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Developing and Characterization of Aluminum 6063 Reinforced with Electric Arc Furnace Slag

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Abstract

This work aims to fabricate an aluminum composite reinforced with disposal/waste industrial reinforcement slag as a filler material instead of the usual expensive industrial ceramic reinforcements such as SiC, Al_2O_3, and Ti_2O. Optimized processes were performed to produce 6063 aluminum metal matrix composites reinforced with an electric arc furnace with a slag weight percentage of 5 wt.% by a stir casting technique and subsequent hot-rolling. The SEM images show that the EDFS powder was dark grey with irregular and subregular sharp particles. The XRD of EDFS powders reveals the presence of intermetallic compounds. Comparative morphological, hardness, and tensile tests were studied, and it was noticed that the strength and hardness of eco-aluminum composite produced using an electric arc furnace slag exhibited comparable strength and hardness results to unreinforced aluminum samples. The microstructure images show low porosity and confirm the presence of particles. The hardness and tensile strength of the composite were enhanced, reaching 71 HV and 162.5 MPa, respectively.

Keywords: Electric Arc Furnace Slag; Aluminium metal matrix composites; Stir Casting; Hot Rolling.

1. Introduction

Aluminum Metal Matrix Composites (AMMCs) with micro or nano reinforcements are becoming highly promising materials in several applications, such as lightweight vehicles, aerospace, electronics, space shuttles, and biomedical and automotive applications. This is due to their favorable properties: low density, high stiffness, strength-to-weight ratio, controlled thermal expansion coefficient, high fatigue resistance, superior dimensional stability at elevated temperatures, and high wear and corrosion resistance [1].

Aluminum matrix composites (AMCs) offer good mechanical and physical properties, while the matrix, reinforcement, and interface between the matrix and reinforcement are the constituent parts of a composite. The AMCs are fabricated by the dispersion of reinforcement material, such as ceramic particles or fibers, within an aluminum matrix [2].

Stir casting is one of the most popular, promising, low-cost, sustainable fabrication processes for producing AMMCs. This liquid state approach is widely utilized because of its ease of use, versatility, affordability, and simple equipment preparation, all of which facilitate industrial mass production [3].

During AMMC processing, achieving a homogenous reinforcement distribution is complex, greatly impacting the properties. For good mechanical and physical properties, the particles should be dispersed uniformly in the matrix with firm solid/liquid boundaries during solidification [4].

Due to different casting techniques, subsequent processing, such as the rolling process, is widely used as a secondary process. The rolling process strengthens the composites by rapid plastic deformation, which enhances mechanical properties [5].

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Electric Arc Furnace Slag (EAFS) by-products are now recycled as supplementary secondary raw materials in the road or construction sector, like cement concrete, bricks, asphalt ceramics, and other applications [6,7]. Adding EAFS waste to new materials is considered an affordable, economical, and effective way of by-product recycling, allowing the development and enhancement of industries while minimizing negative environmental impacts [7]. Previous research has recently proven that EAFS improved the radiation shielding ability in the cement-marble industry [8].

This study shows the potential of utilizing sustainable MMCs by developing a novel approach incorporating EAFS as a reinforcement material in 6063 aluminum alloy. A comprehensive morphological and mechanical analysis of the composites was conducted, demonstrating the feasibility of using EAFS as an alternative to traditional reinforcement materials and sustainable replacement that aligns with economic and environmental objectives. This work studied the microstructural, physical, and mechanical properties of AA6063 alloy and AA6063 reinforced with 5 wt% EAFS in cast and rolled conditions.

2. MATERIALS AND FABRICATION METHODS

The matrix in this study is Aluminum AA6063 (Al-Mg-Si type). Table 1 illustrates the chemical analysis of the AA6063 alloy.

EAFS was supplied from Ezz Steel Factory, collected, in Table 2, and subjected to a milling process to reduce particle size. The milling process was carried out using a ball mill, with a ball-to-powder ratio of 5:1, at a speed of 30 rpm for one hour. The resulting powder was sieved through a 200-mesh sieve to obtain particle sizes below 75 µm. EAFS was preheated at 320ºC for three hours before introducing the molten matrix alloy to remove moisture and ensure good wettability between slag particulates and aluminum alloy.

A 1.5km AA6063 alloy charge was introduced into a crucible and heated to 750ºC for 2-3 hours to allow rapid melting and minimize oxidation during the melting process. The melt was degassed with argon gas to degas the melt and prevent atmospheric reactions. During the casting process, 1% wt. of Mg was added during casting to enhance wettability. Five wt.% of EAFS powders were introduced into the aluminum melt, and a mechanical stirring process was performed to ensure homogeneous, uniform particle distribution. The composite slurry was poured horizontally into a preheated stainless-steel mold and allowed to cool naturally in the air. The casted sample was first homogenized at 450°C, followed by an initial rolling pass. Subsequently, the sample was subjected to additional rolling passes, achieving a total reduction ratio of 75%. A standard AA6063 sample was taken as a reference—the composite, hereafter abbreviated to AA6063/5%EAFS composite.

