Semisolid Casting of Aluminium Alloy using an Inclined Slope

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***Abstract*— Solidification of metals plays a crucial role in both scientific research and industrial development. Semisolid metal (SSM) processing of alloys has been long under investigation, in which non-dendritic solid particles are dispersed in a liquid matrix. Furthermore, suppression of dendritic growth is beneficial for mechanical property enhancement of the final product. In all the alloy systems, with the application of low shear, non-dendritic structures could be achieved with an improvement in the mechanical properties. Low superheat, high angle of the slope, optimum slope temperatures resulted in higher shape factor of the primary grains. The setup can be used conveniently as slurry on demand process. In the present work thermo-physical modelling of this setup has been done to deduce the physio-thermal properties of the melt exiting this slope set-up. Modelling has been done for different mass influx velocities, temperature of pouring, different inclinations of the slope set-up and different modifications to the furnace. The results show some interesting observations and could provide quantitative estimates of the processing parameters.**

Keywords- Semisolid metal; superheat; primary grains; influx velocity.

I. INTRODUCTION

The solidification process, by which a liquid metal freezes, plays a critical role in determining the physical and mechanical properties of the as-cast alloy. These properties are extremely sensitive to the microstructure formed during solidification. Morphological development during casting solidification has been of tremendous interest for academic and industrial research [1]. Introduction of convection by mechanical or electromagnetic techniques during the initial stages of solidification affects the dendritic solidification of castings and ingots this in turn affect many processes such as solute redistribution, inter-dendritic fluid flow etc., that take place simultaneously within the semisolid region [2]. Today, SSM processing has established itself as a scientifically sound and commercially viable technology for the production of metallic components and metal matrix composites with high integrity, improved mechanical properties, complex shape, and tight dimensional control [3]. Semisolid metal processing is broadly classified into rheocasting and thixocasting though many other techniques like thixoforging, thixoforming, rheomolding, etc., are in use [4]. Among the several methods developed to produce non-dendritic feedstock, the most popular is the MHD process. In spite of its attributes, it has the limitation of non-uniform structures (rosettes, spheroids or globules). Thus interest is being shown in developing the process and making it technologically simple and viable. One such route suggested is processing the alloys in inclined controlled heated plates or cooling slopes [2,5-17]. The sloping plate can provide very strong under-cooling and cause a large quantity of nuclei to form, which creates fundamental conditions for fine spherical grain formation [18-19]. Various parameters such as melt superheat, slope length, angle, inclined plate material and mold material can affect the final microstructure.The studies did so far have been helpful to some extent in understanding the complicated microstructure evolution during the shear processing of the alloys. But detailed explanation of microstructural evolution during low shear inclined slope semisolid processing is still not available. However, the inclined slope process is attractive due to flexibility and the ease of processing that has been the limiting factor to great extent in the development of semisolid processing. The cooling system used in current study is of 2 meters in length inclined at an optimum angle to provide sufficient amount of shear force so as to avoid dendritic grains in the final structure. Two meters long channel is of mild steel on which a definite amount of alumina coating is applied , the thermal properties of alumina and mild steel is also taken into account to study the effect of sloped channel on the morphology of Al-Si melt when it passes through the channel. So the prime objective is semi-solid processing of aluminum alloys using the inclined slope method). Then optimizing the operating parameters of the setup such as angle of the slope, superheat, slope temperatures to ensure non-dendritic morphologies. Investigation of the effect of the operating parameters on the microstructural changes and mechanical properties of the as-cast samples through characterization techniques is to be done. The effect of modification on the structure and mechanical properties of low shear semisolid cast Al alloys has to be studied. Then the low shear technique with optimized working parameters has to be used for semi-solid processing of other ferrous and non-ferrous alloy systems.

