Optimization of Stir Casting of Aluminum Matrix Composites (AMCs) with Filler of Recycled Glass Powder (RGP) for The Mechanical Properties

Yusup Hendronursito[1*], Tumpal Ojahan[2], Anang Anshori[2], Asep Yunanto[2]

[1]Research Unit for Mineral Processing, Jl. Ir. Sutami Km. 15 Tanjung Bintang Lampung Selatan, 35361, Indonesia
[2]Department of Mechanical Engineering, Faculty of Engineering, University of Malahayati – Lampung, Indonesia
*Corresponding author: yusuph_ugm07@yahoo.com

ABSTRACT

A study of making Aluminum Matrix Composites (AMCs) uses recycled glass powder (RGP) as a filler has been carried out through the stir casting process. The experimental design uses the Taguchi method of 3^3 orthogonal array L9 with the parameters of powder size (20>x> 80, 80>y> 200, 200>z> 325), percentage of filler vs matrix (2%, 7%, 12%), and stirring time (30 Seconds, 3 Minutes, 12 Minutes). The optimum conditions for the hardness of Al-GRp composites were obtained from specimens with Mesh powder size parameters 200> z> 325, the percentage of glass vs aluminum powder was 12% wt, stirring time was 12 minutes. The experimental factor that has the greatest contribution to the hardness value of Al-GRP composites is the size of glass powder of 73.77%, followed by the percentage of glass powder to aluminum by 19.98%, and the stirring time of 1.21%. The optimum experimental parameters for tensile strength can be obtained from specimens with particle size parameters of 20> x> 80, the percentage of glass powder to the weight of aluminum 12%, and the stirring time of 30 seconds. The biggest contribution to the tensile strength value of the Al-GRP composite was the stirring time of 72.71%, followed by the percentage of glass powder to aluminum by 13.67%, and the size of the powder was 9.97%.

Keywords: Aluminum, composite, glass powder, mechanical, Taguchi method

I. Introduction

Aluminum matrix composites (AMCs) are a material that continues to be developed in the automotive and aircraft industries because it has several advantages such as high hardness, good strength to weight ratio, corrosion resistance, and so on [1]. The addition of filler in the form of SiC to AMCs has been shown to have an effect on superior mechanical properties. Silicon carbide or carborundum is a derivative of silicon compounds with the molecular formula SiC. This material is formed by the covalent bonding of the elements Si with C. The production process for SiC is complex and requires high energy which causes high costs. Synthesis of SiC at least requires a temperature of 1200°C at the furnace through microwave sintering furnace, plasma sintering, and hydrothermal processes to deform the SiO_2 and C bonds into SiC [2] – [6]. Meanwhile, the synthesis of SiC using low temperatures is still a challenge for researchers [7]. Alternative materials are researched to obtain maximum results. The use of waste materials, such as glass waste, needs to be studied more deeply.

Glass has a dominant content of Si, so in this research, an experiment conducted on adding glass powder to aluminum composites. A reinforcing filler made from glass powder or what is often referred to as recycled glass powder (RGP) is one of the most widely used research materials as a reinforcement filler in composites [8]. The addition of RGP material as a filler in composites has been shown to reduce the expansion of the silica reaction so that the volume of the composite material is smaller [8]. The use of glass waste as a filler was also studied, stating that the use of glass waste can produce high strength and can reduce the porosity of composite materials [9]. The hardness of the oxide glass ranges from 5 to 7 on the Mohs scale, the highest obtained in silica glass. While the hardness of SiO_2 and $CaO.SiO_2$ glass reaches 635 kg/mm^2 and 650 kg/mm^2 [10]. So it is possible to use it as a reinforcement that can be used to increase the hardness of aluminum matrix composites where the hardness of used aluminum waste based from piston is only 54 HRB or equivalent to 98.4 kg / mm^2 [11]. Besides having the advantages that have been mentioned in several studies above, the use of waste as a composite material will provide an alternative to waste treatment, especially glass waste.

