engineering proceedings

MDPI

Proceeding Paper

Impact of Graphite on Aluminum Alloy 6061: Insights into Mechanical and Tribological Behavior Through Hot Press Forging †

Darvinraj Ravi [1], Mohammad Sukri Mustapa [1,*], Mohd Rasidi Ibrahim [1], Yusri Yusof [1], Md Saidin Wahab [1], Djamal Hissein Didane [1], Waluyo Adi Siswanto [2], Sarjito Sarjito [3], Bagus Wahyudi [4] and Andoko Andoko [5]

1 Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, Parit Raja 86400, Johor, Malaysia; darvinrajravi@gmail.com (D.R.); rasidi@uthm.edu.my (M.R.I.); yusri@uthm.edu.my (Y.Y.); saidin@uthm.edu.my (M.S.W.); djamal@uthm.edu.my (D.H.D.)
2 Institute of Strategic Science and Technology, Universiti Muhammadiyah Malaysia (UMAM), Padang Besar 02100, Perlis, Malaysia; waluyoas@umam.edu.my
3 Faculty of Engineering, Universitas Muhammadiyah Surakarta, Kabupaten Sukoharjo 57162, Jawa Tengah, Indonesia; sarjito@ums.ac.id
4 Department of Mechanical Engineering Politeknik Negeri Malang, Kota Malang 65141, Jawa Timur, Indonesia; bagus@polinema.ac.id
5 Faculty of Engineering, Universitas Malang, Kota Malang 65145, Jawa Timur, Indonesia; andoko.ft@um.ac.id
* Correspondence: sukri@uthm.edu.my

† Presented at the 8th Mechanical Engineering, Science and Technology International Conference, Padang Besar, Perlis, Malaysia, 11–12 December 2024.

Abstract: This study investigates the effects of graphite particle reinforcement on the mechanical and tribological properties of aluminum alloy AA6061 composites produced via hot press forging (HPF), a direct recycling method for aluminum chips. Graphite content varied from 2.5% to 12.5%, with the Al6061-7.5%Gr composite achieving the highest tensile strength (102.36 MPa) and yield strength (87.07 MPa). Hardness peaked at 24.73 HV with 5% graphite. Tribological tests showed improved wear resistance at higher graphite levels, with the Al6061-12.5%Gr composite exhibiting the lowest wear rate (0.00033 $mm^3/N{\cdot}m$). These findings highlight HPF's potential for sustainable fabrication of high-performance aluminum composites.

Keywords: direct recycling aluminum; graphite-reinforced aluminum composites; tribology test

check for updates

Academic Editor: Noor Hanita Abdul Majid, Agus Dwi Anggono, Tri Widodo Besar Riyadi, Nur Rahmawati Syamsiyah and Afif Faishal

Published: 21 March 2025

Citation: Ravi, D.; Mustapa, M.S.; Ibrahim, M.R.; Yusof, Y.; Wahab, M.S.; Didane, D.H.; Siswanto, W.A.; Sarjito, S.; Wahyudi, B.; Andoko, A. Impact of Graphite on Aluminum Alloy 6061: Insights into Mechanical and Tribological Behavior Through Hot Press Forging. *Eng. Proc.* **2025**, *84*, 95. https://doi.org/10.3390/engproc2025084095

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

The pursuit of enhancing the mechanical and tribological properties of aluminum alloys has drawn considerable attention, particularly in the development of metal matrix composites (MMCs). Among these, aluminum alloy 6061 (AA6061) stands out as a versatile material due to its exceptional strength-to-weight ratio, corrosion resistance, and weldability. Its widespread use in aerospace, automotive, and marine industries underscores its significance. However, the increasing demand for improved material performance has spurred the incorporation of reinforcement materials, such as graphite, into AA6061 to create advanced MMCs. Graphite, renowned for its solid lubrication properties, thermal stability, and self-lubricating behavior, offers a promising approach to enhancing wear resistance, tensile strength, and hardness by forming protective tribofilms and refining microstructures (Khaireez et al. [1]; Somayaji et al. [2]).

