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Parametric Optimization for Producing Semi-Solid A383 Alloy using Cooling Slope Casting Process

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Abstract

Cooling slope casting is a simple technique to produce semi-solid feedstock with a non-dendritic structure. The cooling slope technique depends on various parameters like slope length, slope angle, pouring temperature etc, that has been investigated in the present study. This work presents an extensive study to comprehend the combined effect of slope angle, slope length, pouring temperature, on hardness and microstructure of A383 alloy. Response Surface Methodology was adopted for design of experiments with varying process parameters i.e. slope angle between 15° to 60°, slope length between 400 to 700 mm, and pouring temperature between 560 ºC to 600 ºC. The response factor hardness was analysed using ANOVA to understand the effect of input parameters and their interactions. The hardness was found to be increasing with increased slope length and pouring temperature; and decreased with slope angle. The empirical relation for response with parameters were established using the regression analysis and are incorporated in an optimization model. The optimum hardness with non-dendritic structure of A383 alloy was obtained at 27° slope angle, 596.5 mm slope length and 596 ºC pouring temperature. The results were successfully verified by confirmation experiment, which shows around 2% deviation from the predicted hardness (87.11 BHN).

Keywords: Design of experiment, ANOVA, Response surface methodology, Non-dendritic microstructure, Hardness

1. Introduction

Semi-solid processing is the processing of non-dendritic material between its liquids and solidus temperatures. In recent years researchers have started exploring and understanding the mechanisms and phenomena involved in this process [1-2]. The inherent properties of semi-solid materials at the semi-solid processing temperature such as lower heat content, relatively higher viscosity (comparable to liquids) and low flow stresses, enables the semi-solid process to demonstrate distinct advantages over fully liquid and/or fully solid-state processes. In semi-solid processing two basic phenomena, namely Rheology and Thixotropic, plays a major role [3-6]. In Rheology the apparent viscosity of a material in the liquid state varies with change in shear rate. This enables the liquid like slurry to be processed even at sufficiently high solid contents [7]. Thixotropic, on the other hand, is the ability of a material to regain the liquid like slurry state from a solid state when shear is applied. The cooling slope technique is quite simple but very effective to produce semi solid slurry with a non-dendritic microstructure [8]. The microstructure obtain by the cooling slope casting depends on the different parameters like slope angle, slope length, slope vibration, pouring temperature and cooling rate etc. [9-10]. There are several dependent parameters of cooling slope technique which effect the final microstructure [11-13]. There is a need to investigate the effect of these parameters for better understanding of this process. P. Das et al. studied the impact of parameters using the Taguchi design of experiments methodology and reported that slope length has maximum impact on the degree of sphericity [13]. D. Kumar et al. also used Taguchi analysis for parametric optimization of cooling slope for producing composite of A356-5TiB_2 and observed the optimum values of pouring temperature, slope angle and slope length as 640˚C, 60˚, 300 mm, respectively [14]. G. Kumar et al. optimized the processing parameters of cooling slope of ADC12 alloy and reported the optimum values with better mechanical properties are pouring temperature, slope length and slope angle were 585˚C, 500 mm, 45^0 respectively [15]. One another study showed optimum values as pouring temperature of 660 °C, cooling length of 360 mm, slope angle of 48°, and isothermal holding time of 9 min [16].

It was observed that though the cooling slope process offers very simple equipment setup to produce non dendritic structure of an alloy, however the growth of non-dendrite structure and corresponding mechanical properties of cast part significantly depended on various operating parameters like slope length, slope angle, pouring temperature and many more. Nevertheless, the interdependency of parameters is also very critical factor affecting the process efficiency. In general, there seems to be very limited work reported to understand the interaction of these parameters on casting quality. Thus, there was a need for understanding the combined effect of critical process parameters on microstructure and mechanical properties of slope casted part. A systematic parametric optimization was taken up in this work for the better understanding and application of the slope casting process. The objective of this work was to optimize the cooling slope casting process parameters for obtaining non dendritic microstructure with high hardness. Selection of process variables and its varying ranges were incorporated with the design of experiments, and analysis of variance was used to understand the relationship between response and input parameters. A eutectic alloy A383 alloy with 12 wt% Si with dendritic microstructure, and which possess high strength, high thermal stability, and low ductility (about 1%), was used for this study.

