Processing–Structure–Property Correlation in AA2024–SIC Aluminium Matrix Composites Developed Through Stir-Assisted Casting

Rakesh Oza[1] Anand B. Dhruv[2]
[1]Research Scholar [2]Professor
[1,2]Department of Mechanical Engineering
[1]Gujarat Technological University, Ahmedabad, Gujarat, India [2]Government Engineering College, Patan, Gujarat, India

Abstract — In the present study, AA2024–SiC aluminium metal matrix composites were successfully fabricated using the stir casting technique with varying silicon carbide (SiC) reinforcement contents of 2 wt.%, 4 wt.%, and 6 wt.%. The fabrication process was carried out at a melting temperature of 850 °C to achieve uniform reinforcement distribution and improved interfacial bonding. The prepared composites were characterized through density measurement, porosity analysis, optical microstructural examination, microhardness testing, and tensile strength evaluation. The results indicated that the incorporation of SiC significantly enhanced the composite properties. Experimental density increased from 2.546 g/cm³ to 2.701 g/cm³, while porosity decreased from 2.245% to 1.768% with increasing SiC content. Microstructural analysis revealed refined grains and improved particle dispersion at higher reinforcement levels. Furthermore, microhardness and tensile strength increased from 67.35 HV to 84.23 HV and 89.63 N/mm² to 124.95 N/mm², respectively. The 6 wt.% SiC composite exhibited the best overall performance.

Keywords: AA2024 Aluminium Alloy, Silicon Carbide (SIC), Stir Casting, Microstructural Analysis, Mechanical Properties

I. Introduction

The increasing demand for lightweight, high-strength materials in aerospace, automotive, marine, and defense industries has accelerated the development of advanced engineering materials with superior mechanical and tribological properties [1] [2]. Conventional aluminium alloys are extensively utilized in structural applications because of their low density, good machinability, and excellent corrosion resistance [3]. However, their relatively lower hardness, wear resistance, and load-bearing capability restrict their application in severe service environments. To overcome these limitations, aluminium metal matrix composites (AMMCs) have emerged as promising alternatives due to their enhanced mechanical and thermal characteristics compared with monolithic aluminium alloys [4]. AMMCs are engineered materials in which a metallic matrix is reinforced with ceramic particulates, whiskers, or fibers to achieve improved strength, stiffness, hardness, and wear resistance. Among various reinforcement materials, silicon carbide (SiC) has attracted considerable attention owing to its high hardness, excellent thermal stability, low density, and superior wear resistance [5]. The incorporation of SiC particles into aluminium matrices significantly enhances the mechanical performance through mechanisms such as load transfer strengthening, grain refinement, strengthening, and thermal mismatch-induced dislocation strengthening [6]. Nevertheless, achieving a uniform dispersion of reinforcement particles within the molten matrix remains a major challenge due to poor wettability, particle agglomeration, and interfacial reactions during processing.

Among the commercially available aluminium alloys, AA2024 has been widely used in aerospace and transportation sectors because of its high strength-to-weight ratio, good fatigue resistance, and satisfactory machinability [7]. The alloy primarily contains copper as the major alloying element, which contributes to its superior mechanical strength. Despite these advantages, AA2024 still exhibits limitations in terms of wear resistance and surface hardness under demanding operating conditions. Reinforcing AA2024 with ceramic particles such as SiC can significantly improve its tribological and mechanical properties, thereby expanding its industrial applicability [8].

Various fabrication techniques have been employed for producing AMMCs, including powder metallurgy, squeeze casting, infiltration, and stir casting. Among these methods, stir casting is considered one of the most economical and industrially viable techniques because of its simplicity, scalability, and suitability for mass production. In the stir casting process, reinforcement particles are mechanically stirred into the molten metal to achieve a homogeneous mixture prior to casting. However, the quality of the fabricated composite strongly depends on processing parameters such as stirring speed, stirring time, melting temperature, reinforcement preheating temperature, and mould preheating conditions. Improper parameter selection may lead to porosity formation, reinforcement clustering, and weak interfacial bonding, ultimately deteriorating composite performance [9].

