Production of semi-solid feedstock of A356 alloy and A356-5TiB$_2$ in-situ composite by cooling slope casting

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Abstract. Cooling Slope casting process has gained significant importance for manufacturing of semi-solid feedstock Al alloys and composites which find applications in automotive and aerospace industries. The primary objective of this research is to generate the semi-solid feedstock suitable for thixoforming process. The current work discusses the phenomena involved in the evolution of microstructure of the semi-solid feed stock by Cooling Slope casting process and the effect of various parameters. The process parameters like the angle and length of inclined plate affect the size and morphology of α-Al phase. The Cooling slope process resulted in the formation of fine grain size of about 38 µm of α-Al phase, compared to that of 98 µm processed conventionally. Further, the pouring temperature played a crucial role in the generation of semi-solid microstructures in case of both the alloy and composites. Moreover, fine TiB$_2$ particles of size 0.2-0.5 µm are uniformly distributed in the almost spherical α-Al grains and at the grain boundaries in the composite feed stock. Cooling slope casting route is a suitable and economical route for semi-solid slurry generation by effectively varying the process parameters.

Keywords: Semi-solid processing; Rheocasting; Cooling Slope; A356 alloy; TiB$_2$ in-situ composite;

1. Introduction
Semi-solid Metal Processing (SSMP) has been posed to be a potential route to form near-net-shape products in the automotive, aerospace and other engineering industries. The key element in the SSMP is the globular microstructure rather than dendritic microstructure and it is the thixotropic behaviour of the semi-solid slurry which reduces the segregation and porosity in the castings [1-2]. Compared with conventional techniques, SSMP provides several advantages like higher product quality, lower forming temperature, higher production rate and improvement of the mechanical properties through microstructural refinement [3]. SSMP methods require thixotropic feedstock materials as starting material for further thixoforming process [4]. Over the past four decades, much research is underway...
around the globe to develop cost effective feedstock production methods and recently in the last 
decade, Cooling slope (CS) casting has emerged as viable route for generation of feedstock [5]. 
Extensive research on CS casting process was initially carried out by T. Haga and research group and 
they reported that CS casting process is a simple, has minimal equipment requirements and which is 
able to produce feedstock material for semisolid processing [6]. Later, Birol [7] reported that when the 
feedstock is reheated to the semisolid temperature range, nondendritic, spherical solid particles in a 
liquid matrix suitable for thixoforming are obtained [8]. Robert et al. [9] produced semi-solid A356 
alloy by CS route and stated that thixotropic property is greatly influenced by CS processing route. In 
addition, Legoretta et al. [10] developed a thorough understanding of the microstructural development 
of A356 alloy during the CS process and demonstrated the effect of process parameters on the CS cast 
feed stock. Taghavi and Ghassemi [11] investigated on the effects of the length (20, 30, 40, 50, 60 cm) 
and angle of inclined plate (20°, 30°, 40°, 50°) on the thixotropic microstructure of A356 aluminum 
alloy. Their results indicated that 40° and 40 cm condition is optimum inclined plate angle and length 
presenting the minimum grain size of 28μm and maximum shape factor of 0.70 with highest 
uniformity. Das et al. [12] has conducted experiments and studied the effects of slope angle and 
addition of grain refiner on microstructure evolution of the solidifying melt through rheocasting 
process employing cooling slope (CS) casting route. They reported that there is a significant increase 
in the tensile properties of the rheocast feed stock processed by CS casting route. Recently, Deepak et al. [13] conducted a review on Cooling Slope casting process of semi-solid Aluminium alloys and reported that CS casting process is gaining popularity for the generation of metal matrix composite feedstock with globular microstructure for further thixoforming. From the 
literature survey, it is clear that very few works exists on the semi-solid feedstock production of Al 
based metal matrix composites. Thus, the present work is an attempt to investigate the feasibility of 
this Cooling Slope casting process to generate semi-solid A356-5TiB₂ in-situ composite feedstock 
suitable for thixoforming process.