II. EXPERIMENTAL

Inclined slope setup of about 2 meters length was used to study the effect of low shear during the semisolid processing of LM25 aluminum alloy. The slope is essentially a sillimanite tube enclosed in a mild steel casing. The sillimanite tube is assembled in two equal halves. The angle of inclination can be varied between 0º to 60º. The furnace slope is plugged with removable thermal insulation on both the ends to reduce heat losses during heating. The signal output devices (voltmeters, ammeters, and temperature indicators), mounted on a control panel were set to get the designed temperatures. K-type thermocouples were placed at several locations for continuous monitoring of the temperatures over the length of the slope. The schematic and the actual experiment setup are shown in **Fig. 1** and **Fig. 2** respectively. The higher end (entry end) temperature is maintained below the liquidus and the exit end near to the solidus of the alloy to be cast. The sillimanite tube is painted with Zirconia in its inner radius to prevent sticking of the liquid metal being poured through it. The paint is air dried well before pouring. The experimental setup also includes an induction furnace for melting, crucibles, pair of sand and graphite molds. The melting practice adopted for various alloy systems are discussed further in subsequent sections.

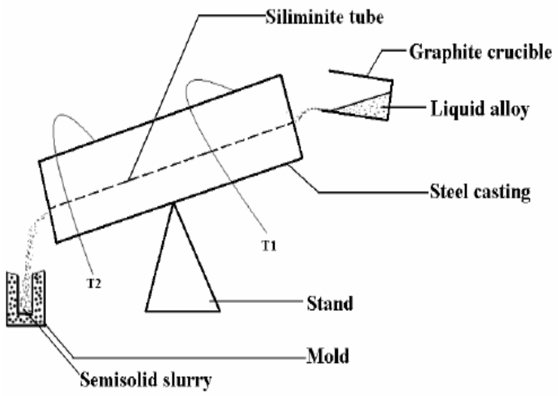

Fig.1 Schematic diagram of the inclined slope setup

Hypo-eutectic Al-Si alloy, commercially known as LM25 or A356 was chosen for the initial study. Presence of Si increases the fluidity of aluminium. Al-Si alloys are known for their good castability, high strength to weight ratio. They have a long freezing range, which enables better semi solid processing over the inclined slope. The chemical composition analyzed (with Optical Emission Spectroscopy) of the commercially available LM25 used for semisolid processing is given in the **Table 1**.

Material	*Element (major)*	*Al*	*Si*	*Mg*	*Fe*	*Cu*	*Mn*	*Ti*	*Zn*
Raw material	(Wt %)	92.00	7.01	0.40	0.20	0.08	0.04	0.12	0.1

Table1 Chemical composition of the LM25 alloy used

Fig 2 Actual experiment setup (inclined slope)

About 1500 gm of the LM25 alloy was placed in a graphite crucible and melted in an induction furnace, which was then de-oxidized with flux (hexa-chloro ethane) and then poured onto the inclined slope. The pouring temperature was around 898K (superheat of 10 K) and the temperature obtained at the lower or exit end of the furnace was measured with the help of a thermocouple. The semisolid slurry obtained at the lower end was cast in sand and graphite molds (10 mm diameter and 200 mm length). The sand and graphite molds were prepared and preheated for 3 hrs at about 393K. They are taken out from the furnace about 30 minutes prior to pouring. The slope furnace is allowed to soak and homogenize at the set temperatures for an hour before the experiment is commenced. In the present work, the alloy samples cast through the slope were analyzed and compared with the conventionally cast samples to investigate the effect of low shear. Study was done at 10º, 20º and 30º angle of inclinations to analyze the effect slope angle on the morphology and mechanical properties of the semisolid cast alloy. A set of sand and graphite mold samples were also cast conventionally (without pouring on to the inclined slope) for the comparative study of the low shear semisolid casting.