Several researchers have investigated the fabrication of SiC-reinforced aluminium composites using stir casting techniques. Recent studies reported notable improvements in hardness, tensile strength, and wear resistance with increasing SiC content due to enhanced load transfer and matrix strengthening effects [10]. Furthermore, preheating of reinforcement particles has been shown to improve wettability between the matrix and reinforcement, thereby reducing particle agglomeration and promoting uniform distribution. Similarly, mould preheating minimizes thermal gradients during solidification and reduces casting defects [11]. Despite these advancements, limited studies have comprehensively examined the combined influence of process parameters and reinforcement distribution on the microstructural evolution and mechanical performance of AA2024–SiC composites.

Therefore, the present work focuses on the fabrication and characterization of AA2024–SiC metal matrix composites using the stir casting technique at a melting temperature of 850 °C. The experimental procedure involved material preparation, melting of AA2024 alloy, stir casting setup, addition of preheated SiC particles, mould preheating, and casting followed by solidification. The primary objective of this study is to achieve improved reinforcement dispersion and enhanced interfacial bonding within the aluminium matrix to obtain superior mechanical and microstructural properties. Detailed characterization techniques are employed to evaluate the fabricated composites and to understand the influence of SiC reinforcement on the overall performance of the developed AMMC system.

II. EXPERIMENTAL PROCEDURE

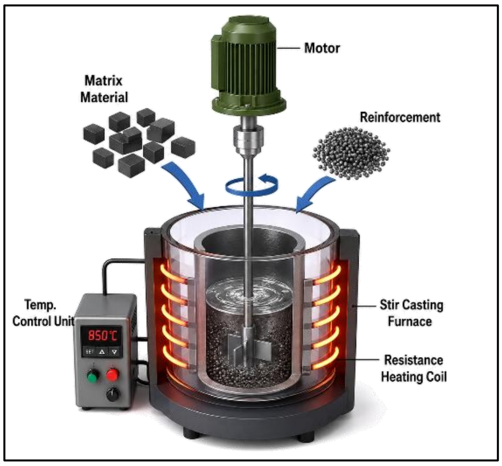

Fig. 1: Schematic diagram of the stir casting setup

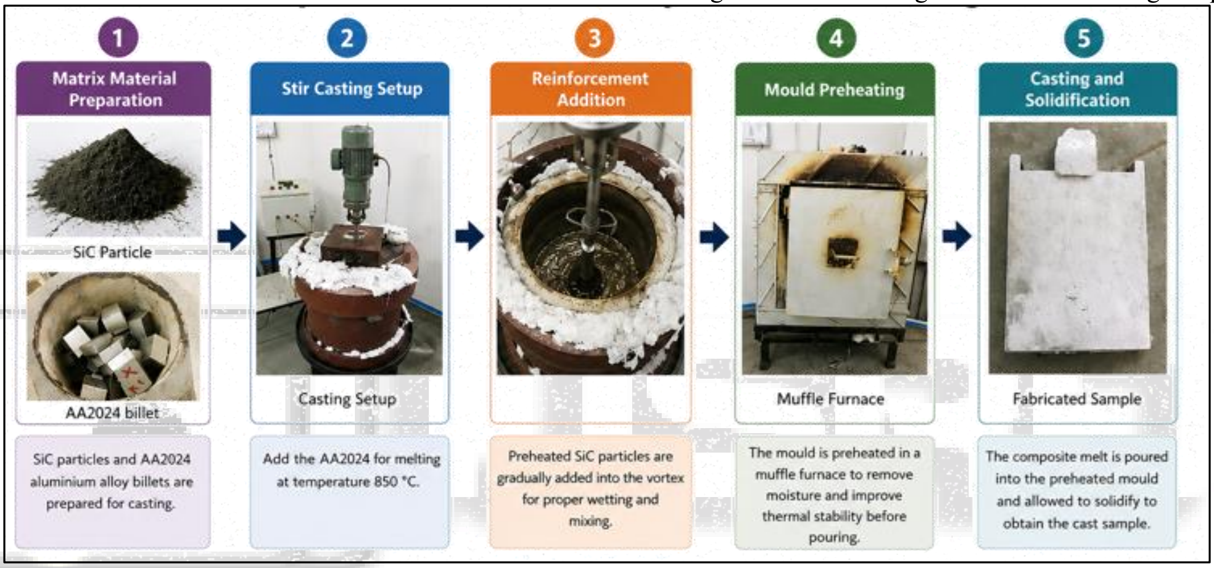

Fig. 2: Experimental procedure layout adopted for fabrication of AA2024–SiC composite

The AA2024–SiC metal matrix composites were fabricated using the stir casting technique. Initially, AA2024 aluminium alloy billets and silicon carbide (SiC) reinforcement particles were prepared as matrix and reinforcement materials, respectively. The schematic representation of the stir casting setup is illustrated in Fig. 1, while the complete experimental procedure adopted during composite fabrication is presented in Fig. 2. The AA2024 alloy billets were charged into the graphite crucible and heated to a melting temperature of 850 °C using an electrically controlled resistance furnace. To ensure proper melting and homogeneous temperature distribution, the molten alloy was maintained at the desired temperature for a specific duration [12]. Subsequently, the stir casting setup equipped with a mechanical stirrer was employed to generate a vortex within the molten metal. The SiC reinforcement particles were preheated prior to their addition into the molten matrix to improve wettability and minimize moisture-induced porosity. In the present investigation, SiC particles were incorporated into the AA2024 matrix with reinforcement concentrations of 2 wt.