

Development of Composite Materials Reinforced with Hybrid GNP and B₄C

Melik ÇETİN

Karabük University

Hayrettin AHLATÇI

Karabük University

Kenza DJEBARI

Karabük University

To Cite This Chapter:

Çetin, M., Ahlatci, H., & Djebari, K. (2025). Development of composite materials reinforced with hybrid GNP and B₄C. In H. Gokmese, S. Bulbul, & Y. Uzun (Eds.), *Innovative approaches in materials science and applications* (pp. 104–127). ISRES Book Series. ISRES Publishing.

Introduction

Composite materials hold a significant position in modern industry due to their high hardness-to-density and strength-to-density ratios. These materials are widely used in sectors where weight is critical, such as the aerospace and aviation industries. The high efficiency and performance enhancement provided by composite structures have rendered them indispensable in these fields (Liu et al., 2016).

In practical applications, randomly oriented particle-reinforced metal matrix composites (MMCs) are frequently preferred. The primary reason for this preference is the desire to obtain isotropic properties (Miyazaki et al., 2004). MMCs combine the ductility and toughness of metals with the high strength of ceramics, enabling their use in essential engineering applications (Asthana et al., 2006). Particle reinforcement is an effective method for improving the mechanical properties of composites, providing a noticeable increase in strength compared to the unreinforced metal matrix.

Although the production of composite materials generally involves liquid-state processes such as casting, solid-state techniques, including powder metallurgy, have been gaining increasing importance (Del Monte et al., 1999). With recent technological advancements, there has been a shift from traditional methods toward advanced manufacturing techniques, and powder metallurgy has become particularly prominent in the fabrication of particle-reinforced MMCs (Ma et al., 2020; Zhang et al., 2020). However, the oxidation-sensitive nature of Mg and Mg-based alloys remains a critical factor that increases production costs (Blawert et al., 2004).

Among the expected properties of composite matrix materials are low density, corrosion resistance, fracture toughness, and compatibility with the reinforcement phases. While the matrix transfers the applied load to the reinforcing phases, it also protects them from corrosive environmental effects and limits the propagation of brittle cracks. Therefore, the matrix material plays a critical role in the mechanical and thermomechanical performance of composite structures.

Light metals are frequently chosen as matrix materials due to their high toughness and excellent mechanical properties. Owing to its low density, magnesium (Mg) has gained prominence in modern lightweight structural design (Monticelli et al., 2019). In armoured vehicles, mobility and multidirectional manoeuvring capability are closely associated with the use of lightweight materials. For this reason, Mg alloys are increasingly preferred in armor systems that require high ballistic resistance (Alaneme et al., 2021; Luo et al., 2013). In recent years, Mg alloys have become increasingly competitive with Al alloys, offering environmentally friendly and efficient solutions for engineering applications where weight reduction is critical (Liu et al., 2024). Mg provides strength levels close to those of Al while offering advantages in many fields due to its lightweight nature combined with adequate strength (Alaneme et al., 2021; Liu et al., 2024).

Aluminium and its alloys are widely used in automotive, aerospace, construction, and energy sectors owing to their high corrosion resistance, low density, and favourable mechanical properties. Aluminium matrix composites (AMCs) are distinguished by their high specific strength and hardness, as well as their superior wear and temperature resistance. The Al5754 alloy is particularly known for its high ductility, strength, and corrosion resistance; however, it may be susceptible to certain forms of corrosion under harsh environmental conditions, such as marine atmospheres. Ceramic reinforcements such as B_4C and GNP (graphene nanoplatelets) are commonly incorporated into AA5754 matrix composites, offering advantages including high melting temperatures, low densities, and high elastic moduli.

However, incorporating GNP into an Al matrix is quite challenging due to wetting difficulties. Although the literature includes studies on GNP reinforcement in Mg-based composites, research on GNP reinforcement in AA5754 remains limited (Zhang et al., 2020; Zhang et al., 2017; Prakash et al., 2011). This study aims to investigate the structural characteristics of nano-sized ceramic-reinforced composites based on the Al5754 matrix, thereby addressing this gap in the literature and enhancing the commercial application potential of these materials. In this study, the Al5754 alloy was reinforced with various proportions of GNP, B_4C , and GNP+ B_4C mixtures. The composites were produced via the stir-casting method, cold-rolled to 30%, and subsequently subjected to a recrystallization heat treatment.

Materials and Methods

The Al5754 Al–Mg wrought alloy, whose chemical composition is given in Table 1, was procured as plates from SEYKOÇ ALUMINIUM. The initial quantities of the reinforcements (GNP and B₄C) used for producing the composites namely Al5754+0.5% GNP, Al5754+0.5% GNP+15% B₄C, Al5754+1% GNP+15% B₄C, and Al5754+15% B₄C are presented in Table 2. Before induction melting, the nano-sized carbon GNP and B₄C ceramic reinforcements were mixed both dry in a V-type ball mixer and magnetically ultrasonically in alcohol. The steps of the homogeneous mixing process are shown in Figure 1. Finally, to ensure complete removal of ethanol from the system, the mixed powders were placed in a furnace at a controlled temperature and dried for 12 hours. The prepared GNP- and B₄C-containing mixtures were then pressed in a 30-ton capacity hydraulic press at 350 °C to form compacts of 32×30 mm diameter within a mold, and these compacts were partially sintered at 500 °C for 3 hours.

Together with the sintered compacts, the Al5754 Al–Mg alloy (initial masses provided in Table 2) was melted in an S6 gas-shielded induction melting furnace using an alumina-lined graphite crucible, and the stir-casting method was applied to ensure homogeneous incorporation of the added reinforcements. The melt was poured into rectangular steel molds preheated to 300 °C, with dimensions of 35×25×200 mm as shown in Figure 2(b), producing the as-cast AA5754 alloy and the Al-matrix GNP- and B₄C-reinforced composites. The cast composites were then wrapped in Al foil and subjected to a homogenization heat treatment at 490 °C for 5 hours in an atmosphere containing B₄C and graphite powders.

Table 1

Chemical composition of Al5754 alloy.

Alloy	Mg	Mn	Si	Cr	Fe	Al
Al 5754	3.650	0.526	0.349	0.112	0.348	Rest.

Table. 2

The amount (in grams) of carbon- and ceramic-reinforced Al5754 matrix composites produced in this study.

Alloy	GNP (g)	B ₄ C (g)	Gd-Nd (g)	AA5754 (g)
Al+%0,5GNP	5	0	10	985
Al+%0.5 GNP+%15 B ₄ C	5	150	10	835
Al+%1 GNP+%15 B ₄ C	10	150	10	830
Al+%15 B ₄ C	0	150	10	840

Figure 1

Preparation process of powder mixtures.

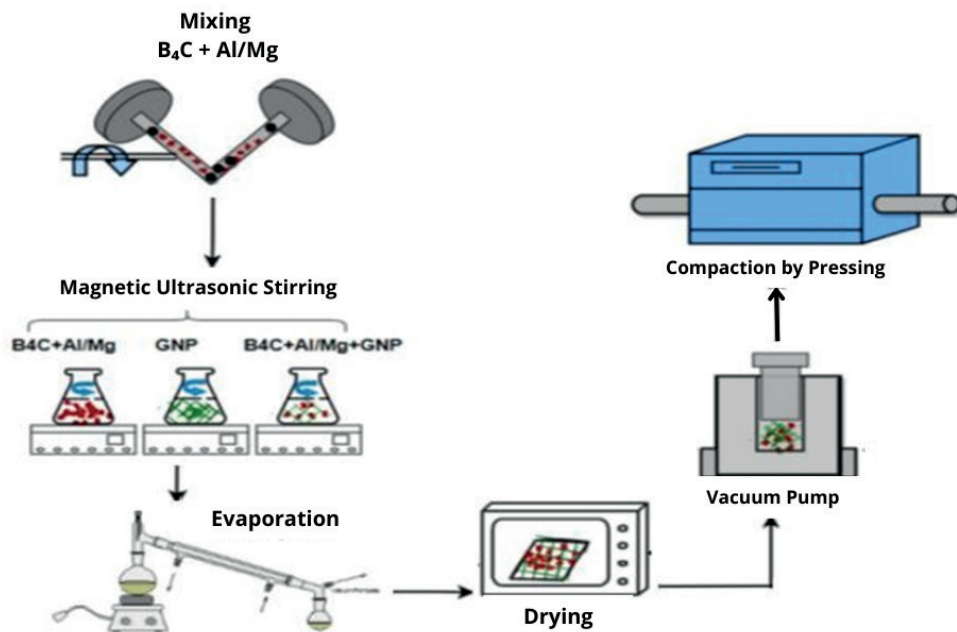
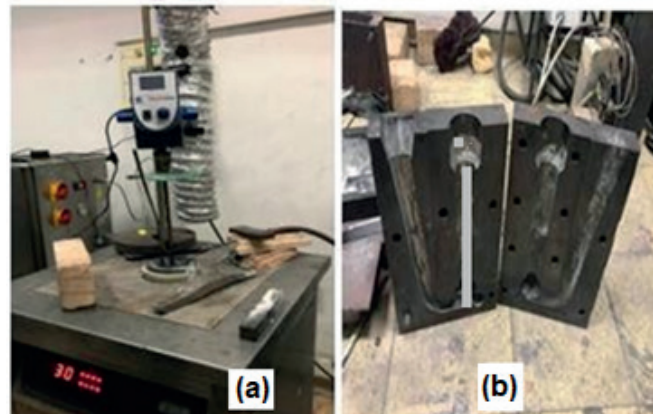


Figure 2

Induction melting furnace and specimen production mold.



