Journal of Mineral and Material Science (JMMS)
ISSN: 2833-3616
Volume 5 Issue 2, 2024
Article Information
Received date : March 26, 2024
Published date: Apri 11, 2024

*Corresponding author
Essam B Moustafa, Mechanical Engineering Departments, Faculty of Engineering, King Abdulaziz University, 21589, Jeddah, Saudi Arabia

DOI: 10.54026/JMMS/1084

Key Words
Powder Metallurgy; Fly Ash; B_4C; BN; TiO_2; Mechanical Properties; Tribological Behavior; Hybrid Mg Composites

Research Article

An Investigation of the Tribological and Mechanical Properties of the Hybrid Mg Nanocomposites Manufactured by Mechanical Alloy

Abdulraheem H Alyoubi and Essam B Moustafa*
Mechanical Engineering Departments, Faculty of Engineering, King Abdulaziz University, 21589, Jeddah, Saudi Arabia

Abstract

This work explores the impact of fly ash and nanoparticle reinforcements (TiO_2, hBN, B_4C) on the mechanical and tribological properties of magnesium nanocomposites produced via mechanical alloying. The investigation revealed that incorporating these reinforcements increased the compressive strength and microhardness of the composites compared to pure Mg. Notably, the Mg-fly ash + B_4C composite exhibited the highest microhardness (50.74 HV), representing a 71.3% increase. Tribological analysis demonstrated that the Mg-fly ash composite and Mg-fly ash + TiO_2 composite displayed slightly lower friction coefficients than pure Mg. The Mg-fly ash + hBN composite exhibited the lowest friction coefficient due to the lubricating nature of hBN. In contrast, the Mg-fly ash + B_4C composite showed the highest friction coefficient due to its inherently rough surface. These findings suggest that the developed hybrid magnesium nanocomposites offer a compelling combination of enhanced mechanical properties and tunable tribological behavior, making them suitable for applications demanding both wear resistance and reduced friction.

Introduction

Magnesium (Mg) alloys have great promise in different industries because of their lightweight properties, high strength-to-weight ratio, and outstanding castability. Magnesium, the least dense structural metal, has recently attracted much attention for its ability to help reduce weight in the aerospace, automotive, and portable electronics industries [1,2]. Yet, its strength and wear resistance constraints impede its wider implementation in structural contexts. To address these constraints, researchers have investigated different ways, with reinforcement by adding additional phases to the Mg matrix as a promising method. This method results in the creation of Metal Matrix Composites (MMCs), which combine the superior features of the reinforcing phase with the beneficial attributes of the Mg matrix, producing a material with improved overall performance [3,4]. The different reinforcement particles, such as fly ash, B_4C (Boron Carbide), BN (Boron Nitride), and TiO_2 (Titanium Dioxide), enhance the mechanical characteristics of Mg alloys and their hybrid composites [5]. Incorporating different reinforcing particles like nanosized Al_2O_3, hybrid Al-CNT, and aluminum nanoparticles has greatly improved the mechanical characteristics of magnesium (Mg) alloys. The improvements consist of higher microhardness, dynamic elastic modulus, yield strength, ultimate tensile strength, and ductility, as reported by [5-7]. In addition, combining (B_4C) particles with aluminum (Al) has been discovered to enhance the mechanical properties of Mg-based nanocomposites, especially in terms of tensile and compressive strength [8-10].

The results indicate that incorporating reinforcing particles via powder metallurgical methods has significant promise for addressing the inherent limitations of Mg alloys. Fly ash, a residue from burning coal, is a cost-efficient and environmentally benign choice for reinforcing. When added to magnesium alloys, it improves the microstructure by impeding the movement of dislocations and increasing strength [11]. Research indicates that using fly ash can enhance the Ultimate Tensile Strength (UTS) and Yield Strength (YS) of metal matrix [12]. Studies show that fly ash, a residue from coal burning, can greatly improve the mechanical characteristics of metal matrix composites. Incorporating fly ash into Al-4Si-Mg composites resulted in higher porosity and reduced hardness [13]. Polypropylene fiber enhanced the strength and durability of fly ash blended concrete [14]. Incorporating fly ash into aluminum composites enhanced their mechanical characteristics.