2. Experimental Details

2.1. Theme of Experiments

The motivation of this study is to develop Aluminium alloy A383 casting using cooling slope and to optimize the processing parameters to achieve the non-dendritic structure with high hardness. An industrial grade A383 alloy ingot was used for this study. The liquidus and solidus temperature of A383 alloy are 549°C and 516°C respectively. The chemical composition of the material was analysed using the OES (Optical Emission Spectroscopy), and shown in Table 1.

Table 1.
Chemical Composition of A383 (wt. %)

Element	wt. (%)	Element	wt (%)	Element	wt. (%)	Element	wt. (%)
Si	10.7655	Mn	0.160967	Fe	0.7935	Cu	1.8339
Mg	0.116233	Sn	0.0359	Zn	1.4136	Cr	0.0101
Ti	0.0436	Ni	0.0489	Pb	0.0507	Be	0.000133
Sr	0.001267	Zr	0.036733	Ca	0.003067	Al	84.82753

2.2. Cooling Slope Casting Set-up

The in-house developed Cooling Slope Casting set-up at Foundry Technology Department, National Institute of Advanced Manufacturing Technology, Ranchi, provides flexibility to vary the angle of the cooling slope, the pouring length and cooling. The cooling slope set-up is made of mild steel and used for semi-solid slurry generation. A semicircular hollow mild steel channel of 1m length, 100mm internal diameter, and 150mm external diameter allows the melt to flow through it. The water flows underneath in a counter direction to melt flow act as a coolant. The flow rate of water ~ 3.50 l/min at room temperature was measured with a rotameter. The coating of boron nitride was used on the surface of the slope channel, which avoids the adhesion of melt to the cooling slope channel and allow resistance-free flow. Fig. 1(a) and Fig. 1(b) shows the CAD model and developed set-up of the cooling slope casting facility, respectively. The k-type thermocouple with data acquisition system was used to monitor the temperature of the melt along the slope channel. The solidification starts along the surface of the slope channel and subsequent solidification happens inside the mould. The semi-solid melt of A383 was poured in a trapezoidal-shaped steel metallic mold with bottom width of 51 mm, a top width of 70 mm and a height of 51 mm.

2.3. Multivariate Design of experiments

2.3.1 Preliminary Experiments:

To study the effect of varying process parameters in slope casting, the casting experiments were designed using Response surface based design of experiments (DOE). In the present study the slope length, pouring temperature and slope angle were selected as the input processing variables. All the parameters and their ranges in which they are varied, are shown in Table 2. The ranges were selected by considering the information variables in the literature and based on the few preliminary laboratory test trails. The effect of varying process parameters on the hardness and microstructure of the cooling slope were considered as the response variable for this investigation.