The specimens were prepared using standard metallographic procedures, involving sequential grinding with SiC papers ranging from 240 to 2500 mesh, followed by final polishing with a 1 μm alumina suspension. They were then etched using 100 mL of Keller's solution (1 cm^3 hydrofluoric acid; 1.5 cm^3 hydrochloric acid; 2.5 cm^3 nitric acid; 95 cm^3 water), rinsed with water and alcohol, and dried with hot air. The microstructures of the specimens were examined using a Nikon optical microscope and SEM-EDAX analyses. The hardness of the as-cast specimens was measured in Brinell units using an HB-3000B Brinell hardness tester. In contrast, the hardness of the rolled and subsequently recrystallized specimens was measured using an FV-700 model FUTURETECHCOPP Vickers hardness tester.

The rolling process for the unprocessed AA5754 alloy and composites reinforced with varying amounts of GNP and B₄C was carried out on a double-cold roller mill. Specimens measuring 10 × 25 × 55 mm were rolled at room temperature with 10% reductions per pass, resulting in a total decrease of 30%. To investigate the diffusion and recrystallization behaviour of the 30% cold-rolled unreinforced AA5754 and GNP- and B₄C-reinforced composites, and to evaluate the effect of heat treatment on hardness and corrosion resistance, the specimens were held at 300 °C for 1 hour and then cooled to room temperature outside the furnace.

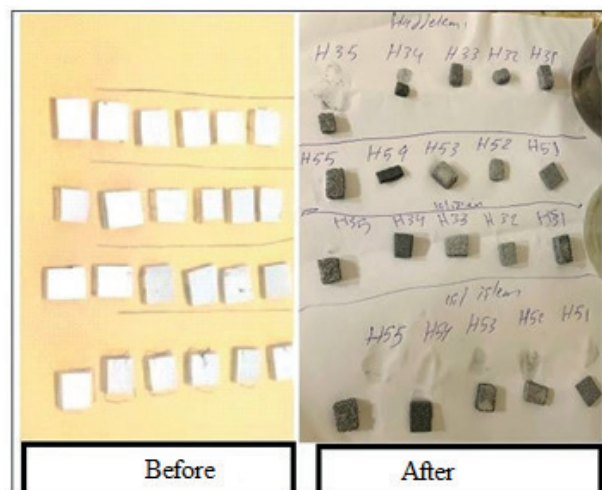
Wear tests were conducted on the reciprocating wear test apparatus shown in Figure 3 under a constant load of 20 N, a sliding speed of 0.1 m/s, and a total sliding distance of 1000 m. Wear was measured and recorded every 200 m of sliding distance. The friction force generated during testing was measured instantaneously using a load cell attached to the tribometer arm and transferred to a computer. A 6 mm-diameter AISI 52100-grade steel ball was used as the counter material. Specimen weight measurements were performed using a RADWAG AS 220.R2 balance with a precision of 10⁻⁴.

Figure 3

Schematic representation of the reciprocating wear test apparatus.



The worn surfaces of the specimens were examined in detail using a Scanning Electron Microscope (SEM), and the corresponding wear mechanisms were identified. Five wear tests were performed for each specimen, and the results were evaluated based on the average values obtained. To investigate the corrosion behaviour of Al5754 aluminium composites, an immersion corrosion test was conducted in a mixed solution of 3.5% NaCl and 3.5% HCl, using the glass containers shown in Figure 4. The initial weights and surface areas of all specimens were measured before immersion. The specimens were left in the solution for 3, 6, and 24 hours, respectively. At the end of each exposure period, the specimens were reweighed, and their surface measurements were recorded. Images of the corrosion specimens before and after immersion in 3.5% NaCl and 3.5% NaCl + HCl solutions are presented in Figure 5.

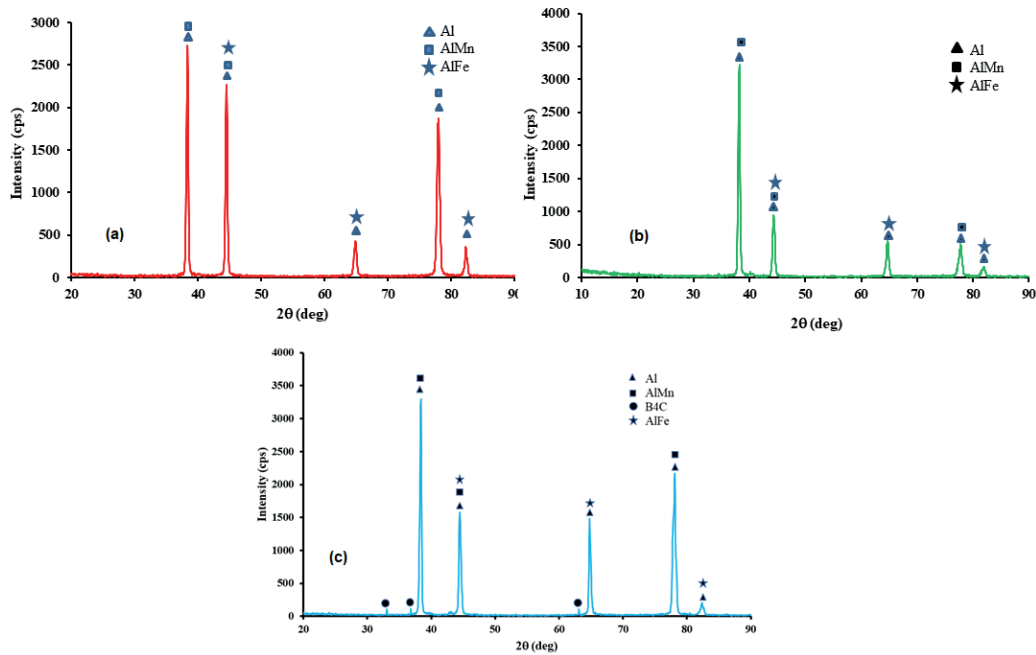
Figure 4*Immersion of the specimens.***Figure 5***Appearance of the deformed-rolled Al5754 composites before and after the immersion corrosion test.*

Characterization Results and Discussion

The X-ray diffraction (XRD) analyses of the as-cast unreinforced specimen and the composites reinforced with 0.5% GNP and 15% B₄C are presented in Figures 6(a-c). According to these results, when the alloy and composites are evaluated as a whole, the presence of binary intermetallic phases formed by Al, Cu, Mn, Mg, B, Cr, Ni, Zn, and C, namely AlMn, AlFe, and B₄C intermetallic, was identified. The findings are consistent with the literature (Hamid et al., 2025).

Figure 6

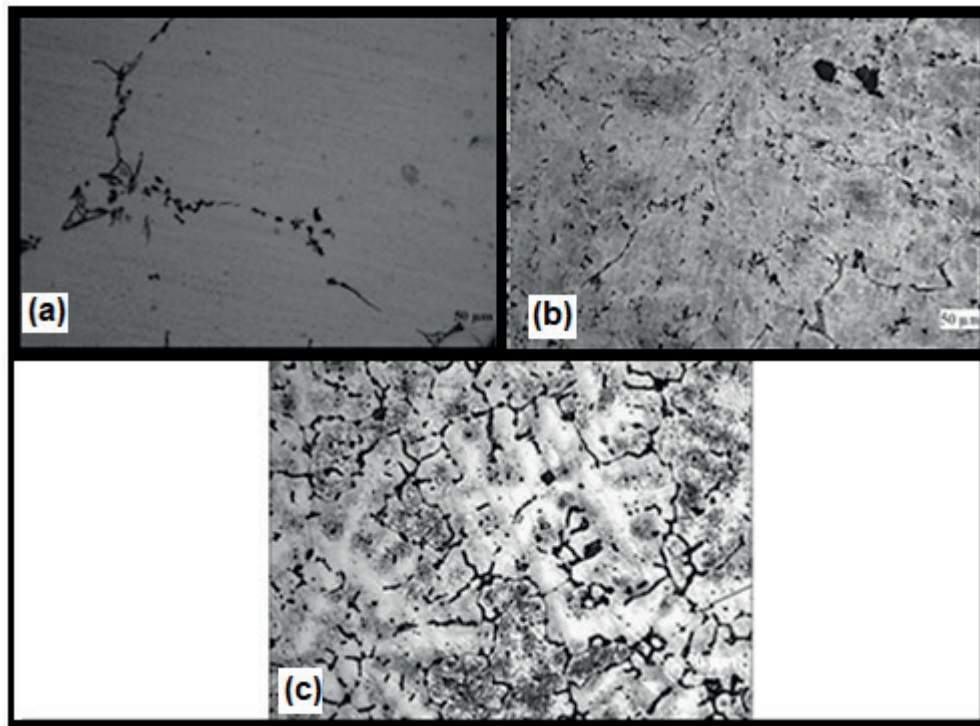
(a) X-ray diffraction analysis of the as-cast specimen, (b) the 0.5% GNP-reinforced specimen, and (c) the 15% B₄C-reinforced specimen.