Muruganandhan reported a 20% boost in strength, while Patil observed a 58% increase in tensile strength. Both experiments discovered that the corrosion resistance of the composites decreased when fly ash was added [15]. According to studies, (B_4C) is a potent reinforcing agent in magnesium alloys, greatly improving their strength and wear resistance [16-18]. Adding B_4C can enhance the Ultimate Tensile Strength (UTS) and Yield Strength (YS) of magnesium alloys by up to 50% and 70%, as reported by Gao M, et al. [19]. The significant increase in strength results from the effective restriction of dislocations in the magnesium matrix by B_4C particles, which impedes their movement [20]. (hBN) has been discovered to greatly improve the strength and malleability of magnesium alloys, offering potential uses across several industries. Managing grain boundaries in magnesium alloys can enhance their mechanical characteristics, such as toughness [21]. Including BN nanoplatelets can enhance ceramic materials' fracture toughness, strength, and wear resistance [22]. Adding BN to magnesium matrix composites significantly improves wear resistance, with Aydın highlighting BN's function as a solid lubricant [23,24]. These studies emphasize the potential of (BN) as a crucial element in improving the mechanical and tribological characteristics of magnesium alloys.

Adding TiO_2 to (Mg) alloys has greatly improved their mechanical characteristics. TiO_2 enhances the interfacial bonding in Mg composites, reducing degradation rate and higher compressive strength [25]. Adding nanosized Al_2O_3 particles to Mg composites significantly boosted microhardness, yield strength, and ultimate tensile strength [5,26]. Tun. et al. [27] corroborated these results by demonstrating that including nanoscale (Al_2O_3 + Cu) hybrid reinforcements in Mg composites enhanced microhardness, yield strength and ultimate strength. Adding a TiO_2 coating to $Mg_2B_2O_5$w-reinforced AZ91D magnesium matrix composites can improve the bonding between materials and boost the mechanical characteristics of the composite [28]. Hybrid composites use the distinct benefits of each constituent ingredient by incorporating various reinforcing materials. Utilizing B_4C with fly ash or BN can enhance strength and mitigate the negative impacts of pollutants in fly ash [29]. Combining BN with B_4C makes it possible to balance increased strength, wear resistance, and lubrication [30]. Powder metallurgy is crucial for producing magnesium alloy composites reinforced with different particles [31]. This technique allows for accurately mixing the reinforcement material with the Mg powder, followed by compression and sintering to achieve the desired composite structure [32]. Therefore, in the current investigation, the fly-ash hybrid with ceramics nanoparticles is added to the Mg powder to fabricate a hybrid nanocomposite Mg matrix using the powder metallurgy method. The investigation aims to study the effect of hybrid particles on the mechanical and tribological behavior of the fabricated composites.

Experimental Procedures

This study aimed to fabricate HMBCs using the powder metallurgy technique. Five distinct composite formulations were investigated, as detailed in Table 1. The experimental procedures employed throughout this work were conducted entirely within a controlled laboratory environment.

Material selection and powder mixing

Magnesium alloy powders were chosen as the metal matrix material for the HMBCs. The initial stage involved powder mixing, a fundamental step in the powder metallurgy process for metal matrix composite production. A multifunctional mixing machine was utilized to achieve a homogenous mixture of the base powders and designated additives within its chamber. The specific composition details outlined in Table 1 were strictly adhered to during this process. The mixing action was achieved through the combined effect of the blade's horizontal rotation at 34,000 rpm and its concurrent vertical movement. A consistent mixing time of 30 minutes was employed for all five composite formulations.

Table 1: Five distinct composite formulations.

	Mg	Fly ash	TiO_2	hBN	B_4C	Total	Appriviation
Sample 1	100% vol.	0% vol.	0% vol.	0% vol.	0% vol.	Mg	Mg
Sample 2	94% vol.	6% vol.	0% vol.	0% vol.	0% vol.	Mg + 6 vol. fly ash	Mg FA
Sample 3	91% vol.	6% vol.	3% vol.	0% vol.	0% vol.	Mg + 6 vol. fly ash + 3 vol. TiO_2	Mg FA TiO_2
Sample 4	91% vol.	6% vol.	0% vol.	3% vol.	0% vol.	Mg + 6 vol. fly ash + 3 vol.BN	Mg FA BN
Sample 5	91% vol.	6% vol.	0% vol.	0% vol.	3% vol.	Mg + 6 vol. fly ash + 3 vol.B_4C	Mg FA B4C