SEM images and EDX analysis of the slag powder were analyzed using a Scanning electron microscope QUANTA FEG 250, revealing particle shape, size, and distribution. Vickers micro-hardness tester was used to test the hardness values of the cast/rolled composites. The hardness load was 98 N with 15 second dwell time at 25 °C. The tensile strengths of the composite materials were determined on flat dog bone-shaped specimens of 2.5 mm thickness and 25 mm gauge length using a Universal Testing Machine (UTM). The fractography of the tensile test samples was examined using SEM.

Table 1 Chemical analysis in wt. % of AA6063 alloy using Spectrometric analysis.

Element	Si	Fe	Cu	Mn	Cr
Measured	0.472	0.457	0.051	0.065	0.010
Element	Zn	Ti	Ni	Al	-
Measured	0.071	0.015	0.003	Bal.	-

Table 2 Chemical analysis in wt. % of Electric arc furnace slag using EDX analysis.

Fe	Al	Ca	Mg	Si	Mn
36.99	2.42	27.38	1.94	4.64	2.46
O	C	Ti	Cr	-	-
20.6	2.49	0.17	0.93	-	-

3. RESULTS AND DISCUSSION

3.1 Morphological Analysis

Fig. 1 illustrates the SEM image of EAFS particulates at low and high magnifications, showing dark grey color and irregular or subregular sharp particles with non-uniform shapes. The images show that the mean particle size of EAFS particulates is 2.32 µm, with a small amount of large particles (<38 µm). The shape of the particles may be due to the effect of shear influence during the ball milling process. The shear influence led to a variable range of shapes, surface textures, and particle sizes of slag particulates. Fig. 2 and Table 3 illustrate the XRD pattern and analysis of EAFS particulates, which include compound names, chemical compositions, and weight % of the constituent compounds. The XRD analysis indicates that several phases exist in electric arc furnace slags. Some of these are larnite (Ca_2SiO_4), calcium silicate, magnesium manganese oxide, $[(Mg_{0.629}Mn_{0.371})((Mg_{0.371}Mn_{1.629})O_4)]$,wüstite (FeO),

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grossular ($Ca_3Al_2(SiO_4)_3$), and brownmillerite ($Al_{0.55}Ca_2Fe_{1.45}O_5$). The presence of calcium silicates and iron oxide phases can enhance the mechanical properties of aluminum metal matrix composites [9,10].

Fig. 3 (a and b) presents the optical micrographs of the AA6063 alloy in stir-cast and after a 75% reduction in thickness by hot rolling condition. Fig. 3a shows the typical microstructure of stir-cast AA6063 alloy, characterized by relatively large porosity. In contrast, Fig. 3b illustrates the microstructure of a hot-rolled AA6063 alloy characterized by low porosity.

Fig. 3c presents the microstructure of AA6063/5% EAFS composite after stir casting condition. The porosities and agglomerations of EAFS particulates were observed, which can be attributed to the addition of slag particulates to the aluminum matrix. The clusters of EAFS particles were dispersed throughout the aluminum matrix with sharp and irregular dark particulates.

Fig. 3d illustrates the microstructure of the AA6063/5% EAFS composite after hot rolling. The EAFS particulates were uniformly distributed and aligned in the rolling direction, with low voids or porosities, which is expected to enhance the mechanical and physical properties of the composites.

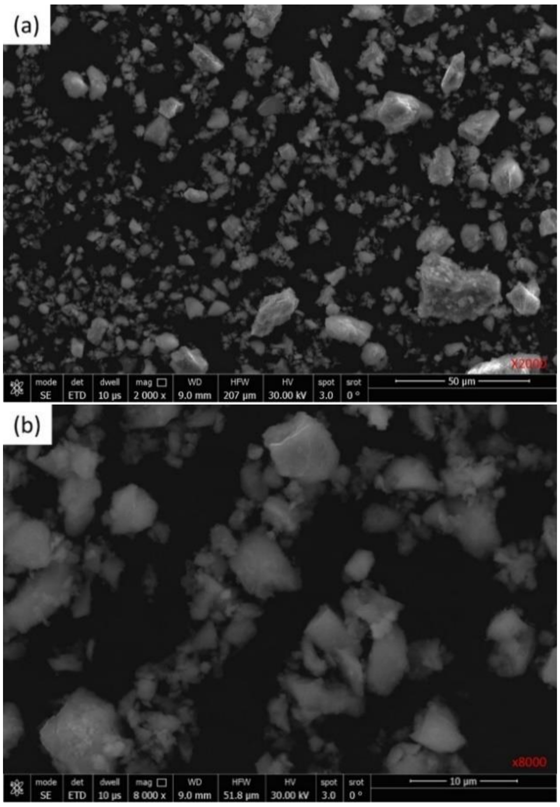

Fig. 1 (a, b) SEM image of EAFS particulates with different magnifications.

