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Optimization of Casting Conditions for Semi-Solid A356 Aluminum Alloy

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ABSTRACT

RSM and DOEs approach were used to optimize parameters for hypoeutectic A356 Alloy. Statistical analysis of variance (ANOVA) was adopted to identify the effects of process parameters on the performance characteristics in the inclined plate casting process of semisolid A356 alloy which are developed using the Response surface methodology (RSM) to explain the influences of two processing parameters (tilting angle and cooling length) on the performance characteristics of the Mean Particle Size (MPS) of α-Al solid phase and to obtain optimal level of the process parameters. The residuals for the particle size were found to be of significant effect on the response and the predicted regression model has extracted all available information from the experimental data. By applying regression analysis, a mathematical predictive model of the particle size was developed as a function of the inclined plate casting process parameters. In this study, the DOEs results indicated that the optimum setting was approx. (44) degree tilt angle and (42) cm cooling length with particle size (30.5) µm.

1. Introduction

The DOEs is useful in engineering design activities in which new products are developed and existing ones improved. To optimize a manufacturing process, the trial and error method is used to identify the best parameters to manufacture a quality product. However, this method demands extensive experimental work and, it results in a great waste of time and money. Thus, design of experiments appears to be an important tool for continuous and rapid improvements in quality. These experimental methods may be employed to solve problems related to a manufacturing process, and to understand the influence of various factors on the final quality of a given product [1, 2].

The DOEs is an experimental technique that helps to investigate the best combinations of process parameters, changing quantities, levels and combinations in order to obtain results statically reliable. It is a systematic route that may be followed so as to find solutions to industrial process problems with greater objectivity by means of experimental and statistical techniques. Furthermore, DOEs method is utilized to obtain an optimal parameter setting from a regression equation relating to the desired outputs with the significant factors

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identified by the Analysis of Variance (ANOVA) [2, 3].

Inclined plate casting process is recently considered to be a viable alternative in the production of cast Al-Si alloys. This process presents a solution to the problems associated with both conventional casting and metal working processes due to its capability to use temperatures lower than those used in casting and a less energy used in conventional processes. Besides, both of the primary α-Al and eutectic phases are refined and modified and uniformly distributed, this attributed to casting conditions in inclined plate casting process. This technique is used by pouring the molten metal over an inclined plate or tube, so that the nucleation together with mixing occur during the flow of the liquid, thereby producing a fine and less dendritic primary microstructure [4, 5].

Semi-solid processing of Al-Si alloys using cooling plate casting method was investigated and reported in the literature. Haga and Suzuki [6], assessed the factors which affect the spheroidicity of α-Al particles in ingots attained by casting Aluminum alloys using a cooling slope (mild steel) at a range of temperatures of 640 to 680°C. They deduced that the cooling rate strongly affect the globularization of primary α-Al particles and obtained a small particle size. Motegi, et al. [7], implemented experiments using a water cooled copper slope, with tilt angles of 40, 60 and 80°, and cooling lengths of 80, 160, 200 and 240 mm. They poured an Al-1.63%Si- 0.54%Mg alloy at a range of temperatures of 656 to 696°C. They found that the cooling slope is suitable in producing many crystal seeds. The optimum condition was at tilt angle 60° and 656°C pouring temperature. It was found that if the cooling length is too long, the slurry could form solid shell on the slope plate. Instead, if it is too short, nucleation sites may be inadequate. They found indication that rise in pouring temperature resulted in a larger particle size. Sung-Yong Shim, et al. [8] analyzed the effect of cooling plate parameters on microstructure of Al-Zn-Mg alloy via analysis of variance and the Taguchi design method. They showed that the pouring temperature is the main effect factor in the cooling plate method. To get SSM billets with a satisfactory level of reproducibility, the pouring temperature was set to a superheat (ΔT) < 20°C to encourage the creation of separate crystals on the cooling plate and support crystal growth in the mold. Ying Zhang, et al. [9] studied the evolution of microstructure of semi-solid magnesium alloy using cooling slope and mechanical stirring under different technological parameters. The results showed that the technological parameters have significant affect on the microstructure of the semi-solid magnesium slurry. They showed that the optimum parameters of cooling slope method were: pouring temperature 630°C, tilt angle of slope 60° and cooling length of slope 0.57m.