Compaction and sintering

The uniformly blended powders were subjected to compaction after the thorough mixing process. This step involved applying a uniaxial pressure of 120 bar using a hydraulic compactor. Applying this intense pressure compressed the powder mixture into a compact form, often referred to as a "green compact". Sintering, a subsequent and critical stage in powder metallurgy, was then performed. All the green compacts were placed in a heat treatment furnace and exposed to an elevated temperature of 550 °C for one hour. This temperature, strategically chosen to be just below the magnesium melting point (650 °C), facilitated particle fusion through heat application. The elevated temperature during sintering promotes enhanced particle adhesion, ultimately forming the desired HMBCs.

Measurement of density The theoretical density of the Mg composite was determined through the rule of mixtures [33]. The densities of pure Mg and the composite were determined using Archimedes' principle [34]. Weighed in the air as Wa, the cylindrical sample was suspended in distilled water and weighed again as Ww. The density was determined using Equation (1). The formula provided calculated the actual density of a cylindrical sample based on its mass in air, mass in distilled water, and density of distilled water [35]. It was weighed using a photoelectric balance with an accuracy of 0.1 mg (Figure 1).

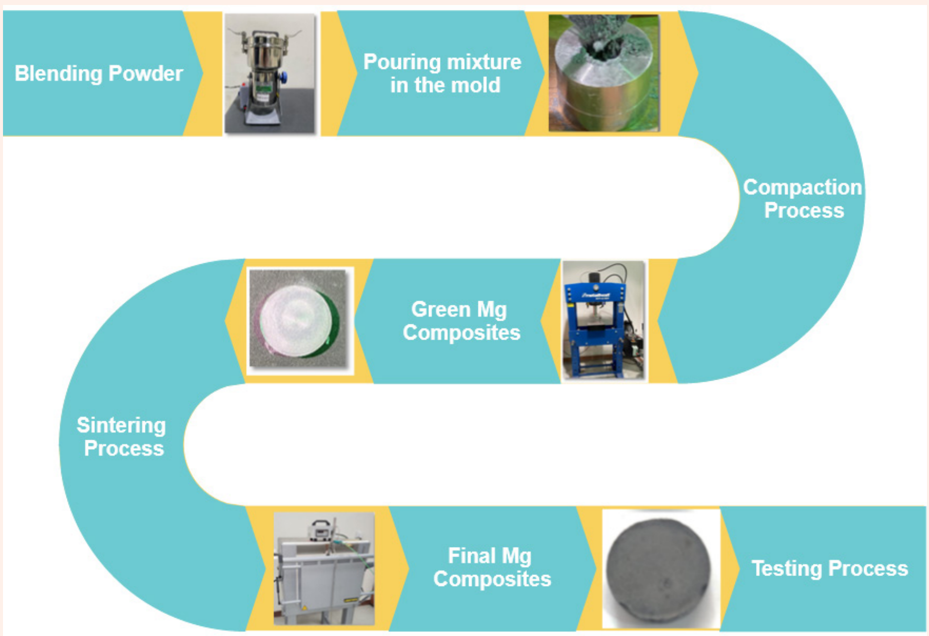

Figure 1: The manufacturing process of the Mg composite matrix using the Powder metallurgy method.

Results and Discussion

Microstructure

SEM micrographs of Fly ash, TiO_2, BN, and B_4C particulates reinforced Mg Hybrid MMCs fabricated by P/M are displayed in Figure 2.The images suggest that the reinforcements exhibit stability within the magnesium material. Gray particles consist of fly ash, TiO_2, BN, and B_4C. Some agglomeration of the reinforcement particulates was observed, but the distribution seemed fairly uniform within the magnesium matrix. Moreover, the particulates of Fly ash, TiO_2, BN, and B_4C are small and irregular, measuring approximately 10 µm. Using Tabel 1, one can determine the density of each material and subsequently calculate the porosity using Equation (1).

