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SSF Technology

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ABSTRACT

In most casting applications, dendritic microstructure morphology is not desired because it leads to poor mechanical properties. Forced convection causing sufficient shearing in the mushy zone of the partially solidified melt is one of the means to suppress this dendritic growth. The dendrites formed at the solid-liquid interface are detached and carried away due to strong fluid flow to form slurry. This slurry, consisting of rosette or globular particles, provides less resistance to flow even at a high solid fraction and can easily fill the die-cavity. The stated principle is the basis of a new manufacturing technology called "semi-solid forming" (SSF), in which metal alloys are cast in the semi-solid state. This technique has numerous advantages over other existing commercial casting processes, such as reduction of macrosegregation, reduction of porosity and low forming efforts. Among all currently available methods available for large scale production of semisolid slurry, the use of mechanical stirrer, electromagnetic stirrer and cooling slope have proved to be very effective in both semisolid slurry production and near net shape components manufacturing, and therefore possess the utmost potential for commercialization in a wide range.

Keywords: SSF, Slurry, Semisolid, Technology.

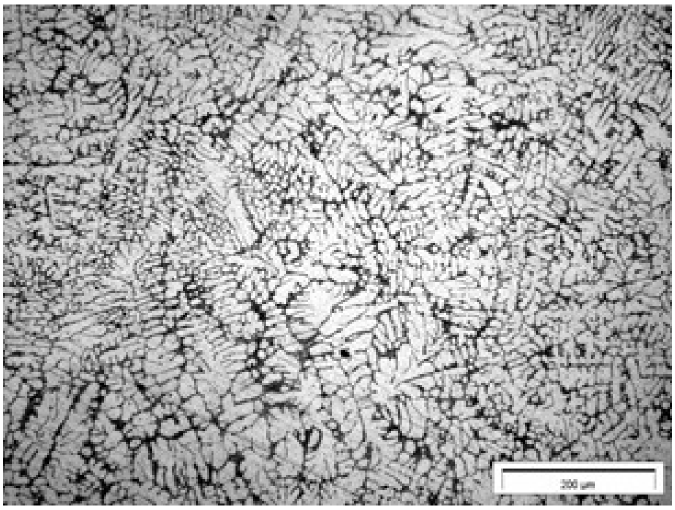
I. INTRODUCTION

Increase in awareness about environmental policies leads to enhanced demand of materials and products which are environmental ecofriendly and ecologically sustainable as well. This leads to search for materials and products which are physically realizable from the standpoint of economic and environmental feasibility. In this perspective, some metal alloys, which have the potential to meet most of the stated requirements, are found to be extremely vital for our society.

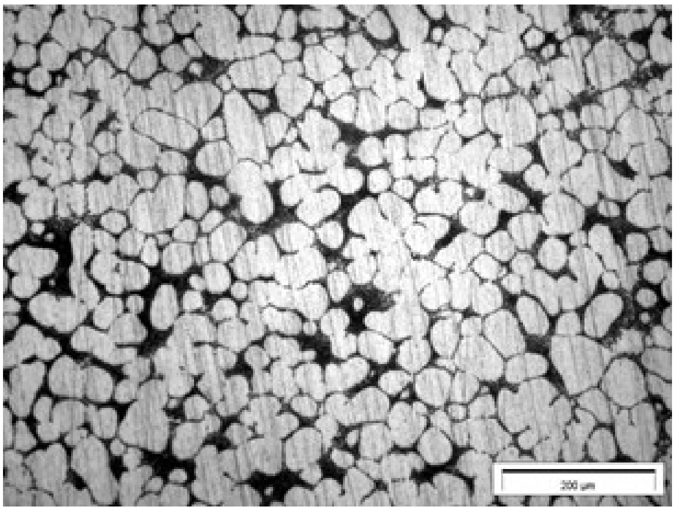
Since some metal alloys are used in almost all industrial sectors including safety-critical applications, there is a continuous need for innovation of defect free and robust production processes. Until now, several methods have been established for manufacturing of safety-critical along with high-performance components. Some of these methods related to casting practices are pressure die casting, gravity die-casting, squeeze casting, liquid metal forming etc. Although the components thus manufactured are within the acceptable cost limit with enhanced mechanical properties, a common problem encountered in these processes is the evolution of dendritic microstructure morphology of the cast products, resulting in defects and cracking. In addition, some other problems faced by these casting practices are shrinkage, porosity, and turbulent filling of mould. Search for new techniques to surmount these problems paved the way for a novel forming practice, termed as the semisolid forming (SSF), for manufacturing of commercial products with defect free microstructure and excellent properties.

