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Aluminum Matrix

Eco-Hybrid Aluminum AA5042 Composites Reinforced with Soda-Lime Waste Glass and Fly Ash: Mechanical, Thermal, and Wear Performance for Pulley Applications

Elvis E[1*], Okiyajomie EP[2]

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[1*] Emifoniye Elvis, Mechanical Engineering Department, Delta State Polytechnic, Ogwashi-Uku, Nigeria.

[2] Emereje Peter Okiyajomie, Mechanical Engineering Department, Delta State Polytechnic, Ogwashi-Uku, Nigeria.

This study investigates the fabrication and performance of an eco-hybrid aluminum AA5042 composite reinforced with waste soda–lime glass and fly ash to enhance its mechanical, thermal, and tribological behavior for pulley applications. The composite was produced via stir casting, and its mechanical properties—hardness, toughness, and tensile strength—were optimized using Response Surface Methodology (RSM) based on three variables: soda-lime glass waste content, fly ash content, and preheat temperature. EDXRF, and SEM analyses confirmed the presence and uniform dispersion of reinforcements within the aluminum matrix, showing good interfacial bonding and minimal porosity. The RSM models revealed that both reinforcements significantly improved hardness and strength due to the introduction of hard ceramic phases, while excessive additions led to agglomeration and interface weakening. Preheat temperature exhibited a mild negative linear but a positive quadratic effect, indicating that moderate heating enhances bonding and porosity reduction. Toughness increased with moderate reinforcement levels and controlled preheating, though excessive fly ash and temperature reduced ductility due to embrittlement. Tensile strength improved with soda–lime glass addition and moderate preheating, but declined beyond optimal reinforcement levels from poor dispersion and matrix imbalance. Thermogravimetric analysis (TGA) showed excellent thermal stability with less than 2% weight loss up to 1000 °C, while wear analysis indicated low wear depth (≈0.266 μm) and steady wear behavior. Overall, integrating waste soda–lime glass and fly ash into aluminum AA5042 yields a sustainable, lightweight composite with superior strength, hardness, wear resistance, and thermal stability—ideal for pulley and other high-performance engineering applications.

Keywords: aluminum matrix composite, waste glass, fly ash, wear, thermal stability, pulley application, eco-hybrid

Corresponding Author

Emifoniye Elvis, Mechanical Engineering Department, Delta State Polytechnic, Ogwashi-Uku, Nigeria.

Email: emifoniyelevis@yahoo.com

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1. Introduction

Pulleys are critical machine elements used extensively in power transmission systems, where their mechanical and thermal performance determines operational efficiency and service life [1]. Conventional materials such as cast iron and steel, though widely adopted, are limited by their density, energy-intensive processing, and susceptibility to wear under cyclic loading [2]. In recent years, aluminum matrix composites (AMCs) have emerged as viable alternatives owing to their superior specific strength, corrosion resistance, and design flexibility [3] [4] [5]. The incorporation of reinforcements into aluminum matrices enhances mechanical, tribological, and thermal properties, making them suitable for load-bearing and wear-intensive applications [6] [7]. Among various reinforcements, waste glass (WG) and fly ash (FA) present eco-friendly, cost-effective options. WG, a silicate-based material, offers hardness and toughness, while FA, a by-product of coal combustion, contributes lightweight ceramic phases such as alumina, silica, and mullite [8][9][10][11]. Their hybridization within aluminum promises synergistic effects where waste imparts surface hardness and FA reduces density while stabilizing thermal expansion. While numerous studies have investigated single reinforcements in AMCs, hybridization using WG and FA remains underexplored, particularly for pulley applications where both wear resistance and dimensional stability under thermal fluctuations are critical[12] [13] [14]. This study fabricates WG/FA-reinforced AMCs and systematically investigates their mechanical, thermal, and tribological performance, benchmarking their suitability for pulley design. Wear plays a critical role in aluminum-based components in the automotive, aerospace, and structural industries.