The formula can be expressed as $P = 1 - P_a/P_t$ ....(1)

P represents the material's porosity, P_a is the actual density, and P_t is the theoretical density. Table 1 displays various composites' theoretical density, actual density, and porosity, including as-cast pure Mg and Mg/Fly ash, Mg/Fly ash + TiO_2, Mg/Fly ash + BN, and Mg/Fly ash + B_4C. Figure 2a-2c illustrates a small microporosity. The porosity of pure Mg is lower compared to the investigated composites. The variation in porosity can be explained by the phase transition during the production of pure Mg and the sintering process in the study, which is influenced by solid diffusion and the compaction load during hot-pressed treatment. Compressive resistance rises as the reinforcement volume fraction increases under a fixed compaction load of 120 bar. Typically, porosity increases as the reinforcement volume fraction increases [36,37].

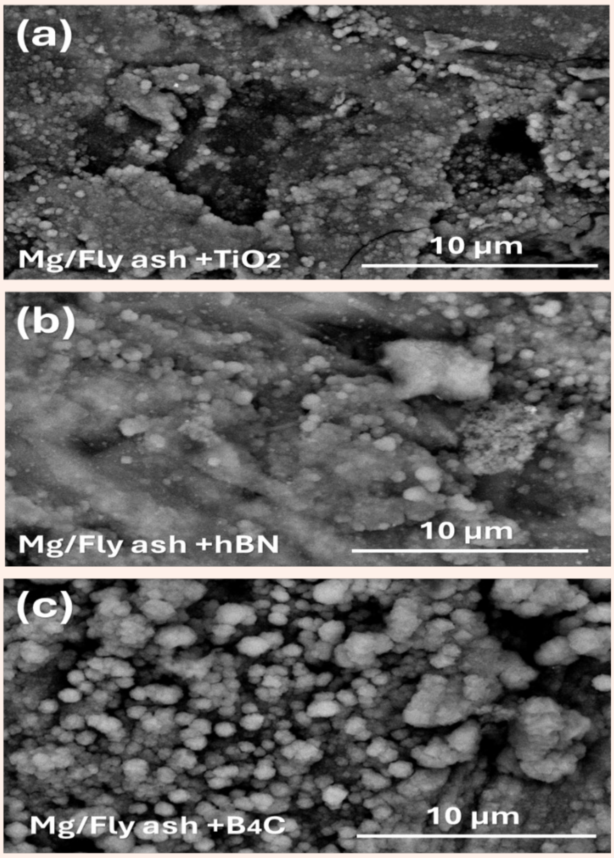

Figure 2: SEM images of the hybrid Mg composite, (a) Mg/ fly ash /TiO_2, (b) Mg/ fly ash /hBN, (c) Mg/ fly ash /B_4C.

Microhardness

Adding 6 volume percent of fly ash to pure Mg increased the microhardness from 29.64 HV to 33.25 HV, showing a 12.3% enhancement. By incorporating 3 vol.% of TiO_2, hBN, or B_4C nanoparticles into the Mg-fly ash composite, a significant improvement in microhardness was observed compared to the Mg-fly ash composite without nanoparticles.

The composites' microhardness values are listed below: The hardness values are as follows: 37.54 HV for Mg-fly ash + TiO_2 with a 26.7% increase, 46.54 HV for Mg-fly ash + BN with a 56.7% increase, and 50.74 HV for Mg-fly ash + B_4C with a 71.3% increase. These observations align with the findings documented in the scientific literature, which demonstrate that adding fly ash and nanoparticles enhances the mechanical characteristics of magnesium composites by employing different strengthening methods.

The mechanisms encompass Structural impact: Including more rigid reinforcing particles such as fly ash and nanoparticles enables them to distribute a portion of the applied stress during indentation, thereby decreasing the load carried by the softer Mg matrix and increasing hardness. Dislocation hindrance refers to the obstruction or prevention of the movement of dislocations, which are line flaws inside a material that allow for plastic deformation (Figure 3). The scattered nanoparticles impede the motion of these dislocations, rendering the material more difficult to deform and leading to increased hardness. Grain refinement occurs when fly ash particles are nucleation sites for forming new magnesium (Mg) grains during solidification, resulting in a more finely structured grain arrangement. The increased impediment of dislocation movement by grain boundaries in finer grains generally leads to higher hardness relative to bigger grains, contributing to the observed microhardness improvement.