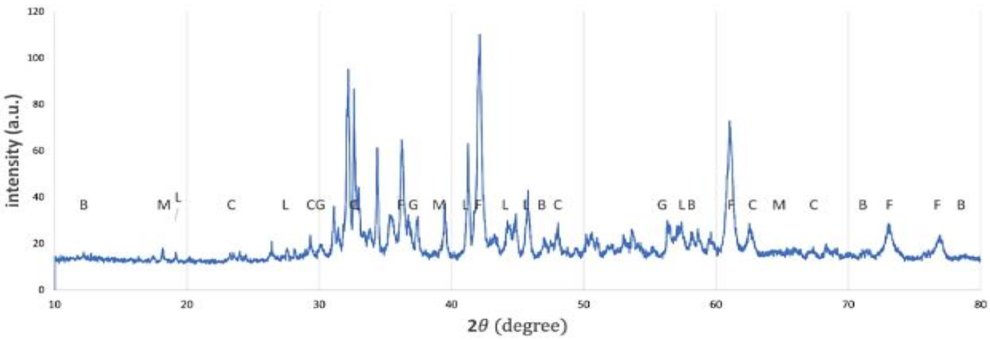

Fig. 2 XRD pattern of EAFS particulates.

Table 3 XRD analysis of EAFS particulates.

Name	Chemical Composition	Wt.%	Label in the XRD pattern
Larnite	Ca_2SiO_4	42.4	L
Magnesium Manganese Oxide	$(Mg_{0.629}Mn_{0.371})((Mg_{0.371}Mn_{1.629})O_4)$	11.5	M
Calcium Silicate	Ca_2SiO_4	24.1	C
Wüstite	FeO	10.9	F
Grossular	$Ca_3Al_2(SiO_4)_3$	5.1	G
Brownmillerite	$Al_{0.55}Ca_2Fe_{1.45}O_5$	6.0	B

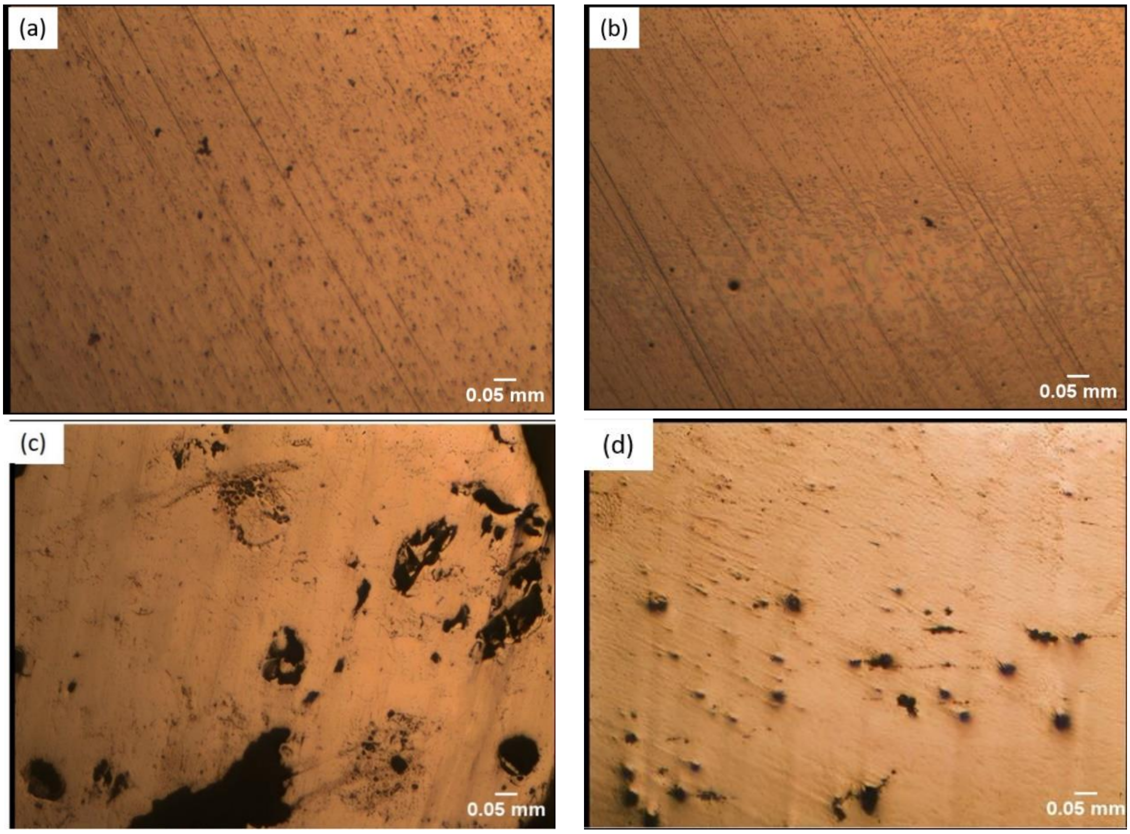

Fig. 3 Optical Micrographs of (a) stir cast AA6063 alloy, (b) Hot Rolled AA6063, (c) stir cast AA6063/5%EAFS composite and (d) hot Rolled AA6063/5%EAFS composite.