Also, this method was stated as a suitable technique for high melting metals, such as gray cast iron and ductile iron, where an improved structure of fine globular primary particles with a high degree of sphericity and phases clearly distinct from adjacent one was obtained [4-13]. The aim of this work is to optimize effect of inclined plate casting parameters (tilting angle and cooling length) on the α-Al solid microstructure of an A356 aluminum alloy and obtain results of optimal parameters.

2. Methodology

The experimental results of Semi-Solid A356 aluminum alloy which produced by inclined plate casting process and conducted by Farshid Taghavi and Ali Ghassemi [13] were considered in this study. The chemical composition of A356 alloy is given in Table 1. J-Image software was employed to calculate the grain size of α-Al particles. The grain size (d_{eq}) of α-Al phase in all samples is calculated by the following eq. (1) [15]:

$$\text{deq} = \sqrt{\frac{4A}{\pi}} \quad (1)$$

where (d_{eq}) is the grain size of α-Al phase and (A) the area of α-Al phase. The mean particle size (MPS) of α-Al phase was chosen as the performance evaluation of microstructure for this study.

2.1. Design of Experiments (DOEs)

To identify an optimal setting for minimizing grain size of α-Al phase of A356 alloy, an experimental design was created, and it employed factorial arrangements, that is, the design comprised all possible combinations of factors considering different levels. Table 2 shows both uncoded and actual values of the processing parameters and their ranges. And, Table 3 lists the different levels in the form of actual values for each parameter investigated. The following steps are followed for process optimization:

1. Defining the independent input variables and desired responses with the design constraints.
2. Calculating the statistical analysis of variance (ANOVA) for the independent input variables and finding which parameter affects significantly the desired response.
3. Performing the regression analysis with the quadratic model of RSM, the relationship between the

inclined plate casting process parameters and targeted output of grain size.

4. Indicating the targeted output of grain size, i.e., desirability function. Minimizing grain size, in this work.
5. Optimization Plot.

2.2. Response Surface Modeling (RSM)

In this work, a statistical model is proposed to model the effects of the inclined plate process parameters on the performance characteristics of the MPS of α-Al solid phase. The mean particle size MPS of α-Al solid phase was chosen as the performance evaluation of A356 aluminum alloy microstructure.

Table 1. Chemical composition of A356 aluminum alloy [13].

Al (%)	Si (%)	Mg (%)	Fe (%)	Cu (%)	Mn(%)	Zn (%)	Other elements
92.47	6.58	0.326	0.290	0.199	0.00150	0.00470	< 0.1

Table 2. Control factors and their ranges

Factor	Units	Ranges
A: Tilt angle	(degree)	30-60
B: Cooling length	(cm)	20-60

Table 3. Control factors for each experimental combination

Experiment No.	Tilt angle (degree)	Cooling length (cm)
1	30	20
2	30	30
3	30	40
4	30	50
5	30	60
6	40	20
7	40	30
8	40	40
9	40	50
10	40	60
11	50	20
12	50	30
13	50	40
14	50	50
15	50	60
16	60	20
17	60	30
18	60	40
19	60	50
20	60	60

The microstructure of an A356 aluminum alloy which produced via Inclined plate at 40cm cooling length and different tilt angles, is shown in Fig. 1. The mathematical model exploits the RSM to express the influences of processing parameters. The RSM is a statistical modeling approach for determining the relationship between various process parameters and responses with the various desired criteria, and further searching the significance of these process parameters on the coupled responses. It employs the sequential experimentation strategy for building the empirical model. Therefore, RSM is a collection of mathematical and statistical procedures that are useful for the modeling and analysis of problems; the response is affected by several parameters, and the main objective is to optimize this response. Consequently, the RSM is utilized to describe and identify, with a great accuracy, the influence of the interactions between different parameters on the response when they are varied simultaneously. In the RSM, the quantitative form of the relationship between the desired response and independent input parameters can be represented as follows eq. (2) [14]:

$$Y = f(X_1, X_2) \quad (2)$$

where Y is the desired response and (f) is the response function (or response surface). In the procedure of analysis, the approximation of Y was proposed by using the fitted second-order polynomial regression model, which is called the quadratic model. The quadratic model can be written as follows eq. (3) [14]:

$$Y = a_0 + \sum_{i=1}^{n} a_i X_1 + \sum_{i=1}^{n} a_{ii} X_1^2 + \sum_{i<j}^{n} a_{ij} X_1 X_2 \quad (3)$$

where a_0 is constant, a_i, a_{ii} and, a_{ij} represent the coefficients of linear, quadratic and cross product terms, respectively. X_1 (Tilt angle) and X_2 (Cooling length) shows the uncoded variables corresponding to the studied controlled parameters.

The MPS of α-Al solid phase, indicated as Y, was analyzed as response. This model which uses the quadratic model of (f) in this study aims to not only investigate the response over the entire factor space, but also locate the region of desired target, where the response approaches to its optimum.

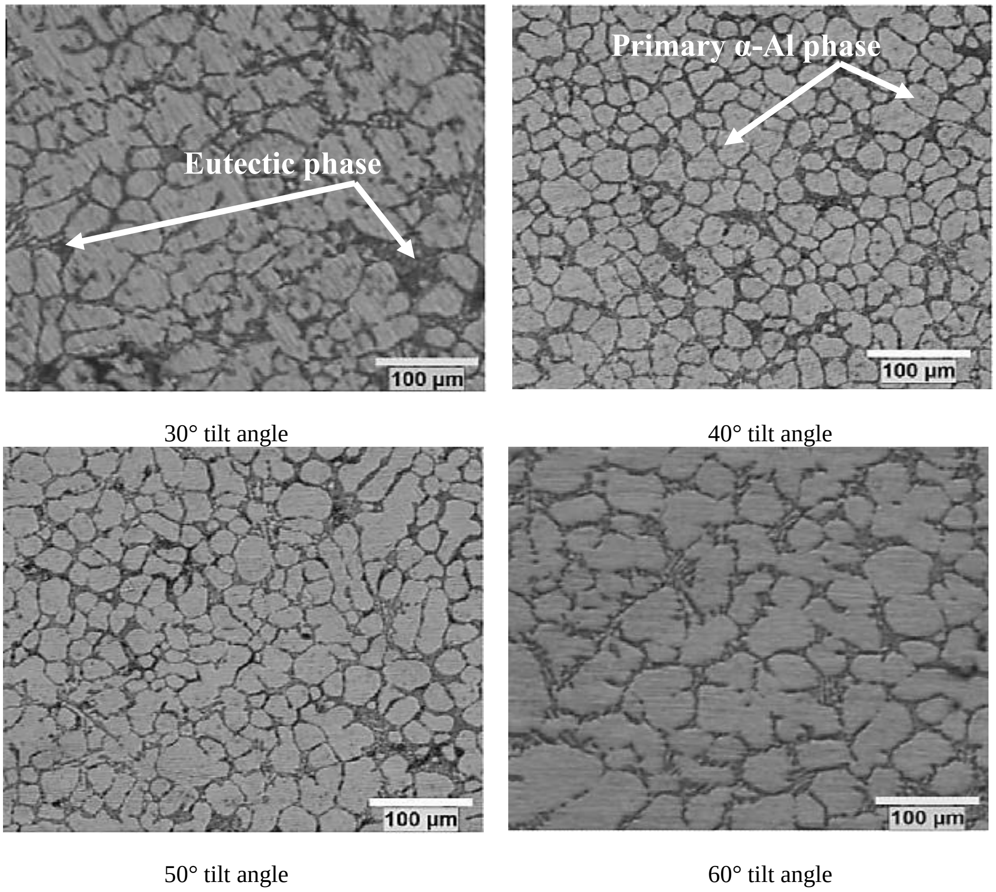


Figure 1. Microstructures of cast samples via inclined plate at the 40 cm length and different tilt angles [13]

3. Results and Discussion

3.1. ANOVA and Mathematical Model for Mean Particle Size

The average values of the MPS of α-Al solid phase along with the 20 experimental runs are listed in Table 4. For the statistical significance of the fitted quadratic model, the ANOVA was conducted, and the results are given in Table 5. It is statistically significant for the fitted quadratic model to analyze the values of Y (mean particle size of α-Al solid phase). A model F Value is calculated from the following eq. (4) [1]:

$$F = Adj.MS/MS\ Residual\ Error \quad (4)$$

It is a test of comparing a model variance with a residual variance. If the variances are close to the same, the ratio will be close to one, and it is less likely that any of the factors has a significant effect on the response.