Alloy used	LM25
Freezing range	615-550 °C
Pouring temperature	625 °C
Temperature at pouring end of slope (T1)	580 °C
Temperature at exit end of slope (T2)	500 °C
Angle of inclination of the slope	10º, 20º, 30º
Length of the slope	2000 mm
Mold material	Sand and graphite

Table 2 Experimental conditions for rheocasting of LM25 alloy

III. MODELLING

CFD modelling of the inclined slope setup has been done using Pro-Cast-2008 platform to find out the temperature and velocity changes taking place inside the sillimanite tube. The slope modelled is made up of walls of Al_2O_3 and Air. The

curved surface is made of Al_2O_3 and the plane surface above the melt is considered to be made of a solid with properties of air in course of modelling, as the melt is covered with air on the plane surface. So this surface is called air wall.
The modelling has been done based on three different factors:

- Temperature at which the melt is poured in
- Angle of Inclination of slope setup
- Velocity of inlet of melt

The values of different factors involved in modelling:

Melt Temperature	625^0C	650^0C	670^0C
Angle of Inclination of slope	10^0	20^0	30^0
Velocity of melt at Inlet	0.25 m/s	0.01 m/s	0.00 m/s

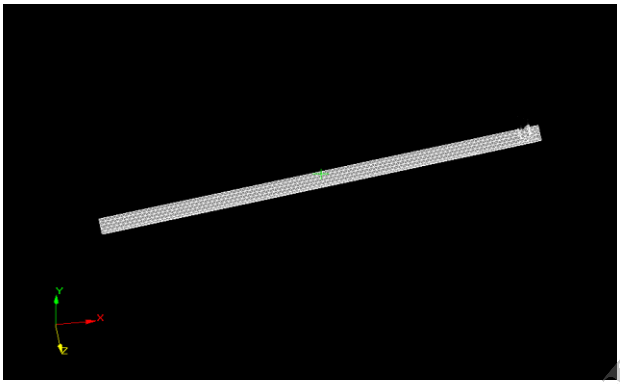

Fig 3 Mesh created for modelling

The physical and thermal properties of materials used in modeling of the slope setup are as:

Alumina:

Heat transfer coefficient	2.2345 w/m^2-K
External emissivity	0
Wall thickness	0.02m
Density	3950 kg/m^3
Cp	1131.537 J/Kg- K
Thermal Conductivity	8 w/m-K

Air wall:

Heat transfer coefficient	40 W/m^2-K
External emissivity	1
Wall thickness	0.02 m
Density	1.225 Kg/m^3
Cp	1006.43 J/Kg-K
Thermal Conductivity	0.0242 W/m-K

LM25:

Heat of Melting	532018J/Kg
Solidus Température	823K
Liquidus Température	888K
Liquid density	2390.6Kg/m^3
Specific Heat Capacity Cp(l)	1203.611J/Kg-K
Thermal Conductivity	151W/m-K
Viscosity	log(n/n0)=-0.7344+ 803.49/T n_o = 1mPas
	0.0015161Kg/m-s(870K)
	0.0014532Kg/m-s(898K)
	0.0013777Kg /m-s(920K)

In the present study mathematical model of solidification of alloy was carried out on the platform of ProCast 2008. ProCast is a commercial software based on finite element method. Numerical simulations of the alloy were conducted by solving the 3-D continuity, Navier–Stokes and energy equations. The mesh of the computational domain was selected after mesh independent test to carry out the simulation. This modelling is done in a step of equations:

The Energy equation: The enthalpy of the material is computed as the sum of the sensible enthalpy, *h*, and the latent heat ΔH.

$$H = h + \Delta H$$

Where,

$$h = h_{\mathrm{ref}} + \int_{T_{\mathrm{ref}}}^{T} c_p dT$$

And,

h_{ref} = reference enthalpy
T_{ref} = reference temperature
C_p = specific heat at constant pressure

The liquid fraction, β can be defined as

$\beta = 0$ if $T < T_{solidus}$
$\beta = 1$ if $T < T_{liquidus}$

So,

$$\beta = \frac{T - T_{\mathrm{solidus}}}{T_{\mathrm{liquidus}} - T_{\mathrm{solidus}}} \quad \text{if} \quad T_{\mathrm{solidus}} < T < T_{\mathrm{liquidus}}$$

