Use of Electromagnetic Stirrer in Semisolid Billet Casting

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Abstract- *The present research work demonstrates various methods developed for production of non-dendritic microstructures like mechanical stirring, passive stirring, shear cooling roll process, gircasting, spray casting and electromagnetic stirring. In addition, it also highlights about the role of process parameters along with the key issues and challenges (like stirrer selection from linear, rotary and helicoidal, electromagnetic stirrers, mould cooling arrangement, stirring intensity, superheat and cooling rate) involved in electromagnetic stirring for producing non-dendritic microstructure. Furthermore, it also illustrates about three different electromagnetic stirrer geometries such as rotary vortex, rotary plate and linear axisymmetric stirrers.The electromagnetic stirring is identified as a potential method to produce large feed stocks of non-dendritic microstructure with consistent quality. Despite, very few issues and challenges, this method can also be used commercially for producing semisolid cast billets with non-dendritic microstructures.*

Keywords- Electromagnetic, Semisolid, Slurry, Billet, Aluminum Alloy, Casting.

I. INTRODUCTION

It is well recognized that in the entire chain of activities of SSF process, the production of consistent quality raw material (in the form of billets with non-dendritic microstructure) plays the most important role. Over the past thirty five years ever since the invention of SSF process, researchers and industries all over the world have tried and experimented numerous techniques to produce non-dendritic microstructure. As of today, various methods have been adopted, and can be broadly classified into two categories: (a) Fragmentation of dendrites by means of forced convection, examples of which are mechanical or electromagnetic stirring and (b) Suppression of dendritic growth by a closed process control such as low superheat or seeding by use of external agents such as nucleants, gas bubbles etc. Some of the techniques falling under the above classification are briefly described as follows.

A. MECHANICAL STIRRING

The simplest and the most direct method for producing nondendritic structure is agitation of the melt, which is kept within the freezing range, using a mechanical impeller. A schematic diagram of mechanical stirring is shown in figure 1. The main drawbacks of the process include undesirable reaction between the impeller and the corrosive liquid metal, and entrapment of gases during agitation.

B. PASSIVE STIRRING

In this process, liquid metal is forced through a static mixing device whose geometry ensures high shear rate in the fluid while heat is being removed from outside.

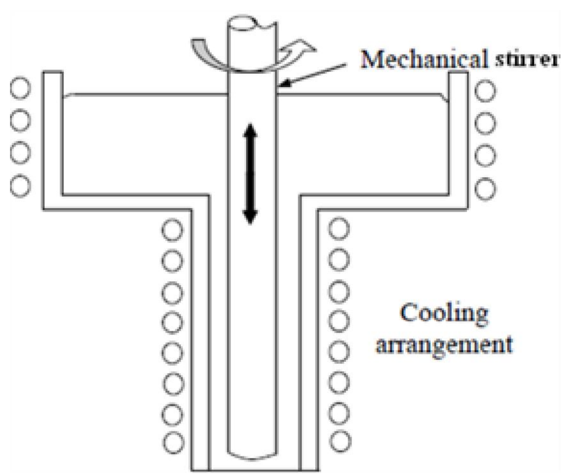


Figure 1. Schematic of mechanical stirring process.

C. SHEAR COOLING ROLL PROCESS

In this process, the molten metal is allowed to pass through a gap between a fixed shoe and a rotating plate producing non-dendritic slurries.

D. GIRCASTING

Liquid metal is centrifuged with a counter weight. After some time, liquid nitrogen is sprayed over the crucible to form a quenched billet with rheocast structure. This method is adopted in a few laboratories but is not suitable for industrial production.

E. SPRAY CASTING

In this method, a stream of liquid metal is atomised by a gas jet and deposited in a semisolid state on a cooled target.