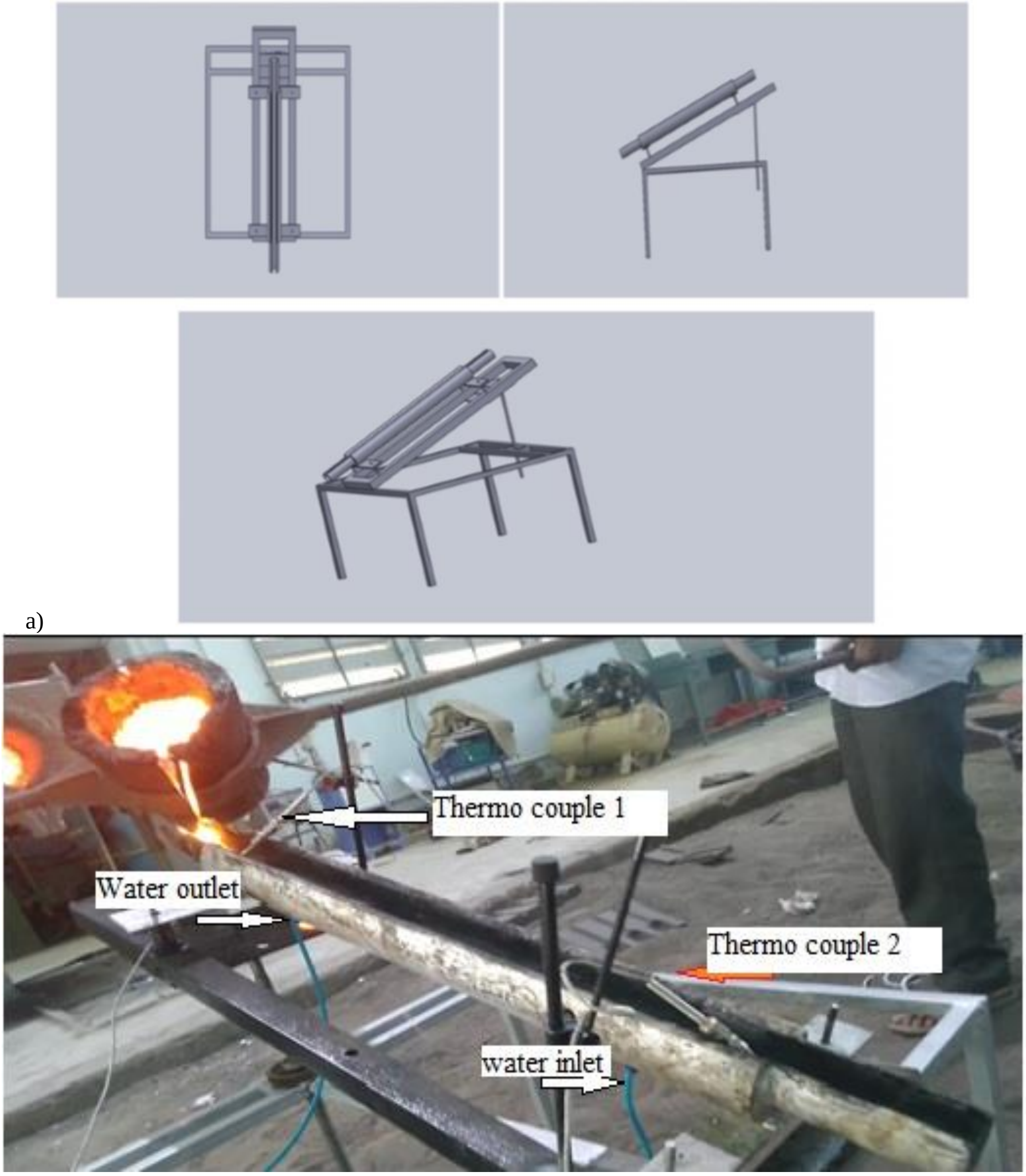

Fig. 1. (a) 3-D model of cooling slope (b) Experimental set-up

Table 2.
Cooling Slope Process Variables with range

Parameters	Range
Slope angle (A)	15 to 60 degree
Slope length (L)	400-700 mm
Pouring temperature (T)	560-600 °C

2.3.2 Response Surface Methodology (RSM)

The response surface methodology based central composite design was used for planning the experiments. The central composite design for experiment plan is shown in Table 3.

2.4. Melting and Pouring

Melting of A383 ingots in an induction furnace at 600 °C. After melting, degassing was performed using benzyl chloride tablet. The melt is poured into a holding furnace, where the required temperature according to the design of experiment, was maintained before pouring. After attaining the required temperature, the cooling slope experimental setup was adjusted to required slope angle and slope length as per Table 3. Once after setting up all the process parameters the pouring was carried out into a metallic mould for each experimental run.

2.5. Characterization

For the examination of microstructure and hardness, samples of size 20 mm diameter and 15 mm thickness were prepared using wire electric discharge machining (EDM). The etching of the samples were performed by using Keller's (95 ml H_2O, 2.5 mL HNO_3, 1.5 ml HCl, 1.0 ml HF) for 8-10 sec. The microstructure was obtained by using the optical spectroscopy of model (Olympus GX5). The Brinell hardness test was carried out using the ball of diameter 10mm with load of 250 kPa.

Table 3.
Layout of Experiments

Standard Run no.	Run Order	Input Variables		
		A slope angle (º)	L slope length (mm)	T Pouring Temperature (°C)
10	1	50	500	580
6	2	45	400	590
18	3	37	500	580
5	4	30	400	590
3	5	30	600	570
16	6	37.50	500	580
13	7	37.50	500	563
19	8	37.50	500	580
8	9	45	600	590
14	10	37.50	500	596
20	11	37.50	500	580
2	12	45.00	400	570
12	13	37.50	668	580
17	14	37.50	500	580
11	15	37.50	331	580
7	16	30	600	590
15	17	37.50	500	580
4	18	45	600	570
9	19	24	500	580
1	20	30	400	570

3. Results and Discussion

3.1. Hardness

The Brinell hardness of all twenty experiments were measured at three locations and average of 3 readings are shown in Table 4. The hardness of sample without cooling slope (conventional Casting) also measured and found to be 55 BHN.