II. Material and Methods

The aluminum matrix used comes from automotive waste aluminum in the form of motor vehicle pistons. RGP as filler material is obtained from beverage glass bottles that have been refined on a ballmill machine and sieved to obtain the particles size. The casting method uses stirr casting, as shown in Figure 1.
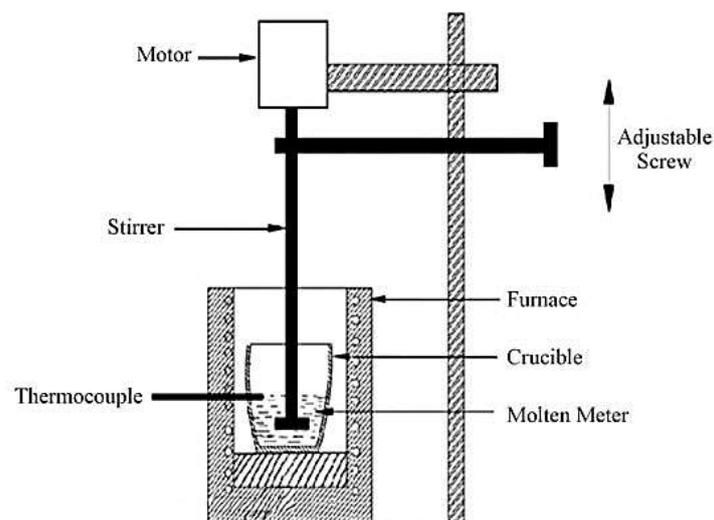

Fig. 1. Experimental schematic of stir casting machine [12]

The experimental design uses the Taguchi method of orthogonal array design L9 with 9 specimens. The parameters used in this study include powder size (mesh), percentage of glass powder to the weight of aluminum (%), and stirring time (minutes). The parameter design using the Taguchi method can be seen in Table 1.

S/N ratio large the better, optimizing by equation 1.

$$\frac{S}{N} = -10 \, Log \left[\frac{1}{n} \sum_{i=1}^{n} \frac{1}{yi^2} \right] \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (1)$$

Where n = number of observations and y = observed data

The choice of level in variable powder size is based on the classification of size groups which are divided into 3 groups, namely large, medium, and small particle sizes. Group 1 has a particle size of 840 μm to 177 μm, group 2 with a particle size of 177 μm to 74 μm, and group 3 with a particle size of 74 μm to 37 μm. Particle sizes greater than 1 μm allow less perfect integration with the matrix due to the influence of heat on the stirr casting process.

Table 1. Taguchi: L9 orthogonal array

No. sample	A	B	C
Run order	Powder size	% Powder vs Al	Stirring time
1	20 > x > 80	2%	30 Seconds
2	20 > x > 80	7%	3 minutes
3	20 > x > 80	12%	12 minutes
4	80 > y > 200	2%	3 minutes
5	80 > y > 200	7%	12 minutes
6	80 > y > 200	12%	30 Seconds
7	200 > z > 325	2%	12 minutes
8	200 > z > 325	7%	30 Seconds
9	200 > z > 325	12%	3 minutes

Sample testing to determine the optimization of the process that has been designed includes mechanical tests in the form of hardness and tensile strength. The hardness test uses the Rockwell hardness tester while the tensile strength test uses the Universal Testing Machine (UTM) HT 2402 with a capacity of 100 kN at the Non Metal Material Laboratory, BPTM - LIPI by following the ASTM E8-M standard.

III. Results and Discussions

A. *Taguchi Analysis for Composite Hardness*

Hardness testing is carried out on the sample at several points and take the average value for Taguchi and Anova analysis. The hardness value obtained from an average of three times the test, as shown in Table 2.

The results of the Taguchi analysis include the S/N ratio and means value are shown in Table 3 and Figures 2 - 3. The ranking of each experimental factor is shown in Table 3 where powder size gets the first rank, percentage of GRP powder to basalt 2nd rank, and stirring time 3rd rank. This rating shows the most dominant value on the test results, in this case the hardness of the composite.

Main effects plots for means show the average value of each parameter and the levels that can be achieved. The highest average value for factor A is obtained from level 3, factor B is obtained from level 3, and factor C is obtained at level 3. From the main effects plot graph for the average value in Figure 2, it can be seen that factor A indicates the existence of increase in the average score at each level.

Table 2. Results of hardness testing

No sample	Experimental parameters			Hardness test results (average)
	A (Powder size)	B (% Powder vs Al)	C (Stirring time)	HRB
1	1	1	1	58
2	1	2	2	60
3	1	3	3	72
4	2	1	2	78
5	2	2	3	81
6	2	3	1	88
7	3	1	3	83
8	3	2	1	87
9	3	3	2	92