The optical microscope images of the as-cast alloy and composite specimens are presented in Figure 7. In Figure 7(a), the microstructure of the as-cast Al5754 specimen exhibits a typical granular morphology consisting of randomly distributed, irregularly shaped, and large intermetallic particles, along with evidence of dendritic structure formation. In Figures 7(b) and 7(c), the microstructure of the Al5754 composites containing GNP and B₄C shows that both reinforcements are uniformly distributed as dark-coloured phases within the matrix. The exceptionally uniform distribution of B₄C results in higher hardness values for this specimen than for either the other reinforced samples or the unreinforced alloy (Figure 8). As observed, B₄C particles appear dark and exhibit a regular distribution throughout the microstructure. In the microstructure of the AA5754 composite reinforced with 0.5% GNP and 15% B₄C, the dark and homogeneous distribution of the reinforcements has also been reported. Furthermore, the increase in hardness observed for the specimen reinforced with 0.5% GNP + 15% B₄C is evident in Figure 8 (Liu et al., 2024).

Figure 7

Optical microscope images of (a) as-cast AA5754, (b) the 1% GNP + 15% B₄C composite, and (c) the 0.5% GNP + 15% B₄C composite.

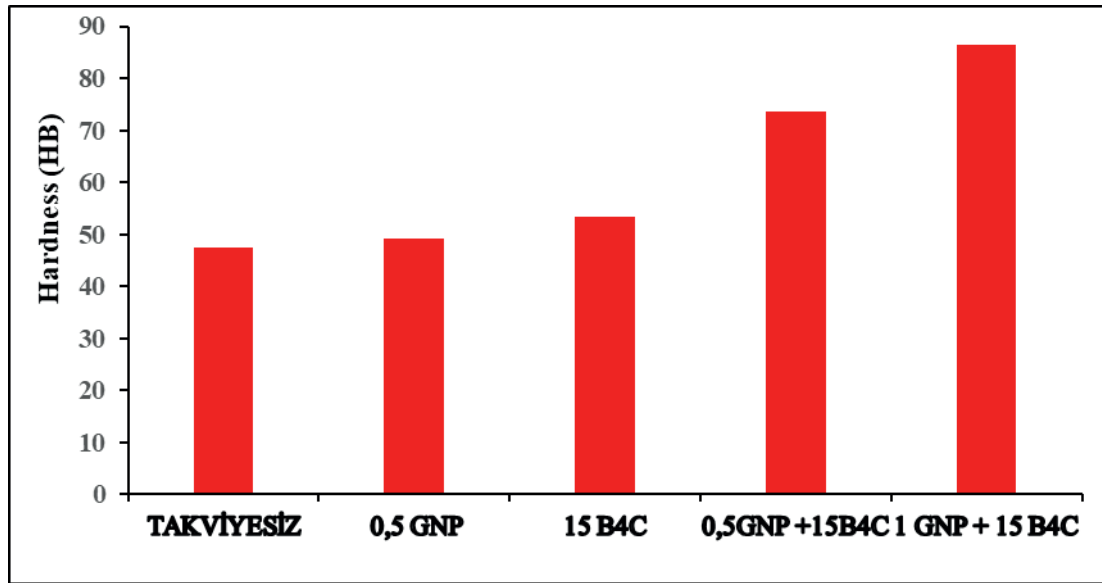


As shown in Figure 8, the highest hardness was measured for the composite specimen reinforced with 1% GNP and 15% B₄C, yielding 86.54 HB. This was followed by the specimen reinforced with 0.5% GNP + 15% B₄C, which exhibited a hardness of 73.6 HB. The specimens reinforced with 15% B₄C and 0.5% GNP, as well as the unreinforced specimen, showed hardness values of 53.4 HB, 49.2 HB, and 47.4 HB, respectively. The superior hardness of the as-cast specimen containing 1% GNP + 15% B₄C is attributed to the combined effect of GNP and B₄C reinforcement, as well as the presence of B₄C in the microstructure, which is evident in the X-ray diffraction patterns shown in Figure 6. Although B₄C is present in the microstructures of both specimens shown in Figure 6, the combined effect of 0.5% GNP + 15% B₄C in the initially produced composite is determined to be more influential than the individual contributions of 15% B₄C or 0.5% GNP alone. Examination of the XRD profiles (Figure 6) reveals that the common diffraction peaks in all specimens correspond to Al, AlMn, and AlFe phases.

Upon further evaluation of Figure 8, the highest hardness value was again observed for the composite specimen reinforced with 1% GNP + 15% B₄C, at 87.4 HB. The specimen containing 0.5% GNP + 15% B₄C exhibited a hardness of 82.33 HB, while the composites reinforced with 15% B₄C and 0.5% GNP, and the unreinforced specimen, recorded hardness values of 77.6 HB, 72.6 HB, and 66.2 HB, respectively.

Figure 8

Average hardness variation of the as-cast unreinforced and composite specimens.

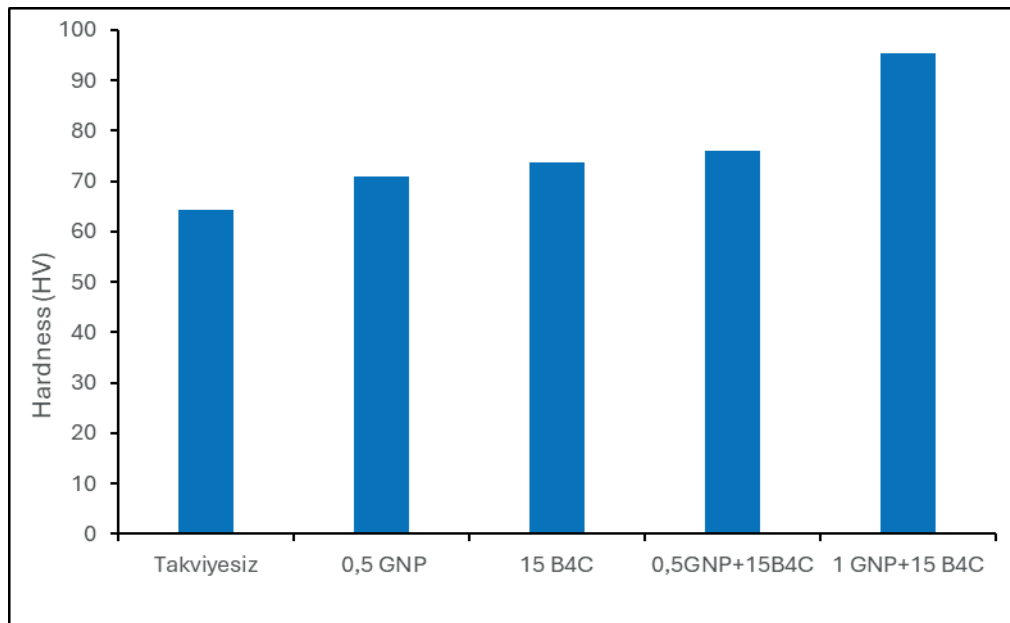


According to Figure 8, the hardness of the unreinforced AA5754 specimen produced by stir casting was measured as 47.35 HB. The addition of 0.5% GNP to Al5754 increased the hardness by 1.01 HB, to 49.17 HB. The hardness of the specimen reinforced with 0.5% GNP + 15% B₄C increased 1.56-fold compared with unreinforced AA5754, reaching 73.7 HB. When the nano-reinforcement ratio was 1% GNP + 15% B₄C and 15% B₄C alone, the hardness increased relative to unreinforced AA5754, yielding values of 86.45 HB and 53.36 HB, respectively. The comparison of hardness values clearly shows that the highest hardness was obtained in the specimens reinforced with 1% GNP and 15% B₄C. After the addition of 1% GNP + 15% B₄C, the hardness of the composite increased approximately 1.83 times compared with the unprocessed Al5754.

From the graphs, it can be observed that adding GNP and B₄C to Al5754 significantly increases hardness. The results indicate that the maximum hardness improvement occurs with a volumetric addition of 1% GNP and 15% B₄C, whereas varying the reinforcement ratio decreases hardness. This behavior can be explained by increased porosity due to the combined reinforcement effect and, in the case of the 1% GNP nanocomposite, potential GNP agglomeration/clustering (Liu et al., 2024). The presence of tough reinforcement phases within AA5754+15% B₄C, AA5754+0.5% GNP+15% B₄C, and AA5754+1% GNP+15% B₄C also contributed to increased hardness values. Literature reports confirm that similar trends have been observed in numerous studies (Wang et al., 2021; Sivakaruna et al., 2017; Rebba et.al., 2014). Figure 9 illustrates the effect of different reinforcement types (GNP and B₄C) on the hardness of specimens heat-treated at 300 °C.

Figure 9

Effect of the 300 °C recrystallization treatment on the hardness of the 30% cold-rolled specimens.