3.2. Mathematical Modelling

The relationship between hardness and input variables can be expressed as Equation 1.

$$H = f\,(A\,,L\,,T) \qquad (1)$$

Equation (1) shows that response variable H (Hardness), is the function of slope angle (A), slope length (L) and pouting temperature. For the present case the equation 1 shows the nonlinear relationship.

Where H is representing response values for n factors. To represent the response surface the second-order regression equation was used and given as Equation (2)

$$H = a_0 + \sum_{i=1}^{n} a_i x_i + \sum_{i,j=1}^{n} a_{ij} x_i x_j + \sum_{i=1}^{n} a_{ii} x_i^2 \tag{2}$$

Where a0 is free term of equation and $a_1, a_2 \ldots\ldots a_n$ are the linear term, $a_{11}, a_{22} \ldots\ldots a_{nn}$ are the Second-order term and $a_{12}, a_{13} \ldots\ldots a_{n-1}$, n are the interaction terms. For three input variables such as pouring temperature, slope angle and slope length the selected polynomial can also be expressed as Eq 3

$$H = a_0 + a_1 A + a_2 L + a_3 T + a_{12} AL + a_{23} LT + a_{13} AT + a_{11} A^2 + a_{22} L^2 + a_{33} T^2 \tag{3}$$

Equation 3 gives the values of the coefficients of the polynomial that have been calculated by the multiple regression method. The Minitab version 19 software has been used to calculate the coefficient values. The goodness of fit of the model was evaluated by the coefficient of determination (R^2) and its statistical significance was checked by the F-test.

Table 4.
Experimental results

Standard Run no.	Run Order	Factors			Average Hardness
		slope angle (°)	Slope length (mm)	Pouring Temperature (°C)	(BHN)
10	1	50	500	580	64.2
6	2	45	400	590	73.3
18	3	37.50	500	580	79.6
5	4	30	400	590	80.2
3	5	30	600	570	72.5
16	6	37.50	500	580	77.9
13	7	37.50	500	563	70.0
19	8	37.50	500	580	80.0
8	9	45	600	590	77.3
14	10	37.50	500	596	82.0
20	11	37.50	500	580	79.6
2	12	45	400	570	71.5
12	13	37.50	668	580	78.4
17	14	37.50	500	580	79.0
11	15	37.50	331	580	73.0
7	16	30	600	590	83.2
15	17	37.50	500	580	79.3
4	18	45	600	570	72.5
9	19	24	500	580	81.0
1	20	30	400	570	71.0

Table 5.
ANOVA Analysis Matrix

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	414.077	46.009	9.38	0.001
Linear	3	302.005	100.668	20.53	0.000
Slope Angle	1	102.348	102.348	20.87	0.001
Slope Length	1	24.060	24.060	4.91	0.051
Pouring Temperature	1	173.830	173.830	35.45	0.000
Square	3	85.016	28.339	5.78	0.015
Slope Angle*Slope Angle	1	67.652	67.652	13.80	0.004
Slope Length*Slope Length	1	17.751	17.751	3.62	0.086
Pouring Temperature*Pouring Temperature	1	13.115	13.115	2.67	0.133
2-Way Interaction	3	24.674	8.225	1.68	0.234
Slope Angle*Slope Length	1	0.031	0.031	0.01	0.938
Slope Angle*Pouring Temperature	1	22.111	22.111	4.51	0.060
Slope Length*Pouring Temperature	1	2.531	2.531	0.52	0.489
Error	10	49.040	4.904		
Lack-of-Fit	5	46.347	9.269	17.21	0.004
Pure Error	5	2.693	0.539		
Total	19	463.117			
Model Summary:	R-sq: 91.41%;	R-sq(adj) : 86.77%;	R-sq(pred): 79.65%		

