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OPTIMIZATION OF PROCESS PARAMETERS OF ALUMINIUM ALLOY (A*L*6061) – ALUMINA (AL_2O_3) COMPOSITES FABRICATED BY STIR CASTING

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ABSTRACT

The present study deals with the Optimization of process parameters of Aluminium alloy (Al6061) – Alumina (Al_2O_3) Composites fabricated by Stir casting used in Ship hulls. The sample specimens are made by varying the percentage of reinforcements with respect to aluminium alloy. The evaluation of mechanical properties indicates the variations in tensile strength, hardness and impact energy for different composite combinations. Aluminium is compared with the Al6061- Al_2O_3 composites because the composite samples have improved mechanical properties than the aluminium alloy. Finally, the most suitable composite that is having the best properties is optimized using Box Behnken technique in Response Surface Methodology.

Keywords: aluminium; alumina; stir casting; box behnken; response surface methodolgy; composites; ship hulls

1. INTRODUCTION

Composite is a material composed of two or more distinct phases (matrix phase and dispersed phase) and having bulk properties significantly different form those of any of the constituents. Metal Matrix Composite (MMC) is a material consisting of a metallic matrix combined with a ceramic (oxides, carbides) or metallic (lead, tungsten, molybdenum) dispersed phase.

Aluminum Matrix Composites (AMC) is the widest group of Metal Matrix Composites. Matrices of Aluminum Matrix Composites are usually based on aluminum-silicon (Al-Si) alloys and on the alloys of 2xxx and 6xxx series. Aluminum Matrix Composites (AMC) are reinforced by: Alumina (Al2O3) or silicon carbide (SiC) particles (particulate Composites) in amounts 15-70 vol%; Continuous fibers of alumina, silicon carbide, Graphite (long-fiber reinforced composites); Discontinuous fibers of alumina (short-fiber reinforced composites).

Aluminum Matrix Composites can be manufactured by Powder metallurgy (sintering), Stir casting and Infiltration methods. The following properties are typical for Aluminum Matrix Composites, High strength even at elevated temperatures, High stiffness (modulus of elasticity), Low density, High thermal conductivity and Excellent abrasion resistance.

2. MATERIALS AND METHODS

A. Selection of Materials

Matrix

The matrix material to be used was chosen as Al6061 which is a precipitation hardened aluminium alloy, containing iron, silicon and chromium as its major alloying elements as indicated in Table I. It has good mechanical properties and exhibits good weldability, good formability and high corrosion.

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Table I. Chemical composition of aluminium

Constituents	Percentage
Manganese (Mn)	0.108%
Iron (Fe)	0.125%
Copper (Cu)	0.392%
Magnesium (Mg)	0.970%
Silicon (Si)	0.620%
Chromium (Cr)	0.079%
Others (Total)	0.04%
Aluminium (Al)	97.7%

Table II. Physical properties of al6061

Properties	Value	Unit
Density	2.7	g/cm^3
Melting point	582-652	°C
Brinell Hardness	45	
Ultimate Tensile Strength	130	MPa
Yield Strength	276	MPa
Modulus of Elasticity	68.9	MPa
Thermal conductivity	167	W/m-K
Coefficient of Thermal Expansion	23.6×10^{-6}	m/°C

Reinforcement

The materials selected to be reinforced into the metallic matrix is Alumina. Aluminium oxide is a chemical compound of aluminium and oxygen with the chemical formula Al2O3. Alumina is significant in its use to produce aluminium metal, as an abrasive owing to its hardness, and as a refractory material owing to its high melting point. It is reinforced in the Al6061 matrix to increase strength, hardness, stiffness, wear resistance and impact strength. Its attractive properties are listed in Table II.

Table III Properties Of Alumina

Properties	Alumina (Al_2O_3)	Units
Density	3.98	g/cm^3
Melting point	2300	°C
Vickers Hardness	1560	
Fracture toughness	4.9	MPa√m
Elastic Modulus	300	GPa
Tensile Strength	210	MPa
Thermal conductivity	21	W/mK
Coefficient of thermal Expansion	9	m/°C

B. Fabrication process

Stir casting is the most popular commercial method of producing aluminium based composites. In this method, pre heated ceramic particulates are incorporated into the vortex of the molten matrix created by a rotating impeller. In principle, it allows a conventional metal processing route to be used, and hence minimizes the final production cost of the product. This conventional method is also called as vortex method and liquid metallurgy route shown in fig. 2.

