

COMPARATIVE CHARACTERIZATION OF CHEMICALLY MODIFIED HOMOGENEOUS ALLOYS FOR ENHANCED PROPERTIES IN TRICYCLE PISTON APPLICATIONS

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ABSTRACT

This study investigated the performance of recycled aluminium silicon alloys used in tricycle piston applications, where uneven composition and poor mechanical qualities affect service dependability. The goal was to assess the impact of sulphur-based chemical modifications on the mechanical and thermal characteristics of homogenous silumin alloys. The methodology included preparing seven alloy formulations with sulphur additions ranging from 0.0-3.0 wt.% using scrap aluminium from engine blocks and gearboxes, followed by controlled melting, degassing, fluxing, casting, and testing for tensile strength, fatigue strength, Vickers hardness, and thermal linear expansivity; statistical significance was determined using analysis of variance and Tukey post hoc tests. The results showed significant variation across all treatments, with the 1.0 wt.% sulphur alloy achieving the highest hardness of about 60.5 HV and fatigue life of about 7.1 million cycles, while tensile strength declined beyond 1.5 wt.% sulphur, and excessive sulphur reduced overall mechanical performance due to microstructural coarsening and brittle phase formation. The study therefore recommends maintaining sulphur addition at around 1.0 wt.% to achieve the optimal balance of strength, hardness, fatigue resistance, and thermal stability for tricycle piston applications, as well as strict control of sulphur content during alloy formulation to prevent mechanical property degradation.

Keywords: Chemical, modified alloys, Silumin, Sulphur powder, Mechanical properties, characterization, Recycled aluminium alloys, Tensile strength, Fatigue strength, Vickers hardness, Thermal expansivity

1 INTRODUCTION

Chemically modified homogeneous alloys play an important role in improvement of properties of engineering materials. Alloy modification alters microstructure, which influences mechanical strength, hardness, thermal behaviour, and fatigue resistance. Aluminium silicon alloys such as silumin receive wide use in automotive and mechanical applications because of their good castability, corrosion resistance, and moderate mechanical strength. However, enhancement of their mechanical and thermal performance remains necessary for demanding applications such as engine components and tricycle pistons. Researchers therefore focus on alloy modification techniques which refine the internal structure and improve overall performance of the material. One method for enhancing alloy performance is chemical treatment with sulphur powder. According to earlier research, adding sulphur to aluminium alloys improved its hardness, machinability, and structural stability. During casting, sulphur combines with molten aluminium to create aluminium sulphide inclusions. According to [1], these inclusions alter the microstructure and have an impact on mechanical behaviour under service circumstances. Additionally, researchers looked at how microstructural control and alloying elements might enhance the mechanical performance of metallic materials. Aluminium silicon alloys' strength and fatigue resistance are determined by the distribution of eutectic silicon particles,

which is influenced by rare earth elements, nano reinforcements, and grain refinement methods [2, 3]. Enhancement of structural materials also involves surface modification and mechanical alloying. Because smaller grains limit dislocation migration during deformation, grain size reduction increases the hardness and mechanical stability of alloys. Modified alloy systems with better microstructural control can be formed thanks to developments in additive manufacturing and powder metallurgy [4, 5]. Similar modification techniques manage phase distribution and surface morphology to enhance the performance of biomedical alloys [6]. Several researchers also investigated doping strategies involving transition metals such as rhenium. According to research, the interaction between base metals and alloying elements improved microstructural refinement and thermal stability [7]. Through dispersion strengthening and microstructural refinement, the addition of nanoscale composites strengthens aluminium alloys even more [2]. Despite these advancements, little study has been done on sulphur modification of recycled silumin alloys for use in tricycle engines and other light transportation applications. Recycled aluminium alloys are still crucial for sustainable production and cost savings. However, the finished material's mechanical performance is frequently impacted by differences in the composition of the debris. Therefore, to stabilise alloy characteristics and enhance engineering performance, suitable chemical modification is required. This study used sulphur powder treatment to characterise and compare chemically modified homogenous silumin alloys. The study looked at how various sulphur concentrations affected hardness, thermal expansivity, tensile strength, and fatigue strength. The best sulphur formulation was found using statistical analysis, which resulted in better material qualities appropriate for tricycle piston applications. The results offer scientific data for alloy design, recycling procedures, and the enhancement of engineered materials based on aluminium.

