Effect of Locust Bean Pod Ash on the Hardness and Wear Rate of Heat Treated A356 Alloy Metal Matrix Composite for Production of Automobile Brake Rotor

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Abstract
Investigation into development of advanced lightweight composite materials with low densities and tailored properties that could comfortably replace conventional ones is currently the direction of many researches especially in the automobile and aerospace industries. Aluminum reinforced composites are mostly considered due to their inherent properties of low density, good thermal and electrical conductivity, as well as superior mechanical properties. This research focused on production of A356 (Al-7%Si-0.3%Mg)/Locust Bean Pod Ash (LBPA) composites for brake rotor applications using Design Expert software which determined the number of runs of experiments and percentage composition of the input elements. The LBPA which was found to contained crystals such as Al_2O_3, SiO_2 and Fe_2O_3 which are the main elements responsible for improving hardness and wear to the composite was used as reinforcement in the production of the composite by sand casting. The produced composite was machined and subjected to heat treatment. Hardness and wear rate properties tests were conducted followed by metallographic examinations. Models for hardness and wear rate were developed and analyzed using Analysis of Variance (ANOVA), other interfaces of the Design Expert and simulation in Excel environment. The best combination for hardness and wear rate was reached when the volume fraction of the reinforcement was 25% the hardness value of 40.41 HBR and wear rate of 0.0489mm^3/Nm which showed that the hardness and wear rate of the composite samples improved by 57.23% and 47.10% respectively as compared to the matrix alloy. ANOVA results showed that effect of LBPA was significant. The photo-micrograph of the composite shows clearly the homogeneity of dark dispersion of the LBPA and predominantly white metallic phases. From the results, it can be concluded that LBPA can be utilized as reinforcement in the production of brake rotors.

***Keywords*:** Aluminum, Alumina, Brake Rotor, Locust Bean Pod Ash, Hardness, Heat-treatment, Metal Matrix Composite, Sand Casting, Silicon Carbide, Wear rate.

1.0 INTRODUCTION

Demand for advanced lightweight components in the automotive industry is on the increase in order to have improved performances with respect to mechanical properties, stability, aerodynamics, fuel consumption, cost of production, esthetics, low density and tailored properties. As a result of these requirements, several researches were conducted in development and production of composite materials that will meet the aforementioned needs. Aluminum based composites are in the forefront due to their inherent properties in comparison to metals. Composites development have been receiving worldwide attention on account of their superior strength, stiffness, in addition to high wear and creep resistance in comparison to corresponding wrought alloys (Hunt and Miracle, 2001).

Brake disc or rotor is one of the important and crucial components of automobile due to its function from safety point of view, demand for excellent properties, durability, stability and good wear properties under varying conditions of load, velocity, temperature and environments. Because of these functional requirements of brake disc, material for its production must be such that can offer outstanding high frictional characteristics with less abrasive wear at high temperatures, light weight, ease of manufacture and cost of production (Maleque et al., 2010). Aluminum - based composites produced with ceramic particulate reinforcement such as Silicon Carbide (SiC) and Alumina (Al_2O_3) offer good combination of properties for brake system applications that replaced cast iron which hitherto was the main material for brake disc. Additionally, the wear resistance and high thermal conductivity of the Aluminum based composites were found to be superior to cast iron with attendant weight savings of the order of 50 to 60% (Hunt and Miracle, 2001). However, the two major ceramic particulates that are widely used as reinforcement for brake rotors are scarce and very expensive (Mustafa and Adem, 2007; Salako et al., 2019). Research in finding replacement for these expensive ceramic particulates is in the right direction.

Locust Bean Pod Ash (LBPA) produced from Locust Bean Pod (LBP) which is a waste agricultural biomass obtained from the fruit of the African locust bean tree (*Parkia Biglobosa*) contains hard ceramic compounds such as Al_2O_3, SiO_2, MgO, Fe_2O_3 and CaO that could be used as composite reinforcement (Adama and Jimoh, 2011). LBP as agro-waste product is either burnt or buried underground which pollute the environment. However, utilization of LBPA in production of composites will be of benefit in making the environment friendly in areas where these pods are usually discarded and reduce cost of production by substituting the synthetic ceramics.

This work investigated the potentials of LBPA as a replacement for synthetic ceramic compounds that are relatively expensive in the production of automobile brake disc. To achieve this, A356 alloy and A356/LBPA reinforced composite were produced, solution heat treated, and subjected to tests with metallographic analyses. Models for hardness and wear rate were developed and validated using Design Expert software and simulation in Excel environment. The A356/LBPA composite was produced using sand casting.

