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A review on solidification of casting under oscillatory conditions of ferrous and non-ferrous materials

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ABSTRACT

Ferrous, non-ferrous metals and alloys are melt and reshape them into finished shape through pouring molten metal into a mold cavity during solidification. The present review confines itself the understanding of necessary conditions that are affects the casting properties i.e. grain nucleation, grain growth of solidified finished shape. After completion of nucleation, solidification process progresses with the growth of nuclei. In general, finer grain size leads to high mechanical properties such as tensile strength, hardness, toughness, fatigue strength and yield. Grain refinement and enhancement in mechanical properties can be achieved by the mold rotation, mechanical vibration and electromagnetic stirring. This paper also reviews the cooling rate, nucleation presents, grain size, grain growth and change in solidification behavior under static and oscillatory casting conditions.

Introduction

In casting molten metal is poured into a mould cavity and after solidification , molten metal gets the shape of cavity. During the solidification process of any molten metal involves nucleation and growth. Nucleation seems in the liquefied metal in the form of very small solid particles, called as nuclei, when distinct stages of transformation in the metal take place. These nuclei are created by the deposition of atoms and grow into the form of crystal and these crystal results in the completely solidified grains. Nucleation is of two type- homogeneous nucleation and heterogeneous nucleation. Homogeneous nucleation occur without any foreign particle while heterogeneous nucleation needs foreign particle such as sand, dirt and impurities. Heterogeneous nucleation occurs at the surface and these grains are called as equiaxed grains while inside due to without any foreign particle homogeneous nucleation takes place and these grains are called as columnar grains and these columnar grains are poor for electromagnetic properties. These columnar grains grow rapidly and called as dendrites. These dendrites are unwanted in the casting so grain refinement is required [41], Grain refinement is a technique used to refine the mechanical properties of the materials by reducing their grain size. This is also called as inoculation. In this process the refining agents such as Al-5Ti-1B, are mixed to the material to work as nucleant. The major drawback of coarse grain structure is that it may result number of surface defects in alloys. Non uniformity of grain size also diminishes the fatigue performance, yield strength and tensile elongation to fracture [42]. The main benefits of fine grain structure over conventional cast structure is fracture toughness and high strength combination, improvement in low cycle, fatigue life, constancy of properties, comprehensive properties, density of fine powders, generation of a fine powders and randomly oriented equiaxed grain structure during solidification, crystallization of amorphous alloys, distribution of second phase and microporosity on fine scale, better feeding to eliminate shrinkage porosity, improved ability to achieve a uniform anodized surface [42]. Refinement of cast structure can be generated by increasing the number of nucleating seeds, a large number of crystals are generated, affect on each other and restrain each other from further growth. Grain refinement can be divided into three basic methods: mechanical, chemical and thermal. These methods comprise: agitation of the melt during freezing, nucleation promoting ,growth hindering additions and rapid cooling [43]. This nucleant is heterogeneous, in the sense that it arises from solid nucleant either already present in the melt or added purposely, which act as centres for abundant nucleation. These include mould rotation, mechanical vibration and electromagnetic stirring. Many articles describe the benefits of vibration during casting on microstructure and mechanical properties of castings .This paper presents the cooling rate, nucleation, grain size, grain growth and solidification behaviour under stationary and vibratory casting condition. Mechanical vibration has been used to improve microstructure and mechanical properties of castings by way of grain refinement and this practice has been used by researchers.

Ferrous, Non-Ferrous Metals and its Alloys

Ferrous alloy

Cast Irons and Steels (ferrous alloys) represents some of the most complex alloy systems. A wide variety of microstructures and resulting properties are possible, depending on composition, solidification conditions, and appropriateness heat treatment. The intent of this article is to providence a classification system for ferrous alloys. Cast irons are iron-carbon base alloys solidify with a eutectic. They containerization various amounts of Si, Mn, P, S, and trace elements such as Ti, Sb, and Sn. They May useful containerization various amounts of alloying elements. Wide variations in properties can be achieved by Varying the balance between carbon and silicon, by Alloying with various metallic or nonmetallic elements, and by Varying melting, casting, and heat-treating practices. Steels can be classified on the basis of composition such as carbon, low-alloy, and high-

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alloy steel. Microstructure, such as ferritic, austenitic, martensitic, and so forth; or product form, such as bar, plate, sheet, strip, tubing, or structural shape. Common use Further subdivided thesis has broad classifications. For example, carbon steels are classified or at according to carbon content as low-, medium, or high-carbon steels. Alloy steels are classified or at according to the principal Alloying element (or elements) present. Thus, there are nickel steels, chromium steels, chromium-vanadium steels, and so on.