3.2 Physical properties

Table 4 compares the average density of the AA6063 alloy, unreinforced (0% EAFS), and AA6063/5% EAFS composite in stir cast and after a reduction of 75% in thickness by hot rolling. The density of standard AA6063 alloy was 2.714 gm/cm^3, while the density of stir cast and rolled AA6063 samples was 2.700 and 2.702 gm/cm^3, respectively. The negligible change in density from the standard alloy indicates a favorable stir-casting process. However, the density of stir-cast AA6063/5% EAFS composite decreased to 2.435 gm/cm^3, even though EAFS particulates possess a higher density than aluminum alloy, indicating porosity formation. Upon rolling, the density of the AA6063/5% EAFS composite increased by 10.7 % compared to the stir-cast AA6063/5% EAFS composite, indicating reduced porosity. The AA6063 alloy and AA6063/5% EAFS composite samples subjected to the hot rolling process had lower porosity percentages due to the effect of applied pressure during the deformation process.

3.3 Mechanical Properties

Table 4 compares the hardness, tensile strength, and elongation values of AA6063 aluminum alloy, unreinforced (0% EAFS), and AA6063/5% EAFS composite in stir cast and after a 75% thickness reduction by hot rolling.

The hardness of standard 6063 aluminum alloy was 53 HV, while the hardness of stir-cast and hot-rolled AA6063 samples was 30 and 60 HV, respectively. This increase in hardness can be attributed to the strengthening of the precipitates.

For AA6063/5%EAFS composite, the stir cast and hot rolled hardened to 41 and 71 HV, respectively. The results indicate that the hardness values of the samples subjected to the hot rolling process were higher than those obtained from the stir casting process. The enhancement in hardness is likely due to the direct strengthening effect of the uniform distribution of EAFS particulates. Additionally, as previously noted, the porosity of the hot rolled samples was decreased, which directly affected the hardness value of the composite.

Fig. 4 presents the engineering stress-strain curves of hot-rolled AA6063 alloy and hot-rolled AA6063/5% EAFS composite. Two tensile samples were used in the tensile strength test, and their average value was calculated. The tensile strength of hot rolled unreinforced AA6063 samples was 130 MPa. After hot rolling of AA6063/5% EAFS composite, the tensile strength increased to 162.5 MPa, representing a 2.5% enhancement. The observed trend in tensile strength follows the previously discussed hardness trend, which proves the stir-casting process's effectiveness, allowing an effective load transfer between the slag particulates and the aluminum alloy [11]. The hot rolling process promotes plastic deformation, which reduces porosities and lowers reinforcement agglomerations, increasing the surface area between slag particulates and the aluminum matrix, as proved by the microstructural analysis and porosity percentages.

The elongation percentage decreased from 9.3% for the hot-rolled AA6063 unreinforced to 7% for the rolled AA6063/5% EAFS composite, representing a 24.7% reduction. This decrease in elongation may be attributed to the stress concentrations around EAFS particulates or void nucleation at the interfaces between particles and matrix, which inhibit the material's plastic deformation ability [12].

The experimental results in this study were compared with those of Al alloys reinforced by EAFS fabricated by different processes, as reported in different published papers. For example, Flores-Vélez et al. [13] reported that the hardness was enhanced from 50 HV for sintered pure Al to around 65 HV for sintered pure Al reinforced by 5 wt.% EAFS reached around 74 HV for sintered pure Al reinforced by 10 wt.% EAFS. However, the authors reported that the hardness decreased to around 55 HV after adding 20 wt.% EAFS particulates. The authors related this decrease to the porosity and agglomeration of EAFS particles. Soares et al. [14] claimed the potential of producing dense samples of AA7075 alloy reinforced by EAFS particles using the Spark Plasma Sintering technique. The results revealed that the hardness was 108 HV for AA7075 alloy and increased by 56%, reaching 168 HV after adding 15 wt.% of EAFS with a particle size less than 53 µm. The authors claimed this improvement strengthened the mechanism of oxide dispersion. Alves et al. [14] fabricated AA7075 aluminum alloy powder and 5 wt.% EAFS powder using a powder metallurgy technique. The results revealed that adding 5 wt.% of EAFS increased the hardness of AA7075 alloy from 85 HV to 125 HV, and this improvement was related to the presence of iron and zinc oxides. Adeosun et al. [15] concluded that the subsequent cold rolling of cast Al 6063 and steel slag composites improved the mechanical properties. For instance, in the Al 6063 matrix reinforced by 20 wt.% steel slag, the tensile strength and hardness were 76 MPa and 38 HRC, respectively, for as-cast condition, compared to 86.8 MPa and 48 HRC for cold rolled condition. The results contributed to grain refinement and intermetallic compound distribution.