II. SSF TECHNOLOGY

Its name suggests that metal alloys are cast at an intermediate state between solid and liquid termed as semisolid state. This semisolid state exists at a temperature between solidus and liquid temperatures of alloys. In conventional casting, metal alloys are cast at a temperature above liquidus which corresponds to casting of alloys at pure liquid state. The microstructure of the products thus produced from conventional casting is generally dendritic with poor mechanical properties, which is not desirable for engineering design point of view. Casting alloys at semisolid state leads to globular and non-dendritic microstructure morphology with superior and enhanced mechanical properties (see figure 1).



(a) Dendritic microstructure



(b) Non-dendritic microstructure

Figure 1. Dendritic and non-dendritic microstructures

The microstructures of the products cast at semisolid state consists of two different and distinct phases which include globular, non-dendritic primary α-Al phase separated and surrounded by a lower melting, near eutectic secondary phase.

The semisolid forming (SSF) technology involves two separate and distinctive processes. The first process relates to semisolid slurry production, whereas the second one relates to casting of slurry produced at semisolid state. The semisolid slurry production involves partial solidification of melt by cooling, together with the shearing of dendrites formed during partial solidification. The dendrites are sheared off by either melt agitation methods such as stir cast, mechanical or electromagnetic stirring, mechanical or ultrasonic vibration and cooling slopes, or by methods without melt agitation such as with low pouring temperature and partial remelting, stress-induced and melt-activated (SIMA) process and addition of chemical refiners. Thus, the prepared slurry contains equiaxed and fragmented grains uniformly dispersed in liquid matrix. In other words, semisolid slurry is a solid-liquid network which behaves like a solid when at rest and flows like a thixotropic (shear thinning) liquid when pressure is applied.

The semisolid slurry undergoes solidification either to produce cast components directly from slurry or to produce cast billets for further processing (i.e. semisolid billet casting). The former process is called *rheocasting*. In the latter process, the billets thus cast have globular non-dendritic microstructure, and are termed as raw materials or feedstock materials for further processing. When these billets are reheated up to near eutectic temperature, the secondary eutectic phase starts melting, where as primary α-Al phase still remains in solid state. These billets at semisolid state offers low resistance to flow (even at high solid fraction of the order of 50%), and can fill even intricate and complex cavities of die. This behavior of billets at semisolid state is utilized for various forming processes such as pressure die casting, leading to final finished products/ components with superior mechanical properties with homogeneous microstructures and negligible porosity. This process is called *thixoforming* or *thixocasting.*

III. ADVANTAGES AND DISADVANTAGES OF SSF TECHNOLOGY

The SSF Technology is advantageous in many senses over the conventional metal alloy casting processes. A few of these are as follows.

(a) High production rate: The SSF Technology is employed for mass production to manufacture high integrity components used for various applications.

(b) Resistance to high pressures: The SSF products have got excellent resistance to high pressures caused by hydraulic and pneumatic means.

(c) Enhanced mechanical properties: The semisolid cast components usually have better mechanical properties compared to the conventionally cast components, mainly due to their non-dendritic, globular and defect free microstructure morphology. According to available literature, there is around 30% increase in impact strength together with 7-10% increase in fatigue strength, in addition to about 25% increase in elongation. It results in sizeable weight reduction of semisolid cast components leading to material saving.

