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Optimization of Stir Casting Parameters and Hardness Properties of Aluminium Alloy-Graphene-Rice Husk Ash Composites

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ABSTRACT

This study explores the development of innovative lightweight composites by optimizing stir casting conditions and evaluating the hardness properties of aluminium alloy reinforced with graphene and rice husk ash (RHA). A fixed graphene nanoparticle reinforcement of 0.4 wt.% was used, while the RHA content varied at 0.8 %, 1.2 %, and 1.6 % by weight, with particle sizes of 150 µm, 300 µm, and 600 µm respectively. To guarantee even distribution of reinforcements, the stir casting procedure was carried out at a speed of 140 rpm and a duration of 2 minutes. A statistical method called Response Surface Methodology (RSM) was employed to plan the experiments and enhance the process parameters concerning the hardness of the composite. The resulting cast was machined into a suitable coupon for hardness tests in accordance with ASTM standards. In order to build linear regression equations for the attributes of composites produced under these conditions, the obtained data were subjected to an ANOVA at a 5% level of significance. The influence of RHA weight fraction and particle size on the hardness of the hybrid composite was critically analysed. Results indicated that the incorporation of graphene nanoparticles significantly enhance the hardness of the composite due to their superior mechanical properties and effective load transfer at the matrix-reinforcement interface. Additionally, RHA content and particle size had a substantial impact on the composite's hardness, with finer particle at optimal weight fraction contributing to better dispersion and interfacial bonding. The developed RSM model showed a strong correlation between experiment and predicted values, validating its effectiveness in optimizing composite fabrication parameters. This study provides valuable insights into sustainable and cost-effective reinforcement of recycled aluminium cans with graphene and rice husk ash for high-performance aluminium-based composites.

Keywords: Aluminum Matrix Composites; Automotive Application; Hardness; Graphene; Particle Size; Response Surface Methodology; Rice Husk Ash; Stir Casting; Weight Fraction; Optimization.

1.0. Introduction

For most engineering activities, optimization has become a fundamental and frequently applied task. This task is however done in many cases by trial and error using a case study. For such tedious activities to be avoided, a systematic approach should be adopted. Such an approach is as efficient as possible and also provides some assurance that a better solution without the use of this method cannot be found.

The systematic determination of a solution that is optimal could lead to an expansive family of methods and algorithms. Optimization techniques are most effective for determining the appropriate parameter levels needed to ensure the quality of products or services. When process parameters are chosen optimally early in the product and process development process, a high-quality and reasonably priced product can be produced [1].

The impact of stir casting parameters on magnesium hybrid composites supplemented with silicon carbide (SiC) and rice husk ash (RHA) was examined by [2]. Stirring speed (350-450 rpm), time (4-8 min), temperature (800-900 °C), and reinforcement percentage (4-8%) are important variables. The impacts of these parameters on hardness and tensile strength were examined and optimized using the Response Surface Method (RSM) and ANOVA. At 950°C, 450 rpm, 8 minutes, and 8 % reinforcement, the best results were obtained, with a tensile strength of 354.09 MPa and hardness of 159.95HV. The outcomes validate the industrial potential of the composite by showing that stir casting under the conditions greatly improves mechanical characteristics.

A novel AA7475 aluminium metal matrix composite (MMC) reinforced with in situ TiB_2 and ex situ SiN_4 (from rice husk ash) was developed by [3] using the stir casting technique. In order to ensure fine dispersion, reinforcements were precisely introduced using salt-based procedures and thermochemical synthesis. Mechanical testing using 3% SiN_4 + 5% TiB_2 revealed a peak tensile strength of 486.56 MPa and a hardness of 173.3 BHN in accordance with ASTM requirements. Better fatigue strength (288.1 MPa), reduced wear rate, and enhanced creep resistance were all displayed by the composite. Microstructural study confirmed that consistent reinforcement distribution and grain refining are significant performance determinants.

To improve the mechanical and tribological properties of pure aluminium, [4] employed powder metallurgy to create a composite that was reinforced with rice husk ash (RHA). The ideal mixture design was created using Design Expert 13 software to modify mixing parameters including duration and stirring speed. The inquiry led to a 76% increase in hardness, the elimination of wear, and a little drop in the coefficient of friction. The characterisation method included tribological evaluation using a ball-on-disk tribometer, Vickers hardness testing, and microstructural analysis. The optimal composition was found to be 12.552% RHA and 87.448% aluminium at 169.812 rpm and one hour of mixing time.

In a related work, [5] investigated the fabrication and characterization of aluminium 7075-based metal matrix nanocomposites reinforced with rice husk ash (RHA) and 3% Al_2O_3 using the squeeze casting (compression moulding) technique. The RHA content was varied from 0% to 15% in 5% increments to study its effect on mechanical properties. Testing included hardness (BHN), tensile strength (MPa), impact resistance, and microstructural analysis (XRD, SEM, XDS). Results showed significant improvements in hardness (up to 36%), tensile strength (up to 11%), and uniform particle distribution with increased RHA content. The composite demonstrated superior mechanical performance and cost-effectiveness compared to unreinforced aluminium, validating agro waste as a viable reinforcement.