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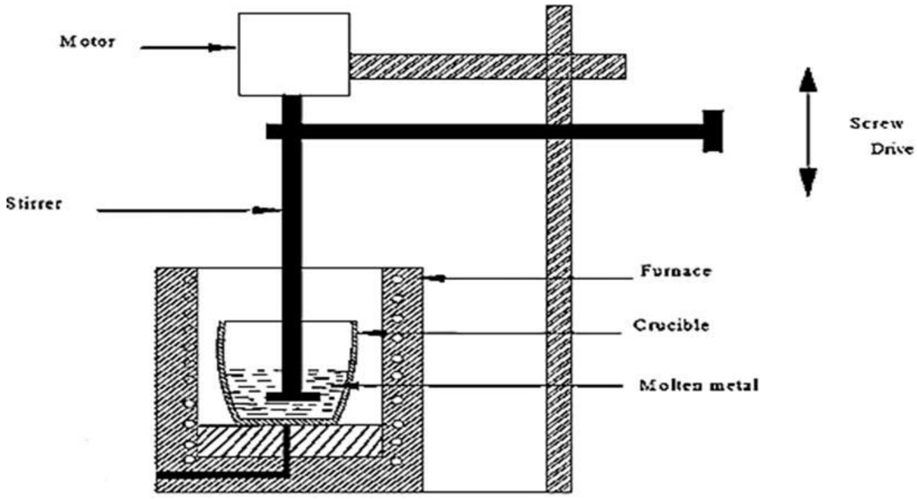

Fig 1. Stir casting diagram

The stir casting process starts with the preheating of graphite crucible in a gas-fired furnace for 20 minutes. The Alumina was initially preheated separately at a temperature of 250°C to remove moisture and to help even distribution within Al6061 alloy. The Al6061 alloy billets were charged into the furnace, fitted with a temperature probe and heated to a temperature of 750 ± 30°C (i.e) above the liquidus temperature of the alloy to ensure that the alloy melts completely. The liquid alloy was then allowed to cool in the furnace to a semi solid state at a temperature of about 600°C. Slag is removed using scum powder. Now with the help of electrical stirrer, the molten alloy is stirred at a constant speed of 450 rpm to create vortex. The preheated Alumina is then charged into the melt at constant pour rate and stirring of the slurry was performed manually for 5-10 minutes. Magnesium about 2% of weight is added to ensure good wettability for all proportions of the reinforcements.

The composite slurry was superheated to 800°C and a second stirring performed using a mechanical stirrer. The stirring operation was performed at a speed of 400 rpm for 10 minutes before casting into prepared sand moulds. Meanwhile the mould is preheated to avoid shrinkage of casting material. Then the melted matrix and reinforced particles are poured into the preheated mould and the pouring temperature should be maintained at 680°C. The entire process is done with either nitrogen gas or inert gas surrounding it to avoid contamination from atmosphere. The final shape of the composite may be a bar, rod or plate whatsoever the shape of the mould.

3. TESTS CONDUCTED

Mechanical tests

The specimens fabricated by Stir casting is cut and machined into test samples of required shape and dimensions for the conduction of various tests.

Tensile test

Tension means pulling force. The tensile test is done in a Universal Testing Machine to determine the tensile strength of the specimen.

$$\text{Ultimate Tensile strength} = \frac{\text{Maximum load given to specimen}}{\text{Area of cross section}}$$

Brinell Hardness Test

Hardness is the ability of the material to resist wear, scratching, abrasion and indentation. Brinell hardness test is done in the hardness testing machine to determine hardness number in the Al6061 based hybrid MMC specimens prepared as per Standard test methods for Brinell Hardness testing 'ASTM E10-14'. In the brinell test, a steel indenter, having diameter of 10 mm is forced in the surface of the composite. Standard load of 250

