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# Use of Cooling Slope in Semisolid Billet Casting

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## ABSTRACT

Presently, the traditional techniques accessible for large scale generation of semisolid slurry are mechanical stirring, electromagnetic stirring, etc. These encounter from disadvantages such as complicated design, high cost, structural inhomogeneity and low efficiency. The cooling slope is taken to be a simple but effective technique owing to its simple design and easy control of process parameters, low equipment and running costs, high production efficiency and reduced inhomogeneity. With this standpoint, the main aim of the current 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 utmost casting uses, dendritic microstructure morphology is not preferred because it results in poor mechanical properties. Forced convection producing adequate 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, comprising of rosette or globular particles, offers less resistance to flow even at a high solid fraction and can effortlessly fill the die-cavity. The said principle is the foundation of a novel production technique t called "semi-solid forming" (SSF), in which metal alloys are cast in the semi-solid state. This technology has several advantages over other usual commercial casting processes, like decrease of macrosegregation, decrease of porosity along with less forming efforts as well.

**Keywords:** Semisold, Slurry, Cooling Slope, Aluminum Alloy, Casting.

## I. INTRODUCTION

The prime and also key motivation 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. 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 illustrated in the representation of figure 1, the molten alloy from a tundish with an initial superheat is poured on a cooling slope which is cooled from underneath by counter flowing water. The temperatures of molten alloy at various locations of cooling slope starting from slope entry to slope outlet are noted experimentally with K-type thermocouples mounted at various locations of cooling slope.

As previously said, in the solidification practice introduced in the current investigation, a cylindrical stainless steel mould is taken for manufacturing of a cast billet. The cylindrical stainless steel mould is water cooled and is utilized to cool the liquid metal by taking heat from the molten alloy. The top surface of the mould is open to atmosphere whereas the bottom surface is closed by an adiabatic ceramic plate. In the present investigation, molten A356 aluminum alloy (which is normally utilized for casting techniques) is chosen for solidification practice with a cooling slope. The initial temperatures of the alloy are predefined.

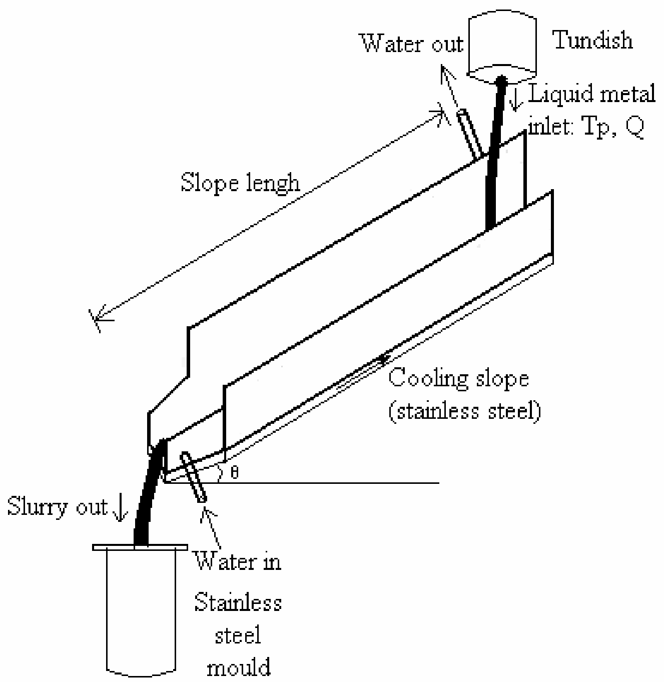



**Figure 1:** Schematic sketch of cooling slope system

## III. PROCESS PARAMEPERS

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 enrichment of flow intricacy of semisolid slurry in the alloy processing is because of distinct behavior of semisolid slurry viscosity compared to that of pure liquid. The effective viscosity of the semisolid slurry is affected by several process variables. In real exercise, the slurry viscosity is a function of solid fraction and shear rate besides the said vital influencing parameters.

## IV. ALUMINUM ALLOY SELECTION CRITERIA 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. The fundamental selection criteria or the decisive factors for SSF alloys are described below.

