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Cooling Slope Practice for SSF Technology

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Abstract: *Currently, the usual methods available for large scale production of semisolid slurry are mechanical stirring, electromagnetic stirring, etc. These suffer from drawbacks like complex design, high cost, structural inhomogeneity and low efficiency. The cooling slope is considered to be a simple but effective method because of its simple design and easy control of process parameters, low equipment and running costs, high production efficiency and reduced inhomogeneity. With this perspective, the primary objective of the present research is to investigate experimentally the solidification on a cooling slope, in addition to the study of final microstructure of the semisolid cast billets. 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.*

Index Terms: *Aluminum Alloy, Casting, Cooling Slope, Semisold, Slurry.*

I. INTRODUCTION

The principal drive of the present research work is the use of a cooling slope for creating sufficient shear and melt flow inertia to break the dendrites that usually grow during alloy solidification. The solidification of molten alloy along a cooling slope is quite complex, as it involves heat transfer, fluid flow, free surface deformation, solid advection, and segregation in the liquid metal alloys [1-7]. As an introductory step towards cooling slope method of slurry preparation, this research work focuses on the basic constructional features and description of a cooling slope for molten alloys.

In this research work, the physical process of a cooling slope system is first considered based on a counter flow heat exchanger approach of the cooling slope for liquid aluminum alloy. The most important feature of the current research work is a demonstration of the experimental practices for metal mould casting experiments using the cooling slope for liquid aluminum alloy, and appropriate instrumentation to realize this procedure. It also illustrates the process variables affecting the final properties of slurry obtained at the slope exit, and the final microstructure morphology of the cast semisolid billets. The blueprint of experiments necessitates selection of an appropriate aluminum alloy for SSF, and developing an experimental methodology along with processing of microstructure and temperature data observed from the experiments.

II. DESCRIPTION OF PHYSICAL PROCESS

As depicted in the schematic in figure 1, the molten alloy from a tundish with an initial superheat is poured on a cooling slope which is cooled from bottom by counter flowing water. The temperatures of molten alloy at different locations of cooling slope starting from slope inlet to slope exit are measured experimentally with K-type thermocouples mounted at different locations of cooling slope.

As already stated, in the solidification process used in the present study, a cylindrical stainless steel mould is considered for production of a cast billet. The cylindrical stainless steel mould is water cooled and is used to cool the liquid metal by extracting heat from the molten alloy. The top surface of the mould is open to atmosphere while the bottom surface is closed by an adiabatic ceramic plate. In the current study, molten A356 aluminum alloy (which is commonly used for casting applications) is preferred for solidification processing with a cooling slope. The initial temperatures of the alloy are predefined.

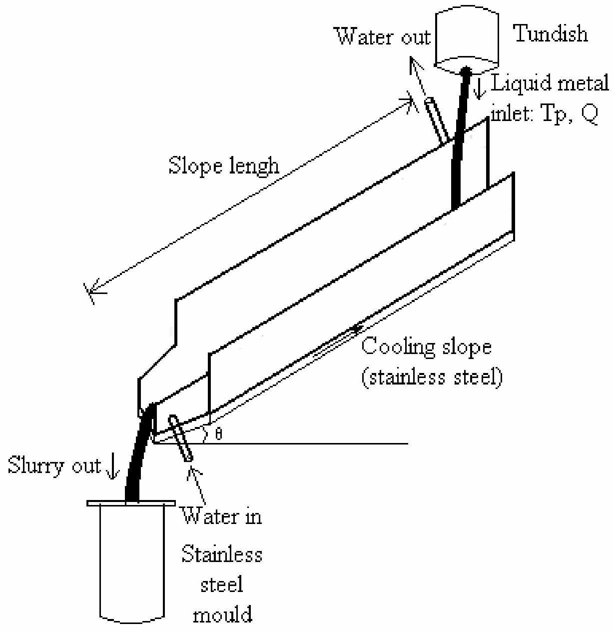

Figure 1: Schematic sketch of cooling slope system

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III. KEY PROCESS PARAMETERS

The stated method of semisolid production process is based on the rheological properties of the semisolid slurry which are influenced by fraction of solid, shear rate, and cooling rate throughout the alloy processing. For that reason, the key process parameters in the present practice of semisolid slurry preparation are, initial melt superheat, slope angle, slope length, and slope cooling rate, etc.

