Jurnal Kejuruteraan 36(2) 2024: 769–776
https://doi.org/10.17576/jkukm-2024-36(2)-33

A Taguchi Optimization of Stir Casting Process Parameters for graphene Nanoplatelets/ A356 Alloy Composite

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Received 30 July 2022, Received in revised form 14 October 2023
Accepted 24 November 2023, Available online 30 March 2024

ABSTRACT

Aluminum metal matrix composite (AMC) is a potential material for diverse applications in the field of automotive and aerospace owing to their superior mechanical properties, lightweight behavior, and low thermal expansion. Graphene nanoplatelets (GNP) have emerged as the preferred reinforcement in AMC. They are incorporated into the matrix by stir-casting methods to generate semi-solid feedstock suitable for thixoforming. The effects of the stirrer parameter and GNP content were examined using Taguchi design of experiments with an L8 (2^3) orthogonal array. The parameters tested were stirring speed (300-500rpm), GNP content (0.3- 0.7 wt%) and stirring time (5-10 minutes). The signal-to-noise ratio (S/N) and hardness of the GNP /A356 composite were used as response variables. The contribution of three factors in enhancing hardness has been identified. The optimum parameter obtained with stirring speed, GNP content, and stirring time is 500rpm, 0.7wt.%GNP and 5 min respectively.

Keywords: Metal matrix composite; graphene; Taguchi method; stir casting

INTRODUCTION

In the automotive industry, the challenges of reducing weight and cost have gained significant attention. The automakers have been making progress in minimizing the weight of their vehicles while catering to customer demands for safety, interior features, comfort, navigation, and entertainment (Anthony et al. 2020). Vehicle makers are using lightweight metals or alloys to address these issues. Due to its lower density compared to steel, light metals such as aluminium emerge as the ideal replacements for steel in vehicle components. For example, automobile components such as alternator housings, gearbox housings, valve covers, and intake manifolds could potentially be substituted with Al alloy. Over the last three decades, extensive research has been conducted on aluminium alloy-based composites, resulting in improved physical and mechanical properties.

Fabrication of aluminum matrix composite with incorporation of additional reinforcing material represents a strategy to enhance the mechanical properties. Researchers have introduced ceramics particles (SiC, Alumina, TiC), and carbon particles (carbon nanotubes, graphene) (Hanizam et al. 2019; Md Ali et al. 2021) to enhance strength and wear properties. Various method has been employed to fabricate the composite which include solid route such as powder metallurgy and spark plasma sintering as well as liquid route like casting. Among these, mechanical stir casting stands out as one of the most cost-effective approaches for producing near-net structures suitable for semi-solid processing. However, limitations arise from poor wettability and porosity. (Bastwros et al. 2014; Bisht et al. 2017; Leng et al. 2020; Saboori et al. 2018; Venkatesan & Anthony Xavior 2018). A proper bonding between matrix and reinforcement is a significant challenge to ensure effective load transfer across phases. This bonding is crucial for the facilitation of good wettability and the optimal selection of process parameters.

Thus, the combination of thixoforming and stir casting is our approach to counter the limitation. Thixoforming is a semi-solid metal processing (SSMP) that requires a near-net shape structure. Components fabricated by SSMP offer several advantages including reduction in macro-segregation, porosity, and enhancement in mechanical properties compared to conventional routes. The main requirement for SSM is the slurry with nearly globular primary α-Al particles. The slurry should exhibit thixotropic behavior with a non-dendritic or near-globular primary phase microstructure and a uniformly distributed fine grain size within the matrix (Samat et al. 2021). To obtain non-dendritic feedstock, various processing routes are employed including strain-induced melt activated (SIMA), magneto-hydrodynamic stirring (MHD), cooling slope and mechanical stir casting (Atkinson et al. 2010).

Researchers have employed the mechanical stir casting method to fabricate the composite. Venkatesan & Anthony Xavior (2018) reported on an aluminium matrix reinforced with graphene content and observed a significant decrease in tensile strength when the graphene content exceeded 0.3% in the aluminum matrix. It is difficult to distribute the reinforcement uniformly into the matrix; consequently, a decrease in the mechanical properties of composites was observed. Prabu et al. (2006)reported that a uniform distribution of graphene in the Al matrix at 600rpm stirring speed and 10 min stirring time led to higher hardness.