### A. Temperature Processing Range ($\Delta T_{TP}$)

Casting practices encounter severe difficulties in temperature control during the alloy solidifications; a bigger temperature processing range for solidification of SSF billets is essential for SSF forging and casting procedures. A temperature difference corresponding to 0.3-0.5 solid fraction is termed as $\Delta T_{TP}$ for SSF casting, whilst, the temperature difference corresponding 0.5-0.7 solid fraction is noted as $\Delta T_{TP}$ for SSF forging.

### B. Solidification Range (ΔT)

The temperature range (ΔT) is defined as the temperature difference between the solidus and the liquidus lines of the alloy. Researchers have revealed that alloys having extremely broad solidification range possess very poor resistance to hot tearing. The solidification range of a SSF alloy is suggested to be within 40-110ºC. On account of this, pure metals and eutectic alloys are not suitable for SSF technology applications, since they do not exhibit a wide range of phase change temperatures.

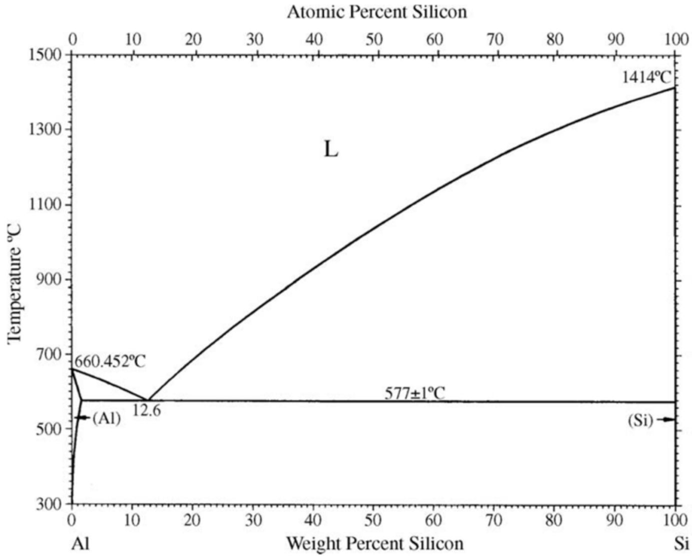



**Figure 2:** (a) Binary phase diagram of Al-Si system

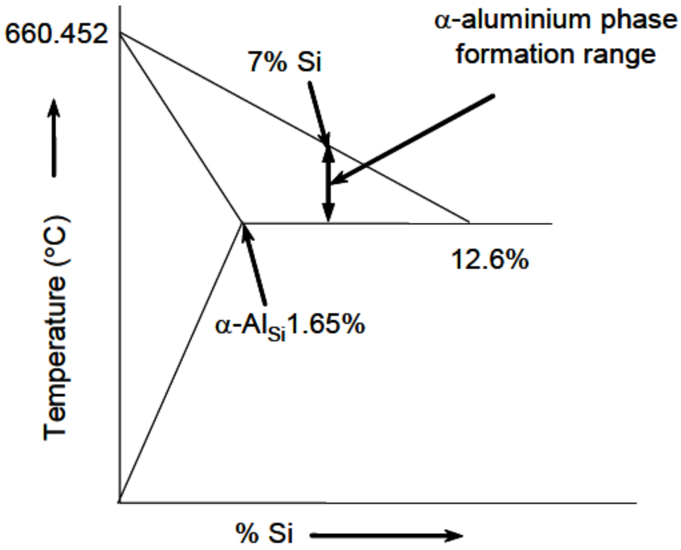



**Figure 2:** (b) Formation zone of primary α-Al phase

### C. Temperature Sensitivity of Solid Fraction

The temperature sensitivity of solid fraction ($f_s$) is defined as the slope of $f_s$ versus T curve at a specified alloy composition. The temperature sensitivity of the solid fraction in the range $0.3<f_s<0.7$ fraction solid should be as small as possible; so as to get hold of precise and accurate processing conditions.