The latent heat content can now be written in terms of the latent heat of the material, *L*:

$$\Delta H = \beta L$$

The latent heat content can vary between zero (for a solid) and *L* (for a liquid). For solidification/melting problems, the energy equation is written as

$$\frac{\partial}{\partial t}(\rho H) + \nabla \cdot (\rho \vec{v} H) = \nabla \cdot (k \nabla T) + S$$

Where,

S = Source term
H = Enthalpy
ρ = Density
υ = Fluid velocity

The Momentum Equation:

$$S = \frac{(1-\beta)^2}{(\beta^3 + \epsilon)} A_{\mathrm{mush}} (\vec{v} - \vec{v}_p)$$

β = liquid fraction
A_{mush} = mushy zone constant
V_p = pull velocity
ϵ = small number 0.001

The turbulence equation:

$$S = \frac{(1-\beta)^2}{(\beta^3+\epsilon)} A_{\text{mush}}\phi$$

Φ = Turbulence quantity

The Contact resistance equation

$$q = \frac{(T-T_w)}{(l/k + R_c(1-\beta))}$$

q = Wall heat flux
T = Fluid temperature
T_w = Wall temperature
R_c = Contact Resistance
k = Thermal conductivity of the fluid
l = Distance between the point of temperature T and T_w

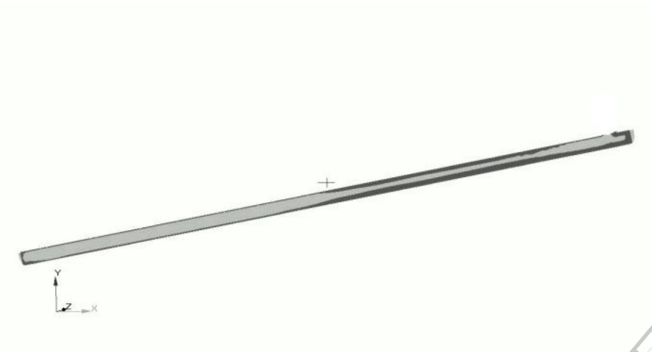

Fig 4 Melt temperature profile in the slope

RESULTS:

Semi-Solid processing of LM25

Comparative study between the semisolid cast and the samples cast without shear (no-shear) was done in terms of morphology and the results from this study has been compared with the results from the model. Also the effect of inclination of the slope on the characteristics of the semisolid cast structures has been analyzed and compared with the expected changes in the model. The detailed morphological analysis and the final model have been summarized in the following section.

Microstructural characterization

The micro-examination of semisolid cast and conventionally cast LM25 alloy shown in **Fig 5.1 to 5.4**, show a significant difference in terms of the morphology of the primary alpha particles cast in sand and graphite molds. The slow cooling associated with sand molds resulted in longer dendrites in the no-shear sand cast samples compared to the graphite mold samples. The tree like dendritic morphology was disintegrated to rosettes or near spheroids with the effect of shear acting on the primary alpha particles, when the liquid is flowed through the inclined slope. The second phase (eutectic) distribution in the semisolid cast samples shows better distribution around the primary phase in accordance with other authors. Also the primary phase particles are more spheroid in graphite cast samples due to faster cooling rates compared to the sand cast samples. **Fig 5.5(a) and 5.5(c)** show the improvement observed in the semisolid cast sand and graphite mold samples cast at different slope inclination i.e. 10º, 20º and 30º. The eutectic distribution is more uniform with the increase of angle of the slope which indicates globularization of the primary grains.