(d) Minimal shrinkage and porosity: The main disadvantage in conventional casting is the development of macroporosity due to solidification shrinkage. The turbulent filling of the die aids air entrapment causing porosity. To overcome these difficulties, semisolid die filling is preferred over the liquid alloy filling. Since the alloy is already partially solidified (in case of semisolid casting) prior to die or mould filling, there is remarkably little solidification shrinkage throughout the casting practice. The semisolid slurry fills easily even the intricate and complex cavities of the die due to its flowability caused by the presence of equiaxed and fragmented grains. The semisolid cast billet (in case of thixocasting or thixoforming) softens after reheating it up to nearly eutectic temperature and hence, the billet deforms smoothly with ease even at a low applied pressure. This trouble-free and simple die filling of the reheated semisolid cast billet eradicates the air entrapment commonly occurring in conventional casting processes of liquid alloys.

(e) Formability: Though the viscosity of semisolid slurry is notably higher than that of liquid metal alloy at a superheat, the slurry fills easily even through small sections of the die cavity due to its thixotropic (i.e. shear thinning) behavior. Thus, even thin-walled components can be cast with better accuracy and precision.

(f) Reduced machining costs: The near net shape casting of a complex component is possible using SSF technology due to superior flowability along with minimal shrinkage and porosity, leading to better surface finish of the cast products. The semisolid slurry or reheated semisold billet fills the die at lower temperature as compared to the conventional casting processes. Thus, the heat content of alloy is less resulting in relatively less thermal shock causing longer tool life. In other words, SSF products yield cost reductions through high production rate and extended mould life.

(g) Internal stresses: Since SSF technology does not involve solidification from fully liquid state, thermal and any other residual stresses are relatively low. SSF technology products possess high resistance to mechanical stresses and have got high tensile strength, ultimate tensile strength, together with good fatigue behavior.

(h) Heat treatment: The SSF products can be easily heat treated for further improvement of mechanical and microstructural properties such as strength, hardness, globularity etc.

(i) Additional miscellaneous SSF technology advantages: The components produced by SSF technology can be joined together by processes such as LASER, TIG, MIG or WIG welding, to produce a bigger and sizable product. The heat treatment in a variety of conditions, of the stated SSF products is possible if required for further improvements of properties.

Though there are several advantages of SSF technology already described apart from easy automation, pressure tightness, tight tolerances and consistency, the technology still suffers from a few drawbacks such as high equipment costs along with running/maintenance costs, together with the need for very well trained/skilled and experienced operators.

IV. CLASSIFICATION OF SSF TECHNOLOGY

There are several ways of classifying SSF Technology depending upon the means of slurry preparation, kind of application and so on. A broad way of categorizing the said technology is as illustrated in figure 2. The two basic routes of the SSF technology are "*rheocasting*" and "*thixocasting*", details of which have already been described in a previous section. The very first step in both processes is to prepare semisolid slurry. There are several methods of preparing semisolid slurry which will be discussed in detail in a later part of this chapter. Rheocasting involves the preparation of slurry next to a die-caster in which the required components are cast directly. In contrast, thixocasting involves solidification of the semisolid slurry to cast billets of non-dendritic microstructure. Thereafter, the cast billets are reheated up to a temperature slightly above eutectic temperature and cast into final components using a die-caster.

