

We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

5,800

Open access books available

142,000

International authors and editors

180M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities



WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com



Magnesium Metal Matrix Composites and Their Applications

*Aqeel Abbas, Veeramanikandan Rajagopal
and Song-Jeng Huang*

Abstract

Magnesium is one of the lightest structural metals have the capability to replace the conventional alloys for mass saving applications and provides higher strength and stiffness. Additionally, it also has the ability to absorb the hydrogen in the form of hydrides and can be used as a future source of energy carrier. The theoretical hydrogen capacity of 7.6 wt% makes it more suitable for future energy sources but needs to reduce the working sorption temperature. Moreover, magnesium is the primary source of the body and has strength equal to the bone, making it more suitable for biomedical applications and higher biocompatibility. Some challenges of magnesium-based metal matrix composites are still encountering structural applications, hydrogen energy storage, and biomedical applications due to manufacturing methodologies and proper materials selection to get required results.

Keywords: magnesium-based metal matrix composites, structural applications, hydrogen energy storage, biomedical applications of magnesium, automotive applications

1. Introduction

In recent decades, the modern world focuses on the research of lightweight metallic materials with high strength for potential applications [1]. Over the past few years, different steel materials and its alloys have been used for the applications such as household constructions and automotive manufacturing industries due to its high strength properties. Even though steel alloys have high strength, many of the light metal alloys systems also have sufficient strength to make sure of their usage in particular applications [2].

Aluminum and magnesium alloys are widely used in industries due to low mass density in recent days. The higher strength to mass ratio makes them as most attractive materials where reducing weight is one of the most significant importance, such as electronic frame production, sports goods, spacecraft machinery production, and ground transports [2]. Even the manufacturing industries using a different kind of light metals with strategic significance are also using magnesium due to its lowest density of 1.74 g/cm³. The magnesium density is two-third of aluminum, one-fourth of zinc, and one-fifth of steel. Among the magnesium alloys, the AZ series are widely used because of their superior properties such as excellent

castability, damping capacity, and higher machinability. In general, the magnesium alloys have low corrosion resistance and low mechanical strength, especially at elevated temperatures [3]. The necessity of lightweight materials for use in challenging applications has spurred widespread efforts to develop magnesium-metal matrix composites and cost-effective fabrication technologies. So, our research team focused on the metal matrix composites system to reach unattainable properties by the single material system.

Apart from several applications, magnesium and its alloys are considered as one of the prominence energy storage materials which can store hydrogen gas in the form of magnesium hydride [4]. Magnesium has a maximum storage capability of 7.6 wt.% as theoretical with excellent thermodynamic reversibility among the current storage materials. However, the processing temperature (300 °C) of magnesium hydrides is too high to reach the target of the department of energy of the united states of America. These poor properties and other issues have limited their commercial implementations that need to be optimized [5].

Magnesium alloys with different additive materials are quite attractive content for scientific investigations. The prepared materials' performance depends on the composition, fabrication methodology, processing techniques, and properties will be varying with materials that added to the magnesium [6]. To improve the material properties, several types of additives such as SiC, Al₂O₃, carbon allotropes, B₄C, TiC, and transition metals (particles/whiskers) have been fabricated using liquid state technique (stir casting, squeeze casting, centrifugal casting) and semi-solid-state techniques (chemical vapor deposition and physical vapor deposition) to attain the superior properties for various applications [7–10]. The above-mentioned techniques are selected depending upon what kind of reinforcement distribution is required in matrix and how much cost can be effective. The secondary processing technique (heat treatment and plastic deformations) influences composites' micro-structures and specific behaviors and alloy materials. The secondary processing techniques are used to refine the microstructure to enhance the ductility and strength of the composites.

By investigating these materials, the characteristics of recrystallization in the magnesium and phase transformations could be recognized towards the applications [11, 12]. We are hopeful that our research studies on magnesium with different additive materials contribute the breakthrough knowledge in the field of mechanical behaviors and energy storage technology, which are viable to future applications.