To improve the mechanical properties of aluminium 6351, [6] used stir casting to fabricate the hybrid composites reinforced with TiB_2 (10 wt.%), Rice Husk Ash (2.0 wt.%), and varying amounts of graphene (0.0-1.5 wt.%). Mechanical properties like hardness, tensile, impact, and flexural strength, along with surface features (SEM, EDS, XRD), were analysed, 1.5 wt.% Graphene gave the highest hardness (78.8 HV0.3), energy absorption (6 J), and lowest surface roughness (0.308 µm), 0.5 wt.% Graphene yielded the highest flexural (418.73 MPa) and tensile strength (154.81 MPa). Surface analyses confirmed a uniform distribution of reinforcements in the composite.

The percentage elongation of Al-Pumice–Carbonized Coal Particle (PP–CCP) hybrid composites was investigated by [7] in relation to the parameters of stir casting. The ideal processing conditions and reinforcement weights were found using Taguchi optimization. It was confirmed that the reinforcements were suitable for metal matrix composites by the presence of hard compounds such as silica, iron oxide, and alumina. While it was 25.43% less than unreinforced Al-alloy, optimal elongation (5.6%) was achieved at 700°C, 200 rpm, 2.5 wt. % PP, 2.5 wt. % CCP, 700 °C, 200 rpm, and 5 min stirring.

AA-7075 alloy reinforced with glass powder (GP) and rice husk ash (RHA) was used to produce aluminum matrix composites by [8]. Variable temperature and composition parameters, along with preheated fillers, were employed in a controlled stir-casting process. According to ASTM guidelines, mechanical attributes including hardness, impact resistance, compressive strength, tensile strength, flexural strength, and yield strength were evaluated. At 700°C, the ideal mixture (7.5% RHA, 6% GP) produced the maximum strength values. ANOVA statistical analysis provided over 95% confidence in the model's significance, dependability, and good fit. More process parameters, however, would enable more optimal composite manufacturing and offer a deeper understanding of process-property connections. A hybrid composite using palm kernel shell ash (PKA) and rice husk ash (RHA) as fillers in an Al-6061 matrix, with 4 wt.% WSD added was developed by [9]. A response surface methodology was employed to design the experiment and optimize outcomes based on varying PKA/RHA proportions and stir casting temperatures. Mechanical properties such as yield strength, tensile strength, impact strength, elastic modulus, and fracture toughness were evaluated. Microstructural properties significantly influenced the responses, with optimal improvements observed at 700–800 °C, while performance declined above 800 °C. The optimal composite formulation was found at 4.03% PKA, 5.12% RHA, and 787 °C, with predictive models validated by minimal error.

Investigation by Durowoju et al., [10] on the development of aluminium metal matrix composites reinforced with rice husk ash (RHA) was conducted. The focus was to produce a cost-effective and sustainable material using the stir casting method, A three-factor experimental design (weight fraction, particle size, stirring time) and Response Surface Methodology (RSM) were applied to optimize hardness properties. The highest hardness (97.7 HV) was achieved with 15% RHA, 150 µm particle size, and 30 minutes stirring time. ANOVA results indicated particle size had the most significant effect, followed by weight fraction and stirring time. The developed model was statistically valid with less than 5% error in confirmation tests, demonstrating RSM's effectiveness in process optimization. In a related work, Yekinni et al., [11] developed aluminium matrix composites (AMMCs) by reinforcing recycled aluminium alloy with rice husk ash (RHA) using the stir casting technique.

Key casting parameters—RHA weight fraction (5–15%), particle size (150–600 µm), and stirring time (10–30 mins at 140 rpm)—were optimized using Response Surface Methodology (RSM). The optimal tensile strength (180.10 MPa) was achieved at 10 wt.% RHA, 150 µm particle size, and 30 min stirring time. Analysis of variance (ANOVA) confirmed the significance of weight fraction and particle size, while the developed model showed high predictive accuracy ($R^2 = 0.9994$). The study recommends using nanoplatelet RHA reinforcements in future work to further enhance mechanical and thermal properties.

In their research, Lakhvir et al., [12] examined the impact of process variables on the hardness, impact, and tensile characteristics of aluminium matrix composites, including alumina particle size, weight percentage of alumina, and stirring time. The stir casting technique was used to develop the composites, which included alumina particle sizes of 75, 105, and 150 microns, reinforcement weight percentages of 3%, 6%, and 9%, and stirring times of 15, 20, and 25 minutes. With the L9 orthogonal array table, various composite specimens were produced. Utilizing analysis of variance (ANOVA), the impact of input process parameters on the chosen responses was examined. It was reported that each process parameter had a significant impact on the responses.