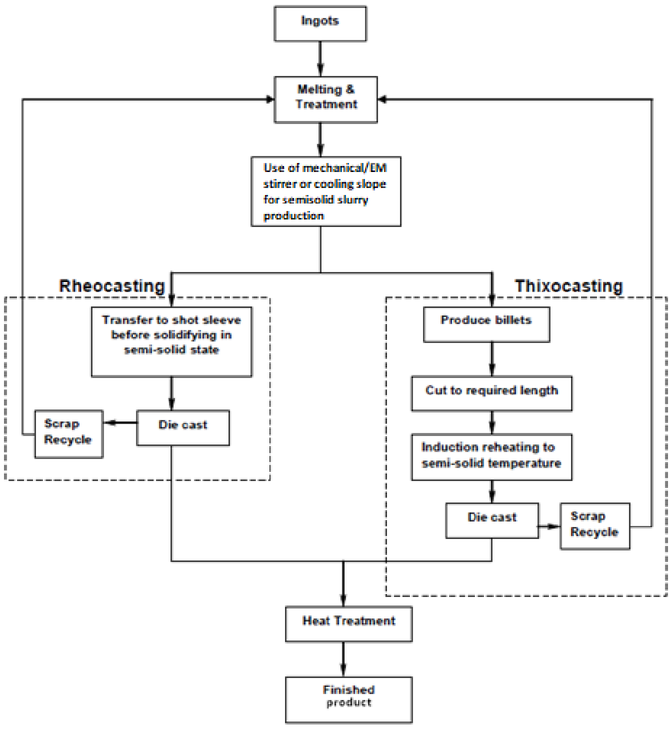


Figure 2. Classification of semisolid processes

V. RHEOCASTING VERSUS THIXOCASTING

Thixocasting has the ability to yield extremely high quality components with enhanced and improved microstructure and mechanical properties, mainly because of the product consistency that can be achieved in feedstocks of pre-cast billets. However, the costs of the feedstock billets, reheating system, and forming machines such as die casters can be quite high. On the other hand, the recent trend in SSF technology is focused more on using the rheocasting route of component production. Rheocasting offers advantages of cost reductions over thixocasting, along with the following additional benefits.

- In case of thixocasting, the scrap produced due to cutting of standard size, pre-cast billets available in the form of feedstocks cannot be recycled on site, whereas scrap produced in any form during or after rheocasting can be recycled on the spot.
- In case of thixocasting, oxidation of the billet surface occurs during reheating of the feedstocks (leading to necessity for specially designed dies to remove oxides during the forming process), whereas there is negligible oxide entrapment occurring during rheocasting.
- Thixocasting may not be appropriate for mass production for which multiple induction heaters (associated with high initial investment costs) are necessary, whereas, in case of rheocasting, mass production can be achieved provided we make arrangements for slurry-on-demand.
- Thixocasting involves loss of metal from the semisolid feedstock during reheating in induction heater and transferring the same to the die-caster just prior to casting, whereas there is negligible semisolid slurry loss during rheocasting process.

VI.APPLICATIONS OF SSF TECHNOLOGY

The potential and promising qualities of semisolid forming technology made it possible to become superior to other manufacturing technologies. Over the past few years, it has got a record of producing components in a wide range of applications staring from household to industrial uses. It includes producing different components in application sectors like transportation, aviation, military, and construction. Some of the major areas of applications along with the components in respective fields are as follows.

(a) Transportation sectors (surface transport, aviation and naval applications in military): The components requiring wear resistance include gear shifting levers, steering systems, cylinder pistons, and brake drums. The high-performance components such as wheels, tie rods, seat belt retainer housings, engine mounts, knuckles, and suspension components can be made using SSF technology. In addition, safety critical components demanding extreme pressure tightness, such as air conditioner compressor housings, master brake cylinders, fuel rails, anti-lock braking systems are appropriate candidates for SSF technology.

(b) Space sector: The thin walled cast nodes for producing space frame chassis can be produced by SSF.

On the whole, SSF technology gives remarkable cost reductions to the manufacturers. In recent years, there is a striking revolution regarding wide acceptability for producing high performance and safety critical components in automotive sectors using SSF technology.

VII. FUNDAMENTAL OF SOLIDIFICATION AND SSF TECHNOLOGY

It is worthwhile to have a look at a typical binary eutectic alloy system (with a partition coefficient $k_p < 1$ as demonstrated in figure 3) for understanding the physics of solidification of any binary alloy. The solidification of a binary alloy of initial composition C_i begins with the formation of a small amount of solid having composition k_pC_i at temperature T_L, in the very first instance of onset of solidification. On account of difference in solubility of the solute in the solid and liquid phases (solubility of solute in solid is much smaller compared to that of liquid), the balance solute is rejected (at the solid-liquid interface) to the surrounding liquid matrix. As solidification progresses, the remaining liquid keeps getting enriched with solute, and the composition approaches the eutectic, as illustrated in figure 3. Hence, the solid that forms in a later stage of solidification contains more amount of solute.

