

Fabrication and mechanical properties of copper and silicon carbide-reinforced aluminum metal matrix composites processed by powder metallurgy

Tito Endramawan, Adi Kusmayadi*, Dedi Suwandi, Ayatullah Hudayef

Department of Mechanical Engineering, Politeknik Negeri Indramayu, Indramayu 45252, Indonesia

*Corresponding Author: adikusmayadi@polindra.ac.id

Abstract

Metal-matrix composites (MMCs) offer superior mechanical properties, making them ideal for advanced engineering applications. However, achieving optimal strength and hardness remains a challenge. This study investigated the role of copper (Cu) reinforcement in enhancing the mechanical performance of aluminum-silicon carbide (Al-SiC) composites fabricated via powder metallurgy. Composites were synthesized with 5 wt.% and 10 wt.% Cu and sintered at 500°C, 550°C, and 600°C. The results indicate that increasing Cu content significantly improved hardness and bending strength, with the 80%Al-10%Cu-10%SiC composition exhibiting the highest hardness (96.86 kg/mm²) and bending strength (29.08 MPa) at 600°C representing a 37.86% and 74.03% increase, respectively, compared to the 5 wt.% Cu composites. Microstructural analysis confirmed uniform Cu and SiC dispersion, improved matrix bonding, and reduced porosity at elevated sintering temperatures. These findings highlight the potential of Cu-reinforced Al-SiC composites for high-performance applications, particularly in wear-resistant and structural components

Keywords:

Metal matrix composites, aluminum-silicon carbide, copper reinforcement, powder metallurgy, mechanical properties enhancement.

1 Introduction

Metal-Matrix Composites (MMCs) have emerged as a vital class of materials in advanced engineering applications owing to their excellent mechanical properties such as high strength, superior wear resistance, and thermal stability [1]. Aluminum is the preferred matrix material owing to its lightweight, corrosion resistance, and ease of fabrication. However, pure aluminum often falls short of meeting the mechanical demands of modern industries such as aerospace, automotive, and defense [2]. To address these limitations, reinforcing aluminum with secondary materials has been proven to enhance its mechanical performance.

Silicon Carbide (SiC), a ceramic material, is widely acknowledged as an excellent reinforcement for aluminum matrices due to its superior hardness, thermal stability, and wear resistance [3]. Adding SiC significantly improves the load-bearing capacity and durability of aluminum composites, making them suitable for high-stress environments [4]. Additionally, Copper (Cu) is widely used as a metallic reinforcement because it enhances the strength and ductility of the metal matrices. The combination of SiC and Cu in aluminum MMCs is expected to synergistically enhance their mechanical properties, providing a pathway for the development of advanced materials with superior performance [5].

Powder metallurgy has emerged as a versatile and efficient method for synthesizing MMCs, offering precise control over

material composition and processing parameters. This technique involves compacting a mixture of metal powders under high pressure and sintering them at elevated temperatures to achieve densification and improved bonding between the matrix and reinforcements [6]. Despite their advantages, the influence of reinforcement composition and sintering parameters on the mechanical and microstructural properties of aluminum MMCs remains underexplored, particularly for composites reinforced with both Cu and SiC. However, despite the well-documented benefits of individual reinforcements, such as SiC and Cu, comprehensive studies on their combined effects in aluminum MMCs are still lacking, especially concerning their mechanical and microstructural behavior under different sintering conditions. Moreover, the optimal reinforcement composition and processing parameters for maximizing the strength and ductility remain unclear. Addressing these gaps is essential to fully harness the potential of Al-SiC-Cu composites for advanced engineering applications.

This study aimed to fabricate and analyze aluminum metal matrix composites reinforced with copper and silicon carbide using powder metallurgy. It investigated the impact of the reinforcement composition and sintering parameters on the composites' mechanical properties and microstructural characteristics. This research seeks to enhance the material performance by optimizing the synthesis process, contributing to the development of high-strength, durable composites for advanced engineering applications.

2 Materials and methods

2.1 Materials

This study utilized carefully selected materials to develop a high-performance metal matrix composite. The matrix consisted of 280-mesh aluminum powder (85% activated aluminum) for its lightweight, corrosion resistance, and excellent conductivity [7]. Copper powder (230-mesh, 99.5% purity) enhanced mechanical properties, while 280-mesh SiC provided hardness, thermal stability, and wear resistance [8]. Supporting materials, including 96% alcohol for dispersion, aluminum nitrate for SiC wettability, and stearic acid as a lubricant during compaction, optimized the composite's structure and performance.