Examination of Figures 10 and 11 shows the steady-state wear rates of the unreinforced and nano-reinforced composites after 30% cold-rolling, followed by a recrystallization heat treatment. As seen in Figure 10, after a sliding distance of 1000 m, the nano-reinforced composite containing 0.5% GNP + 15% B₄C exhibited the highest at 0.022 g, while the composite containing 1% GNP + 15% B₄C showed the lowest wear loss at 0.016 g. Overall, it can be stated that the 30% cold-rolling + recrystallization heat treatment improved the wear-loss performance of both the 0.5% GNP + 15% B₄C and 1% GNP + 15% B₄C nano-reinforced composites and simultaneously enhanced their mechanical strength.

When the hardness and steady-state wear rates (g/m) of the specimens subjected to 30% rolling + recrystallization are evaluated together (Figure 11), the unreinforced AA5754 specimen, which had the lowest hardness (65.25 HV), exhibited a steady-state wear rate of 0.000017814 g/m. In contrast, the AA5754 + 1% GNP + 15% B₄C composite, which had the highest hardness (90.99 HV), showed a wear rate of 0.000014943 g/m. However, the composite with the second-highest hardness (86.28 HV), AA5754 + 0.5% GNP + 15% B₄C, exhibited the highest wear rate of 0.000021071 g/m. These findings indicate that although 30% rolling + recrystallization increased the hardness of the specimens, it also increased their wear rates.

Literature reports (Baradeswaran et al., 2014). indicate that B₄C-reinforced composites generally exhibit higher wear loss compared to GNP-reinforced ones. The dry sliding test results in this study similarly demonstrate that the addition of 0.5% GNP is more

effective than 15% B₄C in improving wear resistance. High amounts of B₄C alone are believed to make the composite more brittle, thereby reducing its resistance to wear. Graphene's high wear resistance and solid-lubrication behaviour reduce friction during sliding, thereby decreasing wear loss. shows that using B₄C up to 5% improves wear behaviour, whereas increasing the B₄C ratio beyond this level negatively affects wear performance. (Sathish Kumar et al., 2020).

Figure 10

of the specimens subjected to 30% cold rolling and recrystallization treatment.

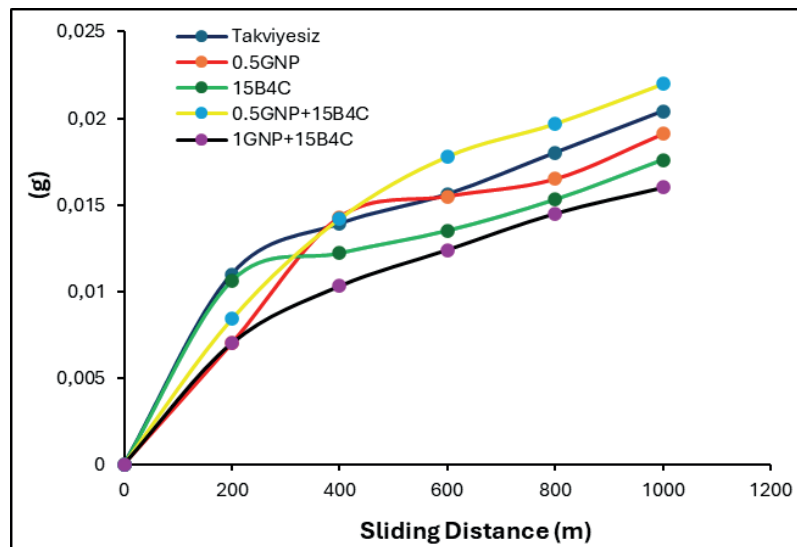
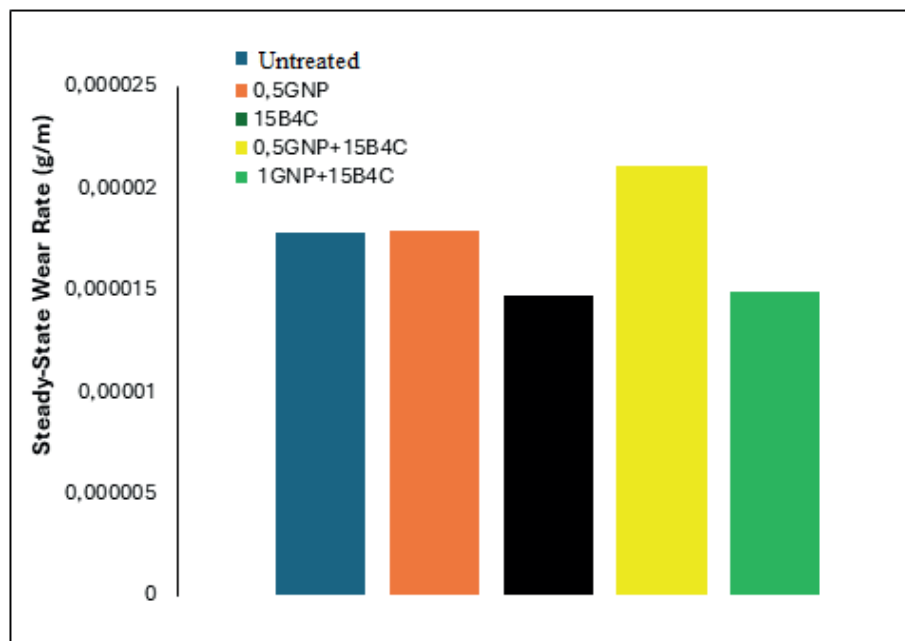


Figure 11

Steady-state wear rate of specimens subjected to 30% cold rolling and recrystallization treatment.



The reciprocating wear tests conducted in this study enabled a comparative evaluation of the wear performance of specimens processed with different reinforcement materials

(GNP graphene nanoplatelets and 15% B₄C boron carbide) and subjected to various thermomechanical treatments. The findings demonstrate that the reinforcement phases and thermomechanical processing significantly influence microstructural integrity, hardness, and wear resistance. Compared with the unprocessed specimen, all GNP- and B₄C-reinforced specimens exhibited lower es. Notably, the specimen containing 1% GNP + 15% B₄C showed a total of 0.0167 g at the end of the sliding distance, indicating a clear improvement over the unreinforced 5754 Al specimen. This result is consistent with the literature. According to Tang et al., aluminium matrix composites reinforced with graphene exhibit substantially enhanced tribological properties, where the formation of a transfer film on the sliding surface increases wear resistance (Chawla et al., 2006).

The addition of boron carbide also resulted in significant improvements in hardness. The 15% B₄C specimen, with a hardness of 75.45 HB, demonstrated greater structural resistance than the unreinforced specimen. This increase in hardness reduced surface deformation during wear. According to Chawla, harder surfaces exhibit greater resistance to mechanisms such as micro-cutting and plastic deformation (Kumar et al., 2015).

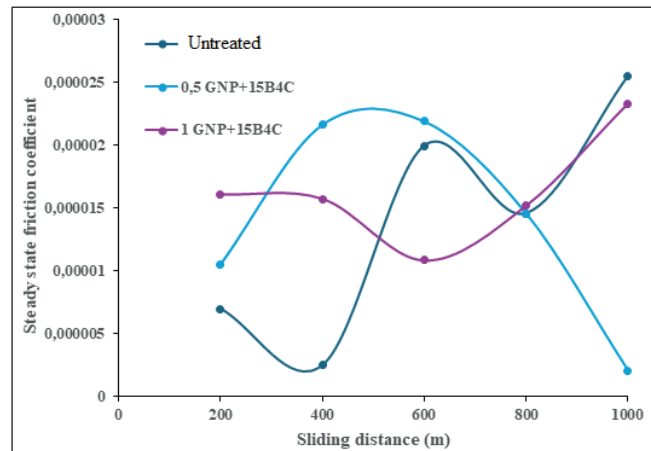
Specimens subjected to rolling generally exhibited lower steady-state wear rates. The 15% B₄C specimen exhibited a steady-state wear rate of 0.00002005 g/m, indicating improved performance compared to the unprocessed specimen. Kumar and Srivastava reported that grain refinement and a more homogeneous microstructure after rolling improve surface strength and reduce wear (Tjong et al., 2007).

The results obtained from heat-treated specimens were also highly favourable. The specimen reinforced with 1% GNP + 15% B₄C exhibited the best performance, with a steady-state wear rate of 0.000014943 g/m and a hardness of 90.99 HB. According to Tjong, precipitation structures formed after heat treatment promote a more stable distribution of reinforcement phases within the matrix, thereby enhancing wear resistance (Zhang et al., 2014).

The obtained findings show that both the amount of reinforcement and the applied thermomechanical treatments have a direct influence on wear performance. However, improvements become limited beyond a certain level of reinforcement. This behaviour is attributed to phase saturation and the deterioration of distribution homogeneity. Zhang and Chen reported similar observations in the wear analyses of graphene-reinforced composites (Mishra et al., 2005). The average steady-state coefficient of friction for specimens subjected to a 30% rolling + recrystallization heat treatment is shown in Figure 12. Although the 30% rolled specimens, the 30% rolled + recrystallized specimens, and the as-cast specimens exhibited similar trends in friction coefficient, the overall steady-state friction coefficient values were lower in the 30% rolled + recrystallized specimens.