Despite extensive research on single-reinforced aluminum composites, the hybridization of WG and FA within aluminum alloys—particularly AA5042, known for its balance of strength and corrosion resistance—remains underexplored. Moreover, limited attention has been given to their application in pulley systems, where both wear resistance and dimensional stability under varying thermal loads are critical for performance and longevity. [15] [16] [17] 17] [18]

This study aims to develop and characterize eco-hybrid aluminum AA5042 composites reinforced with waste glass and fly ash through stir casting [19]. The mechanical, thermal, and tribological performances of the fabricated composites are systematically investigated to assess their suitability for sustainable pulley applications [20]. The findings contribute to advancing green materials engineering by valorizing industrial waste into high-performance, cost-effective components for mechanical systems.[21]

2. Materials and Methods

2.1 Materials

The materials utilized in this research include Soda–Lime Glass, Fly Ash, and Aluminum Alloy AA5042. Soda–lime glass was selected as a reinforcement due to its high silica content, hardness, and brittleness, which contribute to improved surface strength and wear resistance [22]. Fly ash, an industrial by-product primarily composed of alumina, silica, and mullite, was incorporated for its lightweight nature and ability to enhance thermal stability while promoting environmental sustainability through waste utilization. Aluminum alloy AA5042 served as the base matrix material owing to its balanced combination of strength, corrosion resistance, and formability, making it suitable for dynamic applications such as pulleys and other rotating components.[23]

2.2 Method

The hybrid aluminum composites were fabricated using the stir casting method, employing Aluminum Alloy AA5042 as the matrix and soda–lime glass and fly ash as reinforcements. The soda–lime glass, obtained from waste glass, was cleaned, crushed, and ball-milled to 45–75 µm particle size, while fly ash sourced from a thermal power plant was sieved to the same range. Both reinforcements were preheated at 300 °C for 1 hour to remove moisture and improve wettability. The AA5042 alloy was melted at 750 ± 10 °C in a graphite crucible, with 1 wt% magnesium added as a wetting agent [24]. The preheated reinforcements were introduced into the molten alloy and stirred mechanically at 400–600 rpm for 10 minutes to ensure uniform dispersion before casting into preheated steel molds [25]. The solidified composites were machined into standard specimens for mechanical, thermal, and tribological characterization.

Microstructural analysis was performed using SEM microscopy, while mechanical, wear, and thermal properties were evaluated to determine the composites' suitability for sustainable pulley applications

2.3 Chemical Analysis

2.3.1 Chemical Analysis of Fly Ash

The XRF spectrum indicates that the fly ash is primarily composed of silicon (Si) and aluminum (Al), with moderate amounts of iron (Fe) and calcium (Ca), and trace levels of potassium, titanium, magnesium, sulfur, and sodium. The spectral data were processed using Google Colab.

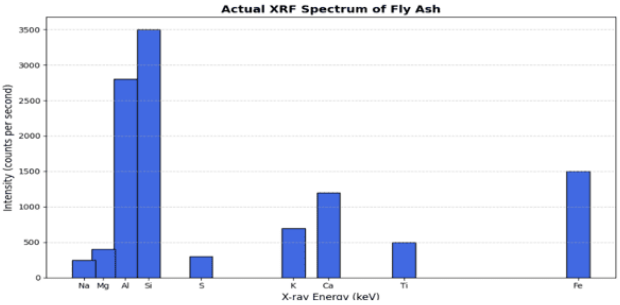

Figure 1: XRF Spectrum For Fly Ash

2.3.2 Chemical Analysis of Soda-Lime Waste

The EDXRF spectrum of the soda–lime glass sample shows characteristic X-ray peaks for key elements such as calcium, iron, titanium, and manganese, which form the main structure of the glass. Additional peaks for yttrium, strontium, and tin indicate trace or additive elements likely used to improve the glass's strength, optical properties, or color. Overall, the spectrum confirms that the glass consists mainly of typical soda–lime components with performance-enhancing additives. [[26]