2.0 MATERIALS, EQUIPMENT AND METHODS

The following materials, equipment and methods were used and adopted in this work based on standard practice and recommendations.

2.1 Materials

The following materials were used in the production of A356 alloy and A356/LBPA reinforced composite:

(i) Pure Aluminum wire
(ii) Magnesium ribbon
(iii) Silicon (powdered)
(iv) Locus bean pods
(v) Green sand for casting

2.2 Equipment

Equipment used include:

(i) Charcoal fired furnace
(ii) Digital weighing balance
(iii) Scanning electron microscope (SEM)
(iv) Resistance heat treatment furnace
(v) Rockwell Hardness Testing Machine

2.3 Methodology

The following steps and sequence were followed:

2.3.1 Production of the A356 /LBPA Composite

Locust Bean Pod (LBP) was collected, dried, grinded to ash, and sieved to obtain ash powder. The powder was milled and sieved using 38 µm sieve after drying at temperature of 900^0C (Pavitra et al., 2018; Abdulwahab et al., 2017). The samples were prepared based on the ratio of the Alloy (A356) to reinforcement from Design Expert as shown in Table 1.

Table 1: Elemental Composition (%) of the Composites

No. of Runs	LBPA (%)	LBPA (g)	A356 (Al-7%Si-0.3Mg Alloy) (g)
1.	6.25%	37.50 g	562.5 g
2.	25.00%	150 g	450 g
3.	18.75%	112.5 g	487.5 g
4.	0.00%	0 g	600 g
5.	12.50%	75 g	525 g
6.	25.00%	150 g	450 g
7.	0.00%	0 g	600 g

In order to produce the matrix, Aluminum wire was charged into the crucible of a charcoal furnace, melted completely and left to superheat after which 7% of Silicon was added. After mixing the melt for 5 minutes, 0.3% of Magnesium was then added to the melt. The crucible was then removed from the furnace before the LBPA was introduced and stirred continuously. To produce the composites according to the seven (7) experimental runs suggested by Design Expert, 0% to 25% volume fraction was adopted as recommended (Abdulwahab et al., 2017; Mohammed, 2014; Mohammed et al., 2015). The seven samples were produced as shown in Figure 1 based on the combinations suggested by Design Expert as shown in Table 1.

Figure 1: Samples of the Produced Composites

2.3.2 Hardness Test

Before conducting the hardness tests, the samples were machined and subjected to solution heat treatment by heating to 540^0C for 1 hour, quenched in warm water at a temperature of 65^0C and aged to 180^0C for 2 hours. Hardness test was conducted on Indentec Universal Electric Powered Rockwell Hardness Testing Machine, Model 8187.5LKV (B), 1/16-inch size indenter to determine the hardness values of the samples. The tests were performed on B scale in accordance with ASTME 18-11 using a Minor load of 10kg and Major load of 100kg. For each sample, three hardness readings were taken on randomly selected regions in order to eliminate the segregation effects and to get a representative value of the material hardness.

2.3.3 Wear Rate Test

Machined and solution heat treated samples of the composite were subjected to wear rate test on a pin-on-disc wear testing tribometer for dry sliding wear behavior in accordance with ASTM G99 standards. The test was conducted on 10mm diameter and 30mm long cylindrical specimens against a rotating En-32 steel disc. The tangential friction force and wear rate were monitored with the help of electronic sensors. These two parameters were measured as a function of load and sliding distance. For each specimen, tests were conducted at 8N normal load and keeping the sliding speed fixed at 10cm/s at room temperature without lubrication.

2.3.4 Photo-micrograph

Samples of the A356 alloy and A356/LBPA composite were cut to size, grind with different grid sizes from rough to smooth grades, polished and etched according to standard practice. Photos of the samples were taken with good magnifications.

2.3.5 Hardness and Wear Rate Models Development

Models for hardness and wear rate were developed by the Design Expert after subjecting the data to series of tests. Response Surface Methodology (RSM) with one factor design was adopted. The software suggested maximum of seven (7) runs after series of randomization to take care of the effects of unexpected variability of the responses. The models were subjected to series of statistical test to ascertain their goodness of fit and wide adoptability.

3.0 RESULTS AND DISCUSSION

After conducting necessary test, modeling and analysis, the following results were obtained.

3.1 Measured Hardness and Wear Rate of the Produced Samples

The mechanical properties which are the experimental response values of the produced A356/LBPA Composites are presented in Table 2.