Fig 5.1 No shear LM25 cast in sand mold show in dendritic morphology of primary α-Al (bright phase)

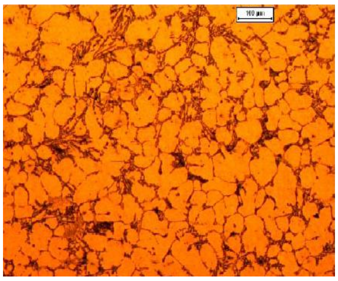

Fig 5.2 Low shear rheocast LM25 in sand mold with 20º slope, showing rosettes or sheroidal structures of the primary α-Al

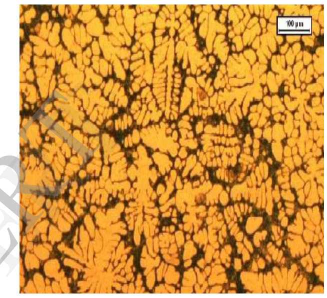

Fig 5.3 No-shear LM25 cast in graphite mold showing dendritic morphol

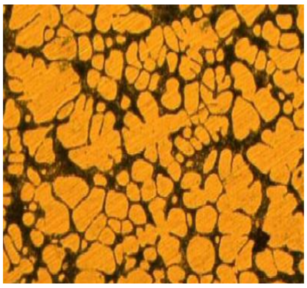

Fig 5.4 Low shear rheocast LM25 in graphite mold with 20º slope, showing rosettes or spheroidal structures of the primary α-Al

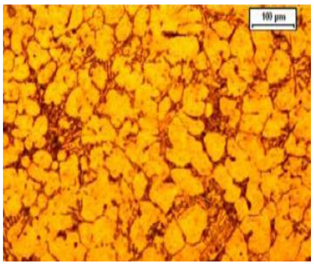

Fig5.5 (a) Semisolid cast LM25
at at 10º slope in sand mold

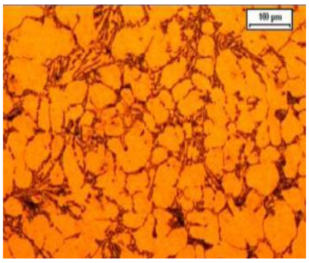

Fig 5.5 (b) Semisolid cast LM25
20º slope in sand mold

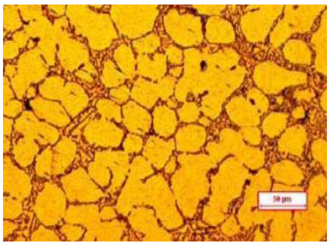

Fig 5.5 (c) Semisolid cast LM25 at 30º
slope in sand mold

Temperature profile of the melt

Plot of temperature profiles are shown below in Figure 6.1 , 6.2 and 6.3. The plot is for melt at 625^0 C, 650^0 C, 670^0 C at different slope angle i.e at 10^0 , 20^0 and 30^0.