As for a "Model P Value", if the "Model P Value" is very small, less than 0.05 (i.e., α= 0.05 or 95% confidence), then the terms in the model have a significant effect on the response [3]. Similarly, an "F Value" of any individual parameter terms is calculated from a term mean square divided by a residual mean square. It is a test that compares a term variance with a residual variance. If the variances are close to the same, the ratio will be close to one, and it is less likely that the term has a significant effect on the response. Furthermore, if a "P Value" of any model terms is very small (less than 0.05), the individual terms in the model have a significant effect on the response. In the ANOVA table, the important coefficient R^2, called determination coefficients, is defined as the ratio of the explained variation to the total variation and is a measure by the degree of fit. When R^2 approaches to a unity, the better the response model fits the actual data that presents the less difference between the predicted and actual values. The coefficients of regression model are estimated by ANOVA, as shown in Table 6, the analysis was done using uncoded units. Considering the most significant terms listed in Table 6, one can develop a regression model. The mathematical predicted model for the mean particle size (Y) is as follow eq. (5):

$$Y = 328.185 - 12.155X_1 - 1.448X_2 + 0.142X_1^2 + 0.022X_2^2 - 0.008X_1X_2 \quad (5)$$

where; (X_1) tilting angle and (X_2) cooling length.

Furthermore, from the above regression model, the proportions of total variability in the deviation can be explained by the following eq. (6):

$$R^2 = \frac{SS_{Model}}{SS_{Total}} = \frac{4622.88}{4764.27} = 97.03\% \quad (6)$$

where; SS is the abbreviation of "sum of squares". The above mathematical model can be used to predict the values of MPS within the limits of the factors studied.

3.2. Normality Test of Residuals for MPS

The residuals are defined as the differences between the actual and predicted values for each point in the design. If a model is adequate, the distribution of residuals should be normally distributed. Minitab15 software is used to perform a normality test as seen in Fig.2. For the normality test, the hypotheses are listed as follows [14]:

1) Null hypothesis: the residual data follows a normal distribution.
2) Alternative hypothesis: the residual data does not follow a normal distribution.

The vertical axis of Fig.2 has a probability scale and horizontal axis with a data scale. As a "P-Value" that is smaller than 0.05, it will be classified as "significant", and the null hypothesis has to be rejected. The "P-values" are smaller than 0.05; thus, the residuals for the particle size have a significant effect on the response and the predicted regression model has extracted all available information from the experimental data. The rest of the information, defined as residuals, can be considered as errors resulted from performing the experiments.

3.3. An Optimal Setting

The objective of this study is to identify an optimal setting by minimizing particle size of α-Al phase of A356 alloy. Hence, the goal value "grain size minimize" is selected to identify the target value (15μm) for inclined plate experiments. Using Minitab 15 software, the predicted responses are calculated, as given in Table 7. using the global solution factor levels. The predicted responses are the responses you can expect if the global solution factor levels are used. There is only one local solution, which is the best of all the global solutions. The local solution is the "best" combination of factor settings for achieving the desired responses. A local solution is (Tilt angle = 43.9394° and Cooling length = 42.2222 cm).