Using the L_{16} orthogonal array based on the Taguchi technique, optimization of process parameters to reduce the specific wear of Al-SiC composites was investigated by [13]. Silicon carbide with a particle size of 400 µm was used to reinforce aluminium alloy by the stir casting method. Melt temperature, stirring speed and stirring duration, each at 4 levels were used as experimental factors to produce the Al-SiC composites. The composites' microstructures were observed by scanning electron microscope (SEM). The best results were obtained with a 15-weight percent SiC content, a melt temperature of 740 ^oC, a stirring speed of 300 rpm, and a stirring time of 10 minutes. However, the most significant of the process parameters which affected the specific wear of the Al-SiC composite was the weight fraction of SiC. It contributed an 88.6 % improvement in specific wear at a 15 % weight fraction.

To maximize the effects of casting parameters on the hardness and tensile strength characteristics of stir-cast LM 26/RHA/RM hybrid composites. The Taguchi approach was used by [7,14]. The data was analysed using the conceptual signal-to-noise (S/N) ratio methodology, Taguchi's optimization method, and Analysis of Variance (ANOVA). Both hardness and tensile strength were maximized at 15% particle weight fraction, 12 minutes of stirring, 100 rpm for hardness, and 200 rpm for tensile strength. The weight percentage of reinforced particles was shown to have a substantial impact on the examined properties of L26/RHA/RM hybrid composites.

The L9 Orthogonal array Taguchi approach was used by [15] to maximize the stir-cast Al/RHA composite's hardness and tensile strength. The composites were prepared using a weight percentage of RHA reinforcement (6, 9, 12%), stirring duration (6, 9, 12 minutes), and stirring speed (100, 200, 300 rpm). From the Analysis of Variance, the order of influence of the process parameters on the measured properties is wt. % of RHA reinforcement, stirring time and stirring speed respectively. The predictive model developed was found to agree with the experimental results.

Numerous studies have thoroughly investigated the effects of stir casting parameters—such as stirring speed, duration, and temperature—on the mechanical properties of aluminium-based composites. Various reinforcements, including rice husk ash (RHA), silicon carbide (SiC), titanium diboride (TiB_2), graphene, and alumina, have been employed, resulting in notable enhancements in tensile strength, hardness, wear resistance, and microstructural uniformity. While many of these studies focus on optimizing immediate mechanical performance, few examine the long-term behaviour or durability of these composites under real-world operating conditions—factors that are especially critical in the automotive industry, where materials must endure fluctuating loads, high temperatures, and corrosive environments. Addressing this gap is essential for a more comprehensive understanding of material reliability and lifecycle performance.

In this context, the present work focuses on optimizing stir casting parameters for the fabrication of Al/G/RHA composites, with special emphasis on the multifunctional role of rice husk ash (RHA). Beyond being a sustainable and cost-effective reinforcement, RHA has been reported to significantly aid in the dispersion of graphene within the molten aluminium matrix, mitigating agglomeration and promoting uniform particle distribution. Moreover, recent findings suggest that RHA may facilitate the in-situ transformation of graphene into fullerene structures under specific thermal and chemical conditions during casting—a transformation that can further refine the composite's microstructure and enhance mechanical performance [16,17]. By leveraging these effects, this study aims to develop advanced aluminium composites tailored for automotive applications, such as high-strength engine components, thermally stable brake systems, and wear-resistant suspension parts, where improved performance and material reliability are paramount.

1.1. Objectives of the Study

Objectives of the study are as follows:

1) To optimize the stir casting process parameters for producing aluminium matrix composites.
2) To investigate the combined effects of rice husk ash and graphene nanoparticles on composite hardness.
3) To analyse the influence of particle size and weight fraction on the hardness of the composites.
4) To apply Response Surface Methodology (RSM) for modelling and optimization of process variables.
5) To determine the optimal composition and process settings for improved hardness and performance.
6) To evaluate the suitability of the developed composites for automotive applications.

2.0. Materials and Methods

2.1. Materials

The matrix chosen for this study is discarded aluminium cans, with graphene nanoparticles and rice husk ash serving as reinforcements (Figures 1 and 2).

2.2. Methodology

Hybrid composites of aluminium, graphene, and rice husk ash were produced by combining three distinct particle sizes (150 µm, 300 µm, and 600 µm) with varying weight percentages of RHA (0.8, 1.2, and 1.6) and 0.4 weight percent graphene nanoparticles. A crucible furnace was used to melt the mixture while maintaining a consistent stirring period of 2 minutes and a stirring speed of 140 rpm. Nevertheless, the 0.4 weight percent graphene nanoparticles utilized in this investigation were consistent with [18].

The experiment for developing the composites was designed using Response Surface Methodology (RSM) based on a 3-factor historical data model. Design Expert version 6.0.8 was employed to model the selected variables. The factors analyzed included the weight fraction and particle size of RHA, stirring speed, stirring time, with hardness as the response variable. The experimental ranges for these variables are presented in Table 1.

