patterns. This phenomenon is called a lattice shape, which normally defines the properties of the casting alloy.

Atomic movement into and out of the crystal structures occurs, even in the solid state. This accounts for the solid solubility of each element. The faster freezing rates experienced in high pressure die casting diminish this movement. This explains the finer and denser grain structures that enhance the mechanical properties.

During solidification, one metal governs the behavior of the crystal lattice structure. This is why each casting alloy demonstrates a specific freezing range. During this time, both liquid and solid phases exist. The actual state of the alloy can be described as mushy during this period between the liquidus and solidus temperatures. When the eutectic occurs prior to the end of cavity fill, internal defects can be expected.

Initially, crystals are formed which have composed of the base metal (aluminum, magnesium, zinc, etc.). The crystal lattice is repeated until solidification is completed. Then, the individual crystals contact each other at the grain boundary, which establishes the grain structure. During solidification, crystal growth progresses and forms dendrite arms. The freezing rate determines the size and spacing of the dendritic structure. This is not critical in die casting because of the rapid freezing. Distribution is similar to castings produced by other processes that are heat treated to the T4 level at solution temper. For this reason, high pressure die castings are rarely heat treated. In today’s competitive environment, the array of alloys has expanded and the application of heat treatment is becoming more prevalent.

Dendrites form when casting alloys solidify. So it is appropriate to discuss them and the grain structures. ‘‘Dendrite’’ derives from the Greek word for tree, which is the shape taken when they group together in a grain. A grain is a family of dendrites that originate from the same nucleolus. The finger shape of dendrites drives the latent heat of fusion away from the liquid–solid interface. A more familiar but similar heat transfer takes place when the fingers of your hand are exposed to cold. Gloves retard some of the heat escape, but mittens work better because there are no fingers. To start the rapid solidification that occurs in die casting, the formation of dendrites takes place on a schedule defined by the chemical composition of the alloy. It is gradual even though rapid as shown in **Figure 2.7**.

Metallurgically speaking dendrite fingers are called arms. The intricate network of arms inhibits free movement of the remaining liquid alloy during solidification so that the microscopic spaces formed between the arms are starved of the liquid necessary to make up for solidification shrinkage. In these voids two dendrites are illustrated that have come together and the microporosity is described by the crosshatched area. Eutectic silicon is also found between the arms of aluminum alloys. Understanding liquid and solid starts with the TTT chart that presents the thermal behavior of pure base metals. If the temperature reaches a level in which the metal is fully liquid, a point referred to as the liquidus has been achieved.

However, die casting alloys are not pure metals as they are usually a combination of two (binary) or three (ternary) base metals. The behavior of a specific alloy is determined by this combination. Progression of dendrite formation during solidification is shown in **Figure 2.7** and micro-porosity as depicted in **Figure 2.8**

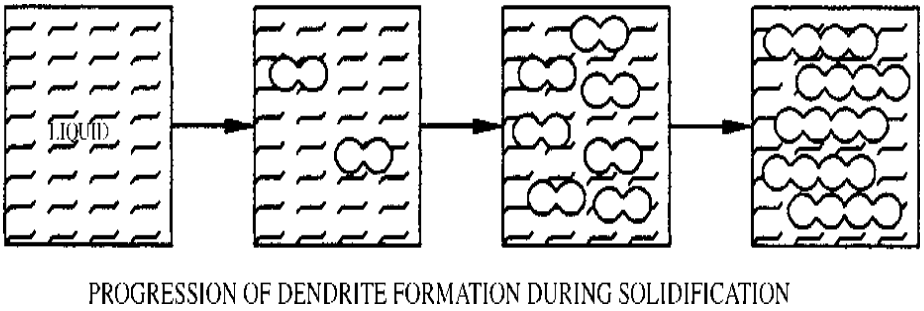


Figure 2.7 Progression of dendrite formation during solidification

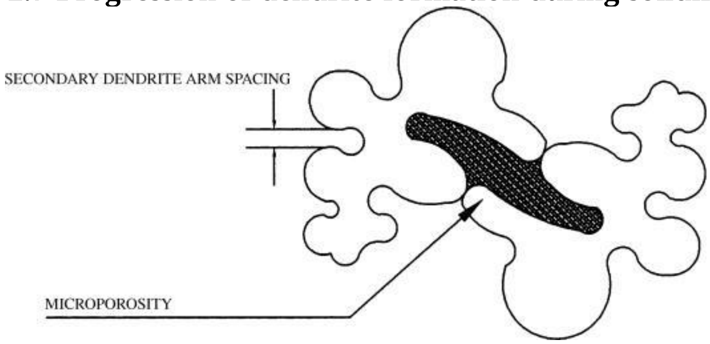


Figure 2.8 Micro porosity as depicted [50]

The latent heat of fusion, sometimes referred to as the heat of transformation occurs when the melting point or freezing temperature is reached. The TTT chart defines a temperature that remains constant as solidification continues, even though heat energy is lost. The total energy given up during freezing is defined by the length of the flat part of the cooling curve. The transformation from the liquid to the solid state occurs because of this energy exchange. The amount of heat is specific and defined in terms of BTUs per pound or calories per gram. When defined in this manner, it is called the latent heat of fusion. The equilibrium diagram in **Figure 2.9** provides a graphic explanation. The eutectic is the lowest melting point of a metal in an alloy system. Therefore, the flat part of the TTT curve is called eutectic arrest.

Aluminum alloy A13 is sometimes referred to as the eutectic alloy because of the effect of the 12.6% silicon content upon the liquidus temperature. Since the 380 binary aluminum alloy is in such common use, an equilibrium diagram for this aluminum silicon alloy is offered (**Figure 2.9**). Note that the fluidity varies about the eutectic line for silicon. In addition to freezing characteristics similar to pure metals, eutectic alloys in the solid state are homogeneous mixtures, under conditions of equilibrium, of the combining metals. The metals may also be described as isothermal reversible reactions so that the liquid combination solidifies into two intimately mixed solids upon cooling. Chemical composition in die castings is alloyed into secondary aluminum alloys that are generated from scrap rather than from primary material that is refined from the bauxite ore that is the original source of aluminum.