Table 4. Design layout and experimental results

Tilt angle	Cooling. length	MPS	RunOrder	Blocks	FITS1	Coef1	PLimLo1	PLimHi1
30	20	66.0	1	1	66.1824	328.185	57.7202	74.6447
30	30	64.0	2	1	59.9833	-12.155	52.2784	67.6881
30	40	56.5	3	1	58.1056	-1.448	50.4504	65.7607
30	50	59.5	4	1	60.5493	0.142	52.8444	68.2541
30	60	66.5	5	1	67.3144	0.022	58.8522	75.7767
40	20	42.4	6	1	42.5184	-0.008	34.7428	50.2940
40	30	35.2	7	1	35.4773		28.1431	42.8115
40	40	28.0	8	1	32.7576		25.3491	40.1660
40	50	36.5	9	1	34.3593		27.0251	41.6935
40	60	42.2	10	1	40.2824		32.5068	48.0580
50	20	49.0	11	1	47.3044		39.5288	55.0800
50	30	38.0	12	1	39.4213		32.0871	46.7555
50	40	32.0	13	1	35.8596		28.4511	43.2680
50	50	38.0	14	1	36.6193		29.2851	43.9535
50	60	45.0	15	1	41.7004		33.9248	49.4760
60	20	78.0	16	1	80.5404		72.0782	89.0027
60	30	73.8	17	1	71.8153		64.1104	79.5201
60	40	71.6	18	1	67.4116		59.7564	75.0667
60	50	68.6	19	1	67.3293		59.6244	75.0341
60	60	66.3	20	1	71.5684		63.1062	80.0307

Table 5. ANOVA for SPC process at 95% confidence limits

Source	DF	Seq.SS	Adj. SS	Adj. MS	F	P
Regression	5	4622.88	4622.88	924.58	91.55	0.000
Linear	2	278.98	3363.92	1681.96	166.55	0.000
Square	2	4308.46	4308.46	2154.23	213.31	0.000
Interaction	1	35.45	35.45	35.45	3.51	0.082
Residual Error	14	141.39	141.39	10.10		
Total	19	4764.27				

SD = 3.17790 Predicted residual error of sum of squares (PRESS) = 350.462

R^2 = 97.03% R^2(predicted) = 92.64% R^2(adjusted) = 95.97%

Table 6. Estimated Regression Coefficients for Aspect ratio by ANOVA

Term	Coef.	SE Coef.	T	P
Constant	328.185	17.1988	19.082	0.000
Tilt angle (X_1)	-12.155	0.6674	-18.214	0.000
Cooling length (X_2)	-1.448	0.3986	-3.632	0.003
Tilt*Tilt (X_1* X_1)	0.142	0.0071	20.018	0.000
Length*Length (X_2* X_2)	0.022	0.0042	5.088	0.000
Tilt*Length (X_1* X_2)	-0.008	0.0045	-1.874	0.082

Predicted responses or an optimal setting is obtained by predicating appropriate combinations of factors that minimize the desirability function from random starting points. Predicted responses give a minimized value of desirability by the DOEs method, as shown in Table 8. It can represent the optimum setting or the relationship between the predicted responses for grain size of α-Al phase against the pouring tilt angle and cooling length based on the optimization plot which is drawn by Minitab15 software, as shown in Fig.3. It is clear that the value of mean grain size of α-Al phase (MPS) decreases about 30.5μm at approx. 44° tilt angle and 42 cm cooling length. The view of Minitab15 software used in this work is illustrated in Fig.4.

4. CONCLUSIONS

This study includes the database of inclined plate casting process parameters and the output of mean particle size of α-Al solid phase from the literature, both of mathematical model and optimum levels were acquired. From ANOVA results, the mathematical relationship for the grain size of α-Al phase (Y) is resulted as follows:

$$Y = 328.185 - 12.155X_1 - 1.448X_2 + 0.142X_1^2 + 0.022X_2^2 - 0.008X_1X_2$$

The DOEs results indicates that the optimum setting is (43.9394) deg. tilt angle and (42.2222) cm cooling length with mean particle size (30.4921) µm.