2.2 Mixing

The materials were mixed using the wet mixing technique, incorporating a polar solvent to achieve a uniform blend. Two compositions were prepared: 85% Al-5% Cu-10% SiC and 80% Al-10% Cu-10% SiC. The weighed powders were combined with 96% alcohol and stirred for 15 minutes to ensure homogeneity. The mixture was then sealed to prevent oxidation, ensuring even distribution and preserving material integrity for further process [9].

2.3 Compaction

Compaction involves densifying the powder into a specific shape using a mold. The process begins with the preparation and lubrication of an ASTM D790 mold to reduce friction [10]. A 15-gram powder mixture was weighed, poured into the mold, and compacted in a machine under a 14 tons-force for 5 min. The specimen was then carefully removed using a push pin to maintain its integrity, ensuring a uniform and durable sample for further testing.

2.4 Sintering

The sintering process was performed at three different temperatures 500°C, 550°C, and 600 °C with each condition maintained for a holding time of 2 h to evaluate the effects of temperature on the composite's structural properties and performance [11].

2.5 Analytical methods

The analytical methods used include hardness, bending, and microstructural tests. Hardness testing involved polishing the

specimen with Autosol and velvet cloth for a smooth finish, placing it securely in the machine, and applying a 1 kg load for 30 s [12]. The diagonal lengths (D1 and D2) were measured under a microscope to calculate hardness. The bending test followed ASTM D790 standards using rectangular specimens (125 mm x 12 mm x 4 mm), with dimensions measured and aligned before applying a constant load until fracture, recording the maximum load [13]. Microstructural testing utilized an Olympus BX53M microscope with magnifications of 20x, 50x, and 100x [14]. Specimens were polished with sandpaper (400–2000 grit) and Autosol for clear visibility, enabling precise surface observation and analysis.

3 Results and discussions

3.1 Impact of composition and sintering temperatures on hardness properties

Hardness testing in this study employed the Vickers method, using a 1 kgf load and 30-second dwell time to assess material hardness. Fig. 1 shows the Vickers Hardness Number (VHN) for two compositions, 85%Al–5%Cu–10%SiC and 80%Al–10%Cu–10%SiC, at sintering temperatures of 500°C, 550°C, and 600°C. The results indicated that hardness increased with higher sintering temperatures due to improved particle bonding and reduced porosity [15]. For 85%Al–5%Cu–10%SiC, VHN rose from 53.76 kg/mm² at 500°C to 70.26 kg/mm² at 600°C, while 80%Al–10%Cu–10%SiC increased from 78.55 kg/mm² to 96.86. The Al 80%Al–10%Cu–10%SiC composition consistently showed higher hardness, attributed to the higher copper content, strengthening the matrix and reinforcing SiC particles [16]. This highlights the beneficial effect of higher copper content and sintering temperature on mechanical properties, making 80%Al–10%Cu–10%SiC a better choice for applications demanding higher hardness and durability.

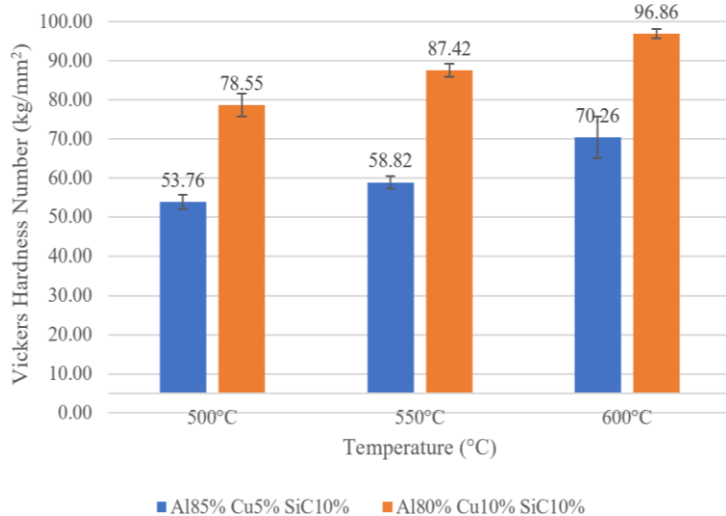


Fig. 1. Vickers hardness number of 85%Al–5%Cu–10%SiC and 80%Al–10%Cu–10%SiC composites at sintering temperatures of 500°C, 550°C, and 600°C