F. ELECTROMAGNETIC STIRRING

The melt undergoing solidification is subjected to an electromagnetic force field, which creates forces in the metal to stir and shear the dendrites formed at the solid/liquid interface. A schematic diagram of this process in the context of direct chilled casting is shown in figure 2. Although it may seem to be an expensive proposition due to high energy costs involved, the major advantage is that the stirring device has no physical contact with the melt. As a result, this method can overcome some of the disadvantages pertaining to mechanical stirring.

While majority of the methods described above is restricted to laboratory research, only some are successfully implemented. All the currently adopted methods have their own merits and demerits and an ideal method to produce desirable microstructure consistently with minimal defects is yet to emerge. Such an ideal process, which can also be scalable for commercial production, is the key objective for most current researchers engaged in the development of SSF technology. Among all the methods, EM stirring in SSF is gaining popularity from a commercial point of view to produce large feed stocks having non-dendritic microstructure and consistent quality.

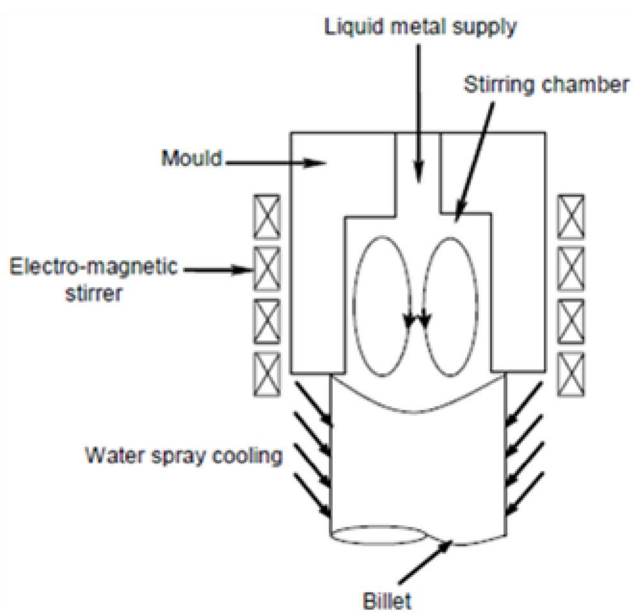


Figure 2. Schematic of an electromagnetic stirring system.

II. ROLE OF ELECTROMAGNETIC STIRRING IN PRODUCING NON-DENDRITIC MICROSTRUCTURE

Electromagnetic stirring influences solidification during the casting process by inducing strong rotation of melt in the mould. The intense forced convection promotes homogenisation of the melt temperature and fragmentation of dendrites at the solidification interface. The fragmented dendrites are transported into the bulk liquid and form a semisolid slurry in the melt. These surviving broken dendrites then form additional nucleation sites upon which further grain growth will occur, thereby resulting in grain refinement in the final casting products. Thus, the billet produced by this process has a microstructure composed of clustered degenerate-dendritic particles. Also the intense stirring causes uniform macrosegregation patterns at the interface, thereby resulting in a more or less uniform final composition in semisolid billet formed by SSF technique. Electromagnetic stirring harnesses the electrical conducting properties of metals to induce eddy current by external magnetic fields. The externally imposed magnetic field and induced eddy currents generate electromagnetic forces in liquid metal, eventually resulting in stirring of the melt. One of the biggest advantages of EM stirring is that the nature of stirring, intensity, and direction can be modulated externally. A number of examples can be found in the literature in which electromagnetic forces have been applied to induce fluid flow during solidification in order to refine grain size. It is found that the dendritic structure is greatly affected by convection during early stages of solidification. In the limit of vigorous convection and slow cooling, grains become spheroidal.