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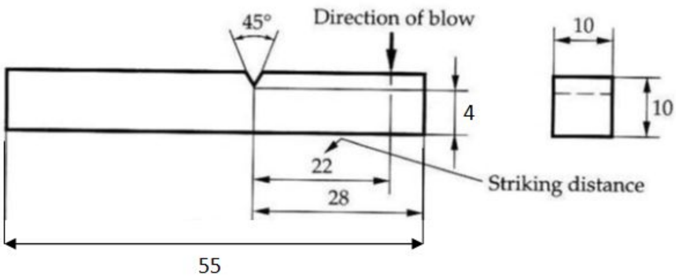
kgf is supplied and maintained constant for 10 seconds and then removed. Brinell hardness number is calculated from the impression of the indentation.

$$\text{Brinell Hardness number} = \frac{2P}{\pi D\,[D - \sqrt{(D^2 - d^2)}]}$$

where,
P = load applied on indenter(250 kgf)
D = diameter of steel ball indenter(10 mm)
d = diameter of ball impression in mm

Charpy impact test

Impact strength is the capacity of a material to withstand blows without fracture [7]. The Charpy impact test is done on the Al6061 based hybrid MMC specimens as per Standard test methods for notched bar tensile strain Impact test method 'ASTM E23-14' in Impact testing machine. In impact test, a notch is cut in the specimen upto 4mm which is struck by a single blow in testing machine. The energy absorbed in breaking the specimen can be measured from the scale provided in the machine. The results are tabulated in Table VI.



In Charpy test of impact strength, the test sample is fixed horizontally to the machine base just as a simply supported beam and the striking hammer is blown to hit the specimen behind the v-notch. The Charpy impact test is conducted.

4. EXPERIMENTAL PROCEDURE

Response Surface Methodology

Response Surface Methodology is a collection of mathematical and statistical procedures used for analyzing of problems in which a particular response is influenced by multiple variables. A standard RSM Technique called Box-Behnken Design Technique (BBD) was selected to study hardness, impact test and tensile test. BBD for three parameters composition, stirring speed and stirring time each with two levels was used as experimental design model. The BBD model allows the usage of relatively least combinations of variables for determining the complex response function. In many experimental conditions, it is possible to represent independent factors in quantitative form as given in Eq.(1).

These factors can be treated as having a functional relationship or response similar to:

$$Y = \Phi\,(x_1, x_2, \ldots\ldots, x_k) \pm e_r \quad (1)$$

Where, the response Y and x_1, x_2 ,…….., x_k of k quantitative factors, the function is called response surface or response function, the residual e_r measures the experimental errors. When the mathematical form of Φ is not known, it can be approximate satisfactorily within the experimental region by polynomial.

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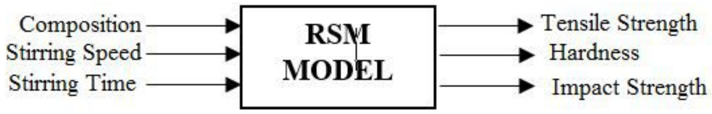

The regression equation of second order polynomial was used to represent the response surface 'Y' is given by equation 2.

$$y = \beta_0 \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i=1}^{k} \sum_{i \neq j=1}^{k} \beta_{ij} x_i x_j + \varepsilon \quad (5)$$

Experimental Design by RSM -Box Behnken Method

All the specimens were prepared according to the experimental runs developed by the DESIGN EXPERT 8. The controlling parameter set for running the design matrix is given Table 1.

Table 1: Controlling Parameter and their Levels for the Study

Symbol	Factor	Experimental values	
		Low level (1)	High level (2)
A	Composition of Alumina (wt %)	5	15
B	Stirring speed (rpm)	200	600
C	Stirring time (minutes)	2	6

Table 1. gives the layout of Full Factorial for Box Behnken design composite design with results