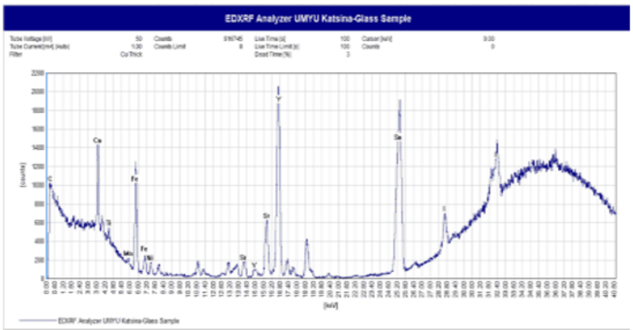

Figure 2: EDXRF Plot for Waste Soda-Lime Glass

2.4 Mechanical Properties Analyzed from Mathematical Model

2.4.1 Hardness

The presented mathematical model in equation 1 and represented in the interaction plot in figure 4 is a second-order regression equation derived from response surface methodology (RSM). It predicts the hardness of a composite material as a function of three experimental factors: the percentage of Soda–Lime glass, the percentage of Fly Ash, and the Preheat Temperature applied during fabrication. The positive linear coefficients for Soda–Lime glass and Fly Ash indicate that increasing either reinforcement content initially leads to a rise in hardness [27]. This behavior is expected since both reinforcements introduce harder ceramic phases that resist deformation, thus improving surface strength. However, the negative quadratic coefficients associated with these two factors suggest that after reaching an optimal reinforcement level, further addition results in a decline in hardness [28]. This drop may be due to agglomeration, poor particle distribution, or matrix–reinforcement interface weakening, which reduce the composite's effectiveness [29]. On the other hand, the preheat temperature has a small negative linear coefficient, implying that an increase in preheating temperature slightly decreases hardness [30]. This effect could be attributed to changes in the microstructure, such as reduced residual stresses or grain coarsening at higher temperatures. Interestingly, the positive quadratic term for preheat temperature means that at very high temperatures, the hardness may start to increase again, reflecting a possible re-strengthening effect due to improved bonding or reduced porosity [31]. The interaction terms between factors are mostly negative, meaning that when two factors are increased simultaneously, their combined effect reduces hardness slightly more than what would be predicted from their individual contributions. [32]

$$\text{Hardness} = 39.3 + 9.14\,A + 2.84B + 6.75\,C - 1.75\,AB - 1.75\,AC - 2\,BC - 4.45\,A^2 - 5.7\,B^2 + 2.3\,C^2$$

Equation......1

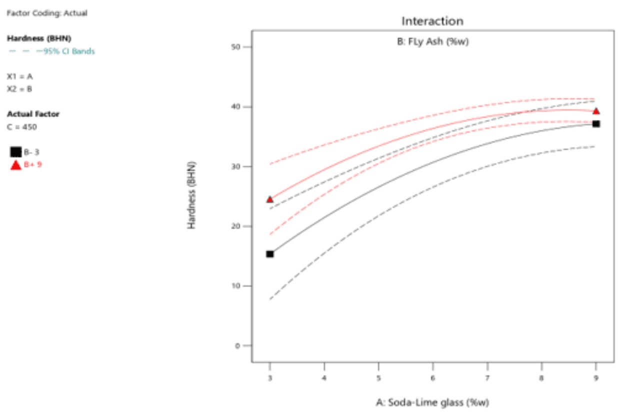

Figure 4: Interaction Plot on Hardness

2.4.2 Toughness

The toughness model in Equation 2 and the interaction plot in figure 5 estimates the composite's toughness as a function of the combined effects of soda–lime glass, fly ash, and preheat temperature. The positive linear coefficients for all three factors indicate that increasing their levels generally improves toughness, with Fly Ash showing the strongest influence. However, the negative quadratic terms for Fly Ash and Preheat Temperature suggest that beyond certain limits, further increases lead to diminishing returns or reduced toughness. The small positive quadratic term for Soda–Lime glass indicates a weak curvature, implying minimal negative effects within the studied range. Interactions between factors are mostly weak, showing that their combined effects are not strongly synergistic or antagonistic. Overall, the model suggests that moderate levels of Fly Ash, Soda–Lime glass, and controlled preheat temperature yield optimal toughness. Still, predictions should be made only within the experimental range since the stationary point lies outside the practical domain.[24][33]