III. GENERAL ISSUES AND CHALLENGES INVOLVED IN ELECTROMAGNETIC STIRRING

From the aforementioned texts, to the best of author' knowledge, it is very clear that there is not a single complete numerical study relating to the effects of water based nanofluids (namely Water-SiO_2, Water-Al and Water-Al_2O_3) on heat transfer performance of electronics modules. With this standpoint, the present paper demonstrates numerical investigations with the stated nanofluids on thermal characteristics of electronics modules. And also, the numerical model includes additional key factors like inertia, viscosity and gravity effects apart from the usual issues concerning the present physical problem. However, the stated model ignores both compressibility and viscous heat dissipation effects. The model is very well demonstrated for the detailed numerical investigations on the influences of the already stated nanofluids (as they significantly affect the cooling characteristics) by taking electronics module heat flux and duct inlet nanofluid velocity as the important model parameters. Finally, the model predictions concerning about the various nanofluids are also along the lines of expectations.

A. SELECTION OF STIRRER TYPE

The electromagnetic stirrers are designed to produce forced convection in the melt. Magnetic fields generated by low-frequency currents are known to produce Lorentz forces with better penetration into the molten metal pool. Various EM stirring techniques are in operation for producing semisolid slurry of aluminium alloys. Essentially, there are three main types of stirring systems that exist, as shown schematically in figures 3-5. The three common stirring systems are linear, rotary, and helicoidal. A linear stirrer operates essentially in the same way as an induction furnace. The design entails the placement of a stack of coils around the casting metal to generate a primary motion that recirculates along the casting direction. In the case of linear stirring, as shown in figure 3, the dendrites are fragmented near the solidification front, and are recirculated up to the hotter zone of the stirring chamber where they may partially remelt.

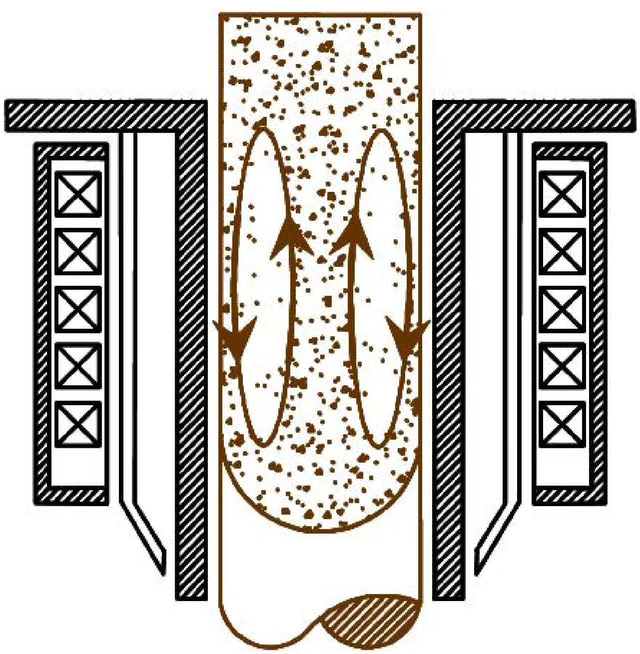


Figure 3. Linear electromagnetic stirring.

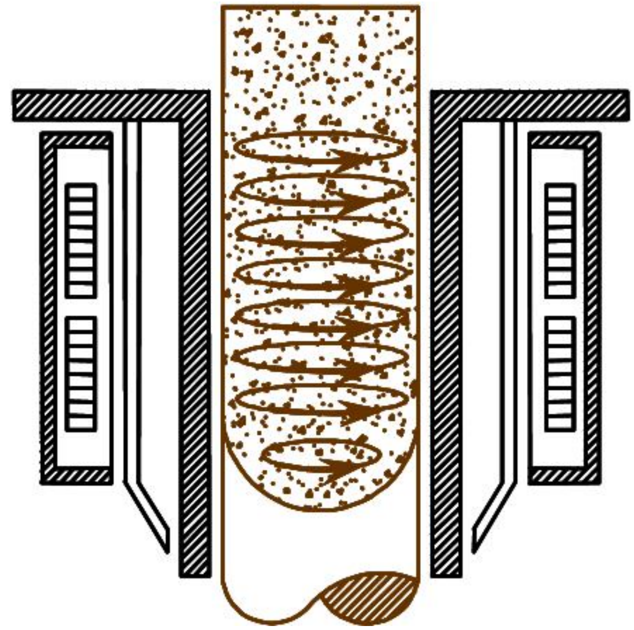


Figure 4. Rotary electromagnetic stirring.

