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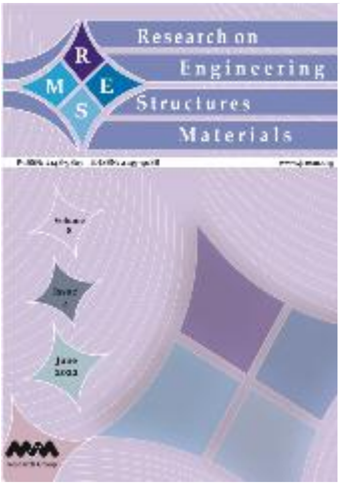

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Research Article

Prediction and optimization of heat treatment effects on hardness and electrical conductivity of aluminum composite reinforced with nano alumina based on response surface methodology

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Abstract

In this study, three non-linear mathematical models were developed using a central composite design for the prediction of heat treatment effects on Vickers micro hardness (HV), Rockwell hardness (RHN), and electrical conductivity (%IACS) of nano Al_2O_3 reinforced Al composite fabricated by a two-step stir casting method. As per the investigation, both process variables of heat treatments such as solution temperature and aging temperature considerably influence the changes in hardness and electrical conductivity of Al composite. For the two-way interaction analysis of variance test, the R^2 values for HV, RHN, and %IACS were 89.29%, 96.23%, and 91.50%, respectively, with a 95% confidence level and 5% significance level. As per the regression equation, the optimized process variables of heat treatment such as solution temperature and aging temperatures are 531.428^{0}C and 180^{0}C which can provide an improvement of 23.15%, 33.57%, and 9.57% respectively for HV, RHN, and %IACS in contrast to their as-cast conditions., Here, the maximum error (%) measured between experimental and prediction are respectively 3.52%, 6.09%, and 2.69%. The microstructure reveals an almost uniform distribution of nano Al_2O_3 in Al composite with fewer agglomeration. The formation of intermetallic compounds at different heat treatment processes identified in SEM impacted the changes in the electro-mechanical properties of fabricated Al composite.

1. Introduction

Aluminum composites (Al composites) are a type of materials that hold great potential for use in the automotive and aerospace sectors. This is because they possess characteristics such as low weight, high specific strength, and effective resistance to wear and corrosion [1, 2]. Researchers all over the world are constantly studying how to enhance the electro-mechanical characteristics of aluminum composites. They do this by using various manufacturing methods, adjusting process parameters, and applying heat treatment techniques. A variety of fabrication techniques are available to create Al composites, including stir casting, ultrasonic assisted casting, composite casting, powder metallurgy process, etc. [3]. When making Al composites, the stir casting method is preferred to its counterparts since it is more widely applicable [4]. The stir casting technique's benefits stem from its ease of use, adaptability, and suitability for large-scale production [5]. Al composites with reinforcement volume fractions up to 30% can be developed using this fabrication method [6]. The main drawback of this fabrication technique is that the distribution of the reinforcing particles in the matrix might not be entirely uniform [7]

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because of density variations and the development of porosity, which reduces the material properties of the composite. Two-step stir casting [8-10] is one of many methods available to mitigate the said issue.

The fabrication process, the types, and sizes of reinforcement particles, the interaction between reinforcement and matrix, the morphology, and the volume fraction reinforcement all have a significant impact on the properties of an Aluminum Metal Matrix Composite (Al MMC) [11]. Numerous researchers from all over the world are constantly investigating whether it is possible to create straightforward, affordable, and effective processing conditions for the production of MMCs [12-13]. According to number of research papers and textbooks, the characteristics of developed Al MMCs are largely dependent on the various stir casting processes and parameters including speed of stirring [14], duration of stirring [15], casting temperature [16], squeeze pressure [17–18], reinforcement size [19], and preheating temperature [20–22]. Constant attempts are also being made to enhance the electro-mechanical properties of Al MMC by including different reinforcing particles such as Al_2O_3, SiC, Gr, B4C, and TiC [23–28]. Due to its greater interfacial affinity and resistance to chemical deterioration by molten aluminum alloys, Al_2O_3 is the most often used reinforcing material among them [29–30]. When the heat treatment technology is used in a different way, the characteristics of the Al composites are considerably altered. Aluminum Associations have standardized a number of heat treatment procedures, including T4, T5, T6, T8, etc. [31]. The effect of heat treatment on the electro-mechanical properties of aluminum composites can vary depending on the type of heat treatment, the temperature, and the cooling rate. Therefore, it is important to carefully select the heat treatment process and parameters to achieve the desired mechanical properties for the specific application. Chandra et al. (32) fabricated MoS_2-reinforced AA6061 by a stir casting technique and carried out heat treatment at a solutionized temperature of 540°C for 1 hour. On completion of solution treatment, test specimens were quenched immediately in water and then thermally aged at 180°C. They observed improvement in hardness, and flexure strength compared with as-cast composites. Tiwari et al. (33) investigated the influence of heat treatment on the mechanical properties of aluminum alloy-fly ash composites, where the solution temperature was maintained at 490°C followed by thermal aging at various temperatures of 130°C, 150°C, 170°C, 200°C, and 240°C, respectively, and observed a gradual improvement in the mechanical properties.

Response surface methodology (RSM) is utilized for creating, enhancing, and optimizing the process variables of different heat treatment processes [34]. Orthogonal array designs employed in trials are scarce and might not be able to evaluate all interactions between the process variables being studied [35]. A two-level factorial design has been employed in numerous experimental studies to investigate how heat treatment affects electro-mechanical properties. However, for analyzing the nonlinearity of output characteristics, this method allows for the creation of linear input-output interactions, and each factor must have at least three levels [36]. As the number of parameters and their levels rises, so does the number of experiments.

It may be mentioned that RSM is a type of regression analysis that examines the connections between a number of explanatory factors and one or more response variables. It relies on findings estimated at various places in the design space to create an approximation mathematical model in place of a complex one [37].

In a study, Vickers micro hardness, Rockwell hardness, and Electrical conductivity of 2.5 wt. % of Al_2O_3 reinforced Al composite were obtained respectively as 35.72 HV, 24.33 RHN, and 45.15 %IACS as a casted condition [38], which can be improved further by various heat treatment processes. However, a single heat treatment process is insufficient to achieve the desired characteristics as per the requirement of the automotive and aerospace industry. For the fabricated Al composite to work at its best, a combination of natural and artificial heat treatment processes can be taken into account to observe the changes in the electro-mechanical properties of fabricated Al composites. Reviewing the effects of different solution and thermal aging temperatures on electro-mechanical properties of fabricated Al composites carried out by different researchers, two factors, i.e., factor 1 and factor 2 have been set as a solution treatment temperature and thermal aging temperature respectively. The purpose of the present study was to identify the most accurate correlation between solution temperature and thermal aging for the highest improvement of Vickers micro hardness (HV), Rockwell hardness (RHN), and Electrical Conductivity (%IACS) of fabricated Al composite under different heat treatment processes in comparison. Another objective of the study was to predict the Hardness and Electrical conductivity of Al composite and optimization of the Heat treatment process based on the Response Surface Methodology.

2. Material under Study

The base metal used for the casting of composites is aluminum ingots collected from RUSAL of Russia. Olympus Vanta C Series XRF Analyzer was used to analyze the chemical composition of the aluminum, and the results are shown in Table 1. The reinforcement particle used for the fabrication of Al composite is Alumina (Al_2O_3) in grain size of 20 nm provided by Hebei Suoyi New Material Technology Co. Ltd. in China. Its physical properties are shown in Table 2 and its microstructure is presented in Fig.1. In this current study, an Al composite was fabricated having 97.5 wt. % of Al along with 2.5 wt. % of Alumina.

