Mechanical Characterization of Aluminum 6013-Red Mud Particulate Composites for Sustainable Structural Applications

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Editor's note: Red mud, a by-product of the Bayer process, is an abundant and eco-friendly material that can serve as a low-cost alternative for enhancing the mechanical and tribological properties of aluminum alloys. Chandrashekara K.N. et al. reinforced aluminum 6013 with red mud using liquid melt metallurgy. The results indicated that increasing the content of red mud improved various mechanical properties, including ultimate tensile strength, compressive strength, elongation, and hardness of aluminum 6013. These enhancements were attributed to factors such as particle distribution and grain refinement. The findings underscore the potential of red mud as a sustainable reinforcement material, promoting environmental sustainability in structural applications.

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Original Research

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Abstract

In this study, the mechanical characteristics of aluminum 6013-red mud particulate composites were fabricated using the liquid melt metallurgy technique. Test samples were fabricated according to ASTM standards, and their mechanical properties, including ultimate tensile strength (UTS), compressive strength (CS), percentage elongation, and Brinell hardness, were systematically evaluated. The results revealed significant improvements in the mechanical behavior with increasing red mud content. UTS increased from 67.86 MPa for the base alloy to 142.20 MPa at 6 wt.% reinforcement, while compressive strength improved from 148 MPa to 182.42 MPa. The elongation percentage also increased from 44% to 72%, indicating enhanced ductility and strain hardening. Hardness values showed a steady increase from 54.92 BHN to 70.41 BHN with higher reinforcement. The observed enhancements are attributed to the uniform particle distribution, grain refinement, dislocation strengthening, and thermal mismatch effects between the matrix and reinforcement. These discoveries validate that red mud-reinforced aluminum 6013 composites are promising materials for structural applications in automotive, aerospace, and industrial sectors. Furthermore, this study highlights the sustainable use of red mud waste as an economical reinforcement material, contributing to the circular economy and environmental sustainability.

Keywords: Aluminum 6013 composites; Red mud particulates; Metal matrix composites; Mechanical properties; Industrial waste utilization; Sustainability.

1. Introduction

The demand for lightweight, high-performance, and sustainable materials has accelerated research into aluminum matrix composites (AMCs). These materials offer an exceptional strength-to-weight ratio, stiffness, and superior wear and corrosion resistance compared to conventional alloys [1-3]. Alongside mechanical performance, environmental sustainability and cost-effectiveness are becoming crucial. This has spurred interest in using industrial by-products and agricultural

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residues as reinforcements, promoting a circular economy while enhancing composite properties. Hybrid reinforcement strategies, combining natural fibers and industrial waste, have been shown to significantly improve tensile strength, hardness, and wear resistance, making AMCs suitable for automotive, aerospace, and defense applications [4, 5].

Conventional reinforcements such as SiC, B_4C, and Al_2O_3, while effective, are costly, restricting their industrial adoption [4, 6, 7]. In contrast, red mud, an abundant industrial by-product of the Bayer process, offers a low-cost, eco-friendly alternative, improving the mechanical and tribological performance of aluminum alloys [5, 8-10]. The mechanical performance of AMCs critically depends on uniform particle distribution and strong matrix–reinforcement bonding, which governs hardness, ductility, and wear resistance [6, 11, 12]. Evidence from studies on Al_{6061}, AA_{2017}, and hybrid Al_{7075} composites demonstrates that well-integrated reinforcements significantly enhance structural performance [10, 13, 14].

Although aluminum alloys such as Al_{6061} and Al_{7075} have been widely studied [15, 16], limited work has focused on Al_{6013} reinforced with red mud particulates. Al_{6013} offers good strength, corrosion resistance, and weldability [2, 3], while red mud, a major industrial waste, enhances mechanical properties through particle strengthening and grain refinement [8-10]. In this study, Al6013 was selected because its balanced properties and heat-treatable nature enable effective tailoring of mechanical behavior through particulate reinforcement, while the limited literature on sustainable reinforcements in Al6013-based composites highlights a clear research gap. This study aims to fabricate and characterize Al_{6013}–red mud composites produced by liquid metallurgy, evaluating the effect of red mud content on tensile, compressive, and hardness properties. The results are expected to identify an optimized, lightweight, and eco-friendly composite suitable for sustainable engineering applications [7, 9, 12].