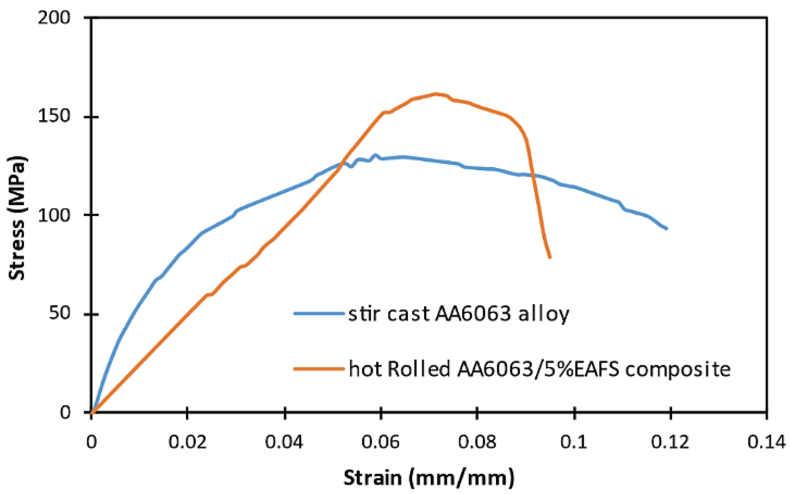

Fig. 4 Typical stress-strain curve of hot rolled AA6063 alloy and (c, d) hot rolled AA6063/5%EAFS composite.

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Table 4 Density, Voids%, Hardness, Tensile strength, and Elongation of 6063 measured as a reference, 0% EAFS slag, and AA6063/5%EAFS composite

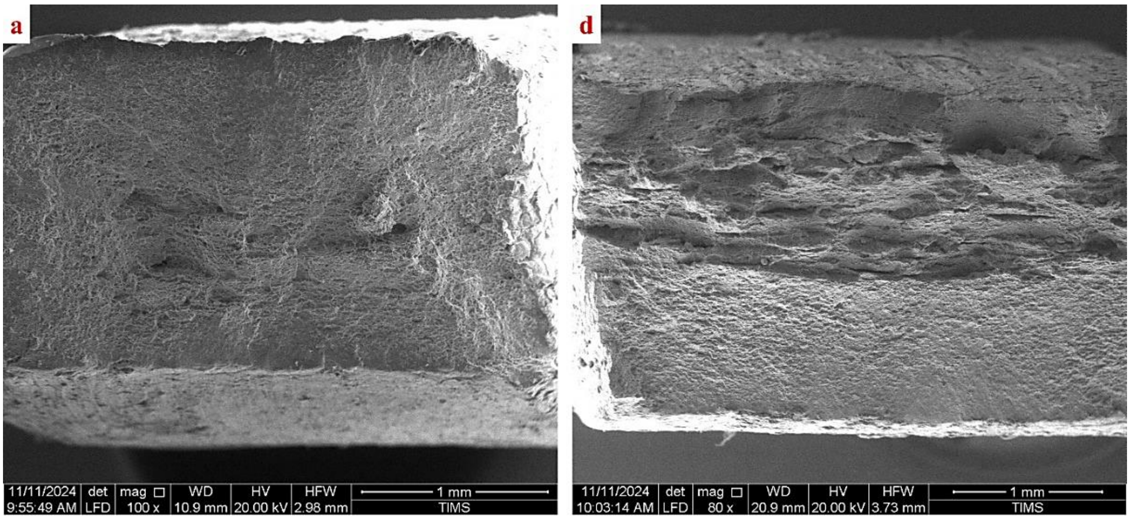
	Density (gm/cm^3)	Voids (%)	Hardness (HV)	Tensile strength (MPa)	Elongation (%)
AA6063 alloy	2.714	-	53	-	-
stir-Cast AA6063 alloy	2.7	0.5	30	-	-
Stir cast AA6063/5%EAFS composite	2.438	11.9	41	-	-
Hot Rolled AA6063 alloy	2.702	0.4	60	130	9.3
Hot rolled AA6063/5%EAFS composite	2.699	2.5	71	162.5	7.1

3.4 Fractography

Fractography analysis can help understand the fracture behavior of composites. Fig. 5 shows the tensile fractography of hot-rolled AA6063 aluminum alloy and AA6063/5% EAFS composite at different magnifications. The matrix alloy AA6063 fracture surface depicts fine, deep equiaxed dimples and micro-voids, which indicate the ductile behavior of the rolled alloy as a result of the plastic deformation that happened before failure; the same behavior had been observed by Y. Pazhouhanfar et al. [16].