From Table 2, it can be seen that the hardness values of 40.3, 40.5 and 40.5 of the composite occurred at runs 2, 3 and 6 with corresponding values of LBPA addition of 25%, 18.75% and 25% respectively. Similarly, least wear rates of 0.0492 mm^3/Nm, 0.0474 mm^3/Nm and 0.0492 mm^3/Nm corresponding to highest values of hardness at runs 2, 3, and 6. Since the maximum number of runs possible from the Design Expert as determined for this experiment is seven (7) and the optimum values for both hardness and wear rate occurred twice at 25% of reinforcement, it can be deduced that the optimal combination for hardness and wear rate for this composite is when volume fraction of reinforcement is 25%.

Table 2: Experimental Response Values of the Produced A356/LBPA Composites

Std	Run	Reinforcement (LBPA) (%)	Hardness (HRB)	Wear Rate (mm^3/Nm)
3	1	6.25	33.5	0.0511
5	2	25.00	40.3	0.0492
4	3	18.75	40.5	0.0474
1	4	0.00	25.7	0.0896
7	5	12.50	37.3	0.0505
6	6	25.00	40.5	0.0492
2	7	0.00	25.9	0.0896

3.2 Hardness and Wear Rate Models

The developed models for hardness and wear rate are as shown in equations 1 and 2. Hardness model was suggested to be best described with quadratic form as both single and third order forms was found not to be suitable by the software as the model parameters did not suggest good fit. On the other hand, wear rate model was found to be more suitable as suggested by the software based on the tests results.

$$Y_1 = \text{Hardness} = +25.87681 + (1.32986 \text{ x Reinf}) - (0.029941 \text{ x Reinf}^2) \quad \ldots(1)$$

$$Y_2 = \text{Wear rate} = +0.089254 - (8.76962 \text{ x } 10^{-3} \text{x Reinf}) + (5.67745 \text{ x } 10^{-4} \text{ x Reinf.}^2) - (1.12640 \text{ x } 10^{-5} \text{ x } Reinf^3) \quad \ldots(2)$$

Analysis of variance (ANOVA) was used in analyzing the models with the results shown in Table 3 and 4 respectively. From Table 3, the model terms (A and A^2) were found to be significant base on their p - values being less than the chosen confidence interval of 0.05 which suggest goodness of the model. Likewise, the lack of Fit F-value of 14.04 implies there is a 6.65% chance that a lack of Fit to occur due to noise.

Table 3: Analysis of Variance of the Hardness Model

Source	Sum of Squares	df	Mean Square	F value	p-value Prob> F	
Model	264.59	2	132.29	879.41	< 0.0001	Significant
A-Reinf	237.62	1	237.62	1579.55	< 0.0001	
A^2	26.97	1	26.97	179.26	0.0002	
Residual	0.60	4	0.15			
Lack of Fit	0.56	2	0.28	14.04	0.0665	Not Significant
Pure Error	0.040	2	0.020			
Cor Total	265.19	6				
R-Squared = 0.9977						
Adj R-Squared = 0.9966						
Pred R-Squared =0.9932						

Table 4 shows the results of ANOVA for wear test model, it was observed that apart from the reinforcement *A* (that had a p-value greater than the selected confidence interval of 0.05 , the p - values of all the other model factors A^2 and A^3 were found to be less than 0.05 which indicates that the model terms are significant.

The validity of the models was further investigated by simulating the model equations obtained using Microsoft Excel Spreadsheet. The results of the model simulations were compared with the experimental values as shown in Figures 2 and 3 where no significant difference was noticed from two results which suggests that the models are in agreement with practical realities as no residual values are noticeable. It generally means that the model equations could conveniently predict correct mix ration in developing A356/LBPA composite with reasonable degree of accuracy.

Table 4: Analysis of Variance of the Wear Rate Model

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	2.274E-003	3	7.582E-004	68.69	0.0029	Significant
A-Reinf	9.042E-007	1	9.042E-007	0.082	0.7933	
A^2	6.355E-004	1	6.355E-004	57.57	0.0047	
A^3	1.210E-004	1	1.210E-004	10.96	0.0454	
Residual	3.311E-005	3	1.104E-005			
Lack of Fit	3.311E-005	1	3.311E-005			
Pure Error	0.000	2	0.000			
Cor Total	2.308E-003	6				
R-Squared = 0.9857						
Adj R-Squared = 0.9713						
Pred R-Squared = 0.8479						