Non-ferrous alloy

A non-ferrous metal and alloys, that does not consist iron in sufficient amounts. Generally more costly than ferrous metals, non-ferrous metals are used because of advantageous properties such as low weight (e.g., aluminum), higher conductivity (e.g., copper),[44] non-magnetic property or resistance to corrosion (e.g., zinc)[48]. Some non-ferrous materials are also used in the iron and steel industries. For example, bauxite is used as flux for blast furnaces, while others such as wolframite, pyrolusite and chromites are used in making ferrous alloys[49]. Vital non-ferrous metals comprise aluminum, copper, lead, nickel, tin, titanium and zinc, and alloys such as brass. Precious metals such as gold, silver and platinum and exotic or rare metals as cobalt, mercury, tungsten as cobalt, mercury, tungsten, beryllium, bismuth, cerium, cadmium, niobium, indium, gallium, germanium, lithium, selenium, tantalum, tellurium, vanadium, and zirconium are also non-ferrous[49].They are usually achieved through minerals such as sulfides, carbonates, and silicates[50].

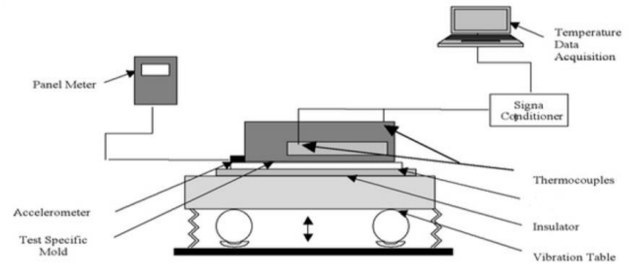


Figure 1. Schematic illustration of the assembled apparatus for applying mechanical vibrations to a permanent steel mold.[89]

Effect of Dendrite Growth, Grain Growth and Nucleation during solidification on Microstructure Dendrite Growth

When under cooling occurs in the band of liquid connecting the interface, any existing swelling on the solid face tends to become stable and to act as a centre for preferential growth. Whilst general advance of the interface is slow down by the latent heat or solute barrier, such local growth centers can explore further into the zone of under cooling. These are favorable situation for dendritic growth, with its quality tree-like form. This is the type of growth most commonly encountered in the freezing of commercial casting alloys forming solid solutions.The primary axis of the dendrite is the result of preferred growth at an edge or corner of an existing crystallite. The projection generate into a needle and subsequently a plate following the general direction of heat flow; this growth direction is usually associated with a particular crystallographic direction as exemplified in the literature [45-46]. Lateral growth of the primary needle or plate is controlled by the same latent heat or solute accumulation as withdrawn general growth at the original interface, but secondary and tertiary branches can develop by a similar mechanism to that which led to the growth of the primary stem (Figure:1). The secondary spacing, which decreases with increasing cooling rate, was originally seen as resulting from normal growth of the dendrite arms into undercooled liquid, but it was later established that the overriding influence on the final spacing is the mechanism of Ostwald ripening, which accounted for certain discrepancies between theoretical and measured spacings. This and other condition of dendrite arm spacing were examined [52-53],following establishment of the initial spacing by the previously discussed branching mechanism, the structure undergoes progressive coarsening during the remaining period of solidification. This occurs through the influence of boundary curvature on the surface energy, so that the smaller arms remelt and vanish, at the same time as the neighboring larger arms continue to grow and enhance their surface area. The final spacing is thus much more than the original.