Figure 12

Average steady-state friction coefficient of specimens subjected to 30% cold rolling and recrystallization.



The friction coefficient values obtained from different reinforcement materials and processing routes (as-cast condition, 30% cold rolling, and recrystallization heat treatment) were comparatively evaluated in this study. The friction coefficient is a critical parameter for understanding how surface properties and interfacial interactions influence wear behaviour. Compared with the as-cast matrix material, lower friction coefficient values were generally observed in the hybrid-reinforced composites (0.5% GNP + 15% B₄C and 1% GNP + 15% B₄C). This behaviour may be attributed to the formation of a protective surface film by the reinforcement phases or to increases in microhardness, both of which reduce surface contact (Tang et al., 2017). Similarly, after 30% rolling, notable variations in friction coefficient values were observed depending on the reinforcement type and amount. In particular, the composite containing 1% GNP + 15% B₄C exhibited lower friction coefficients under most loading conditions than the composite containing 0.5% GNP + 15% B₄C, indicating that cold rolling improves reinforcement distribution and enhances frictional resistance. This observation is consistent with the literature, which reports that plastic deformation enhances the homogeneity of reinforcement particle dispersion (Zhou et al., 2018).

In the specimens subjected to recrystallization heat treatment, friction coefficient values were generally lower and more stable. This is attributed to heat treatment's ability to refine and reorganize the grain structure, thereby reducing surface energy and limiting surface wear. The friction coefficient values of the 0.5% GNP + 15% B₄C and 1% GNP + 15% B₄C specimens after heat treatment further indicate a synergistic effect of hybrid reinforcement on surface behaviour (Rajmohan et al., 2013).

Figure 13 presents the SEM images of the dry-sliding wear surfaces of the AA5754 + 0.5% GNP + 15% B₄C + 30% cold rolled + recrystallized composite and the AA5754 + 1% GNP + 15% B₄C + 30% cold rolled + recrystallized composite. In the composite

reinforced with 1% GNP and 15% B₄C, subjected to cold rolling and recrystallization, mild abrasive wear was observed on the worn surface. A high carbon/graphene signal was detected on the worn region, indicating the presence of reduced graphene oxide particles after wear. This suggests that GNP particles detached during wear reattached to the surface, influencing the wear characteristics.

Examination of Figure 13 further shows that adhesive wear dominates the worn surface of the AA5754 + 0.5% GNP + 15% B₄C + 30% cold rolled + recrystallized composite. This adhesion-dominated wear mode is typically associated with the transfer of counter-material particles (originating from the steel ball) onto the specimen surface during sliding. The presence of oxygen in the structure shown in Figure 14 was confirmed by EDX analysis. Regions 1-7 contain high Al levels, corresponding to the matrix. Examination of Figure 14 shows that EDX analysis performed on the worn surface of the AA5754 + 1% GNP + 15% B₄C composite revealed a high carbon content in region 4. The increased elemental carbon content is associated with complete particle fracture and pullout from the matrix, leading to the formation of a brittle interfacial layer and crack-assisted wear. Additionally, carbon detachment from widely distributed B₄C particles contributed to adhesion, thereby increasing the wear rate. In regions labelled 3, the high Mg concentration indicates the formation of a thick MgO layer on the surface, which contributed to increased mass loss.

Figure 13

SEM images of the wear surfaces of the as-cast unreinforced and composite specimens.

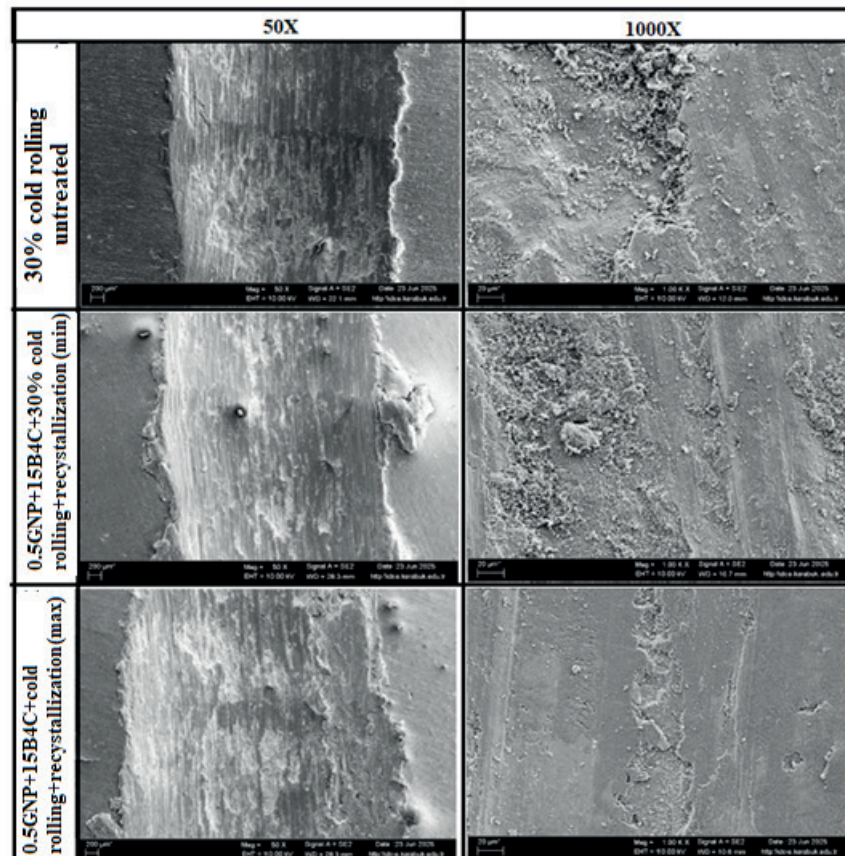
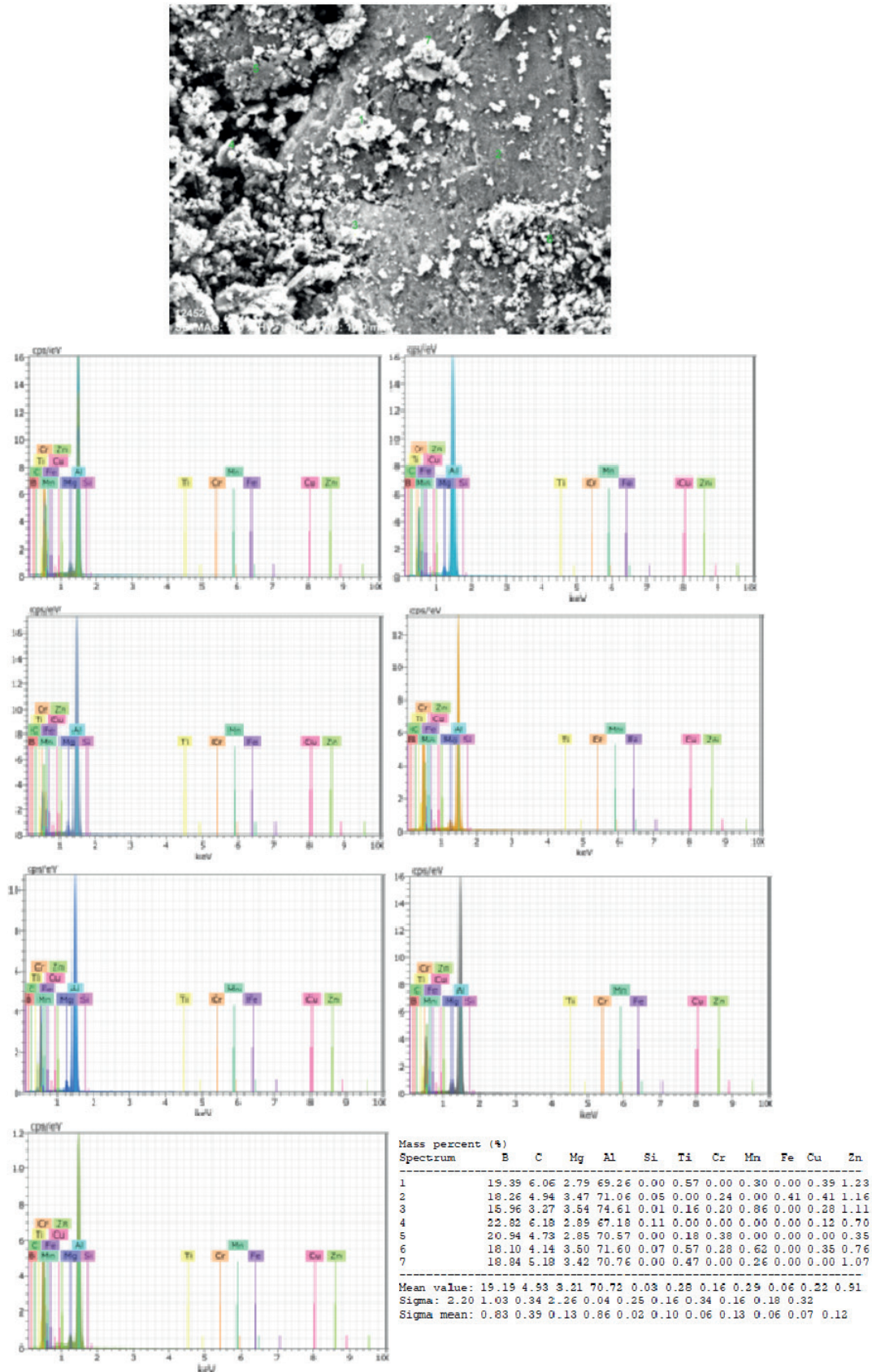


Figure 14

SEM–EDAX elemental analysis of the most severely worn specimen containing 0.5% GNP + 15% B₄C after 30% rolling and recrystallization.