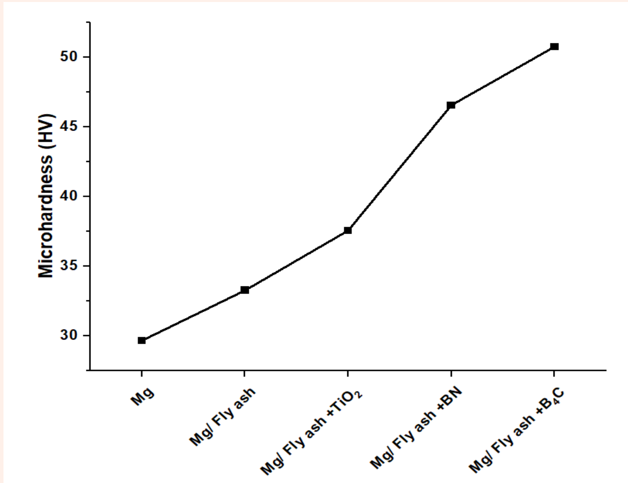

Figure 3: Microhardness behaviour of the Mg composites.

Tribological behavior

The Mg/fly ash composite has a lower coefficient of friction than unreinforced magnesium, while the Mg/fly ash+TiO_2 composite has a slightly lower coefficient of friction than unreinforced magnesium. The Mg/fly ash+hBN composite has the lowest coefficient of friction among all samples. On the other hand, the sample Mg/fly ash+B_4C has the highest coefficient of friction compared to all other samples, as shown in Figure 4. The inclusion of various reinforcing elements has a significant effect on the coefficient of friction of magnesium. Both fly ash and hBN (hexagonal boron nitride) show a reduction in the coefficient of friction. This is most likely due to their lubricating properties. Fly ash particles can form a protective layer or roll/shear under friction. On the other hand, hBN is a widely recognized solid lubricant that effectively reduces friction between surfaces that come into contact with each other. Conversely, adding B_4C significantly increases the coefficient of friction. Boron carbide is an exceptionally durable ceramic substance characterized by its coarse structure. This rough surface improves the material's ability to interlock with other surfaces on contact and resist wear, ultimately leading to a higher coefficient of friction. The data confirm the trends described above. Adding lubricating elements such as fly ash or hBN can increase the strength of magnesium, especially in situations where lower friction is required B_4C reinforcement is often used in wear-resistant applications where high friction is not a priority.

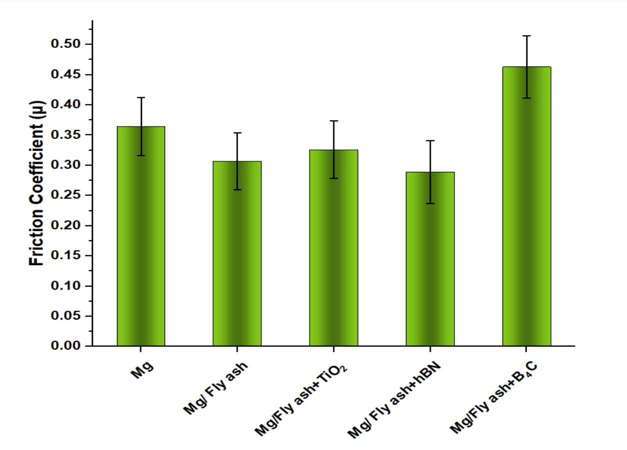

Figure 4: Friction Coefficient of the Mg composites.

Conclusion

a. This study investigated the tribological and mechanical properties of hybrid magnesium nanocomposites fabricated using mechanical alloying. The addition of fly ash and various nanoparticles (TiO_2, hBN, B_4C) significantly influenced the composites' porosity, hardness, and friction coefficient compared to pure magnesium.

b. Compressive strength increased with reinforcement volume fraction, while porosity generally increased.

c. Microhardness was significantly enhanced by incorporating fly ash and nanoparticles. The Mg-fly ash + B_4C composite exhibited the highest microhardness (50.74 HV), representing a 71.3% increase compared to pure Mg.

d. The Mg-fly ash composite and Mg-fly ash + TiO_2 composite demonstrated slightly lower friction coefficients than unreinforced Mg. Notably, the Mg-fly ash + hBN composite displayed the lowest friction coefficient due to its lubricating properties. Conversely, the Mg-fly ash + B_4C composite exhibited the highest friction coefficient due to its inherently rough surface.

References

1. Esmaily M, Svensson JE, Fajardo S, Birbilis N, Frankel GS, et al. (2017) Fundamentals and advances in magnesium alloy corrosion. Progress in Materials Science 89: 92-193.