To date, no systematic study has investigated the effects of red mud reinforcement on the mechanical behavior of Al6013-based composites. Given the promising results achieved in other Al alloys [10, 11, 13, 14], and considering Al6013's suitability for high-performance applications [2, 3], this study aims to explore the mechanical, microstructural, and tribological characteristics of Al6013/red mud composites fabricated through liquid metallurgy techniques.

2. Experimental

2.1. Materials

The base metal used in this investigation was Aluminum 6013 alloy, selected for its combination of good castability, mechanical strength, and tribological performance [15-17]. This alloy is particularly suitable for lightweight and durable components in structural and automotive applications. The detailed chemical composition is provided in Table 1.

The reinforcing material chosen was red mud, a fine, industrial by-product from alumina manufacture, with the size of the particle ranging between 50–80 µm [18]. This specimen was extracted from HINDALCO, Renukoot, India.

2.2. Composite preparation

The composites were fabricated using a liquid metallurgy route (stir casting), following methods adapted from Chandrashekara et al. [19, 20]. Stir casting is a cost-effective and scalable technique for producing particle-reinforced metal matrix composites. The Al 6013 alloy was melted in a graphite crucible using an electric resistance furnace at 750 ± 10°C [21]. Red mud particles were preheated to 300°C to remove moisture, and hexachloroethane was used for degassing the molten metal. Red mud was gradually introduced into the melt under continuous stirring at approximately 500 rpm for 10 minutes to achieve uniform particle distribution. The molten slurry was poured into preheated metal molds to produce castings. Three composite variants were prepared, containing 2, 4, and 6 wt.% red mud. The homogeneity of reinforcement was confirmed using scanning electron microscopy (SEM).

Table 1. Chemical composition of Al 6013 alloy (wt.%)

Element	Al	Mg	Si	Cu	Mn	Fe	Zn	Cr	Ti
Wt.%	94.8	0.80	0.60	0.60	0.20	0.50	0.25	0.10	0.10

2.3. Measurements

After solidification, the composite castings were machined into standardized test specimens using CNC lathes. Only defect-free test bars were selected for mechanical testing. The following ASTM standards were followed: Tensile testing: ASTM E8/E8M, Compression testing: ASTM E9, Hardness testing: ASTM E10.

Tensile specimens were prepared with a 20 mm diameter, 120 mm overall length, 40 mm gauge length, and 12 mm gauge diameter. Tensile tests were conducted using an Instron 1175 universal testing machine at a crosshead speed of 0.5 mm/min, recording ultimate tensile strength (UTS) and elongation. Compression specimens were cylindrical (20 mm diameter, 20 mm height) and tested at 0.2 mm/min. Brinell hardness was measured using a 5 mm steel ball under a 500 kgf load for 30 seconds, taking multiple readings for each sample to obtain reliable averages.

3. Results and discussion

3.1. Microstructural Analysis

SEM analysis was conducted to evaluate the dispersion of red mud particles within the Al 6013 matrix and to identify any casting defects. Figures 1a–1d show micrographs of the unreinforced alloy and composites containing 2, 4, and 6 wt.% red mud. The base alloy exhibited a typical dendritic aluminum structure with intermetallic phases (Figure 1a). In the composites, red mud particulates were homogenously dispersed through the matrix (Figures 1b–d), with minimal agglomeration at lower reinforcement levels. Slight clustering was noted at 6 wt.% red mud, consistent with trends reported by Alaneme et al. [22]. No significant porosity or interfacial cracking was observed, indicating strong matrix-reinforcement bonding. The uniform particle distribution is attributed to effective stirring and preheating during fabrication, in line with previous work on ceramic-reinforced aluminum composites.

3.2. Tensile Properties

The outcomes of tensile tests are briefed in Table 2 and illustrated in Figure 2. Six samples were verified per composite type, and average values are reported. The ultimate strength (UTS) of the unreinforced Al 6013 alloy was 67.86 MPa. With the addition of 2 wt.% red mud, the UTS increased to 123.76 MPa, an 82% improvement. Further reinforcement with 4 wt.% and 6 wt.% red mud