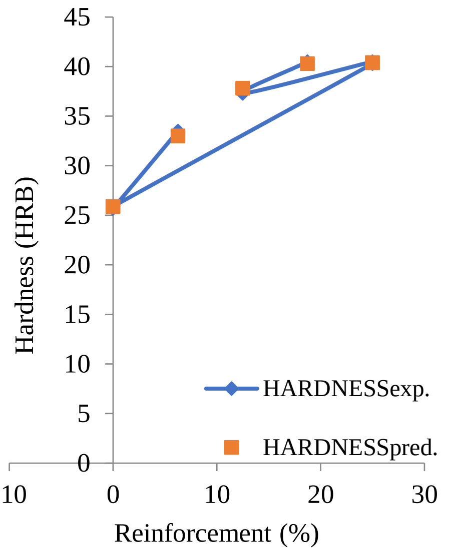

Figure 2: Experimental and Model Simulations Hardness against Reinforcement

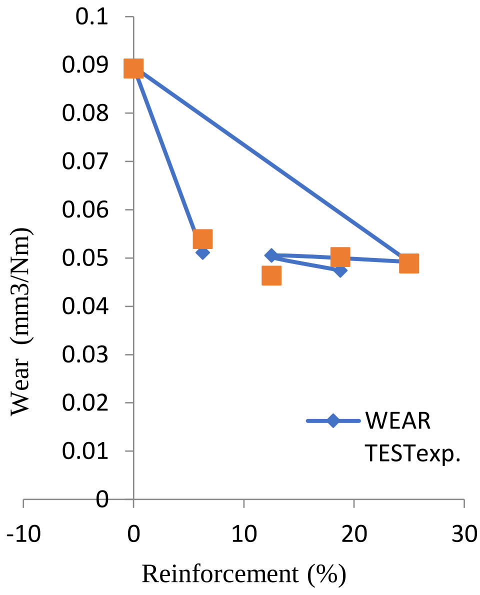

Figure 3: Experimental and Model Simulations for Wear Rate against Reinforcement.

The comparison between the experimental simulation and model simulation results of the responses that is (Hardness and Wear rate) established the good fits between the two simulation results. This is another indication of the goodness of the developed models and in support of their significance. In addition, numerical optimization of each response was carried out using the Design Expert interface with results as shown in Table 5. The result is in agreement with those of ANOVA, experimentation and simulation in Excel.

Table 5: Solution of Optimization of Reinforcement and the Responses

No.	Reinf. (%)	Hardness (HRB)	Wear Rate mm^3/Nm	Desirability
1	25.00	40.4101	0.0488537	0.980

The hardness was also noticed to be increasing as the volume fraction of LBPA particles increased as shown in Figure 2 due to the increasing percentage of a hard and brittle phase of ceramic in the matrix which agreed with the findings of Aigbodion and Hassan, (2007). This hardness increase is as a result of LBPA particles creating obstacles to dislocation movement by increasing the dislocation density at the interface layer. It was discovered that during the casting process, some percentage of the LBPA particles were not mixed and wetted completely at the bottom of the crucible which indicates that the shearing action of the stirrer blade against the liquid was not enough due to the inclining blade causing upward movement with little centrifugal motion of the LBPA (Du et al., 2012). This behavior was also noticed when the hardness was analyzed using the design expert software as shown in Figure 4.

Wear resistance of the composites was noticed to be improving as the percentage addition of LBPA increased as shown in Figure 3. This behavior was as a result of good bonding characteristics between the matrix and the LBPA and depth of penetration similar to the works of (Abdulhaq et al., 2018; Mazahery and Shabani, 2013). Unlike in the unreinforced Al alloys, the wear resistance is as a result of stick-formed silicon particles that formed as product of eutectic reaction in the process of alloy solidification (Venc et al., 2010). It can be concluded that the wear rate of the produced composite was controlled by LBPA particles by lowering the real contact area (Single et al., 2009). Also, the wear rate could have been influenced by either $MgO.SiO_2$ or $MgAl_2O_4$ spinel at the interface layer which could minimize particle pull-out that may occur during the test process (Kumar and Kumar 2001; Musert et al., 2002; Devaraju et al., 2013). The wear rate behavior also agreed with the design expert analysis as shown in Figure 5.