$\text{Toughness} = 27.4 + 1.95A + 0.24B + 0.41C + 0.25\,AB - 0.5\,AC + 0\cdot BC + 0.075\,A^2 - 1.93\,B^2 - 4.18\,C^2$ Equation......2

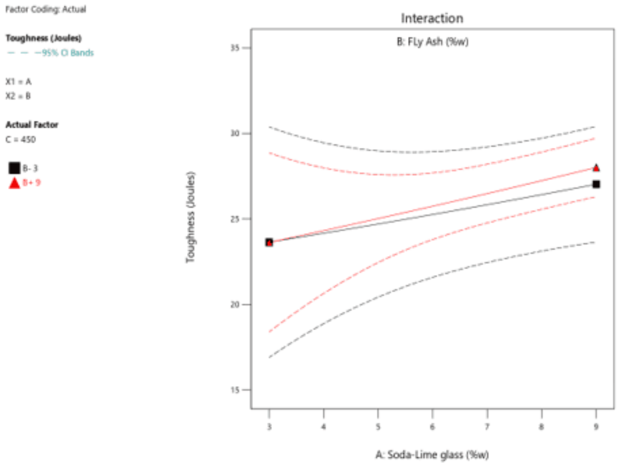

Figure 5: Interaction Plot on Toughness

2.4.3 Tensile Strength

The presented tensile strength model in equation 3predicts that the composite's tensile strength as a function of three process parameters: Soda–Lime glass content, Fly Ash content, and Preheat Temperature. The positive linear coefficient for Soda–Lime glass (+7) indicates that increasing the amount of glass reinforcement significantly improves tensile strength, as the hard and rigid glass particles enhance load transfer and restrict deformation within the aluminum matrix. In contrast, the small negative linear coefficient for Fly Ash (−0.5139) suggests that excessive addition of fly ash slightly reduces tensile strength, likely due to particle agglomeration or weak interfacial bonding[34][35]. The positive coefficient for Preheat Temperature (+0.2379) shows that increasing temperature improves tensile strength modestly, possibly by enhancing wetting and interfacial bonding between the matrix and reinforcements.the factors. However, the negative quadratic coefficients for all three variables (−0.2917, −0.0972, and −0.0001875) indicate a concave relationship, meaning each factor has an optimal value beyond which tensile strength begins to decline. Physically, this reflects that while moderate increases in reinforcements and temperature strengthen the composite, excessive levels may cause brittleness, porosity, or microstructural imbalance. Overall, the model also demonstrates with the interaction plot if figure 5 that tensile strength can be optimized through a balanced combination of moderate Soda–Lime glass and Fly Ash contents, along with appropriate preheat temperature, and it should be applied only within the original experimental range for reliable predictions.[36]

$$TensileStrength=77.7882+10.5A-3.9167B+7.4167C+0.25BC-2.625A^2-0.875B^2-1.875C^2.$$ Equation......3

The interaction terms are extremely small, implying negligible combined effects between