Table 1. Design of Parameters and Factor Level for the Stir Casting Process

Factors	Code	Level		
		Low (-1)	Normal (0)	High (+1)
Proportion by weight (%) RHA	A	0.8	1.2	1.6
Dimension of Particle (µm) RHA	B	150	300	600
Graphene Nano particles (%) G	C	0.4	0.4	0.4

2.3. Procurement of graphene powder (1st reinforcement)

In the present work, graphene powder (NanoCarbon Platelets) was purchased from United Kingdom (Figure 1).

2.4. Production of rice husk ash (2nd reinforcement)

The rice husk was supplied by the local rice mill. The husk was meticulously sifted before being burned for about two hours at 700 ^{o}C in a muffle furnace within a crucible pot lined with cotton wool. As seen in figure 2, the residue was sieved and sorted into three distinct particle sizes: 150 µm, 300 µm, and 600 µm.

Figure 1. Graphene (NanoCarbon Platelets) Powder

Figure 2. Graded rice husk ash

2.5. Preparation of aluminium alloy billet (aluminium matrix) and Al/G/RHA composites

Aluminium billet was produced from compressed waste aluminium cans. The cans were charged into the crucible pot placed inside a diesel-fired crucible furnace and melted in a continuous process at about 850 °C. Using a tong, the crucible pot was removed from the furnace once it had completely melted. To get rid of the slag, the molten aluminium alloy in the pot was vigorously agitated while it was outside the furnace. Before being poured into the steel mould, the molten aluminium was thoroughly degassed to avoid blow holes in the cast billet. Later, the aluminium billet formed from the solidified metal was taken out of the steel cavity mould.

Each of the aluminium billets was further re-charged into the crucible furnace and re-melted for homogeneity. This is necessary since the waste aluminium cans that produced the billets were obtained from different sources. The billets were again re-cast in the steel cavity mould. Each of the billets has an average weight of 1000 g. While one of the billets was used as a control sample, the remaining billets were used to produce the composites. The control billet sample at this stage was machined to produce specimens for characterization and property measurement.

The unreinforced aluminium alloy billet was further reinforced with a mixture of graphene and rice husk ash under the experimental runs to produce the hybrid composites for characterization, hardness and tensile property measurement. A crucible furnace was used to perform the melting. Each billet of aluminium alloy was preheated at 450 ^{0}C before melting at 750 ^{0}C. Meanwhile, a mixture of graphene and rice husk ash of the required percentage weight fraction and particle size was measured and prepared to about 100 degrees Celsius before being added to the melt.

To increase the wettability between the alloy melt and the reinforcements, one weight percent of magnesium was simultaneously added to the molten melt in line with [19] who stressed that particles of rice husk ash and similar materials will be rejected without the addition of magnesium.

The homemade stirrer agitated the molten metal for two minutes at 140 rpm. This stirring speed and stirring time were carefully chosen, considering the capacity/dimensions of the crucible pot, the weight of molten aluminium (about 1 kg) and the pouring temperature. The molten composites at this stage were degassed while slags and any form of impurities were removed and then poured in the fabricated die cavity steel moulds to produce Al/G/RHA in circular and rectangular forms for preparation of specimens. After cooling, specimens were machined for characterization and mechanical analysis.

2.6. Hardness determination

The Vickers diamond test was conducted at the University of Lagos using a Vickers hardness tester (LECO AT700 Micro Hardness Tester). The specimen was mounted on a Vickers hardness testing machine using phenolic powder, which was ground and then polished to provide a hardness specimen with a smooth surface finish. All samples were prepared using fine-grained emery polishing papers. The depth of penetration of the diamond indenter on the specimen was then measured and read straight from the machine's calibrated gauge after it had been indented three times with a ten-second dwelling time. The hardness of the specimens was determined by averaging the highest values.

3.0. Results and Discussions

3.1. Matrix and reinforcements composition

The elements makeup of the unreinforced aluminium alloy billet (matrix) and the chemical analysis of graphene are shown in Tables 2 and 3, respectively. Nonetheless, the XRF analysis's results for the chemical components of rice husk ash are consistent with those of [10, 20].

Table 2. The weight percentage of each element in the unreinforced cast aluminium alloy ingot

Al	**Si**	**Fe**	**Cu**	**Mn**	**Mg**	**Zn**	**P**	**Ni**	**Ti**
94.0218	0.825	0.332	1.065	0.770	0.0046	2.014	0.021	0.053	0.912
S	**Cr**	**Sn**	**Mo**						
0.016	0.005	0.0023	0.006						

Table 3. Graphene nanoparticle chemical analysis

Elemental Analysis		
1.	Carbon	> 90 atm.%
2.	Oxygen	< 7.5 atm.%
3	Thickness Lateral Size	< 5µm 0.5 - 5µm

3.2. Design of parameters and responses for Al/G/RHA composites

The experimental runs generated from the design of the experiment with the hardness and tensile test results are shown in Table 4.