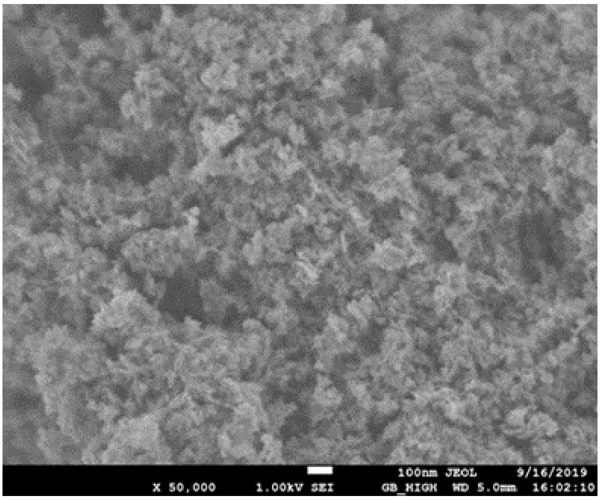


Fig. 1 SEM of Reinforcement particles Al_2O_3 with grain size of (05-20) nm

Table 1. Composition of Aluminum

Element	Al	Si	Fe	Cu	Zn	Zr	Pb
Percentage (%)	99.052	0.614	0.323	0.002	0.008	0.0007	0.0009

Table 2. Physical Properties of Alumina (Al_2O_3)

Melting point (°C)	Boiling point(^{0}C)	Limit of application (°C)	Bulk Density (g/cm3)	Hardness (Moh's Scale)	Molecular weight (g/mol)	Fracture toughness (MPa-m1/2)
2072	2977	1175	.1-.3	7.5	101.96	3.5

3. Experimental Details

3.1 Selection of Two-Step Stir Casting Technique

In order to optimize the dispersion of reinforcing particles in aluminum composites, the two-step stir-casting method modifies the traditional stir-casting process. The procedure entails two stirring stages with a little break in between, and it can produce a more uniform distribution of the reinforcing particles. The molten aluminum is swirled in the initial step of the process to better moisten the reinforcing particles. This ensures that the particles are spread evenly throughout the molten metal and lessens the agglomeration of the particles. Agglomerates of the reinforcement particles are dispersed during the first step of stirring, resulting in a more even distribution of the particles. In order to further homogenize the composite mixture, the molten aluminum is churned once more during the second step of the process. This guarantees that the reinforcement particles are dispersed uniformly throughout the matrix and that any leftover agglomerates are broken up. The deposition of the reinforcing particles during casting can also be decreased by using the two-step stir casting technique. This is due to the fact that while the first round of stirring serves to suspend the particles in the molten aluminum, the second round of stirring makes sure they stay suspended. Overall, the two-step stir casting technique can aid in enhancing the dispersion of reinforcing particles in aluminum composites, producing composites with more consistent mechanical properties.

3.2 Selection of Process and Parameters

The characteristics of developed Al composites are largely dependent on the various stir-casting processes and parameters, including speed of stirring, duration of stirring, casting temperature, squeeze pressure, reinforcement size, preheating temperature, etc. which are discussed here. In the case of low stirrer rpm, there is no room for the reinforcement particles (dispersed phase) to scatter evenly throughout the matrix due to the low stirrer rpm's reduced shearing force on the matrix metal. Moreover, the scattered phase has the propensity to cluster and agglomerate in lower rpm as it occurs because there isn't enough force to overcome it. In the case of higher stirrer rpm, the dispersed phase can flow inside through the vortex that is formed by stirring because there is more shearing force being applied to the matrix metal. The energy generated by the stirrer's high-speed spinning is sufficient to disperse the dispersed phase's particles, resulting in the dispersed phase's uniform distribution throughout the matrix. With faster stirrers, there is a potential that the matrix's porosity will increase as the gas particles move around inside it. Therefore, an optimum stirring speed of 400 rpm has been selected.

The duration of stirring is crucial in ensuring that dispersed phases are distributed evenly throughout the matrix. The clustering of the reinforcement particles results from less stirring time. Moreover, it can be noticed that some of the matrix lacked inclusions of the reinforcing particles. Increased porosity and oxidation development are two potential drawbacks of longer stirring times, which can also serve to improve the homogeneity and distribution of the reinforcing particles. The mechanical properties of the composite may be significantly impacted by increasing porosity brought on by air entrainment as a result of prolonged stirring durations. Moreover, a prolonged stirring of the molten metal can promote greater oxide development, which can impact the composite's mechanical properties. In summary, whereas extended stirring durations can increase the homogeneity and distribution of the reinforcing particles, they can also have a negative impact on the composite's cost and attributes. The ideal stirring period will vary depending on the particular materials and manufacturing conditions. Based on the literature review, the time duration of stirring has been selected as 5 minutes in a two-step.

Preheating the mold and reinforcing material is essential to reducing porosity. The entrapped gases from the metal and reinforcement particles are released through pre-heating. Reviewing recent works from different researchers, preheating of base metal Al selected at a temperature of 500°C for 60 minutes and reinforcement particle Al_2O_3 at a temperature of 300°C for 120 minutes. One of the most important factors that influence the stir-casting process is casting temperature. Due to an increased chemical reaction between the reinforcement particles and the metal matrix, the viscosity reduces as the casting temperature rises, and the distribution of the particles is impacted. The reinforcing particles in the casting temperatures of 750°C and 800°C were discovered to be uniformly dispersed based on the microstructure analysis of several study articles. Due to variations in the viscosity of the liquid Al matrix, particle agglomerations were observed at processing temperatures of 700°C, 850°C, and 900°C. Therefore, casting temperature was set at 800°C.

3.3 Fabrication Procedure of Al Composite

The Al metal was placed in the crucible and heated in the furnace without activating the blower, which generated around 300°C heat. After 15 minutes, the electric blower was activated, and the base metal was preheated at 500°C for 60 minutes. At the same time, the reinforcement particles were preheated in the oven at 300°C for 120 minutes. It took approximately 60 minutes to fully melt the metal. Then, the stirring machine was used for 5 minutes with an rpm of 400 in two steps to ensure proper mixing of the molten metal with Al_2O_3. Once ready, the metal was poured into a sand mold. The mixing rate of Al_2O_3 in the crucible was maintained at 20 gm/minute. Fig.2 depicts the layout of the fabrication procedure.

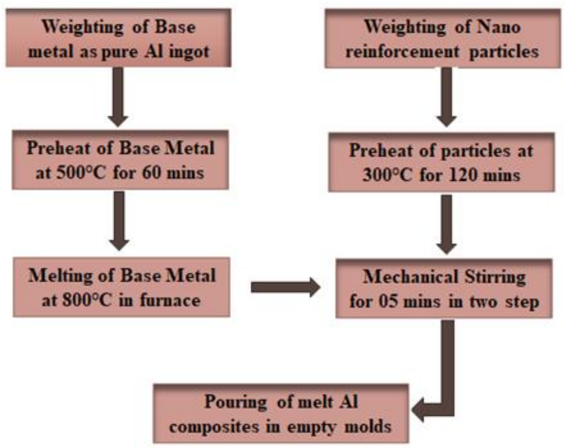
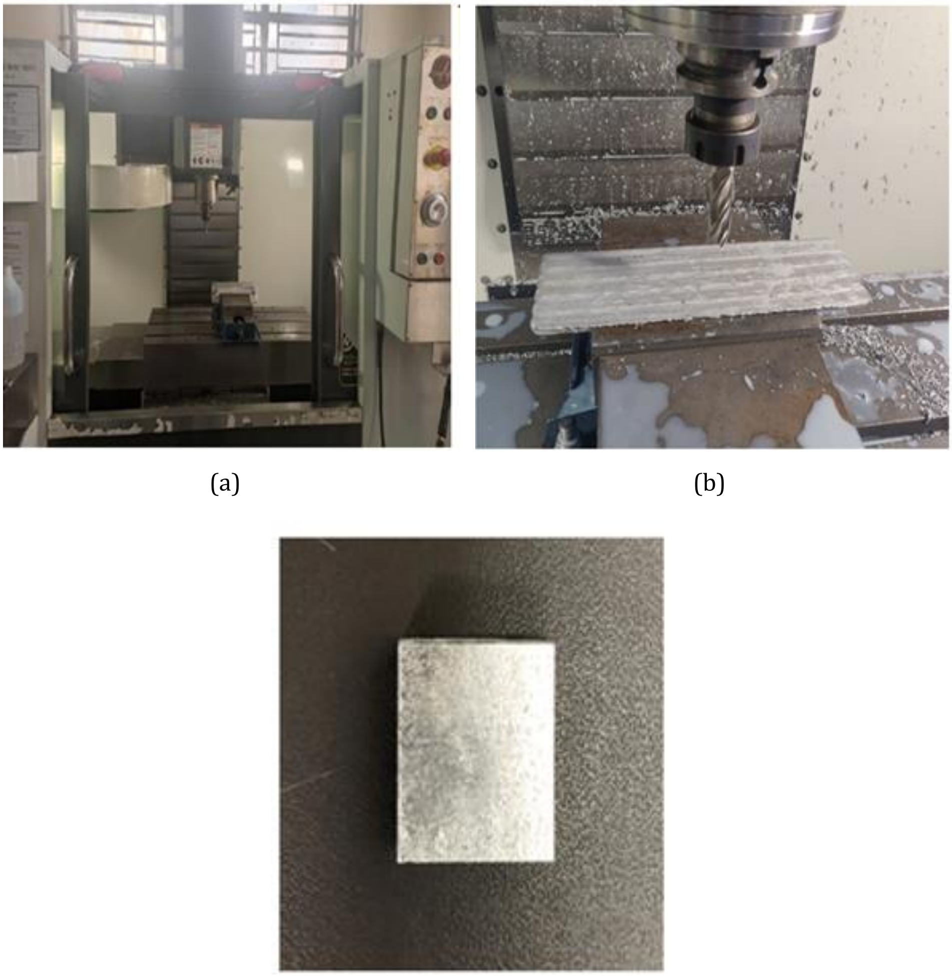