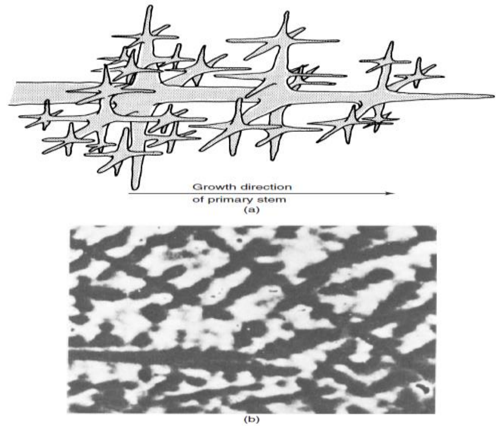


Figure 2. Dendritic growth. (a) Classical concept of a dendrite, (b) dendritic microstructure in carbon–chromium steel. X5 approx[55]

It will later be shown that the facial appearance of the dendrite substructure are more significant than grain size in relation to the properties of many cast alloys, although some refining treatments produce copious nucleation of small grains without dendritic features.

Whilst picture,figure:1.0 of dendrite progress has been presented in terms of unidirectional growth from a major interface – this would produce columnar-dendritic grains – dendritic growth may equally be associated with a crystal growing independently within the melt. In this case the growth interface is the whole periphery of the crystal and the fully developed grain is something like equiaxed.

Dendritic growth in a pure metal can only be detected by interrupted freezing and decantation, but is evident in alloys through the tenacity of compositional differences, exposed on etching as the characteristic cored structure. Coring results from the aforementioned differential freezing process, which leaves the centres of the dendrites in short of solute compared with the inter dendritic zones. Finally we can say that compositional gradient can only be removed at high temperature diffusion in the solid state, time for which is not normally available during cooling from the casting temperature.

Expanded annealing or homogenization can bring about entire diffusion of the solute, but even in this case visible evidence of the original coring may keep it up as a pattern of segregated impurities. The actual time for homogenization is less when grain size and the spacings of the dendrite substructure are small, since the diffusion distances are then shorter. Dendritic growth in alloys is preceded, with less marked undercooling, by the formation of a highly distinctive cellular substructure, direct evidence for which was originally obtained by the examination of interfaces from which the liquid had been decanted. This structure (see Figure 2.0) is produced as a cluster of hexagonal rods which grow into the liquid and throw out solute to their boundaries. On attain a certain level of under cooling, the cellular gives way to the dendritic mode of growth by the better development of a limited number of cells. Intermediate rod-like structures have been described by Flemings[88] as 'fibrous dendrites'. The successive steps in the evolution of the substructure from a plane interface to the full dendritic condition were examined in detail by Biloni and Chalmers[56]. A substantial review of much of the modern work or dendritic structure, including detailed aspects of the growth processes operating under the special conditions of directional and quick solidification, is that by Trivedi and Kurz[57].

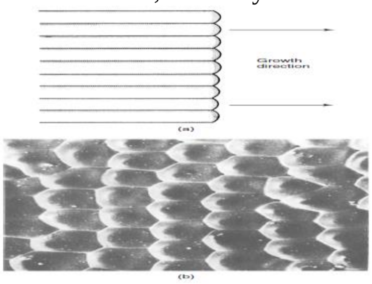


Figure 3. Cellular substructure formed by undercooling. (a) Structure in growth direction, (b) hexagonal cells on growth interface [55]

Grain Growth

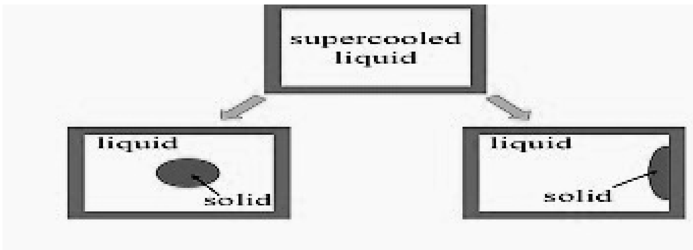
The service life and technological properties of structural steels affected by characteristics of structural steels like the most important are the size of austenite grains and their tendency to grow. A good deal of research has been done on the development of grains and grain growth. Most investigators consider that the basic mechanism of grain growth for austenite resulting from the $\alpha \rightarrow \gamma$ transformation is boundary migration. However, the rate of grain growth is usually much higher than the rate of boundary migration that is possible on the basis of diffusion concepts.