Table 3. Response larger is better of S/N ratios for hardness value

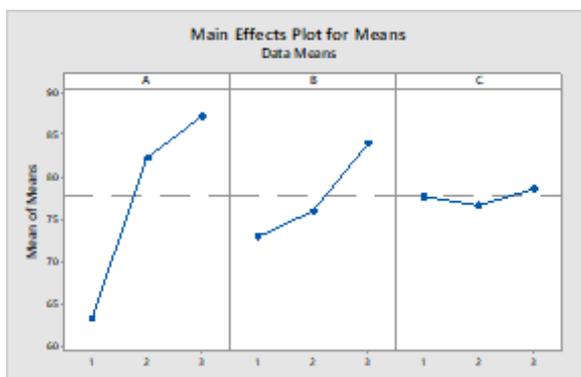| Experiment factors	Response for levels in factor parameters			
	1	2	3	Ranking
A (Powder size)	35.99	38.30	38.82	1
B (% Powder vs Al)	37.16	37.51	38.44	2
C (Stirring time)	37.65	37.56	37.90	3

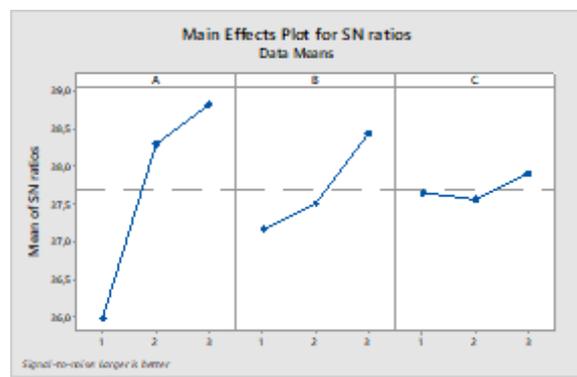Fig. 2. Main effects plot for Means to the hardness value

Fig. 3. Main effects plot for S/N (Larger is better) ratio to the hardness value

The effect of the size of the glass powder as a filler shows an increase from the size of $20>x>80$ of 63.33 HRB to 82.33 HRB at the powder size of $80>y>200$ and it increases again when the powder size is $200>z>325$ to 87.33 HRB. The change in powder size from large to smaller sizes has a directly proportional effect on the average value of hardness. The smaller of the size, the greater the average hardness obtained. Likewise in factor B, it can be seen that the average value is directly proportional to the level used. At level 1 the percentage of glass powder to aluminum is 2% w/t, has an average hardness value of 73 HRB,increases to 76 HRB at level 2 with the percentage of glass powder to aluminum is 7% w/t, and again increases to 84 HRB at level 3 with the percentage of glass powder to

aluminum is 12% w/t. However, it is different in factor C; there is a value that goes up and down at level 1 and falls at level 2 and rises to reach a peak at level 3. Level 1 of C parameter, namely the stirring time of 30 seconds, gives an average hardness value of 77.67 HRB and decreased to 76.67 HRB when stirring for 3 minutes.

From the S/N ratios graph in Figure 3, it can be seen that the optimum conditions are at the following parameters and levels: A3B3C3. The optimum conditions for A3B3C3 represent the sample with the following parameters, A3 is the size of the mesh powder 200> z> 325, B3 is The percentage of glass powder vs aluminum is 12% w/t, and C3 is the stirring time of 12 minutes.

B. Analysis of Variance (Anova) for Composite Hardness

Anova using the Minitab 17 software can be used to determine the significant parameters that affect the hardness results. The variables used in this experiment include A (RGP size in mesh), B (percentage of glass powder vs Aluminum), C (stirring time). This significant effect can be seen from the P-value obtained from the results of data processing. Important requirements in drawing conclusions based on data or statistical groups are as follows:

If the P-Value > α, then hypothesis zero (Ho) is accepted, and hypothesis one (H1) is rejected. If the P-Value < α, then hypothesis Zero (Ho) is rejected and hypothesis one (H1) is accepted. The α value in the experiment was set at 5%.

The null hypothesis of the Anova test states that there is no relationship between the independent variable and the dependent variable. This means that in the formulation of the hypothesis being tested is the conclusion that it is not true that the independent variable affects the dependent variable. The alternative hypothesis (H1) states that there is a relationship between the independent variable (x) and the dependent variable (y) under study. This means that in the formulation of the hypothesis, the conclusion is that the results of the H1 calculation will be used as the basis for searching research data.

The Anova test results are shown in Table 4. From these results, the P-value is obtained from the smallest value to the largest value, respectively, are parameter A with a value of 0.000, parameter B with a value of 0.001, and parameter C with a value of 0.323. This concludes that for parameter A and parameter B then Ho is rejected and H1 is accepted. The size of the powder and the percentage of glass powder on aluminum have a significant effect on the hardness of the composite. While the parameter C value of P-value is greater when compared to α = 5%. So that in this study, the stirring time did not have a significant effect on the hardness of aluminum composites. The analysis of Anova, the P-value in accordance with the Taguchi test in Table 3, which shows the highest ranking is obtained from parameter A (grain size of glass powder).