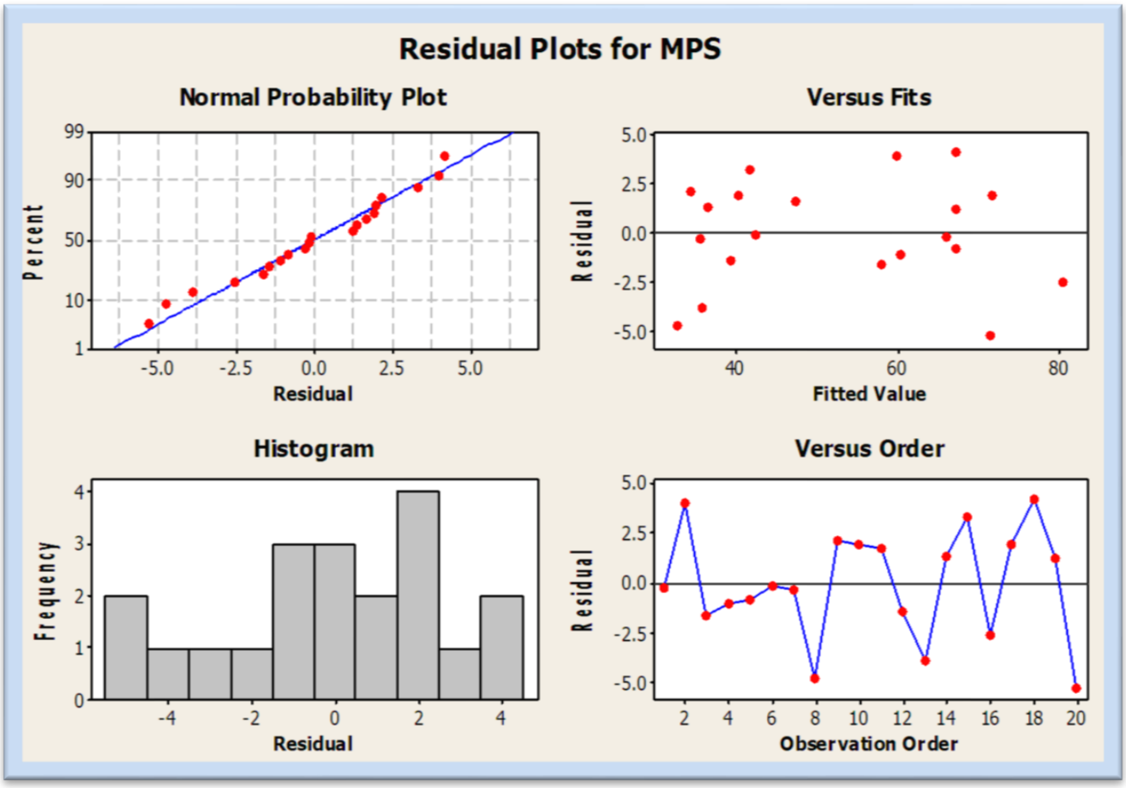


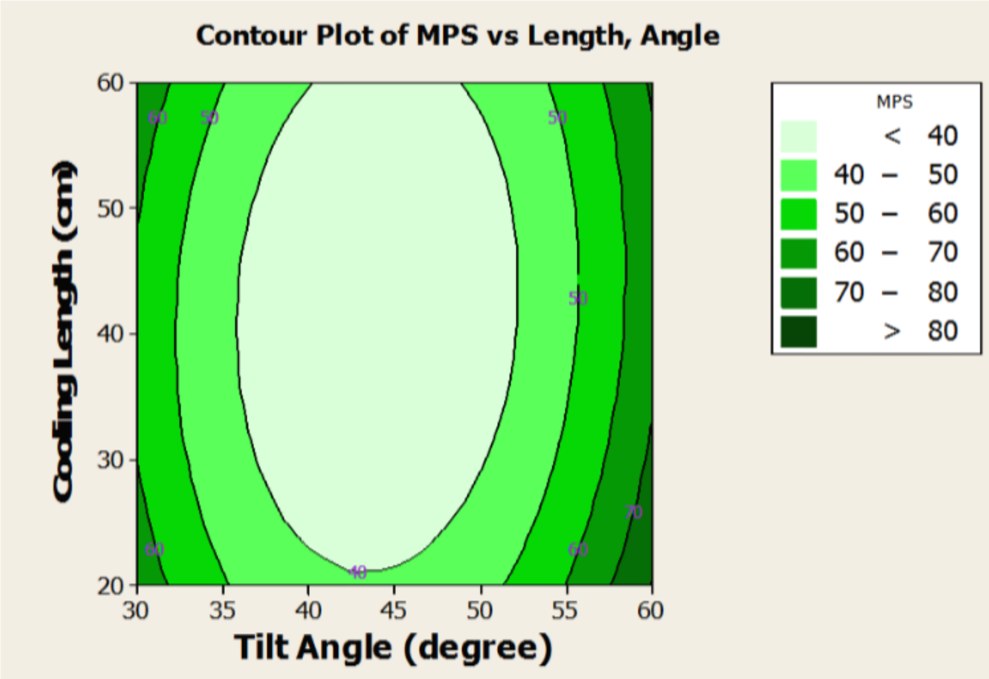
Figure 2. Normality test result for residuals of the particle size.