%, 4 wt.%, and 6 wt.%. Accordingly, three different composite cast samples were fabricated under identical processing conditions. The preheated SiC particles were gradually introduced into the vortex region to achieve uniform particle dispersion and enhanced interfacial bonding between the matrix and reinforcement phases. Simultaneously, the metallic mould was preheated in a muffle furnace to reduce thermal gradients during solidification and to prevent casting defects [13]. After achieving homogeneous mixing, the molten composite slurry was poured into the preheated mould cavity and allowed to solidify under atmospheric conditions. The fabricated composite specimens were then removed from the mould and prepared for subsequent characterization and mechanical testing.

III. RESULTS AND DISCUSSION

A. *Density and Porosity of The Composites*

The density and porosity behaviour of the fabricated AA2024–SiC composites were evaluated using density measurements and ImageJ software analysis. The obtained results are presented in Table 1, while the variation in porosity and density is illustrated in Fig. 3 and Fig. 4, respectively. The experimental and theoretical density values increased with increasing SiC reinforcement content. The experimental density increased from 2.546 g/cm³ for 2 wt.% SiC to 2.701 g/cm³ for 6 wt.% SiC, whereas the theoretical density increased from 2.654 g/cm³ to 2.737 g/cm³. This increase is attributed to the higher density and improved packing effect of SiC particles within the AA2024 matrix. The porosity analysis revealed a gradual reduction in porosity with increasing reinforcement concentration. The porosity decreased from 2.245% for 2 wt.% SiC to 1.768% for 6 wt.% SiC. Similarly, the average void size reduced from 9.619 to 5.605 with increasing SiC content. The reduction in porosity may be attributed to improved wettability, better reinforcement distribution, and reduced gas entrapment due to preheating of the reinforcement particles and mould [14] [15]. Lower porosity and improved density indicate enhanced composite quality and stronger interfacial bonding between the matrix and reinforcement phases.

SiC Content (wt.%)	Experimental Density (g/cm³)	Theoretical Density (g/cm³)	% Porosity	Average Size of Void Content
2	2.546	2.654	2.245	9.619
4	2.595	2.695	1.935	6.898
6	2.701	2.737	1.768	5.605

Table 1. Density and porosity analysis of AA2024–SiC composites.