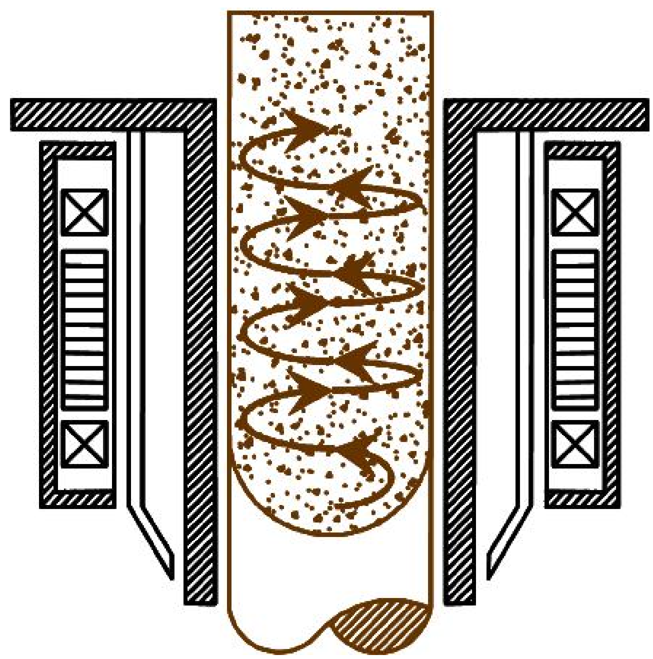


Figure 5. Helicoidal electromagnetic stirring.

A rotary stirrer is similar to an electric motor. It uses a rotating magnetic field to produce a swirling flow in the liquid pool as shown in figure 4. In rotary stirring, there is a probability of dendrite growth at the mould centre due to weak or complete absence of stirring in the central regions of the mould. In addition, rotary stirring may result in free surface deformation and depression at the top due to centrifugal action. However, these problems can be overcome by using linear stirring or helicoidal stirring. Figure 5 represents helicoidal stirring that combines the arrangements of both rotary and linear stirring techniques. There can be other arrangements to provide stirring action in the melt. One such method involves generation of a rotating magnetic field created either by rotating permanent magnets or by rotating the mould. There can be other combinations of rotary and linear stirring to create multiple rotating loops in the melt. As it can be imagined, a large number of combinations are possible. Therefore, it is not surprising that this subject is still at the heart of today's research and that a comprehensive picture of combination stirring is yet to emerge. The discussion of all possible different stirring arrangements is beyond the scope of present work. Hence, in the present work, we focus only on the stirring arrangement that produce a rotation as shown in figure 3.