The enhancement of flow complexity of semisolid slurry during the alloy processing is due to distinct behavior of semisolid slurry viscosity compared to that of pure liquid. The effective viscosity of the semisolid slurry is influenced by numerous process parameters. In actual practice, the slurry viscosity is a function of solid fraction and shear rate apart from the stated key influencing factors.

IV. ALUMINUM ALLOY FOR SSF APPLICATION

Aluminum-silicon (Al-Si) alloys are generally preferred for SSF applications because of their high fluidity, low flow resistance even at a high solid fraction, and low solidification shrinkages. In binary aluminum-silicon system, a simple eutectic appears at 577°C and 12.5% Si with some degree of silicon solubility at both ends. The primary α-Al-phase includes maximum silicon content of 1.65% at the eutectic temperature. A schematic illustration of the binary Al-Si phase diagram is depicted in figure 2. Even though various Al-Si alloys are normally found to be suitable in aluminum castings, only a few of them are appropriate for semisolid forming (SSF) technology applications.

A356 is an excellent candidate material from semisolid processing standpoint. The composition of A356 alloy chosen for metal mould casting experiments in the current research investigation is summarized in table 1.

Table 1: Composition of A356 alloy chosen in current experiments

Alloy element	Si	Mg	Fe	Mn	Cu	Ti	Al
Percentage by weight	7.32	0.31	0.086	Max 0.010	Max 0.010	0.157	Balance