Table 4. Design of experiment model range

Std	Run	Block Control Sample	Factor 1 A: %	Factor 2 B: µm	Factor 3 C: %	Response Hardness HV
2	1	Block 1	0.8	150	0.4	108.50
1	2	Block 1	1.2	150	0.4	109.20
4	3	Block 1	1.6	150	0.4	115.60
7	4	Block 1	0.8	300	0.4	93.40
3	5	Block 1	1.2	300	0.4	94.20
8	6	Block 1	1.6	300	0.4	96.30
5	7	Block 1	0.8	600	0.4	97.00
9	8	Block 1	1.2	600	0.4	103.60
6	9	Block 1	1.6	600	0.4	105.00

Note: At table 4, A = Weight fraction of Rice Husk Ash, B = Particle Size of Rice Husk Ash, C = Weight Fraction of Graphene Nanoparticles.

3.3. Hardness measurement

Figure 3 presents the hardness values obtained from the experimental results compared with the model equation. The experimental data illustrate the influence of reinforcement weight percentage on the microhardness of Al/G/RHA composites. Observations clearly indicate that an increase in reinforcement weight percentage leads to a corresponding increase in composite hardness. This enhancement is attributed to the increased surface area of the matrix, which results in grain size reduction. Additionally, the presence of hard-surfaced reinforcing particles improves resistance to plastic deformation, thereby further increasing hardness.

When compared to the hardness values of the control sample (75.5HV), all the composites showed an increase in hardness. The highest increase of 53.1% of hardness was obtained when the reinforcements were added at Al/0.4G/1.6RHA (150 µm particles of RHA). The higher resistance to localized plastic deformation during indentation can also be attributed to the harder particles of the graphene-rice husk ash mixture which is distributed within the aluminium matrix. Additionally, a decrease in the size of RHA particles was found to increase the material's hardness. This is because the matrix contains and distributes more RHA and graphene fines. Figure 3 further shows that the hardness increases with decreasing particle size for Al/G/RHA composites. At 600 µm, 300 µm, and 150 µm mesh sizes, the greatest hardness values for Al/G/RHA composites are 105.00 HV, 96.30 HV, and 115.60 HV, respectively.

According to Dhadsanadhep et al. [21], the hardness of Al/RHA composites increased from 17 HRV at 0% (control sample) to 30 HRV at 15% RHA. In contrast, Luangvaranunt et al. [22] showed that the reactive area and as-aged hardness increased from 17 HRV at 0% RHA (control sample) to 48 HRV and 45 HRV at 15% RHA. The hardness increased from 68 BHN at 0% RHA to 83 BHN at 8% RHA, according to Prasad and Krishna [23]. However, [18, 24] found that the amount of graphene used increased the toughness and tensile strength by two to three times compared to the unreinforced aluminium material. It is believed that an increase in sintering temperature from 550 ^oC to 650 ^oC will result in an equal rise in hardness value due to enhanced particle packing and improved microstructural characteristics of the composite samples [18]. Though a decrease in hardness due to the formation of Al_4C_3 with graphene filler is also possible according to [25].

The Model F-value of 7.27 in Table 5 indicates that the model is significant. A "Model F-value" this large could only be the result of noise in 0.25% of cases. "Prob > F" values less than 0.0500 indicate that the model terms are significant. In this case, B and C are crucial model terms. If the values exceed 0.1000, the model terms are not important. One independent parameter had two model terms that were significant at p<0.05. The Al alloy's hardness is most significantly impacted by the composite type (C). In this instance, the sample that was reinforced with G/RHA had the lowest p-value and the highest F-value. Particle size came next, and the weight fraction showed the least amount of change.

The evaluation result for the developed and evaluated model is displayed in Table 6. A correlation coefficient of 0.7986, which is strong, shows that the model is accurate. In a decent amount of agreement with the "Adj R-Squared" of 0.6887 is the "Pred R-Squared" of 0.5035. "Adeq Precision" calculates the signal-to-noise. A ratio above 4 is preferred. With a ratio of 8.051, the signal is sufficient.