B. MOULD COOLING ARRANGEMENT

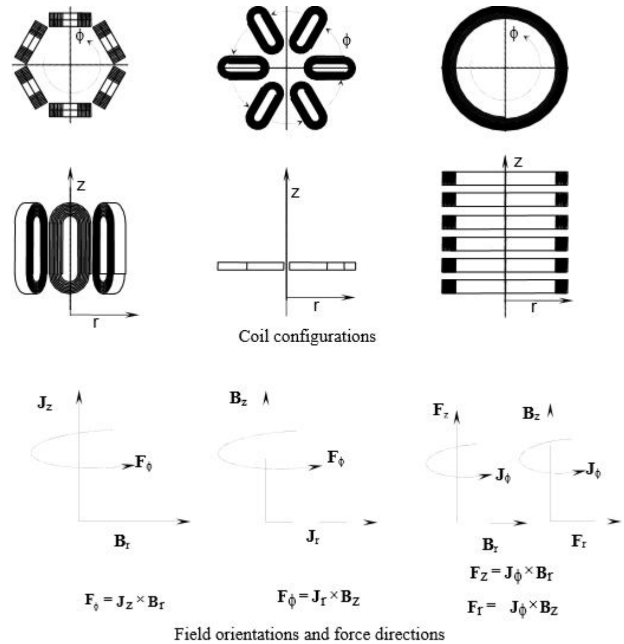
Mould cooling arrangement and cooling rate is one of the most important process parameters in the control of internal structure of semisolid billets cast in the presence of EM stirring. The two basic requirements of the mould cooling arrangement are as mentioned: (a) The required heat removal rate from the molten metal, and (b) The need to maintain a near-constant liquidus temperature in the stirring zone of the mould. In order to achieve the desired result of a uniform mixture of solid globular structure in a eutectic liquid matrix, the dendrites growing at the phase change interface need to be sheared. Hence, the direction of heat extraction and mould cooling rate should facilitate the convective flow due to EM stirring to constantly scrape the dendrites formed at the phase change interface and transport them into the bulk liquid region. In the process, the transported sheared dendrites either remelt or are coarsened into rounded structures by the flow of liquid around them. Equally important for creating the globular microstructure is keeping it uniformly distributed within the mixture. Therefore, the cooling rate needs to be precisely controlled to prevent rapid solidification and also provide sufficient time for the fragmented dendrites to complete spheroidisation. The cooling arrangement depends on two factors: (1) type of EM Stirrer employed, and (2) type and composition of the alloy used. In case of rotary stirrers circumferential cooling is preferred as the tangential rotation provided by EM stirring would be more effective in shearing the dendrites growing inwards towards the axis of the mould. Whereas, bottom cooling arrangement is preferred for linear or helicoidal stirring as vertical convective flow would be more effective in shearing the dendrites upwards into the bulk liquid. In certain cases like aluminium-copper alloys where the density difference between the solid and liquid phases is large, depending upon the initial composition, there is a tendency of the solid particles to either settle down or float. This would result in uneven distribution of the solid particles in the mould. However, this problem can be significantly avoided if vertical stirring with bottom cooling arrangement is employed. Hence, the cooling arrangement and selection of EM stirrer are equally important in controlling the final microstructure.

C. STIRRING INTENSITY

In addition to the thermal requirements for creating semisolid slurry discussed above, it is necessary to provide adequate shearing forces to the mixture to generate the globular particles and prevent agglomeration of the solidified globules.In the case of EM stirring, the shearing force depends on the magnitude of the Lorentz force produced by the stirrer. The Lorentz force depends on the current input, frequency and the electrical conductivity of the melt. Hence, for a given alloy type, the Lorentz force depends on the input current and frequency. For a given input current and frequency, one can estimate the net force produced in the melt. This force can be then be compared with minimum shear force/liquid velocities required for dendrite fragmentation reported in the literature. Accordingly, the current and frequency can be selected to produce the minimum force required to shear the dendrites.

IV. ELECTROMAGNETIC STIRRER GEOMETRIES

In this section the magnetic field orientations and a coil configuration for basic stirrer geometries is briefly discussed. A cylindrical coordinate system for force field calculations is adopted due to axisymmetric nature of most stirrer geometries. The direction and magnitude of the Lorentz force, F, in the melt is governed by the variables as mentioned: (i) Induced current J (A/m^2), and (ii) Induced magnetic field density B (T) The above two variables, J and B, in the metal follow the signature of the primary excitation current, I. The direction of J opposes the excitation current and the direction of B is normal to it. The direction of the excitation current, geometrical placement of the primary solenoid and location of the secondary conductor (molten metal) are key parameters in the design of an electromagnetic stirrer. Depending on the requirement of force direction, the primary conductors are spatially arranged to obtain various field orientations in r, φ and z directions. The possible orientation of primary conductor and the resulting magnetic field directions are schematically represented in figure 6. The three coil configurations shown in figure 6 are commonly used in the design of electromagnetic stirrers. Essentially, all the stirrers are similar and can be transformed to one another by simple geometric transformations as shown in figure 7. The stirrer configurations commonly used in liquid metal stirring are briefly described in the following subsections.