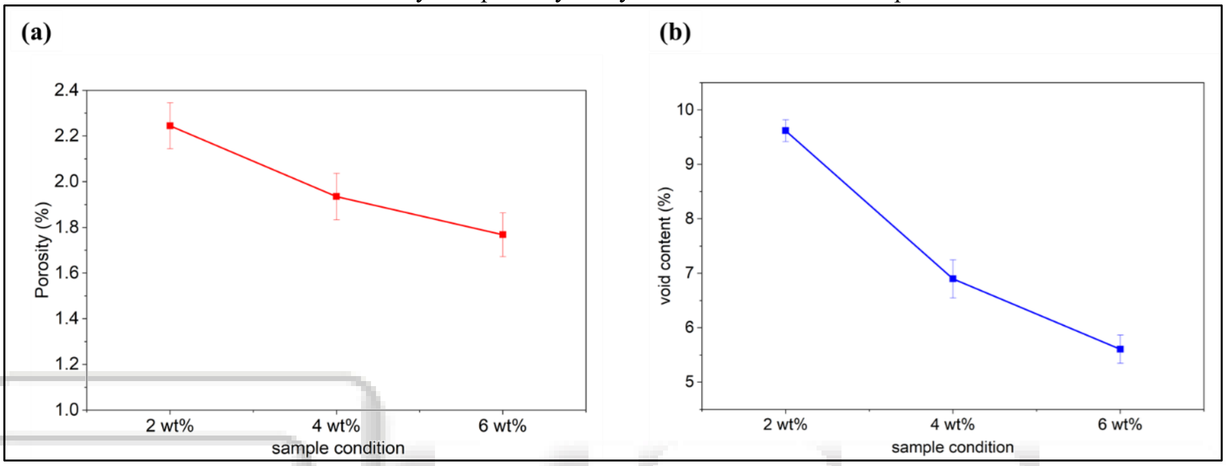

Fig. 3: AA2024–SiC composites (a) porosity level and (b) void content present with varying SiC reinforcement content.

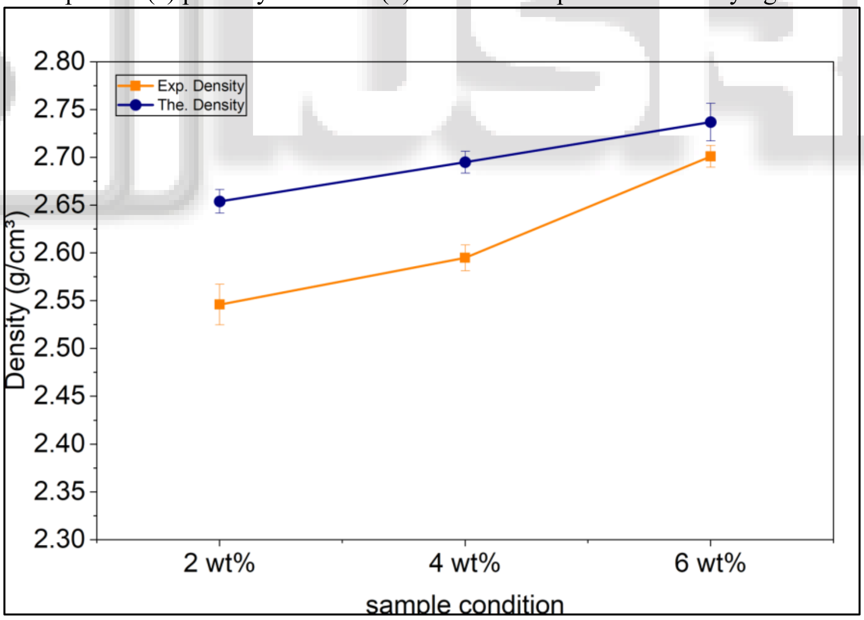

Fig. 4: Experimental and Theoretical density of AA2024–SiC composites.