3.2 Impact of composition and sintering temperatures on bending strength

Fig. 2 illustrates the bending strength of 85%Al–5%Cu–10%SiC and 80%Al–10%Cu–10%SiC composites at sintering temperatures of 500, 550, and 600°C. The results show a consistent increase in strength with higher temperatures. At 500°C, 85%Al–5%Cu–10%SiC achieves 8.9 MPa, while 80%Al–10%Cu–10%SiC reaches 16.04 MPa. At 550°C, these values increase to 11.39 MPa and 27.65 MPa, peaking at 600°C with 16.71 MPa and 29.08 MPa, respectively. The superior performance of 80%Al–10%Cu–10%SiC is attributed to its higher copper content, enhancing ductility, matrix bonding, and load distribution [17]. These findings highlight the synergistic effect of copper content and sintering temperature on mechanical properties, making 80%Al–10%Cu–10%SiC ideal for applications requiring high bending strength and durability.

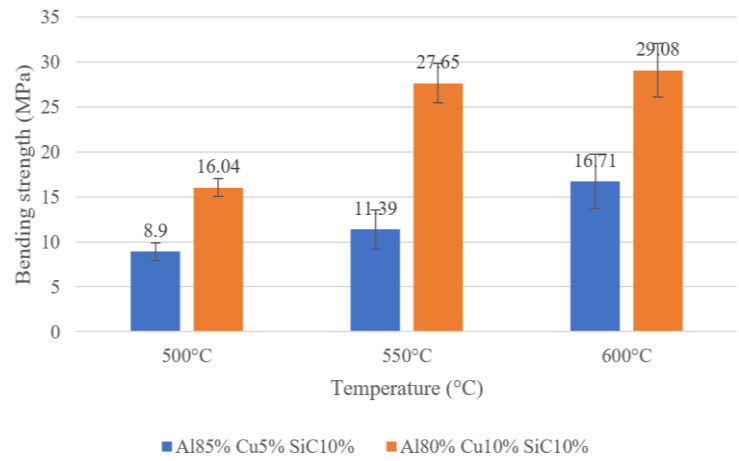


Fig. 2. Bending strength of 85%Al–5%Cu–10%SiC and 80%Al–10%Cu–10%SiC composites at sintering temperatures of 500°C, 550°C, and 600°C

3.3 Effect of composition and sintering temperatures on microstructure properties

Fig. 3 illustrates the microstructure of the 85%Al–5%Cu–10%SiC composite sintered at 550°C, observed at 100x magnification. The microstructure reveals the following key components: Al as the matrix, Cu as the metallic reinforcement, and SiC as the ceramic reinforcement. While copper and silicon carbide particles were embedded within the aluminum matrix, their distribution was uneven, with noticeable clustering and porosity. This clustering leads to an uneven reinforcement distribution, creating localized weaknesses that reduce the strength, fracture resistance, and overall performance. It also diminishes the effectiveness of SiC and copper, lowering the hardness, toughness, and wear resistance while hindering the thermal conductivity and structural integrity [18]. The observed porosity suggests incomplete densification during sintering, which may introduce weaknesses that negatively affect the mechanical properties of the composite [19]. A sintering temperature of 550°C appears to improve particle bonding compared to lower temperatures, as evidenced by the better integration of Cu and SiC within the matrix.