2 MATERIALS AND METHODS

2.1 Materials

The study's foundation material for alloy preparation was silumin aluminium alloy made from scrap gearboxes and engine blocks that were acquired from Jimeta Ultra-Modern Market in Adamawa State, Nigeria. The International Organization for Standardization's ISO 3522 classification system was used to identify the alloy's chemical composition in compliance with ASTM International ASTM E1251. The scrap materials were cleaned and treated to eliminate impurities before melting. An electric resistance furnace was used for melting in a graphite crucible, and ASTM International ASTM B917 rules were followed for melt treatment to guarantee homogeneity and impurity control. In accordance with The Aluminium Association's guidelines for aluminium melt treatment, degassing was carried out using a combination of argon and sulphur hexafluoride. To facilitate oxide removal and inclusion separation, a fluxing agent comprising 10% non-hygroscopic sodium fluoride was used in accordance with recognised aluminium refining practices published by Zhang et al. (2023). To increase machinability through the production of aluminium sulphide inclusions, sulphur powder of Analytical Reagent grade with a minimum purity of 99.5% that complies with American Chemical Society reagent criteria was added as a modifying ingredient. The International Organization for Standardization's ISO 13320 was followed in determining the sulphur particle size range of 1 μm to 50 μm . In accordance with ASTM International ASTM B26/B26M, the treated melt was cast into heated moulds. All processing parameters were regulated to guarantee uniformity, repeatability, and adherence to standard metallurgical procedure.

2.2 Equipment and Tools

The experimental study made use of a variety of laboratory and mechanical testing tools from various universities. A 1.5-10 kg, 4 kW laboratory ceramic muffle furnace at Ahmadu Bello University's Department of Materials and Metallurgy, Zaria, was used for preheating the charge materials and moulds. Alloy melting was carried out separately in a 40 kg graphite crucible using an 18 kW electric resistance furnace. Mass measurements were taken on an AS 220 R2 analytical balance, which was calibrated and traceable to International Organization for Standardization norms to assure measurement accuracy. Mechanical testing was carried out using a DVS-1AT-BP Vickers hardness tester, with hardness measurements made in line with International Organization for Standardization ISO 6507 across seven experimental runs and three replications. Test specimens were machined on a MAS SN200

engine lathe, and specimen preparation adhered to ASTM International ASTM E8 dimensional criteria to assure uniformity and comparability of findings.

2.3 Scrap Preparation

The silumin scrap polluted with hydrocarbons, oxides, and particle matter was subjected to a two-stage decontamination process. In compliance with ASTM International ASTM G1, an initial chemical cleaning was carried out using detergent, petrol and acetone. Adhered contaminants were then removed by mechanical cleaning. Following treatment, the materials were washed in warm water to avoid recontamination and dried for 2 h at 105 °C in a controlled atmosphere to remove any remaining moisture. A hacksaw, anvil, and hammers were among the cutting and impact equipment used to reduce the cleaned waste into small pieces to aid melting. The cleaned engine-block and gearbox scrap fractions, weighing 42 kg and 30 kg, respectively, were combined, melted together, and homogenised to obtain a uniform alloy. The homogeneous melt was then cast into ingots, which were sorted, marked, and stored for subsequent alloy formulation.

2.4 Experimental Design

The design of the experiment and the production of the alloy were carried out using randomized complete design [8]. The chemical modification was done by varying sulphur content from 0.0 to 3.0 wt.% at 0.5 wt.% intervals as shown in Table 1 with three replications as shown in Table 2. Characterization of physical, mechanical, thermal, technological, tribological, and micrographic properties was carried out, and the results analyzed, the best formulation was then selected.

Table 1. Experimental design for silumin sulphur formulation

Level	Sample code	Percentage of recycled grade of silumin (%)	Recycled grade of silumin (kg)	Sulphur Powder Weight (kg)	Percentage Powder Weight (%)	No of samples produced
1	GS0.0SP	100	4.00	0	0	1 × 7
2	GS0.5SP	99.5	3.98	0.02	0.5	3 × 7
3	GS1.0SP	99.0	3.96	0.04	1.0	3 × 7
4	GS1.5SP	98.5	3.94	0.06	1.5	3 × 7
5	GS2.0SP	98.0	3.92	0.08	2.0	3 × 7
6	GS2.5SP	97.5	3.90	0.10	2.5	3 × 7
7	GS3.0SP	97.0	3.88	0.12	3.0	3 × 7