Process design layout using box-behnken design and test results

Run	Composition of Alumina	Stirring speed	Stirring time	Tensile strength	Brinell hardness	Impact strength
	Wt. %	rpm	min.	MPa	BHN	J/mm^2
1	10.00	200.00	2.00	96	44.8	0.275
2	5.00	200.00	4.00	107	47.4	0.275
3	5.00	600.00	4.00	114	40.2	0.400
4	10.00	600.00	2.00	92	42.4	0.425
5	5.00	400.00	2.00	109	40.2	0.325
6	15.00	600.00	4.00	84	64.6	0.275
7	10.00	400.00	4.00	90	53.4	0.300
8	10.00	400.00	4.00	90	53.4	0.300
9	10.00	600.00	6.00	98	50.3	0.335
10	10.00	400.00	4.00	90	53.4	0.300
11	15.00	400.00	6.00	82	53.8	0.225
12	10.00	400.00	4.00	90	53.4	0.300
13	10.00	200.00	6.00	88	44.8	0.350
14	15.00	200.00	4.00	78	50.3	0.250
15	5.00	400.00	6.00	98	40.2	0.500
16	15.00	400.00	2.00	81	50.3	0.225
17	10.00	400.00	4.00	90	53.4	0.300

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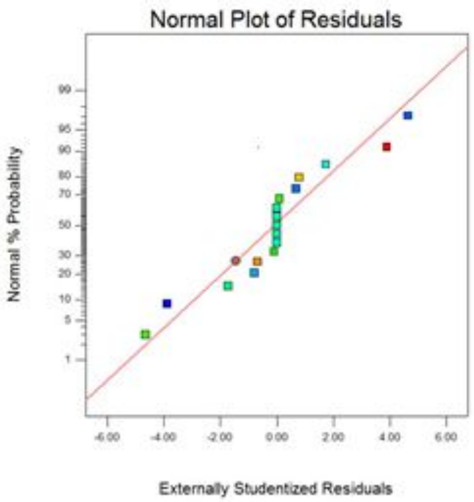
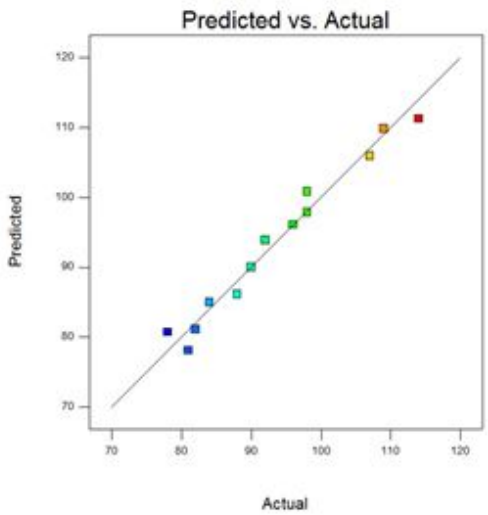
ANOVA for Response Surface Quadratic model for Tensile Strength

	Sum of		Mean	F	p-value	
Source	**Squares**	**df**	**Square**	**Value**	**Prob > F**	
Model	1550.81	9	172.31	28.55	0.0001	significant
A-Composition	1326.12	1	1326.12	219.71	< 0.0001	
B-Stirring Speed	45.13	1	45.13	7.48	0.0292	
C-Sirring Time	18.00	1	18.00	2.98	0.1278	
AB	0.25	1	0.25	0.041	0.8445	
AC	36.00	1	36.00	5.96	0.0446	
BC	49.00	1	49.00	8.12	0.0247	
A^2	23.75	1	23.75	3.93	0.0877	
B^2	47.96	1	47.96	7.95	0.0258	
C^2	0.066	1	0.066	0.011	0.9198	
Residual	42.25	7	6.04			
Lack of Fit	42.25	3	14.08			
Pure Error	0.000	4	0.000			
Cor Total	1593.06	16				

The Model F-value of 28.55 implies the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise. "Values of ""Prob > F"" less than 0.0500 indicate model terms are significant. "In this case A, B, AC, BC, B++2+- are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model.