Fig. 2 Fabrication step of Al Composite

3.4 Test Sample Preparation

The Al composite developed had a rough surface and contained few air bubbles, which made it unsuitable for testing electro-mechanical properties directly. In order to improve the surface quality, a Model VF-2 type CNC machine was used for surfacing, as illustrated in Fig. 3(a). A tungsten carbide end mill with a diameter of 12 mm was employed as the cutting tool for the surfacing process, as shown in Fig. 3(b). The casted sheet had an initial thickness of 30 mm, but after surfacing, the thickness was reduced to 26 mm, and the metal surface on both sides were smoothed out, as depicted in Fig. 3(b). The test specimens were prepared for hardness (Rockwell and Vickers micro) and electrical conductivity as per ASTM standards E18-20, E92-17, and E1004-17 with the same dimensions of 20 mm×20 mm×08 mm, as shown in Fig. 3(c).



(a) (b)

(c)

Fig. 3 (a) CNC machining set up; (b) End mill tool with smooth surface; (c) Test specimen

3.5 Process of Heat Treatment

A Carbolite laboratory chamber furnace, model CWF 13/13 from the United Kingdom, with a maximum operating temperature range of 1300°C, was used to perform the heat treatment. During the heat treatment process, the chamber furnace's reported heating rate was 16.66°C per minute. Heat treatment involves solution treatment of test specimens at different temperatures from 501^{0}C to 550^{0}C and thermal aging at different temperatures from 123^{0}C to 236^{0}C as per the design matrix from RSM. All heat treatment procedures took place for 60 minutes, were followed by water quenching, and were then allowed to naturally age for 72 hours at room temperature in both solution treatment and thermal aging. After the aforementioned heat treatment steps were finished, tests on Vickers micro hardness, Rockwell hardness, and electrical conductivity were done. The step-by-step procedure of heat treatment are shown in Fig.4.

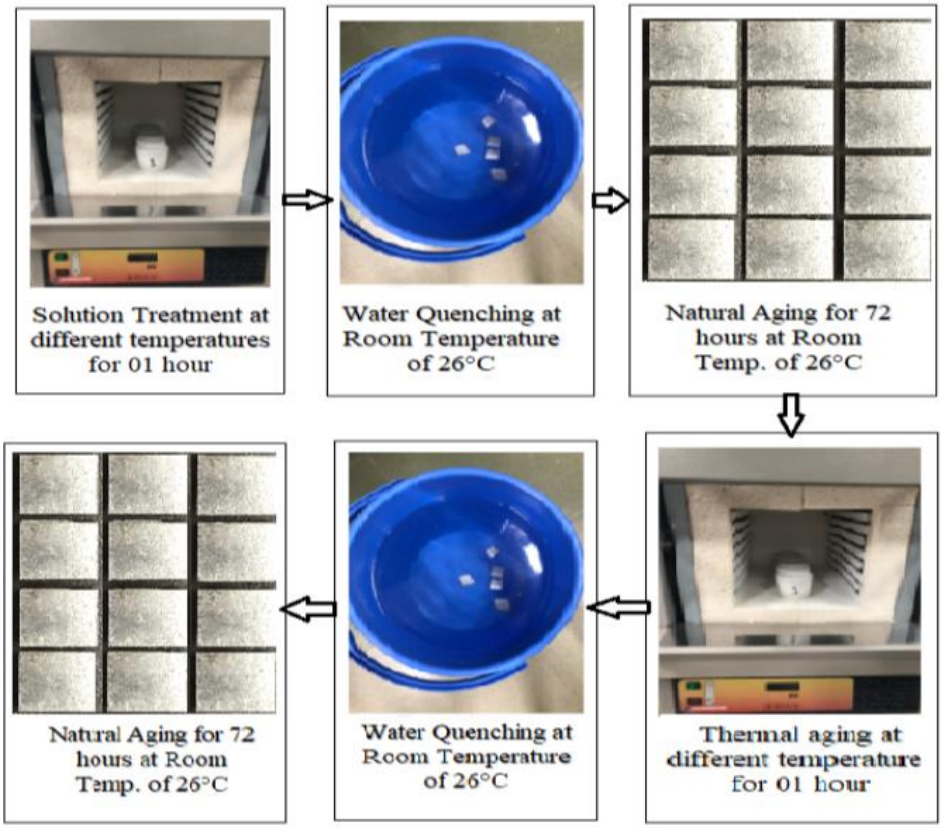


Fig. 4 Heat treatment process of Al composite

3.6 Response Surface Methodology

The goal of the current study was to use Response Surface Design, based on Central Composite design, to simulate and optimize the various heat treatment processes of manufactured Al composite. Below is presented the equation for the second-order polynomial response surface methodology.

$$y= \beta_0 + \sum kj=1\ \beta j\ Xi + \sum kj=1\ \beta jj\ X2j + \sum\sum ki<j=2\ \beta ijXiXj \tag{1}$$

The relationship between the answer and a number of independent variables is mathematically modeled. The coefficients of mathematical modeling based on the response surface regression form were determined using the MINITAB program version 18. As indicated in Table 3, Central Composite design of RSM, DOE ran a total of 14 experiment runs using the optimized model of heat treatment for Al MMC. According to the best results obtained from DOE, a confirmation experiment was carried out. Table 3 displays the experimental findings for the specified matrix for Vickers microhardness

(HV), Rockwell hardness (RHN), and electrical conductivity (%IACS). The non-linear mathematical model based on CC has been developed for the response of HV, RHN and %IACS having continuous factor of Solution temperature (lower level: 510°C and higher level: 550°C) and Thermal aging (lower level: 140°C and higher level: 220°C). Significance and ANOVA tests have been carried out to check the statistical adequacy of the models.

Table 3. Design matrix and experimental results

Run Order	Pt Type	Blocks	Solution Temperature(°C)	Thermal Aging Temperature(°C)	HV	RHN	%IACS
1	0	2	530.00	180.00	43.99	32.50	49.47
2	-1	2	501.72	180.00	42.08	30.04	48.53
3	-1	2	530.00	123.43	42.15	26.90	48.33
4	-1	2	530.00	236.57	43.83	27.25	45.70
5	-1	2	558.28	180.00	43.42	30.15	47.93
6	0	2	530.00	180.00	43.99	32.50	49.47
7	0	2	530.00	180.00	43.99	32.50	49.47
8	0	1	530.00	180.00	43.99	32.50	49.47
9	1	1	510.00	140.00	40.61	26.25	46.16
10	1	1	550.00	220.00	41.95	27.25	45.99
11	1	1	550.00	140.00	41.33	26.75	48.12
12	1	1	510.00	220.00	43.39	26.00	45.41
13	0	1	530.00	180.00	43.99	32.50	49.47
14	0	1	530.00	180.00	43.99	32.50	49.47

4. Statistical Analysis

4.1 Analysis of Electro-mechanical properties

According to the established model, 89.29% and 80.12%, respectively, are the derived values of R^2 and adj R^2 for Vickers micro hardness. R^2 and adj R^2 for Rockwell hardness were calculated to be 96.23% and 92.99%, respectively. Additionally, for electrical conductivity, R^2 and adj R^2 values were determined to be 91.5% and 84.22%, respectively. The polynomial performs better at characterizing the system's behavior when the R^2 values are higher. This set of parameters is the only set where the model is valid (solution temperature and thermal aging temperature). The model shown in the Eq (1) is created using the regression coefficients.