Taguchi provides a straightforward and systematic technique to reduce costs while enhancing performance and quality. Signal-to-noise (S/N), which assesses quality with variable emphasis, and orthogonal arrays (OA), which control multiple design elements simultaneously, are two crucial tools in this design. Meanwhile, analysis of variance (ANOVA) is a computational procedure that quantifies and expresses the relative contribution of each control factor as a percentage. Kumar et al. (2014) applied the Taguchi method to optimize cooling slope parameters for semi-solid A356 alloy reinforced 5TiB2 composite. They reported that Taguchi had effectively estimated the hardness value for A356 alloy as it is correlated with the experimental results. Ahmadkhaniha et al. (2015) studied the influence of rotational tool speed, travel speed, tilt angle, and penetration depth on the hardness value of Mg via the Taguchi method. Past studies demonstrated that Taguchi method enables a comprehensive understanding and combined effects with a minimal number of experiments (Abdelgnei et al. 2020; Arifin et al. 2017; Hanizam et al. 2019).

Hence, this study presents the optimization of manufacturing GNP reinforced A356 alloy via mechanical stir casting process focusing on variables such as stirring speed, stirring time and graphene content, on the hardness behaviour of semi-solid A356/ GNP composite. The Taguchi method is employed to achieve optimization considering two varying factorial level for each variable. The effect on hardness was assessed and larger is better as the target value was used in the S/N ratio. The relationship between microstructure analysis and the hardness was also revealed.

EXPERIMENTAL PROCEDURE

MATERIALS

In the present experiment, a commercial A356 alloy and A356/GNP composites were fabricated by the mechanical stir casting process. The chemical composition of the alloy was obtained using Optical Emission Spectrometer and presented in Table 1. Figure 1(a) shows a collection of GNP powder for each run while Figure 1(b) illustrated the composite in billet form with a dimension length and height of 25 mm and 120 mm respectively.

TABLE 1. Chemical composition of the base material A356 alloy

Si	Mg	Fe	Mn	Cu	Ni	Sn	Al
6.5%	0.3%	0.1%	0.03%	0.02%	0.1%	0.05 %	Balance

FIGURE 1. (a) GNPs in powder form (b) Sample composite cast

PROCESSING OF GNP-A356 COMPOSITE

The GNP-A356 composite was fabricated using the stir-casting method as depicted schematically in Figure 2(a). Initially, approximately 400g of aluminium alloy was melted at 700 °C in an induction furnace and then reduced to 650 °C. To eliminate dissolved gas and prevent porosity issues, 1 wt% of hexachloroethane was added as degassing agent. The melt was then agitated using a stirrer to create a vortex. Then, the reinforcement GNPs and wetting agent magnesium (Mg) were weighted and wrapped in aluminium foil forming a small tube that were subsequently added to the aluminium melt. Mg powder (0.5 wt%) was mixed to improve the wettability between Al alloy and GNP particles. In Figure 2 (b), the three-blade stirrer was inserted inside the crucible at a distance of 2/3 from the top. Next, the molten alloy slurry was continuously stirred under the different processing conditions, varying the GNPs weight per cent content, stirring speed, and stirring time. The rotational speed of the stirrer was set at either 300 rpm or 500 rpm as per the design experiment. Stirring time of 5 and 10 minutes were recorded after adding 0.3 wt% and 0.7 wt% GNP during the process. Finally, the molten metal at a temperature of 650 °C was then poured into the permanent mould of 25 mm in diameter and 110 mm in height.

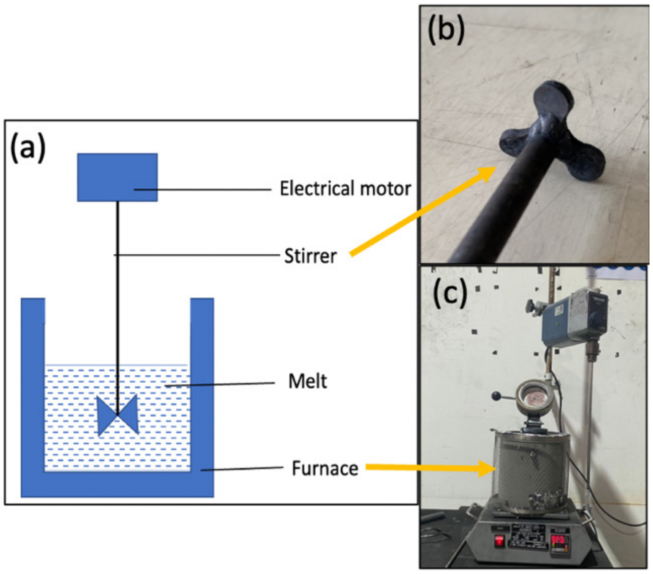

FIGURE 2. (a) A schematic image of stir-casting set-up, (b) a three-blade stainless steel stirrer (c) experimental work set-up