The study showed that the mechanisms of the formation and growth of austenite grains differ in different temperature ranges. Three basic mechanisms of austenite grain growth were clearly apparent: i) coalescence of groups of grains into one with "resorption" ("solution") of the boundaries of resorbed grains; II) formation of new boundaries and new grains; Ill) boundary migration. Let us consider the characteristics of these mechanisms of grain growth.

Nucleation

Nucleation is the appearance at points in the liquid of centres upon which further atoms can be deposited for the growth of solid crystals. Nucleation is of two type- homogeneous nucleation and heterogeneous nucleation.

Homogeneous nucleation and Heterogeneous Nucleation: Solidification of any molten metal involves nucleation and growth. Nucleation developed in the molten metal in the form of tiny solid particles, called as nuclei, when phase conversion in the metal occurs. These nuclei are from by the deposition of atoms and grow into the form of crystal and these crystal results in the totally solidified grains. Nucleation is of two type- homogeneous nucleation and heterogeneous nucleation. Homogeneous nucleation does not need any foreign particle while heterogeneous nucleation needs foreign particle such as sand, dirt and impurities. Heterogeneous nucleation takes places at the surface and these grains are called as equiaxed grains while inside due to absence of any foreign particle homogeneous nucleation takes place and these grains are called as columnar grains and these columnar grains are not good for electromagnetic properties. These columnar grains grow rapidly and called as dendrites.



Homogeneous Nucleation Heterogeneous Nucleation

Figure 4. Homogeneous nucleation and Heterogeneous nucleation [58]

Review on nucleation, grain growth, solidification and variation in Mechanical Properties under stationary condition

M. Kaplan and A.K. Yildiz,[61] have been observed that the structure of the sand mold casting contains fine rounded grains along outermost cross section and lengthwise inclined column grains towards inside and big grains innermost. Considering such grain structure, it can be suggested that die mold before casting should be preheated up to 450 – 500 ^oC to remove the negative effects of heterogeneous solidification structure on the use of the material for technological purposes. Finally, it was observed that the production of Cu4Ni9Al4Fe aluminum bronze casting in a sand and die mold which are being cold or hot during the casting and with/without the application of the heat treatments affected the mechanical properties and microstructure of casting.

S. Lun Sin, D. Dubé, and R. Tremblay,[62] have been investigated the microstructure and mechanical properties of vacuum-assisted solid investment cast AZ91D magnesium alloy at different process parameters. The microstructure and tensile properties of as-cast specimens are not significantly influenced by casting and mould preheating temperature. It was found that improvement of tensile strength and elongation with decrease of section thickness in bottom-filled specimens. It was essentially ascribed to a reduction of the grain size and secondary arm spacing. The thinnest top-filled specimens display decreasing properties. This was ascribed to the presence of porosity and abnormally large grains.Finally, the ultimate tensile strength and yield strength obtained were higher than the minimum requirements of ASTM B403 for AZ91C-F magnesium alloy. The results were slightly lower than those obtained by sand casting and permanent mould casting, but higher than those obtained by foamed plaster casting.

Davenport and Orton, [63] have studied the mechanical properties of investment cast AZ63 and AZ92 magnesium alloys, in the as-cast state. Their properties were similar to those obtained by sand casting, for specimens having comparable solidification time. to better tensile properties

Herrick [64] reported that mould temperature (from 20 to 340 °C) and casting temperature (from 670 to 740 °C) as well as section thickness (from 1.6 to 12.7 mm) had minor influence on the average grain size.

Kim et al.,[65] observed a decrease of the grain size and an increase in the hardness and the ultimate tensile strength with a decrease of the mould temperature. They also found that any casting temperature variation on the interval of temperature considered (650–710 °C) produced little variation on the hardness.

M. Go´ rny, [66]reported as It is well known that the section sensitivity of ductile iron is lower than in gray iron, which contributes to the homogeneity of the structure of castings. However, in the case of thin-walled castings, section sensitivity of ductile iron should be taken into consideration because of the entry to the high cooling rate range.