4.2 Study of Variance

A 95% confidence level and a 5% significance level were used in the regression analysis for Vickers micro hardness (HV), Rockwell hardness (RHN), and electrical conductivity (%IACS). The relevance of numerous aspects, including the regression model, linear terms, 2-way interaction terms, and lack of fit, was determined by analysis. To determine whether or whether the results are statistically significant, one uses the P-value. Regression equations (2) through (4) were determined based on the analysis, and they are as follows for Vickers microhardness, Rockwell hardness, and electrical conductivity:

Regression Equation of;

$$HV= -663 + 2.467ST + 0.547TA - 0.002206ST*ST - 0.000477\ TA*TA - 0.000675\ ST*TA \quad (2)$$

Regression Equation of;

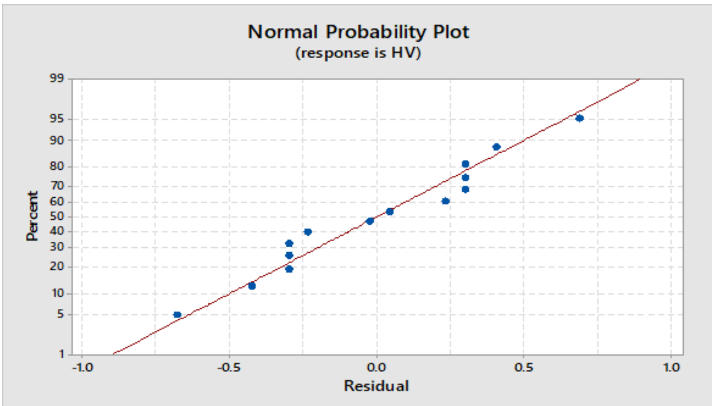
$$RHN=-1217 + 4.496\ ST + 0.602\ TA - 0.004270\ ST*ST - 0.002011\ TA*TA + 0.000234\ ST*TA \quad (3)$$

Regression Equation of;

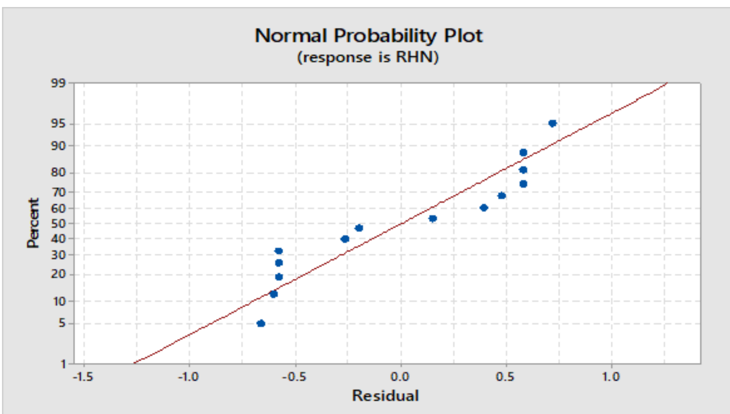
$$\%ICAS=-670 + 2.524\ ST + 0.550\ TA - 0.002298\ ST*ST - 0.000954\ TA*TA - 0.000429\ ST*TA \quad (4)$$

Where ST is Solution temperature at ^{0}C and TA is Thermal Aging at ^{0}C.

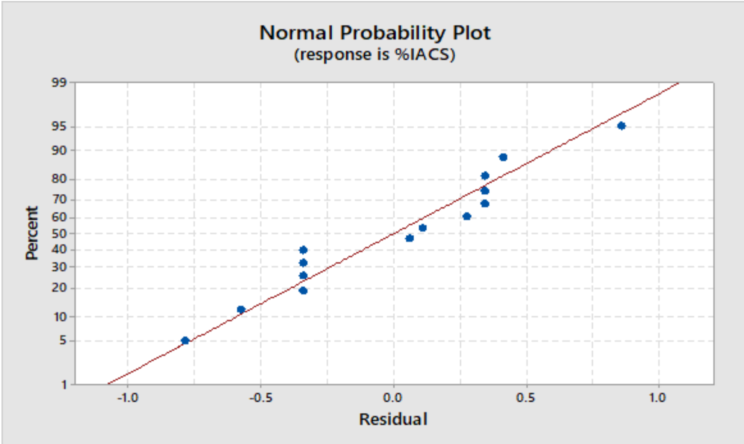
Vickers micro hardness, Rockwell hardness, and electrical conductivity of the manufactured Al MMC are all impacted by linear and two-way interactions. Eqs (2)–(4) shows that the HV, RHN, and %IACS are affected by positive sign parameters for increasing and negative sign parameters for decreasing, respectively. The normal probability plots for Vickers micro hardness, Rockwell hardness, and electrical conductivity are shown in Fig. 5 (a) through (c) respectively.



(a)



(b)



(c)

Fig. 5. Normal probability plot for (a) Vickers micro hardness; (b) Rockwell hardness; (c) Electrical Conductivity

4.3. Comparison between Experimental and Predicted Results

Mathematical modeling provided Equation (2)-(4) for predication of Vickers micro hardness (HV), Rockwell hardness number (RHN) and Electrical conductivity (%IACS) respectively for fabricated Al MMC. For each solution temperature (ST) and aging temperature (AT), Eqs (2)-(4) provides a predicated value of HV, RHN and %IACS respectively as shown in Table 4. We also calculated the Error percentage (%) of predicated HV, RHN and % IACS with respect to the experimental results as below. The negative (-) sign in Error % Calculation means that predicated results are found higher in some cases than the experimental results.

Table 4. Analysis of Experimental and Predicated Results with % of Error

Factor 1	Factor 2	Experimental Results			Predicted Results			Error (%) Calculation		
ST (°C)	AT (°C)	HV	RHN	%IACS	HV	RHN	%IACS	HV	RHN	%IACS
530.00	180.00	43.99	32.50	49.47	43.45	31.96	49.38	1.22%	1.65%	0.18%
501.72	180.00	42.08	30.04	48.53	41.49	28.21	47.23	1.41%	6.09%	2.69%
530.00	123.43	42.15	26.90	48.33	40.94	25.41	47.50	2.88%	5.53%	1.72%
530.00	236.57	43.83	27.25	45.70	42.92	25.65	45.15	2.08%	5.89%	1.21%
558.28	180.00	43.42	30.15	47.93	41.89	28.89	47.85	3.52%	4.19%	0.17%
530.00	180.00	43.99	32.50	49.47	43.45	31.96	49.38	1.22%	1.65%	0.18%
530.00	180.00	43.99	32.50	49.47	43.45	31.96	49.38	1.22%	1.65%	0.18%
530.00	180.00	43.99	32.50	49.47	43.45	31.96	49.38	1.22%	1.65%	0.18%
510.00	140.00	40.61	26.25	46.16	40.43	26.90	47.20	0.46%	-2.50%	-2.26%
550.00	220.00	41.95	27.25	45.99	42.11	27.55	45.97	-0.39%	-1.09%	0.05%
550.00	140.00	41.33	26.75	48.12	41.79	27.01	48.32	-1.11%	-0.96%	-0.43%
510.00	220.00	43.39	26.00	45.41	42.91	26.70	46.22	1.11%	-2.67%	-1.79%
530.00	180.00	43.99	32.50	49.47	43.45	31.96	49.38	1.22%	1.65%	0.18%
530.00	180.00	43.99	32.50	49.47	43.45	31.96	49.38	1.22%	1.65%	0.18%

5. Analysis of Response Optimization

It is possible to derive the Vickers micro hardness (HV), electrical conductivity (%IACS), Rockwell hardness (RHN), and optimality searches based on the proposed second-order response surface equations, i.e., Eqs (2)–(4). This is done in order to figure out the best electro-mechanical parameter combination and how it will affect the required response criterion [39]. Response surface methodology is the foundation of the optimality search model for the various process variable positions for optimizing the %ICAS, RHN, and HV values.