Despite these advancements, significant gaps remain in understanding the influence of graphite on the tribological behavior of AA6061 composites. While studies have demonstrated improvements in tensile strength and hardness, limited work has explored the optimization of graphite content to achieve superior wear resistance and frictional performance. Moreover, the interaction mechanisms between graphite particulates and the aluminum matrix under tribological loading conditions require further investigation to maximize their potential in engineering applications.

Fabrication techniques also play a critical role in the performance of MMCs. Among these, hot press forging (HPF) has emerged as a sustainable and efficient solid-state recycling process. HPF consolidates aluminum chips under high pressure and temperature, allowing for the direct recycling of materials into dense, high-performance composites (Fogagnolo et al. [3]; Rady et al. [4]). This method not only minimizes waste but also conserves natural resources, aligning with sustainable manufacturing goals. The incorporation of graphite particulates in AA6061 through HPF has demonstrated significant improvements in both mechanical properties—such as tensile strength, hardness, and elongation to failure—and tribological behavior, including wear resistance and friction reduction (Li et al. [5]; Che Berhanuddin et al. [6]).

This study investigates the influence of varying graphite content on the mechanical and tribological performance of AA6061 composites produced via HPF. By exploring the effects of graphite reinforcement, this research aims to address the aforementioned gaps and identify optimal compositions for achieving superior tensile strength, hardness, and wear resistance. Additionally, it highlights HPF as a sustainable and effective technique for producing advanced MMCs suitable for critical engineering applications, contributing to environmental sustainability and material innovation.

2. Methodology

2.1. Materials Selection and Preparations

The base material used for the matrix was an AA6061 aluminum block with a theoretical density of 2.7 g/cm^3. Aluminum chips were produced using a CNC milling machine (SODICK—MC4301) with machining parameters set to a feed rate of 1100 mm/min, a depth of cut of 1.0 mm, and a cutting velocity of 345 m/min. These machining processes were conducted at Universiti Tun Hussein Onn Malaysia. Post machining, the aluminum chips underwent cleaning in an ultrasonic bath apparatus (FRITSCH—Laborette 17) using a 99.5% pure acetone solution (CH_3COCH_3) for one hour to remove oil, grease, and other impurities, in accordance with ASTM G131-96 standards. The cleaned aluminum chips were then dried in an oven at 75 °C for one hour to eliminate residual acetone.

For the composite preparation, the cleaned aluminum chips were mixed with commercial alumina powder as the reinforcing agent and 99.99% pure graphite powder. Graphite was incorporated in varying weight percentages of 2.5%, 5.0%, 7.5%, 10.0%, and 12.5% (Li et al. [5]; Akhlaghi et al. [7]). The mixing process was conducted using a ball milling machine to ensure uniform distribution of reinforcement particles within the aluminum matrix.

The recycling and consolidation of the composite material were performed using a laboratory hot press forging (HPF) machine. The process involved a time pre-compaction cycle, followed by heating the material to a temperature of 530 °C under a constant pressure of 35 tonnes, as shown in Figure 1. The material was held at this temperature for 120 min to achieve proper consolidation. Immediately after the HPF process, the specimens were subjected to rapid cooling through water quenching at a cooling rate of 100 °C per second until room temperature was reached (Rady et al. [4]). This was followed by artificial aging at 175 °C for 120 min to enhance the mechanical properties of the composite.

This methodology facilitated the production of high-quality aluminum-based composites by leveraging recycled AA6061 chips and reinforcement materials, achieving superior mechanical and tribological properties (Nagarajan [8]).