Microstructure

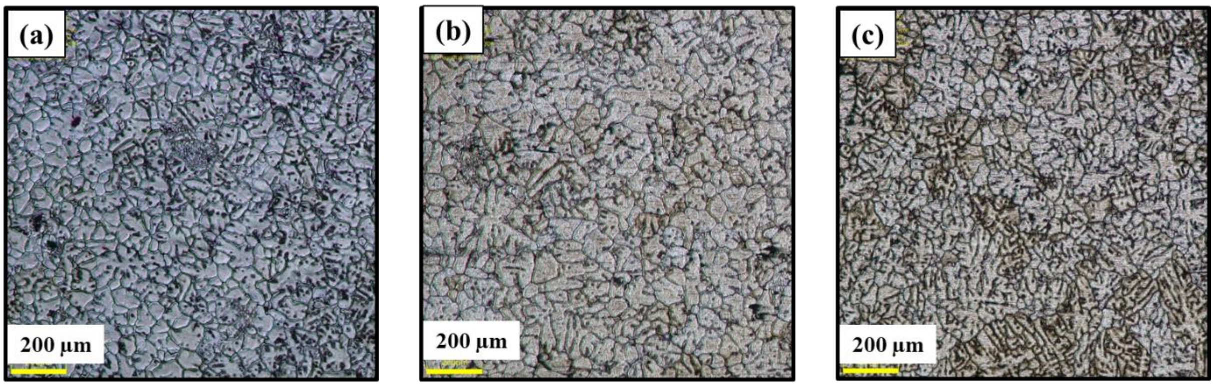

Fig. 5: Optical microscopy images of (a) AA2024-2 wt% SiC (b) AA2024-4 wt% SiC (c) AA2024-6 wt% SiC

The optical micrographs of the fabricated AA2024–SiC composites are shown in Fig. 5. The microstructural analysis revealed progressive grain refinement and improved reinforcement distribution with increasing SiC content. Similar observations have been reported for SiC-reinforced aluminium matrix composites fabricated through stir casting [16]. The microstructure of the 2 wt.% SiC composite shown in Fig. 5(a) exhibited relatively coarse grains with visible interdendritic regions and minor localized porosity. The SiC particles were distributed within the matrix; however, slight agglomeration was observed due to incomplete wettability during solidification. In contrast, the composite reinforced with 4 wt.% SiC in Fig. 5(b) displayed improved particle dispersion and reduced interdendritic spacing. The enhanced distribution of SiC particles promoted heterogeneous nucleation, resulting in refined grain boundaries and improved matrix compactness. Further improvement was observed in the 6 wt.% SiC composite shown in Fig. 5(c), where a finer and denser microstructure with reduced void formation was obtained. The increased SiC content restricted grain growth and enhanced matrix–reinforcement interfacial bonding [17]. The uniform distribution of reinforcement particles indicates the effectiveness of the stir casting process in producing composites with improved structural integrity and refined microstructure [18].

B. Microhardness analysis

The microhardness results of the fabricated AA2024–SiC composites are presented in Fig. 6. The hardness values increased progressively with increasing SiC reinforcement content. The composite reinforced with 2 wt.% SiC exhibited a microhardness of 67.35 HV, which increased to 75.84 HV and 84.23 HV for 4 wt.% and 6 wt.% SiC composites, respectively. Each value represents the average of seven readings obtained from different locations on the specimen surface. The improvement in hardness is mainly attributed to the presence of hard SiC ceramic particles, which enhance resistance to localized plastic deformation [19]. Furthermore, grain refinement, effective load transfer, and increased dislocation density contributed significantly to the improved hardness behaviour of the composites [20].