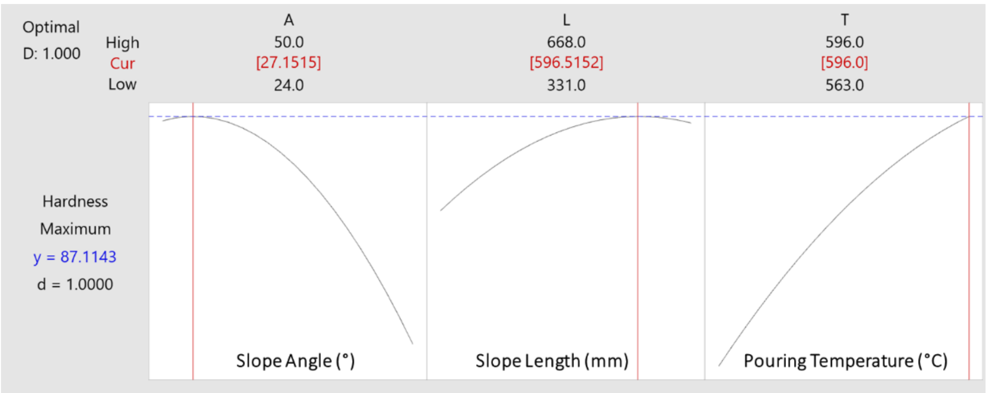

Fig. 2. Optimal conditions for maximum hardness

3.3. ANOVA Analysis

Analysis was carried out on the responses of each experiments using Minitab V19 and results are shown in Table 5. The ANOVA determines the stability and the significance of the predictive model. The model possesses a confidence interval (CI) of 95% ($P<0.05$). The F-value of model is observed as 9.38 which implies that model is significant, there is chance of 0.1% that F-value of this magnitude could be error due to noise. The R^2 value indicates the stability of the model fit, whereas the adjusted R^2 value shows the significance of the predictor variable as shown in table 5. The model summary shows that the value of the coefficients of determination R^2 and adjusted R^2 are 91.41 and 86.77%, respectively, which represents the high significance of the model. The quadratic regression coefficients obtained by employing a least squares method technique to predict quadratic polynomial models for Hardness is given as Equation (4). For Hardness, the linear term, and the quadratic terms with interaction terms of A, L, and T were observed significant ($P<0.05$). The empirical models in terms of actual factors for hardness is shown below:

*Hardness = - 3813 + 15.15 A - 0.21 L + 12.29 T- 0.037 A*A - 0.0001 L*L - 0.0098 T*T + 0.00008A*L - 0.02 L*T* (4)

3.4. Optimal Process Condition

The objective is to predict the optimal values of processing condition for manufacturing A383 aluminium alloy casting using cooling slope technique. The optimization was performed using RSM method. The constraint optimization formulation considers the maximization of Hardness as the objective function. The constraints are derived from the relationship between input variables with hardness values as per the results and the predicated optimized parameters are shown in Fig. 2. It can be observed that the slope angle of 27.15°, slope length of 596 mm and pouring temperature of 596 °C. The optimum parameter conditions used for the predict the hardness and found to be 87.114 BHN.

3.5. Analysis of Parametric Integrations:

The combined effect of input parameters on the response variable can be visualized using interactive plots. Fig. 3 shows the 2D counter plots, which indicates the correlation by examining discrete counters of the expected response variable. Fig. 3 (a) shows the contour plot of hardness with respect to pouring temperature and slope length. From the plot it can be observed