2. Manufacturing methodologies to fabricate the metal matrix composites

The metal matrix composites (MMCs) composed of low-density magnesium reinforced with fibers or particles. MMCs offer high strength and high stiffness operating at higher temperatures and possess excellent wear-resistant properties as the properties are tailored according to required properties. However, MMCs have many disadvantages than metallic alloys, such as higher manufacturing costs for better performance and low ductility. This materials group has become attractive for the use in construction and functional applications. The demand for MMCs materials has been increased and is expressed in **Figure 1**.

The manufacturing methodologies are categorized into following

- Solid-state processing

- Liquid state processing
- In-situ processing

Each process is further categorized and express in the following chart.

2.1 Solid-state processing

The principal manufacturing methodologies included in solid-state processing are physical vapor deposition, powder blending and consolidation, and additive manufacturing.

2.1.1 Physical vapor deposition

The fibers are continuously passed over the substrate of the metal with high partial pressure. The vapors produced are inserted in the process and condensed to make the coating on the surface. The deposition rate is 5-10 μm per minute. The coating fibers are consolidated by hot isostatic pressing. Sputtering is a physical vapor deposition method in which argon ions are used for bombarding cathodically connected target to deposit the coating.

2.1.2 Powder blending and consolidation

The magnesium powder is mixed with reinforcement to get uniformity under a neutral environment. The blending steps, along with powder size, control the mechanical properties of composites. The uniform and homogeneous mixture is compacted under controlled temperature. The oxides are supposed to be produced on the surface as magnesium is highly reactive to oxygen.

2.1.3 Additive manufacturing

The reinforcements are uniformly distributed and dispersed in the matrix using 3D manufacturing techniques. The complex geometry and graded density

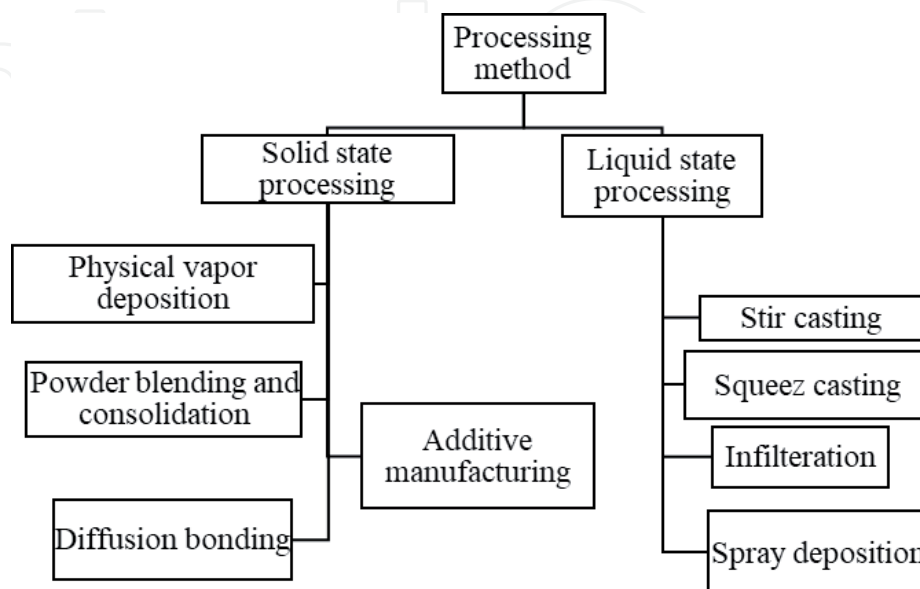


Figure 1.
Manufacturing methodologies for MMCs.

composites can be developed. The protection of magnesium powder from oxides is very critical in this method.

2.1.4 Diffusion bonding

It is a very important solid-state technique to combine two metals. The cleaned surfaces are pressed at elevated temperature leading to bonding of the metals.

