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Review Article

Magnezyum Matrisli Kompozitlerdeki Gelişmeler: Deneysel Çalışmaların İncelenmesi

Progress in magnesium matrix composites: A review of experimental studies

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Öz
Son yıllarda hafif malzemelere olan ihtiyaç giderek artmakta olup araştırmacılar yüksek performanslı düşük ağırlıklı malzemeler geliştirmek için çalışmaktadır. Magnezyum (Mg) matrisli kompozitler düşük yoğunluk, yüksek spesifik mukavemet, iyi aşınma performansları sayesinde havacılık, otomotiv ve biyomedikal alanlarında büyük kullanım potansiyeline sahiptir. Mg matrisli kompozitlerin üretimi için seramik takviyeler yaygın olarak kullanılmakta olup, karıştırma döküm ve toz metalurjisi gibi geleneksel yöntemlerle beraber eklemeli imalat yöntemleri de son yıllarda kullanılmaktadır. Üretim yöntemi, üretim parametreleri, takviye çeşidi, takviye partikül boyutu, takviye oranı, üretilen kompozitlerin özelliklerini doğrudan etkilemektedir. Bu çalışma, Mg matrisli kompozitlerin mekanik, aşınma ve korozyon performanslarını incelemektedir. Ayrıca, bu çalışmada Mg matrisli kompozitlerle ilgili kısıtlamalar, çözüm yolları ve gelecekteki çalışmalara yönelik öneriler hakkında da ayrıntılı bilgi verilmiştir.

Anahtar Kelimeler
Mg matrisli kompozitler, Mikroyapı, Mekanik, Aşınma, Korozyon

Abstract
In recent years, the need for lightweight materials has been increasing, and researchers have been working to develop high-performance, low-weight materials. Magnesium (Mg) matrix composites have great potential for use in the aerospace, automotive and biomedical fields owing to their low density, high specific strength and enhanced wear performance. Ceramic reinforcements are widely used for the production of Mg matrix composites, and additive manufacturing methods have been used in recent years, along with traditional methods such as stir casting and powder metallurgy. The production method, production parameters, reinforcement type, size and content directly affect the properties of the produced composites. This study examines the mechanical, wear and corrosion performances of Mg matrix composites. In addition, detailed information is provided in this study regarding the challenges, solutions and future work suggestions related to Mg matrix composites.

Key Words
Mg matrix composites, Microstructure, Mechanical, Wear, Corrosion

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1. Introduction

Magnesium (Mg) alloys are used in the automotive, aerospace, biomedical and electronic industries due to their several advantages such as low density, perfect castability, high damping ability, recyclability, excellent machinability, electromagnetic shielding and biocompatibility [1-4]. However, besides the advantages of Mg alloys, some important disadvantages limit their use. Low strength and plasticity, poor wear and corrosion resistance are major disadvantages of Mg alloys [5-7]. To improve the weak properties of Mg alloys, researchers have developed Mg matrix composites offering improved specific strength, elastic modulus, wear resistance, and high-temperature performance by adding different reinforcements [8-10]. Up to now, more than 50 reinforcement elements have been used for Mg matrix composites, the most commonly used are SiC, B_4C, TiB_2, Al_2O_3, GNPs, and Ti [11-13]. The size of the reinforcement particles and the reinforcement content are of critical importance, and the determination of the optimum reinforcement content has been studied for many years. The highest reinforcement content does not always mean having the best properties; on the contrary, it can significantly reduce the properties of the composite due to agglomeration [14,15]. There are different production methods. Powder metallurgy and friction stir processing are solid-state processes; stir casting and infiltration are liquid-state production methods. Production methods should be selected by considering features such as reinforcement distribution, reinforcement content, interfacial reactions, cost and product size [16]. Additionally, additive manufacturing methods have become popular in recent years due to their short production cycle, high material utilization rate, and design freedom [17]. Many novel articles are published every year on Mg matrix composites. The examination of these studies is very important in terms of new reinforcement elements used in Mg matrix composites, current production methods and new approaches. This review explores the effect of different reinforcement elements on the mechanical, wear and corrosion performance of Mg matrix composites.

2. Recent studies on Mg matrix composites

The matrix and reinforcement materials used to produce Mg matrix composites, production methods and experimental studies are given in Table 1. It is seen that the most commonly used matrix alloy and reinforcement particles are AZ91 and SiC. However, different alloys such as Mg-8Al-1Sn and Mg-8Al-1Sm were used as matrix materials and different reinforcements such as TiNi, UCNPs and $CaSiO_3$ were used. Researchers still widely use traditional methods such as powder metallurgy and stir casting. However, additive manufacturing methods such as binder jetting additive manufacturing and laser powder bed fusion attract attention as novel production methods. The most studied subjects are microstructure, mechanical, wear and corrosion, respectively. Investigation of elevated temperature mechanical and wear properties and prediction of mechanical properties by machine learning are innovative studies.