### D. Potential for Heat Treatment

The SSF alloys need to demonstrate adequate potential for heat treatment, so as to realize high strength. The concentration difference (ΔC) of the alloying elements in the primary α-phase between the quenching and reheating temperatures, governs the potential for heat treatment of a phase.

Among all the existing Al-Si alloys, lined up with the stated factors, A356 aluminum alloy possesses extremely minute $df_s/dT$ values in the solid fraction range of economical and practically feasible forming operations. Besides, this alloy also exhibits a broad freezing range because of high volume of eutectic phase (nearly 50%), thus bringing about the control over solid fraction. When reheated, the comparatively large eutectic fraction gives rise to a variety of improved morphological and mechanical properties. On the whole, in overall SSF technology applications, the final microstructure is influenced mostly by the eutectic phase distribution. Hence, A-356 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 |
|---|---|---|---|---|---|---|---|
| % by weight | 7.32 | 0.31 | 0.086 | Max 0.010 | Max 0.010 | 0.157 | Balance |

## V. DESCRIPTION OF BILLET CASTING PROCEDURE

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 (as shown in figure 3) 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.

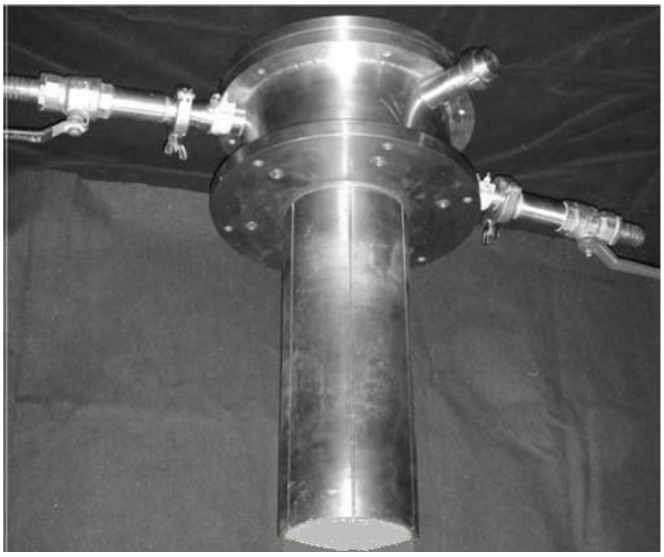


**Figure 3:** Photograph of metal mould

## VI. METHODS AND MEASUREMENTS

Figure 4 illustrates a photograph of the experimental facility (consisting of tundish, cooling slope, metal mould, etc.) for the cooling slope experiments.