(a) (b) (c)

Figure 6. Common coil configurations inelectromagnetic stirrers.

(a) Rotary vortex stirrer.
(b) Rotary plate stirrer.
(c) Linear axisymmetric stirrer.

A. ROTARY VORTEX STIRRER

In this arrangement the mould carrying liquid metal is placed in the annular region enclosed by the primary conductors. The conductors are oriented in a manner such that the resulting field is radially distributed, as shown in figure 6 (a). Field B, in the φ direction is absent due to circular symmetry. Therefore, with the above arrangement, only tangential forces can be generated. The primary coils are displaced in space by 2π/3 radians around the metal core to produce a rotating field. When the primary conductors are excited by a three phase alternating current, the resulting rotating field induces eddy currents J in the metal to generate tangential forces. With reference to figure 6 (a) for magnetic field orientations, the tangential force is given by $\mathbf{F}_\phi = \mathbf{J}_z \times \mathbf{B}_r$. This force creates a strong vortex in the molten metal to shear off dendrites formed at the solid-liquid interface. The absence of axial mixing mechanism and the vortex formation restricts the depth of the mould. Another disadvantage is the undesirable generation of centrifugal forces which limits the operating frequency of the primary current. The resulting flow pattern created by rotary stirring is shown schematically in figure 8.

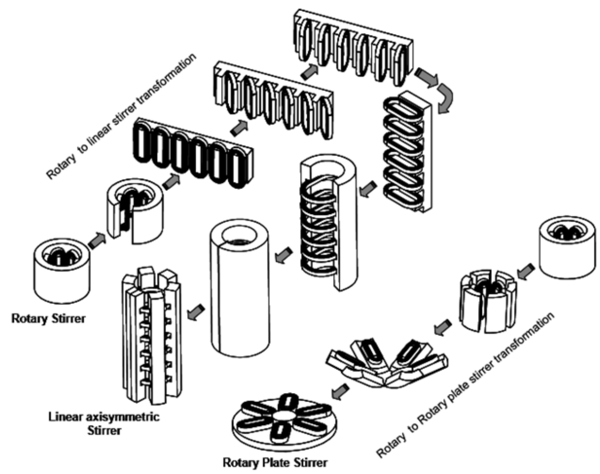


Figure 7. Geometric transformation of rotary to linear electromagnetic stirrers.

B. ROTARY PLATE STIRRER

This type of stirrer also uses the rotating field, the difference being that the tangential forces are generated at the surface of the stirrer as shown in figure 9. Tangential forces can be generated by two ways: (i) by circumferentially placing the primary conductors around the mould to get $\mathbf{J}_z$ and $\mathbf{B}_r$ as in case of the rotary vortex stirrer described previously (figure 6 (a)), and (ii) by radially placing the primary conductors to get components $\mathbf{J}_r$ and $\mathbf{B}_z$ (figure 6 (b)). The Lorentz force field for the above two cases are given by the equations as mentioned: for case (i) $\mathbf{F}_\phi = \mathbf{J}_z \times \mathbf{B}_r$ and for case (ii) $\mathbf{F}_\phi = \mathbf{J}_r \times \mathbf{B}_z$. The corresponding magnetic field orientations are shown in 6 (a) and (b). In a rotary plate stirrer, the eddy currents in the metal are established in the radial direction and the induced magnetic field is in the axial direction. The net result is a rotating force generated at the coil surface. Since the force field is developed at the surface of the stirrer, these stirrers can be mounted externally without much modification of the mould. The absence of special mould arrangements and convenience in installation has made this type of stirrer quite popular in steel industries. Depending on the mounting arrangement these stirrers can produce the desired convective pattern in the melt pool. Common practice is to mount it at the bottom of the mould of an ingot caster to obtain uniform and symmetric stirring without gravity induced effects as shown in figure 9. However, many other researchers have mounted such stirrers vertically on one of the side walls of the mould to produce vertical stirring as shown in figure 10. In the case of vertical mounting, one major disadvantage is that convection in the melt is strong only in a region close to the wall on which the stirrer is mounted. This puts a restriction on the width of the mould.