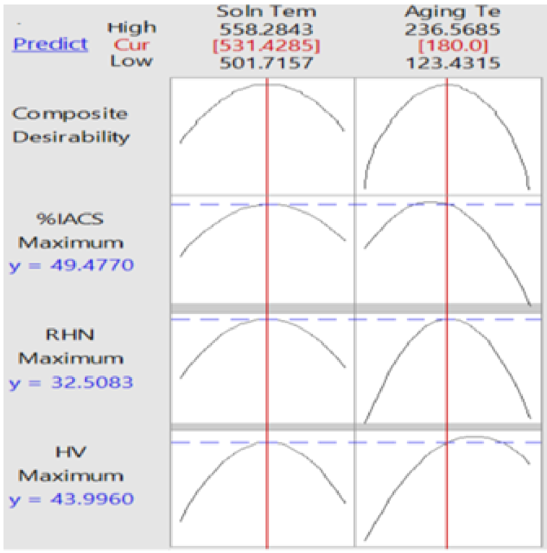


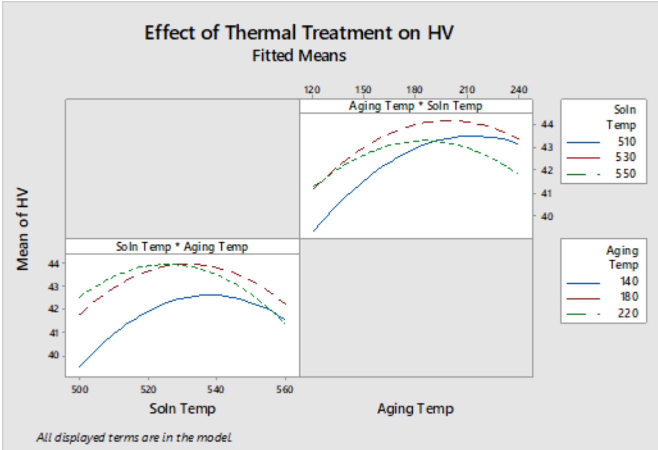
Fig. 6 Optimum Response results for maximum %IACS, RHN and HV

Fig. 6 shows that Solution Temperature of 531.428^{0}C and Aging Temperature of 180^{0}C as the most favorable values of Electrical Conductivity (%IACS), Rockwell hardness (RHN) and Vickers micro hardness (HV) which are 49.4770 % IACS, 32.5083 RHN and 43.9960 HV, respectively, through the optimized parametric combination.

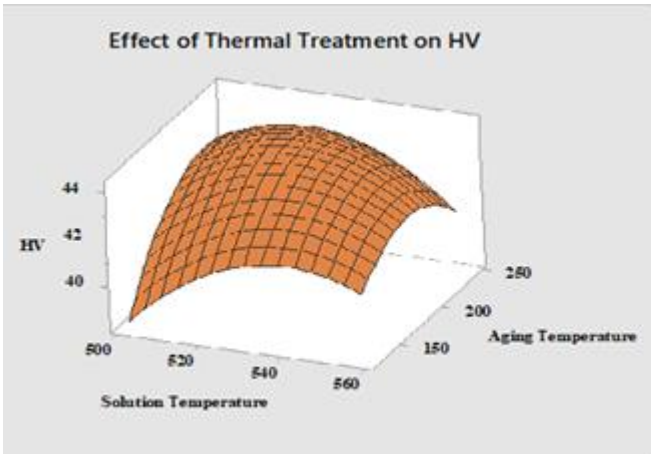
6. Results and Discussion

6.1 Effect of Heat Treatment on Vickers Micro hardness

As per the central composite (CC) design of RSM, a total 14 sets of heat treatments were carried out with different solution temperatures from 500°C to 560°C and aging temperatures from 120°C to 240°C for 1 hour for investigation of Vickers micro hardness. As per Fig. 7 (a) and Fig. 7 (b), the highest Vickers micro hardness of 43.99 HV was obtained for the solution temperature of 530°C and thermal aging at 180°C which is an improvement of 23.15% of HV in comparison to as-casted condition. Rajasekaran et al. (40) investigated T4 and T6 heat treatment effects on Al-15 Vol. % SiCP composite. As per their observation, the hardness profile of aging showed a sharp increase in hardness after the solution heat treatment at 558°C for 1 hour. In our current investigation, we also observed heat treatment at a solution temperature of 530°C and thermal aging at 180°C. We also observed that aging at higher temperatures, especially after 200°C led to softening of the alloy and the ductility also decreased. As a result, hardness also decreased with an increase in aging temperature which goes in line with the observation of Mahadevan et al. [41].



(a)

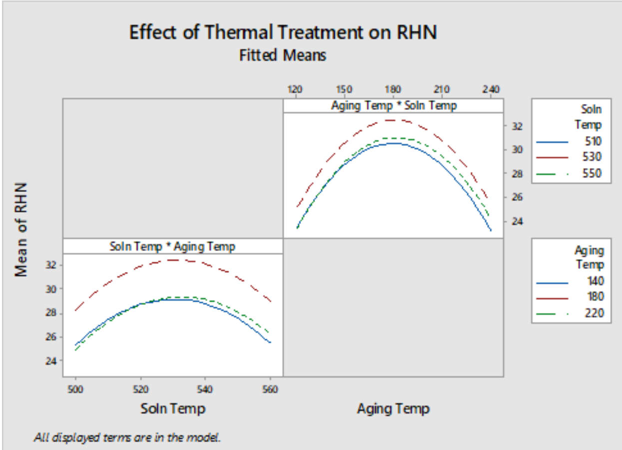


(b)

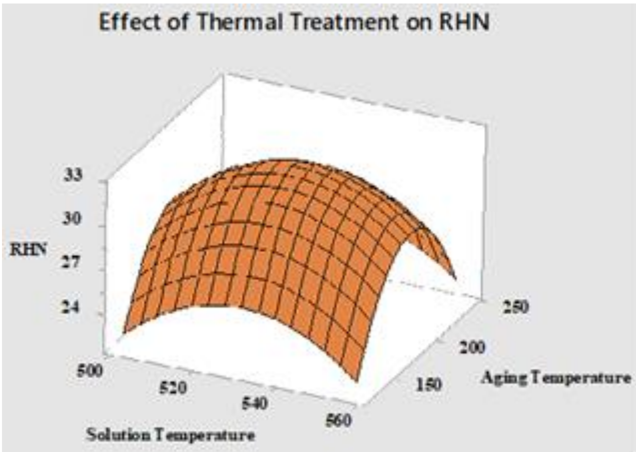
Fig.7 (a) Fitted means and (b) Surface plot for Vickers micro hardness of Al Composite

6.2 Effect of Heat Treatment on Rockwell hardness

As per the central composite (CC) design of RSM, a total of 14 set heat treatments were carried out with different solution temperatures from 500°C to 560°C and aging temperatures from 120°C to 240°C for 1 hour for investigation of Rockwell hardness. As per Fig. 8(a) and Fig. 8(b), the highest Rockwell hardness of 32.5 RHN was obtained for the solution temperature of 530°C and thermal aging at 180°C which is an improvement of 33.57% of RHN in comparison to the as-casted condition. Salleh et al. (42) studied the optimization of T6 heat treatment for aluminum alloy where they investigated the hardness values for different solution temperatures such as 510°C, 520°C, and 530°C and thermal aging temperatures such as 160°C, 170°C, and 180°C. As per their investigation, the highest hardness value was obtained for the solution temperature of 530°C and thermal aging temperature of 180°C. Therefore, our finding goes in line with the findings from Salleh et al. (42).



(a)



(b)

Fig.8 (a) Fitted means; (b) Surface plot for Rockwell hardness of Al Composite.

The results of this study indicate that heat treatment has a significant effect on the hardness of the aluminum composite. The hardness of the composite increases with an increase in the aging temperature, up to a certain point, and then decreases with a further increase in the aging temperature. This behavior can be explained by the precipitation of hardening phases during the aging process, which increases the strength and hardness of the composite up to a certain point. Beyond this point, over-aging can lead to the coarsening of these phases, which can decrease the hardness and strength of the composite. The results also show that the composite exhibits higher hardness values when subjected to a combination of solution treatment and aging compared to just aging. This can be attributed to the fact that the solution treatment allows for a more uniform distribution of the hardening phases, leading to an overall increase in the hardness of the composite. Farokhpour et al. (43)investigated the heat treatment effect of aluminum alloy at an aging temperature from 180^{0}C to 230^{0}C and observed the hardness and microstructure. As per their investigation, they observed the highest hardness values of an aluminum alloy at an aging temperature of 180^0C. Our findings and microstructure observation goes in line with Farokhpour et al. (43).