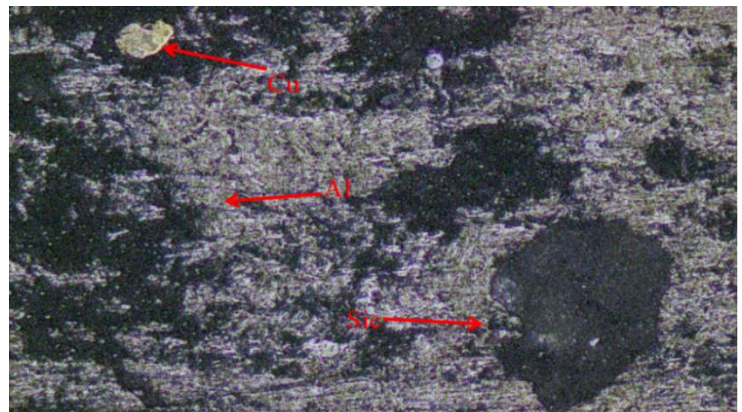


Fig. 3. Microstructure of 85%Al–5%Cu–10%SiC at 550°C, magnification 100x

Fig. 4 depicts the microstructure of the 85%Al–5%Cu–10%SiC composite sintered at 500°C, observed under a microscope at 100x magnification. This figure highlights the dispersion of Cu and SiC particles within Al matrix. The distribution of these reinforcement particles appears uneven, which may contribute to variations in the localized mechanical properties. Additionally, areas of porosity were visible, suggesting incomplete densification during sintering at this temperature [20]. The observed microstructure reflects the influence of sintering temperature on particle bonding, material homogeneity, and the presence of defects, which are critical factors affecting the overall mechanical performance of the composite.

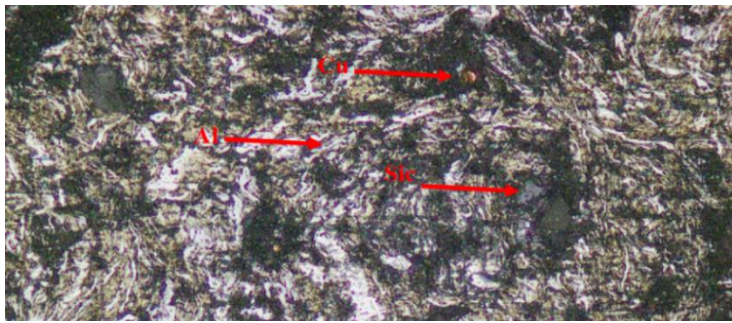


Fig. 4. Microstructure of 85%Al-5%Cu-10%SiC at 500°C, magnification 100x

Fig. 5 shows the microstructure of the 80%Al-10%Cu-10%SiC composite sintered at 550°C (100x magnification). The aluminum matrix integrated copper as a metallic reinforcement and SiC as a ceramic reinforcement, with well-distributed Cu particles and SiC appearing as darker, irregular regions. A higher Cu content enhances matrix bonding and load transfer, although clustering and non-homogeneity persist, potentially affecting the mechanical properties [21]. Minimal porosity indicates improved densification, suggesting its suitability for applications that require enhanced strength and hardness.

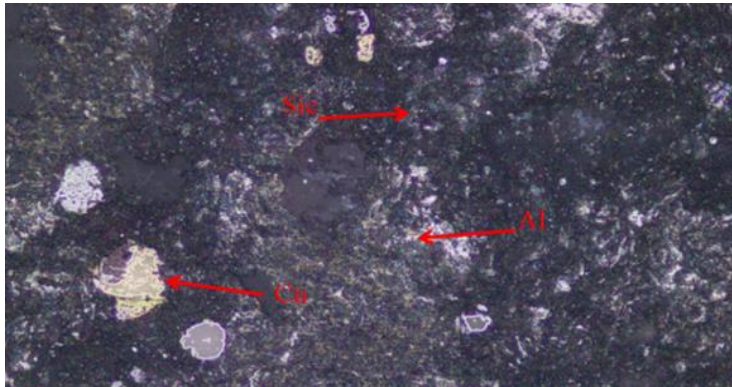


Fig. 5. Microstructure of 80%Al-10%Cu-10%SiC at 550°C, magnification 100x

Fig. 6 illustrates the microstructure of the 80%Al-10%Cu-10%SiC composite sintered at 500°C, observed under a microscope at 100x magnification. Al matrix is evident, with Cu particles and SiC as reinforcements dispersed throughout. While the copper and SiC particles were visible, their distribution appeared uneven with noticeable clustering and gaps within the aluminum matrix. The lower sintering temperature of 500°C likely limits the diffusion and bonding of the particles, resulting in visible porosity and incomplete densification [22]. This irregular dispersion and porosity may affect the mechanical properties of the composite, such as reduced strength and hardness, compared to those sintered at higher temperatures [22].