The fracture surface of the AA6063/5% EAFS composite indicates a more complex morphology, showing a mixed mode of both brittle and ductile fractures. The introduction of slag particulates into the aluminum matrix alloy acts as a stress concentration region. The fractography analysis supports the tensile strength test results, confirming the improvement in the mechanical strength of the aluminum matrix.

Fig. 6 shows the EDX analysis of the hot rolled unreinforced AA6063 alloy and the AA6063/5% EAFS composite. The EDX analysis of the unreinforced aluminum alloy revealed the presence of key elements such as Al, Si and Fe. At the same time, the reinforced composite showed a notable increase in weight concentrations of Si, Fe, and Cu, especially the iron content, which confirms the incorporation of slag particulates within the aluminum matrix. The results are compatible with the EDX analysis of the aluminum alloy and slag powder in Table 1 and Table 2.



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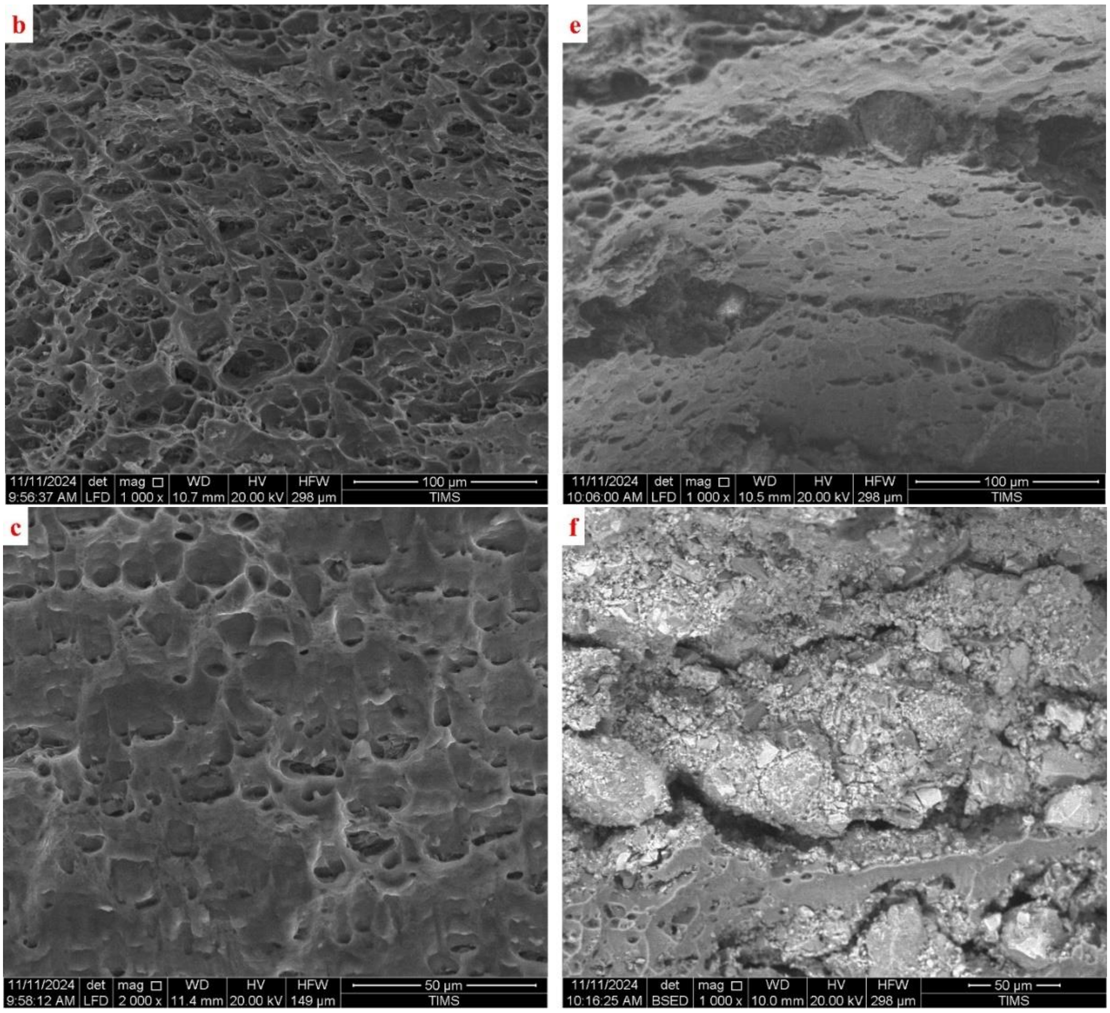
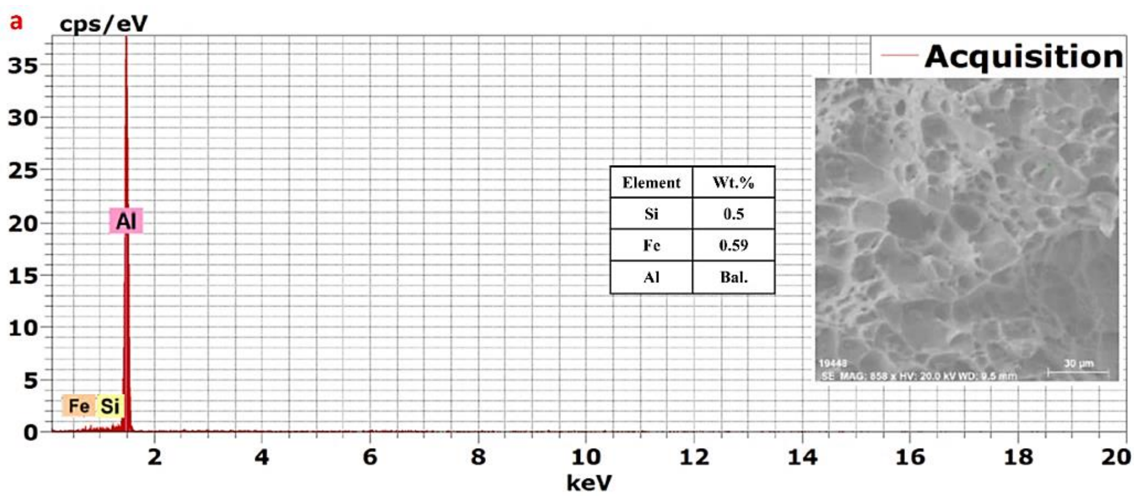