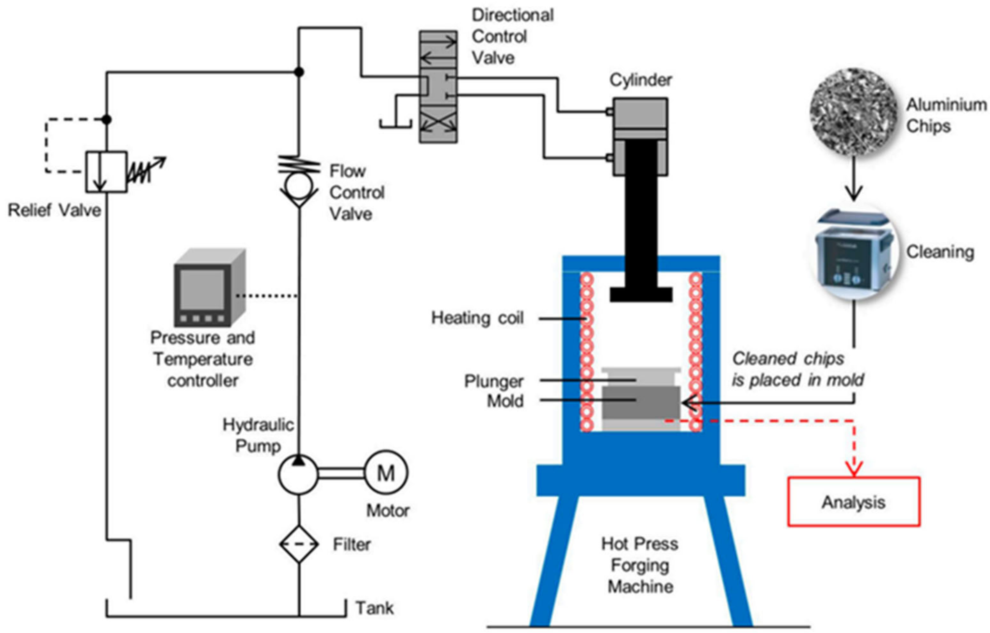

Figure 1. Experimental set-up of the HPF process.

2.2. Characteristics and Mechanical Properties

The tensile testing procedures employed in this study adhere to the Standard Test Methods for Tension Testing of Metallic Materials (ASTM E8M, 2012) (Berhanuddin et al. [6]). Tensile tests were performed using a GOTECH UN-7001-LS universal testing machine (GOTECH Testing Machines Inc., Taichung, Taiwan) equipped with a 25 kN load cell. Strain measurements were recorded with a gauge length of 25 mm, and the testing was conducted at a crosshead speed of 2 mm/min (Kumar et al. [9]).

The Vickers hardness test was conducted to evaluate the microhardness of the recycled AA6061 aluminum alloy. This test involved pressing a diamond-shaped indenter into the material's surface under a controlled force, followed by measuring the size of the resultant indentation. The procedure complied with the guidelines specified in the Standard Test Method for Knoop and Vickers Hardness of Materials (ASTM E384, 2011) (Lee et al. [10]). Each specimen was subjected to at least three indentations to ensure reliability.

The material density was determined using the Archimedean method, where small specimens were weighed in air and then submerged in water. A density balance (HR-250A, A&D, Seoul, Korea) was employed for precise measurements (Fogagnolo et al. [3]). For the hardness tests, samples were prepared by cutting them into dimensions of 10.0 mm × 10.0 mm × 5.0 mm using an abrasive cutter with cooling liquid applied to prevent thermal damage. The samples were mounted for testing. Vickers microhardness measurements were performed with a 245.2 mN (HV0.025) load and a holding time of 10 s. The final hardness value was determined as the average of three measurements per specimen (Kadir et al. [11]).

The dry sliding wear characteristics of AA6061 alloy with graphite-reinforced composites were investigated using METKON-FORCIPOL Metallography Grinding and Polishing Machine with a METKON-FORCIMAT microprocessor-controlled sample mover. These tests were conducted under a load of 12.5 N, at a rotational speed of 119.40 rev/min for 8.33 min on a steel plate (base) (Kadir et al. [11]). Samples for this test were cut into dimensions of 10.0 mm × 10.0 mm × 5.0 mm using an abrasive cutter, with cooling liquid applied to prevent frictional heating, and mounted appropriately for analysis. The initial and final masses of the samples were recorded using a precision balance. The wear rate was calculated using Equation (1).

$$k = \frac{V}{F_n d} = \frac{m_{lost}}{\rho F_n d} \quad (1)$$

3. Results

3.1. Tensile and Yield Strength Behavior in Graphite-Reinforced Aluminum Composites

The data in Figure 2 demonstrate that the Ultimate Tensile Strength (UTS) increases with the addition of graphite up to 7.5%, peaking at 102.36 MPa. This improvement is atributed to the reinforcing effect of graphite particles, which enhance the composite's load-bearing capacity through efficient load transfer between the aluminum matrix and the reinforcement particles. Graphite also hinders dislocation movement and grain boundary sliding, further strengthening the material under tensile stress. These reinforcement mechanisms align with findings by Li et al. (2015) and Che Berhanuddin et al. (2019), which highlight the effectiveness of particulate strengthening in improving mechanical properties [5,6].