Std. Dev.=2.45676907456; R-Squared = 0.97347869433572; Mean = 92.764705882353; Adj R-Squared = 0.93937987276736; C.V. % = 2.6483877151249; Pred R-Squared = 0.57565910937154; PRESS = 676; Adeq Precision = 17.579884239711-2; Log Likelihood; 63.720557294657; BIC = 92.052690735219; ICc = 120.38722396132





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ANOVA for Response Surface Quadratic model for Hardness

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	675.31	9	75.03	86.96	< 0.0001	significant
A-Composition	325.13	1	325.13	376.80	< 0.0001	
B-Stirring Speed	13.01	1	13.01	15.07	0.0060	
C-Sirring Time	16.25	1	16.25	18.83	0.0034	
AB	115.56	1	115.56	133.93	< 0.0001	
AC	3.06	1	3.06	3.55	0.1016	
BC	15.60	1	15.60	18.08	0.0038	
A^2	5.21	1	5.21	6.04	0.0436	
Source	**Sum of Squares**	**df**	**Mean Square**	**F Value**	**p-value Prob > F**	
B^2	11.64	1	11.64	13.49	0.0079	
C^2	159.90	1	159.90	185.32	< 0.0001	
Residual	6.04	7	0.86			
Lack of Fit	6.04	3	2.01			
Pure Error	0.000	4	0.000			
Cor Total	681.35	16				

The Model F-value of 86.96 implies the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A, B, C, AB, BC, A^2, B^2, C^2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model.

Std. Dev.	0.93	R-Squared	0.9911
Mean	49.19	Adj R-Squared	0.9797
C.V. %	1.89	Pred R-Squared	0.8582
PRESS	96.64	Adeq Precision	34.319
-2 Log Likelihood	30.65	BIC	58.98
		AICc	87.32

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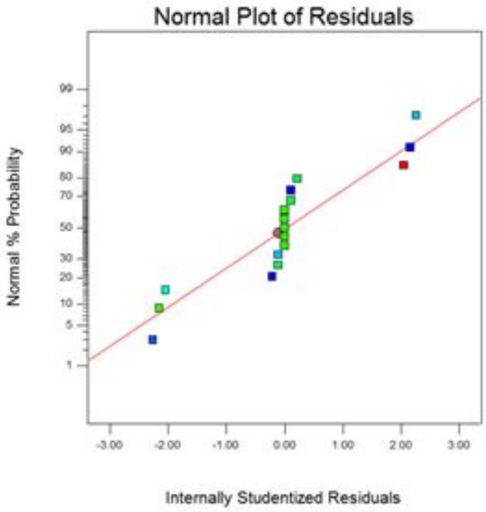

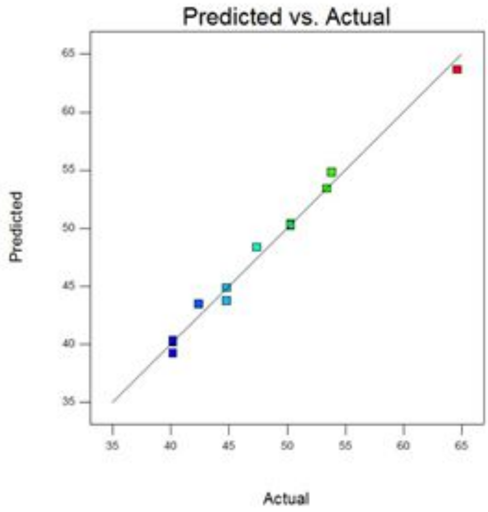

ANOVA for Response Surface Quadratic model for Impact Strenth

	Sum of		Mean	F	p-value	
Source	**Squares**	**df**	**Square**	**Value**	**Prob > F**	
Model	0.065	6	0.011	6.40	0.0054	significant
A-Composition	0.034	1	0.034	20.52	0.0011	
B-Stirring Speed	9.453E-003	1	9.453E-003	5.63	0.0391	
C-Sirring Time	2.812E-003	1	2.812E-003	1.67	0.2247	
AB	2.500E-003	1	2.500E-003	1.49	0.2504	
AC	7.656E-003	1	7.656E-003	4.56	0.0585	
BC	7.656E-003	1	7.656E-003	4.56	0.0585	
Residual	0.017	10	1.679E-003			
Lack of Fit	0.017	6	2.799E-003			
Pure Error	0.000	4	0.000			
Cor Total	0.081	16				

The Model F-value of 6.40 implies the model is significant. There is only a 0.54% chance that an F-value this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A, B are significant model terms. Values greater than 0.1000 indicate the model terms are not significant.If there are many insignificant model terms (not counting those required to support hierarchy),model reduction may improve your model.