Table 7. Predicted Response for New Design Points Using Model for Particle Size.

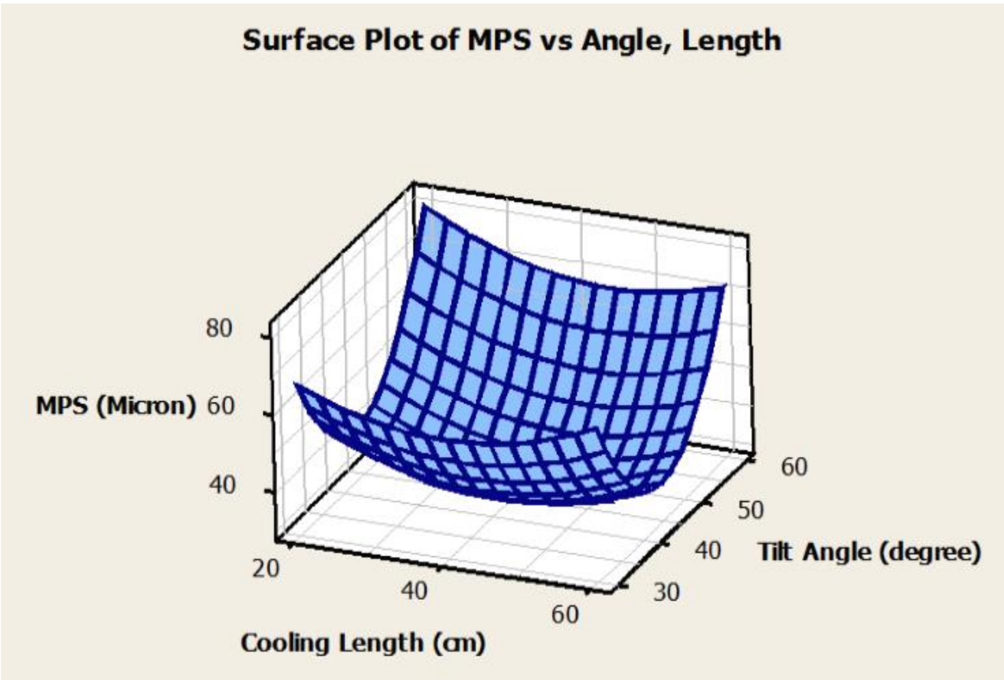
Point	Fit	SE Fit	95% CI	95% PI
1	66.1824	2.33835	(61.1672, 71.1977)	(57.7202, 74.6447)
2	59.9833	1.67514	(56.3905, 63.5761)	(52.2784, 67.6881)
3	58.1056	1.62486	(54.6206, 61.5906)	(50.4504, 65.7607)
4	60.5493	1.67514	(56.9565, 64.1421)	(52.8444, 68.2541)
5	67.3144	2.33835	(62.2992, 72.3297)	(58.8522, 75.7767)
6	42.5184	1.74474	(38.7763, 46.2605)	(34.7428, 50.2940)
7	35.4773	1.26262	(32.7692, 38.1853)	(28.1431, 42.8115)
8	32.7576	1.35361	(29.8544, 35.6608)	(25.3491, 40.1660)
9	34.3593	1.26262	(31.6512, 37.0673)	(27.0251, 41.6935)
10	40.2824	1.74474	(36.5403, 44.0245)	(32.5068, 48.0580)
11	47.3044	1.74474	(43.5623, 51.0465)	(39.5288, 55.0800)
12	39.4213	1.26262	(36.7132, 42.1293)	(32.0871, 46.7555)
13	35.8596	1.35361	(32.9564, 38.7628)	(28.4511, 43.2680)
14	36.6193	1.26262	(33.9112, 39.3273)	(29.2851, 43.9535)
15	41.7004	1.74474	(37.9583, 45.4425)	(33.9248, 49.4760)
16	80.5404	2.33835	(75.5252, 85.5557)	(72.0782, 89.0027)
17	71.8153	1.67514	(68.2225, 75.4081)	(64.1104, 79.5201)
18	67.4116	1.62486	(63.9266, 70.8966)	(59.7564, 75.0667)
19	67.3293	1.67514	(63.7365, 70.9221)	(59.6244, 75.0341)
20	71.5684	2.33835	(66.5532, 76.5837)	(63.1062, 80.0307)