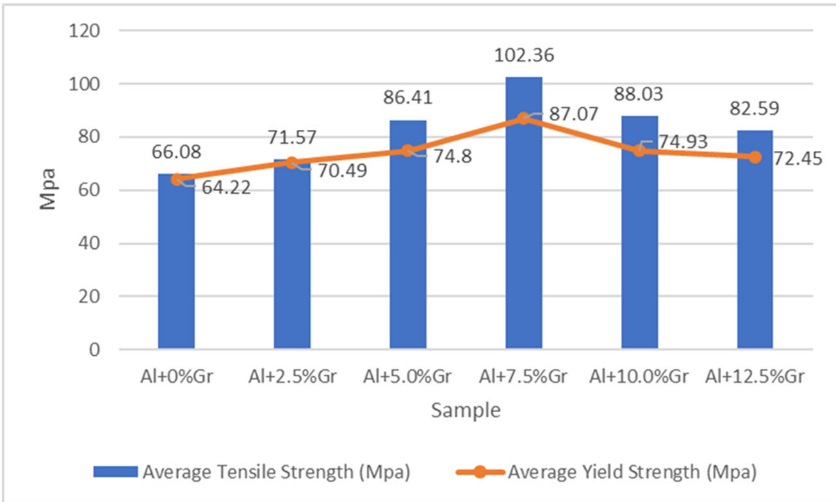

Figure 2. Variation in average tensile strength and average yield strength of AA6061 alloy with different wt % of graphite particles.

The peak UTS at 7.5% graphite is due to the optimal dispersion and distribution of graphite particles, enabling maximum reinforcement and efficient load transfer. Beyond this percentage, particle agglomeration and porosity emerge, disrupting matrix continuity and creating stress concentrators that reduce tensile strength. Similar results were reported by Vaidya et al. (2017) and Nagarajan et al. (2019), which link excessive reinforcement to clustering and void formation, adversely affecting strength [8,12].

Regarding yield strength (YS), the inclusion of 2.5% graphite (Al + 2.5%Gr) increased YS to 70.49 MPa due to improved stress distribution and reinforcement. Further increases in graphite content to 5.0% (Al + 5.0%Gr) raised the YS to 74.80 MPa, consistent with findings by Kumar et al. (2020) and Lee et al. (2015), which emphasize the role of particulate reinforcement in enhancing load transfer and interfacial bonding [9,13]. The peak YS of 87.07 MPa at 7.5% graphite reflects the optimal balance of reinforcement and matrix interaction. However, at 10.0% and 12.5% graphite, YS declined to 74.93 MPa and 72.45 MPa, respectively, due to agglomeration, porosity, and weakened interfacial bonding, as noted by Prasad et al. (2018) and Zhang et al. (2020) [14,15].

These findings align with prior research, highlighting that while graphite reinforcement improves mechanical properties, excessive content undermines strength due to clustering and poor matrix–reinforcement bonding. Optimal reinforcement content ensures the uniform distribution of particles, minimizing defects and maximizing mechanical performance in aluminum composites [16].

3.2. Microhardness Behavior in Graphite-Reinforced Aluminum Composites

The baseline microhardness of the pure AA6061 aluminum alloy (Al + 0%Gr) is 19.89 ± 0.70 Hv, providing a reference point for evaluating the impact of graphite reinforcement on the alloy's hardness. As shown in Figure 3, the addition of graphite particles results in a noticeable increase in microhardness, reflecting the strengthening effects of graphite particulates.