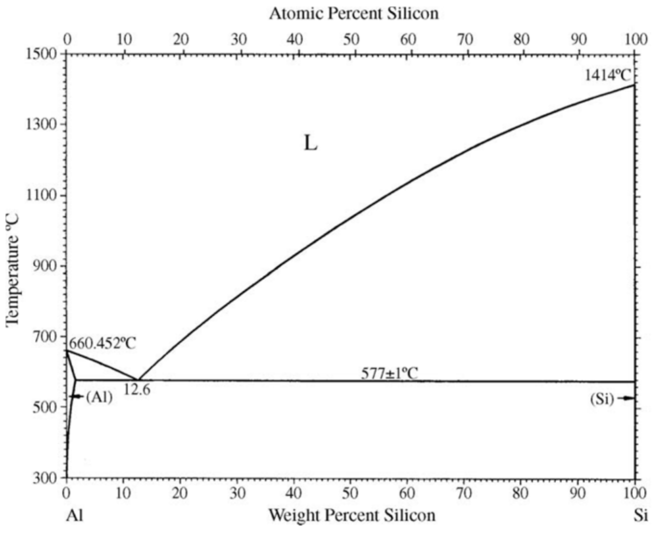

Figure 2: (a) Binary phase diagram of Al-Si system

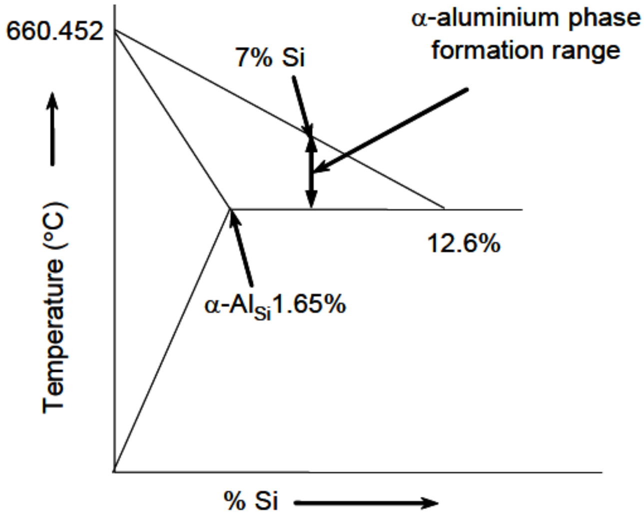

Figure 2: (b) Formation zone of primary α-Al phase

V. DESCRIPTION OF BILLET CASTING PROCEDURE: METHODS AND MESEARUMENTS

The liquid aluminum alloy at a predetermined superheat is poured on the cooling slope. The semisolid slurry collected at the slope exit is allowed to solidify in a metal mould kept just after the slope exit. It is quite obvious that most of the heat transfer taking place during solidification of the slurry occurs at the mould wall. There will be cooling due to convection and radiation at the top of the mould as it is exposed to air. The stated mould cooling arrangement would result in radially inward advancement of the solidification front. The rate of advancement of the solidification interface would depend on other parameters such as cooling rate at the mould wall, mould material and movement of the mould such as rotation. The cast billet is of length 250 mm and diameter 60 mm.

Figure 3 illustrates a photograph of the experimental facility (consisting of tundish, cooling slope, metal mould, etc.) for the cooling slope experiments.

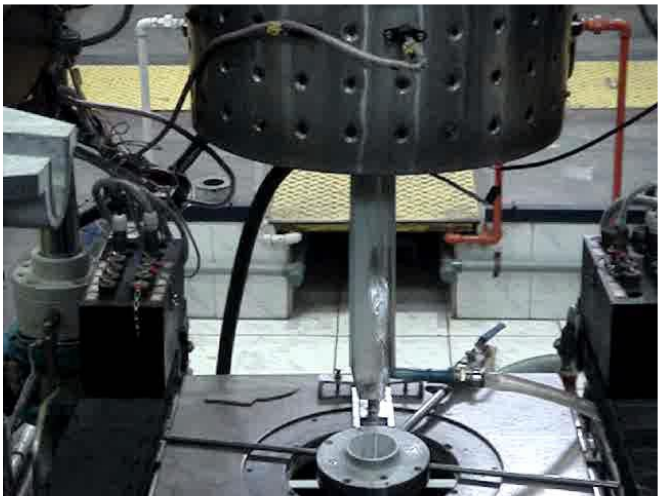

Figure 3: Photograph of the experimental facility

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The melting practice and treatment of A356 aluminum alloy is depicted in figure 4. In addition, protective aluminized aprons, shoes, safety glasses, hand gloves and helmets (as illustrated in figure 5) are also used by the technical personnel while conducting experiments with molten aluminum.

Figure 4: Photograph during melting practice and treatment

Figure 5: Photograph of technical personnel while conducting experiments

Pre-calibrated Class I, K-type mineral insulated (MI) twisted-pair thermocouples from TC Ltd. (UK) are introduced for the molten alloy temperature measurement at different locations on the cooling slope. In order to measure the flow rate (in terms of litres per minute) of water circulated through the thin rectangular channel of the cooling slope, a rotameter is used. A rotameter consists of a graduated glass tube with a metallic float under the action of upward drag and downward gravity as shown in figure 6.

Figure 7 shows semisolid cast billet sample and intermittently quenched samples. Optical microscopy and image analysis software are used to measure the heterogeneity in microstructural morphology of the stated samples.

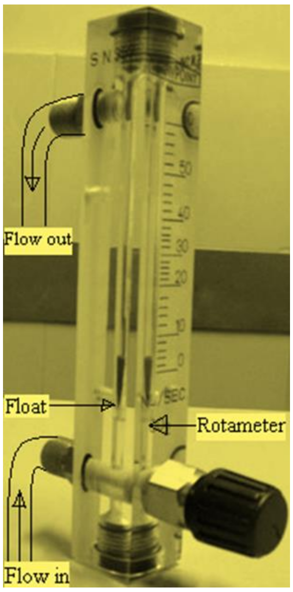
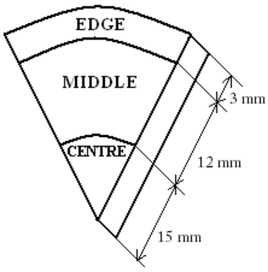


Figure 6: Photograph of rotameter



(a) Billet sample (b) Intermittently quenched samples

Figure 7: Billet and intermittently quenched samples

VI. RESULTS AND DISCUSSIONS

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 (as shown in figure 8) with poor mechanical properties, which is not desirable for engineering design point of view. Casting alloys at an intermediate state between solid and liquid (i.e. at semisolid state) using cooling slope leads to globular and non-dendritic microstructure morphology (as depicted in figure 9) with superior and enhanced mechanical properties.