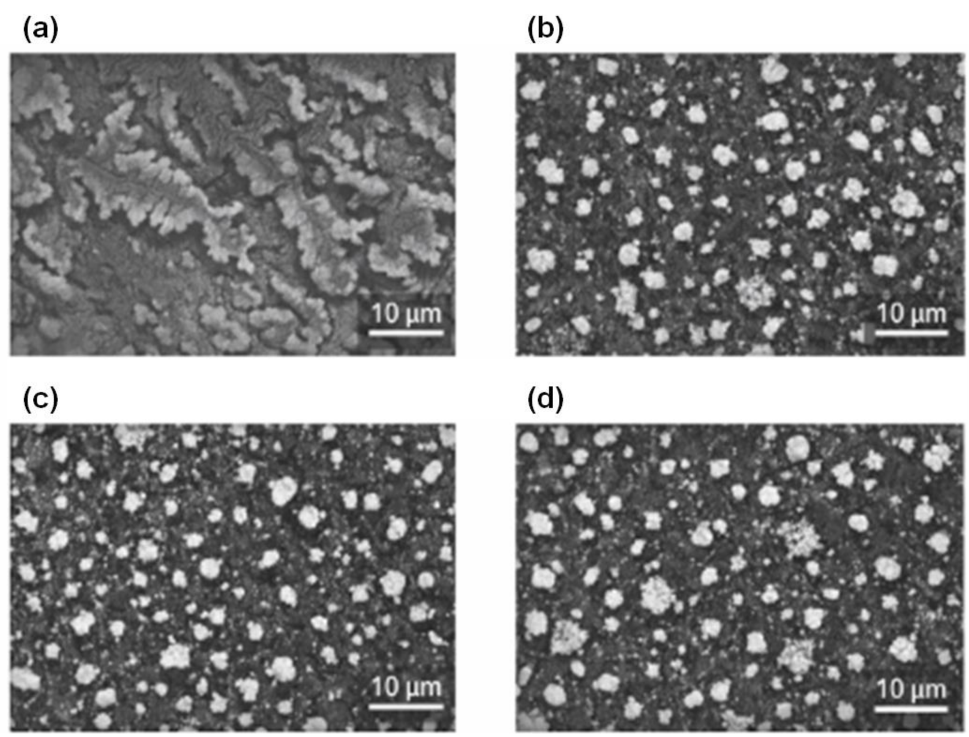

Figure 1. SEM images of: (a) Al 6013 alloy, and composites reinforced with (b) 2, (c) 4, and (d) 6 wt.% of red mud.

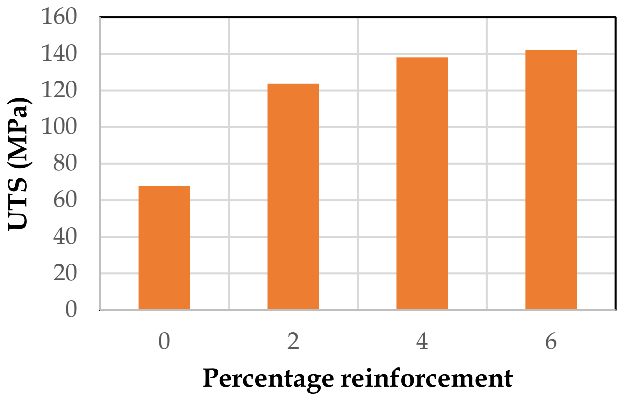

Figure 2. UTS values against reinforcement.

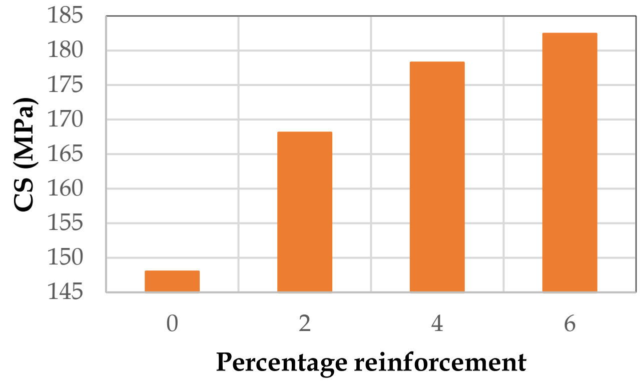

Figure 3. CS values against reinforcement.

led to UTS values of 138.10 MPa and 142.20 MPa, respectively. The improvement in tensile strength is attributed to the existence of rigid red mud particulates, which restrict dislocation motion and plastic flow; grain refinement caused by heterogeneous nucleation at ceramic interfaces; and enhanced dislocation density from the thermal mismatch between the aluminum matrix and ceramic particles [23]. These mechanisms are consistent with findings by Arzum Işıtan et al. [24], who described analogous behavior for Al 6013 reinforced with Al_2O_3 nanoparticles. A slight reduction in ductility was observed with increasing red mud content, which is a typical behavior in particle-reinforced metal matrix composites [23].