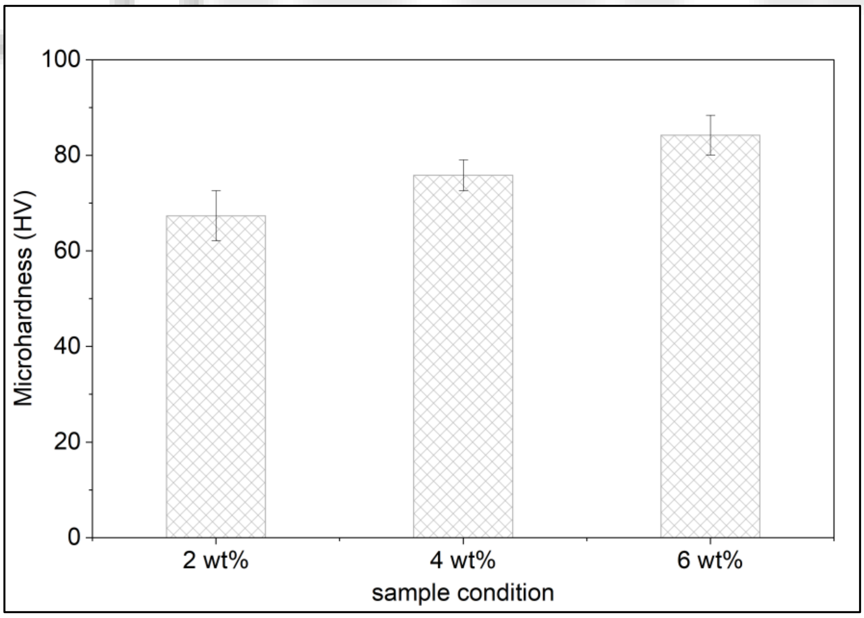

Fig. 6: The variation of Microhardness with different fraction of SiC

C. Tensile strength

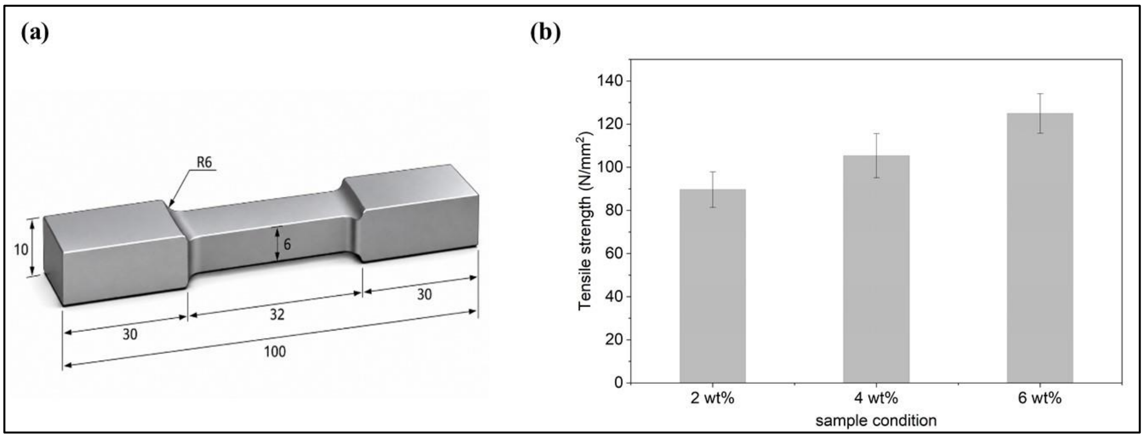

Fig. 7: Composite (a) Tensile sample geometry (b) Tensile stress of varying wt% of SiC

The tensile strength results of the fabricated AA2024–SiC composites are presented in Fig. Y, while the ASTM E8 tensile specimen geometry is shown in Fig. 7. The tensile strength increased progressively with increasing SiC reinforcement content. The composite reinforced with 2 wt.% SiC exhibited a tensile strength of 89.63 N/mm², which increased to 105.37 N/mm² and 124.95 N/mm² for 4 wt.% and 6 wt.% SiC composites, respectively. The improvement in tensile behaviour is attributed to effective load transfer between the AA2024 matrix and hard SiC particles, grain refinement, and enhanced dislocation strengthening [6] [21]. Furthermore, improved interfacial bonding and reduced porosity contributed significantly to increased resistance against plastic deformation and crack propagation [22].