Table 1. Production methods and applied tests for the Mg matrix composites

Matrix	Reinforcement	Production methods	Study and tests	Ref.
AZ91 (37.44 μm)	SiC (0.5, 1, 1.5, 2, 2.5% - 5 μm)	Binder jetting additive manufacturing	Microstructure and phase analysis: OM, SEM, XRD Mechanical: Tensile and compression	[18]
Mg-5Al	Ti (4 vol%, 15-53 μm)	Powder metallurgy	Microstructure and phase analysis: OM, SEM, EBSD, XRD Mechanical: Tensile	[19]
Mg-6Zn	GNPs (0.32 and 0.61 vol%)	In situ	Microstructure and phase analysis: OM, SEM, TEM, XRD Mechanical: Tensile	[20]
ZK60	Al (3.6 wt% Al-45 μm) SiC (0.5, 1, 2 vol%-40 nm)	Stir casting	Microstructure and phase analysis: OM, SEM, IPF, PF, TEM Mechanical: Tensile	[21]
AZ61 (70 μm)	TiC (1 wt%- 50 nm)	Powder metallurgy	Microstructure: OM, SEM, IPF, TEM Mechanical: Hot compression	[22]
AZ91	Ti-6Al-4V (2 vol%, 5-18 μm)	Semi-solid stir casting	Microstructure and phase analysis: SEM, OM, XRD, IPF Mechanical: Tensile	[23]
AZ91 (42 μm)	TiC (2 wt%, 2-4 μm)	Laser powder bed fusion	Microstructure and phase analysis: SEM, TEM, XRD, IPF Mechanical: Tensile	[24]
AZ91 (35 μm)	SiC (1, 2, 3 wt%- 272 nm)	Stir casting	Microstructure and phase analysis: XRD, SEM, EBSD, TEM Mechanical: Tensile	[25]

Table 1 (continued)

Matrix	Reinforcement	Production methods	Study and tests	Ref.
Pure Mg (100-300µm)	$Ti_{49.2}Ni_{50.8}$ (5, 10, 15, 20, 25 vol.%-30 µm)	Powder metallurgy (Hot pressing)	Microstructure and phase analysis: XRD, SEM, DSC Mechanical: Compression	[26]
AZ31	Fly ash	Friction stir processing	Microstructure and phase analysis: OM, SEM, Mechanical: Tensile Optimization and prediction: RSM, GA-ANN, GA-ANFIS	[27]
Mg-8Al-1Sn	SiC (0.25, 0.5, 1 vol.%- 40 nm)	Powder metallurgy	Microstructure and phase analysis: SEM, TEM, XRD Mechanical: Compression Wear: Pin-on-disc	[28]
Mg-8Al-1Sm	GNPs (0.4 wt%)	Powder metallurgy (Hot pressing)	Microstructure and phase analysis: OM, SEM, XRD, TEM, IPF Mechanical: Tensile	[29]
ZE41	TiB_2	In situ	Microstructure and phase analysis: SEM, TEM, XRD, EBSD Wear: Pin-on-disc (Elevated temperature)	[30]
ZE41	TiB_2 (10 wt%)	In situ	Microstructure and phase analysis: OM, SEM, TEM, XRD, EBSD Wear: Pin-on-disc	[31]
Mg (<180 µm)	Al_2O_3, MnO_2, SiO_2, Si_3N_4 and Y_2O_3 (10 vol.%, 3-4 µm)	Powder metallurgy	Microstructure and phase analysis: SEM, XRD, EBSD Wear: Ball-on-disc	[32]
AZ31	WC (0.5, 1, 2 wt%-20 nm)	Stir casting	Microstructure: SEM Wear: Pin-on-disc	[33]
Mg-1Sn	HA (2, 5, 7 wt%-10-15 µm)	Powder metallurgy	Wear: Pin-on-disc	[34]
ZE41	TiB_2 (10 wt%-765 nm)	In situ	Microstructure and phase analysis: SEM, EBSD, TEM, XRD Corrosion: Immersion, EIS, PDP Mechanical: Tensile	[35]
Mg-4Zn	UCNPs ($NaYF_4$:Yb^{3+}, Er^{3+}) (10 wt.%-<250 nm)	Powder metallurgy (Hot pressing)	Microstructure and phase analysis: SEM, XRD Corrosion: Immersion, In vitro, In vivo	[36]
Pure Mg (<100 µm)	$CaSiO_3$ (10, 12.5, 15 wt%-<100 µm), Al_2O_3 (2.5, 5 wt%-25 nm)	Powder metallurgy	Microstructure and phase analysis: OM, SEM, XRD Mechanical: Compression Corrosion: PDP, immersion	[37]
Mg-1Zn	CaO (0.5, 1 wt%)	Stir casting	Microstructure and phase analysis: OM, SEM, XRD, EBSD, TEM Mechanical: Tensile Corrosion: PDP, EIS immersion	[38]
Mg-1Zn-0.4Ca	MgO (1wt%)	Stir casting	Microstructure and phase analysis: OM, XRD, SEM Mechanical: Tensile Corrosion: PD, EIS, Immersion	[39]