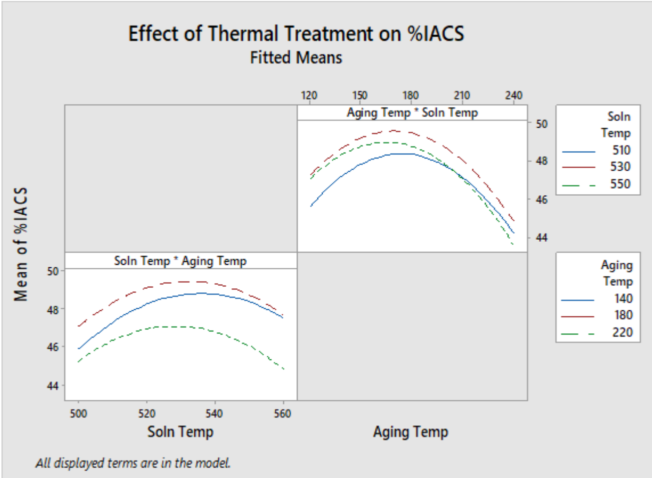
6.3 Effect of Heat Treatment on Electrical Conductivity

Heat treatment of aluminum composites affected the electrical conductivity due to changes in their microstructure. During the heat treatment process, the alloying elements in the Al composite form precipitate, which enhanced or hindered the flow of electrical current through the material as the temperature changed.

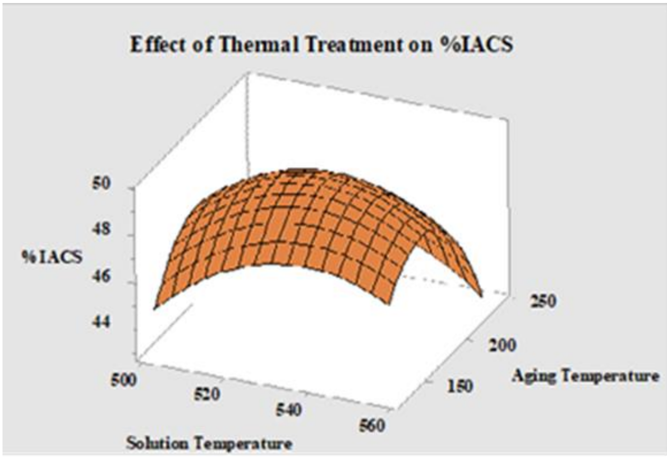
In particular, the formation of intermetallic compounds during heat treatment can negatively impact the electrical conductivity of the composite by hindering the movement of electrons. These compounds can act as barriers to the flow of current, reducing the number of conductive pathways in the material. Additionally, the coarsening of the precipitates during over-aging further decreases the electrical conductivity of the composite. This is because coarser precipitates can lead to a reduction in the number of conductive pathways, as the particles are further apart, and the composite becomes less conductive. On the other hand, heat treatment can also improve the electrical conductivity of aluminum composites by reducing the number of intermetallic compounds and increasing the number of conductive pathways through the material. This can be achieved by controlling the heat treatment process to ensure that the precipitates are uniformly distributed throughout the composite, leading to a more homogeneous microstructure and enhanced conductivity. By carefully selecting the heat treatment parameters, it is possible to optimize the electrical conductivity of aluminum composites for specific applications.

As per the central composite (CC) design of RSM, a total of 14 set heat treatments were carried out with different solution temperatures from 500°C to 560°C and aging temperatures from 120°C to 240°C for 1 hour for investigation of electrical conductivity. As per Fig.9(a) and Fig.9(b), the highest electrical conductivity of 49.47 %IACS was obtained for the solution temperature of 530°C and thermal aging at 180°C which is an improvement of 9.57% of electrical conductivity in comparison to the as-casted condition.

Diehl et al. (44) investigated that electrical conductivity increases significantly at various temperatures and constant times. They observed the removal of foreign atoms from the lattice of the parent alloy during precipitation hardening eliminates much distortion of electron disturbance in the lattice. Hence, these actions favor the movement of electrons through the metal and therefore result in higher conductivity. Pankade et al. (45) also investigated the influence of heat treatments on the electrical conductivity of AA 7075-T6 aluminum alloy where duplex aging at 163°C. The study reveals that duplex aging at 163˚C shows better results for electrical conductivity. Debih et al. (46) investigated the influence of heat treatment on mechanical properties and electrical conductivity of AA6101 Aluminum alloy. In their experiment, they performed heat treatment of Al alloy in three categories namely natural aging, artificial aging and combination of natural aging. As per their investigation, they observed highest improvement of micro hardness (HV) and electrical conductivity (%IACS) at combination of natural aging at 20^0C for 72 hours and artificial aging at 180^0C for 6 hours. In our present research work, we performed combination of natural aging of 72 hours and artificial aging of a constant time of 1hr at different temperatures from 120°C to 240°C as per CC of RSM. Here we observed the progressive improvement of electrical conductivity up to an aging temperature of 180°C. Therefore, our current findings go in line with the results outcome of Diehl et al. (44), Pankade et al. (45) and Debih et al. (46).



(a)



(b)

Fig. 9 (a) Fitted means; (b) Surface plot for electrical conductivity of Al composite

7. Microstructure

Two test samples of Al composite with dimensions of 05mm x 05mm x 05mm were prepared for microstructure observation using a scanning electron microscope (SEM), model TESCAN VEGA 4. As we noticed improvements in the electromechanical properties of our Al composite at various solution temperatures, the microstructure of the first sample was observed respectively at a solution temperature of 510^{0}C, and the second sample was observed at a solution temperature of 550^{0}C. In order to better understand how different heat treatment settings affected the distribution of reinforcement particles in Al composite, which helped to increase electromechanical parameters including hardness and electrical conductivity, SEM microstructure observation was used. The heat treatment at solution temperatures from 501°C to 550°C for 01 hour resulted in a breakdown of the course of Al dendrites and Al_2O_3 particles.

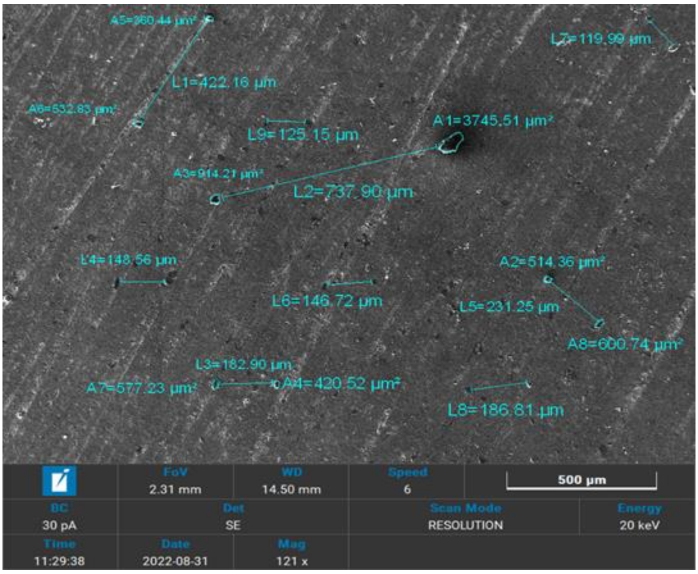


Fig.10 Microstructure observation of Al composite at solution temperature of 510⁰C.

As seen in Fig. 10, microstructure observation of an Al composite was done at a solution temperature of 510⁰C, with a FoV of 2.32 mm, WD of 14.5 mm, speed of 6 mm, 20 keV energy, 121 x magnification, and 500 µm. The shape of Al_2O_3 particles, as depicted in Fig. 10, is primarily amorphous or almost elliptical. The metal matrix contains Al_2O_3 particles that are evenly dispersed at a solution temperature of 510⁰C. SEM measurements are depicted in Fig.10 for the elliptical area submerged by some of the reinforcements (Al_2O_3) in the Al composite, labeled as A1 to A8. At a solution temperature of 510⁰C, the distances between some of the reinforcement particles in the metal matrix were also measured and designated as L1 to L9, as shown in Fig. 10.

As seen in Fig. 11, image processing is used to determine the distance and area that the reinforcement particles Al_2O_3 are submerged in the matrix after undergoing a 550⁰C solution treatment, respectively. Al_2O_3 reinforcement particles spread out in the matrix as a result of the heat treatment. We found that the measured distance between reinforcement Al_2O_3 particles in thermally treated conditions is greater than in cast conditions by comparing the microstructure images of the two situations. The electro-mechanical characteristics, such as hardness and electrical conductivity, displayed better conditions than when the reinforcement Al_2O_3 particles were cast, as a result of the solution and aging temperature effects on the matrix.

The use of proper process parameters during stir casting has helped in achieving the uniform distribution of reinforcement Al_2O_3 at base Aluminum with minor clustering. The fabrication of Al composites reinforced with SiC particles by a stir casting method, which was a low-cost way of MMC production, was carried out by Singla et al. (9) using a two-step mixing/stirring methodology. Their approach and testing with various SiC weight percentages on the assumption that all other factors would remain constant produced positive results for uniform matrix reinforcement dispersion, which effectively improved the strength and hardness of made-to-order Al composites. While we used a two-step stirring procedure to create our Al composite, we also see a similar uniform distribution of reinforcement particles in both Figs. 10 and 11. This discovery is consistent with Singla et al (9).