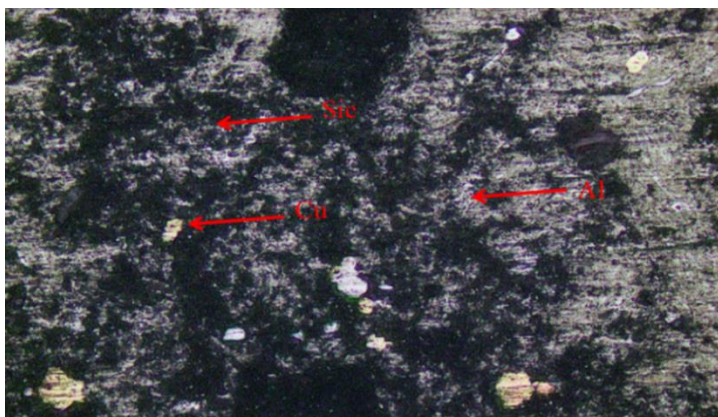


Fig. 6. Microstructure of Al80% Cu10% SiC10% at 500°C, magnification 100x

Fig. 7 shows the microstructure of the 85%Al-5%Cu-10%SiC composite sintered at 600°C observed under a microscope at 100x magnification. Al matrix, Cu particles, and SiC reinforcements are identifiable. At this higher sintering temperature, the distribution of Cu and SiC particles appeared to be more integrated into the Al matrix than at lower sintering temperatures. However, some clustering of copper and uneven dispersion of SiC particles were still visible. The improved densification at 600°C likely reduces porosity and enhances particle bonding, which contributes to better mechanical properties such as increased strength and hardness [23].

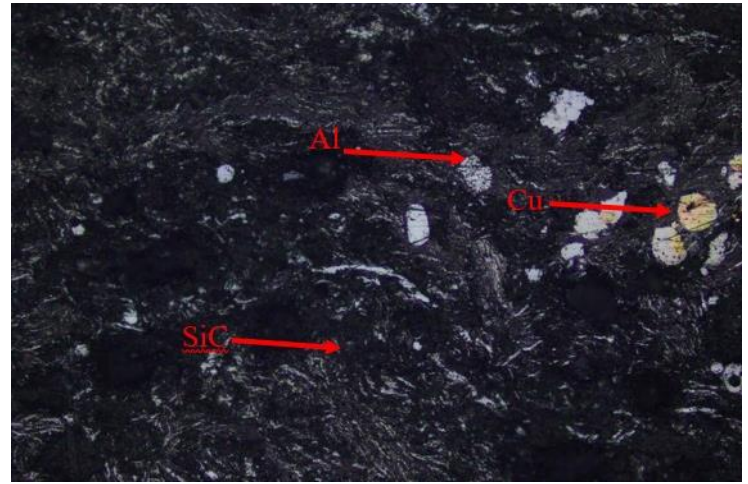


Fig. 7. Microstructure of 85%Al-5%Cu-10%SiC at 600°C, magnification 100x

Fig. 8 depicts the microstructure of the 80%Al-10%Cu-10%SiC composite sintered at 600°C, observed at 100x magnification. Al served as the matrix, while Cu and SiC acted as reinforcements.

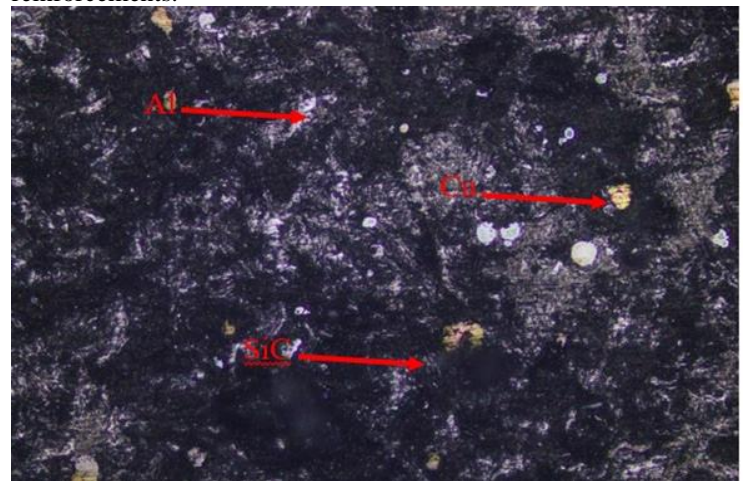


Fig. 8. Microstructure of 80%Al-10%Cu-10%SiC at 600°C, magnification 100x

At this sintering temperature, the microstructure showed better integration of the reinforcement particles into the matrix than at lower temperatures [24]. The copper particles are prominently distributed, contributing to enhanced bonding within the matrix, while the SiC particles, although visible, still exhibit slight clustering and uneven distribution. A higher sintering temperature facilitates improved particle diffusion and densification, minimizes porosity, and enhances mechanical properties, such as strength and hardness [7].