Table 2. Experimental Replication for silumin and sulphur formulation

REPLICATES 1	REPLICATES 2	REPLICATES 3
GS1.0SP	GS0.5SP	GS2.5SP
GS2.5SP	GS1.0SP	GS2.0SP
GS0.5SP	GS3.0SP	GS1.5SP
GS3.0SP	GS2.0SP	GS0.5SP
GS0.0SP	GS2.5SP	GS1.0SP
GS2.0SP	GS0.0SP	GS3.0SP
GS1.5SP	GS1.5SP	GS0.0SP

2.5 Formulation of Chemically Modified Silumin Sample

All needed silumin alloy melts were developed and cast in line with ASTM International ASTM B26/B26M, with alloy classification based on the International Organization for Standardisation ISO 3522. A total of 72 kg of the homogenised silumin ingots was cut into appropriate pieces, preheated, and used to prepare the seven sulphur formulations in three replications. For each melt, the appropriate charge was placed in a 40 kg graphite crucible and melted in the 18 kW electric resistance furnace described in Section 2.2. The melt was degassed using an argon-sulphur hexafluoride combination containing 0.2% SF₆ at a flow rate of 10-15 L/min for 5-10 min, following The Aluminium Association's aluminium melt treatment recommendations. A 10% non-hygroscopic sodium fluoride flux was added to improve impurity removal, and the melt was agitated with an alumina-coated paddle for 2-5 min to guarantee uniform distribution and avoid sedimentation. Based on ASTM International ASTM B917/B917M standard, the molten alloy was kept at 800 ± 20 °C for 30 min to establish homogeneity and dissolve intermetallic phases, which reduced the production of sludge. Seven sample compositions were made. To encourage inclusion separation, the melt for each batch was mixed and then left to stand for 20 min. To regulate microstructure and guarantee uniformity across all samples, casting was done in warmed sand moulds at 200-300 °C with an anticipated cooling rate of 5-10 °C/s.

Table 3. Percentage weight of charge material per cast bar in mass and percentage

Sample	M _{SN} (Kg)	M _{SN} (Wt%)	M _S (g)	M _S (Wt%)
GS0.0SP	4.00	100	0	0
GS0.5SP	3.98	99.5	20	0.5
GS1.0SP	3.96	99	40	1.0
GS1.5SP	3.94	98.5	60	1.5
GS2.0SP	3.92	98	80	2.0
GS2.5SP	3.90	97.5	100	2.5
GS3.0SP	3.88	97	120	3.0

2.6 Testing of Chemically Modified Silumin Sample and Analysis

The following tests were carried out on the modified silumin samples: tensile strength, fatigue strength, Vickers hardness, thermal linear expansivity, and thermal conductivity. The tests followed ASTM E8/E8M [13], ASTM E466 [14], ISO 6507-1 [15], ASTM E228 [16], and ASTM E1530 [17], respectively.

2.7 Statistical Analysis of Chemically Modified Silumin Material

Analysis of variance (ANOVA) was conducted using SAS version 9.4 (SAS Institute, Inc., Cary, NC, USA) to determine whether silumin material modification affects its mechanical properties (tensile strength, hardness, fatigue strength, Thermal linear expansivity test and thermal conductivity) to further determine the suitable chemical modification for further heat treatment. Pos hoc test was done using Tukey's mean comparison method for the level of effect of silumin chemical modification (Sulphur weight percentages of 0.5 wt.% (GS0.5P), 1.0 wt.% (GS1.0P), 1.5 wt.% (GS1.5P), 2.0 wt.% (GS2.0P), 2.5 wt.% (GS2.5P), 3.0 wt.% (GS3.0P), and control with 0 wt.% on the mechanical properties of the silumin material.

3 RESULTS AND DISCUSSION

3.1 Effects of Sulphur addition on Tensile strength, Fatigue strength, Vickers hardness, and Thermal linear expansivity of silumin material

An analysis of variance (ANOVA) evaluated the effect of sulphur powder addition on tensile strength, fatigue strength, Vickers hardness, thermal linear expansivity, and thermal conductivity of Silumin material. The ANOVA results showed significant differences among the sulphur treatment groups for all measured properties and results of F-value and p-values are summarized in Table 4. The result showed that tensile strength, the ANOVA result was significant at F (6.14, 20) = 147.44 and p = 0.0001.