OM: Optical microscopy SEM: Scanning electron microscopy EBSD: Electron backscatter diffraction IPF: Inverse pole figure PF: Pole figure TEM: Transmission electron microscopy XRD: X-ray diffraction DSC: Differential Scanning Calorimetry RSM: Response Surface Methodology GA-ANN: Genetic algorithm artificial neural network GA-ANFIS: Genetic algorithm adaptive neuro-fuzzy inference system PDP: Potentiodynamic polarization EIS: Electrochemical impedance spectroscopy HA: Hydroxyapatite

Brief information is provided below for a better understanding of production processes and production parameters. Li et al. [18] produced AZ91/SiC composites by binder jetting additive manufacturing. An ultrasonic device was used to disperse SiC, which was stirred three times for 15 min each time by a mechanical mixer. The binder jetting method used a lower feed piston to supply powder and a reverse rotating cylinder to spread the composite to a thickness of 100 μm per layer. Finally, the powder bed was dried at 50°C for 2 h for the removal treatment. Zhou et al. [19] produced Mg-5Al/Ti composites by powder metallurgy. The powders were compacted under 400 MPa pressure, and then sintered at 600 °C for 2 h. The sintered materials were extruded at 350 °C with a reduction ratio of 13. Li et al [20] manufactured Mg-6Zn/GNPs composites by in situ method. The authors reported that GNPs were synthesized by in situ reaction of CO_2 vapour and Mg-6Zn liquid by sending CO_2 gas into the liquid melt. After production, the materials were extruded at 380°C with an extrusion ratio of 16:1 and an extrusion speed of 0.1 mms^{-1}. The extruded materials were firstly solution heat treated at 340 °C for 3h and water quenched, then aged at 200 °C for 0-24 hours. Sun et al. [21] produced ZK60/Al and ZK60/SiC by stir casting. Vacuum sintering was used in the preparation of the master alloy. Before extrusion, the casted samples were heat-treated at 450 °C for 8h. After that, the samples were extruded with an extrusion ratio of 4:1, punch speed of 1 mm/s, and temperature of 350°C. Zhao et al. [22] produced AZ61/TiC composites by powder metallurgy. Firstly, the ball milling was applied for 20 h at 150 rpm. After that, the powders were pressed at 650 MPa and sintered at 520 °C for 2 h. The sintered products were then hot pressed at 400°C with 300 MPa pressure for 15 min. Finally, the samples were extruded at 350°C with a 20:1 extrusion ratio. Zheng et al. [23] manufactured AZ91/Ti6Al4V composites by semi-solid stir casting. The casted composites were heat treated at 350 °C for 24 h. After that, the samples were extruded with extrusion ratios of 25:1, 40:1, 60:1 at 350°C and an extrusion speed of 0.5 mm/s. Gu et al. [24] manufactured AZ91/TiC composites by laser powder bed fusion. Firstly, the AZ91 and TiC powders were mixed by ball milling. The rotation speed and time were 60 rpm and 1 h, respectively. For the production, laser power, scan speed, layer thickness, and hatch spacing were 100-140W, 200-400 mm/s, 30 μm and 100 μm, respectively. Xu et al. [25] produced Mg-9Al-1Zn/SiC composites by stir casting. After casting, heat treatment was applied at 400 °C for 10 h, and then the samples were extruded at 400 °C with an extrusion speed of 1 m/min and an extrusion ratio 40:1. Kelen et al. [26] manufactured Mg/TiNi composites by hot pressing. The composite materials were pressed with a pressure of 50 MPa at 600 °C for 1 hr. Sagar et al. [27] used friction stir processing for the production of AZ31/Fly ash composites. The authors used a tool rotational speed of 850-1650 rpm, a tool travel speed of 25-45 mm/min, and a number of passes of 2-4. Ma et al. [28] produced Mg-8Al-1Sn/SiC composites by powder metallurgy. The cold compaction was applied at a pressure of 70 MPa for 2 min. The sintering was applied at 733 K for 45 min. Finally, the composites were pressed at 105 MPa for 10 min. Yu et al. [29] synthesized Mg-8Al-1Sm/GNPs composite by powder metallurgy. The ball-milled powders were hot-pressed at a pressure of 250 MPa, at 585 °C for 2 hr. The produced billets were extruded at extrusion temperatures of 300, 350 and 400 °C, with an extrusion ratio of 2 and an extrusion speed of 1 mm/s. Panigrahi et al. [30] produced ZE41/TiB_2 composites by in-situ method. Ball-milled Ti and B powders were placed together with ZE41 ingot, and production was carried out by liquid state bottom pouring casting. After production, partial warm rolling was applied. Finally, materials were heat treated for 2 h at 300 °C and followed by aging at 175 °C up to 110 h. Somekawa et al. [32] produced Mg matrix composites by powder metallurgy. The authors first pressed the powders with a hand-pressing machine and then held them at 523 K for 1800 s. Then, they pressed them with 1500 kN for 300 s. The produced materials were extruded with an extrusion ratio of 16:1 and an extrusion speed of 0.2 mm/s. Goyal et al. [34] manufactured Mg1Sn/HA composites through powder metallurgy. The powders were mixed by ball milling. The mixed powders were pressed with 100 MPa compaction pressure. Sintering was applied at 460 °C for 30 min in an argon atmosphere. Wang et al. [36] produced Mg-4Zn/UCNPs via powder metallurgy. The sintering temperature was 550 °C. Rodríguez-Reyes et al. [37] produced Mg/$CaSiO_3$-Al_2O_3 hybrid composite by powder metallurgy. The milling was applied at 450 rpm for 4 h. The ball-milled powders were cold compacted and sintered at 450°C for 60 min. Lyu et al. [38] produced MgZn/CaO composites by casting method. The solution heat treatment was applied for 24 h at 400 °C and 450°C, followed by quenching in warm water. The heat-treated composites were extruded at 300°C with extrusion ratio of 56:1 and extrusion rate of 1 mm/s. Lyu et al. [39] produced Mg1Zn0.4Ca/1MgO composite by stir casting. The casted sample was solution treated at 420 °C for 16 h, followed by water quenching. The heat-treated samples were extruded at 280 °C, 310 °C, and 330 °C. The extrusion speed and extrusion ratio were 2 mm/s and 29:1, respectively.