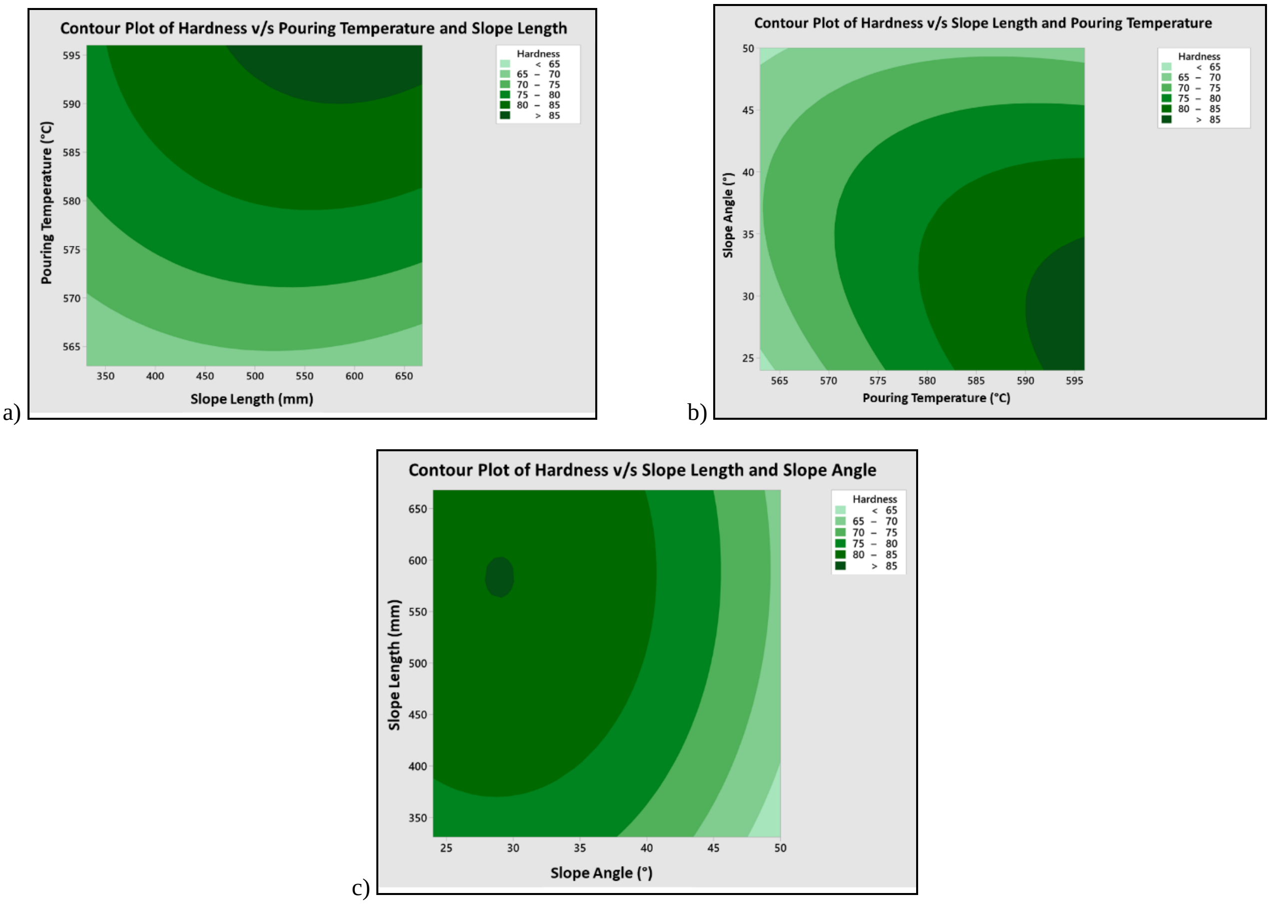

Fig. 3. Interaction plot of hardness with cooling slope process parameters

that the region with slope length of 500mm to 600mm with pouring temperature of 590 - 595 °C gives higher hardness. Fig. 3(b) shows the counter plot of hardness w.r.t. slope angle and pouring temperature. It can be observed that pouring temperature with range of 590 - 595 °C and slope angle of 25° - 35° is showing maximum hardness. Again, the Fig. 3 (c) shows the counter plot of hardness w.r.t slope length and slope angle. It can be observed that at the slope length between 500 - 600 mm and slope angle around 30 degree, shows the maximum hardness. From all the interaction plots, it was reflected that higher harness can be achieved by using higher slope length and pouring temperature, whereas increasing the slope angle had adverse effect on hardness value. This is because, with an increase in slope length the contact time between slope channel surface and melt increase, which lead to increase in shearing effect. Whereas an increase in slope angle decreases the contact time of melt and cooling slope surface which lead to reducing shearing effect.