This result indicates the addition of sulphur produced significant differences in the tensile strength of Silumin at 95% confidence level. The mean tensile strength values obtained from the different sulphur treatment levels are not equal. At least one treatment mean differs from the others. ANOVA identifies the presence of differences among the group means but does not identify the specific treatment groups responsible for the variation. A post hoc procedure using Tukey's test identifies the exact treatment levels with significant differences. The results of fatigue strength, also indicated that the ANOVA result was significant at $F(6.14, 20) = 338.48$ and $p = 0.0001$. This result shows the addition of sulphur produced significant differences in fatigue strength of Silumin. The means of fatigue strength generated from the sulphur treatment levels differ across the groups. At least one mean fatigue strength value differs from the others. ANOVA does not indicate the location of these differences among the treatment groups. A Tukey post hoc comparison provides detailed pairwise comparisons between the treatment means. Similarly, table 4 demonstrated that Vickers hardness result was significant at $F(6.14, 20) = 5.07$ and $p = 0.006$. This result indicates sulphur addition produced significant variation in the hardness of Silumin. The mean hardness values from the sulphur treatments differ, and at least one treatment mean differs from the others. ANOVA confirms the presence of differences but does not specify which treatment levels differ. Tukey's post hoc test identifies the specific sulphur treatment groups responsible for the differences. The thermal linear expansivity indicated a significant ANOVA result at $F(6.14, 20) = 9.34$ and $p = 0.00001$. This finding indicates sulphur addition significantly influenced the thermal linear expansivity of Silumin. The mean expansivity values associated with the sulphur treatments are not equal, and at least one treatment mean differs from the others. ANOVA identifies overall variation among the means but does not indicate the exact groups responsible. Tukey's post hoc analysis provides the detailed comparison among treatment means.

Table 4. ANOVA results for the effects of sulphur power addition on Tensile strength, Fatigue strength, Vickers hardness, and Thermal linear expansivity of silumin material

Property	df	F-value	p-value
Tensile strength	(6.14,20)	147.44	0.0001
Fatigue strength	(6.14,20)	338.48	0.0001
Vickers hardness	(6.14,20)	5.07	0.006
Thermal linear expansivity	(6.14,20)	9.34	0.00001

Figure 1 presents the mean Tensile Strength of Silumin in MN/m^2 under different sulphur powder additions. The control sample GSSP recorded the highest yield stress, about 130. Samples GS0.5SP, GS1.5SP, and GS1.0SP recorded similar values near $120 MN/m^2$, $115 MN/m^2$, and $114 MN/m^2$. These treatments share the same Tukey grouping letter "a"[1], which indicates no significant difference in Tensile Strength among them. This result shows sulphur addition up to about 1.5 wt.% maintained the Tensile Strength of the alloy. The sample GS2.5SP recorded a lower Tensile Strength near $48 MN/m^2$ and carries the letter "b", which indicates a significant reduction compared with the first group. The samples GS2.0SP and GS3.0SP recorded the lowest values, about 25 and $10 MN/m^2$, and share the letter "c". This grouping indicates no significant difference between them but shows a clear reduction compared with the other treatments. The pattern shows Tensile Strength decreases as sulphur content increases beyond 1.5 wt.%, which indicates higher sulphur levels weaken the mechanical strength of the Silumin alloy. These findings have significant implications for foundry practice and alloy design. While trace sulphur might be unavoidable in recycled aluminum feedstocks, the data clearly indicates that sulphur content must be rigorously controlled below 1.5 wt.% to preserve adequate tensile strength in silumin castings. This threshold behaviour contrasts with other alloying elements like strontium or antimony, which are intentionally added as modifiers to improve silicon morphology and enhance mechanical properties [9].