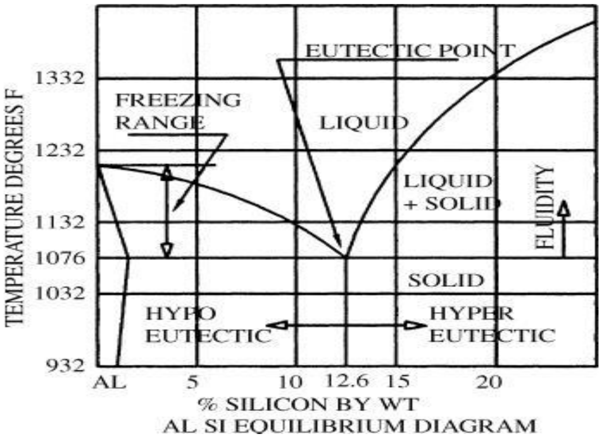


Figure 2.9 Al-Si Equilibrium Diagram [45]

Aluminum is not used without alloying for any purpose except for electrical motor rotors because of its low strength and hardness as well as its poor machinability. Other elements are therefore added to improve upon these properties. The elements most commonly alloyed with aluminum are copper, silicon, and magnesium. To a lesser extent, manganese, iron, zinc, and nickel are alloyed. In general, the addition of elements to aluminum is limited to approximately 15%. Beyond this point, alloys become increasingly brittle, which takes away from their engineering value.

Copper improves the strength and hardness progressively until it reaches a level of about 4%. Above this point, the alloy becomes too brittle. It greatly enhances machinability and also improves properties at elevated temperatures. It lowers corrosion resistance but increases fluidity. At 4%, copper increases the tendency for hot cracking, but further additions decrease the incidence of hot cracking.

Silicon is an important addition to aluminum alloys since the casting characteristics are greatly enhanced. There is a progressive improvement in fluidity with a reduction in hot cracking. Up to the eutectic point of 12.6%, the incidence of solidification shrinkage decreases, making it easier to produce castings free of shrinkage and cracks. This condition suggests that the Al–Si system alloy is the choice for pressure tight castings. Care must be exercised, however, as this is a premium priced alloy.

The trade off for an increase in strength and hardness is a commensurate decrease in ductility. These properties, however, are improved by the rapid solidification.

Magnesium produces a gradual increase in strength up to 6%, although hardness is not affected by magnesium until the 10% level is reached. Therefore, the binary Al–Mg aluminum systems have excellent mechanical properties, resist corrosion, and have good machinability. The impact resistance is good, as is ductility, and they maintain these good properties at elevated temperatures.

Why then are these alloys not used more? The fluidity is so poor that castibility becomes a real problem. The solidification range for these alloys is also very narrow, so that premature freezing during cavity fill must be carefully handled through thorough mathematical analysis.

Iron is a natural ingredient in aluminum alloys due its association with iron in bauxite ore and the aggressive affinity that iron has to go into solution with aluminum. Some metallurgists even go so far as to call aluminum the universal solvent. For this reason iron crucibles cannot be used to hold liquid aluminum, as the bath will eventually dissolve the pot.

Iron forms a eutectic with aluminum at 1.7% and it has a solidification point of 1211F. Although iron is commonly considered as an impurity, it performs a useful function as long as the content is below 1.7%. It increases strength and hardness and reduces the tendency for hot cracking. The limit in ingot or liquid alloys is 1%; iron up to 1.7% significantly reduces soldering and is allowed in castings. In this researcher’s experience, secondary aluminum with iron as an allowed impurity is preferable to primary alloy because of the tendency toward higher iron content.

This tendency for iron pick up when the alloy comes into contact with steel dies and shot sleeves limits the number of passes a batch of aluminum can make before being re-melted. Iron content should not exceed the 1.5–2.0% level, provided that manganese and chromium are present to avoid large concentrations of Fe Al3 needles in the microstructure.

Manganese and chromium are beneficial in small quantities, but the tendency to sludge becomes a problem if the levels get out of control. Excessive sludging is the penalty for losing control and is to be avoided. It is a major contributor to melting loss of metal.

2.5 Solidification of Al-Si Alloys

Al-Si alloys solidify by a primary precipitation of dendrites; an illustration of primary aluminum dendrite (α-Al) structure embedded in Al-Si eutectic is shown in **Figure 2.10**. In hypoeutectic Al-Si alloys primary aluminum solidifies dendritically and grows in <100>direction. Dendrites are often drawn having four secondary arms growing around the primary stem at each junction which is true for cubic structures **[13]**. The undercooling depends on the cooling rate, the concentration of the alloying element in the melt and the type of the alloying element. It is well established that the undercooling increases with increasing cooling rate and increasing concentration of the alloying element **[14].**

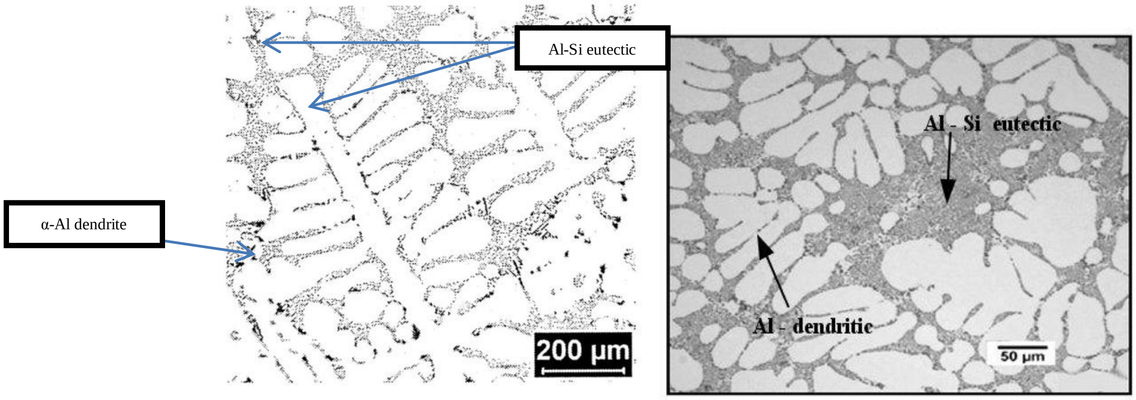


Figure 2.10 Solidification structure of hypoeutectic Al-Si alloy [15]

The solidification of the alloy continues with formation of Al-Si eutectic mixture. In eutectic solidification two phases of Al and Si precipitate simultaneously from the liquid at constant temperature **[16-17]**. **Figure 2.11** presents a phase diagram of the Al-Si system with a eutectic point. The eutectic point is at 12.6 wt. % Si and the eutectic temperature is 577 °C. Aluminum dissolves a maximum of 1.6 wt. % of Si while the solubility of Al in Si is almost zero **[17]**. Eutectic alloys provide a natural composite which gives good properties for the alloy. **[16, 17].** Commercial aluminum alloys often contain other alloying elements such as Cu and Mg in addition to Si. The eutectics of these alloys may be more complex than those observed when looking at the binary system. Formation of Cu- and Mg-bearing intermetallic phases often occurs after eutectic formation.