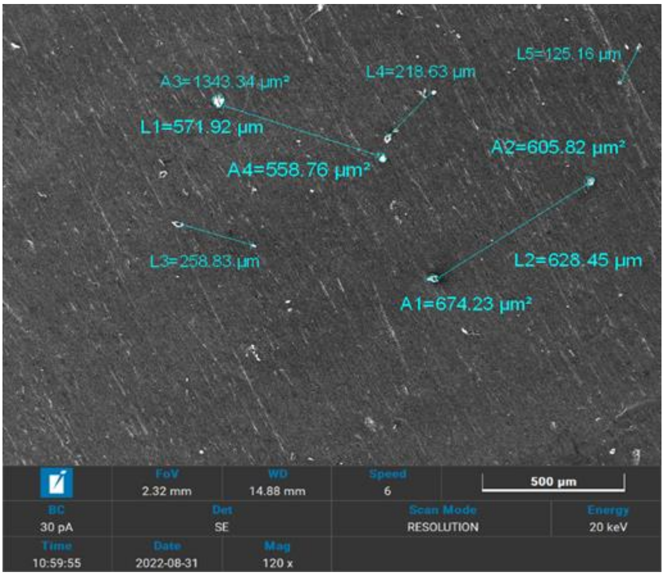


Fig.11 Microstructure observation of Al composite at solution temperature of 550⁰C.

It is also seen that higher solution temperatures create a uniform distribution of Al_2O_3 particles and dispersion of agglomeration in the Al matrix. Also, higher temperatures followed by rapid cooling (quenching) cause Al_2O_3 to diffuse more homogeneously across the interface. As per the analysis of microstructure, we can verify the changes in readings/test results through Hardness (Vickers and Micro & Rockwell) and Eddy Current Electrical Conductivity. The changes in electro-mechanical properties such as hardness and electrical conductivity have been revealed by microstructure with a clear distribution of reinforcement particles Al_2O_3 in Al composite for different heat treatment processes. The impact of heat treatment on the microstructure characteristics of Al 6063 alloy was examined by Azeez et al. (47). Taking into account the size and dimensions of the sample specimen, they used a heat treatment furnace to execute heat treatment at 450^0C and soaked it for an hour. They then quickly quenched the water. Their composites' morphology showed that the Al 6063 alloy used for heat treatment had reinforcing particles distributed evenly and uniformly throughout. In this investigation, we also used SEM to observe the microstructure under the following conditions: (a) at a solution temperature of 510^0C, and (b) at a solution temperature of 550^0C. Moreover, we saw a reasonably homogeneous distribution of reinforcement particles in both the heat-treated and as-cast conditions, which is consistent with Azeez et al. (47).

8. Conclusion

In the current study, an Al MMC has been developed using a two-step stir casting method, and its properties were investigated in a series of experiments as well as predicted using customized models. , The following is the summary of the current work:

- Three non-linear mathematical models have been developed through Central Composite design based on response surface methodology (RSM) for prediction of Hardness such as Vickers micro & Rockwell hardness and Electrical conductivity of manufactured Al MMC where R^2 obtained for HV, RHN and % IACS are respectively 89.29%, 96.23% and 91.50%.
- The most favorable values of HV, RHN, and %IACS achieved respectively as 43.99 HV, 32.5 RHN, and 49.47% IACS through the optimized parametric combination

of solution temperature of 531.428^{0}C and aging temperature of 180^{0}C. The optimized parameters of heat treatments contributed to the improvement of 23.15%, 33.57% and 9.57% respectively for Vickers micro, Rockwell hardness, and Electrical conductivity in comparison to as casted condition.

- As per the regression equation, the lowest and highest error (%) calculated between the experimental and prediction of HV are respectively 0.39% and 3.52%. For Rockwell hardness, the lowest and highest error (%) calculated between the experimental and prediction of RHN are respectively 0.96% and 6.09%. For Electrical conductivity, the lowest and highest error (%) calculated between the experimental and prediction of %IACS are respectively 0.05% and 2.69%.
- The microstructure reveals an almost uniform distribution of nano Al_2O_3 in Al composite with fewer agglomeration. The use of proper process parameters during stir casting has helped in achieving the uniform distribution of reinforcement Al_2O_3 at base Aluminum with minor clustering. It also revealed the formation of intermetallic compounds at different heat treatment processes which impacted the changes in the electro-mechanical properties of fabricated Al composite.
- As a whole the developed mathematical models can be considered useful for predicting purposes of thermal treatment effects of Al MMCs.

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References

[1] Swamy PK, Mylaraiah S, Gowdru Chandrashekarappa MP, Lakshmikanthan A, Pimenov DY, Giasin K, Krishna M. Corrosion Behaviour of High-Strength Al 7005 Alloy and Its Composites Reinforced with Industrial Waste-Based Fly Ash and Glass Fibre: Comparison of Stir Cast and Extrusion Conditions. Materials. 2021;14(14):3929. https://doi.org/10.3390/ma14143929

[2] Naik MH, Manjunath L, Koti V, Lakshmikanthan A, Koppad PG, Kumaran SP. Al/Graphene/CNT hybrid composites: Hardness and sliding wear studies. FME Trans. 2021;49:414-421. https://doi.org/10.5937/fme2102414N

[3] Gebre Fenta Aynalem. Processing Methods and Mechanical Properties of Aluminum Matrix Composites. Advances in Materials Science and Engineering. 2020;2020:3765791. https://doi.org/10.1155/2020/3765791

[4] Kumar KV, Jayahari L. Study of mechanical properties and wear behaviour of aluminum 6063 matrix composites reinforced with steel machining chips. Materials Today: Proceedings. 2018;5(9):20285-20291. https://doi.org/10.1016/j.matpr.2018.06.400

[5] Singh J, Jawalkar CS, Belokar RM. Analysis of mechanical properties of AMC fabricated by vacuum stir casting process. Silicon. 2020;12(10):1-7. https://doi.org/10.1007/s12633-019-0078-3

[6] Sable AD, Deshmukh SD. Preparation of MMCs By Stir Casting Method. International Journal of Mechanical Engineering and Technology. 2012;3(3):299-305.

[7] Reddy BR, Srinivas C. Fabrication and characterization of silicon carbide and fly ash reinforced aluminum-metal matrix hybrid composites. Materials Today: Proceedings. 2018;5(2):8374-8381. https://doi.org/10.1016/j.matpr.2017.11.531

[8] Gopalakrishnan S, Murugan N. Production and wear characterisation of AA 6061 matrix titanium carbide particulate reinforced composite by enhanced stir casting method.