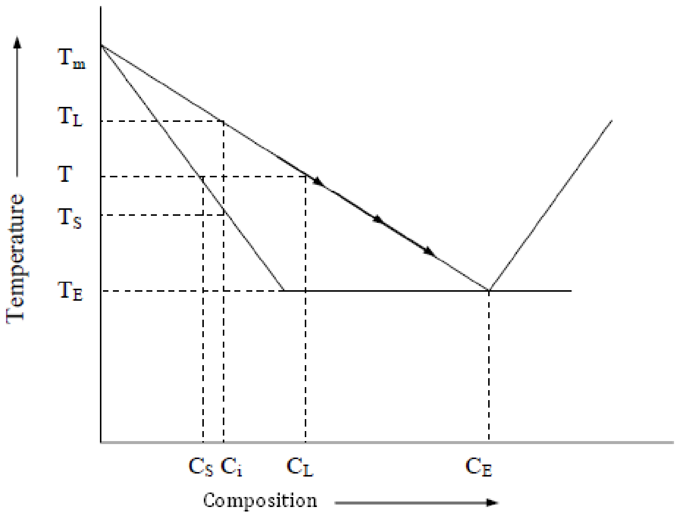


Figure 3. Typical phase diagram of a binary alloy

In case of conventional casting, natural convection caused by both thermal and solutal buoyancies transports the rejected solute further than the solid-liquid interface and gives rise to macrosegregation. The intensity of mushy zone convection determines the degree of segregation. The quality of the final cast product depends on the nature and degree of macrosegregation. The dendritic morphology and extensively varying macrosegregation patterns of mushy zone formed during alloy solidification is generally responsible for poor mechanical properties and various other defects of the final component.

The conventional casting involves the formation of two kinds of dendrites namely, columnar and equiaxed dentrites. A number of interrelated and interdependent physical phenomena such as crystallization, solute redistribution, ripening, interdendritic fluid flow and solid movement occur simultaneously during conventional casting. The interdendritic fluid flow and solid movement caused by solutal and thermal buoyancies (because of concentration and temperature gradients) have got significant effects in conventional casting during dendritic solidification.

In case of SSF technology involving binary alloy semisolid slurry preparation, the partially solidified molten alloy is subjected to forced convection by means of mechanical or electromagnetic stirring, mechanical or ultrasonic vibration and cooling slopes or stress-induced and melt-activated (SIMA) process. An overview of a solidification process accompanying appearance of different phenomena along with solid phase movement by melt convection is demonstrated in figure 4.

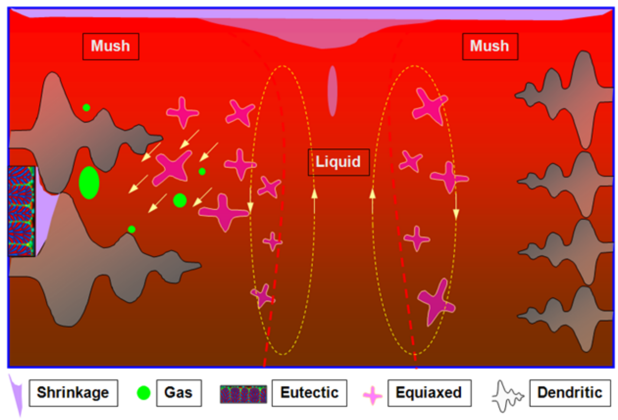


Figure 4. Schematic of an overview of a solidification process

The dendrites are detached from the solid-liquid interface due to the strong fluid flow and are washed away into the mould to form slurry. The slurry gets solidified in the mould to cast billets having globular and non-dendritic microstructure. In order to understand the physics of solidification related to globular non-dendritic microstructure during forced convection, several mechanisms have been proposed which include dendrite arm bending/fragmentation, secondary/tertiary dendrite arm root remelting and growth controlled mechanisms. These mechanisms are discussed below. Figure 5 portrays the schematic of dendrite fragmentation caused by dendrite arm bending and dendrite arm root remelting.