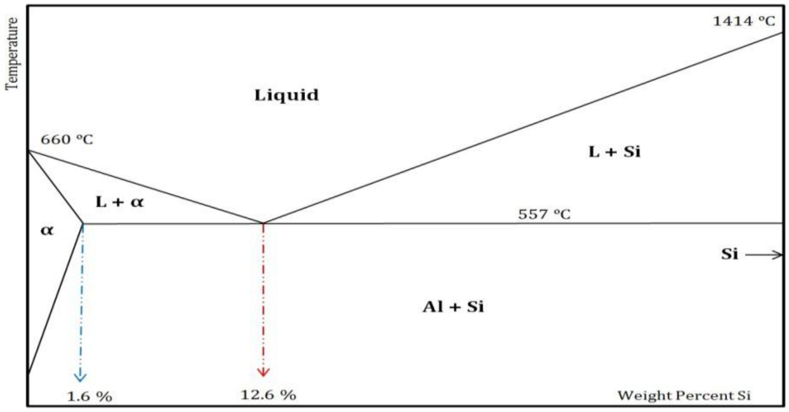


Figure 2.11 The schematic phase diagram of Al-Si [16]

2.6 Casting Defects

The level and type of defects in Al-Si castings depend on the condition of the melt, the manufacturing process and post solidification treatments. Such defects in the castings cause an unfortunate scattering of the mechanical properties and degrade the performance of the component. Lowered defect content results in more reliable castings which enable designers to design thinner sections; lowering weight and material use. The reduction in weight is important because a large portion of the aluminum castings, roughly two thirds, are manufactured for the automotive industry **[18]**. The most typical defect in Al-Si originates from either processing or chemical composition. Gas porosity and oxides are two common irregularities which are initiated through poor melt treatment or non-optimized casting route. High levels of iron are also associated with formation of deleterious compounds which appear as defects in the casting. Once solidification of the alloy progresses, any excess hydrogen, not soluble in the solid and not able to escape the solidified section will form porosity within the casting, reducing its properties. If the die cavity filling is not in steady state, additional pores will appear in the casting, an effect which is more probable in the HPDC process. When the melt meets with oxygen, aluminum will immediately oxidize forming a skin of oxide. If the oxide skin is removed or cracked, a new oxide layer will immediately form. The oxide film formed on aluminum has an amorphous structure and has a low permeability and therefore creates a protective layer at the surface of the liquid aluminum. As long as the oxides are at the surface of the melt they do not present any significant threat to the quality of the liquid metal. However, melting, pouring and transferring liquid metal will certainly entrain newly formed thin oxides into the melt making them possibly harmful **[19].** Beside the porosity and oxides, iron is the most common impurity, and possibly the most detrimental, in Al-Si cast alloy. The solubility in solid aluminum is about 0.05 wt. % at 660°C.The solubility is even less at room temperature and when iron is present in the melt it will form quite harmful intermetallic compounds. Increasing the Fe content drastically reduces the ductility of the alloy. However a minor amount of 0.8-1.0 wt. % is normally favorable to avoid die soldering. Increasing the iron content even more will also affect the tensile strength, however the reduction in tensile strength is less severe [20]. There are a number of intermetallic phases that have been identified in aluminum-Si based alloys. The most important phases are α-Al15 (Fe, Mn) 3Si2 and β-Al5FeSi, where α phase appears as Chinese script or polyhedrons and the β phase appears as 2-D needles and 3-D platelets. The β phase is the most undesirable Fe-bearing phase due to its morphology which is causing a greater reduction in ductility. The most efficient way of promoting formation of α phase in favor of the more detrimental β phase is neutralization with Mn addition. The amount of Mn addition is related to the Fe content and cooling rate.

2.7 Microstructure of the Al-Si Alloys

The microstructure of the Al-Si cast alloys primarily consists of a primary phase (α-Al) and eutectic mixture of Al-Si. The amount of eutectic mixture in the microstructure depends on the level Si. The eutectic mixture contains soft Al as matrix containing Si particles. The morphology of Si-particles is plate-like which may be altered upon modification treatment. The presence of Cu, Mg and Fe in the alloy leads to formation of various intermetallic compounds in the microstructure of the alloy. The most common intermetallic phases are Al_2Cu, Mg_2Si, α-$Al_{12}(Fe,Mn)_3Si_2$ and β-Al_5FeSi. The cooling rate has a marked effect on the size, morphology, and distribution of all the microstructural constituents. Increasing cooling rate refines all microstructural features in size, decreases SDAS, changes the morphology of eutectic Si from large and elongated plates-like to small and rounder ones and decreases the size of all intermetallic compounds regardless of their type. Although an increased cooling rate refined eutectic Si-particles, the plate-like morphology of them remained unaffected. However a Sr treatment may modify the coarse plate-like morphology of Si-particles to fine fibrous. The mechanisms of both cooling rate refinement and Sr-modification of eutectic Si particles are briefly explained in the following sections.

2.8 Cooling Rate Refinement and Mechanisms

The cooling rate refinement of eutectic Si-particles has been described based on the surface energy of the Al-Si solid interface **[21]**. This theory is one of the widely accepted theories for quench modification. The rate of advance of the solidification interface depends on a balance between the rate of heat flow from the liquid to the solid through the interface and the latent heat of fusion released during solidification. The thermal conductivities of Al and Si in their pure form are 205 and 83 W/(m K) respectively, and their latent heats of fusion are 396 and 1411 J/g respectively. Since the difference between the magnitude of the thermal conductivity of pure Al and pure Si and the difference between the magnitude of the latent heat of fusion of pure Al and pure Si are large, Al will solidify much faster than Si. Thus, Al gains a lead during solidification of the eutectic as shown in Figure 3(a).

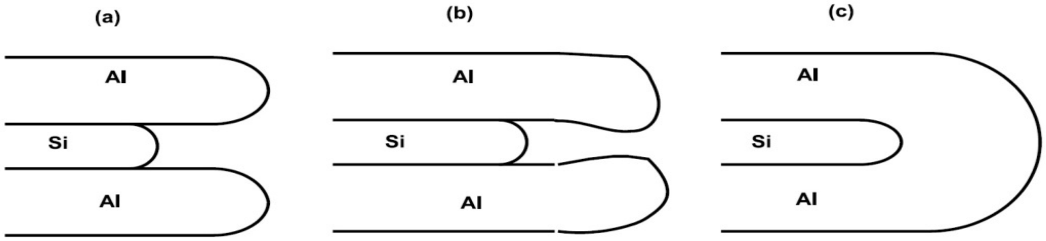


Figure 2.12 Eutectic solidification in unmodified chill cast Al–Si alloys [21].