3. Properties of Mg matrix composites

3.1. Mechanical properties

Table 2 and Table 3 give the mechanical properties obtained by tensile and compression tests, respectively. Li et al. [18] found the highest tensile strength for AZ91/SiC composites at 1% SiC content, and the strength decreased for higher reinforcement contents. The increase in tensile strength was attributed to grain refinement and load transfer mechanism. If the applied stress exceeds the interfacial bond strength between the matrix and the reinforcement, the reinforcement is pulled out from the matrix. Li et al. [20] investigated the effect of aging time on the tensile strength of Mg-6Zn/GNPs composites. It was reported that the aging treatment increased yield strength and tensile strength, while elongation was reduced. The YS and UTS increase with increasing GNPs content. The authors reported that there was a large difference between the grain sizes of the alloys and composites. It is known that material with a smaller grain size has larger grain boundary area, which better inhibits dislocation movements. In addition, the presence of secondary phases inhibits the slip of dislocations and increases the deformation resistance of the metal [40]. It was noted that smaller-sized and more closely spaced precipitates result in greater strengthening. Considering the effect of GNPs, high GNPs content has high-density precipitates, and the Orowan strengthening effect is higher. Sun et al. [21] investigated the tensile performance of the ZK60/SiC composites. The addition of SiC leads to an increase in YS and UTS. The main strengthening mechanisms are thermal mismatch, grain