2. Moustafa EB, Aljabri A, Abushanab WS, Ghandourah E, Taha MA, et al. (2024) A comprehensive study of Al-Cu-Mg system reinforced with nano-ZrO_2 particles synthesized by powder metallurgy technique. Scientific Reports 14(1): 2862.

3. Yang Y, Xiong X, Chen J, Peng X, Chen D, et al. (2023) Research advances of magnesium and magnesium alloys worldwide in 2022. Journal of Magnesium and Alloys 11(8): 2611-2654.

4. Park SH, Kim YJ, Kim HJ, Jin SC, Lee JU, et al. (2023) Recent research progress on magnesium alloys in Korea: A review. Journal of Magnesium and Alloys 11(10): 3545-3584.

5. Hassan SF, Gupta M (2005) Enhancing physical and mechanical properties of Mg using nanosized Al_2O_3 particulates as reinforcement. Metallurgical and Materials Transactions A 36: 2253-2258.

6. Hassan SF, Gupta M (2006) Effect of type of primary processing on the microstructure, CTE and mechanical properties of magnesium/alumina nanocomposites. Composite Structures 72(1): 19-26.

7. Abdizadeh H, Ebrahimifard R, Baghchesara MA (2014) Investigation of microstructure and mechanical properties of nano MgO reinforced Al composites manufactured by stir casting and powder metallurgy methods: A comparative study. Composites Part B: Engineering 56: 217-221.

8. Dirisenapu G, Reddy SP, Dumpala L (2019) The effect of B_4C and BN nanoparticles on the mechanical and microstructural properties of Al7010 hybrid metal matrix. Materials Research Express 6: 105089.

9. Baradeswaran A, Elaya Perumal A (2013) Influence of B_4C on the tribological and mechanical properties of Al 7075–B_4C composites. Composites Part B: Engineering 54: 146-152.

10. Habibi MK, Hamouda AS, Gupta M (2013) Hybridizing boron carbide (B_4C) particles with aluminum (Al) to enhance the mechanical response of magnesium based nano-composites. Journal of Alloys and Compounds 550: 83-93.

11. Latip NA, Sofian AH, Ali MF, Ismail SN, Idris DND (2020) Promising utilization of fly ash as an eco-friendly sustainable additive for enhancement in flame retardancy of composite production: A review. IOP Conference Series: Materials Science and Engineering 736: 052009.

12. Nagaraja S, Nagegowda KU, Kumar VA, Alamri S, Afzal A, et al. (2021) Influence of the fly ash material inoculants on the tensile and impact characteristics of the aluminum AA 5083/7.5SiC Composites. Materials 14(9): 2452.

13. Doroshenko YV, Kogut GM, Rybitskyi IV, Tarayevs'kyy OS, Pyrig TY (2021) Numerical investigation on erosion wear and strength of main gas pipelines bends. Physics and Chemistry of Solid State 22(3): 551-560.

14. Gencel O, Yavuz Bayraktar O, Kaplan G, Benli A, Martínez-Barrera G, et al. (2021) Characteristics of hemp fibre reinforced foam concretes with fly ash and Taguchi optimization. Construction and Building Materials 294: 123607.

15. Patil A, Banapurmath NR, Hunashyal AM, Hallad S (2020) Enhancement of mechanical properties by the reinforcement of fly ash in aluminium metal matrix composites. Materials Today: Proceedings 24(2): 1654-1659.

16. Zan YN, Zhang Q, Zhou YT, Wang QZ, Xiao BL, et al. (2019) Enhancing high-temperature strength of B_4C–6061Al neutron absorber material by in-situ Mg(Al)B_2. Journal of Nuclear Materials 526: 151788.

17. Guo H, Zhang Z, Zhang Y, Cui Y, Sun L, et al. (2020) Improving the mechanical properties of B_4C/Al composites by solid-state interfacial reaction. Journal of Alloys and Compounds 829: 154521.

18. Chen HS, Wang WX, Nie HH, Zhou J, Li YL, et al. (2018) Microstructure evolution and mechanical properties of B_4C/6061Al neutron absorber composite sheets fabricated by powder metallurgy. Journal of Alloys and Compounds 730: 342-351.

19. Gao M, Kang H, Chen Z, Guo E, Fu Y, et al. (2020) Enhanced strength-ductility synergy in a boron carbide reinforced aluminum matrix composite at 77 K. Journal of Alloys and Compounds 818: 153310.