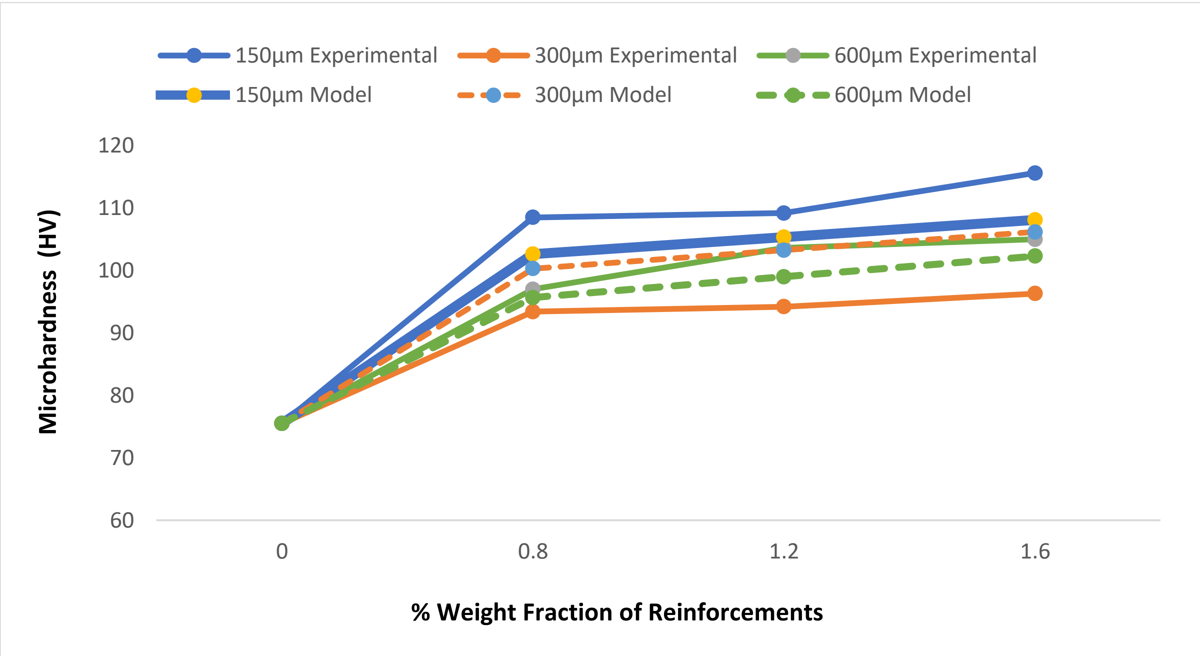


Figure 3. Hardness of Experimental results versus Model Equation

Table 5. ANOVA for the hardness response surface 2FI model

Source	Sum of Squares	DF	Mean Square	F Value	Prob>F	
Model	1493.9	6	248.98	7.27	0.0025	Significant
A	68.77	1	68.77	2.01	0.1842	
B	195.92	1	195.92	5.72	0.0358	
C	1221.06	1	1221.06	35.65	< 0.0001	

AB	0.68	1	0.68	0.02	0.8904
AC	4.56	1	4.56	0.13	0.722
BC	7.68	1	7.68	0.22	0.6451
Residual	376.81	11	34.26		
Cor Total	1870.72	17			

Note: At table 5, A = Weight fraction of Rice Husk Ash, B = Particle Size of Rice Husk Ash, C = Weight Fraction of Graphene Nanoparticles.

Table 6. Model estimation result for hardness

Std. Dev.	5.85	R-Squared	0.7986
Mean	94.31	Adj R-Squared	0.6887
C.V.	6.21	Pred R-Squared	0.5035
PRESS	928.88	Adeq Precision	8.051

Regression Equation

The regression equation for hardness is given as follows:

Hardness = +99.82083+6.38542 * A-0.017964 * B+3.18452e^{-3}* A* B

Where A = Weight Fraction, B = Particle Size

Figure 4 displays the actual and projected values. Data points were in line with the straight line, the residual plot showed little overfitting, and the predicted vs actual plot showed a perfect linear plot, all of which demonstrated that the built model was sufficiently predictable.