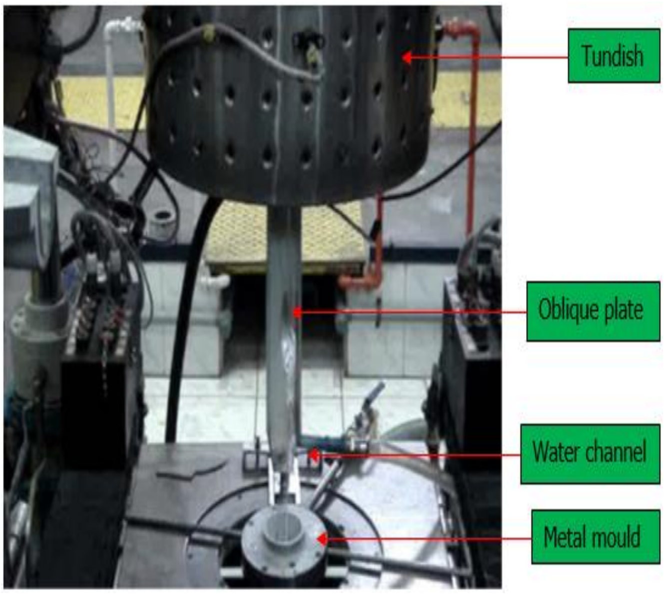



**Figure 4:** Photograph of the experimental facility

### A. Melt Preparation and Treatment

The melting practice and treatment of A356 aluminum alloy is depicted in figure 5. Ahead of each experiment, around 20 kg of the A356 aluminum alloy ingots is loaded into a mica glazed silicon carbide crucible kept in a tilting electric resistance furnace and is then melted at 720°C. Once the metal reaches molten stage, the molten alloy is held for about 45 min at 720°C ± 5°C, to allow for attaining temperature uniformity and complete dissolution of alloying elements. Subsequently, it is degassed. A provision is made in the furnace cover for introducing a degassing tube into the molten alloy. The degassing practice is continued inside the furnace crucible by blowing dry nitrogen into the molten alloy by means of a silicon carbide tube having 10 mm inside diameter. The usual degassing time is 30 min with a nitrogen flow rate of 40 litres per minute. The temperature of the alloy is allowed to remain between 700-720°C throughout the degassing stage. After degassing of the alloy, the slag accumulated at the top is removed.

This is subsequently followed by the addition of predetermined quantities of grain modifiers and refiners. In all the experiments, aluminum-strontium (Al-Sr) master alloy is used as a modifier. Several trial experiments are conducted with different quantities of modifier and the resulting microstructures are examined to ensure the appropriate amount of strontium necessary for the finest and best possible modification of the eutectic Si-phase. As a result, in each melt, aluminum-strontium master alloy amounting to 0.25% of the total melt weight of the alloy is added prior to each pour. The examination by melt spectroscopic analysis reveals that this amount corresponds to about 50 ppm necessary for the finest and best possible modification. Also, this is consistent with the experiments reported in literature. Similarly, in all the experiments, titanium-boron tablet is used as a grain refiner. In each melt, titanium-boron (Ti-B) tablet amounting to 0.125% of the total melt weight of the alloy is added for grain refinement. After that, before pouring into metal mould, the melt is allowed to soak for about 15 minutes to entirely feel the effects of grain modifier and refiner. Throughout the experiments, depending on the melt quantity and amount of superheat, a 40-50°C drop in temperature is normally noticed while transferring the molten alloy from electric resistance furnace to the metal mould. This ascertains the requirement of holding such an elevated temperature in the heating furnace.

**Figure 5:** Photograph during melting practice and treatment

### B. Melt Transfer to the Tundish

The preheated metal mould is positioned just at the exit of the cooling slope. This preheating step is very essential from the operational safety standpoint, so that no moisture remains in the metal mould. Also, preheating offers enough time for the particles in the slurry to grow by ascertaining that the semisolid slurry does not solidify instantaneously upon entering the metal mould. The usual mould preheating temperature is 200°C±5°C.

For each experiment, about 1.5 kg of molten alloy is removed from the furnace and then transferred into a tundish. The molten alloy temperature in the tundish is frequently monitored by means of a K-type thermocouple. The molten alloy is slowly poured into the metal mould via a cooling slope at the predetermined molten alloy superheat temperature. To ascertain laminar filling and consistency, the pouring of molten alloy is carried out progressively and gently.

### C. Temperature Measurement

The molten alloy temperature, starting from the tundish to the metal mould, is measured at several strategic locations on the cooling slope (it also includes the temperature measurement of the melt in the tundish and inside the metal mould as well, if required) as it undergoes partial solidification at the slope wall while flowing over it. It may be noted here that the partial solidification of the melt at the slope wall is due to the water circulation through the thin channels underneath the cooling slope. The methodology and the corresponding practices for all types of temperature measurements in liquid metal are explained lucidly as follows.

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. The measuring junction of the thermocouple is of ungrounded type with a diameter of 0.8 mm. The thermocouple wires are covered with inconel shield to 1.5 mm outer diameter. The response time is 0.8 s and the measurement uncertainty is ±0.002T (where T is the measured temperature in degrees Celsius), as provided in the manufacturer's handbook. In order to expose the junction tip to the molten alloy, the MI thermocouple assembly is incorporated into another inconel sheath of 2 mm ID and 3.6 mm OD. The annular region between the outer inconel sheath and the thermocouple assembly is filled with insulating ceramic cement. Such an arrangement is adopted, to get rid of the instabilities owing to the direct contact of molten alloy to the thermocouple wires. Some independent trials are performed in the molten alloy with and without water circulation underneath the cooling slope to ascertain the importance of the protective sheathing practices. A representative thermocouple-tube assembly employed in the current experimental practices is illustrated in figure 6.