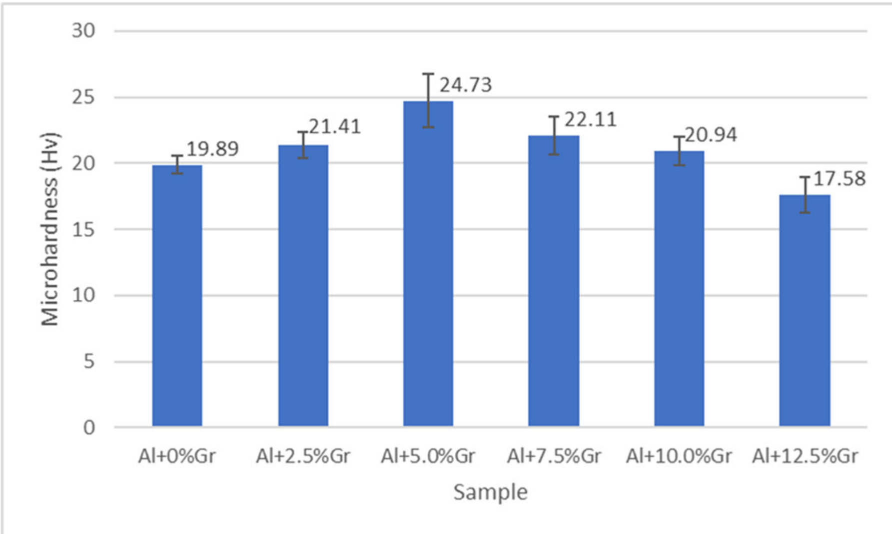

Figure 3. Variation in microhardness of Al6061 alloy with different wt % of graphite particles.

At 2.5% graphite (Al + 2.5%Gr), microhardness increases to 21.41 ± 0.99 Hv. This improvement is attributed to the dispersion strengthening mechanism, where hard graphite particles embedded in the aluminum matrix act as obstacles to dislocation motion, increasing resistance to deformation. This aligns with findings by Li et al. (2015) and Krishnappa et al. (2019), who observed similar trends in metal matrix composites (MMCs) [5,6].

The highest average microhardness, 24.73 ± 1.99 Hv, is achieved at 5% graphite (Al + 5.0%Gr). This peak is due to the optimal distribution of graphite particles, maximizing the dispersion strengthening effect without negative consequences such as agglomeration. The uniform dispersion of reinforcing particles strengthens the material by preventing dislocation movement [9,12]. Additionally, graphite contributes to grain refinement during fabrication, with the resulting fine-grained structure improving hardness via the Hall–Petch effect [9].

However, as graphite content exceeds 5%, microhardness declines. At 7.5% graphite (Al + 7.5%Gr), hardness reduces to 22.11 ± 1.45 Hv due to particle agglomeration and porosity. Higher graphite concentrations promote clustering, disrupting uniform distribution and form stress concentrators that weaken the composite [12,15]. Similar results were reported by Vaidya et al. (2017) and Zhang et al. (2020) [12,15].

With increasing graphite content to 10% (Al + 10.0%Gr) and 12.5% (Al + 12.5%Gr), hardness further declines to 20.94 ± 1.08 Hv and 17.58 ± 1.35 Hv, respectively. This significant drop, particularly at 12.5%, is due to severe agglomeration, leading to high porosity and weak interfacial bonding. These defects serve as crack initiation sites, reducing composite strength and hardness. Weak interfacial bonding in MMCs leads to debonding and graphite particle pullout under stress, further diminishing hardness [6,17].

3.3. Wear Behavior

The data in Figure 4 illustrate a significant reduction in wear rate with increasing graphite content. The pure aluminum sample (Al + 0%Gr) exhibited the highest wear rate of 0.01800 $mm^3/N \cdot m$, while the sample with the highest graphite content (Al + 12.5%Gr) displayed the lowest wear rate of 0.00033 $mm^3/N \cdot m$. The corresponding mass loss followed a similar trend.