refinement, Orowan, and load transfer. The enhanced ductility of composites was attributed to grain refinement and release of stress concentration. Zhao et al. [22] explored the hot deformation behaviour of AZ61/TiC composites by compression at 250°C-400°C and strain rates ranging from 10^{-4} to 0.1 s^{-1}. They reported that the optimum parameters of hot working were 260-320°C and 0.0009-0.03 s^{-1}. Continuous dynamic recrystallization and discontinuous dynamic recrystallization mechanisms are detected during the hot deformation of bimodal AZ61/TiC. Zheng et al. [23] explored the effect of extrusion ratio on the tensile properties of AZ91/Ti-6Al-4V composites. It was reported that the increase in extrusion ratio increased yield strength and tensile strength. Grain refinement and mismatch in the coefficient of thermal expansion were identified as strengthening reasons. The elongation increases up to an extrusion ratio of 40 and decreases thereafter. This is attributed to the complete refinement of grains, which decreases the plasticity. Gu et al. [24] studied the effect of LPBF scan speed on the tensile strength of the AZ91/TiC composites. The maximum tensile strength was obtained for the highest scan speed. The strengthening mechanisms are grain refinement, Orowan strengthening, dislocation strengthening and load transfer. The enhanced elongation was attributed to: a) reduction in metallurgical defects. This reduces the probability of crack initiation during deformation and b) grain refinement. The increase in grain boundaries prevents crack formation. Xu et al. [25] investigated the interfacial bonding on the mechanical properties of Mg9Al1Zn/SiC composites. The yield strength increases with increasing SiC content. The authors reported that the strengthening mechanisms are grain refinement (Hall-Petch), load transfer, dislocation strengthening, and Orowan. The Hall-Petch mechanism is reported to have the highest effect on yield strength. The reason why the experimental strength is lower than the theoretical strength is attributed to the brittle Al_4C_3 phase. This phase can not resist high load and fractures, which reduces the yield strength. The reason for the decrease in tensile strength at 2% reinforcement is excessive interface reactions. Brittle phases lead to crack propagation and reduce tensile strength. Kelen et al. [26] investigated the effect of test temperature on the compression strength of the Mg/TiNi composites. The authors reported that TiNi did not significantly reduce the ductility of pure Mg when compared with other metallic reinforcements. This is attributed to the absence of detrimental secondary phases or intermetallic compounds at the matrix and reinforcement interface and the absence of micropores and cracks. For composite materials, the yield strength increases up to 100°C. This was attributed to the stress-induced martensitic transformation. The Ti_3Ni_4 phase leads to an increase in strength for composite materials.

Sagar et al. [27] used machine learning models to optimize and predict the tensile strength of AZ31/FA composites. The prediction accuracy of GA-ANN and GA-ANFIS was 98.50 % and 98.42%, respectively. Machine learning is a sub-branch of artificial intelligence and is used for many purposes such as prediction of wear, mechanical and corrosion properties for different materials, simulation, image processing and design of new materials [41-45]. The use of machine learning for Mg matrix composites is a hot topic, and it will maintain its importance for the next 10 years.

Yu et al. [29] investigated the effect of extrusion temperature on the tensile strength of Mg-8Al-1Sm/0.4GNPs composites. The maximum strength was obtained for the extrusion temperature of 300°C, strength decreased above 300 °C. As the extrusion temperature increased to 350 and 400°C, complete recrystallization was observed. The dislocation density decreased, the grain size increased, and the number of grain boundaries that prevented dislocations during deformation decreased. As a result, the yield strength decreased. Panigrahi et al. [35] immersed tensile test samples in 0.1 M NaCl solution for 15 min, 1, 2, 3 h and then applied tensile tests for ZE41 and ZE41/TiB_2 composite. As the immersion time increased, the mechanical properties of the base alloy decreased significantly. The mechanical properties of ZE41/TiB_2 composite were higher than that of the base alloy. The high-stress corrosion cracking resistance of the composite was attributed to blockage of dislocation, twins and corrosion tunnels and formation of back stress, which led to crack deflection tendency. Rodríguez-Reyes et al. [37] reported a significant increase in ultimate compressive strength for Mg/$CaSiO_3$-Al_2O_3 composites, and this was attributed to reduction in grain size and enhanced load-bearing capacity by homogenous distributed reinforcement particles.

Table 2. Tensile test results of Mg matrix composites

Materials	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation (%)	Ref.
AZ91		~ 70	~ 0.7	[18]
AZ91 / 0.5% SiC		~110	~2	
AZ91 / 1% SiC	-	172.22	4.2	
AZ91 / 1.5% SiC		~143	~3.1	
AZ91 / 2% SiC		~90	~1.5	
AZ91 / 2.5% SiC		~86	~1	
Mg-5Al/ 4vol%Ti	115	252	12.5	[19]
Mg-6Zn (0 h)	152	283	21.4	[20]
Mg-6Zn (4 h)	200	295	9.9	
Mg-6Zn/0.32 vol% GNPs (0 h)	158	292	18.2	
Mg-6Zn/0.32 vol% GNPs (3.5h)	220	299	9.4	
Mg-6Zn/0.61 vol% GNPs (0 h)	181	305	9.4	
Mg-6Zn/0.61 vol% GNPs (3 h)	274	324	8.3	