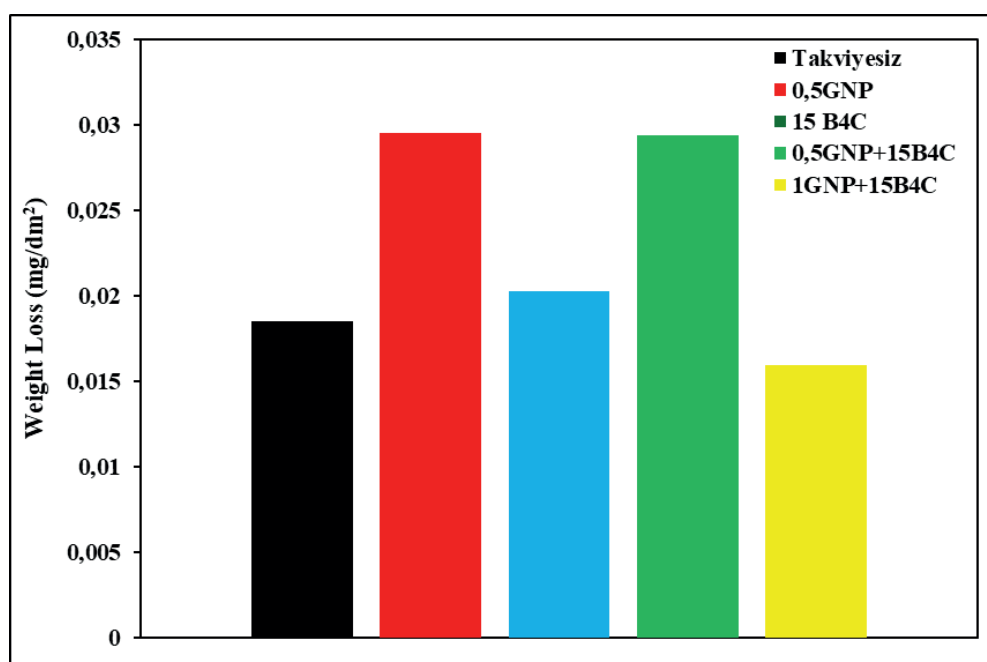


The es measured after the 24-hour immersion corrosion test for the specimens subjected

to 30% rolling and recrystallization are presented in Figure 15. Examination of Figure 15 shows that the unreinforced AA5754 specimen experienced a value of 0.01849784 mg/dm². The composite with the highest value was the AA5754 + 0.5% GNP specimen, with a value of 0.02955899 mg/dm². The of the AA5754 + 15% B₄C composite specimen was measured as 0.0202653 mg/dm², while the AA5754 + 0.5% GNP + 15% B₄C composite exhibited a of 0.02937684 mg/dm². The lowest value was observed in the AA5754 + 1% GNP + 15% B₄C composite specimen, at 0.01594177 mg/dm².

Figure 15

of specimens subjected to 30% rolling and recrystallization after the 24-hour immersion corrosion test.



The corrosion behaviour of Al5754 aluminium matrix composites reinforced with different proportions of graphene nanoplatelets (GNP) and boron carbide (B₄C) was evaluated in this study using the immersion method. The tests were carried out on specimens subjected to 30% rolling followed by recrystallization heat treatment. The corrosion rate (mg/dm²), calculated from, was used as the basis for discussion. In immersion tests using a more aggressive solution prepared by adding HCl to NaCl, the acidic medium rapidly activated the electrochemical cells, leading to significant mass loss. This finding is consistent with the literature, which reports that aluminium alloys exhibit more severe localized corrosion (particularly pitting corrosion) in NaCl + HCl environments (Nagaral et al., 2015, El Garchani et al., 2024).

Among the as-cast composites, the lowest corrosion rate was observed in the unreinforced Al5754 specimen, at 0.011 mg/dm². The addition of individual GNP and/or B₄C to the Al5754 matrix increased corrosion rates. The highest corrosion rate, 0.029 mg/dm², was recorded for the Al5754 + 0.5% GNP composite. This behaviour can be explained

by the possibility that GNP promotes the formation of anodic–cathodic cells, thereby accelerating microgalvanic corrosion (Zheng et al.,2021). Interestingly, however, in the composites containing Al5754 + 0.5% GNP + 15% B₄C and Al5754 + 1% GNP + 15% B₄C, the increase in corrosion rate remained more limited, and the corrosion values were comparatively lower. This suggests that a synergistic interaction between GNP and B₄C may partly contribute to improved corrosion resistance.

The observed increase in corrosion rate in specimens subjected to 30% cold rolling can be attributed to the higher density of grain boundaries, accumulation of internal stresses, and formation of microcracks during cold rolling, which increases the surface area exposed to the corrosive medium (Yu et al., 2018). Notably, the Al5754 + 0.5% GNP composite exhibited a markedly higher corrosion rate of 0.050 mg/dm². The heterogeneous distribution of GNP on the surface and the microstructural differences it introduces may contribute to this increase.

In the specimens subjected to 30% rolling followed by recrystallization heat treatment, a reduction in corrosion rates was observed in some cases. This can be attributed to heat treatment's ability to relieve microstresses, reorganize grain boundaries, and improve surface homogeneity (Tang et al.,2017). For example, the corrosion rate of the 30% cold-rolled unreinforced AA5754 specimen decreased to 0.018 mg/dm², whereas the AA5754 + 1% GNP + 15% B₄C composite exhibited the lowest corrosion rate at 0.015 mg/dm². This result indicates that the appropriate combination of reinforcement content and recrystallization heat treatment can enhance corrosion resistance. When used alone, GNP may reduce corrosion resistance due to microgalvanic cell formation; however, its use in combination with B₄C may help mitigate this effect. The 30% cold rolling process increases structural stresses and surface defects, thereby increasing corrosion rates; therefore, an appropriate post-cold rolling heat treatment is essential. The AA5754 + 1% GNP + 15% B₄C composite, after 30% cold rolling and recrystallization, exhibited the best corrosion resistance and can be considered the optimum reinforcement combination.

Figures 16 and 17 show that, at the beginning of the test, the primary corrosion attack in both undeformed and deformed specimens occurred around Si-rich intermetallic particles, while Fe-rich particles remained unreactive. Local corrosion around Si-rich constituents led to cavitation around these particles, consistent with previous observations (Eckermann et al.,2008). As exposure time increased, crystallographically enlarged pits were observed more frequently in the original material compared with the deformed regions. Such crystallographically enlarged pits, bounded by steep walls of the crystal lattice, have been reported in Al and Al alloys, and their pit-growth kinetics have been previously described (Eckermann et al.,2008; Zaid et al., 2008). Furthermore, in acidic chloride-containing solutions, corrosion tunnelling has been identified as the dominant mode of pit propagation (Eckermann et al.,2008).

Considering the corrosion behaviour in chloride-containing solutions, the chemical composition of coarse particles is also essential. The Si-rich coarse intermetallic observed in AA5754 also contained Mg and Al. Previous reports have clearly shown that Mg dissolves rapidly from intermetallic particles during exposure, leading to their rapid disintegration (Yasakau et al., 2007; Zhu et al., 2018). The findings of earlier studies (Zhu et al., 2018, Zheng et al., 2020) explain the dissolution mechanism of Mg and Al from coarse particles predominantly composed of Mg and Si in Al–Mg–Si alloys. The results of this investigation demonstrate that, at the beginning of immersion, preferential and selective dissolution of Mg occurs, which alters the Volta potential of the particle. This transformation changes the nature of Mg-containing particles from anodic to cathodic, thereby forming a galvanic couple with the Al matrix. As these locally formed galvanic cells approach equilibrium, the cathodic particle promotes the galvanic dissolution of the anodic matrix, resulting in matrix corrosion.

The increased dislocation density near the coarse particles promotes corrosion reactions, leading to more pronounced trench formation around Mg- and Si-rich particles. This behavior is attributed to the higher dislocation density formed in the bent (deformed) region of the specimen, which, due to its less regular structure, facilitates the propagation of deeper pits (Brunner et al., 2010, Pouraliakbar et al., 2011).

Figure 16

SEM–EDAX elemental analysis of the surface of the as-cast unreinforced specimen, showing the lowest corrosion.