3.3. Compressive strength

The results of the compressive strength (CS) tests for Al 6013–red mud composites are shown in Table 3 and Figure 3. The average values reported were obtained from six specimens per composition. A noticeable improvement in CS was observed with increasing red mud content. The unreinforced Al 6013 alloy exhibited a CS of 148 MPa. The addition of 2 wt.% red mud raised this value to 168.1 MPa, while further increments to 4 wt.% and 6 wt.% resulted in strengths of 178.25 MPa and 182.42 MPa, respectively. This enhancement can be attributed to the load-bearing capacity provided by the rigid red mud particulates, which restrict matrix deformation under compressive loads. Moreover, the incorporation of these particles helps reduce casting defects such as microvoids and porosity, promoting a denser, more compact microstructure. Similar improvements in compressive strength with ceramic reinforcements in aluminum alloys have also been reported by Pruthviraj et al. [25].

3.4. Elongation behavior

The percentage elongation values of the Al6013–red mud composites are presented in Table 4 and Figure 4. A progressive increase in elongation was observed with increasing red mud content, which is unusual for ceramic particle–reinforced metal matrix composites, where ductility typically decreases due to particle-induced stress concentrations and embrittlement [26]. In this study, the enhanced elongation can be attributed to the uniform dispersion of fine red mud particulates, which promotes effective load transfer between the aluminum matrix and the reinforcement. Additionally,

Table 2. UTS values of matrix and composites

Specimen	Average UTS (MPa)
Matrix alloy Aluminum 6013	67.86
Aluminum 6013 + 2% Red mud particulates	123.76
Aluminum 6013 + 4% Red mud particulates	138.10
Aluminum 6013 + 6% Red mud particulates	142.20

Table 3. UTS values of matrix and composites

Specimen	Average CS (MPa)
Matrix alloy Aluminum 6013	148
Aluminum 6013 + 2% Red mud particulates	168.1
Aluminum 6013 + 4% Red mud particulates	178.25
Aluminum 6013 + 6% Red mud particulates	182.42

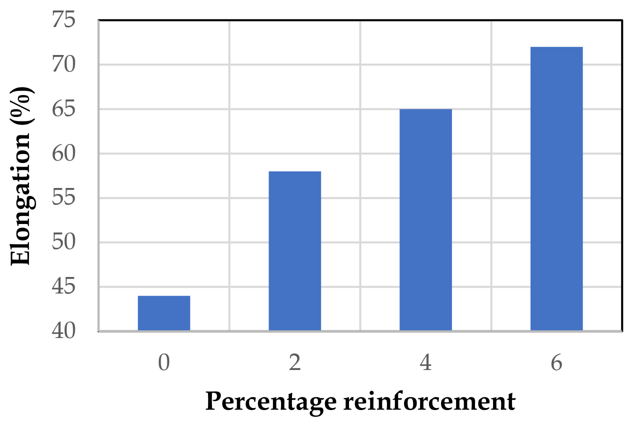

Figure 4. Elongation values against reinforcement.

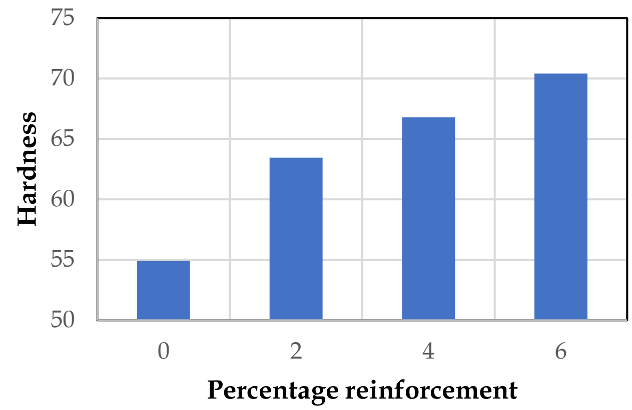

Figure 5. Hardness values against reinforcement.

the red mud particles act as sites for heterogeneous nucleation during solidification, leading to grain refinement and a more uniform microstructure. This refined microstructure facilitates uniform plastic deformation, delays localized necking, and suppresses premature crack initiation, collectively improving ductility. Moreover, the fine particle size and optimized content of red mud minimize stress concentrations and reduce the likelihood of particle clustering, which often causes embrittlement in conventional composites. Similar trends have been reported in aluminum-based composites where controlled reinforcement and proper processing resulted in simultaneous enhancement of ductility, strength, and hardness [27]. These results indicate that red mud can serve as an effective and sustainable reinforcement for Al6013 without compromising its ductility.