2.2 Liquid state processing

The liquid state processing is cost-effective and complex geometries can be achieved with good interfacial bonding and excellent dispersion. The excellent bonding and uniform dispersion of reinforcement lead to enhancement in mechanical properties. Stir casting, squeeze casting, and infiltration are the prominent liquid state processing techniques.

2.2.1 Stir casting

The particle reinforcement is mixed into a molten matrix using rotating impellers and then solidified to room temperature. The problem raised during stir casting is uniform distribution and sediments in the molten alloy. The 30% of the particles in size of 5–100 micrometers can be incorporated in the metal alloy.

2.2.2 Squeeze casting

The molten metals are poured into the closed die and pressed under some constant pressure. The heat is transferred from molten metal to die. With the high pressure of dies, grain refinement happens, and castings have very little porosity and lead to the composites' increased strength.

2.2.3 Infiltration process

The molten metal alloy is unfiltered into the porous form of reinforcement under the pressurized gas to apply the pressure. The pressure causes the penetration and dispersion of molten metal into reinforcement, which have a volume fraction of 10–70% depending upon porosity level. Some binding agents are required to maintain the integrity and shape of porous form. The infiltration processes are classified into the following three categories

- Gas Pressure Infiltration
- Spray Deposition
- Chemical Vapor Deposition (CVD)

The gas is applied in the gas infiltration process to penetrate the molten metal into porous reinforcement. The reinforcements of porosity 5–10% are sprayed on the surface of metal alloy in the spray deposition process. The sprayed particles are consolidated by further processing. The particle/fibers spacing impacts the volume fraction and distribution.

2.2.4 Spray deposition

The spray deposition is a technique in which droplets of molten metal or continuous feeding of cold metal is spread over rapid heat injection zone. The process is adopted for bulk production by directing the atomized stream of droplets on the substrate. The adaptation of this technique for the building of MMCs by injecting ceramic powder into spray has commercially succeeded. The droplet/powder velocities are typically 20-40 m/s, and the thin layer of semisolid reinforcement is present on the surface of the ingot. The MMCs produced by spray deposition often exhibit inhomogeneous distribution, and the ceramic layer is normal to growth direction, which leads to hydrodynamic instabilities in powder injection. The porosity in MMCs in the as-sprayed state is typically 5–10%.

In the chemical vapor deposition process, the vapors react/decompose and form a coating on another substrate. The process is carried out at elevated temperatures. The in-situ processing is a unique process in which chemical reaction results in the development of reinforcement in MMCs. The reinforcement can be formed from precipitations of the liquid of solid. The method provides the thermal compatibility between matrix and reinforcement, and surfaces are free of contaminations.

3. Secondary processes

The processes performed after the manufacturing of the composites to enhance the strength and modify the microstructure are often referred to as a secondary process. The most common secondary processes are Heat treatment and Plastic deformation.

3.1 Heat treatment

The processes of heat treatments are performed to dissolve some phases and to generate some new phases. There are different processes and methods to perform heat treatments, which are explained in **Table 1**. The heat treatment processes increase the corrosion resistance and strength of the composites. The heat treatments are classified into the following categories

- Solution heat treatment
- Homogenization
- Aging

In solution heat treatments, the casted alloys/composites are heated to a specific temperature for a particular period of time to develop the desired constituent in the matrix. The billets are then quenched suddenly to sustain the phases develop.

Homogenization heat treatments are performed to enhance the workability of cast billets. The brittle nonequilibrium phases are dissolved, and a homogenous microstructure is developed. The homogenization of the billets is performed at the recrystallization temperature of the materials.