IV. CONCLUSION

The experimental results demonstrated that the incorporation of SiC particles significantly improved the physical, microstructural, and mechanical properties of the composites. The density of the composites increased with increasing SiC content, while porosity and void size were reduced, indicating improved composite compactness and reduced casting defects.

Microstructural analysis revealed refined grain boundaries, uniform distribution of SiC particles, and enhanced matrix–reinforcement interfacial bonding at higher reinforcement concentrations.

Furthermore, the microhardness increased from 67.35 HV to 84.23 HV, while tensile strength improved from 89.63 N/mm² to 124.95 N/mm² with increasing SiC content.

Among all the fabricated samples, the 6 wt.% SiC reinforced composite exhibited the best overall performance due to improved load transfer, grain refinement, and reduced porosity. The study confirms that stir casting is an effective and economical technique for developing high-performance AA2024-based composites.

REFERENCES

[1] J. Suthar and K. M. Patel, "Processing issues, machining, and applications of aluminum metal matrix composites," Mater. Manuf. Process., vol. 33, no. 5, pp. 499–527, 2018.
[2] B. Kumar and J. V Menghani, "Aluminium-based metal matrix composites by stir casting: a literature review," Int. J. Mater. Eng. Innov., vol. 7, no. 1, pp. 1–14, 2016.
[3] G. Moona, R. S. Walia, V. Rastogi, R. Sharma, and others, "Aluminium metal matrix composites: a retrospective investigation," Indian J. Pure \& Appl. Phys., vol. 56, no. 2, pp. 164–175, 2018.
[4] J. M. d Torralba, C. E. Da Costa, and F. Velasco, "P/M aluminum matrix composites: an overview," J. Mater. Process. Technol., vol. 133, no. 1–2, pp. 203–206, 2003.
[5] P. Sharma, S. P. Dwivedi, V. Dabra, N. Sharma, and R. Sharma, "Mechanical behavior of AA2024/SiC AMCs," in Materials Today: Proceedings, 2019, vol. 25, pp. 938–941. doi: 10.1016/j.matpr.2020.03.467.
[6] J. H. Shin, H. J. Choi, and D. H. Bae, "The structure and properties of 2024 aluminum composites reinforced with TiO2 nanoparticles," Mater. Sci. Eng. A, vol. 607, pp. 605–610, Aug. 2014, doi: 10.1016/j.msea.2014.04.038.
[7] Gunawan, A. Arifin, M. Reza, and A. N. P. Wijaya, "Development of aluminum matrix composite with hybrid reinforcement using stir casting route," IOP Conf. Ser. Mater. Sci. Eng., vol. 857, no. 1, 2020, doi: 10.1088/1757-899X/857/1/012007.
[8] G. Kiourtsidis and S. M. Skolianos, "Corrosion behavior of squeeze-cast silicon carbide-2024 composites in aerated 3.5 wt.% sodium chloride," 1998.
[9] M. Patel, B. Pardhi, M. Pal, and M. K. Singh, "SiC Particulate Reinforced Aluminium Metal Matrix Composite," Adv. J. Grad. Res., vol. 5, no. 1, pp. 8–15, Sep. 2018, doi: 10.21467/ajgr.5.1.8-15.
[10] T. Lin, C. Tan, B. Liu, and A. McDonald, "Microstructure of AA2024-SiC nanostructured metal matrix composites," J. Mater. Sci., vol. 43, no. 23–24, pp. 7507–7512, Dec. 2008, doi: 10.1007/s10853-008-2726-7.
[11] M. Balakrishnan, I. Dinaharan, R. Palanivel, and R. Sathiskumar, "Influence of friction stir processing on microstructure and tensile behavior of AA6061/Al 3 Zr cast aluminum matrix composites," J. Manuf. Process., vol. 38, no. December 2018, pp. 148–157, 2019, doi: 10.1016/j.jmapro.2018.12.039.
[12] S. Gopalakrishnan and N. Murugan, "Production and wear characterisation of AA 6061 matrix titanium carbide particulate reinforced composite by enhanced stir