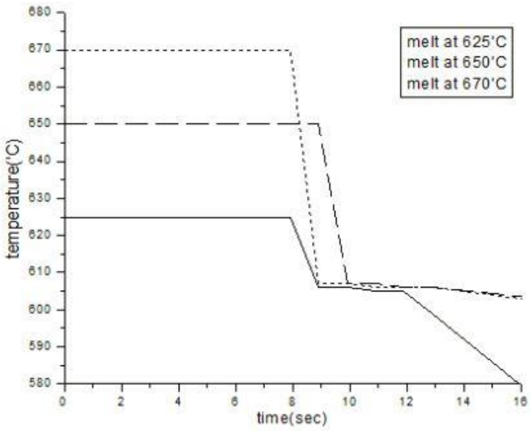

Fig.6.1: Solidification profile at slope angle 10^0

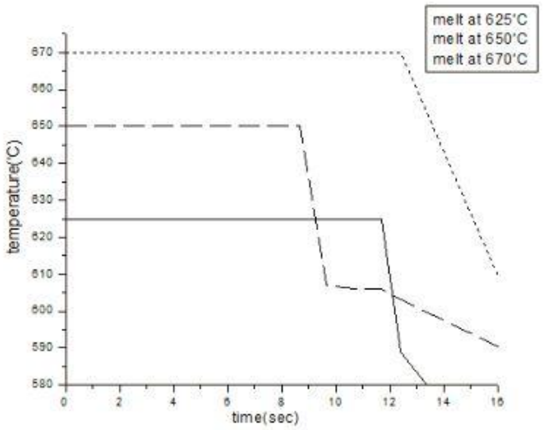

Fig.6.2: Solidification profile at slope angle 20^0

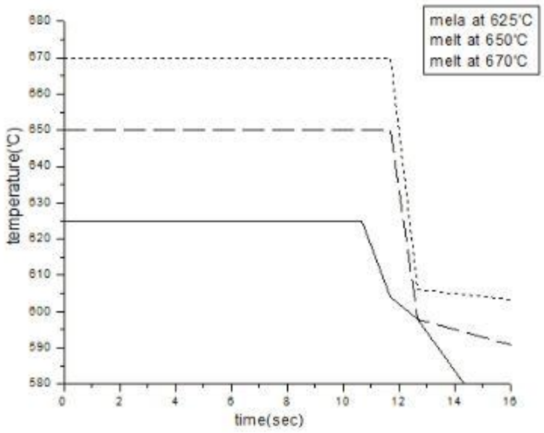

Fig.6.3: Solidification profile at slope angle 30^0

DISCUSSION

In the low shear setup, shearing of the dendrites takes place while the liquid flows through the inclined slope. When the liquid is poured on the slope, the temperature of the melt falls down due to the gradient between the liquid melt and the slope and the gradient between the two ends of the slope. The microstructural development when continuous shearing is applied during solidification can take place in two ways. In the first instant, solidification can start on the wall of the slope when the melt temperature falls below the solidus. The growing dendrites may fragment due to the shear force exerted by gravity and get carried away in the melt. However, it can be argued that due to low shear process, on cooling the melt below the solidification temperature, the nucleation of the primary phase does not necessarily start at the slope wall. It may also take place in the region above the slope surface, in the flowing melt. The melt temperature profile is generated assuming solid/liquid interface is at the melt temperature. The liquidus profile schematic is generated assuming solute build up in front of the solid–liquid interface. The dotted profiles are schematic assumed to take place when the melt is stirred. The undercooling would become low on continuous shearing as the heat and solute would be transported fast due to the convection induced due to shearing. Thus, the overall undercooling in front of the growing solid would be lowered. At low undercooling, the interface of the fragmented dendrites and the freshly nucleated particles would grow as cellular. Thus, we see the rosette or cells in the microstructure of the low shear cast samples. The liquid melt may also penetrate in between the cells due to convection and on further cooling or holding the melt and continuing shearing, the liquid pockets in between the cells freeze and the rosettes look like ellipsoids. But this tendency was not significantly seen for the sample processed in the inclined slope associated with low cooling rates. The above proposition is in conformity with the suggestions of earlier authors that the primary solid in rheocast alloys first grow as rosettes by cellular growth morphology, which is likely to be more, stable due to higher convection levels and low temperature gradients. Liquid entrapment may occur in between the growing Spheriodal or angular pre-quench solidifying phase quenched at low superheat.

Therefore while modeling it was crucial to obtain the semi solid slurry coming out of the slope such that the solid fraction has attained cellular or rosette morphology before it exits the slope. Accordingly the modeling parameters were chosen and the modeling runs performed. The modeling exercise shows that the inlet velocity of the melt is an often neglected but very crucial parameter that decides the outlet temperature of the slurry at the exit end. This is followed by the set temperatures at the two ends of the inclined slope processor. The modeling results have shown a significant correlation between the processing parameters and the resultant slurry solid contents quantitatively. When the modeling was carried out in modified furnace it gave better results for the production of semi solid slurry , it showed a greater decrease in temperature of the out-coming slurry and better equi-axed structures.

CONCLUSION

When the inlet velocity is low and the temperature of pouring is below 900K the melt solidifies while being in the slope setup irrespective of the slope angle used (from 10-30) . The inclination of the slope however plays a very pivotal role in changing the microstructures as it affects the shear force when all the other parameters are same. The preferential setup for optimum quantity of non-dendritic morphological structure to form in the present set up is at a slope angle of 20^0, pouring velocity of 0.01 m/sec and outlet temperature of 843K.

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