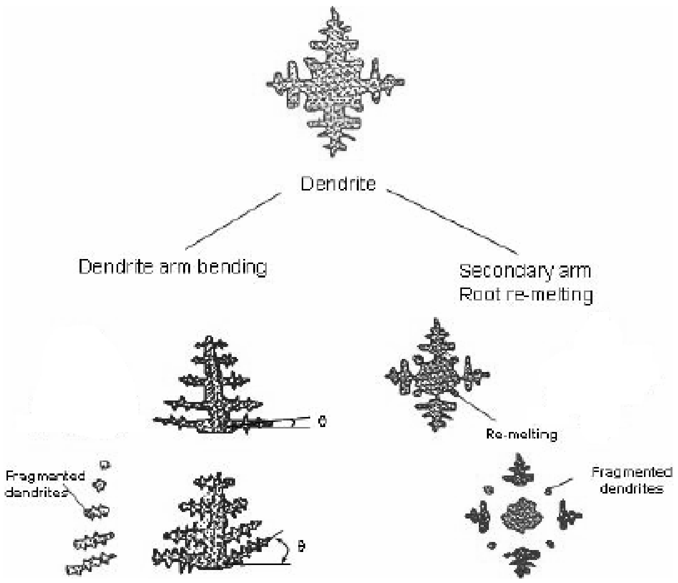


Figure 5. Schematic of dendrite fragmentation

(a) dendrite arm bending and fragmentation

There is bending of dendrite arms under the action of shear force created by forced convection, and when the shear goes beyond a critical value dendrite breaking or fragmentation occurs. To account for non-dendritic microstructure morphology due to forced convection, The dendrite arm fragmentation mechanism lucidly explains grain multiplication. There is plastic dendrite arm bending under the action of shear force caused by forced convection. The hot bending tests on single crystals of aluminum show the formation of high and low angle grain boundaries for bending angles more than 55°. The plastic bending causes large mis-orientations into the dendrite arms, and it appears as 'geometrically necessary dislocations'. However, these suggestions are controversial because it is not fully established how effective forced convection is in imparting such a huge bending moment to break tiny dendrite arms. The bending of dendrite arms will occur due to the viscous force provided the inter-dendritic flow is in the dendritic scale, and if it can cause extremely high shear rates. In other words, it actually means that it is not possible to produce such a high magnitude of force for bending and fragmentation of secondary dendrite arms with laminar flow alone.

(b) secondary and tertiary dendrite arm root remelting

Investigations show the evidence of root remelting as a possible cause of dendrite fragmentation by flow visualization experiments using transparent organic systems. It is suggested that root remelting can be due to advection of hotter or solute enriched liquid towards the mushy zone. By following this idea, a fragmentation criterion is proposed for secondary or ternary dendrite arms detachment by dendrite arm root remelting due to solute enrichment owing to thermosolutal convection. With this background, the investigations on the role of solute trapping and species diffusion in the neck regions in causing side arm attachment is also done.

Both the above stated mechanisms are based on proposed theory, as visualization of dendrite fragmentation during solidification of an opaque metallic system is usually impossible. However, high-energy X-ray studies have confirmed some of the above hypotheses by revealing the visualization of dendrite fragmentation in real metallic alloys.

(c) growth controlled mechanisms

None of the above proposed mechanisms could explain clearly the formation of rosette type morphology of metal alloy, as fragmented dendrite arms are likely to continue growing dendritically in the liquid metal. Hence, the evolution of particle morphology under forced convection does not appear from any mechanical fragmentation mechanism, but may result from a growth phenomenon. This growth mechanism proposes that severe mixing action caused by forced convection homogenizes both temperature and composition fields inside the bulk liquid metal by promoting copious nucleation mechanism. Simultaneously, heterogeneous nucleation occurs throughout the entire liquid phase, later giving rise to fine grained equiaxed morphology. In the perspective of SSF technology, this mechanism is at present widely accepted and presented experimentally. In summary, the development of globular microstructures can be either by heterogeneous nucleation stimulated by growth controlled mechanisms or due to fragmentation of dendrites caused by dendrite arm bending or root remelting owing to high shear on account of forced convection.