Based on Figure 4, the experimental factor that has the largest contribution to the hardness value of Al-GRP composites is the size of glass powder of 73.77%, followed by the percentage of glass powder to aluminum by 19.98%, an error of 5.04%, and stirring time of 1, 21%. Based on the Taguchi test of the S/N ratios value, the optimum grain size to use was 200>z>325 mesh. A filler with good characteristics will have positive effect on the composites made. The RGP filler has a high hardness that will increase the hardness distribution of the aluminum matrix composite. The presence of harder filler and well bonded RGP particles in aluminum matrix that impede the movement of dislocations increases the hardness of AMCs [13].

Table 4. Anova test results on the hardness (HRB) of Al-GRP

Source	DF	Seq SS	Adj SS	Adj MS	F-Value	P-value
Regression	3	1049.97	1049.97	349.99	31.39	0.001
A (Powder size)	1	815.66	815.66	815.66	73.15	0.000
B (% Powder vs Al)	1	220.9	220.9	220.9	19.81	0.007
C (Stirring time)	1	13.41	13.41	13.41	1.2	0.323
Error	5	55.76	55.76	11.15		
Total	8	1105.73				

The contribution of each factor to the hardness value of the Al-GRP composites is shown in Figure 4.
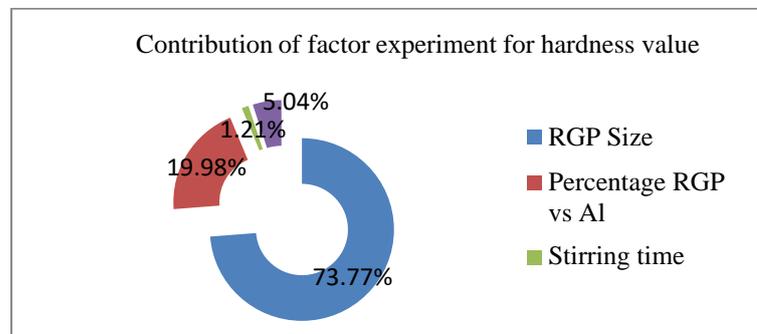

Fig. 4. Contribution of experimental factors to the hardness of Al-GRP composites

Based on Table 5, it is known that the coefficient of determination R-Square is 0.9496, which is the square of the correlation coefficient "R" which is 0.9745. The coefficient of determination of 0.9496 indicates the independent variable (x) simultaneously (together) affects the dependent variable (y) by 94.96%. While the remaining 5.04% is influenced by other variables outside the regression equation or other variables that are not included in the experimental parameters. The magnitude of the influence of this other variable is called error. The value of R-sq, which is close to the value of 100%, indicates that the influence of the independent variable (x) is getting stronger on the dependent variable (y).

Table 5. Output model summary

Model summary for transformed response				
S	R-sq	R-sq (adj)	Press	R-sq (pred)
3.33935	94.96%	91.93%	156.242	85.87%

The formula for predicting the hardness value of Al-GRP composites in terms of the factors and levels used in this experiment are as follows:

$$\text{HRB} = 77.667 - 14.333\,A\_1 + 4.667\,A\_2 + 9.667\,A\_3 - 4.667\,B\_1 - 1.667\,B\_2 + 6.333\,B\_3 + 0.0\,C\_1 - 1.000\,C\_2 + 1.000\,C\_3 \quad \text{..........................} \quad (2)$$

From equation (2), it can be seen that the value of hardness without independent variables (A, B, C) is predicted to be at a value of 77 HRB. Important factors that affect the value of hardness which is indicated by the high regression coefficient values, namely A1 and A3. This is in accordance with the ranking obtained from Table 3. It is also seen that the factor that is not too influential is the length of stirring (C) with a small regression coefficient value. In addition to predicting the hardness value obtained by multiplying the number against the experimental factor, it can also be predicted the value of hardness through the relationship of two parameters used, for example, the interaction between parameter A and parameter B (A vs B), parameter A with parameter C (A vs C), and parameter b with parameter C (A vs C).