X. H. Zhan et al.,[67] state the during solidification process in the weld pool influenced that complicated thermal field, solute diffusion field and competitive growth the simulation of outcome and average primary dendrite spacing changes

Brooks, et al. [68] states that stainless steels with a value of Creq/Nieq = 1.5 are susceptible to solidification cracking, while stainless steels with values of Creq/Nieq > 1.5 are protected to solidification cracking, or nearly so. The review of the tendency for cracking weakness of austenitic stainless steels is based on the concentration of P + S and on the values of the Creq/Nieq ratio, because the Creq quantifies the influence of the ferritizing elements while the Nieq quantifies the austenizing compounds.

S.A. David et al.,[69] observed the parameters which affect the typical properties of casting that control the solidification of castings and microstructure of welds. On the other hand, a variety of physical processes that occur due to the interaction of the heat source with the metal during welding add a new dimension to the understanding of the weld pool solidification.

Braccini, M. et al.,[70] have been less studied about crack growth mechanisms and they were found balance between transverse displacement, liquid feeding, and crack advancement are influenced due to strain rate may likewise play a direct role.

Reddy G.M. et al.,[71]observed the formation and presence of equiaxed grains in aluminum alloy 8090, in the solution heat-treated and aged condition, under gas tungsten arc (GTA) welding process. However, no such zone was evident in the as-cast condition of the alloy. No convincing hypothesis was put forth for the nucleation and growth of equiaxed grains.

Dubé D et al.,[72] defind solidification time and estimated by measuring the secondary dendrite arm spacing (SDAS), using the following relation obtained for AZ91D magnesium alloy solidified under various conditions :

$$\lambda = 35{:}5\tau^{-0.31} \quad \text{-----(1)}$$

where λ (μm) is the secondary arm spacing and τ (K s^{-1}) is the cooling rate during solidification. Measurements of SDAS were made at a minimum of ten different locations on dendrites revealing at least four secondary arms.

Busk RS. et al.,[73] suggested the porosity of tensile specimens cab be evaluated by using density measurements in distilled water (Archimede's method) and calculated using the following relation:

$$\%\ \text{Porocity} = 100X\frac{Dt - Da}{Da} \quad -----------(2)$$

where Da is the actual density of the specimen and D_t is the theoretical density of the alloy, taken as 1.81 g cm−3 for AZ91D magnesium alloys .

Flemings MC., [74] was found that during solidification, the cooling rate of cast specimens and their microstructure are influenced by wall thickness.

Lun Sin S, et al.,[75] reported about both pouring temperature and mould preheating temperature influence mould–metal reactivity and cooling rate during solidification.

T. Skaland [76]and D. Venugopalan [77], have suggested the cooling rate of a casting is primarily a function of its section size, pouring temperature, the material mold ability to absorb the heat and increasing the cooling rate significantly influences the mechanical properties and increase the chilling tendency, which result in a higher hardness, decrease the strength and castings machinability can be severely impaired. The as-cast microstructure is governed by the solidification process and also by the subsequent eutectoid transformation. The inoculation practice and the cooling rate control the nodule count, while the matrix microstructure depends on the conditions under which the eutectoid reaction occurs.

Mahesh, B.P. et al.,[78] observed the quality of castings in a green sand mould are influenced significantly by its properties, such as green compression strength, permeability, mould hardness and others which depend on input parameters like sand grain size and shape, binder, water, etc

Eady, J.A. [79] was reported about improper casting procedures may give rise to defects such as pin hole, porosity, shrinkage cavity and which are largely responsible for poor mechanical properties of aluminum alloys produced .

Mohammad B.[80] studied the behaviour of aluminum alloy casting under different pouring speed and temperature. In this study the pouring speed range was 2.0 cm/s to 16.0 cm/s, while the temperature range for the investigation was 680 0 C to 750 0 C. At this range of pouring temperature, good mechanical properties achieved. And at this range of pouring speed, an optimum value of hardness and tensile strength was obtained.