VIII. METHODS OF PRODUCING NON-DENDRITIC MICROSTRUCTURES

It is obvious form the earlier description that globular non-dendritic microstructure morphology can be achieved by forced convection caused by vigorous agitation. Some of the slurry production methods are described below briefly.

(a) Mechanical stirring: The simplest and also the oldest method of producing non-dendritic microstructure is by direct melt agitation using a mechanical impeller. Figure 6 illustrates schematic sketch of a mechanical stirring system. This method is simple, but it suffers from some drawbacks such as unwarranted reaction between the impeller and the corrosive liquid metal, and entrapment of gases during the melt agitation.

(b)

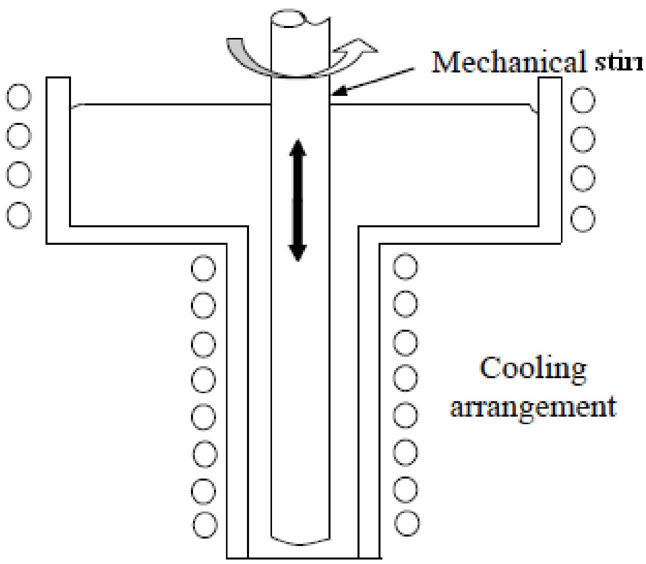


Figure 6. Schematic of mechanical stirring system

(c) Electromagnetic stirring: It is a non-intrusive method which involves subjecting the melt to undergo partial solidification in presence of a strong electromagnetic force field. The vigorous stirring by the electromagnetic force field creates the necessary circulation which causes shearing of dendrites formed at the solid-liquid interface. Figure 7 depicts a schematic sketch of a typical electromagnetic stirring (EM stirring) system in the context of direct chilled (DC) casting. Since there is no physical contact between the melt and the device, it is advantageous compared to the mechanical stirring system. However, it is a relatively more expensive process because of high equipment cost and electric power consumption. The mechanism of shearing of dendrites by either of the stirring techniques is demonstrated in figure 8.