Based on Figure 5, the contour plot of the hardness value of the interaction of parameter A and parameter B, it can be seen that the highest hardness value is symbolized in the dark green area. This area is obtained when the level on parameter A and parameter B increases.
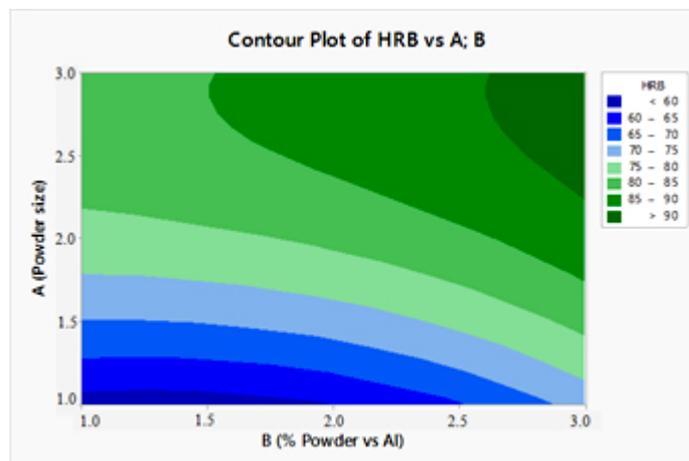

Fig. 5. Prediction of the relationship between A vs B and the resulting violence
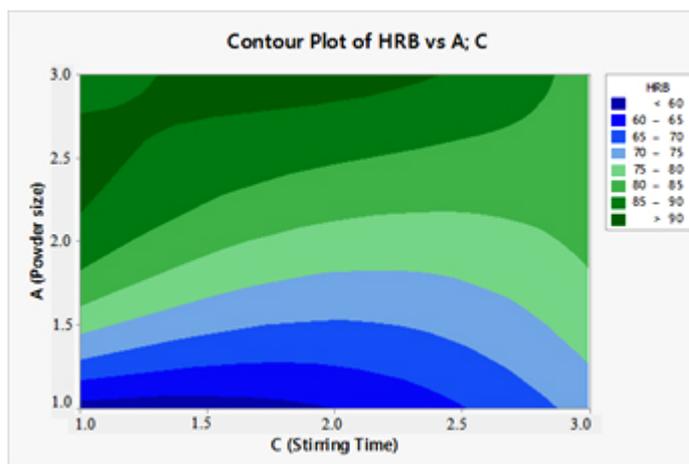

Fig. 6. Prediction of A vs C relationship to the resulting violence

In the contour plot of hardness obtained from the interaction of parameter A and parameter C as shown in Figure 6, it can be seen that the highest hardness value can be

obtained in parameter A starting at level 2 to 3, but parameter C is the choice of level that can be used from level 1 to level 2.5.

The prediction of the relationship between B vs C and the resulting hardness can be seen in Figure 7. The area bordered by dark green is the area with the highest hardness value, more than 90 HRB. When seen in the picture, this area is very narrow. This is in accordance with the significant contribution and influence that these two parameters contribute less and less significant effect on violence.
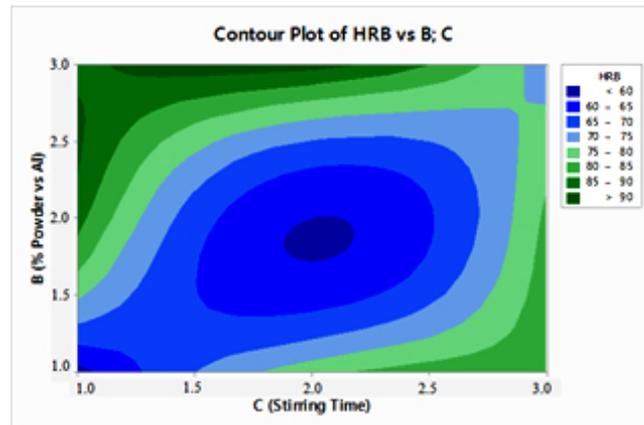

Fig. 7. Prediction of the relationship between B vs C and the resulting violence

C. Taguchi Analysis for Composite Tensile Strength

The results of the test for the tensile strength of the Al-GRP composite sample are shown in Table 6. The highest tensile strength was obtained from sample 6th is 11.24 N/mm^2. Sample 6th was obtained from various parameters and levels of A2B3C1, with parameters of glass powder grain size 80>y>200, percentage of glass powder vs aluminum 12% w/t, stirring time 30 seconds. While the lowest value is obtained from sample 4th with a tensile strength value of 2.76 N/mm^2. Sample 4th was obtained from A2B1C2 parameters, namely glass powder grain size 80>y>200, percentage of glass powder vs aluminum 2% w/t, stirring time 3 minutes.

Table 6. Tensile strength results

No sample	Experimental parameters			Tensile strength (N/mm2)
	A (Powder size)	B (% Powder vs Al)	C (Stirring time)	
1	1	1	1	9.55
2	1	2	2	4.66
3	1	3	3	8.14
4	2	1	2	2.76
5	2	2	3	2.81
6	2	3	1	11.24
7	3	1	3	4.15
8	3	2	1	8.15
9	3	3	2	3.66

The response data from the tensile test results are then processed to create a response table for the average tensile strength and the S/N ratios table. The results of data processing are shown in Table 7 and Figure 8 - 9.