TAGUCHI AS EXPERIMENT DESIGN METHOD

A trusted and well-known tool for a superior system design is Taguchi's experiment design. The design is optimized systematically for cost, performance, and quality. In this study, a design of experiments with two levels and three factors and eight numbers of experiments has been used. The stir casting process parameters such as the GNP content, stirring speed and stirring time were assigned to the first, second and third rows respectively shown in Table 2.

The larger-the-better was used to obtain the optimum hardness value of AMC. The response for the hardness values of composite based on Vickers Micro hardness was determined. The Vickers hardness at 0.3kgf load was used to measure the hardness of composite processed at a dwell time of 15 sec according to ASTM BE384. The Vickers micro-hardness measurement was carried out at ten different regions of each sample and the average value was recorded. The analysis of the experimental data was carried out by MINITAB 19 software.

TABLE 2. Process factors and their respective levels for stir casting

Factor	Levels	
	L1	L2
GNP content (wt%)	0.3	0.7
Stirring speed (rpm)	300	500
Stirring time (min)	5	10

SIGNAL-TO- NOISE RATIO

A signal-to-noise (S/N) ratio was calculated by employing the average hardness values of the measurement. The quality characteristic used was the "larger-the-better" since the performance was measured in terms of average hardness, and it is expected to be as high value as possible which is represented by the following Equation (1) (Nalbant et. al. 2007).

$$\frac{S}{N} = -10\ log\left[\frac{1}{n}\sum_{i=1}^{n} {y_i}^2\right] \tag{1}$$

where n is the number of measurements (here n= 10 and y_i is the i^th^ response value of hardness for each noise repetition of the number while subscript i refer to number of design parameters in orthogonal array.

Statistical analysis was performed by ANOVA to determine significant differences among the factors. It evaluates the significance of the controlling factor by evaluate the F-ratio and the percentage contribution. Sum of squares (SS) degrees of freedom (DOF), mean of square (MS) and associated F-test of significance (5%) can be calculated as follows in Equation (2)-(6) (Nalbant et al. 2007).

$$SS_T = \left[\sum_{i=1}^{N}\left(\frac{S}{N}\right)i^2\right] - \frac{T^2}{N} \tag{2}$$

Where SS_T is the sum of squares due to total variation, N is the total number of experiments.

$$SS_A = \left[\sum_{i=1}^{K_a}\left(\frac{Ai^2}{n_A}\right)\right] - \frac{T^2}{N} \tag{3}$$

where SS_A is the sum of squares due to the factor A; K_a is the number of levels for factor A; A_i is the sum of the total in the the level of the factor A. V_{total} is the variance of degrees of freedom, V_{factor} is the variance of factors, V_{errors} is the variance of errors, SS_{factor} is the sum of squares of the factor and F_{factor} is the F ratio of the factor as follows.

$$V_{Total} = N - 1 \tag{4}$$

$$V_{factor} = \frac{SS_{Factor}}{V_{Factor}} \tag{5}$$

$$F_{factor} = \frac{V_{factor}}{V_{error}} \tag{6}$$

RESULTS AND DISCUSSION

TAGUCHI OPTIMIZATION

Table 3 presents the average hardness values and their corresponding S/N ratio values obtained from the experiments. The data highlights that run 7 recorded the highest hardness value at 80.09 HV accompanied by an S/N value of 38.07. Conversely, run 1 exhibited the lowest hardness value of 67.91HV aligning with an S/N value of 36.63.

TABLE 3. Hardness and S/N ratio response value based on L8 Orthogonal Array (OA)

Experiment No.	Factors			Response	
	Graphene content (wt%)	Stirring speed (rpm)	Stirring time (min)	Average Hardness (HV)	S/N ratios
1	0.3	300	5	67.91	36.63
2	0.3	300	10	71.09	37.03
3	0.3	500	5	72.64	37.22
4	0.3	500	10	78.00	37.84
5	0.7	300	5	73.33	37.30
6	0.7	300	10	72.64	37.22
7	0.7	500	5	80.09	38.07
8	0.7	500	10	79.09	37.96

The response efficiency relies on the S/N ratio. This relationship is depicted in Table 4, which presents the response table showcasing the mean S/N ratio of hardness for each factor. The optimal condition for achieving desired hardness values was identified by considering the sequence Stirring speed > Graphene percentage > Stirring time. The impact of stirring speed on hardness values is particularly notable, as indicated by the delta rank value derived from the S/N ratio measurements.