Table 2 (continued) Materials	**Yield strength (MPa)**	**Ultimate tensile strength (MPa)**	**Elongation (%)**	**Ref.**
ZK60	280	325	8.4	[21]
ZK60/3.6wt%Al	430	435	1.5	
ZK60/0.5vol%SiC	287	345	7.96	
ZK60/1vol%SiC	291	356	9.03	
ZK60/2vol%SiC	295	346	9.22	
AZ91/2 vol% Ti-6Al-4V (As cast)	101	154	2.5	[23]
AZ91/2 vol% Ti-6Al-4V (ER25)	237	333	7.1	
AZ91/2 vol% Ti-6Al-4V (ER40)	257	357	9.8	
AZ91/2 vol% Ti-6Al-4V (ER60)	266	364	7.0	
AZ91		~295	~1.4	[24]
AZ91/ 2 wt%TiC (200 mm/s)	-	~331	~3.6	
AZ91/ 2 wt%TiC (300 mm/s)		~339	~3.5	
AZ91/ 2 wt%TiC (400 mm/s)		~345	~4.1	
AZ91	245	341	12.5	[25]
AZ91 / 1wt%SiC	250	350	15.1	
AZ91/ 2 wt%SiC	253	344	9.1	
AZ91/ 3 wt%SiC	258	340	6	
Mg8Al1Sm/0.4wt%GNPs (S)	82	134	5.4	[29]
Mg8Al1Sm/0.4 wt%GNPs (E) 300°C	286	334	9.8	
Mg8Al1Sm/0.4 wt%GNPs (E) 350°C	261	312	7.1	
Mg8Al1Sm/0.4 wt%GNPs (E) 400°C	231	295	7.5	
Mg/10 vol%Al_2O_3	111			[32]
Mg/10 vol%MnO_2	121			
Mg/10 vol%Si_3N_4	108	-	-	
Mg/10 vol%SiO_2	106			
Mg/10 vol%Y_2O_3	109			
ZE41 (Air)	105	202	10.5	[35]
ZE41 (15 min)	-	-	9.2	
ZE41 (1 h)	-	-	4.9	
ZE41 (2 h)	-	-	3.3	
ZE41 (3 h)	12	23	1.9	
ZE41 / 10 wt%TiB_2 (Air)	125	246	8	
Mg-1Zn	219	259.6	16.9	[38]
Mg-1Zn/0.5 wt%CaO	334.9	314	8.9	
Mg-1Zn/1 wt%CaO	367.7	340.1	4.6	
Mg-1Zn-0.4Ca/1 wt%MgO (ET: 280°C)	305	312	15.1	[39]
Mg-1Zn-0.4Ca/1 wt%MgO (ET: 310°C)	249	271	15.2	
Mg-1Zn-0.4Ca/1 wt%MgO (ET: 330°C)	181	240	15.4	

S: Sintered E: Extruded ER: Extrusion rate ET: Extrusion temperature

Table 3. Compression test results of Mg matrix composites

Materials	**Yield strength (MPa)**	**Ultimate compressive strength (MPa)**	**Ductility %**	**Ref.**
AZ91		165.85	-	[18]
AZ91/0.5%SiC		~180		
AZ91/1%SiC	-	~210		
AZ91/1.5%SiC		235		
AZ91/2%SiC		~200		
AZ91/2.5%SiC		~190		
Pure Mg	56	220	29.7	[26]
Mg/5TiNi (25°C)	60	232	26.6	
Mg/10TiNi	67	250	24	

Table 3 (continued) Materials		Yield strength (MPa)	Ultimate compressive strength (MPa)	Ductility %	Ref.
Mg/15TiNi	(25°C)	74	262	22	
Mg/20TiNi		80	273	19	
Mg/25TiNi		86	296	17.8	
Pure Mg		48	158	38.5	
Mg/5TiNi		75	165	34.6	
Mg/10TiNi		84	185	31.4	
Mg/15TiNi	(100°C)	100	198	26.8	
Mg/20TiNi		110	216	22.8	[26]
Mg/25TiNi		124	230	17.2	
Pure Mg		44	116	38.8	
Mg/5TiNi		70	130	36.8	
Mg/10TiNi		80	135	31.9	
Mg/15TiNi	(150°C)	84	143	28.7	
Mg/20TiNi		97	161	24.8	
Mg/25TiNi		107	184	22.3	
Pure Mg		34	80	39.4	
Mg/5TiNi		62	102	37.8	
Mg/10TiNi	(200°C)	67	117	35.6	
Mg/15TiNi		75	129	30.8	
Mg/20TiNi		90	144	27	
Mg/25TiNi		97	162	24.4	
(vol.%)					
Mg8Al1Sn		164	300	9.8	[28]
Mg8Al1Sn /0.25 vol%SiC		172	377	13.0	
Mg8Al1Sn /0.5 vol%SiC		176	424	15.7	
Mg8Al1Sn /1 vol%SiC		178	387	12.5	
Mg		-	186.33	-	[37]
Mg/15 wt%$CaSiO_3$			243.90		
Mg/12.5wt%$CaSiO_3$-2.5wt%Al_2O_3			329.13		
Mg/10 wt%$CaSiO_3$-5 wt%Al_2O_3			319.50		