Table 7 shows the ranking of factor parameter. It has shown the stirring time give the best ranking followed by percentage of glass powder and powder size, respectively.

Table 7. Response of S/N ratios larger is better (dB) for tensile strength

Experiment factors	Response for levels in factor parameters			
	1	2	3	Ranking
A (Powder size)	17.06	12.94	13.95	3
B (% Powder vs Al)	13.59	13.52	16.83	2
C (Stirring Time)	19.61	11.15	13.18	1

The effect of reducing the grain size of glass powder from mesh 20> x> 80 to 200> z> 325 causes the average tensile strength of the composites to decrease by 28.59%. The tensile strength of the composite decreased from 7.45 to 5.32 N/mm^2. Meanwhile, by increasing the percentage of glass powder from 2% w / t to 12% by weight of aluminum, it can increase the tensile strength from 13.59 N/mm^2 to 16.83 N/mm^2. However, the percentage of 7% wt of glass powder to aluminum decreased slightly by around 0.07 N/mm^2. However, this value tends to be small, namely around 0.5%, the graphical trend that is increasing with the addition of the percentage of glass powder. In the parameter of stirring time, there was a decrease in the tensile strength value of the Al-GRC composite by 47.83%. Stirring time of 30 seconds gives the highest average tensile strength value of 9.647 N/mm^2, presented in Figure 9.

S / N ratio analysis shows the effect of the most optimum experimental parameters that can be obtained from the experimental parameters, namely A1B3C1. A1B3C1 parameter represents particle size 20> x> 80, percentage of glass powder to weight of aluminum 12%, and stirring time 30 seconds.
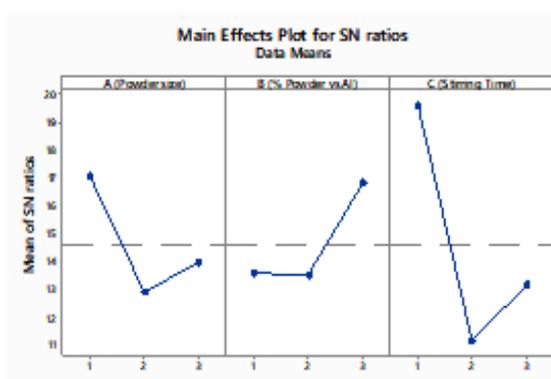

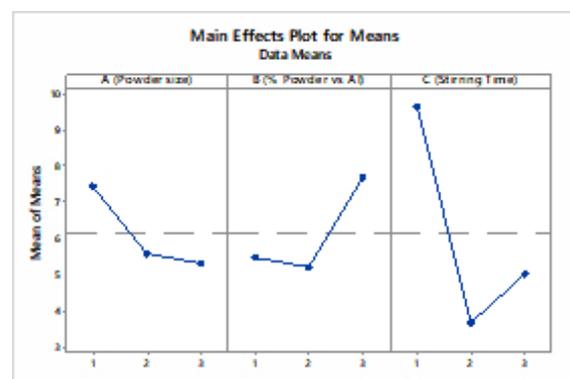Fig. 8. Effect of experimental factors on S/N Ratios larger is better for tensile strength

Fig. 9. The main effects of experimental factors on the average tensile strength of the Al-GRP composite

D. Analysis of Variance (Anova) for Composite Tensile Strength

The Anova test results are shown in Table 8. From these results, the P-value from the smallest to the largest value is parameter C with a value of 0.048, parameter B with a value of 0.211 and parameter A with a value of 0.268, respectively. This concludes that in parameter C, Ho is rejected and H1 is accepted. The duration of stirring has a significant effect on the tensile strength of the composite. While parameter A and parameter B, the P-value is greater when compared to α 5%. So that in this study, the grain size of glass powder and the percentage of glass powder on the weight of aluminum did not have a significant effect on the tensile strength of aluminum composites. The analysis of ANOVA shows conformity to the ranking results obtained from Table 7. Anova analysis, the P-value for the conclusion of the hypothesis taken is in accordance with the Taguchi test, which shows that the highest ranking is obtained from parameter C (stirring time).