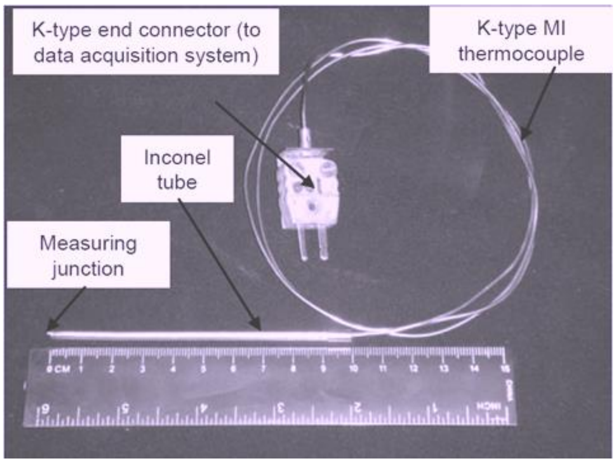



**Figure 6:** Typical K-type MI thermocouple assembly

The different strategic locations of the thermocouples on the cooling slope for the temperature measurement are such that the distance between any two consecutive thermocouples is 50 mm. The present experimental practices lead to the following benefits: i) the strategic locations of temperature measurement are not changed during flow of molten alloy over the cooling slope, ii) consistency in measurement locations between different trials and iii) averting lateral drifts of thermocouples due to partial solidification of the melt while flowing down the slope. The individual microstructures and trial times observed with and without mounting of the thermocouples revealed that there are negligible effects on the resulting outcomes.

**D. Flow Measurement**

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 7. Water at a particular flow rate enters at the bottom inlet and exits at the top outlet by pushing the float to a particular position of the tube corresponding to an indication of an appropriate flow rate. For getting finer results the rotameter is also calibrated. The measurement uncertainty of rotameter is ±0.01 times the flow rate in lpm, as provided in the manufacturer's handbook.

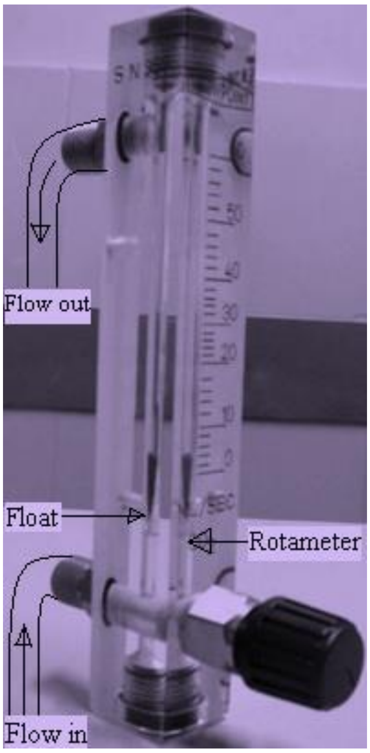
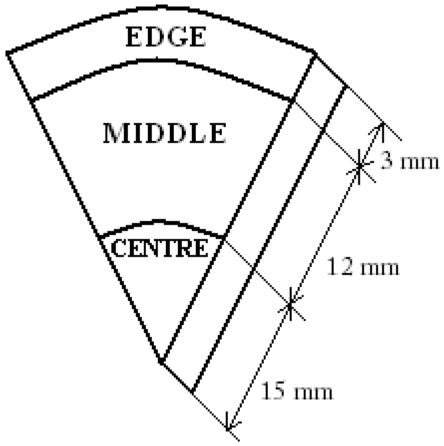


**Figure 7:** Photograph of rotameter

**E. Microstructure Sample Preparation**

The billets are cast by quenching semisolid slurry of metal alloy in a metallic mould. The small sections were sliced vertically from the cast billets to form 15 mm thick disks. The disks are then marked as "edge", "middle" and "centre" (as shown in figure 8 (a)) in accordance with the radial locations of the initially solidified cast billet. For metallographic analysis, all the sliced samples are polished by means of emery papers of various grades, subsequently followed by SiC powder polishing together with diamond paste polishing. Each of the polished specimens obtained by the already described procedure are etched using Keller's reagent (1ml HF, 1.5 ml HCl, 2.5 ml $HNO_3$ and 100 ml $H_2O$) at the ambient temperature for about 10 minutes.