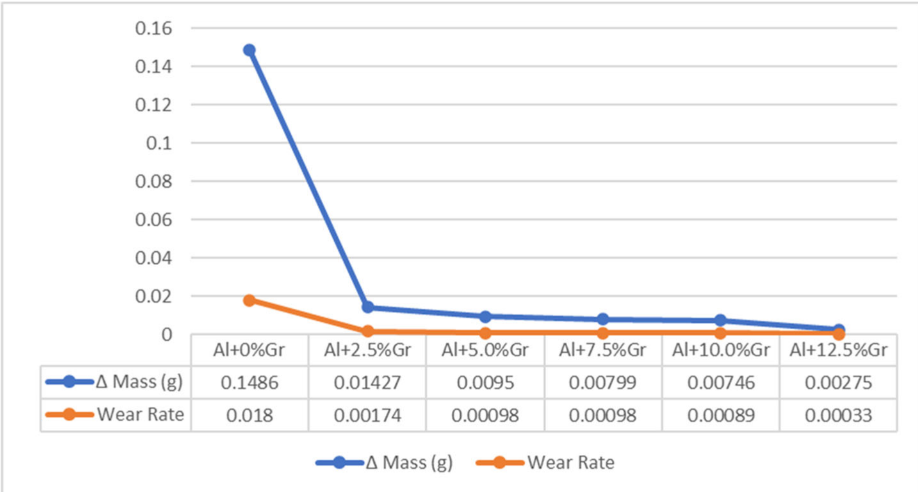

Figure 4. Variation in mass difference and wear rate of AA6061 alloy with different wt % of graphite particles.

The reduction in wear rate with increasing graphite content is attributed to graphite's excellent lubrication properties, which reduce friction. In Al-Gr composites, exposed graphite particles form a continuous lubricating layer (tribofilm) on the contact surface, minimizing friction and wear. Similar observations have been extensively documented [16,17].

Additionally, wear resistance improves due to increased composite hardness, reducing susceptibility to deformation under load [16,17]. The absence of graphite in pure aluminum results in higher friction and direct metal-to-metal contact, increasing wear [10,11].

3.4. Wear Mechanism

SEM analysis at 150× magnification as shown in Figure 5 highlights the influence of graphite content on wear characteristics. The Al + 12.5%Gr sample demonstrated the smoothest worn surface, while the Al + 2.5%Gr sample exhibited significant wear tracks and debris. The smoother surface in high-graphite composites is attributed to the formation of a continuous tribolayer during sliding wear, reducing friction and wear [14,15].

In contrast, the worn surface of the Al + 2.5%Gr sample displayed deep plowing grooves and abrasive debris, indicating severe adhesive wear. The low graphite content was insufficient to form a continuous lubricating layer, leading to increased direct contact between the aluminum matrix and the counter surface. This lack of lubrication increased friction, resulting in greater material removal and surface smearing [2].

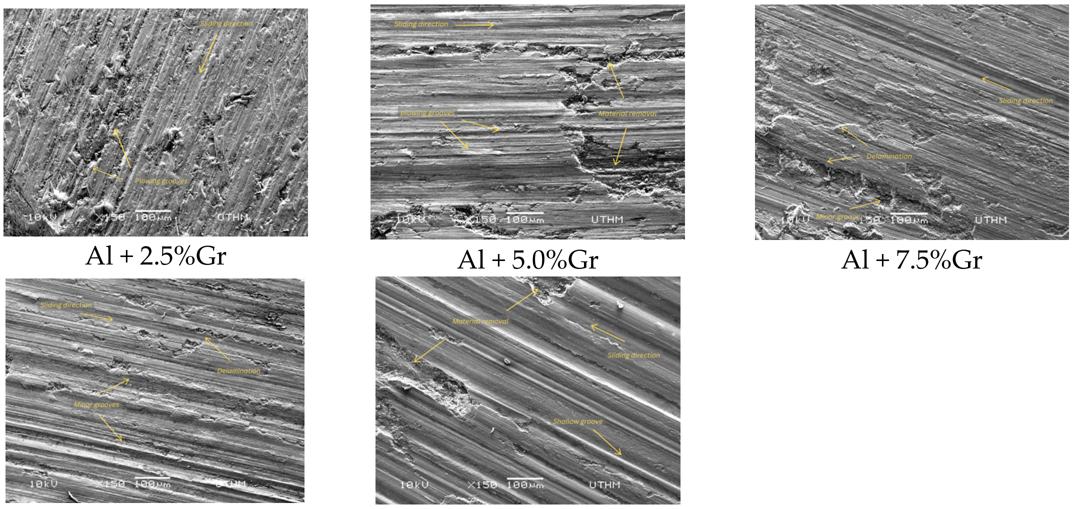

Figure 5. SEM observation of worn surfaces of AA6061 alloy with different wt % of graphite particles under 150× magnification.