Table 8. Anova test results on tensile strength (N/mm^2) of Al-GRP composites

Source	DF	Seq SS	Adj SS	Adj MS	F-Value	P-value
A (Powder size)	2	8.027	8.,027	4.014	2.73	0.268
B (% Powder vs Al)	2	11.006	11.006	5.503	3.75	0.211
C (Stirring time)	2	58.521	58.521	29.26	19.93	0.048
Error	2	2.936	2.936	1.468		
Total	8	80.49				

The contribution of each factor to the tensile strength value of the Al-GRP composite is shown in Figure 10.
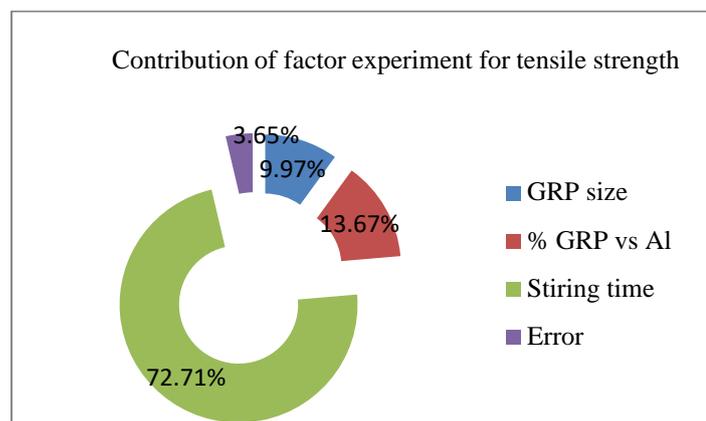

Fig. 10. Contribution of experimental factors to the tensile strength of Al-GRP composites

Based on Figure 10, the experimental factor that has the greatest contribution to the tensile strength value of Al-GRP composites is the stirring time of 72.71%, followed by the percentage of glass powder to aluminum by 13.67%, powder size of 9.97%, and 3.65 %. Based on the Taguchi test of the S/N ratios value, the optimum stirring time is 30 seconds. The stirrer rotation makes a vortex effect that draws the particle into the aluminum melt. The filler needs to be subjected to constant centrifugal currents over a certain period of

time to achieve dispersion all through the aluminum melt. Longer stirring time produces more agitation in the molten composite, which increases the tendency to form more porosity. There is an optimum range of stirring time to achieve uniform distribution with least porosity. If stirring continues beyond the optimum range, the gas absorbability of the molten aluminum will increase. Thus, the formation of porosity becomes unavoidable [14].

Based on Table 9. Output model summary, it is known that the coefficient of determination R-Square is 0.9435 which is the square of the correlation coefficient "R", which is 0.9816. The coefficient of determination of 0.9435 indicates that the independent variable (x) simultaneously (together) affects the dependent variable (y) by 94.35%. While the rest, 5.65% is influenced by other variables outside the regression equation or other variables that are not included in the experimental parameters. The magnitude of the influence of this other variable is called error. The value of R-sq, which is close to the value of 100%, indicates that the influence of the independent variable (x) is getting stronger on the dependent variable (y).

Table 9. Output model summary

Model summary for transformed response				
S	R-sq	R-sq (adj)	Press	R-sq (pred)
1.21156	96.35%	85.41%	59.449	26.14%

The formula for predicting the tensile strength of the Al-GRP composite in terms of the factors and levels used in this experiment are as follows:

$$\text{Tensile Strength} = 6.124 + 1.326A\_1 - 0.521A\_2 - 0.804A\_3 - 0.638B\_1 - 0.918B\_2 + 1.556B\_3 + 3.522C\_1 - 2.431C\_2 - 1.091C\_3 \quad \text{... (3)}$$

From equation (3), it can be seen that the value of tensile strength without independent variables (A, B, C) is predicted to be at a value of 6.124 N/mm^2. Important factors that affect the value of tensile strength which is indicated by the high regression coefficient values, namely C1 and C2. This is in accordance with the ranking obtained from Table 3. It is also seen that the factor that is not too influential is the particle size (A) and percentage of GRP (B) with a small regression coefficient value. In addition to predicting the tensile strength obtained by multiplying the number against the experimental factor, it can also be predicted the value of tensile strength through the relationship of the two parameters used, for example, the interaction between parameter A and parameter B (A vs B), parameter A with parameter C (A vs C), and parameter B with parameter C (A vs C).