Aging is referred to as the process of heat treatment in which precipitates developed during homogenization are decomposed at some elevated temperature. The aging leads

Suffix	Heat treatment conditions
T1	Cooled from elevated temperature and naturally aged
T2	Cooled from elevated temperature, cold worked and naturally aged
T3	Cooled from elevated temperature, quenched, cold worked, and naturally aged
T4	Solutionized, quenched, and naturally aged
T5	Rapidly cooled and artificially aged
T6	Solutionized, quenched, and artificially aged
T7	Solution heat treatment, quenched and overaged
T8	Solution heat treatment, cold worked and artificially aged
T9	Solution heat treatment, artificially aged cold worked
T10	Cooled from elevated temperature (recrystallization temperature) cold worked and artificially aged

Table 1.
Types of heat treatment employed to MMC for microstructure modification.

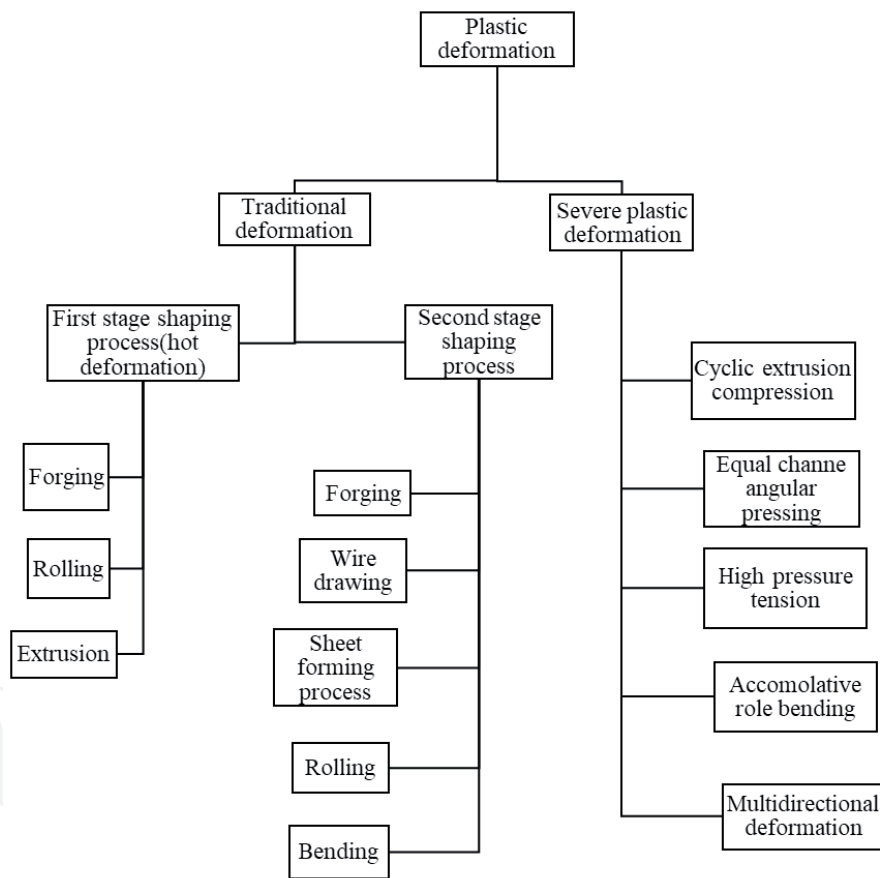


Figure 2.
Types of plastic deformation used for MMCs.

to an increase in yield strength and hardness of the alloy/composite. The aging process may be natural (at room temperature) or artificial aging (at elevated temperature).

Some terms have been introduced by the aluminum association for aluminum and its alloys and are explained in **Table 1**.

3.2 Plastic deformation

The metal matrix composites are deformed into different shapes, and the microstructure is changed to increase the strength of the composites. The

plastic deformation can be categorized into traditional deformation and severe plastic deformation. The deformation could be hot or cold deformation. The shape of the composite is changed, and mechanical properties are moderately enhanced in traditional deformation, but severe plastic deformation alters the microstructure, and mechanical properties are exceptionally increased. The composition of the microstructure is changed, but the shape of the composite remains the same. The type of plastic deformation is given in the following flow chart **Figure 2**.