3.5. Hardness

Table 5 and Figure 5 display the variation in Brinell hardness (HB) with increasing red mud content in Al 6013 composites. The values represent the average of six measurements for each composition. A progressive enhancement in hardness was witnessed with the addition of red mud particulates. The unreinforced alloy exhibited a baseline hardness of ~75 HB, which steadily increased with 2, 4, and 6 wt.% red mud content. This improvement is primarily recognized due to the existence of hard ceramic phases like Fe_2O_3, TiO_2, and SiO_2 within red mud, which act as effective barriers to dislocation motion and enhance resistance to localized plastic deformation. Furthermore, the rigid particulates contribute to load sharing during indentation, thereby increasing the material's ability to withstand static loads, abrasion, and surface wear. Similar trends were reported in TiO_2-reinforced aluminum alloys and by Zhang et al. for various ceramic-reinforced MMCs. The outcomes endorse that red mud serves as a cost-effective reinforcement for improving the surface hardness of Al 6013 alloys [28].

4. Conclusions

Aluminum 6013–red mud metal matrix composites were fabricated via the liquid metallurgy method with varying red mud contents, such as 2, 4, and 6 wt.%. The accumulation of red mud particles led to significant improvements in tensile strength (~82% increase in UTS)

Table 4. Elongation values of matrix and composites

Specimen	Elongation (%)
Matrix alloy Aluminum 6013	44
Aluminum 6013 + 2% Red mud particulates	58
Aluminum 6013 + 4% Red mud particulates	65
Aluminum 6013 + 6% Red mud particulates	72

Table 5. Hardness values of matrix and composites

Specimen	Hardness
Matrix alloy Aluminum 6013	54.92
Aluminum 6013 + 2% Red mud particulates	63.45
Aluminum 6013 + 4% Red mud particulates	66.78
Aluminum 6013 + 6% Red mud particulates	70.41

and compressive strength (~23% enhancement) compared to the unreinforced alloy, primarily due to dispersion strengthening, grain refinement, and increased dislocation density arising from the thermal mismatch between the matrix and the ceramic-rich reinforcement. The Brinell hardness also increased progressively with reinforcement, as the hard phases in red mud acted as effective barriers to dislocation motion. Although a marginal reduction in ductility and durability was perceived with increasing red mud content typical for ceramic particle-reinforced composites, these values persisted within tolerable ranges for many structural applications. SEM analysis confirmed a uniform particle distribution with good interfacial bonding, contributing to the observed mechanical enhancements. This study establishes that red mud, a low-cost industrial waste, can be effectively valorized as a sustainable reinforcement for aluminum 6013 alloys, with an optimal balance of mechanical properties achieved at 4 wt.% addition, offering promising applications in automotive, aerospace, and structural components.

Conflict of Interest

The authors declare no conflict of interest.