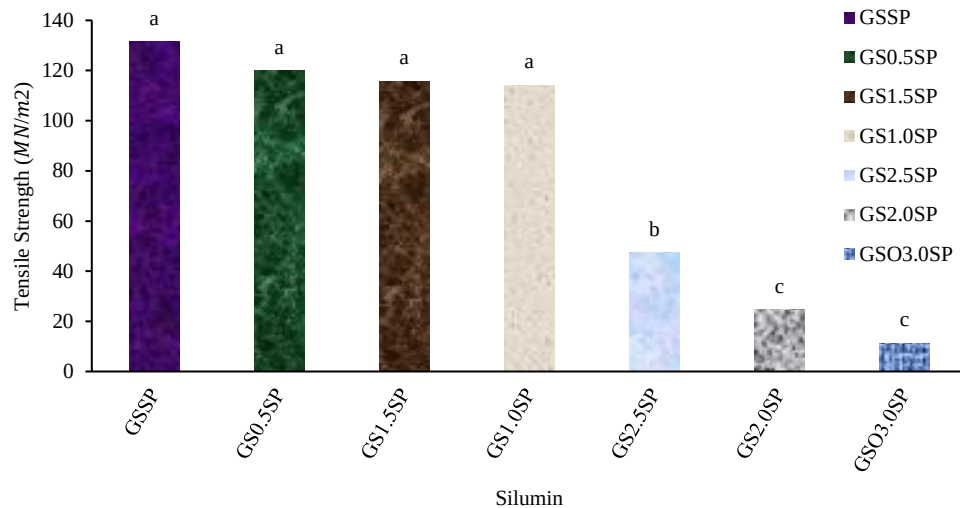


Figure 1. The post-hoc Tukey's test for means of the Tensile strength of the modified Silumin

The mean fatigue life (cycles) of the modified Silumin alloys shows variation across the sulphur treatment levels as indicated in Figure 2. Means that do not share the same letter indicate significant differences according to the Tukey grouping method at a 95% confidence interval, $p \leq 0.05$. Treatment GS01.0SP belongs to group “a” and recorded the highest fatigue life of about 7,100,000 cycles, which differs significantly from all other treatments. Treatment GS01.5SP belongs to group “b” with a fatigue life of approximately 2,100,000 cycles, which is significantly lower than GS01.0SP but higher than the remaining treatments. Treatments GS00.5SP, GS03.0SP, GS0SP, GS02.0SP, and GS02.5SP belong to group “c”. These treatments did not show significant differences among themselves but recorded lower fatigue life values ranging from approximately 250,000 to 800,000 cycles. The higher fatigue life observed in GS01.0SP may be attributed to improved microstructural refinement and better distribution of eutectic silicon particles, which enhance crack resistance and delay fatigue crack initiation and propagation. In contrast, excessive sulphur addition may lead to coarser silicon structures or formation of brittle phases that reduce fatigue resistance and shorten fatigue life in aluminium–silicon alloys [10]. Sulphur at the optimal 1.0 wt.% concentration may promote this favourable microstructure through mechanisms such as modifying nucleation kinetics during solidification or influencing the growth habit of silicon phases. However, the exact mechanism differs from traditional modifiers like strontium or sodium, which are known to produce fine fibrous eutectic silicon. Sulphur's role appears more complex and concentration-dependent, potentially involving interactions with iron-rich intermetallic as suggested by [11], who observed that sulphur promotes dendritic Chinese script-like $Al_{15}(Fe,Mn)_3Si_2$ phases in Al-Si 319 alloy [1].

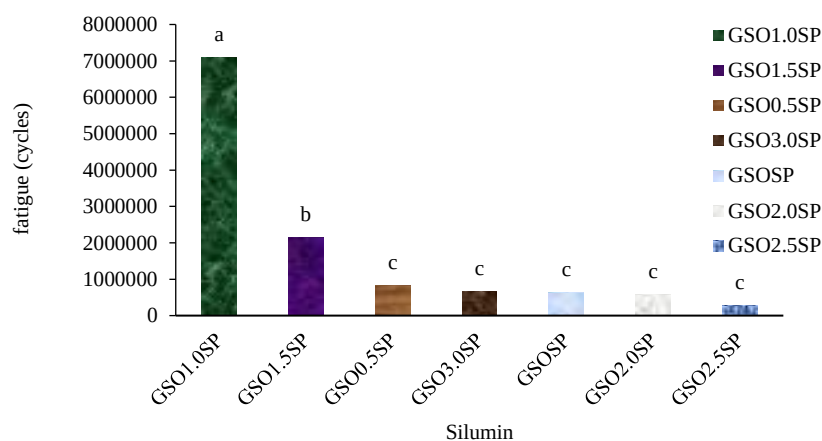


Figure 2. The post-hoc Tukey's test for means of the fatigue of the modified Silumin