Table 8. Predicted Response for Mean Particle Size.

State	Tilt angle (deg.)	Cooling length(cm)	MPS (µm)	desirability	Composite Desirability
Inclined plate casting	43.9394	42.2222	30.4921	0.754094	0.754094



a) Contour plot of the particle size response surface.



b) A three – dimensional response surface showing the expected particle size as a function of tilt angle and cooling length.

Figure 3. Optimization plot of inclined plate casting process for (α-Al) refinement

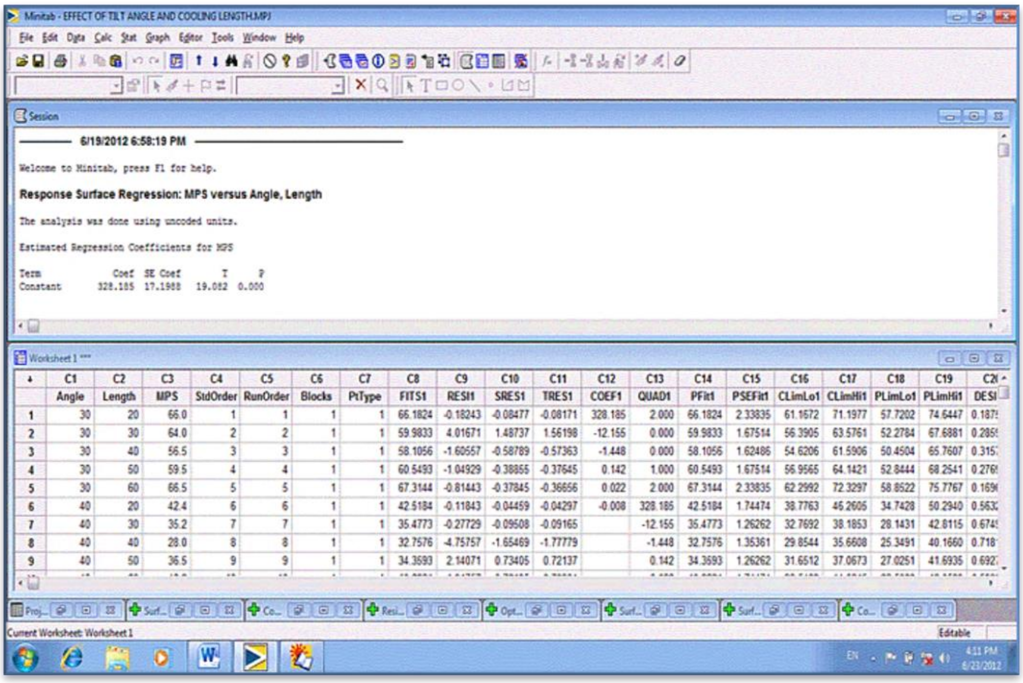


Figure 4. The view of Minitab15 software used in this work

Nomenclature

RSM	Response Surface Methodology
DOEs	Design of experiments
MPS	Mean Particle Size
ANOVA	Analysis of Variance
deq	The grain size
A	The area of α-Al phase
X_1	Tilt angle
X_2	Cooling length
PRESS	Predicted residual error of sum of squares
R^2	Coefficient of determination
SS_{Model}	Sum of squares for model
SS_{Total}	Total sum of squares

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