References

1. D. Miracle. Metal matrix composites – From science to technological significance. *Composites Science and Technology*, **2005**, *65*, 2526.
2. S.C. Tjong. Novel Nanoparticle-Reinforced Metal Matrix Composites with Enhanced Mechanical Properties. *Advanced Engineering Materials*, **2007**, *9*, 639.
3. R. Dasgupta. Aluminium Alloy-Based Metal Matrix Composites: A Potential Material for Wear Resistant Applications. *ISRN Metallurgy*, **2012**, *2012*, 1.
4. M.K. Surappa. Aluminium matrix composites: Challenges and opportunities. *Sadhana*, **2003**, *28*, 319.
5. P. Samal, R.K. Mandava, and P.R. Vundavilli. Dry sliding wear behavior of Al 6082 metal matrix composites reinforced with red mud particles. *SN Applied Sciences*, **2020**, *2*, 313.
6. M. Kok. Production and mechanical properties of Al2O3 particle-reinforced 2024 aluminium alloy composites. *Journal of Materials Processing Technology*, **2005**, *161*, 381.
7. S.V. Prasad and R. Asthana. Aluminum Metal-Matrix Composites for Automotive Applications: Tribological Considerations. *Tribology Letters*, **2004**, *17*, 445.
8. K.N. Chandrashekara, et al. Corrosion Properties of Advanced Materials like Aluminium 6013 Metal Matrix Composites Reinforced with Red Mud Particulates in Acid Chloride Medium. *Asian Journal of Chemistry*, **2016**, *28*, 1770.
9. S.M. Quader, B.S. Murthy, and P. Ravinder Reddy. Processing and Mechanical Properties of Al₂O₃ and Red Mud Particle Reinforced AA6061 Hybrid Composites. *Journal of Minerals and Materials Characterization and Engineering*, **2016**, *04*, 135.
10. N.D. Chinta, N. Selvaraj, and V. Mahesh. Mechanical characterization of aluminium – red mud metal matrix composites. *Materials Today: Proceedings*, **2018**, *5*, 26911.
11. J. Hashim, L. Looney, and M.S.J. Hashmi. Particle distribution in cast metal matrix composites—Part I. *Journal of Materials Processing Technology*, **2002**, *123*, 251.
12. D.J. Lloyd. Particle reinforced aluminium and magnesium matrix composites. *International Materials Reviews*, **1994**, *39*, 1.
13. B. Geetha and K. Ganesan. Effects of Red Mud Reinforcement on Hardness, Wear Behaviour of Cast Al-6Si-0.45 Mg Alloy. *Applied Mechanics and Materials*, **2015**, *787*, 658.
14. M. Gangadharappa, et al. Corrosion behavior of Al6061 hybrid composites reinforced with red mud particles and E-glass fiber. *Materials Today: Proceedings*, **2021**, *46*, 6068.
15. A. Heinz, et al. Recent development in aluminium alloys for aerospace applications. *Materials Science and Engineering: A*, **2000**, *280*, 102.
16. M.R.W.S. Abdala, et al. Thermoelectrical power analysis of precipitation in 6013 aluminum alloy. *Materials Characterization*, **2008**, *59*, 271.
17. M. Ayvaz. Determination of the effect of artificial aging parameters on dry sliding wear resistance of 6013 aluminum alloy (Al-Mg-Si-Cu). *International Advanced Researches and Engineering Journal*, **2021**, *5*, 181.
18. S.K. Tripathy and A.K. Senapati. A review on turning analysis of industrial waste reinforced aluminum metal matrix composite. *Materials Today: Proceedings*, **2020**, *33*, 5740.
19. N. Panwar, et al. Fabrication of Aluminum 6061 Red-mud Composite using Stir Casting and Micro Structure Observation. *Materials Today: Proceedings*, **2020**, *21*, 2014.
20. J. Hashim, L. Looney, and M.S.J. Hashmi. Metal matrix composites: production by the stir casting method. *Journal of Materials Processing Technology*, **1999**, *92-93*, 1.

21. G. Siva Karuna, S.V.G. Swamy, and G.S. Naidu. Effect of Blast Furnace Slag and Red Mud Reinforcements on the Mechanical Properties of AA2024 Hybrid Composites. *Advanced Materials Research*, **2018**, *1148*, 29.

22. K.K. Alaneme and M.O. Bodunrin. Corrosion Behavior of Alumina Reinforced Aluminium (6063) Metal Matrix Composites. *Journal of Minerals and Materials Characterization and Engineering*, **2011**, *10*, 1153.

23. J. Singh and A. Chauhan. Fabrication characteristics and tensile strength of novel Al2024/SiC/red mud composites processed via stir casting route. *Transactions of Nonferrous Metals Society of China*, **2017**, *27*, 2573.

24. A. Işıtan, S. Aytekin, and V. Onar. Enhancing the Microstructure and Mechanical Properties of Cast Aluminum Matrix Composites Through Nano-Al2O3 Reinforcement via CMT and PMC Welding. *International Journal of Metalcasting*, **2024**, *18*, 3166.

25. D.R. Ramya and R.D. Pruthviraj. Mechanical behaviour of As-Cast and Heat-Treated: AA2024 Alloy Silicon Carbide-Al2O3 Hybrid Composites. *Bulletin of Pure & Applied Sciences-Chemistry*, **2020**, *39c*, 56.

26. Y.-y. Chen, et al. Enhancing strength–ductility synergy of AlNp/Al composite by regulating heterostructure of matrix grain and particle distribution. *Transactions of Nonferrous Metals Society of China*, **2024**, *34*, 1049.

27. D. Mao, et al. Strength-ductility balance strategy in SiC reinforced aluminum matrix composites via deformation-driven metallurgy. *Journal of Alloys and Compounds*, **2022**, *891*, 162078.

28. H. Pi, et al. Microstructure, Hardness and Corrosion Resistance of Al-TiC MMC Prepared by Laser Cladding on AZ31B Magnesium Alloy. *Coatings*, **2024**, *14*, 211.