(a) Schematic sketch of billet sample

(b) Photograph of intermittently quenched samples

**Figure 8 :** Billet and intermittently quenched samples

Furthermore, intermittently quenched samples (as shown in figure 8 (b)) are also polished and etched by following similar practices, and the corresponding micrograph images are taken. The evolution of solid fraction as a function of temperature for intermittently quenched samples was predicted by using two methods: (a) utilization of thermodynamic data in Scheil model assuming binary composition of Al–Si alloy, and (b) quantitative metallographic analysis of microstructures of the quenched samples. Results from the two methods are compared for examining the slurry quality in terms of solid fraction and temperature at the slope exit.

### F. Microstructural Evaluation

Optical microscopy and image analysis software are used enumerate and measure the heterogeneity in microstructural morphology. The micrograph images of samples are then snapped at the centre, middle and edge for characterization with image analysis using Leitz optical microscope at 20x magnification for quantitative and metallographic analysis. Sigma Scan Pro image (version. 4.0) analysis software is deployed for quantitative metallographic analysis such as for determining the area and perimeter of primary α-Al particles.

The microstructural characterizations of the snapped images are carried out based on the under-mentioned parameters:

a) Fraction of primary α-Al phase (%): It is determined in accordance with the area ratio of primary α-Al phase and eutectic Si phase.

b) Grain size: It is estimated by means of the intercept method.

c) Shape factor: It is a measure of globularity of the primary α-Al phase. It is evaluated with the use of the formula, $S = 4\pi A/P^2$, where A is the area of the primary α-Al phase and P is the perimeter of the primary α-Al phase.

For an ideal circle the value is 1, and for a dendrite the formula yields a value tending to zero. For a rosetted structure, depending on the amount and degree of irregularity, it yields a value between 0 and 1.

d) Particle density: Otherwise termed as grain density, it is the number of primary α-Al globules per unit area; bigger this number, superior is the amount and degree of dendrite multiplication or breakdown.

## VII. SAFETY PRECAUTIONS

Notwithstanding the fact that very high temperature is related to cooling slope experiments, adequate safety procedures have to be considered in all stages. It is rather apparent that direct contact between liquid aluminum alloy and water is extremely harmful which can create severe explosions. Therefore, highest safety precautions are adopted to ensure that water supply to the cooling slope along with metal mould is leak proof and the neighboring zone to experimental setup is completely dried out.

Apart from the said preventive actions, the tube assembling the thermocouples is preheated up to about

200°C using a gas burner to eliminate trapped moisture before it is mounted on the cooling slope. In addition, protective aluminized aprons, shoes, safety glasses, hand gloves and helmets (as illustrated in figure 9) are also wore by the technical personnel when performing experiments with molten aluminum.

**Figure 9:** Photograph of technical personnel while conducting experiments

## VIII. CONCLUSION

A complete fact about the simple constructional features and illustration of a cooling slope for molten alloys is demonstrated and the several elements of cooling slope geometry are exemplified. A basic analysis of a cooling slope for solidification practice based on a counter flow heat exchanger approach of the cooling slope for liquid aluminum alloy and the related thermal challenges are described. The experimental cooling slope technique also reflects the influences of process parameters on the final properties of slurry extracted at the slope outlet and the final microstructure of the cast semisolid billets. In other words, this also comprises an illustration of the schematic of the experimental setup, melt preparation, temperature measurement procedures, techniques for flow measurements, and procedures for microstructure investigations. The safety measures adopted while performing experiments are also underlined. In overall, the current study illustrates the experimental practices for metal mould casting experiments by means of the cooling slope for liquid aluminum alloy and proper arrangement to gather this exercise.

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