3.2. Wear performance

The most important test parameters affecting the wear parameters are load, sliding speed, wear temperature, and wear environment. The changes in these parameters directly affect the wear rate, and the analysis of parameter variables is critical for tribological performance [46-49]. The findings of wear studies are briefly presented below. Panigrahi et al. [30] studied the elevated temperature wear performance of ZE41/TiB_2 composites. The wear rate increases with increasing load for all materials. The best wear performance was obtained in the ZE41/ TiB_2 (peak aged) composite. This was attributed to the presence of fine bimodal precipitates. Additionally, the highest wear rate was obtained at the highest wear temperature (400 °C). The enhanced high-temperature wear performance of ZE41/TiB_2 (peak aged) was attributed to the uniformly distributed in situ TiB_2 particles and bimodal-sized precipitates. Generally, abrasion, adhesion and oxidation wear mechanisms are present for low temperature and low load, while delamination and melt wear mechanisms are dominant for high temperature and high load. Panigrahi et al. [31] also explored the synergistic effect of in situ TiB_2 particles and nano precipitation on the tribological performance of ZE41/TiB_2 composites. It was reported that ZE41/TiB_2 composite had a high wear performance under high loads compared to base alloy. The in-situ TiB_2 particles resist the propagation of fatigue-induced cracks and reduce heavy delamination. Somekawa et al. [32] reported that a sudden drop in the coefficient of friction of Mg matrix composites reinforced by different particles. It was reported that as wear progresses, the friction coefficient suddenly drops to ~0.1. Krishnan et al. [33] investigated the wear performance of AZ31/WC composites under loads of 10, 20, 30 and 40 N. The wear performance is enhanced with increasing WC content. This was attributed to the high hardness and wear resistance of WC particles. The increase in the load-carrying capacity of composite materials has also increased wear performance. Goyal et al. [34] studied the tribological performance of Mg-1Sn/HA composites. The addition of HA particles improves the wear performance. The improved wear

performance is attributed to the oxide layer formed during sliding, acting as a lubricant [50]. Abrasion and delamination are wear mechanisms for base alloy, and oxidation is the main mechanism for Mg1Sn/7HA composite.

3.3. Corrosion performance

The corrosion performance of Mg-based materials is poor, especially in NaCl solutions. Although researchers have improved mechanical and wear performance by adding reinforcement particles, this does not always mean increased corrosion performance. There are studies in which the corrosion rate increases with the addition of reinforcement for different reasons [13,51-54]. Therefore, a detailed evaluation of the corrosion performance is important. It is strongly recommended that electrochemical test results for Mg-based materials be supported by immersion or H_2 evolution tests [55-58].

Panigrahi et al. [35] performed the electrochemical (PDP and EIS) and immersion tests for ZE41 and ZE41/TiB_2. The weight loss of ZE41/TiB_2 composite is significantly lower than ZE41. For composite material, micro galvanic corrosion is reduced by fine and uniformly distributed TiB_2 particles, which act as insulators. Wang et al. [36] investigated the immersion behaviour of Mg-4Zn and Mg-4Zn/UCNPs composite in simulated body fluid at 7, 14 and 21 days. The corrosion rate of the composite was lower than base alloy. This is attributed to the homogeneously distributed nanoparticles preventing matrix deformation and strong interfacial bonding between the matrix and reinforcement. Rodríguez-Reyes et al. [37] investigated the corrosion performance of Mg/$CaSiO_3$ and Mg/$CaSiO_3$-Al_2O_3 composites by potentiodynamic polarization and immersion tests. It was reported that the Mg/10$CaSiO_3$-5Al_2O_3 hybrid composite has the lowest corrosion current density (122 μA/cm^2) and highest corrosion resistance. The immersion test showed that the lowest corrosion rate was obtained for Mg/10$CaSiO_3$-5Al_2O_3. The enhanced corrosion performance was attributed to the formation of a protective layer during the immersion test. The authors reported that the protective layer is $Mg(OH)_2$, which acts as a protective barrier and reduces the rate of degradation. Lyu et al. [38] investigated the corrosion performance of Mg-1Zn/ CaO composites by electrochemical and immersion tests. The samples were immersed in SBF solution for 1 hour and 7 days, and then potentiodynamic polarization tests were performed. For 1 hr, the corrosion rate decreases at 0.5 wt% CaO content and increases above it. After 7 days of immersion, the corrosion rate of all samples decreased, and this was attributed to the corrosion inhibition of the corrosion product layer. For the unreinforced MgZn alloy, the stable product layer after 7 days causes significant passivation. For long-term immersion test, the corrosion performance of the composites deteriorated. Long-term immersion corrosion increased the layer thickness. However, galvanic corrosion caused the deterioration of this layer and increased the corrosion rate of the composites. Lyu et al. [39] also studied the effect of extrusion temperature on the corrosion performance of Mg1Zn0.4CaO/1MgO composite. The lowest extrusion temperature exhibited the best corrosion performance. For the sample with the lowest extrusion temperature, denser grain boundaries facilitate the formation of the protective layer, resulting in a more uniform corrosion profile. In addition, the conversion of MgO particles to $Mg(OH)_2$ protects against crack formation. Homogeneously distributed small secondary phases reduce pitting formation. For the highest extrusion temperature, the low corrosion performance of the composite was attributed to the high lattice distortion and big grain size. The corrosion test results of Mg matrix composites are given in Table 4.