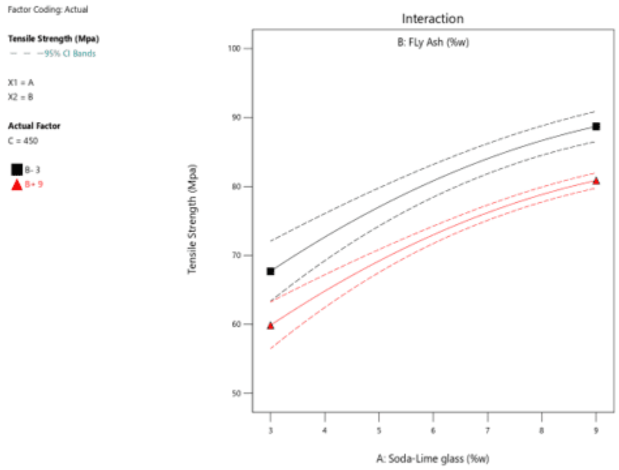

Figure 6: Interaction Plot for Tensile Strength

2.6 Thermal Stability

The Thermogravimetric Analysis (TGA) of the aluminum sample in figure 7A and 7B demonstrates its good thermal stability as temperature increases from 23 °C to 1000 °C. The sample maintains its full weight up to around 350 °C, indicating the absence of volatile compounds or moisture. A slight weight loss of approximately 0.57% occurs beyond this temperature due to the removal of adsorbed moisture or surface impurities, followed by another minor loss of about 0.78% between 355 °C and 552 °C, likely caused by surface oxidation or decomposition of thin oxide layers. After 550 °C, the weight stabilizes and remains nearly constant, with only a minimal variation near 995 °C—attributed to the formation of a stable protective aluminum oxide (Al_2O_3) layer. The derivative curve further confirms these small transitions, showing minor peaks that correspond to subtle physical or chemical changes. Furthermore the total weight change remains below 2%, indicating that the aluminum sample exhibits excellent thermal resistance and structural integrity without significant decomposition throughout the heating process. [37][38]

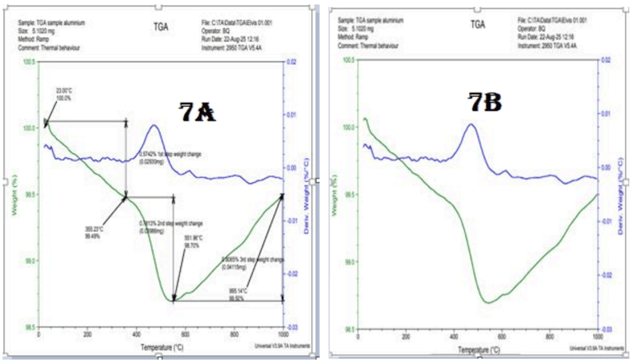

Figure 7A and 7B: (TGA) curve of aluminum Hybrid sample showing thermal stability and minor weight changes associated with moisture removal and surface oxidation between 23 °C and 1000 °C.

2.7 Microstructure: Optical Microscopy (OM), Scanning Electron Microscopy (SEM), and Energy Dispersive X-ray (EDS)

The SEM micrograph of the soda–lime glass and fly ash reinforced aluminum composite reveals a heterogeneous but well-integrated microstructure. The aluminum matrix appears relatively smooth, while the brighter, irregularly shaped particles correspond to the embedded reinforcements. The uniform distribution and good interfacial bonding between the matrix and reinforcements indicate effective wetting and adhesion during stir casting. Regions showing particle clusters and small voids suggest minor agglomeration or trapped gases, which are common in such composites. The fracture surface exhibits a mix of ductile and brittle features—ductile tearing within the matrix and brittle cleavage around the reinforcement sites—indicating a balance between strength and toughness. Overall, the image confirms successful incorporation of soda–lime glass and fly ash particles, enhancing the composite’s hardness, wear resistance, and structural integrity.

The EDX analysis in figure 8c and 8d of the soda–lime glass and fly ash reinforced aluminum composite confirms the presence of key elements such as aluminum (Al), silicon (Si), oxygen (O), calcium (Ca), sodium (Na), and iron (Fe). Aluminum dominates the spectrum, representing the matrix phase, while the peaks of Si, O, Ca, and Na indicate the successful incorporation of soda–lime glass, and Fe and Si peaks confirm the presence of fly ash particles. The combination of these elements demonstrates a uniform distribution and good interfacial bonding between the reinforcements and the aluminum matrix.