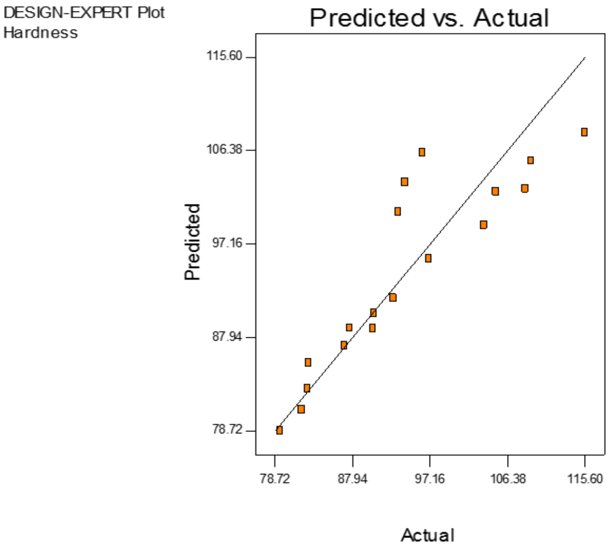
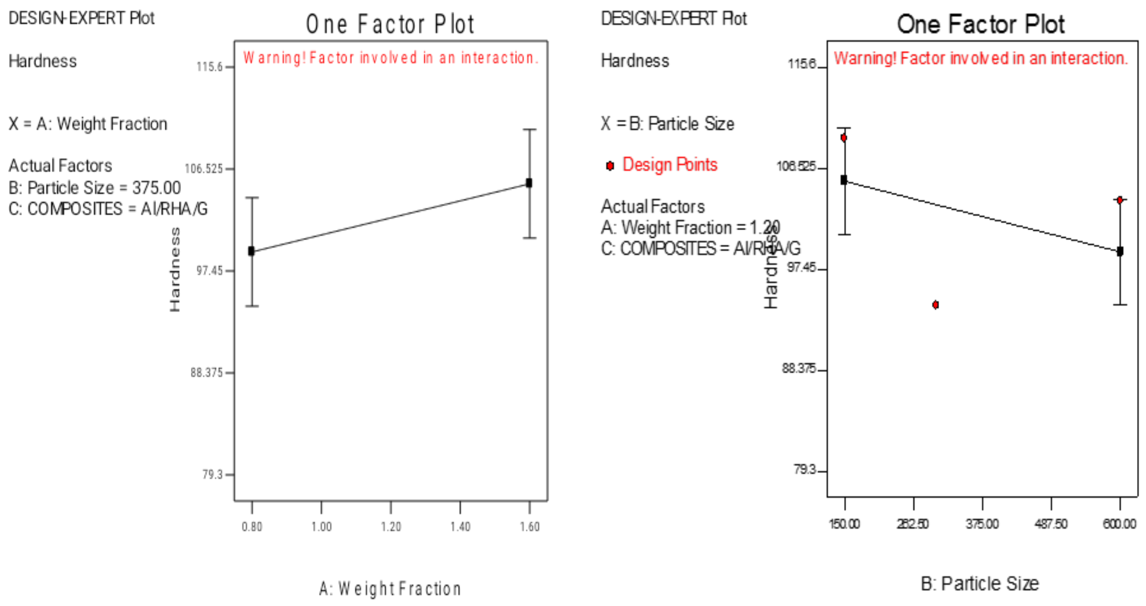


Figure 4. Plot of Predicted against Actual values for Hardness

3.3.1. One variable's impact on the hardness of the Al/G/RHA composite

The effect of weight fraction and particle size against the hardness is shown in Figures 5a and b. Al/G/RHA hardness increases with weight fraction from 99.15 HV to 105.31 HV (Figure 5a) but decreases with particle size from 105.36 HV to 99.00 HV (Figure 5b).

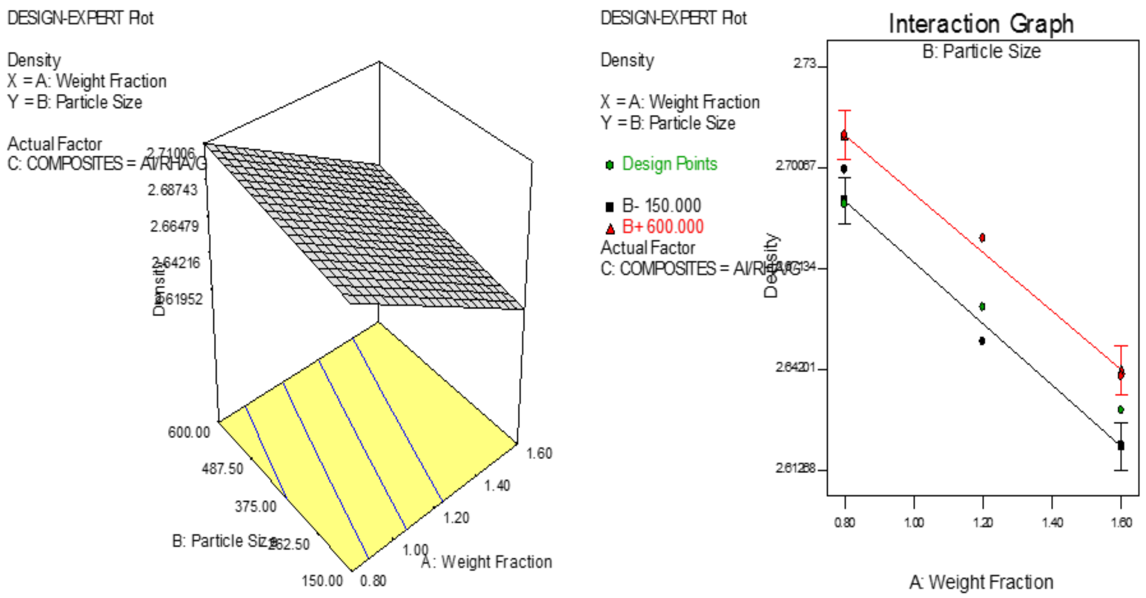


(a) (b)

Figure 5. Plot of the effect of a single variable on the Hardness for (a) Weight Fraction of Al/G/RHA, and (b) Particle Size of Al/G/RHA

3.3.2. Effect of weight fraction and particle size on hardness for Al/G/RHA

The combined impact of particle size and weight fraction on material hardness is depicted in Figures 6a and b. Al/G/RHA composites were observed with about a 1.25 % increase in hardness. That is, at a low particle size of 150 µm, the hardness increases from 102.62 HV to 108.11 HV (Figure 6a) as the weight fraction increases. At a high particle size of 600 µm, the hardness increases from 95.68 HV to 105.00 HV. Therefore, the material hardness is favoured by a low particle size of 150 µm and a high weight fraction of 1.6 wt. % (Figure 6b).