4 Conclusions

This study demonstrated that incorporating Cu reinforcement enhances the mechanical properties of Al-SiC composites, particularly in hardness and bending strength. The Al80%-Cu10%-SiC10% composition showed the best performance, attributed to improved Cu and SiC dispersion, matrix bonding, and reduced

porosity at higher sintering temperatures. These results highlight the potential of Cu-reinforced Al-SiC composites for applications requiring high strength and wear resistance, such as industrial tools and protective coatings. Future research should focus on optimizing reinforcement compositions, improving corrosion resistance, and exploring alternative sintering techniques to further enhance mechanical performance in extreme operational environments.

Reference

- [1] W. Abd-Elaziem *et al.*, "Influence of nanoparticles addition on the fatigue failure behavior of metal matrix composites: Comprehensive review," *Engineering Failure Analysis*, vol. 155, p. 107751, 2024/01/01/ 2024, doi: <https://doi.org/10.1016/j.engfailanal.2023.107751>.
- [2] A. Kar, A. Sharma, and S. Kumar, "A critical review on recent advancements in aluminium-based metal matrix composites," *Crystals*, vol. 14, no. 5, p. 412, 2024, doi: <https://doi.org/10.3390/cryst14050412>.
- [3] A. Bhowmik *et al.*, "Development and wear resistivity performance of SiC and TiB₂ particles reinforced novel aluminium matrix composites," *Results in Engineering*, vol. 24, p. 102981, 2024, doi: <https://doi.org/10.1016/j.rineng.2024.102981>.
- [4] S. K. Sharma *et al.*, "Progress in aluminum-based composites prepared by stir casting: Mechanical and tribological properties for automotive, aerospace, and military applications," *Lubricants*, vol. 12, no. 12, p. 421, 2024, doi: <https://doi.org/10.3390/lubricants12120421>.
- [5] C. Shekhar, M. F. Wani, R. Sehgal, S. S. Saleem, U. Ziyamukhamedova, and N. Tursunov, "Recent progress in particulate reinforced copper-based composites: Fabrication, microstructure, mechanical, and tribological properties—A review," *Advanced Engineering Materials*, p. 2401748, 2024, doi: <https://doi.org/10.1002/adem.202401748>.
- [6] R. Purohit, Y. Dewang, R. S. Rana, D. Koli, and S. Dwivedi, "Fabrication of magnesium matrix composites using powder metallurgy process and testing of properties," *Materials Today: Proceedings*, vol. 5, no. 2, Part 1, pp. 6009-6017, 2018/01/01/ 2018, doi: <https://doi.org/10.1016/j.matpr.2017.12.204>.
- [7] H. Nautiyal, S. Kumari, O. P. Khatri, and R. Tyagi, "Copper matrix composites reinforced by rGO-MoS₂ hybrid: Strengthening effect to enhancement of tribological properties," *Composites Part B: Engineering*, vol. 173, p. 106931, 2019/09/15/ 2019, doi: <https://doi.org/10.1016/j.compositesb.2019.106931>.
- [8] I. Dinaharan, S. Karpagarajan, R. Palanivel, and S. Vigneshwaran, "Silicon carbide particulate reinforced dual phase brass composites with improved wear resistance prepared via friction stir processing," *Advances in Materials and Processing Technologies*, vol. 10, no. 3, pp. 2607-2617, 2024, doi: <https://doi.org/10.1080/2374068X.2023.2223824>.
- [9] Y. Sui, Q. Lai, W. Nie, S. Tang, C. Wang, and H. Bian, "Wet continuous mixing technique based on full formula of carbon black," *Journal of Applied Polymer Science*, vol. 139, no. 40, p. e52971, 2022, doi: <https://doi.org/10.1002/app.52971>.
- [10] J. Manalu *et al.*, "Characterization of eco-friendly composites for automotive applications prepared by the compression molding method," *Polymer Composites*, 2024, doi: <https://doi.org/10.1002/pc.28327>.
- [11] L. Ma, L. Ma, P. Jin, X. Feng, and L. Jia, "Effect of sintering temperature on microstructures and mechanical properties of ZK60 magnesium alloys," *Materials Research Express*, vol. 9, no. 1, p. 016514, 2022, doi: <https://doi.org/10.1088/2053-1591/ac47c7>.