Figure 3 shows the mean Hardness Values (HV) of modified Silumin which do not share the same letter differ significantly according to the Tukey grouping method at a 95% confidence interval with $p = 0.05$. The figure shows that sulphur treated Silumin GS1.0SP recorded the highest hardness value of about 60.5 HV and belongs to group “a”. This treatment differs significantly from GS3.0SP and GS2.0SP which belong to group “b”. However, GS1.0SP does not differ significantly from GS0SP, GS2.5SP, GS1.5SP, and GS0.5SP because these treatments share the letter “ab”. The intermediate group “ab” includes GS0SP, GS2.5SP, GS1.5SP, and GS0.5SP with hardness values between about 58.4 HV and 59.9 HV, which indicates no significant difference among them. The lowest hardness values occur in GS3.0SP and GS2.0SP with mean values of about 58.0 HV and 57.8 HV respectively, and both treatments show no significant difference from each other but differ significantly from GS1.0SP. Overall, sulphur treatment at 1.0SP produced the highest hardness improvement in the Silumin alloy, while increasing the treatment level to 2.0SP and 3.0SP reduced the hardness values. The control specimen GS0SP recorded a hardness value close to 59.8 HV which falls within the intermediate statistical group. Similar trends in hardness variation after alloy modification and reinforcement in aluminium alloys were reported in previous studies, where reinforcement and modification influenced mechanical resistance and hardness behaviour of aluminium based materials [10, 12].

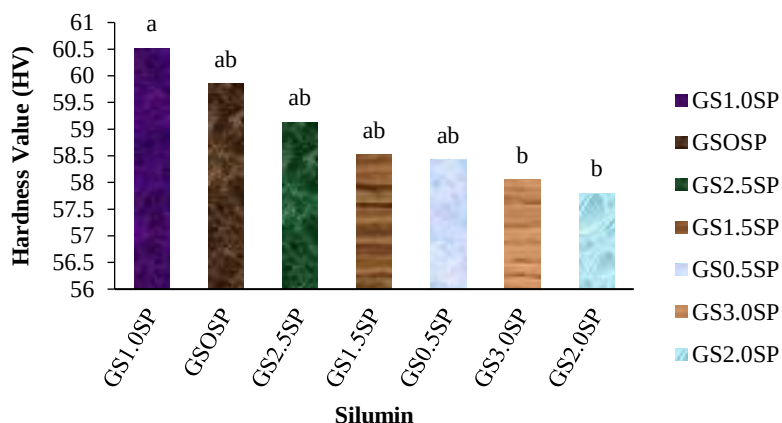


Figure 3. The post-hoc Tukey’s test for means of the hardness value (HV) of the modified Silumin

The mean thermal expansivity values of the modified aluminium silicon alloy vary across the sulphur treatment levels is illustrated in Figure 4. Means with different letters indicate significant differences according to the Tukey test at a 95% confidence interval, $p \leq 0.05$. Treatments GS1.5SP and GS2.0SP belong to group “a” and recorded the highest thermal expansivity values of about $0.000074\text{ }^{\circ}\text{C}^{-1}$ and $0.000067\text{ }^{\circ}\text{C}^{-1}$ respectively, with no significant difference between them. The remaining treatments GS2.5SP, GS0.5SP, GS3.0SP, GS0SP, and GS1.0SP belong to group “b” and show no significant differences among themselves but differ significantly from GS1.5SP and GS2.0SP. Intermediate values occurred in GS2.5SP, GS0.5SP, and GS3.0SP, while the lowest values were recorded in GS0SP and GS1.0SP. The variation in thermal expansivity is associated with sulphur induced microstructural changes in aluminium silicon alloys, particularly the modification of silicon particle morphology and distribution, which influences the alloy’s resistance to thermal expansion [10]. These thermal expansion effects may also be influenced by sulphur’s involvement in altering iron-containing intermetallic phases, as reported by [11]. Their study showed that in Al-Si 319 alloy, sulphur encourages the production of dendritic Chinese script-like $\text{Al}_2\cdot(\text{Fe,Mn})_3\text{Si}_2$ phases.