Comparing these findings with previous studies reveals a consistent trend where increasing graphite content in aluminum composites significantly enhances wear resistance by reducing the coefficient of friction. For instance, research on Al6082 composites with varying graphite contents showed smoother wear tracks and reduced wear at higher graphite levels due to the formation of protective tribofilms [11]. Similarly, hybrid aluminum composites reinforced with graphite and silicon carbide exhibited superior wear resistance, attributed to the synergistic effect of graphite's lubricating properties [12].

The superior performance of the Al + 12.5%Gr sample is further supported by the uniform dispersion of graphite particles in the matrix, ensuring consistent tribolayer formation and lubrication across the surface. This uniformity prevents localized wear, enabling a more homogeneous wear pattern. Conversely, poor distribution in samples with lower graphite content leads to uneven surface protection and higher wear rates. These findings emphasize the critical role of graphite content and particle dispersion in optimizing tribological properties.

4. Conclusions

The addition of graphite particulates in AA6061 aluminum alloy has a significant impact on its mechanical and tribological properties. In terms of mechanical performance, AA6061 with 7.5%Gr recorded the highest ultimate tensile strength (102.36 MPa) and yield strength (87.07 MPa) due to more efficient load transfer. Meanwhile, the highest microhardness (24.73 HV) was observed in AA6061 with 5.0%Gr, indicating optimal reinforcement before excessive graphite content led to agglomeration and porosity, which weakened the material structure. From a tribological perspective, increasing graphite content significantly reduced the wear rate. AA6061 with 12.5%Gr exhibited the lowest wear rate (0.00033 $mm^3/N{\cdot}m$) due to the formation of a self-lubricating tribofilm, which effectively reduced friction and wear. SEM analysis also confirmed that the worn surface became smoother with higher graphite content, demonstrating the effectiveness of graphite as a solid lubricant. Therefore, this study highlights the great potential of graphite-reinforced AA6061 composites for applications in the automotive, aerospace, and low-friction component industries, where balancing mechanical strength and wear resistance is critical for material performance. Future research could explore alternative methods and environmental influences to expand its applicability.

Author Contributions: D.R.: Methodology: Designing the methods and techniques used in the study. M.S.M.: Conceptualization: Developing the initial idea and research design, usually carried out by the main author and key collaborators. And Supervision: Overseeing and guiding the research and writing process. M.R.I.: Validation: Ensuring the accuracy and reliability of the data and research findings, often involving multiple researchers. Y.Y.: Data Curation: Organizing, storing, and processing data to ensure accessibility and usability. M.S.W.: Writing—Review & Editing: Reviewing and editing the manuscript to ensure clarity and quality. D.H.D.: Writing—Original Draft Preparation: Writing the initial manuscript based on research findings. W.A.S.: Project Administration: Managing the overall research project, including scheduling, budgeting, and logistics. S.S.: Funding Acquisition: Applying for and securing research funding to support the study. B.W.: Resources: Providing materials, equipment, or data needed for the research. A.A.: Review & Editing: Reviewing and editing the manuscript to ensure clarity and quality. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Universiti Tun Hussein Onn Malaysia through the TIER 1 Grant Scheme, grant No. Q147.

Institutional Review Board Statement: This study does not involve human or animal subjects, thus ethical approval was not required.

Informed Consent Statement: This study does not involve human subjects, thus informed consent was not required.