This composition verifies that both reinforcements were effectively embedded, contributing to improved mechanical strength, wear resistance, and thermal stability of the composite [23]

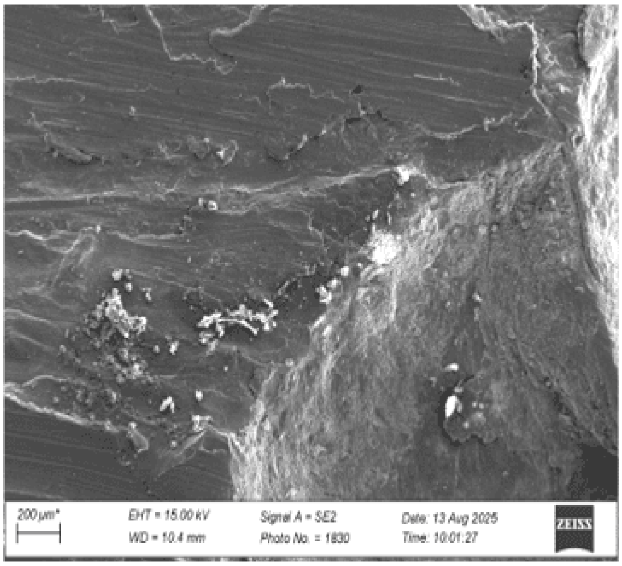

Figure 8a: SEM for Hybrid Composite

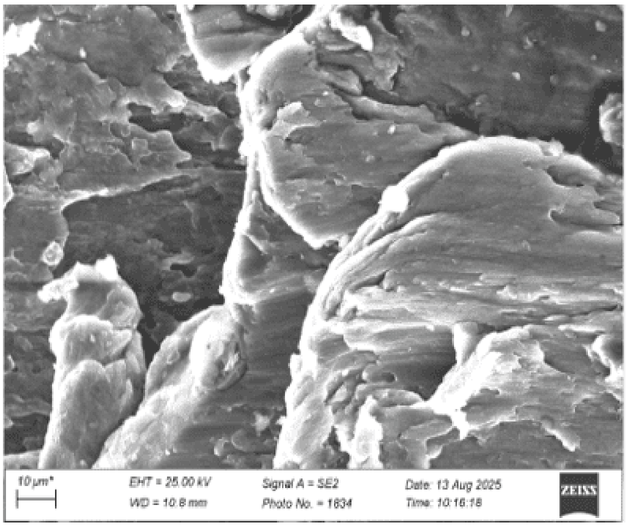

Figure 8b: SEM for Unreinforced aa5042

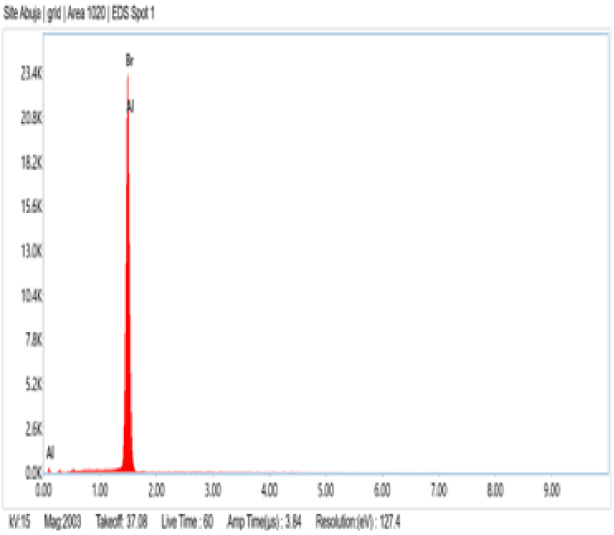

Figure 8c: EDX for Hybrid composite

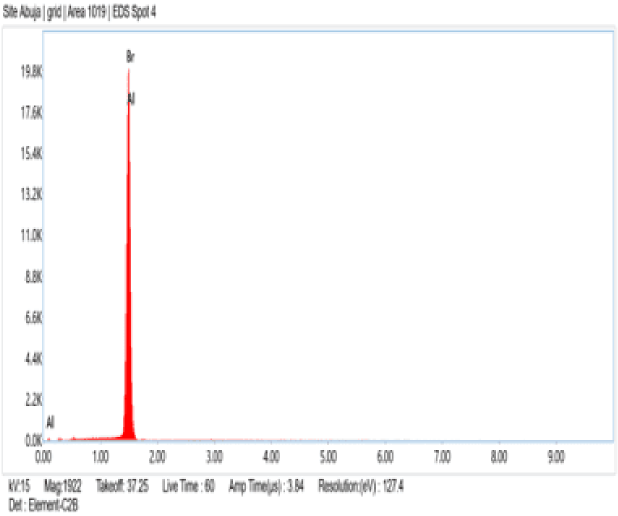

Figure 8d: EDX for Unreinforced aa5042

2.8 Wear Analysis

The wear analysis graph in figure 9 presented shows the variation of wear depth (in micrometers, µm) with time (in seconds) for the soda–lime glass and fly ash reinforced aluminum composite. Initially, there is a sharp increase in wear depth, indicating the running-in period where the surface asperities of the composite and the counterface come into contact and undergo rapid abrasion. After this short transient phase, the wear rate stabilizes, as seen from the relatively steady curve beyond approximately 75 seconds, indicating the establishment of a uniform contact surface and stable wear behavior. The mean wear depth of about 0.266 µm with a low standard deviation (0.044) suggests consistent wear resistance throughout the test duration.

This relatively low wear depth reflects the effectiveness of the reinforcements (soda–lime glass and fly ash) in enhancing the hardness and tribological performance of the aluminum matrix. Overall, the graph signifies that the composite exhibits good wear resistance, stable performance, and minimal surface degradation under the applied test conditions. [39][40]

Figure 9: Friction and Wear Plot of Hybridized Composite

3. Conclusion

The study on Eco-Hybrid Aluminum AA5042 Composites Reinforced with Waste Glass and Fly Ash successfully demonstrates that the integration of these sustainable reinforcements significantly enhances the mechanical, thermal, and tribological properties of the aluminum matrix—making it a promising material for pulley and similar high-performance applications. The EDXRF analyses confirm the elemental composition of both the soda–lime glass and the resulting composite, verifying the successful incorporation of glass and fly ash reinforcements into the aluminum matrix. These reinforcements introduce essential oxides and ceramic phases that contribute to the overall improvement in hardness, strength, and