2. Materials and Methods

2.1. Materials

A commercial A356 alloy and A356-5wt%TiB₂ in-situ composite synthesized by Flux assisted 
synthesis (FAS) technique were used in the present study. The chemical composition of A356 alloy is 
shown in table 1.

| Alloy  | Si    | Mg    | Fe    | Cu    | Mn    | Al   |
|--------|-------|-------|-------|-------|-------|------|
| A356   | 6.87  | 0.297 | 0.12  | 0.01  | 0.003 | 92.70|

2.2. Processing of A356-5TiB₂ in-situ composite

The A356-5wt%TiB₂ in-situ composite was fabricated by FAS technique. Initially, an appropriate 
amount of Al-50Si master alloy and commercial pure aluminium (CPAL) was melted in a graphite 
crucible in a resistance furnace to prepare the Al-7Si alloy. The K₂TiF₆ and KBF₄ halide salts were 
added to the melt which undergo an exothermic, in-situ reaction with molten Al-7Si alloy to create 
titanium-diboride (TiB₂) dispersoids in the melt. The melt was kept at a temperature of 800 °C and 
stirred for every 10 minutes for homogenous formation of TiB₂ particles. After a reaction time of one 
hour, the dross which floats on the top of the melt was decanted and appropriate amount of Al-20Mg 
master alloy was added so as to make the net composition of the composite as Al-7Si-0.3Mg- 5TiB₂. A 
schematic diagram of synthesis of in-situ composites is shown in figure 1.Further details of FAS 
technique can be found elsewhere [14-15].
2.3. Cooling Slope casting

The Cooling slope (CS) casting process was employed as a feedstock production method for both the alloy and composites. The A356 alloy and A356-5TiB$_2$ in-situ composites were melted at 720 °C and 800 °C respectively in a resistance furnace. Previous studies in our group [14-16] suggests that the complete reaction of K$_2$TiF$_6$ and KBF$_4$ halide salts with the molten aluminium alloy takes place at an optimum reaction temperature of 800°C for reaction time of 60 minutes resulting in formation of only TiB$_2$ particles in the molten aluminium alloy. Hence the composites were melted at a higher temperature of 800°C while A356 alloy was melted at 720°C. The melt is then degassed with 1 wt% hexa-chloroethane and was then allowed to cool to desired pouring temperatures. The CS casting experiments involved pouring the molten A356 alloy and A356-5TiB$_2$ in-situ composite over a 50 mm wide and 400 mm long, inclined mild steel plate into a permanent mold with a diameter of 30 mm and a depth of 135 mm. The cooling plate was adjusted at different angles varying from 30° to 60° with respect to the horizontal plane and was cooled by water circulation underneath. The experimental setup of the CS casting process is shown in figure 2 and the experimental parameters are given in Table 2. The flow rate of water circulation was measured using a single jet water meter (Model: LXC-15DS) and is kept constant of 2 L/min throughout the experiments. The surface of the plate was coated with a thin layer of zirconia paste in order to avoid sticking of the melt on the plate. A pre-heated graphite funnel was used as a pouring cup and a graphite cone was used to allow the melt to fill in the mold more easily. Temperatures were monitored with a K-type thermocouple fixed at the start of the slope and one inserted in the mold to record the start and exit temperatures of the melt along the slope. The semi-solid feedstock of the alloy and composites thus generated, is illustrated in figure 3. Thereafter, the composites were characterized by X-ray diffractometer (Model: PW 1710, PHILIPS, Netherlands) using Cu-K$_\alpha$ radiation (wavelength =1.54 Å) to identify the phases, as shown in figure 4.
Table 2. Experimental conditions of CS casting process

| CS Process parameters       | Range                                      |
|----------------------------|--------------------------------------------|
| Cooling slope plate        | Length = 400 mm, 300 mm and 200 mm         |
| Material of plate          | Mild steel                                 |
| CS Plate Dimensions        | Length = 400 mm; width = 50 mm; Radius = 12.5mm (U-Type) |
| Coating on the inclined plate | Zirconia paste                            |
| Pouring Temperatures       | 630 °C, 640 °C, 650 °C                     |
| Cooling slope plate angle  | 30°, 45°, 60°                              |
| Material of Mould          | Mild steel split type                      |
| Mould Dimensions           | Φ30 mm x 135 mm                            |

Figure 3. Semi-solid feedstock of (a) A356 alloy (b) A356-5TiB₂ composite

Figure 4. XRD patterns of A356 alloy and A356-5TiB₂ composites

3. Results and discussion

3.1. Microstructural Investigation of A356 alloy

The morphologies of A356 alloy processed by conventional casting have dendritic structure as shown in figure 5a, while that processed via CS process typically consists of mixture of rosettes and nearly spherical grains as shown in figure 5b. This is attributed due to the inclined plate which acts as a source of nucleation sites, generates crystal nuclei in the melt during its flow along the slope [9-10]. The α-Al crystals nucleate and grow on the slope wall and further, they are detached from the surface of the plate, because of shearing action generated during the melt flow. The solidified strip and the morphology of A356 alloy on CS strip at exit end, poured at 60° angle is shown in figure 6.