casting method," Compos. Part B Eng., vol. 43, no. 2, pp. 302–308, 2012, doi: 10.1016/j.compositesb.2011.08.049.
[13] A. K. Srivastava, B. Sharma, B. R. Saju, A. Shukla, A. Saxena, and N. K. Maurya, "Effect of Graphene nanoparticles on microstructural and mechanical properties of aluminum based nanocomposites fabricated by stir casting," World J. Eng., vol. 17, no. 6, pp. 859–866, 2020, doi: 10.1108/WJE-04-2020-0128.
[14] S. Sarapure, B. P. Shivakumar, and M. B. Hanamantraygouda, "Investigation of Corrosion Behavior of SiC-Reinforced Al 6061/SiC Metal Matrix Composites Using Taguchi Technique," J. Bio- Tribo-Corrosion, vol. 6, no. 2, pp. 1–8, 2020, doi: 10.1007/s40735-020-0328-3.
[15] S. Bhaskar, M. Kumar, and A. Patnaik, "Silicon Carbide Ceramic Particulate Reinforced AA2024 Alloy Composite - Part I: Evaluation of Mechanical and Sliding Tribology Performance," Silicon, vol. 12, no. 4, pp. 843–865, Apr. 2020, doi: 10.1007/s12633-019-00181-x.
[16] K. V. Bhaskar, S. Sundarrajan, M. G. Krishna, and K. Ravindra, "Microstructure and Mechanical properties of Flyash/SiC Particles Reinforced AA 2024 Hybrid Composites," in Materials Today: Proceedings, 2017, vol. 4, no. 8, pp. 7413–7419. doi: 10.1016/j.matpr.2017.07.072.
[17] S. B. Rayjadhav and V. R. Naik, "Characterization of Developed Al 6061-Sic Metal Matrix Composites Produced By the Stir Casting Method," Int. J. Innov. Res. Sci. Eng. Technol., vol. 2, no. 3, pp. 92–103, 2016.
[18] S. Y. Wang et al., "The hot workability of SiCp/2024 Al composite by stir casting," Mater. Manuf. Process., vol. 30, no. 5, pp. 624–630, May 2015, doi: 10.1080/10426914.2014.952027.
[19] N. Subramani, R. Haridass, S. Pramodh, A. Prem Anand, and N. Manikandan, "Mechanical strength analysis of Al6061&Al2024 based metal matrix composite prepared through stir casting method," in Materials Today: Proceedings, 2021, vol. 47, pp. 4513–4517. doi: 10.1016/j.matpr.2021.05.417.
[20] H. S. Kumaraswamy, V. Bharat, and T. K. Rao, "Influence of Boron Fiber Powder and Graphite Reinforcements on Physical and Mechanical Properties of Aluminum 2024 Alloy Fabricated by Stir Casting," J. Miner. Mater. Charact. Eng., vol. 07, no. 03, pp. 103–116, 2019, doi: 10.4236/jmmce.2019.73008.
[21] H. S. Kumaraswamy, V. Bharat, and T. K. Rao, "Influence Of Mechanical & Tribological Behaviour Of Al 2024 MMC Fabricated By Stir Casting Technique-A Review," 2018. [Online]. Available: www.sciencedirect.comwww.materialstoday.com/proceedings
[22] A. Kumar, S. Kumar, and R. Garg, "PRODUCTION & CHARACTERIZATION OF AL 2024-SIC P METAL MATRIX COMPOSITE USING STIR CASTING." [Online]. Available: www.tjprc.org