20. Aatthisugan I, Razal Rose A, Selwyn Jebadurai D (2017) Mechanical and wear behaviour of AZ91D magnesium matrix hybrid composite reinforced with boron carbide and graphite. Journal of Magnesium and Alloys 5(1): 20-25.

21. Somekawa H, Singh A, Inoue T (2014) Enhancement of toughness by grain boundary control in magnesium binary alloys. Materials Science and Engineering: A 612: 172-178.

22. Lee B, Lee D, Lee JH, Ryu HJ, Hong SH (2016) Enhancement of toughness and wear resistance in boron nitride nanoplatelet (BNNP) reinforced Si_3N_4 nanocomposites. Scientific Reports 6: 27609.

23. Aydin F, Turan ME (2019) The effect of boron nitride on tribological behavior of Mg matrix composite at room and elevated temperatures. Journal of Tribology 142(1): 011601.

24. Sun Y, Cevik E, Turen Y, Ahlatci H, Turan ME, et al. (2021) Influence of GNPs and B_4C reinforcements on mechanical, thermal and wear properties of magnesium matrix composite produced by powder metallurgy. Journal of Composite Materials 55(26): 3881-3891.

25. Shuai C, Wang B, Bin S, Peng S, Gao C (2020) TiO_2-induced in situ reaction in graphene oxide-reinforced AZ61 biocomposites to enhance the interfacial bonding. ACS Applied Materials & Interfaces 12(20): 23464-23473.

26. Radha R, Sreekanth D, Bharti N, Rana A (2019) Mg-1Sn/Al_2O_3 biodegradable composites: effect of Al_2O_3 addition on mechanical, *in-vitro* corrosion and bioactivity response. Materials Research Express 6: 105411.

27. Tun KS, Tungala V, Nguyen QB, Chan J, Kwok R, et al. (2011) Enhancing tensile and compressive strengths of magnesium using nanosize (Al_2O_3+Cu) hybrid reinforcements. Journal of Composite Materials 46(15): 1879-1887.

28. Li J, Xia C, Zhang Y, Wang M, Wang H (2012) Effects of TiO_2 coating on microstructure and mechanical properties of magnesium matrix composite reinforced with $Mg_2B_2O_5$w. Materials & Design 39: 334-337.

29. Sahu MK, Sahu RK (2020) Experimental investigation, modeling, and optimization of wear parameters of B_4C and fly-ash reinforced aluminum hybrid composite. Frontiers in Physics 8.

30. Umunakwe R, Umunakwe IJ, Nwigwe US, Eze WU, Oyetunji A (2020) Review on properties of hybrid aluminum-ceramics/fly ash composites. AIMS Materials Science 7(6): 859-870.

31. Tun KS, Gupta M (2007) Improving mechanical properties of magnesium using nano-yttria reinforcement and microwave assisted powder metallurgy method. Composites Science and Technology 67(13): 2657-2664.

32. Dieringa H (2011) Properties of magnesium alloys reinforced with nanoparticles and carbon nanotubes: A review. Journal of Materials Science 46: 289-306.

33. Merola M (1996) Theoretical evaluation of the physical properties of copper-lead rheocast alloys. Materials Science and Engineering: A 214(1-2): 181-185.

34. Moustafa EB, Ghandourah E, Youness RA, Melaibari AA, Taha MA (2022) Ultralight functionally graded hybrid nanocomposites based on yttrium and silica-reinforced $Mg_{10}Li_5Al$ Alloy: Thermal and tribomechanical properties. Materials 15(24): 9052.

35. Moustafa EB, Ghandourah EI, Hammad AH (2022) The effect of V_2O_5 on the BaO–Al_2O_3–P_2O_5 glass for use in optical filters. Journal of Materials Research and Technology 19: 4905-4914.

36. Rizkalla HL, Abdulwahed A (1996) Some mechanical properties of metal-nonmetal Al SiO_2 particulate composites. Journal of Materials Processing Technology 56(1-4): 398-403.

37. Moustafa EB, Sharaf M, Alsoruji G, Mosleh AO, Mohamed SS, et al. (2023) Microstructural and mechanical characterization of the dissimilar AA7075 and AA2024 aluminum alloys reinforced with different carbide particles welded by friction stir welding. Journal of Composites Science 7.