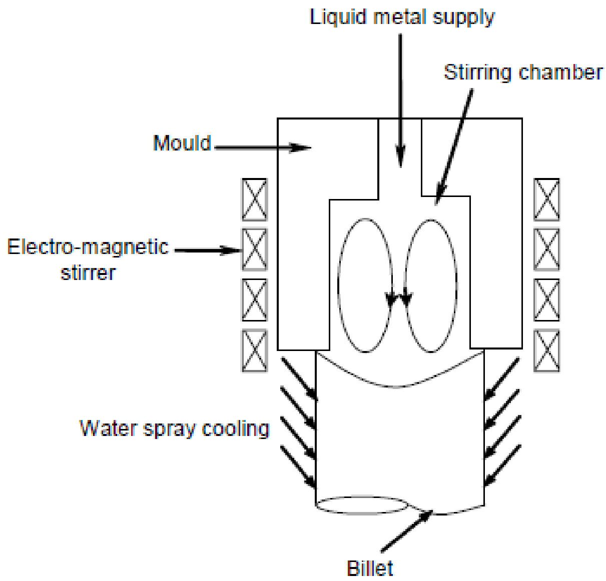


Figure 7. Schematic of an electromagnetic stirring system

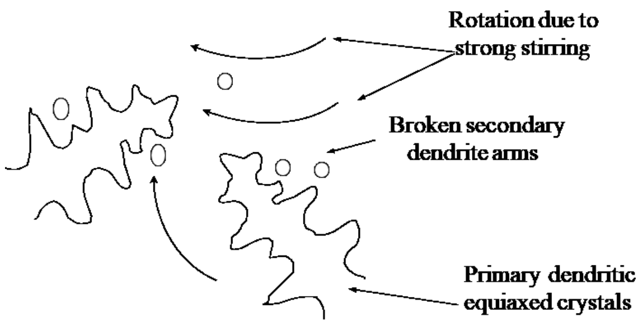


Figure 8. Schematic of mechanisms of shearing of dendrites by melt stirring

(d) *Cooling slope method*: It is a simple but effective method of semisolid slurry preparation to produce globular, non-dendritic microstructure morphology. In this method, the melt is poured down an inclined plate which is cooled from the bottom by counter flowing water. The melt, while flowing down, solidifies partially on the plate causing dendrite formation on slope wall. The plate inclination, along with gravity, provides the necessary inertia to the flowing liquid for dendrite breaking and to form slurry of non-dendritic microstructure at the slope exit. A schematic sketch of the cooling slope setup is portrayed in figure 9.

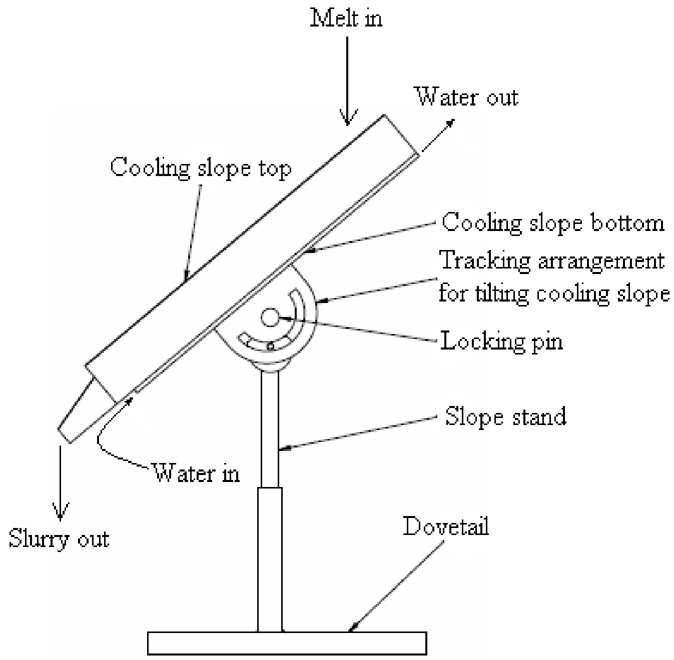


Figure 9. Schematic sketch of the cooling slope setup

Besides the methods already cited, there are some other methods of producing non-dendritic microstructures, either by melt agitation processes such as mechanical and ultrasonic vibration, or by dendritic growth control process such as low superheat, stress-induced and melt-activated (SIMA) process and addition of chemical refiners.

IX.CONCLUSION

It is now well-known that the SSF technology has got enormous and unique advantages over conventional casting processes, and thus it has turned out to be a major R&D thrust. The potential and promising qualities of semisolid forming technology made it possible to become superior to other manufacturing technologies. Over the past few years, it has got a record of producing components in a wide range of applications staring from household to industrial uses. It includes producing different components in application sectors like transportation, aviation, military, and construction. Hence, most of the SSF techniques (such as mechanical stirring, electromagnetic stirring and cooling slope method, etc.) have proved to be effective in both semisolid slurry production and near net shape components manufacturing, and hence hold the maximum potential for commercialization in a gigantic range.

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