Fig. 5 SEM micrographs of the tensile fractography of (a, b, c) hot rolled AA6063 alloy and (d, e, f) hot rolled AA6063/5%EAFS composite.



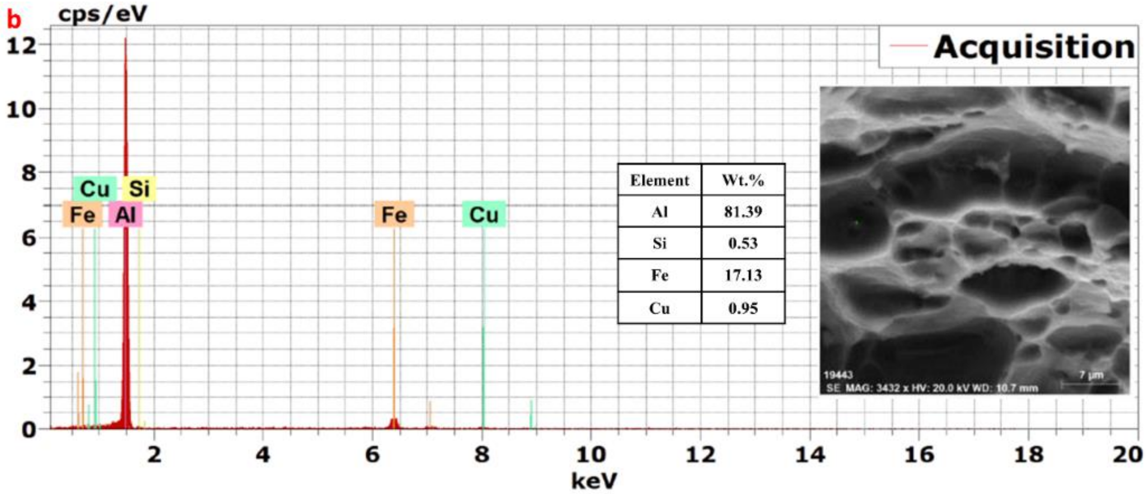


Fig. 6 EDX analysis of (a) hot rolled AA6063 alloy, and (b) hot rolled AA6063/5%EAFS composite.

4. Conclusions

- EAFS particulates were successfully incorporated into the AA6063 matrix, while agglomerations and particle clusters were observed in the stir-cast condition. The reduction of 75% in thickness by the hot rolling process significantly improved the properties, leading to void elimination and uniform particle distribution.
- Due to porosity formation, the density decreased after adding 5% EAFS to the AA66063 matrix. After the hot-rolling process, the density of AA6063/5% EAFS composite increased by 10.7 % compared to the stir-cast condition, which indicated a reduction of voids.
- Adding 5 wt.% EAFS to AA6063 matrix enhanced the hardness in the stir-cast and rolled conditions. The hardness was enhanced and reached 71 HV for the A6063/5% EAFS composite, which can be attributed to precipitate strengthening.
- The tensile strength of hot-rolled AA6063/5% EAFS composite was 162.5 MPa and improved by 2.5% compared to the unreinforced alloy after hot rolling. The elongation decreased by 24.

References

[1] A. Kumar, V.P. Singh, R.C. Singh, R. Chaudhary, D. Kumar, A.H.I. Mourad, A review of aluminum metal matrix composites: fabrication route, reinforcements, microstructural, mechanical, and corrosion properties, J. Mater. Sci. 59 (2024) 2644–2711. https://doi.org/10.1007/s10853-024-09398-7.