As the cooling rate increases, the lead of Al over Si increases causing complete encasement of the lagging Si crystal by the advancing Al as depicted in Figure 3(b) and(c). This theory accounts for the formation of the modified eutectic structure at high cooling rates **[21].**

2.9 Eutectic Si Modification Characteristics and Means

One way to improve mechanical properties of Al-Si based foundry alloys is through modification. The Al-Si eutectic consists of a hard, brittle Si phase in a softer Al matrix which is the reason why most of the mechanical properties of castings, especially the elongation to fracture, are determined by the eutectic microstructure. The term “modification” describes the method in which inoculants in the form of master alloys are added to an Al melt in order to promote the formation of a fine and fibrous eutectic Si structure during the solidification process. Modification of the Al–Si eutectic from a flake-like (**Figure 2.13 a**) to a fine fibrous Si structure (**Figure 2.13 b**) can be achieved in two different ways; by addition of certain elements (chemical-modification) or with a rapid cooling rate (quench-modification). Several modifiers are known (e.g., strontium, sodium, antimony, barium and calcium), of which strontium is the most addition that has been employed in the Al alloy industry in recent years as a chemical modifier owing to the following reasons: (a) it is easy to handle, (b) it is effective and (c) its fading effect is low.

Addition of a few hundred parts per million Sr modifies the eutectic Si morphology from coarse plate-like into fine fibrous and has a beneficial effect on both strength and ductility, which is due to changing the fracture mode from transgranular and brittle to intergranular and interdendritic.

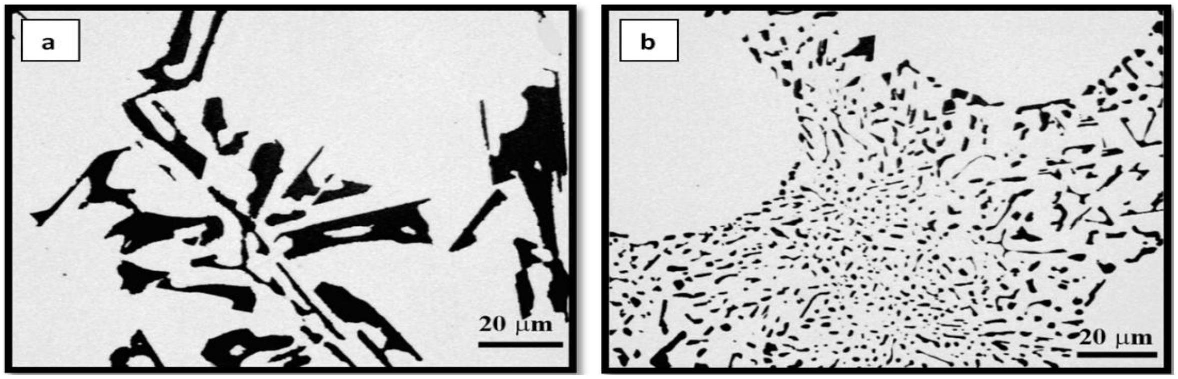


Figure 2.13 The morphology of eutectic Si; (a) Unmodified and (b) Modified structure [22]

In hypereutectic compositions (Si content exceeding 12.6 wt. %), phosphorus is added to the molten alloys which has a marked effect on the distribution and form of the primary Si phase. Investigations have shown that retained trace concentrations as low as 0.0015 through 0.03 % P are effective in achieving the refined structure. No elements are known that beneficially modify both the eutectic and hypereutectic phases. Modification has been recognized to change the amount, characteristics, and distribution of porosity. An impediment to a full acceptance of eutectic modification as a means to improve the mechanical properties of as cast components is that modification often results in increased porosity, although this claim is not fully accepted and porosity is strongly linked to casting parameters. Modification can lose its positive effect by addition of large amounts of modifier (Na > 0.02 and Sr> 0.1 wt. %) which called over modification and which often causes the formation of Al_2Si_2Sr brittle compounds which degrade alloy performance. However eutectic modification is not always a guarantee for improving performance of Al-Si based alloys, and the presence of other undesirable compounds (like Fe-rich intermetallic compounds) or casting defects may dominate properties. Several techniques such as metallographic study, thermal analysis and a method based on physical properties of the alloys have been utilized to assess the modification level of eutectic Si in Al cast alloys. The assessment based on analysis of cooling curves has been introduced as the most accurate and least subjective technique for this purpose [**22**].

2.10 Classification of Aluminum alloy Microstructure:

Various melt treatment processes affect cast microstructure. Micro structural features affect mechanical properties. But, fading, negative reaction with other elements and improper melt treatment result in unmodified or partially modified or non-refined structures. Further, the microstructural transition from acicular to fibrous is not a sharp one but gradual. Hence the concept of modification rating (MR) is used to define the modified structure [**89**].

$$\text{Modification rating (M.R.)} = \sum(\text{fraction of class - class number})$$

The class number refers to the scale of rating from 1 to 6 for the range of structures observed in modified Al–Si alloys.

Class Number	Structure	Description
1	Fully Modified	Si is present in the form of large plate as well as in acicular form.
2	Lamellar	A finer lamellar structure, through some acicular Si may be present (but no large plate).
3	Partially Modified	The lamellar structure starts to break up into smaller pieces.
4	Absence of Lamellae	Complete disappearance of lamellar phase. Some acicular phase still may be present.
5	Fibrous Si eutectic (Fully Modified)	Acicular phase is completely absent.
6	Very Fine Eutectic (Super Modified)	The fibrous Si become so small that individual particle cannot be resolved under optical microscopy.

Table 2.3 Typical Classification of Microstructures [88]

2.11 Improvement in Metallurgical and Mechanical Properties by Mold Oscillation during the Solidification

An attempt has been made in this chapter to systematically present some of significant studies towards the understanding of the above mentioned causes and methods to improve the mechanical properties during solidification of aluminum alloys under vibratory condition. This chapter ends with a concise summary of the state-of-art of understanding to arrive at the objective of present research study.

The mechanical properties of pig iron in castings obtained by the use of vibration have increased in the following manner: yield point from 12.3 to 15&2 kg/mm^2, hardness increased from 170 to 197 units by I Brinell at a more uniform and eddy form of graphite inclusions. The waste due to gas blow holes, often observed on these castings obtained by the conventional method, was totally liquidated by the employment of vibration

Investigations showed, that employing vibration for the metal solidifying in the form, it is possible to actively influence the process of formation of the alloy's structure. This influence consists in the following the structure of the metal is highly refined; structural heterogeneity of castings is eliminated; the content of hydrogen which leads to elimination or sharp reduction in waste due to gas blow holes, decreases considerably; the process of shrinkages result of which shrinkage porosity is decreased and the density of casted detail increases, is made easier; the process of metal crystallization is speeded up.