Higgins, R. A.[81]reported that chemical composition is not the only factor determining what the microstructure constitute, but also rate of cooling prevent or promote graphitization carbidic formation.

Rooy Elwin [82] observed hypoeutectic Al-Si alloys have a microstructure of dendrites of Al rich solid solution in a matrix of Al-Si eutectic which can vary in size from coarse to very fine.

Mark E. [83] investigated the effect of microscopic inclusion locations and silicon segregation on fatigue lifetimes of aluminum alloy A356 castings. it was observed that local fatigue resistance varied substantially along the solidification path while tensile strength was little affected. The amount of Al–Si eutectic and the density of micropores are increased along the solidification path.

John A. Taylor [84] discussed the various sources of iron and how it enters aluminum alloys, the way that iron leads to the formation of complex intermetallic phases during solidification, and how these phases can adversely affect mechanical properties, especially ductility, and also lead to the formation of excessive shrinkage porosity defects in castings.

L.A. Dobrzański et al. [85],these were found that the solidification parameters are affected by the thermal characteristics like cooling rate and study show the cooling rate affects the formation temperatures of various phases of Al-Si-Cu alloy. Also increasing the cooling rate increases significantly affect the nucleation under cooling temperature, decreases the recalescence under cooling the Al nucleate temperature and solidification range. These phenomena lead to an increased number of nucleus that affect the size of the grains and the secondary dendrite arm spacing .

Haizhi [86], studied about Al-Si alloy and find the silicon phase as well as defects such as porosity, Intermetallic precipitates and inclusion usually are affect both of fatigue and wear properties. Due to micro crack initiation available coarse silicon reduces fatigue life due.. Excellent precipitates can generally strengthen the alloy while sharp and coarse precipitates degrade these two properties.

Review on nucleation, grain growth, solidification and variation in Mechanical Properties under vibratory condition

GUO Hong-min, et al.,[1] was 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.,[2] studied about the effect of Fe-containing and ultrasonic vibration on Al−17Si−*x*Fe alloys and suggested with increase of Fe content from 2% to 5% in the Al−17Si−*x*Fe 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. [3] developed the 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 aforesaid condition. The above technique used mechanical vibration to agitate the melt this hold at a temperature below its liquidus in a crucible. Development of the nucleation and formation of a non-dendritic microstructure within the semi-solid slurry due to melt convection by mechanical vibration together with under cooling of melts. WU Shu-sen, et al..[4] 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.,[5]suggested about microstructure evolution of Mg9AlZnY alloy with vibration in lost foam casting during semi-solid isothermal heat treatment concluded 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., [6]study 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., [7]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.

W. Dai et al., [8]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.

ZHANG Liang, et al., [9] 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.,[10]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.,[11]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.[12] 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.,[13]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.,[14] 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.,[15]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% in 50 Hz and15 min .

F. Taghavi et al.,[16] 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.,[17] 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.,[18] evaluate 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.

YAO Lei, et al.[19] 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.

M. Sha et al.,[20]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.

C. Lin et al.[21] 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. And 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.

S. Guo et al.,[22]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.,[23]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.

Table 1. (C. Lin et al.)Chemical compositions of the hypereutectic Al-Si alloys (mass%)

Alloy	Si	Cu	Fe	Ni	Mg	Mn	Al
A0	17	2	0.23	1	0.4	0.4	Balance
A1	17	2	2	1	0.4	0.4	Balance
A2	17	2	2	1	0.4	0.8	Balance

C. Vives [24]studied the effects of electromag netic vibrations induced by the interaction of alternatingelectric and stationary magnetic fields during the solidification of aluminum alloys and obtained good structural refinement.

B.J. Zhang et al.,[25] 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.[26]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 find as the magnetic-field strength and amplitude of the vibrating electromagnetic pressure is very small and so cavitation effects are also small.

K. Kocatepe [27],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.,[28] 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., [29], 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.,[30], grain refinement obtained under induced by the pulsed discharge vibrations The grain size of the β-phase of the Sn–Pb20% alloy under different pulsed discharge frequencies.