Table 4. Corrosion test results of Mg matrix composites

Materials	**Corrosion solution**	**E_{corr} (V)**	**Corrosion current density (μA/cm^2)**	**Corrosion rate (mm/yr)**	**Ref.**
Mg	3.5 wt% NaCl	-1.49	367		[37]
Mg/15 wt%$CaSiO_3$		-1.33	425		
Mg/12.5wt%$CaSiO_3$-2.5wt%Al_2O_3		-1.56	183	-	
Mg/10 wt%$CaSiO_3$-5 wt%Al_2O_3		-1.54	122		
Mg-1Zn	Simulated body fluid 1 h	-1.67	47.62	1.09	[38]
Mg-1Zn/0.5 wt%CaO		-1.43	40.19	0.92	
Mg-1Zn/1 wt%CaO		-1.53	55.74	1.27	
Mg-1Zn	Simulated body fluid 7 d	-1.46	30.69	0.70	
Mg-1Zn/0.5 wt%CaO		-1.37	35.94	0.82	
Mg-1Zn/1 wt%CaO		-1.39	45.54	1.04	
Mg-1Zn-0.4Ca/1wt%MgO (ET 280°C)	Hank's solution	-1.2	2.01	0.46	[39]
Mg-1Zn-0.4Ca/1 wt%MgO (ET 310°C)		-1.198	2.98	0.68	
Mg-1Zn-0.4Ca/1 wt%MgO (ET 330°C)		-1.223	3.35	0.77	

ET: Extrusion temperature

4. Future research directions

The challenges and suggestions of future work for Mg matrix composites are given below.

- Traditional production methods have been preferred for Mg matrix composites for more than 30 years. Additive manufacturing methods with short production cycles and high material utilization rates can be preferred in production.
- Researchers are working to find the optimum reinforcement content in almost all studies. They are also working on optimizing of production parameters. Experimental studies are often expensive and time-consuming. Therefore, machine learning can be utilized to determine optimal reinforcement content and predict material properties.
- The most studied subject regarding Mg matrix composites is mechanical properties. Knowing the corrosion properties of Mg-based composites is of critical importance. Corrosion studies will be one of the most current topics in the near future.
- The properties of the produced composites are examined at room temperature. However, high-temperature tests should be performed according to the operating temperature of Mg matrix composites.
- Experiments on Mg matrix composites are laboratory-scale tests, and tests should be carried out under real-life usage conditions.

5. Conclusions

The important results are given below.

- Powder metallurgy and stir casting are the most commonly used production methods. After production, extrusion and different heat treatments are widely used to improve the properties of the composites.
- For microstructure characterization and phase analysis, in addition to traditional methods such as OM, SEM, and XRD, advanced characterization methods such as TEM and EBSD are also used.
- The addition of reinforcement particles greatly increases the yield strength. The strengthening mechanisms are grain refinement, Orowan, load transfer, and thermal mismatch. It is reported in different studies that elongation both increases and decreases with the addition of reinforcement particles.
- The incorporation of reinforcement particles improves the tribological performance. The enhanced wear resistance is attributed to reinforcement particles with high load-carrying capacity.
- There are studies in which the corrosion rate in composite materials both increases and decreases compared to the base alloy. The increase in corrosion performance is attributed to the formation of the protective layer. The deteriorated corrosion performance is attributed to galvanic corrosion.

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