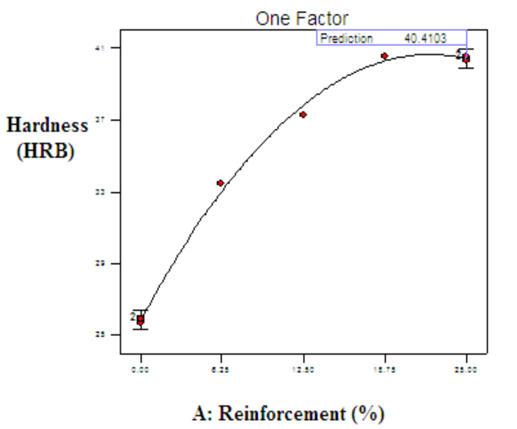

Figure 4: Effect of LBPA on the Hardness of the Produced Composites

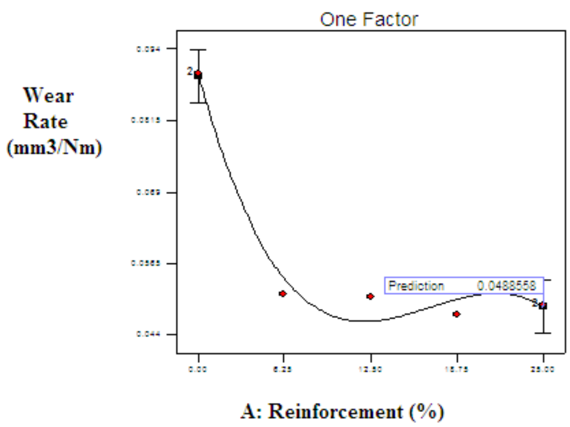

Figure 5: Effect of LBPA on the Wear Rate of the Produced Composites

3.3 Results of the Photo-micrograph

Figure 6 shows the microstructure of the A356 alloy without reinforcement that comprises of mainly a network Θ phase (Mg_2Si) in α -Aluminum matrix with Al_6SiMg_4 intermetallic compounds distributed within the grains (Shehu, 2011; Pawlik et al., 2006).

The microstructure of the A356 reinforced with LBPA is shown in Figure 7 where it reveals uniform distribution of the LBPA particles in the grain boundaries of Aluminum matrix. The uniform distribution of the LBPA in the matrix will obviously offer benefits toward improving both hardness and wear rate as more interface layers would help in ensuring uniform load transmission, offer resistance to dislocation and other mechanisms of failure.

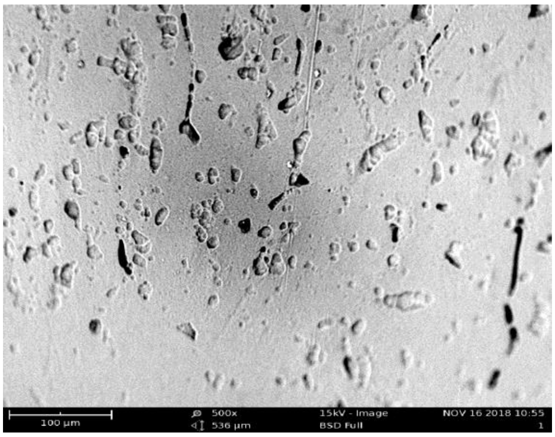

Figure 6: Photo-Micrograph of A356 alloy

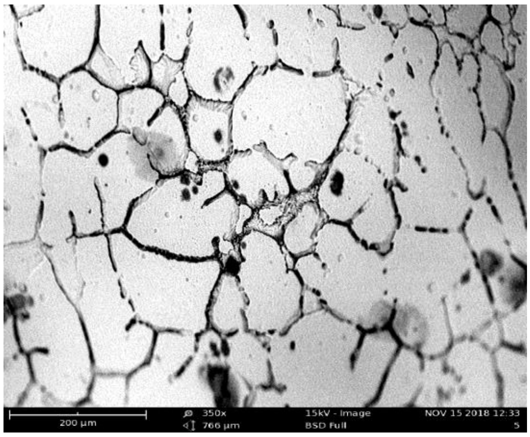

Figure 7: Photo-Micrograph of A356/14.30% LBPA Composite

4.0 CONCLUSION

Potentials of LBPA as reinforcement in the production of A356/LBPA composite for use in automobile brake rotor application by improving hardness and wear rate properties has been established. Model equations for determining the hardness and wear rate of the A356/LBPA composite were developed using design expert software. The model equations were tested and validated using ANOVA, Excel simulation and other interfaces of the design expert with results that suggests their acceptability for application in developing A356/LBPA composite for brake rotor and similar applications. The A356/LBPA composite was produced following the compositional suggestion by design expert software using sand casting technique. The produced composite was tested for hardness and wear rate with results that suggest LBPA as good substitute for expensive synthetic ceramic carbides and alumina as reinforcement production of brake rotor. Optimal values of 40.41 HRB Hardness and 0.0489 mm^3/Nm Wear rate were obtained when the percentage reinforcement reached 25%. The A356/LBPA composite showed remarkable improvement in terms of hardness and wear rate properties when compared to A356 alloy after solution heat treatment with 57.23% and 47.10% improvement respectively. The microstructure of the A356/LBPA composite showed a structure with more grain boundaries than that of the alloy which indicates high potential towards strengthening with benefits of improving hardness and wear resistance.

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