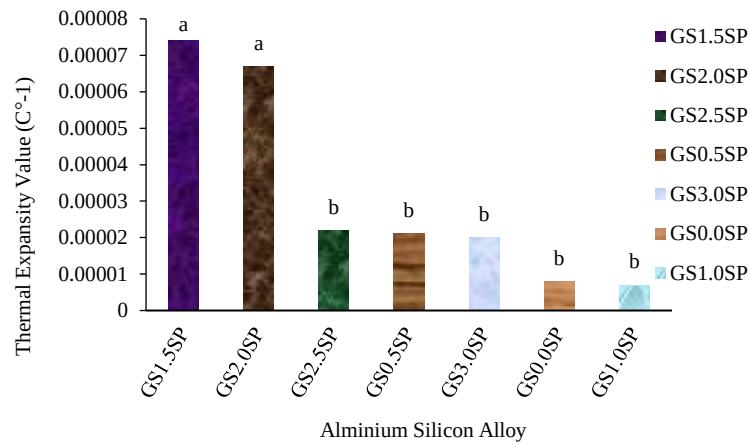


Figure 4. The post-hoc Tukey's test for means of the Thermal Expansivity Value ($^{\circ}\text{C}^{-1}$) of the modified Silumin.

Table 5 presents the Tukey mean separation results for the mechanical and thermal properties of sulphur modified silumin alloys. The statistical grouping indicates significant variation among the formulations. Tensile strength values of samples GSO0.0SP, GSO0.5SP, GSO1.0SP, and GSO1.5SP fall within the same statistical group, which shows comparable strength at lower sulphur additions, while higher sulphur levels such as GSO2.0SP and GSO3.0SP produced significant reductions in strength. The hardness results show the highest value in sample GSO1.0SP at 60.517 HV, which indicates improved strengthening of the alloy matrix. Fatigue strength results strongly support this trend, as GSO1.0SP recorded the highest fatigue life of 7,103,667 cycles and forms a distinct statistical group with superior resistance to cyclic loading. Thermal expansivity values also indicate improved dimensional stability at this sulphur concentration. The combined evaluation of all properties therefore identifies GS1.0, which contains 1 wt.% sulphur addition, as the selected modified silumin alloy because it provides the most balanced combination of mechanical strength, hardness, fatigue resistance, and thermal stability suitable for engineering applications such as tricycle piston components.

Table 5. summary of Mean Separated Turkey's Test for Selection of Modified Silumin

Sample	Tensile Strength (MN/m^2)	Fatigue strength (Cycles)	Hardness (HV)	Thermal Expansivity ($^{\circ}\text{C}^{-1}$)
GSO0.0SP	131.533a	630133c	59.85ab	0.000008b
GSO0.5SP	119.85a	822267c	58.43ab	0.000021b
GSO1.0SP	114.19a	7103667a	60.517a	0.000007b
GSO1.5SP	115.82a	2148333b	58.517ab	0.000074a
GSO2.0SP	24.73c	592367c	57.797b	0.000067a
GSO2.5SP	47.5b	280600c	59.13ab	0.000022b
GSO3.0SP	11.35c	669933c	58.047b	0.00002b

4 CONCLUSIONS

The study looked at how sulphur powder modification affected the mechanical and thermal characteristics of silumin aluminium alloy made from discarded engine parts. Sulphur contents ranged from 0.0-3.0 wt.% in seven alloy compositions. Tensile strength, fatigue strength, hardness, and thermal linear expansivity were all evaluated mechanically and thermally. For every measured property, statistical analysis revealed a significant difference between the sulphur treatment groups. Hardness and fatigue performance were enhanced by a moderate amount of sulphur. The alloy with 1.0 wt.% sulphur had the longest fatigue life and the highest hardness value. These improvements, which show strengthening within the alloy structure, are explained by microstructural refinement and better distribution of eutectic silicon particles inside the aluminium matrix. Mechanical performance was diminished with higher sulphur concentrations. When the sulphur concentration rose above 1.5 wt.%, tensile strength dropped. Because of the development of brittle phases and coarser microstructures, increased sulphur levels also reduced hardness and fatigue resistance. The significance of carefully regulated sulphur addition during alloy alteration is highlighted by these findings. The results validate the improvement of recycled aluminium silicon alloys utilised in light mechanical systems through

chemical treatment. Improved hardness and fatigue resistance from controlled sulphur treatment fulfil the performance requirements of tricycle piston components that are subjected to repeated mechanical loads. The findings offer recommendations for engineering applications in automotive systems, alloy formation, and aluminium recycling procedures.

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