In this way vibration can eliminate or considerably reduce the basic defects in the structure of steel, cast iron and non-ferrous metal castings. To utilize vibration during the casting of metal it is necessary to fix the processing conditions - frequency, amplitude, duration. The fixed vibration parameters depend upon the tenacity of the fusion, and upon the chemical composition, temperatures etc. In this connection the condition of processing the alloy is set up experimentally. The employment of vibration in foundry industry requires no expensive and complex equipment.

2.12 Improvement in Metallurgical Properties by Mold Oscillation during the Solidification

GUO Hong-min, et al., [46] had found the effects of vibration and grain refiner on the microstructure of semisolid slurry of hypoeutectic Al-Si alloy that the primary α(Al) particles become finer and rounder with the increase of vibration frequency. Intense convection can be caused in melt by vibration, which is generated from the free surface of the bulk melt and spreads downwards, consequently leading to the convection in the bulk. Non-dendrite primary α(Al) crystals become finer and rounder with the increase of vibration, and slurry can be prepared with EPD(equivalent particle diameter) of primary α(Al) about 90 μm and ASC(average shape coefficient) above 0.5 under vibration of 20 Hz.

Chong LIN, et al.,[47] studied about the effect of Fe-containing and ultrasonic vibration on Al−17Si−xFe alloys and suggested with increase of Fe content from 2% to 5% in the Al−17Si−xFe alloys, the amount of plate-like or coarse needle-like δ-Al4FeSi2 phase increases while the amount of long needle-like β-Al5FeSi phase decreases. The effect of USV leads to the formation and refinement of δ-Al4FeSi2 phase. Acoustic streaming and cavitations of USV homogenize the solute field and temperature field, and increase the start-freezing temperature of δ-Al4FeSi2 phase, thereby promoting the formation of fine δ-Al4FeSi2 particles.

S. Wu et al. [48] developed a technique of introducing mechanical vibration during isothermal holding period of hypoeutectic A356 Al alloy to prepare semi-solid slurry and examine the formation of non-dendritic microstructure under above condition. The above technique used mechanical vibration to agitate the melt and hold at a temperature below its liquidus in a crucible. Development of the nucleation and formation of a non-dendritic microstructure took place within the semi-solid slurry due to melt convection by mechanical vibration together with under cooling of melts.

WU Shu-sen, et al.[59] analyze the microstructural characteristics of Al−20Si−2Cu−0.4Mg−1Ni alloy formed by rheo-squeeze casting after ultrasonic vibration treatment. A small amount of non-equilibrium α(Al) dendrites in Al−20%Si alloys could form when copper mould used due to higher cooling rate. The rapid cooling rate mainly contributes to the formation of non-equilibrium α(Al) dendrites in squeeze cast Al−20%Si alloy. The formation of non-equilibrium α(Al) particles of semi-solid RSC Al−20% Si alloy with ultrasonic vibration treatment is promoted by the effects of acoustic cavitation.

ZHAO Zhong, et al.[50]suggested about microstructure evolution of Mg9AlZnY alloy with vibration in lost foam casting during semi-solid isothermal heat treatment concluded that the nearly equiaxed grains of Mg9AlZnY alloy can be obtained by vibration solidification and rapid cooling in lost foam casting (LFC). The semi-solid microstructure with a good roundness can be obtained by SSIT at 530 ˚C and 570 ˚C. Microstructure evolution of dentritic grains at SSIT (semi-solid isothermal heat treatment)is different from that of equiaxed grains. The evolution of equiaxed grains shows that small grains tend to be melted and large equiaxed grains tend to grow and spheroidize.

C. Limmaneevichitr et al. [51] studied about metallurgical structure of A356 aluminum alloy solidified under mechanical vibration and suggested that during the solidification process, dendrites that formed normally in the liquid alloy were subsequently disturbed and fragmented by the mechanical vibration introduced into the melt. This effect was enhanced when the vibration was introduced into an alloy with a larger solid fraction, as was observed with solidification at lower pouring temperatures. It was shown that the introduction of mechanical vibration into the A356 melt with adequate solid fraction prior to complete solidification successfully resulted in an as-cast structure featuring semi-solid morphology.

ZHANG Xiao-wei, et al. [52] reported about solidification of horizontally continuous casting, under the action of the periodical forces from electromagnetic vibration (EMV) of super-thin slab of pure tin(Sn-10%Pb alloy) is greatly refined and the extent of grain refinement is increased and promotes the growth of equiaxed grains in the center of super-thin slab with the increasing magnitude of alternating current.

ZHANG Liang, et al. [54] observed the effect of cooling condition in different temperature ranges on microstructure of semi-solid AZ91 slurry produced via ultrasonic vibration process. The results show that fine and spherical α -Mg particles at the nucleation stage, which is mainly attributed to the cavitation and acoustic streaming induced by the ultrasonic vibration.

V.O. Abramov et al. [55] observed the combined effect of electromagnetic forces and ultrasonic vibration during casting of Al-Pb base alloys, modified macro- and microstructures were obtained.

H. Puga et al. [56] studied the microstructure and mechanical behavior of Al–Si–Cu alloy under indirect ultrasonic vibration and measurement of material's homogeneity and thereby also as a measure of efficiency of ultrasonic treatment.

N. Abu-Dheir et al. [57] studied about the silicon morphology modification in the eutectic Al–Si alloy under mechanical mold vibration. The microstructure responsible is where the lamellar spacing tends to reduce and silicon morphology becomes fibrous with the increasing of the vibration amplitude as compared to gravity casting. However, it is also reported that by exceeding a critical value of vibration amplitude, the silicon tends to coarsen.

Zhiqiang Zhang et al.[58]observed the effect of electromagnetic vibration of mould core region on the solidification structure of magnesium alloy and the experimental results showed that the electromagnetic vibration of mould core region can significantly refine the solidification structures and also found that the average grain size of AZ80 alloys in the mould core region decreased firstly and then increased with the increasing of electromagnetic vibration frequency, current intensities and treatment time.

G. Chirita et al. [59] compared the influence of vibration on the solidification behavior and tensile properties of an Al–18 wt%Si alloy at fixed amplitude and different frequencies with gravity castings without vibration and found the tensile strength was improved for low vibration frequencies but decreased for high frequencies.