[2] L. Bhanuprakash, N. Manikandan, L. Varghese, J. Joseph, Study on aluminum metal matrix composites reinforced with SiC and granite powder, Mater. Today Proc. (2023). https://doi.org/10.1016/j.matpr.2023.06.246.

[3] C.G.M. Ravichandran, Investigations on Mechanical and Wear Properties of Molybdenum Trioxide-Reinforced Aluminum Alloy (AA7075) Matrix Composites Produced via Stir Casting Process, Arab. J. Sci. Eng. 48 (2023) 3021–3040. https://doi.org/10.1007/s13369-022-07059-y.

[4] A. Fadavi Boostani, S. Tahamtan, Z.Y. Jiang, D. Wei, S. Yazdani, R. Azari Khosroshahi, R. Taherzadeh Mousavian, J. Xu, X. Zhang, D. Gong, Enhanced tensile properties of aluminum matrix composites reinforced with graphene encapsulated SiC nanoparticles, Compos. Part A Appl. Sci. Manuf. 68 (2015) 155–163. https://doi.org/10.1016/j.compositesa.2014.10.010.

[5] R. Vasanth Kumar, R. Keshavamurthy, C.S. Perugu, M. Alipour, C. Siddaraju, Influence of hot rolling on friction and wear behaviour of Al6061-ZrB2 in-situ metal matrix composites, J. Manuf. Process. 69 (2021) 473–490. https://doi.org/10.1016/j.jmapro.2021.07.058.

[6] P. Sukmak, G. Sukmak, P. De Silva, S. Horpibulsuk, S. Kassawat, A. Suddeepong, The potential of industrial waste: Electric arc furnace slag (EAF) as recycled road construction materials, Constr. Build. Mater. 368 (2023). https://doi.org/10.1016/j.conbuildmat.2023.130393.

[7] A.T. Nair, A. Mathew, A. A R, M.A. Akbar, Use of hazardous electric arc furnace dust in the

construction industry: A cleaner production approach, J. Clean. Prod. 377 (2022) 134282. https://doi.org/10.1016/j.jclepro.2022.134282.

[8] A.M. El-khatib, M.I. Abbas, M.A. Elzaher, M. Anas, M.S. Abd, E. Moniem, M. Montasar, E. Ellithy, M.T. Alabsy, A New Environmentally Friendly Mortar from Cement , Waste Marble and Nano Iron Slag as Radiation Shielding, (2023).

[9] Z. Nissar, A. Kazi, M. Safiulla, M. Faisal, A Thorough Study: In-Situ Aluminium LM6 Metal Matrix Composites Reinforced with Iron Oxide and MWCNTs, Mater. Today Proc. 4 (2017) 11999–12006. https://doi.org/10.1016/j.matpr.2017.09.122.

[10] C. Engineering, albino rats Pr ep rin t n ot pe er re vie we Pr rin t n ot pe er re vie we, 1 (2019) 33–40.

[11] D. Sreeram, R. Pugazhenthi, G. Anbuchezhiyan, R. Saravanan, K. Veeranjaneyulu, An investigation of the effects of hot rolling on the microstructure and mechanical behavior of nano-sized SiC particulates reinforced Al6063 alloy composites, Mater. Today Proc. 64 (2022) 731–736. https://doi.org/10.1016/j.matpr.2022.05.197.

[12] Z. Li, Y. Zhang, H. Xiong, C. Kong, H. Yu, Fabrication of particle-reinforced aluminum alloy composite: role of casting and rolling, Mater. Manuf. Process. 37 (2022) 90–98. https://doi.org/10.1080/10426914.2021.1944198.

[13] L.M. Flores-vélez, J. Chávez, L. Hernández, O. Domínguez, CHARACTERIZATION AND PROPERTIES OF ALUMINUM COMPOSITE MATERIALS PREPARED BY POWDER METALLURGY TECHNIQUES USING CERAMIC SOLID WASTES ALUMINUM COMPOSITE MATERIALS PREPARED BY POWDER METALLURGY, 6914 (2007). https://doi.org/10.1081/AMP-100103693.

[14] E.O. Alves, D.R. Araújo Amaro, E.C. de Oliveira Silva, O.O. de Araújo Filho, K.G. Bezerra Alves, Study on effect of EAFD particulate reinforcement in AA7075 aluminum matrix composites, Mater. Res. 21 (2018). https://doi.org/10.1590/1980-5373-MR-2017-0779.

[15] S.O. Adeosun, E.I. Akpan, O.I. Sekunowo, W.A. Ayoola, S.A. Balogun, Mechanical Characteristics of6063 Aluminum-Steel Dust Composite, ISRN Mech. Eng. 2012 (2012) 1–9. https://doi.org/10.5402/2012/461853.

[16] Y. Pazhouhanfar, B. Eghbali, Microstructural characterization and mechanical properties of TiB2 reinforced Al6061 matrix composites produced using stir casting process, Mater. Sci. Eng. A. 710 (2018) 172–180.