- [12] S. Slamet, S. Khoeron, and S. Suyitno, "The effect of post-casting gamelan blade forging on Cu-25wt.% Sn alloy on microstructure, hardness and sound acoustic," in *AIP Conference Proceedings*, 2024, vol. 3167, no. 1: AIP Publishing, doi: <https://doi.org/10.1063/5.0218125>.
- [13] A. Afshar, D. M. Mihut, D. D. Sellers, E. R. Schmidt, and E. F. Parker, "The design and development of a laboratory for three-point bending tests on 3D printed samples," in *2024 South East Section Meeting*, 2024, doi: <https://doi.org/10.18260/1-2--45569>.
- [14] M. Sivakumar and J. Jerald, "Effect of intrinsic heat treatment in wire arc additive manufacturing on grade 91 steel: Microstructure and mechanical properties," *Progress in Additive Manufacturing*, pp. 1-10, 2024, doi: <https://doi.org/10.1007/s40964-024-00905-5>.
- [15] C. Wang, Y. Li, W. Zhang, T. Zhao, and H. Du, "Effect of temperature on the microstructure and mechanical properties of TiC/Fe matrix composites fabricated by spark plasma sintering," *Journal of Materials Research and Technology*, vol. 33, pp. 1032-1047, 2024, doi: <https://doi.org/10.1016/j.jmrt.2024.09.121>.
- [16] A. Prosviryakov, "SiC content effect on the properties of Cu-SiC composites produced by mechanical alloying," *Journal of Alloys and Compounds*, vol. 632, pp. 707-710, 2015, doi: <https://doi.org/10.1016/j.jallcom.2015.01.298>.
- [17] J. Gayathri and R. Elansezhian, "Enhancement of mechanical properties of aluminium metal matrix composite by reinforcing waste alumina catalyst and nano Al₂O₃," *Materials Today: Proceedings*, vol. 45, pp. 462-466, 2021/01/01/ 2021, doi: <https://doi.org/10.1016/j.matpr.2020.02.003>.
- [18] S.-J. Hong, H.-M. Kim, D. Huh, C. Suryanarayana, and B. S. Chun, "Effect of clustering on the mechanical properties of SiC particulate-reinforced aluminum alloy 2024 metal matrix composites," *Materials Science and Engineering: A*, vol. 347, no. 1-2, pp. 198-204, 2003, doi: [https://doi.org/10.1016/S0921-5093\(02\)00593-2](https://doi.org/10.1016/S0921-5093(02)00593-2).
- [19] L. K. Singh, A. Bhadauria, A. Oraon, and T. Laha, "Spark plasma sintered Al-0.5 wt% MWCNT nanocomposite: Effect of sintering pressure on the densification behavior and multi-scale mechanical properties," *Diamond and Related Materials*, vol. 91, pp. 144-155, 2019, doi: <https://doi.org/10.1016/j.diamond.2018.11.021>.
- [20] L. Huang, L. Geng, and H. Peng, "Microstructurally inhomogeneous composites: Is a homogeneous reinforcement distribution optimal?," *Progress in Materials Science*, vol. 71, pp. 93-168, 2015, doi: <https://doi.org/10.1016/j.pmatsci.2015.01.002>.
- [21] D. K. Sharma, D. Mahant, and G. Upadhyay, "Manufacturing of metal matrix composites: A state of review," *Materials Today: Proceedings*, vol. 26, pp. 506-519, 2020, doi: <https://doi.org/10.1016/j.matpr.2019.12.128>.
- [22] D. V. Dudina, B. B. Bokhonov, and E. A. Olevsky, "Fabrication of porous materials by spark plasma sintering: A review," *Materials*, vol. 12, no. 3, p. 541, 2019, doi: <https://doi.org/10.3390/ma12030541>.
- [23] P. Barick, D. Chakravarty, B. P. Saha, R. Mitra, and S. V. Joshi, "Effect of pressure and temperature on densification, microstructure and mechanical properties of spark plasma sintered silicon carbide processed with β -silicon carbide nanopowder and sintering additives," *Ceramics International*, vol. 42, no. 3, pp. 3836-3848, 2016, doi: <https://doi.org/10.1016/j.ceramint.2015.11.048>.
- [24] A. Wąsik, B. Leszczyńska-Madej, M. Madej, and M. Goły, "Microstructure and mechanical properties of low-cost SiC-reinforced aluminum and Al4Cu matrix composites produced by sintering in vacuum," *Materials*, vol. 16, no. 15, p. 5492, 2023, doi: <https://doi.org/10.3390/ma16155492>.