Based on Figure 11, the contour plot of the tensile strength from the interaction of parameter A and parameter B, it can be seen that the tensile strength is symbolized in the dark green area with a tensile strength value greater than 3 N/mm^2 obtained from parameter A level 2 and parameter B level 2. The area with a high tensile strength value is very narrow and the tensile strength value obtained is also very small (above 3 N/mm^2). It can be understood from the previous explanation that these two parameters (parameter A and parameter B) do not contribute simultaneously to the tensile strength value of the Al-GRP composite.
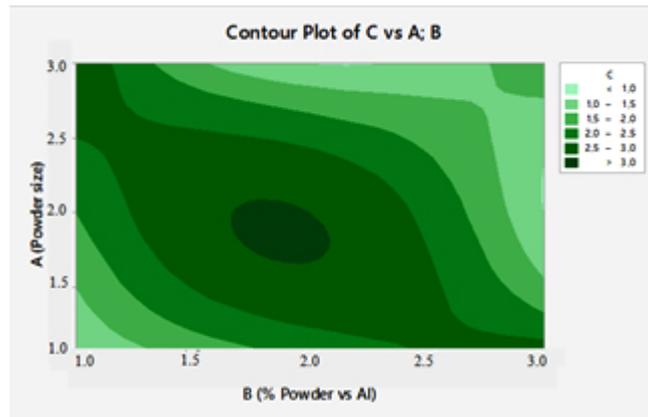
Fig. 11. Contour plot of parameter A vs parameter B to tensile strength

In the contour of tensile strength plot in Figure 12, which is obtained from the interaction of parameter A and C, it can be predicted that the highest tensile strength value is obtained from parameter A at any level as long as it interacts with parameter C level 2.5 to level 3. This is in accordance with the explanation contribution of parameter C, which holds the highest and most significant contribution to tensile strength.
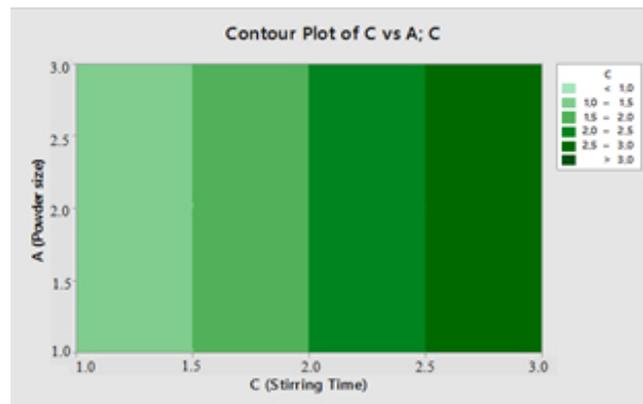

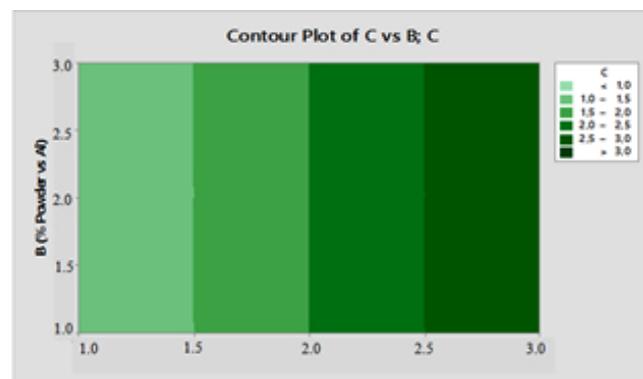Fig. 12. Prediction of A vs C relationship to the resulting violence

Fig. 13. Prediction of the relationship between B vs C and the resulting violence

The prediction of the relationship between B vs C and the resulting tensile strength can be seen in Figure 13. The area bordered by dark green is the area with the highest tensile

strength, more than 3 N/mm^2. It can be predicted that the highest tensile strength value is obtained from any level of parameter B as long as it interacts with parameter C level 2.5 to level 3. This is in accordance with the explanation of the contribution of parameter C, which holds the highest contribution and has the most significant effect on tensile strength.

IV. Conclusions

The manufacture of aluminum matrix composites (AMCs) made from aluminum matrix with glass powder reinforcing filler has been carried out by the stirr casting process using a variety of experimental factors designed using Taguchi and analyzed using the help of Minitab 17 software.

The optimum conditions for the hardness of Al-GRp composites were obtained from specimens with particle size parameters 200> z> 325, the percentage of glass vs aluminum powder was 12% w / t, stirring time was 12 minutes. The experimental factor that has the greatest contribution to the hardness value of Al-GRP composites is the size of glass powder of 73.77%, followed by the percentage of glass powder to aluminum by 19.98%, and the stirring time of 1.21%. The optimum experimental parameters for tensile strength can be obtained from specimens with particle size parameters of 20> x> 80, the percentage of glass powder to the weight of aluminum 12%, and the stirring time of 30 seconds. The biggest contribution to the hardness value of the Al-GRP composite was the stirring time of 72.71%, followed by the percentage of glass powder to aluminum by 13.67%, and the size of the powder was 9.97%.

Acknowledgement

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