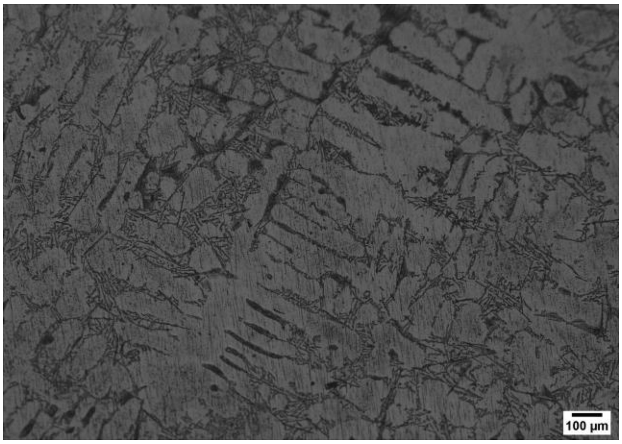

Fig. 4. Microstructure of A383 alloy produced by conventional gravity casting

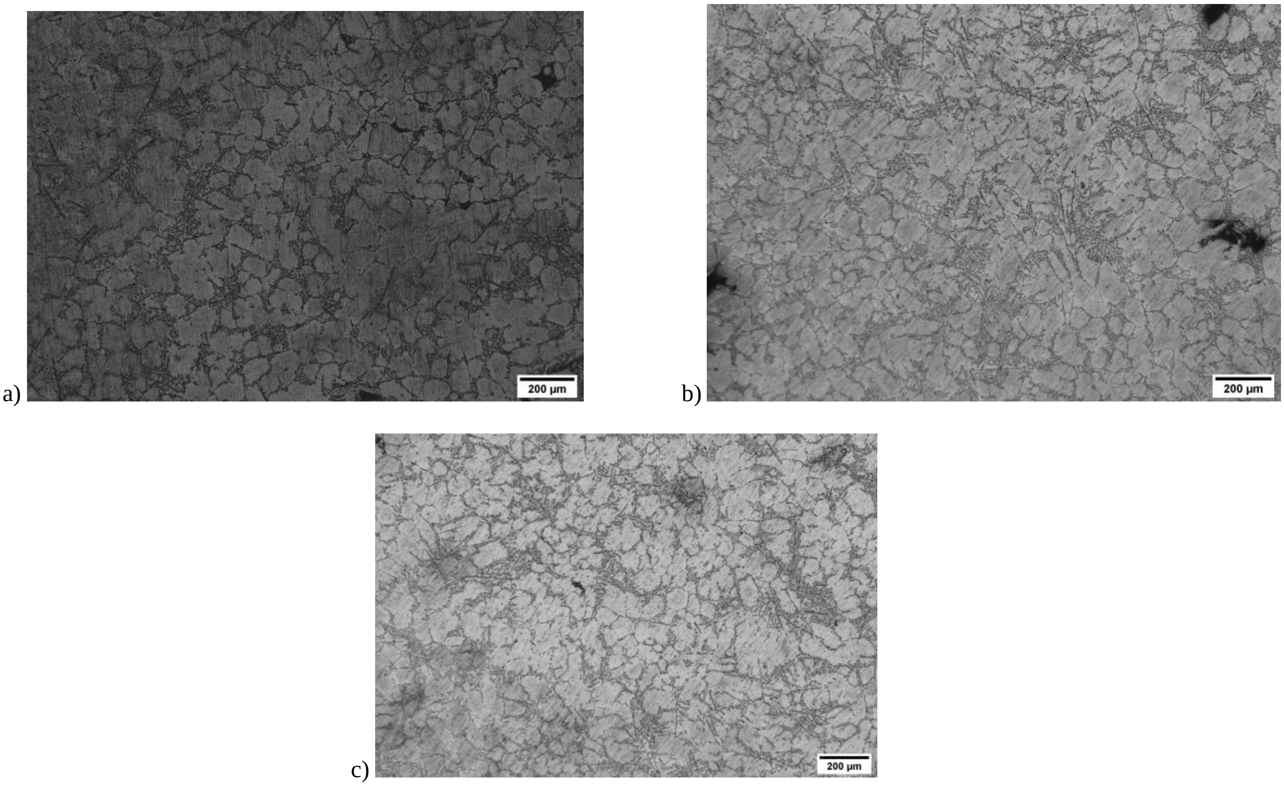

Fig. 5. Microstructure of cooling slope samples prepared using constant pouring temperature (580 ºC) and slope length (500 mm) & slope angle (a) 30º (b) 37.5º (c) 45º