TABLE 4: Means of SN ratio for the hardness of GNP/A356 composite

Level	Factors		
	Graphene percentage(wt%)	Stirring speed (rpm)	Stirring time (min)
1	37.20	37.05	37.32
2	37.65*	37.80*	37.46*
Delta	0.45	0.75	0.14
Rank	2	1	3

*Optimum value

Figure 3 illustrates the main effects plot for SN ratio with the selection of the optimal criteria aimed at maximizing hardness values. Based on the analysis of the S/N ratio (refer to Figure 3 and Table 4), the optimal factors as follows 0.7 wt.% of graphene content, 500 rpm of stirring speed and 10 min of stirring time. The most significant parameter was identified by ANOVA analysis as shown in Table 5. The percentage contribution, P calculation for the process factors is outlined in Equation 7 (Nalbant et al. 2007).

$$F_{factor} = \frac{V_{factor}}{V_{error}} \qquad (6)$$

ANOVA results also highlights that both graphene percentage and stirring speed significantly contribute to the hardness, as demonstrated in Table 5. While the stirring time had relatively lower impact on the hardness of AMC. However, it is important to note that stirring time factor remains a crucial component that cannot be eliminated from the AMC manufacturing process.

The primary factor influencing hardness was the stirring speed percentage, making a significant contribution of 60%. This was followed by graphene content at 23.8%, and lastly, stirring time at 4.8%. The residual error contributed 11.24% to the overall variation. This underscores the collective influence of all significant factors on the average value, underscoring their relevance in the experimental analysis. As per the Taguchi method, the contribution percentage of error is ideally expected to be below 50%.

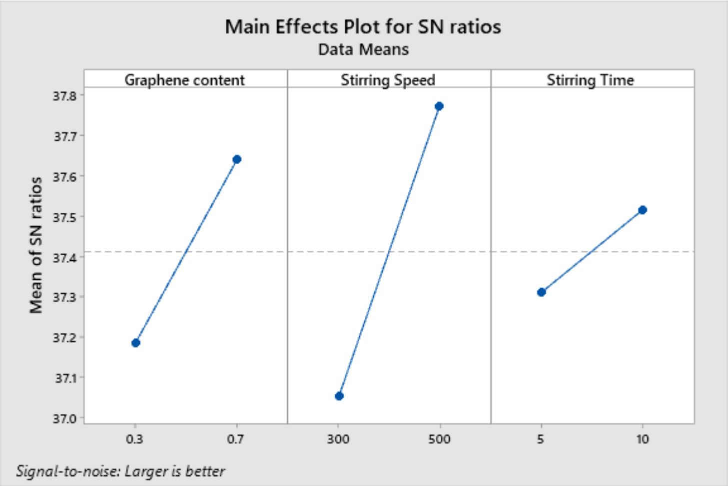

FIGURE 3. Main effect plot for average S/N ratios for hardness

TABLE 5. ANOVA table for S/N ratio hardness value GNP-Al composite

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Contributions
GNPs percentage (wt%)	1	0.415	0.415	0.415	8.47	0.044	23.8%
Stirring speed (rpm)	1	1.047	1.047	1.04793	21.37	0.010	60.0%
Stirring time (min)	1	0.085	0.085	0.08500	1.73	0.258	4.8%
Residual Error	4	0.196	0.196	0.04904			11.2%
Total	7	1.744					

MICROSTRUCTURAL ANALYSIS

Figure 4 displays the microstructure of the received A356. The micrograph presents the dendritic arm microstructure of the α-Al phase surrounded by eutectic Si. Figure 5 shows the comparison between Run 7 which exhibits the highest hardness and Run 1 which reveals the lowest hardness. In the microstructure of Run 7(Figure 5a), the Al phase reveals a transformed appearance with ripened rosette and nearly globular shapes, along with a reduced in grain size. In contrast, Run 1 predominantly exhibits an Al phase characterized by coarse rosette shapes (Figure 5b). The optimised stirring process generates a vortex, effectively subjecting the molten alloy to substantial shearing forces. These forces efficiently fracture dendritic arms, encouraging in the formation of a ripened rosette-like and nearly globular arrangement of primary α-Al phase within the liquid matrix (Ji et al. 2022). Additionally, the high amount of GNP particles was effectively dispersed after 10 minutes of stirring process in Run 7 due to the shearing forces of stirrer. This dispersion and changes in the nearly globular and ripened rosette shapes of α-Al phase shapes contributes to the observed increase in hardness.