F. Taghavi et al.[60]studied grain refinement and density of A356 aluminum alloy under prolonged mechanical vibration and found the mechanical vibration tend to increase in grain refinement and density of A356 aluminum alloy, Maximum achieved grain refinement was 53% at 50 Hz and15 min .

F. Taghavi et al. [61] studied thixotropic microstructure, size and morphology of primary solid phase in order to produce feedstock materials for semisolid metal forming of A356 aluminum alloy under the mechanical vibration. It was found that maximum grain refinement degree obtained at 50 Hz and 15 min vibration condition i.e. 53%, size of primary solid phase was 173 µm.

S. Wu et al. [62] observed the effect of indirect ultrasonic vibration on microstructure and property of rheocasting aluminum-alloy and found the good semisolid slurry of A356 Al alloy could be obtained within 50 s near its liquidus temperature, and the average diameter and shape coefficient of primary α-Al particles were 75 µm and 0.62 respectively.

X. Jian et al. [63] evaluated the effect of ultrasonic vibration on the nucleation and growth of aluminum alloy A356 melt at the temperature close to its liquidus and subsequently cooled quickly. Very difficult to form globular grains when the specimens were treated at isothermal temperatures in the mushy zone. It may be simply that in the paper cavitations-induced heterogeneous nucleation plays a more important role than dendrite fragmentation in the formation of globular grains.

M. Sha et al. [65] studied the combined effects of cobalt addition and ultrasonic vibration on microstructure and mechanical properties of hypereutectic Al–Si alloys with 0.7% Fe. The results show that, when added 0.3%, 0.7%, 0.91%, and 1.05% Co, respectively, into the alloy, the Fe-containing compounds changed from long acicular β-$Al_5(Fe, Ni)Si$ phases to Chinese-script, granular or rod-like α-$Al_{15}(Fe, Co, Ni)_3Si_2$ phases with the increasing of Co content.

S. Guo et al. [67] observed the microstructural refinement of DC cast AZ80 Mg billets by low frequency electromagnetic vibration and the experimental results show that the grains have been greatly refined by applying electromagnetic vibration. The grains over the cross section of the billet tend to become homogenous under certain electromagnetic vibration conditions.

F. Wang et al. [68] studied the changes of solidification parameters and the temperature profiles for the liquid in front of the solid–liquid interface caused by vibration. Uniform and fine-grained casting was obtained.

C. Vives [69] studied the effects of electromagnetic vibrations induced by the interaction of alternating electric and stationary magnetic fields during the solidification of aluminum alloys and obtained good structural refinement.

B.J. Zhang et al.[70] found the large-scale billet casting, to obtain a homogeneous temperature field in the sump, the electromagnetic frequency has to be low.

C. Vives and J. Cryst.[71] observed the effect of the vibration which mainly originates inside the electromagnetic skin depth area and owing to the medium elasticity, is propagated throughout the melt and experimentally found as the magnetic-field strength and amplitude of the vibrating electromagnetic pressure is very small and so cavitation effects are also small.

K. Kocatepe [72] find the enhancement in amount and size of the pores due low frequency vibration of sodium modified LM25 and LM6 alloys .The amount and size of pores were increased with increasing vibration intensity in unmodified LM25 and LM6 alloys.

Kocatepe K.[73] found the modification of eutectic Al–Si alloy with metallic sodium the large pore volume fraction was produced by vibration at low frequency and amplitude in the modified alloy. If the sodium modified melt is stirred more than required, the modification is faded because of sodium losses in the melt.

Shukla DP et al. [74] explained the porosity formation in Al–11.8%Si alloy under low frequency vibration by claiming that the gas bubbles are nucleated at the solid–liquid interface with increasing peak acceleration, and are entrapped between aluminium and silicon phases by the advancing solidification front.

J. Hua et al.[75] obtained grain refinement by the pulsed discharge vibrations. The grain size reduced of the β-phase of the Sn–Pb20% alloy under different pulsed discharge frequencies.

M. Li et al.[76] found the controlling microstructures of AZ31 magnesium alloys by an electromagnetic vibration technique during solidification. This may be responsible for the formation of coarse structures with dendritic morphologies.

W. Wang et al.[77] studied about the crystal nucleation and detachment from a chilling metal surface with vibration and found the exerting vibration to a chilling solid surface is an effective way to produce lots of nuclei for forming equiaxed grains microstructure by preventing the solidifying shell to form and promoting dendrites to break off and shower down not only from the free liquid surface but also from the chilling solid surface. To obtain finer equiaxed grains, it is necessary to increase synchronously vibration frequency as well as amplitude.

J. Wannasin et al.[78] found that the inoculated melt increases the dynamic nucleation electiveness, which consequently yields a finer microstructure of cast samples.

V. S Mudakappanavar et al.[79] reported the vibration successfully broke the dendritic structure into small islands of Aluminum. Inducing vibration also resulted in fragmentation of silicon needles and uniform distribution of silicon flakes resulting in improved properties.

Chworinov, N. [82] and Piwonka, T S.[83] reported as the vibration too is well known as a method of structural refinement. Its beneficial influence on the structure and properties of cast aluminium and copper alloys, a reduction in graphite flake size in cast irons was also reported.

Piwonka, T S.[83] reported the vibration is the principal cause and that during solidification a zone of low-melting liquid exists immediately adjacent to the main crystal growth. Nucleation can occur, and if disturbed by vibration, banding results. This theory further states that growth takes place from these new nuclei in such a manner as to form a sandwich of liquid metal surrounded by solid metal, which is isolated from the liquid bath at the bore .

Ji et al. [85] introduced mechanical vibration into the solidification of AZ91D magnesium alloy via lost foam (LF) casting in order to overcome the defects of coarse microstructure and low mechanical properties. The microstructure with fine uniform dendrite grains was achieved with mechanical vibration. They attributed this to cavitation and the melts flow induced by the mechanical vibration.

Tamura et al. [86]found that the electromagnetic vibrations affected increase in the cooling rate and the decrease in the number of crystal nuclei directly when they investigated the effect of frequency of electromagnetic vibrations on glass-forming ability in Fe-Co-B-Si-Nb bulk metallic glasses. They concluded that vibrations give rise to considerable agitation of the melt and result in the newly formed nuclei being distributed throughout the solidifying pool and crystallization takes place uniformly inside the entire volume.

Radjai et al. [87] studied the effect of such a vibration on the refinement of Al - 17 wt.% Si and concluded that electromagnetic vibration caused a cavitation effect that crushed the primary silicon particles into smaller pieces

Jiang, W., et al. [91] found that the mechanical vibration greatly increased the mechanical properties ,density of A356 , the size, morphology, distribution of α-Al primary phase, eutectic silicon particles, and SDAS were significantly improved and also found with increasing vibration frequency, the grain size and SDAS continuously decreased, and the shape factor gradually increased with the increase of vibration frequency.