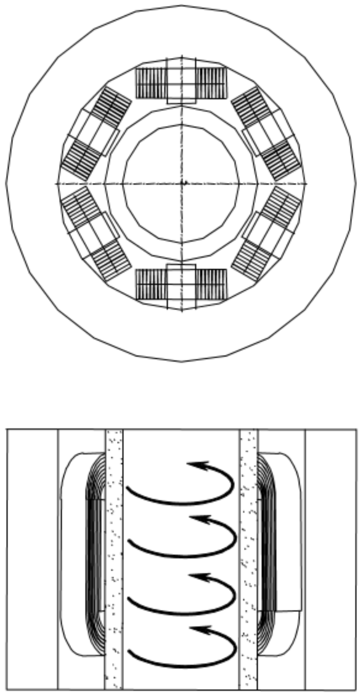


Figure 8. Convective flow pattern in rotary stirrer.

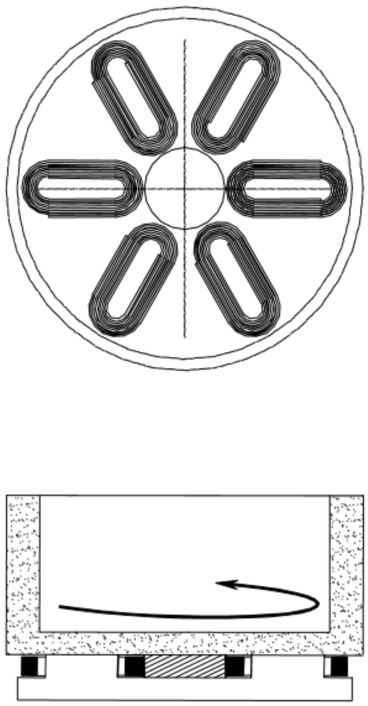


Figure 9. Convective flow pattern in bottom mounted rotary plate stirrer.

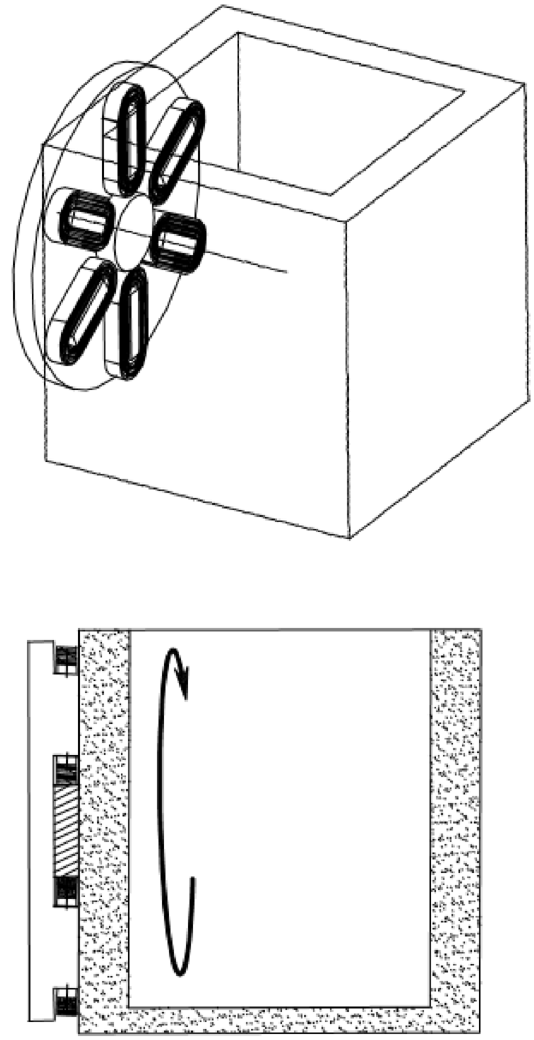


Figure 10. Convective flow pattern in side mounted rotary plate stirrer.