Composites Part B: Engineering. 2012;43(2):302-308. https://doi.org/10.1016/j.compositesb.2011.08.049
[9] Singla M, Dwivedi DD, Singh L, Chawla V. Development of aluminum based silicon carbide particulate metal matrix composite. Journal of Minerals and Materials Characterization and Engineering. 2009;8(6):455-467. https://doi.org/10.4236/jmmce.2009.86040
[10] Dehghan Hamedan A, Shahmiri M. Production of A356-1wt% SiC nanocomposite by the modified stir casting method. Materials Science and Engineering A. 2012;556:921-926. https://doi.org/10.1016/j.msea.2012.07.093
[11] Hassen SB, Aponbide O, Aigbodion VS. Precipitation hardening characteristics of Al-Si-Fe/SiC particulate composites. Journal of Alloy Compounds. 2008;466:268-272. https://doi.org/10.1016/j.jallcom.2007.11.023
[12] Soboyejo W. Mechanical Properties of Engineered Materials. New York: Marcel Dekker, Inc.; 2003. https://doi.org/10.1201/9780203910399
[13] Miracle DB. Metal Matrix Composites: From Science to Technological Significance. Composites Science and Technology. 2005;65(15):256-262. https://doi.org/10.1016/j.compscitech.2005.05.027
[14] Aqida SN, Ghazali MI, Hashim J. The effects of stirring speed and reinforcement particles on porosity formation in cast MMC. Jurnal Mekanikal. 2003;(16):22-30. ISSN 0127-3396.
[15] Mathur S, Barnawal A. Effect of Process Parameter of Stir Casting on Metal Matrix Composites. International Journal of Science and Research (IJSR). 2013;2(12):1-6. ISSN 2319-7064.
[16] Kumar R, Parshuram M. Preparation of Aluminum Matrix Composite by Using Stir Casting Method. IJEAT. 2013;3:570-575.
[17] Sozhamannan GG, Prabu SB, Venkatagalapathy VSK. Effect of Processing Parameters on Metal Matrix Composites: Stir Casting Process. Journal of Surface Engineered Materials and Advanced Technology. 2012;2:11-15. https://doi.org/10.4236/jsemat.2012.21002
[18] Seo YH, Kang CG. The effect of applied pressure on particle-dispersion characteristics and mechanical properties in melt-stirring squeeze-cast SiCp/ Al composites. J Mater Process Technol. 1995;55:370-379. https://doi.org/10.1016/0924-0136(95)02033-0
[19] Kumar A, Singh RC, Chaudhary R. Recent progress in production of metal matrix composites by stir casting process: An overview. Materials Today: Proceedings. 2019;16:2441-2450.
[20] Dao V, Zhao S, Lin W, Zhang C. Effect of process parameters on microstructure and mechanical properties in AlSi9Mg connecting-rod fabricated by semi-solid squeeze casting. Mater Sci Eng A. 2012;558:95-102. https://doi.org/10.1016/j.msea.2012.07.084
[21] Saravanakumar P, Soundararajan R, Deepavasanth PS, Parthasarathi N. A review on effect of reinforcement and squeeze casting process parameters on mechanical properties of aluminium matrix composites. Int J Innov Res Sci Eng Technol. 2016;5:58-63.
[22] Das DK, Mishra PC, Singh S, Pattanaik S. Fabrication and heat treatment of ceramic-reinforced aluminium matrix composites - a review. Int J Mech Mater Eng. 2014;9(6):1-14. https://doi.org/10.1186/s40712-014-0006-7
[23] Sakthivelu S, Sethusundaram PP, Meignanamoorthy M, Ravichandran M. Synthesis of metal matrix composites through stir casting process-a review. Mechanics and Mechanical Engineering. 2018;22(1):351-363. https://doi.org/10.2478/mme-2018-0029
[24] Surappa MK. Aluminium matrix composites: Challenges and opportunities. Sadhana. 2003;28(1-2):319-334. https://doi.org/10.1007/BF02717141

[25] Bhoi NK, Singh H, Pratap S. Developments in the aluminum metal matrix composites reinforced by micro/nano particles - A review. Journal of Composite Materials. 2020;54(6-7):857-878. https://doi.org/10.1177/0021998319865307
[26] Saravanan C, Subramanian K, Ananda Krishnan V, Sankara Narayanan R. Effect of particulate reinforced aluminium metal matrix composite -A review. Mechanics and Mechanical Engineering. 2015;19(1):23-30.
[27] Yuan Z, Li F, Zhang P, Chen B, Xue F. Mechanical properties study of particles reinforced aluminum matrix composites by micro-indentation experiments. Chinese Journal of Aeronautics. 2014;27(2):397-406. https://doi.org/10.1016/j.cja.2014.02.010
[28] [Kok M. Production and mechanical properties of Al_2O_3 particle-reinforced 2024 aluminium alloy composites. J. Mater. Process. Technol. 2005;161:381-387. https://doi.org/10.1016/j.jmatprotec.2004.07.068
[29] Pilania G, Thijsse BJ, Hoagland RG, Laziä I, Valone SM, Liu XY. Revisiting the Al/Al2O3 interface: coherent interfaces and misfit accommodation. Sci. Rep. 2014;4:1-9. https://doi.org/10.1038/srep04485
[30] 30Aybarç U, Ertugrul O, Seydibeyoğlu M. Effect of Al_2O_3 Particle Size on Mechanical Properties of Ultrasonic-Assisted Stir-Casted Al A356 Matrix Composites. International Journal of Metal casting. 2020;14:609-619. https://doi.org/10.1007/s40962-020-00490-7
[31] ASM Handbook. Aluminum and Aluminum Alloy Specialty Handbook. ASM International: Materials Park, OH, USA, 2002.
[32] Manda CS, Surendra Babu B, Ramaniah N. Effect of Heat Treatment on Mechanical properties of Aluminium metal matrix composite (AA6061/MoS2). Advances in Materials and Processing Technologies. 2022;8(sup1):205-222. https://doi.org/10.1080/2374068X.2020.1860593
[33] Tiwari SK, Soni S, Rana RS, Singh A. Effect of Heat Treatment on Mechanical Properties of Aluminium alloy-Fly ash Metal Matrix Composite. Materials Today: Proceedings. 2017;4(2):3458-3465. https://doi.org/10.1016/j.matpr.2017.02.235
[34] Myers RH, Montgomery DC, Anderson-Cook CM. Response Surface Methodology. 3rd ed. Hoboken, NJ: Wiley; 2009.
[35] Mukherjee I, Ray PK. A review of optimization techniques in metal cutting processes. Comput Ind Eng. 2006;50(1-2):15-34. https://doi.org/10.1016/j.cie.2005.10.001
[36] Patel MGC, Krishna P, Parappagoudar MB. Modelling of squeeze casting process using design of experiments and response surface methodology. Int J Cast Met Res. 2015;28(3):167-180. https://doi.org/10.1179/1743133614Y.0000000144
[37] Wang H, Li GY. Optimization of draw bead design in sheet metal forming based on intelligent sampling by using response surface methodology. J Mater Process Technol. 2008;206(1-3):45-55. https://doi.org/10.1016/j.jmatprotec.2007.12.002
[38] Md Jalal Uddin Rumi, Muhammad Muzibur Rahman, Effect of Heat Treatment on Hardness and Electrical Conductivity of nano Al_2O_3 reinforced Al MMC, Metal Science and Heat Treatment, Springer 2023 (in Press).
[39] Llorca J. Fatigue of particle and whisker reinforced metal matrix composites. Programme Material Science. 2002;47:283-353. https://doi.org/10.1016/S0079-6425(00)00006-2
[40] Rajasekaran S, Udayashankar NK, Nayak J. T4 and T6 Treatment of 6061 Al-15 Vol.%SiCP Composite. ISRN Mater Sci. 2012;2012:374719. doi:10.5402/2012/374719 https://doi.org/10.5402/2012/374719
[41] Mahadevan K, Raghukandan K, Pai BC, Pillai UTS. Influence of precipitation hardening parameters on the fatigue strength of AA 6061-SiCp composites. J Mater Process Technol. 2008;198:277-281. https://doi.org/10.1016/j.jmatprotec.2007.06.075

[42] Salleh MS, Hashim H, Omar MZ, Sulong AB, Rahman SA, Yahaya SH, Rashid MWA, Zubaidi SA. T6 Heat Treatment Optimization of Thixoformed LM4 Aluminium Alloy using Response Surface Methodology. Malays J Compos Sci Manuf. 2020;3(1):1-13. https://doi.org/10.37934/mjcsm.3.1.113
[43] Farokhpour M, Aghareb Parast MS, Azadi M. Evaluation of Hardness and Microstructural Features in the Piston Aluminum-Silicon Alloys after Different Heat Treatments. SSRN Electronic Journal. 2022;10.2139/ssrn.4112917. https://doi.org/10.2139/ssrn.4112917
[44] Diehl D, Köhler C, Schneider EL, Gabriel T, Clarke R. Eddy Current at High Temperatures for In-Situ Control of Heat Treatment Precipitation in Hardening Aluminum Alloys. IEEE Sens J. 2020;20(17):9699-9705. https://doi.org/10.1109/JSEN.2020.3008629
[45] Pankade SB, Khedekar DS, Gogte CL. The Influence of Heat Treatments on Electrical Conductivity and Corrosion Performance of AA 7075-T6 Aluminium Alloy. Procedia Manuf. 2018;20:53-58. https://doi.org/10.1016/j.promfg.2018.02.007
[46] Debih A. Influence of heat treatment on mechanical properties and electrical conductivity of AA6101 Aluminum alloy. 2023.
[47] Azeez TM, Lateef M, Adeleke A, Ikubanni P, Olayinka A, Adesina OS. Effect of Heat Treatment on Micro Hardness and Microstructural Properties of Al 6063 Alloy Reinforced with Silver Nanoparticles (AgNps). IOP Conf Ser Mater Sci Eng. 2021;1107(1):012013. https://doi.org/10.1088/1757-899X/1107/1/012013