M. Li et al.,[31], find 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.[32] , studied about the crystal nucleation and detachment from a chilling metal surface with vibration and find 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., [33], find the an inoculated melt increases the dynamic nucleation electiveness, which consequently yields a finer microstructure of cast samples.

V. S Mudakappanavar et al.,[34] observed 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.

J. Campbell [35]suggested the idea “Mechanical vibration” promotes grain refinement and can extend the equiaxed zone.

R.J. Kissling et al. [36] 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.

Chworinov, N. [37] and Dmitrovich, A. M. et al.[38] 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.

Castings ASM Handbook[39]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 .

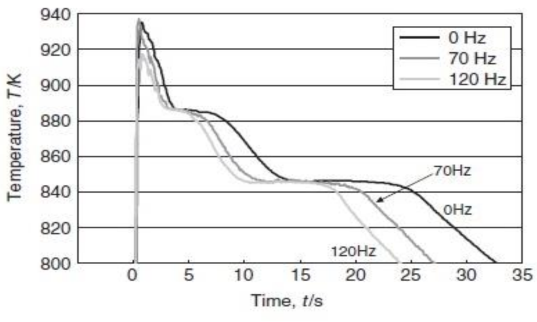
P.A.O. Adegbuyi et al.,[40] suggested the each composition of Aluminum-Copper alloys grain refinements that led to improved properties by specimens were vibrated at different frequencies during solidification (Casting) .The tensile stress (strength) increases with frequency. vibration decreases the ductility of the material as evidence 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.

Ji et al., [59]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.

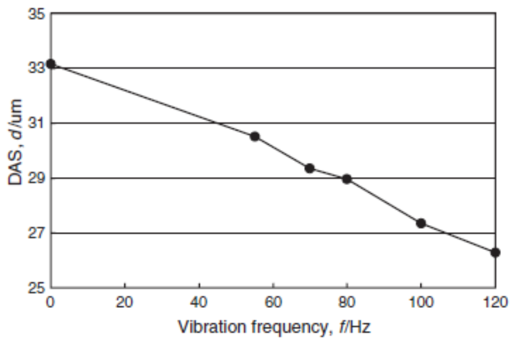
Tamura et al., [60]found that the electromagnetic vibrations affected increase in the cooling rate and the decrease in the number of crystal nuclei directly when they investigated the effect of frequency of electromagnetic vibrations on glass-forming ability in Fe-Co-B-Si-Nb bulk metallic glasses. They 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.

Effects of mechanical vibration on the cooling rate, grain size and their dendrite arms pacing of the melt

The cooling rate of melt increases by imposition of the mechanical vibration, and increases with the increase of the vibration frequency. The maximum temperature of vibrating mold during casting increases and the time to the maximum temperature shortens by imposition of mechanical vibration. The dendrite arm spacing in outer region of specimens decreases by the mechanical vibration, and decreases with the increase of the vibration frequency. The specimen cast without vibration has smooth surface. However, the surface of specimen cast with vibration becomes rough.



(a)



(b)

Figure 5. (a)Effect of vibration frequency on the cooling rate of the melt at bottom area. (b)DAS (Dendrite Arm Spacing) in the outer region of specimen as a function of the vibration frequency [86]

Discussions and Concluding Remarks

A great majority of the past investigations were primarily focused on the search for frequency range that provides the excellent grain refining effects. It found that the grain morphologies and their evolution process in the casting are influenced not only by the cooling conditions but also by the nucleation conditions, competitive growth and the existing microstructure, etc.

In this review paper a collective summary of the underlying micro-mechanisms and effects of vibration during casting on macrostructure, microstructure and mechanical properties of castings are presented. Several examples drawn from the literature suggest that vibration during casting greatly benefits grain structure and mechanical properties of products. Dendrite fragmentation and total cooling rate have been identified as two major factors that contribute to the enhancement (refinement) of grain size of vibrated microstructures. Mechanical properties are dependent on these microstructural changes that take place during solidification of the melt. Mold vibration allows casting of typically difficult-to-cast alloys. Mold vibration may reduce the solidification time, which reduces the overall casting cycle time, and in turn enhances the economic competitiveness of the process.

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