C. LINEAR AXISYMMETRIC STIRRER

Linear axisymmetric stirrers work on the same principle as a tubular linear induction motor. The travelling magnetic field along the axis of the stirrer is responsible for generating axial forces necessary for creating forced convection in the vertical direction (figure 6 (c)). Convection in the vertical direction is ideal for shearing dendrites at the solid/liquid interface for the case of bottom cooled mould. These stirrers are very effective where the aspect ratio of the mould is high (i.e. L/D >>1 where L is the length of stirrer and D is diameter), as in the case of thixo-casting or rheocasting. The resulting flow field in the melt is axisymmetric as shown in figure 11. The direction of force field can be reversed by changing the phase sequence of primary current to overcome gravity induced effects. Also, the radial penetration of the force can be effectively controlled by changing the excitation frequency of the primary current. This ensures good radial mixing in addition to uniform mixing throughout the height of the mould. As mentioned previously, it is now widely accepted by researchers that linear electromagnetic stirring is ideally suited for shearing dendrites in a bottom cooled mould, as in case of thixo-casting or rheocasting operations. In order to keep the terminology short and consistent, the linear axisymmetric stirrer will, henceforth, be referred to as only “linear electromagnetic stirrer” (LEMS) or simply “linear stirrer”.

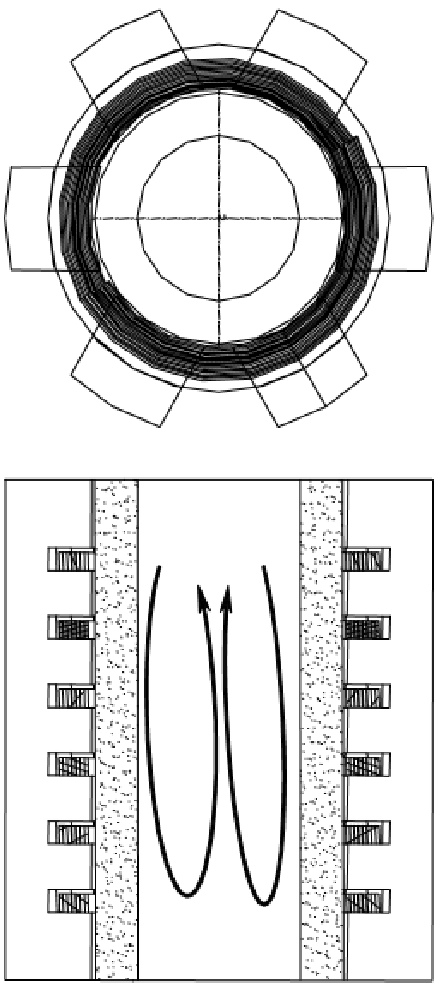


Figure 11. Convective flow pattern in linear axisymmetric stirrer.

V. CONCLUSION

As already described elaborately, the electromagnetic stirring is identified as a very potential technique to produce large feed stocks of non-dendritic microstructure with great consistent quality. Regardless of very few issues and challenges, this technique can also be used commercially for production of semisolid cast billets having non-dendritic microstructures. With this standpoint, the overall research relating to the design, development and characterization of an electromagnetic stirring system can also be extended for casting of aluminium alloy semisolid billets. Through this study, the roles of process parameters such as stirring intensity, superheat, cooling rate and the key issues and challenges can also be highlighted. A356 alloy, a popular die casting aluminium alloy widely used in transport industries can also be selected as the material for experimental, numerical together with analytical studies.

VI. ACKNOWLEDGMENT

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