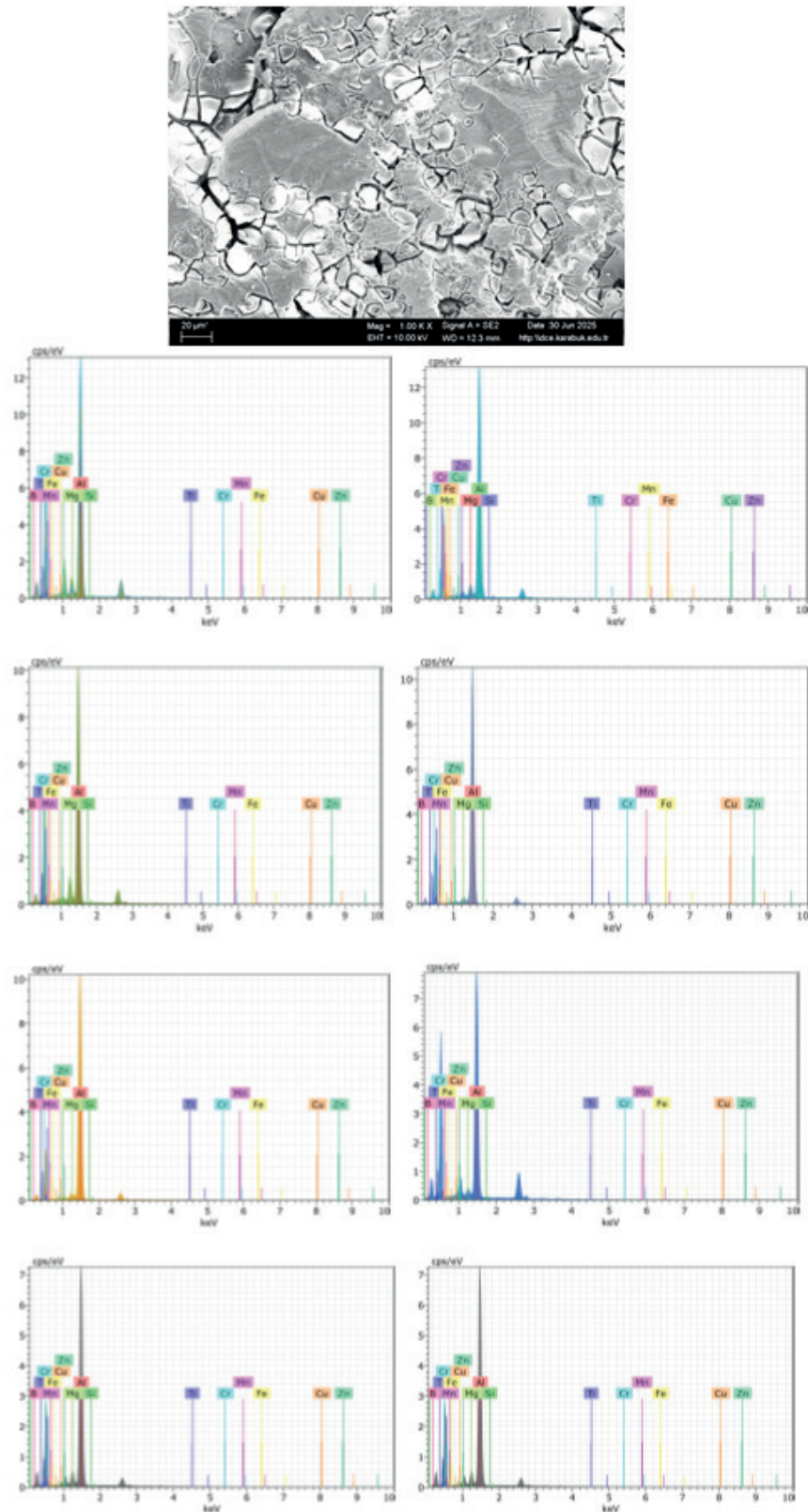
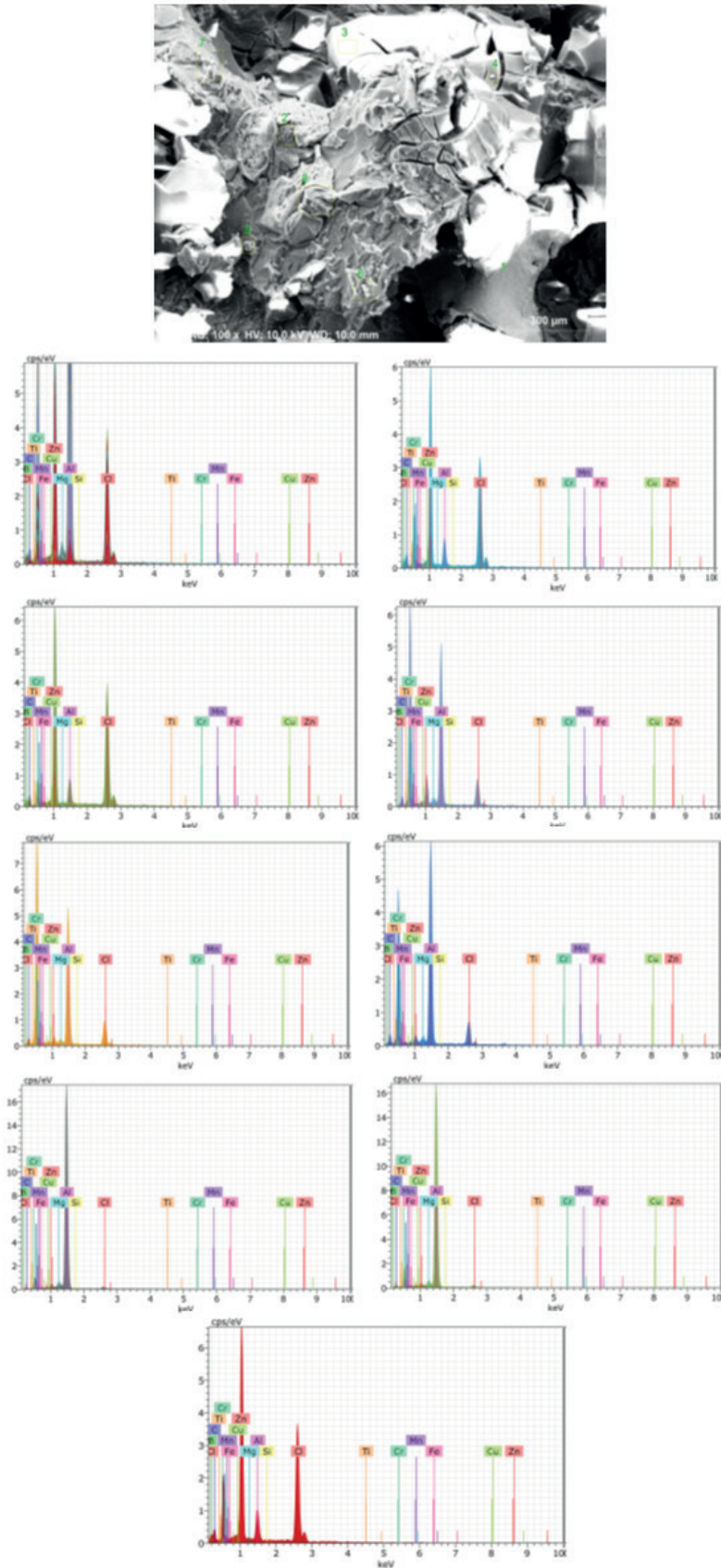


Figure 17

SEM–EDAX elemental analysis of the surface of the AA5754 + 15% B₄C composite specimen rolled by 30% showing the lowest corrosion.



Acknowledgement

This study was supported by Karabük University Scientific Research Projects Coordination with the project code KBÜBAP-24-YL-110. The authors would like to thank the KBÜ-BAP unit for their financial support. They would also like to thank Hiba Waleed Hamid HAMID for his contributions.