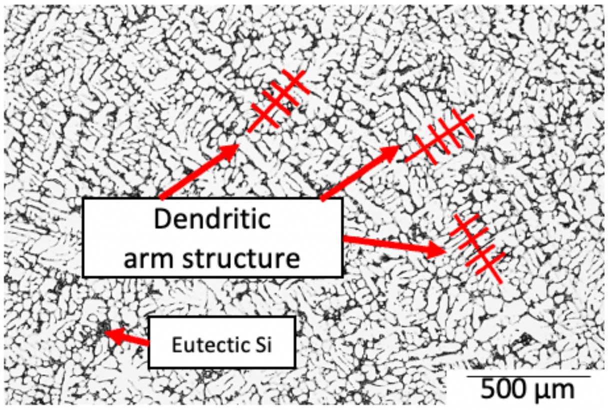

FIGURE 4. As-cast of A356 alloy with dendritic structure

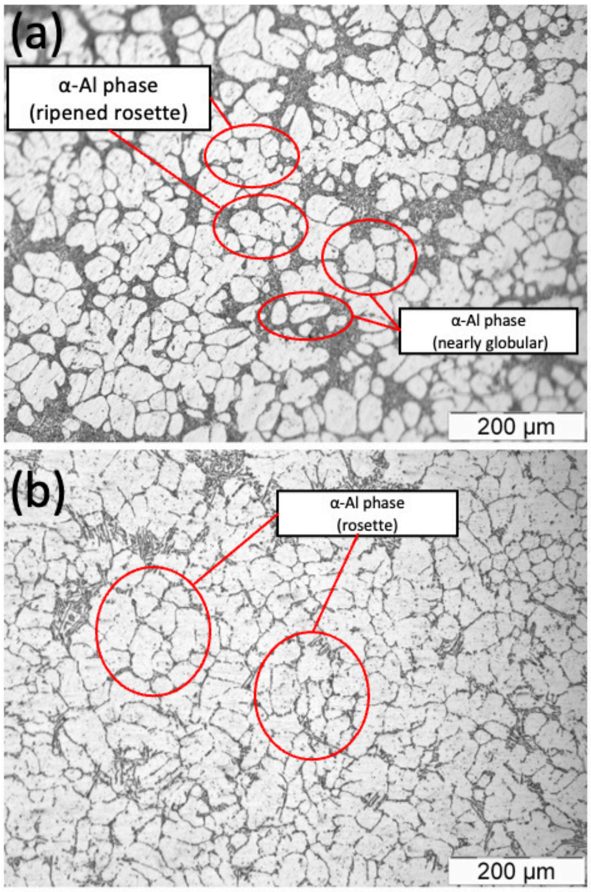

FIGURE 5. Optical micrograph of as-cast GNP-A356 composite in (a) Run 7 and (b) Run 1

CONCLUSION

This study discussed the application of Taguchi method to investigate the effects of stir casting process factors on the hardness surface of GNP-A356 composite. The Taguchi's optimization method using conceptual S/N ratio approach and ANOVA, the present study draws the following conclusions.

1. Taguchi experimental method was performed using an L_8 orthogonal array to analyze the hardness of the composite. The highest hardness value of 80.09 HV was obtained in the Run 7 sample.
2. Taguchi's design of experiments had resulted the optimal combination of stir casting process factors at high stirring speed of 500rpm, a substantial GNP content of 0.7 wt%, and low stirring time of 5 min increased the composite hardness.
3. The ANOVA results reveals that the stirring speed is the most significant factor in the hardness of the composite, accounting for almost 60% followed by GNPs percentage (23.79%) and stirring time (4.8%), respectively.
4. The microstructure resulting from stir-casting process has successfully formed a non-dendritic microstructure which is an excellent candidate as a feedstock for the thixoforming.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support from University Kebangsaan Malaysia (UKM), Universiti Teknikal Malaysia (UTEM), and would like to thank the Higher Ministry of Education Malaysia for the financial support received under research grant FRGS/1/2019/TK03/UKM/01/1. We also appreciate the cooperation from the Centre for Research and Instrumentation (CRIM) UKM for providing instrumentations and facilities.

DECLARATION OF COMPETING INTEREST

None

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