Plotkowski, A. J. [93] suggested the physical refinement due to mechanical vibration. In this method, the mold is subjected to a mechanical vibration with a particular frequency and amplitude. This vibration causes shearing of the dendrite arms, which float into the melt and promote increased nucleation.

Radjai, A., Miwa, K., & Nishio, T. [94] reported that electromagnetic vibrations affect the solidification structure of metallic alloys. The objective is followed by inducing vibrations in a hypereutectic Al-Si alloy melt containing suspended silicon particles and interrupting the process at different temperatures before and after the start of solidification by water quenching.. Establishing the conditions for obtaining identical cooling rates in experiments with different experimental conditions has lead to the exclusion of effects resulting from the differences in cooling rates and recognition of the effects caused only by electromagnetic vibrations. After the start of solidification, particles are locally agglomerated and expelled toward the surrounding walls under a combined influence of electromagnetic vibrations and pinch force squeezing the liquid. The final structure obtained is composed of an almost completely eutectic matrix surrounded by agglomerates of silicon particles along the outer surface.

Mizutani, Y., et al. [96] in their study used the electromagnetic vibrations and temperature gradient to grain refinement of pure aluminum (99.7 mass%). As the pure aluminum melt has been subjected to electromagnetic vibrations with a frequency range from 150 to 500 Hz, crystal grain has become small with increase of vibration frequency. In the case of nonvibrated specimen, the average grain sizes of each cross-section are scattering widely and the total average grain size is approximately 700 µm. On the other hand, the average grain size decreases gradually by the imposition of electromagnetic vibrations with low frequencies until 500 Hz, and scattering for each cross section diminishes. Especially, crystal grains are most refined at the frequency of 500 Hz and the average grain size is about 200 µm.

Jianbo Yu et. al [102] Investigated the solidification structure of eutectic Al-Si alloy experimentally due to electromagnetic vibration.It is found that the eutectic structure has been refined by solely imposing high magnetic field while it is coarsened under the electromagnetic vibration. Polyhedral Si grains and nondendritic α-Al appeared when the electromagnetic vibration strength was sufficient. Strong convection may break co-operative growth of eutectic phases to form polyhedral Si grains and non-dendritic α-Al.

Jia, S., & Nastac, L. [119] suggested that UST produces strong convection and shock waves in the melt which may promote dendrite fragmentation. Convection can promote dendrite fragmentation because it causes local temperature and composition variations and promotes diffusion of solute. Shock waves will induce the breakage of the melting root. The pressure oscillations exist in a melt under UST processing, the liquidus temperature for the melt is changed. Thus, some part of the melt is superheated and the other part is undercooled. This phenomenon occurs at high frequencies and causes increase in the amount of nuclei into the melt.During the cavitation process, very small bubbles are created at low pressure. These bubbles can act as nuclei for the formation of hydrogen and vapor bubbles. Hydrogen will escape from the liquid. The degassing efficiency is proportional to the ultrasonic intensity.

Zhang, L., et al. [120] suggested that any factor which increases the number of nucleation sites or reduces growth rate, yields fine grains in the as-cast aluminum alloys . Based on this, many techniques of grain refinement are available in casting practices, such as rapid solidification , deliberate addition of inoculants , and forced action upon melt which includes mechanical or magneto-hydrodynamic stirring and ultrasonic vibration . The main mechanism of these techniques is increasing the number of nuclei by heterogeneous nucleation during solidification.

Akhlaghi, F., & Taghani, A. [121] used the vibrating cooling slope (VCS) method for enhancing a globular structure in aluminum A356 alloy and found the main effect of vibration on the structure of solidifying metals and alloys is the suppression of columnar growth by fragmentation of the growing dendrites .They also suggest that grain refinement can be explained by several mechanisms such as (i) intensified flow of the liquid metal around dendrite arms; (ii) bending stresses induced on growing dendrites due to vibration induced movement of the liquid between them and (iii) re-melting of dendrite arms at the necks due to increased temperature fluctuations as a consequence strong motion of liquid.

Based on three mechanisms described by them, these crystals, formed by detachment of weak dendrite arms along the cooling plate grow in the mold. Experimental results show that the vibration of the slope results in much pronounced fragmentation of dendrite arms and intensified detachment of them from the cooling plate providing more sites for heterogeneous nucleation of new crystals. In this case, the applied shear stress is sufficient to globularize the structure. The number of the seed crystals and the extent of the shear stress applied on them are therefore affected by the vibration frequency. Therefore the increased vibration frequency increases the number of nucleated crystals and intensifies their fragmentation process resulting in decreased size of globules.Also the increased vibration frequency contributes to the increased shear stress applied on the growing crystals in the solidifying melt resulting in generation of more spherical globules .

Gibb, F. G. [122] suggested that the agitation or vibration can induce supercooled liquids to crystallize due to the mechanical motion facilitating the rearrangement of the atoms necessary to produce an embryo is called mechanical effect. The possibility that vibration may be important in influencing plagioclase crystallization in experiments between the liqudus and solidus temperature has not been investigated due to the difficulties of obtaining a vibration-free environment in a busy laboratory, but it may be more than a coincidence that during a period in which construction work was being carried out in the laboratory (resulting in considerable vibration) a markedly higher proportion of the experiments in this field crystallized feldspar.

2.13 Improvement in Mechanical Properties along with Metallurgical Properties by Mold Oscillation during the Solidification

W. Dai et al. [53] investigated the effects of rheo-squeeze casting parameters on microstructure and mechanical properties of AlCuMnTi alloy and the semisolid slurry of AlCu5MnTi alloy was prepared by indirect ultrasonic vibration (IUV). The tensile strength and elongation were 326.5 MPa and 11% respectively, which were improved by 6.5% and 47% respectively compared with conventional squeeze casting samples.

YAO Lei, et al. [64] obtained fine globular structure and the refining effect of Mg-8Li-3Al alloy with prolonging the ultrasonic treatment time. Solidification structure, properties of Mg-8Li-3Al alloy and morphology of α phase is modified from coarse rosette-like structure to fine globular one with the application of ultrasonic vibration. The mechanical properties improved apparently with ultrasonic vibration. The tensile strength and elongation of alloy improve by 9.5% and 45.7%, respectively, with 170 W of ultrasonic treatment for 90 s.