Figure 5. Microstructures of A356 alloy (a) Conventionally cast (b) Cooling Slope casting
In order to investigate the effectiveness of the cooling slope, a study on the effect of angles of the cooling slope viz. (30°, 45°, 60°) on the microstructure of the A356 alloy was investigated and the corresponding microstructures were shown in figure 7(a-c).

Further, inorder to quantify the morphology and size of primary solid phase (α-Al), the grain size, i.e circular diameter (C.D) and the degree of sphericity, i.e Shape factor (S.F) are calculated according to the following equations Eq. (1) & Eq. (2), reported elsewhere [11,12]. The variation of Grain size and S.F of α-Al phase of A356 alloy at different processing conditions is shown in figure 8.

\[ CD = 2\sqrt{\frac{A_\alpha}{\pi}} \]  

\[ SF = \frac{4\pi A_\alpha}{P_\alpha^2} \]

Where, \( A_\alpha \) and \( P_\alpha \) represent the area and perimeter of α-Al phase, respectively.

It is evident from figure 7(a-c) that, with the increment in the angle of cooling slope from 30° to 45° leads to a decrement of the size of α-Al phase from 74µm down to 52µm and further, increment in the angle of cooling slope from 45° to 60° resulted in the size of α-Al phase to be 38µm, which is comparatively less than that of 98 µm of conventionally cast A356 alloy. Moreover, it has also been observed that there is gradual increase in the S.F. from 0.55 in the as cast condition to 0.82 in the C.S. cast at 60°.

![Figure 6](image1.png)

**Figure 6.** (a) Solidified strip (b) Morphology of A356 alloy on CS strip at exit end, poured at 60° angle

![Figure 7](image2.png)

**Figure 7.** Microstructures of Semi-solid slurry A356 alloy poured at (a) 30° (b) 45° (c) 60° angles
The pouring temperature has great impact on the microstructure of the alloy and composites. The microstructures of the CS cast A356 alloy poured at different temperatures is shown in figure 9. It has been observed that in the current study, for a slant angle of 60°, the temperature suitable for desired semi-solid microstructure was 640°C, while it was found to be 650°C for 30° cooling slope angle. It has been observed from the experiments that higher the inclined plate angle lower the pouring temperature is required.

3.2. Microstructural evolution of rheocast A356-5TiB$_2$ in-situ composite
The feasibility of generation of feed stock of A356-5TiB$_2$ composite was also conducted, and the microstructure of A356-5TiB$_2$ composite obtained through CS casting process is shown in figure 10. It can be observed that TiB$_2$ particles having a range of 0.2-0.5μm along with eutectic silicon are found in the grain boundary region of α-Al matrix.

Figure 8. Variations of Grain size and S.F of α-Al phase of A356 alloy

Figure 9. Microstructures of the CS cast A356 alloy poured at  (a) 630° C (b) 640° C(c) 650° C

Figure 10. (a) Microstructures of CS cast A356-5TiB$_2$ composite, poured at 60° angle and 640° C  
(b) SEM micrograph showing minute TiB$_2$ particles
4. Conclusions
The study in this research has discussed the application of Cooling Slope casting process for the generation of semi-solid feedstock of A356 alloy and its feasibility as a viable route for generation of non-dendritic feedstock of A356-5TiB$_2$ in-situ composite, which subsequently acts as a starting material for further thixoforming.

The following can be concluded from the present study:
- The dendritic primary $\alpha$-Al phase of 98 $\mu$m of conventionally cast alloy transformed to fine and non-dendritic structure of 38 $\mu$m by the application of cooling slope casting process.
- The $\alpha$-Al grains readily transformed to mixture of spherical and rosette type structure after being flowed through cooling slope casting route.
- A significant reduction in grain size from 74 $\mu$m to 38 $\mu$m was observed as the cooling slope plate angle increased from 30° to 60°.
- A maximum sphericity of 0.82 of $\alpha$-Al grains is obtained for a 60° cooling slope angle.
- The optimal combination of cooling slope casting process parameters were found to be, a pouring temperature of 640 °C, slope angle of 60° and cooling length of 300 mm.
- Moreover, minute TiB$_2$ particles of size 0.2-0.5 $\mu$m are uniformly distributed in the spherical $\alpha$-Al structure and at the grain boundaries in the composite feedstock.
- Cooling slope casting route is thus offered as an attractive and alternative route in the production of semi-solid feedstock of both alloy and composites by effectively varying the process parameters.

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