Std. Dev.	0.041		R-Squared	0.7935
Mean	0.31		Adj R-Squared	0.6696
C.V. %	13.02		Pred R-Squared	-0.0076
PRESS	0.082		Adeq Precision	8.557
-2 Log Likelihood	-69.40		BIC	-49.56
			AICc	-42.95

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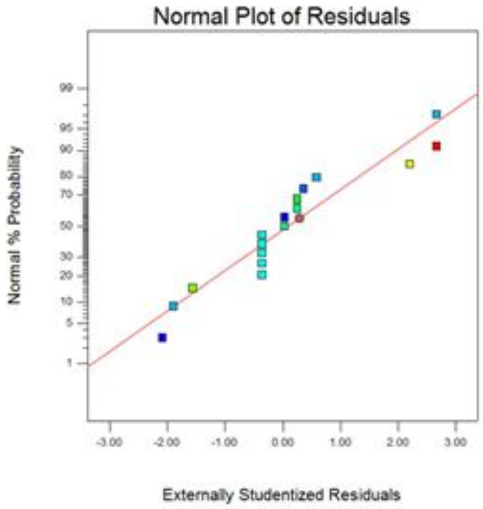

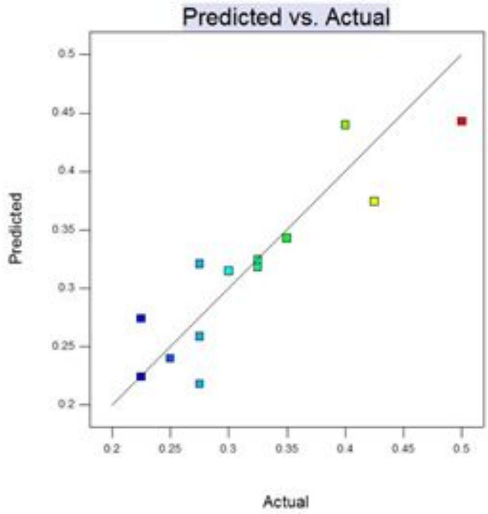

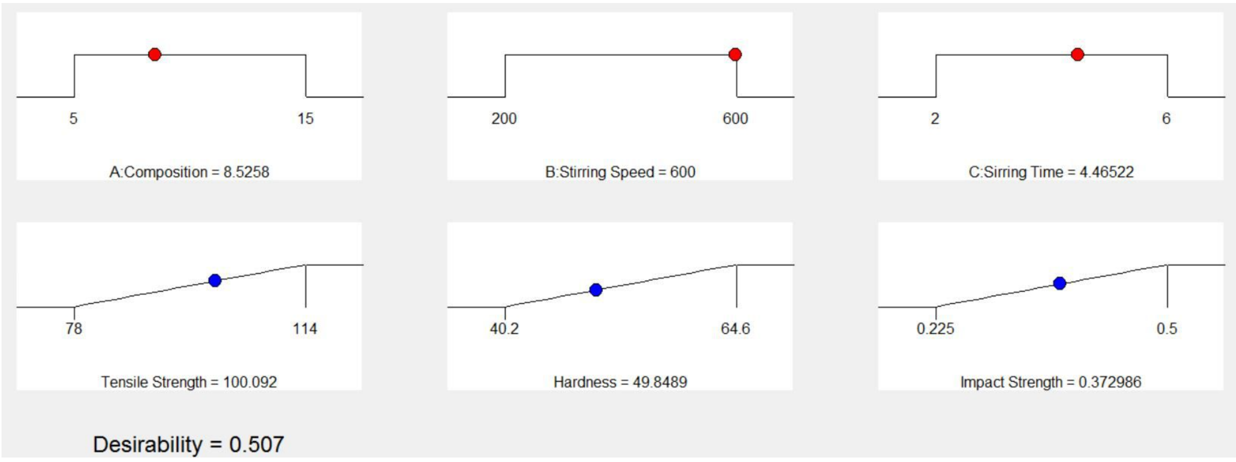

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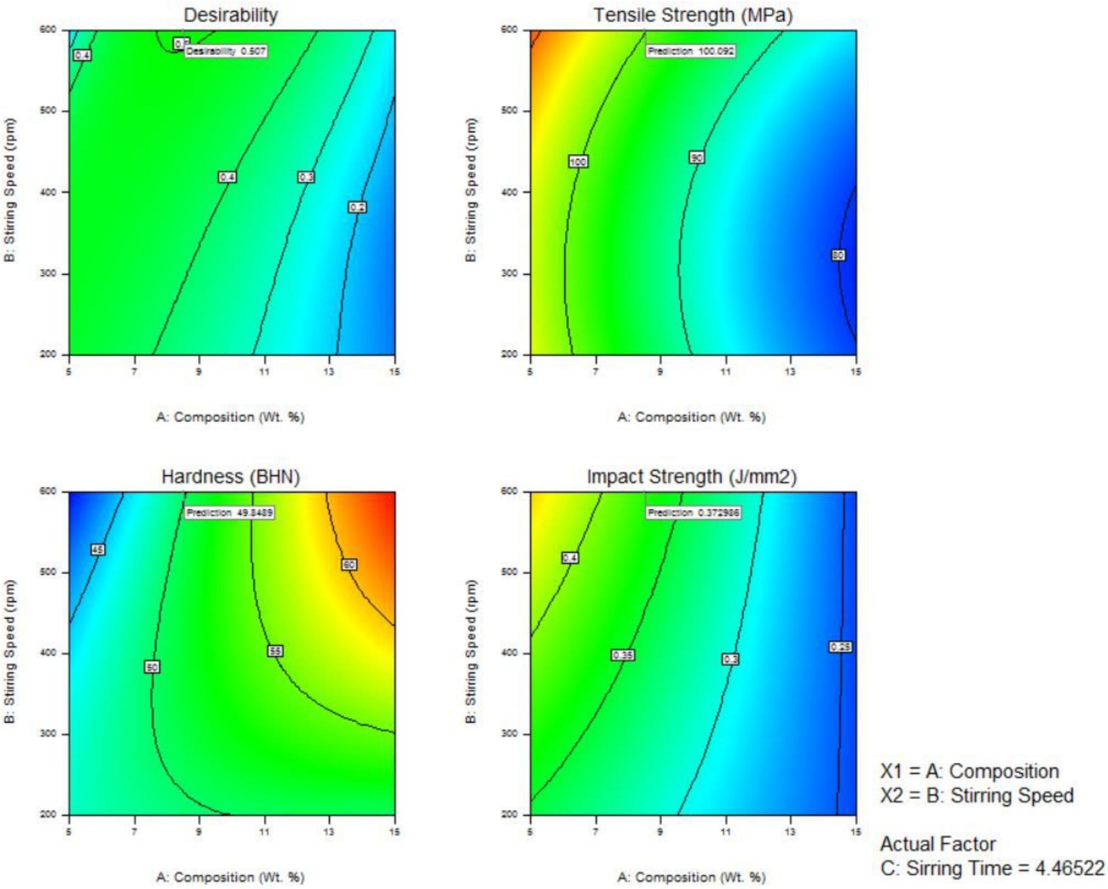

OPTIMIZED VALUE

Number	Composition	Stirring Speed	Sirring Time	Tensile Strength	Hardness	Impact Strength	Desirability	
1	8.526	600.000	4.466	100.092	49.850	0.373	0.507	Selected

5. CONCLUSION

In this study, the aluminium (Al6061) - alumina composites were fabricated by varying the composition of alumina, stirring speed and stirring time. The influence of the three factors were analysed by using Box Behnken design. Also, a quadratic model equation was developed which explains the relationship between the response and the process parameter. The effects of process parameter levels on the response value were analysed using Variance analysis (ANOVA). From the obtained results, the physical properties of the aluminium alumina composites were highly influenced by the composition of alumina. Also the optimized values for obtaining the desired properties is found

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