Chong Lin et al.[66] investigated the effects of ultrasonic vibration and manganese on microstructure and mechanical properties of hypereutectic AlSi alloys with 2%Fe, the UTS(ultimate tensile strengths) of A1 and A2 alloys are increased by 24.3% and 22.5% respectively at room temperature, compared to those of the alloys without USV treatment. The UTS values of them are 271 MPa and 289 MPa respectively. The UTS at 350^{o}C and hardness of A1 and A2 alloys are also improved slightly after USV treatment.

J. Campbell [80] suggested the idea “mechanical vibration” promotes grain refinement and can extend the equiaxed zone.

R.J. Kissling et al. [81] reported to the vibration of a Copper Alloy (Cu-32Zn-2Pb-1Sn) improved yield and tensile strengths by about 15%, with a 10% reduction in grain size from the unvibrated state. In general, the α copper-zinc alloys (<35% Zn) exhibit grain size reduction and greater improvement in properties, while the α-β alloys do not.

P.A.O. Adegbuyi et al.[84] suggested that each composition of Aluminum-Copper alloys grain refinements that led to improved properties by specimens were vibrated at different frequencies during solidification (Casting) .The tensile stress (strength) increases with frequency. Vibration decreases the ductility of the material as evidenced from the percentage elongation and percentage reduction in area and vibration increases the number of grains formed, that is smaller grains and hence fine grain structure.

Knuutinen, A. et al. [92] suggested the mechanical properties of aluminum alloys strongly depend on the solidified microstructure .Fine-grained microstructure is desirable in castings because this improves mechanical properties and brings about more uniform distribution of secondary phases.

Kumar, R., et al. [95] investigated the effect of mould vibration during solidification of Al-Cu alloys to understand the modification in microstructure and mechanical properties of casting. The casting done in a graphite mould and frequencies were varied from 40 to 150 Hz. A casting was also was also made without vibration to compare the results of castings with vibration. The experimental results showed significant grain refinement and remarkable improvement in hardness of castings with mechanical mould vibration during solidification.

Guo, H. M.,et al. [97] found the mechanical vibration during the solidification of AZ31 magnesium alloy casting can significantly improve mechanical performance, with a simultaneous increase in both strength and elongation. With increasing vibration acceleration from 2.5 to 19 m s^2 , the ultimate strength increased from 152 to 213 MPa, the yield strength increased from 71 to 122 MPa, and the elongation increased from 4.8 to 11.5 pct. These findings are consistent with the measured grain size , where the highest strength and elongation correspond to the smallest grain size obtained under applied vibration acceleration.

Chaturvedi, V., & Pandel, U. [98] studied the influences of mechanical vibrations on the mechanical properties of AZ91 magnesium alloy . This was tested at constant frequency 40Hz and varied amplitude from 0 to 2 mm. Increased amplitude of mechanical vibration during solidification causes refinement of the grain in the alloy. Tensile strength improved upto a certain point with increasing amplitude and start decreasing with further increment in the amplitude of vibrations. This refinement of the grains also results in an increased percentage elongation and hardness of the alloy samples.

Jiang, W., et al.[99] investegated the effects of vibration frequency on microstructure, mechanical properties, and fracture behavior of the A356 aluminium alloy. Obtained results showed that mold vibration frequency of 100 Hz, the grain size and SDAS decreased by 32 and 19 %, respectively, and the shape factor increased by 262 %, and the average length, width, and aspect ratio of the silicon particles decreased by 45, 6, and 42 %, respectively, compared to that of the sample without vibration. Meanwhile, the tensile strength, yield strength, elongation, and hardness of the A356 alloy sample were, respectively, 35, 42, 57, and 28 % higher than those of the sample without vibration. In addition, the mechanical vibration changed the fractograph of the A356 alloy from a clear brittle fracture nature of the alloy without vibration to an obvious dimple fracture nature, and with the increase of vibration frequency, the dimples were very deep and well distributed with a high density.

Sayuti, M., et al.[100] found the solidifying particulate(TiC) reinforced aluminium alloy(LM6) matrix composite are fabricated by different particulate weight fraction of titanium dioxide to various sources of vibration on the resulting casting quality, a mechanical vibration technique for inducing vibration resulting in enhanced mechanical properties, such as impact properties is devised. Microstructure studies were conducted to determine the impact strength and density. Preliminary work show that the mechanical properties have been improved by using vibration mold during solidification compared to gravity castings without vibration.

K G Basavakumar and P G Mukunda Bull [101] investigated the effect of melt treatment on microstructure and impact properties of Al–7Si and Al–7Si–2·5Cu cast alloys. Alloys exhibited improved impact toughness in as cast condition when compared to those treated by individual addition of grain refiner or modifier. The improved impact toughness of Al–7Si–2.5Cu alloys are related to breakage of the large aluminum grains and uniform distribution of eutectic silicon and fine $CuAl_2$ particles in the inter-dendritic region resulting from combined effect of refinement and modification.

Patel, V. R. [103] suggested that mechanical mould vibration has a significant effect on the alternative layer of eutectic silicon particles in eutectic aluminium-silicon alloys. The eutectic silicon particles show considerable modification and their distribution tends to become more uniform when the casting is solidified with vibration.Highest tensile strength and impact strength is achieved at vibration frequency than stationary casting. Melt treatment along with vibration shows modification in size of eutectic silicon & refinement of α-Al dendrites of eutectic Al-Si alloy.

Anilkumar, T., et al. [104] investigated the influence of vibration during the solidification on the mechanical properties of the Al-Si alloy castings. Grain structure gets reduced,when the alloy is subjected to vibration . Frequency varies from 0 to 12Hz . For 12Hz frequency, the percentage increase in UTS in comparison with ascast is about 16%. This may be attributed to decrease in grain size in comparison with the ascast condition. Hardness values get improved upon subjecting the castings to grain refinement and vibration. The hardness value of 67.75 HRB is observed in the specimen when it is subjected to vibration. (An increase of 7.5% in hardness values is observed upon subjecting the specimens to vibration effect). This indicates that vibration has an influence on the mechanical properties of the Al-Si alloy castings.

After going through to of various researchers in lierature.Review and after critical examination following conclusion have been derived:

1. The increase in mechanical properties due to the fragmentation of the silicon flakes, suppression of undesirable dendritic and development of a fine-grained structure.
2. The increase of grain refinement observed in the case of vibrated alloys may also have contributed to the enhancement of mechanical properties.
3. The improvement in mechanical properties also by combined effects of fracturing of eutectic Si particle and finer grain size together with fine A319 (Al_2Cu, $Fe_{1.7}$ Al_4 Si and Al_2CuM_g) and A356(Mg_2Si and $NiSi_2$) particles inter-metallic phase formed along the inter-dendritic region, due to vibration during solidification .