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 (appearing in white color) separated and surrounded by a lower melting, near eutectic secondary phase (appearing in black color).

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.

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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 cooling slope. 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.

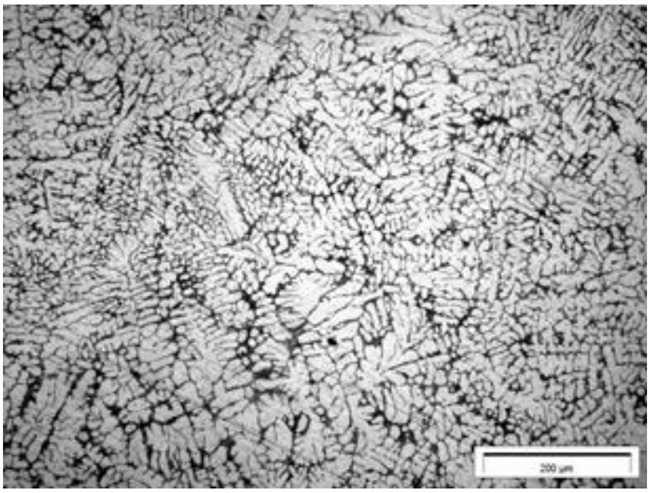

Figure 8. Dendritic microstructure

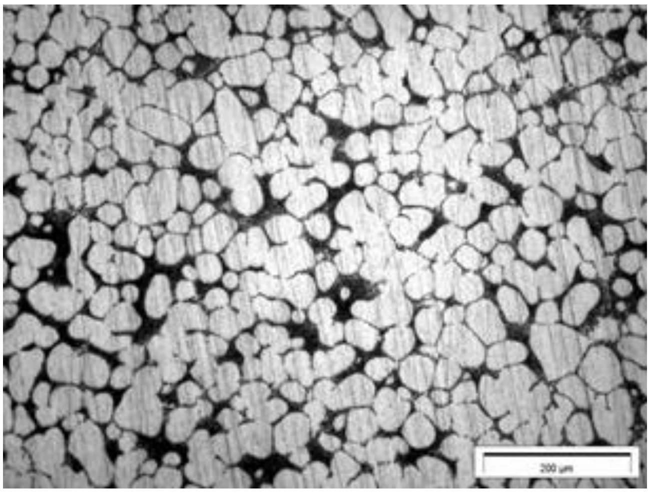

Figure 9. Globular and non-dendritic microstructure

The semisolid slurry undergoes solidification to produce semisolid cast billets for further processing (i.e. semisolid billet casting). The billets thus cast have globular non-dendritic microstructure, and are termed as raw materials or feedstock materials for further processing.

VII. CONCLUSION

A comprehensive detail about the basic constructional features and description of a cooling slope for molten alloys is presented and the various components of cooling slope geometry are illustrated. A simplified analysis of a cooling slope for solidification process based on a counter flow heat exchanger approach of the cooling slope for liquid aluminum alloy and the associated thermal issues are presented. The experimental cooling slope system also considers the effects of process variables on the final properties of slurry collected at the slope exit and the final microstructure of the cast semisolid billets. In other words, this also includes a description of the schematic of the experimental setup, melt preparation, temperature measurement procedures, techniques for flow measurements, and practices for microstructure studies. The safety precautions followed in the experimental trials and practices are also highlighted. As a whole, the present research work demonstrates the experimental arrangement and procedures for metal mould casting experiments using the cooling slope for liquid aluminum alloy and appropriate instrumentation to realize this practice.

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