References

- Alaneme, K.K., Babalola, S.A., Bodunrin, M.O., Chown, L.H., Okotete, E.A., Maledi, N.B. (2021) Hot deformation of nickel particles reinforced aluminium based composites: flow behaviour, microstructural evolution and processing map analyses, *Mater. Res. Express*, 8, 016510. (<https://doi.org/10.1088/2053-1591/ABD5A3>)
- Asthana, R., Tewari, S.N., Lin, N.T.(2006) Metal-matrix composites, *Mater. Sci. Eng.*, 23, 53–64.
- Baradeswaran, A., Vettivel, S.C., Perumal, A.E., Selvakumar, N., Issac, R.F. (2014) Experimental investigation on mechanical behaviour, modelling and optimization of wear parameters of B4C and graphite reinforced aluminium hybrid composites, *Mater. Des.*, 63, 620-632.
- Blawert, C., Hort, N., Kainer, K.U. (2004) Automotive applications of magnesium and its alloys, *Trans. Indian Inst. Met.*, 57(4), 397–408.
- Brunner, J.G., May, J., Höppel, H.W., Göken, M., Virtanen, S. (2010) Localized corrosion of ultrafine-grained Al-Mg model alloys, *Electrochim. Acta*, 55, 1966–1970.
- Chawla, N., Chawla, K.K. (2006) Metal matrix composites, *J. Mater. Sci.*, 41(3), 793–815.
- Del Monte, F., Bernal, M.M., Wenk, H.R. (1999) Metal matrix composites processed by powder metallurgy, *Mater. Sci. Forum*, 312–314, 453–460.
- Eckermann, F., Suter, T., Uggowitzer, P.J., Afseth, A., Schmutz, P. (2008) The influence of MgSi particle reactivity and dissolution processes on corrosion in Al-Mg-Si alloys, *Electrochim. Acta*, 54, 844–855.
- El Garchani, F.E., Kabiri, M.R., Moulay, R. (2024) Effects of heat treatment on the corrosion behavior and mechanical properties of aluminum alloy 2024, *ResearchGate Preprint*, 1356–1370.
- Hamid, H.W.H., Çetin, M., Ahlatçı, H., Al-Mekhlafi, O.H.S. (2025) Karıştırma döküm yöntemiyle nano boyut takviyeli metal matrisli hibrit kompozit üretimi, 10. Latin Amerika Uluslararası Bilimsel Araştırmalar Konferansı, Havana, ISBN: 978-625-5962-70-6.
- Kumar, S., Srivastava, V.C. (2015) Effect of rolling deformation on wear behavior of Al-

- based composites, *Mater. Sci. Eng. A*, 628, 152–160.
- Liu, J., Zhao, Z., Gao, F., Liu, C., Liu, X., Li, C., Zhang, Y. (2024) Effects of Rolling Deformation on the Microstructure and Properties of GNPs/2024Al Composite Materials, *Prot. Met. Phys. Chem. Surf.*, 60(4), 734–742. (<https://doi.org/10.1134/S207020512470206X>)
- Liu, J., Zhao, Z., Gao, F., Liu, C., Liu, X., Li, C., Zhang, Y. (2024) Effects of rolling deformation on the microstructure and properties of GNPs/2024Al composite materials, *Protection of Metals and Physical Chemistry of Surfaces*, 60(4), 734–742.
- Liu, J.H., Khan, U., Coleman, J., Fernandez, B., Rodriguez, P., Naher, S., Brabazon, D. (2016). Powder processing methodology for production of graphene oxide reinforced aluminium matrix composites, *Mater. Des.*, 94, 87, (<https://doi.org/10.1080/2374068X.2016.1244389>)
- Luo, A.A. (2013) Magnesium casting technology for structural applications, *J. Magnes. Alloys*, 1, 2–22.
- Ma, Y.L., Xiong, H.W., Chen, B.Y.(2020) Preparation and corrosion resistance of short basalt fiber/7075 aluminum composite, *Mater. Corros.*, 71, 1824. (<https://doi.org/10.1002/maco.202011771>)
- Mishra, R.S., Ma, Z.Y. (2005) Friction stir welding and processing, *Mater. Sci. Eng. R Rep.*, 18, 1-78.
- Miyazaki, T., Matsuura, H. (2004) Development and applications of metal matrix composites, *J. Mater. Sci.*, 39, 4289–4295.
- Monticelli, C., Zucchi, F., Bonollo, F., Brunoro, G., Frignani, A., Trabanelli, G. (2019) Application of Electrochemical Noise Analysis to Study the Corrosion Behavior of Aluminum Composites *J. Electrochem. Soc.*, 142, 405. (<https://doi.org/10.1149/1.2044035>)
- Nagaral, M., Attar, S., Reddappa, H.N., Auradi, V., Kumar, S.S., Raghu, S. (2015) Mechanical Behavior of Al7025- B4C Particulate Reinforced Composites, *J. Appl. Mech. Eng.*, 4(6), 1000186.
- Pouraliakbar, H., Jandaghi, M.R., Khalaj, G. (2017) Constrained groove pressing and subsequent annealing of Al-Mn-Si alloy: Microstructure evolutions, crystallographic transformations, mechanical properties, electrical conductivity and corrosion resistance, *Mater. Des.*, 124, 34–46.
- Prakash, A., Gupta, M. (2011) Processing and properties of rare-earth reinforced Mg-based composites, *Mater. Sci. Eng. A*, 528, 4489–4494.
- Rajmohan, T., Palanikumar, K., Shankar, S. (2013) Development of hybrid metal

- matrix composites through stir casting – Statistical analysis of friction and wear characteristics, *Mater. Des.*, 48, 92–97.
- Rebba, B., Ramanaiah, N. (2014) Studies on mechanical properties of 2024 Al-B4C composites, *Adv. Mater. Manuf. Character.*, 4(1), 42-46.
- Sathish Kumar, G., Rajaguru, K., Ramkumar, R., Ranjithkumar, M. (2020) Evaluation of Al-C-B4C composites fabricated by powder metallurgy for hardness and wear behaviour, K. Ramakrishnan College of Technology, Tiruchirappalli, 621112, India.
- Sivakaruna, G., Babu, P.S. (2017) A Survey on effects of reinforcement on aluminum metal matrix composites, *Int. J. Mech. Eng. Technol.*, 8(9), 112-131.
- Tang, L., Zhang, C., Zhang, Y., Xie, H. (2017) Graphene reinforced aluminum matrix composites with enhanced tribological properties, *Wear*, 376-377, 653–659.
- Tang, L., Zhang, C., Zhang, Y., Xie, H. (2017) Graphene reinforced aluminum matrix composites with enhanced tribological properties, *Wear*, 376–377, 653–659.
- Tjong, S.C. (2007) Recent progress in development and properties of novel metal matrix nanocomposites reinforced with carbon nanotubes and graphene nanosheets, *Mater. Sci. Eng. R Rep.*, 45(1-2), 1–88.
- Wang, L.W., Zhang, Y., Su, Y., Li, J. (2021) Initial corrosion behavior and mechanism of 7B04 aluminum alloy in NaCl solution, *Trans. Nonferrous Met. Soc. China*, 31(4), 1000–1010.
- Yasakau, K.A., Zheludkevich, M.L., Lamaka, S.V., Ferreira, M.G.S. (2007) Role of intermetallic phases in localized corrosion of AA5083, *Electrochim. Acta*, 52, 7651–7659.
- Yu, F., Camilli, L., Wang, T., Mackenzie, D.M.A., Curioni, M., Akid, R., Bøggild, P. (2018) Complete long-term corrosion protection with chemical vapor deposited graphene, *arXiv Preprint*, arXiv:1805.05102, 1–10.
- Zhang et al., 2017-14. Zhang, Y., Wang, X., Wang, L. (2017) Microstructure and mechanical properties of graphene nanoplatelets reinforced AZ magnesium alloy composites, *Compos. Part B Eng.*, 109, 19–26.
- Zhang, X., Chen, D. (2014) Microstructure and wear properties of graphene/aluminum composites, *Compos. Part A Appl. Sci. Manuf.*, 66, 107–115.
- Zhang, Z., Chen, G., Wang, Y. (2020) Powder metallurgy of magnesium matrix composites: A review, *J. Mater. Sci. Technol.*, 40, 42–56.
- Zheng, S., Li, C., Zhang, Y., Xiang, T., Cao, Y., Li, Q., Chen, Z. (2021) A general strategy towards superhydrophobic self-cleaning and anti-corrosion metallic surfaces: An example with aluminum alloy, *Coatings*, 11(7), 788.

Zheng, Y.Y., Luo, B.H., He, C., Gao, Y., Bai, Z.H. (2020) Corrosion evolution and behaviour of Al–2.1Mg–1.6Si alloy in chloride media, *Rare Met.*

Zhou, W., Xu, Z., Liu, C. (2018) Effect of rolling process on the tribological properties of particle-reinforced aluminum composites, *Mater. Sci. Eng. A*, 710, 92–100.

Zhu, Y., Sun, K., Frankel, G.S. (2018) Intermetallic Phases in Aluminum Alloys and Their Roles in Localized Corrosion, *J. Electrochem. Soc.*, 165, C807–C820.

About Thhe Authors

Melik ÇETİN is a Professor of Metalurgical and Materials Engineering at Karabuk University. He has a Master's and doctoral degree in Metal Education from Gazi University. His main areas of interest are casting technology, corrosion and wear behaviors, and composite materials.

Email: mcetin@karabuk.edu.tr, **ORCID:** 0000-0002-6952-2523

Hayrettin AHLATCI is a Professor of Metalurgical and Materials Engineering at Karabuk University. He has a Master's and doctoral degree in Metalurgical and Materials Engineering from İstanbul Technical University. His main areas of interest are the mechanical behavior of materials, corrosion and wear, casting technology, and composite materials.

Email: hahlatci@karabuk.edu.tr, **ORCID:** 0000-0002-6766-4974

Dr. Kenza DJEBARI is a Materials Engineer with a Ph.D. in Metallurgical and Materials Engineering from Karabük University and an M.Sc. in Computational Pharmaceutical Chemistry. Her work focuses on alloy development, corrosion behavior of biodegradable metals, and microstructural and mechanical characterization.

Email: kenzadjebari@gmail.com, **ORCID:** ORCID: 0000-0003-0158-4741

Similarity Index

The similarity index obtained from the plagiarism software for this book chapter is 10 %.