(a) (b)

Figure 6. (a) Response Surface Interaction Plot of Weight Fraction, and (b) Particle Size against Hardness for Al/G/RHA

3.3.3. Confirmation of Model Equation for Hardness

Table 7 shows the response obtained for hardness from the model equation generated. Comparisons as shown on figure 7 were made between the experimental responses and model equation responses to confirm the accuracy of the developed model equation. The experimental findings and the model equation results are almost same with the least amount of error (±5%), as the figure clearly demonstrated. An adequate degree of accuracy in forecasting the hardness appears to be achievable with the regression equation.

However, optimization for hardness was obtained at 1.6 wt.% rice husk ash, 150 µm particle size and 0.4 wt.% graphene.

Table 7. Responses Generated from the Developed Model Equations

Std	Run	Block	Factor 1 A: Micron	Factor 2 B: %	Factor 3 C: %	Response 1 Hardness HV
2	10	Block 1	0.8	150	0.4	102.6167
1	11	Block 1	1.2	150	0.4	105.3619
4	12	Block 1	1.6	150	0.4	108.1072
3	13	Block 1	0.8	300	0.4	100.3043
6	14	Block 1	1.2	300	0.4	103.2406
5	15	Block 1	1.6	300	0.4	106.1769
7	16	Block 1	0.8	600	0.4	95.67934
9	17	Block 1	1.2	600	0.4	98.99779
8	18	Block 1	1.6	600	0.4	102.3162

3.3.4. Industrial Application of the Developed Composites

There are three conditions necessary for the successful production of the aluminium piston according to [26]. First, a higher coefficient of expansion needs to be considered in the design; second, the right combination; and third, effective foundry practices. All these were observed through casting set up, production of reinforcements and the choice of process parameters used in casting the composites.

Hardness values ranging between 107.0–115.5 HV has been suggested according to European Aluminium Association (EAA) [27] for aluminium piston. Therefore, with optimal hardness of 115.6 HV obtained, it can be affirmed that the composites produced are good candidate materials to produce this selected automobile part.

4.0. Conclusions

This study successfully demonstrated the development of innovative hybrid aluminium matrix composites (AMCs) reinforced with graphene nanoparticles and rice husk ash (RHA) using the stir casting method. By systematically varying the RHA particle size (150–600 µm) and weight fraction (0.8–1.6 wt.%) while maintaining a fixed graphene content (0.4 wt.%), the effects of these parameters on the hardness of the composite were effectively evaluated. The findings confirmed that both the weight fraction and particle size of RHA significantly influence the composite's hardness, with the finest particle size (150 µm) and highest RHA content (1.6 wt.%) yielding the maximum hardness value of 115.6 HV—representing a 53.1% improvement over the control sample. The optimization using Response Surface Methodology (RSM) proved effective, with the developed regression model showing a strong correlation between predicted and experimental results ($R^2 = 0.7986$, Adeq Precision = 8.051). Analysis of variance (ANOVA) further revealed that graphene addition and RHA particle size are statistically significant contributors to hardness enhancement. The optimized composite not only meets but slightly exceeds the European Aluminium Association's recommended hardness range (107–115.5 HV) for aluminium piston applications, highlighting the material’s suitability for automotive components. Furthermore, the incorporation of agricultural waste (RHA) and recycled aluminium cans demonstrates a sustainable and economically viable pathway for producing high-performance composites. In conclusion, the Al/G/RHA hybrid composite developed under optimized stir casting parameters offers a promising material solution for structural and automotive applications, combining enhanced mechanical properties with environmental sustainability.

5.0. Future Suggestions

The following are suggested for future improvement of the work:

1) Additional reinforcement combinations beyond rice husk ash and graphene to further enhance mechanical properties.

2) The effect of other process parameters (e.g., stirring speed, preheating temperature, and cooling rate) on composite performance.

3) Explore other mechanical, wear and thermal properties, as well as scaling up the process for industrial adoption, especially for automotive use.

4) The study can be extended to other aluminium alloys to determine the adaptability of the optimized process across different base materials.

Declarations

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Competing Interests Statement

The authors declare that they have no competing interests related to this work.

Consent for publication

The authors declare that they consented to the publication of this study.

Authors' contributions

All the authors made an equal contribution in the Conception and design of the work, Data collection, Drafting the article, and Critical revision of the article. All the authors have read and approved the final copy of the manuscript.

Institutional Review Board Statement

Not applicable for this study.

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