3.6. Microstructure Analysis

The Fig. 4 shows the optical microstructure of the A383 alloy which was casted using conventional route. The microstructure shows dendritic morphology of primary aluminum along with needle shaped eutectic mixture of Al-Si which are the cause of the lower mechanical properties of the melt. To find the effect of slope angle on microstructure of selected alloy, three experiments carried out with constant temperature of 580°C, Slope length of 500 mm and with different angles varies 30 degree, 37.5 degree, and 45 degree. The microstructures of three experiments shown in Fig. 5 (a), (b), (c). From the Fig. 5. It has been observed that all three experiments shows change in morphology with the non-dendritic structure (rosette form) of a primary α-aluminum from the dendritic structure (as Cast condition) as shown in Fig.4. The increase in pouring angle up to 37.5 degree from 30 degree shows better change morphology change with rosette and near globular structure, this due to increase angle increases the shearing effect, where increase in angle further up to 45 degree shows same as lower angle 30 degree effect this is due to higher angle than optimum decrease the contact time of melt to slope channel surface, there by lesser effect of shear and low heat extraction on melt.

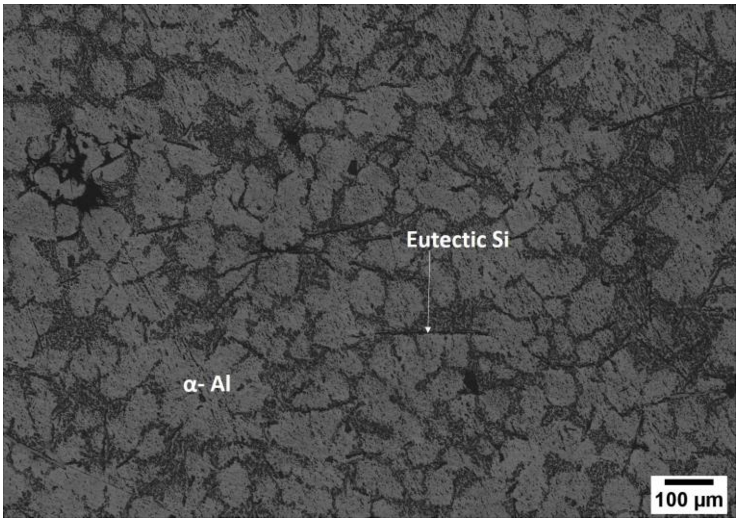

Fig. 6. Optical Micrograph of cooling slope samples at optimum process parameters (Slope Angle 27 degree, Slope Length 596.5 mm, Pouring Temperature of 596 °C

Table 6.
Comparison between actual v/s predicted

	Optimal Condition SL=600 mm, PT= 596 °C, SA = 27 degree	
	Predicted	Experimental
Hardness (BHN)	87.11	85.45

3.7. Model Validation Experiment

For validating the optimal predicted values, a casting was produced using optimal conditions obtained using model of pouring temperature, slope length and slope angle as 596 °C, 600mm and 27 degree respectively. The sample for microstructure and hardness measurement were prepared and examined. The predicted result from optimization model and the actual measured value is shown in Table 6. The deviation between predicted and actual hardness are only around 2% and thus confirm the significance of the model. The confirmation experiment test was performed using the predicted optimum parameters which are obtained from the ANOVA analysis. The optical micrograph of the confirmatory experiment is shown in Fig. 6 that also reveals the near globular structure of α-aluminum (non– dendritic structure).

4. Conclusions

In this work non dendritic structure of A383 alloy was successfully produced using cooling slope casting process. The castings were produced by varying pouring temperature, slope length and slope angle between 15°-60°, 400-700 mm, 560 ºC-600 ºC respectively. The response surface methodology is adopted to understand the effect of respective parameters and their interaction on casting hardness. The hardness of the alloy was found to be increasing with increasing slope length and pouring temperature but decreased with increasing the slope angle. A predictive regression model was developed for predicting the hardness with change in input process parameters combination. The optimal hardness was obtained at 596 °C pouring temperature, 596.5 mm slope length and 27° slope angle. The model was implemented for predicting the hardness and conducting the experiments, which shows good correlation between actual and predicted hardness (within 2%). The micrograph reveals the dendritic morphology of primary aluminum along with needle shaped eutectic mixture of Al-Si. The interaction plots confirms that the increase in the slope length and pouring temperature shows better effect of slope process and increase in angle decrease the effect of slope. The significance of the shear forces mainly depends on the selected input parameters. The study will help in deciding the optimal parameters for producing non dendritic structure of A383 alloy.

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