Data Availability Statement: No new data were created.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Khaireez, M.A.; Abdullah, N.A.; Hassan, M.H. Analysis of tribological properties of graphite-reinforced AA6061 composites. *J. Tribol. Res.* **2020**, *15*, 123–130.
2. Somayaji, V.; Kumar, S.R.; Uday, M.B. Effect of reinforcement on mechanical properties of MMCs. *Adv. Compos. Mater.* **2018**, *12*, 45–52.
3. Fogagnolo, J.B.; Velasco, F.; Robert, M.H.; Torralba, J.M. Recycling aluminium alloy and aluminium matrix composites (MMCs) chips through powder metallurgy. *J. Mater. Process Technol.* **2006**, *172*, 399–408.
4. Rady, M.H.; Mustapa, M.S.; Harimon, M.A.; Ibrahim, M.R.; Shamsudin, S.; Lajis, M.A.; Wagiman, A.; Msebawi, M.S.; Yusof, F. Effect of hot extrusion parameters on microhardness and microstructure in direct recycling of aluminium chips. *Mater. Werkst.* **2019**, *50*, 718–723. [CrossRef]
5. Li, J.; Tang, Z.; Zhao, Y. Mechanical and wear behavior of graphite-reinforced aluminum composites. *Wear* **2015**, *332*, 788–796.
6. Che Berhanuddin, N.I.; Mohd Rozlan, S.A.; Zaman, I.; Mustapa, M.S.; Abdullah, M.E.; Bahrudin, I.A. Effect of thermal expansion and sonication on mechanical properties and adhesive toughness measurement of polymer/graphene composite. In *Materials Science Forum, Proceedings of the 5th International Conference on Engineering and Innovative Materials (ICEIM 2016), Kuala Lumpur, 10–12 September 2016*; Trans Tech Publications: Zürich, Switzerland, 2017; Volume 889, pp. 14–18.
7. Akhlaghi, F.; Niroumand, B. Wear and tribological performance of aluminum–graphite MMCs. *Wear* **2000**, *250*, 5–12.
8. Nagarajan, G.; Singh, A.K.; Venkatesan, M. Mechanical properties of graphite reinforced aluminum composites: A review. *Mater. Res. Express* **2019**, *6*, 025303.
9. Kumar, P.; Sharma, S.; Gupta, V. Characterization and mechanical properties of aluminum-graphite composites: A critical review. *Mater. Today Proc.* **2020**, *26*, 355–362.
10. Lee, S.J.; Park, S.H.; Kim, S. Influence of particulate size on the properties of graphite-reinforced aluminum matrix composites. *J. Compos. Mater.* **2015**, *49*, 1301–1309.
11. Kadir, M.I.A.; Mustapa, M.S.; Mahdi, A.S.; Kuddus, S.; Samsi, M.A. Evaluation of hardness strength and microstructures of recycled Al chip and powder AA6061 fabricated by cold compaction method. In *IOP Conference Series: Materials Science and Engineering, Proceedings of the Colloquium of Advanced Mechanics, CAMS 2016, Batu Pahat, Johor, 18–19 December 2016*; IOP Publishing: Bristol, UK, 2017.
12. Vaidya, B.K.; Reddy, B.V.; Rao, S. The effects of graphite reinforcement on the mechanical properties of aluminum matrix composites. *Compos. Sci. Technol.* **2017**, *148*, 104–113.
13. Li, M.; Kumar, M. Reinforcement of aluminum composites: A review on graphite and its properties. *Mater. Sci. Eng. A* **2019**, *760*, 149–158.

14. Prasad, V.K.; Prakash, C.; Bhowmick, S. Effect of graphite addition on the mechanical properties of aluminum-based composites. *J. Alloys Compd.* **2018**, *735*, 509–516.
15. Zhang, Y.; Zhang, L.; Wang, J. Effect of graphite content on the properties of aluminum-based composites. *Mater. Sci. Eng. A* **2020**, *783*, 139285.
16. Shamsudin, N.; Muhamad, N.; Jamaludin, N.; Suhaimi, S. Sustainable recycling of AA6061 chips using hot press forging technique. In *Green Manufacturing Processes and Technologies*; John, D., Lee, K., Eds.; Springer: New York, NY, USA, 2018; pp. 115–130.
17. Kumar, P.; Sharma, S. Enhancing the mechanical properties of aluminum composites using graphite as reinforcement. *Compos. Part B Eng.* **2018**, *144*, 177–185.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.