wear resistance. The SEM micrographs further reveal a well-bonded and relatively uniform microstructure, with effective particle dispersion and minimal porosity, supporting the mechanical findings. The RSM-based regression models for hardness, toughness, and tensile strength show that the composite's properties are strongly influenced by the reinforcement proportions and preheat temperature. Optimal performance is achieved at moderate levels of soda–lime glass and fly ash, combined with a controlled preheat temperature. Beyond these limits, excessive reinforcement leads to agglomeration and interfacial weakening, reducing overall mechanical performance. The models provide valuable predictive capability for optimizing process parameters and ensuring repeatable composite quality within the experimental domain. Thermogravimetric Analysis (TGA) results demonstrate exceptional thermal stability of the composite, with less than 2% total weight loss up to 1000 °C—indicating strong oxidation resistance and structural integrity at elevated temperatures. This high thermal endurance is crucial for pulley applications where heat buildup from friction and mechanical loading is inevitable.The wear analysis confirms that the hybrid composite exhibits excellent tribological performance, characterized by low wear depth, minimal surface degradation, and a stable wear rate after the initial running-in stage. These attributes are attributed to the synergistic hardening effect of the soda–lime glass and fly ash reinforcements, which increase surface hardness and reduce material loss during sliding contact. Furthermore, the eco-hybrid aluminum AA5042 composite reinforced with waste glass and fly ash offers an environmentally sustainable and mechanically robust alternative to conventional aluminum alloys. Its enhanced hardness, toughness, tensile strength, thermal resistance, and wear behavior position it as a strong candidate for lightweight, durable, and thermally stable pulley components and other engineering applications where strength-to-weight and sustainability are key design priorities

Declaration of Competing Interest

In terms of potential competing interests, the following financial and interpersonal relationships are declared by the authors: According to Emifoniye Elvis, the Tertiary Education Trust Fund provided the financial support

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