4. Structural applications

The magnesium is the third most commonly used structural material after aluminum and steel and is significantly used in automotive, power tools, aerospace, and 3C (computer, communication, and consumer products). Currently, magnesium application in automotive includes transfer case, radiator support, instrument panel beam, and steering components. Magnesium with minimal density is used in mass saving applications to replace aluminum and steel, but magnesium alloys' strength is low. The hard and tough ceramics are added in magnesium alloys using proper manufacturing techniques to improve the strength for structural applications. The extrusion of the metal matrix composites provide strength comparable to aluminum alloys. AZ, ZK and AM series of the magnesium alloys are very common to fabricate the metal matrix composites. The magnesium based metal matrix composites are developed because the wrought magnesium alloys are very less formable at room temperature than aluminum alloys due to hexagonal closed packed crystal structure, although ductility appears reasonable [13].

The materials selection for structural applications is very complex in which component geometries, loading conditions, manufacturing process, materials properties, and the cost is very important. The bending mode is the primary loading condition in automotive structures. Thus, the calculation should be based on bending stiffness and strength. The thickness and mass ratio of magnesium alloy (AZ91) should be 1.67 and 0.39 times the steel to get similar bending strength. AZ91 AZ31 and AZ61 are the most commonly used magnesium alloy in the automobile. The addition of proper reinforcement in AZ series of the magnesium alloys have improved the strength and ductility. AZ61 and AZ80 have higher strength but less extrudability. The higher strength alloy ZK60 is designed for racing cars, bicycle parts, but extrusion speed is very low. The implementation of severe plastic deformation on magnesium alloys have improved the mechanical strength drastically. The new magnesium composites are being developed with a higher extrusion rate and maintaining good mechanical properties such as AM30 (higher strength applications) and ZE20 (higher ductility applications) reinforced with Al₂O₃, WS₂, TiC, and SiC. The presence of aluminum contents in magnesium-based composites improves the strength, hardness, and corrosion resistance but reduces the ductility. The aluminum contents within range of 5–6% yield optimal strength and ductility. Zinc is next to the aluminum alloying element to improve the corrosion resistance but reduces the ductility. Manganese does not affect the tensile strength but increases the yield strength. It is 0.4% recommended by ASTM specification B93-94a to improve the corrosion resistance [14, 15].

The small addition of ceramics (Al₂O₃, TiC, B₄C, SiC, WS₂, MoS₂ etc.) in magnesium improves the ductility and likely reduces the grain size and weakens the texture. The combined addition of zinc and cerium enhances the strength and ductility closer to aluminum. The addition of lithium, zirconium, and cerium has improved the formability and strength of the composites.

4.1 Aerospace applications

Magnesium alloys were extensively used in aerospace in world war I and world war II. The united states air force’s bombers B-36 and B52 contain a large amount of magnesium in casting, forging, and extrusion. The B-36 uses magnesium alloys ranging from 66 lb. to 12200 lbs. in different forms like sheets, castings, and extrusion. The Boeing 727 aeroplanes contain 12 parts, including control surfaces, wheels, engine gearbox, structural items, door frames, and edge flaps are made of magnesium alloys. Soviet air crafty industry, including the TU-95MS plane and TU-134, are using magnesium alloys up to 780Kg at different locations [13]. The International Air Transport Association (IATA) legislation has limited the magnesium application due to magnesium alloys’ higher corrosion performance. Some of the commonly used alloys and their applications are mentioned in **Table 2**. It is expected that magnesium will be a major element in a future world in structural materials in aerospace.

4.2 Automotive applications

The first application of magnesium in automotive was in engines of racing cars. England used commercial magnesium applications such as in crankcases of buses and tractors’ transmission housing in the 1930s. The demand for magnesium applications in automotive was increased in world war I and II. The major parts which use magnesium are given in **Table 3**. The major problems in applications of magnesium in automotive are limited thermal conductivity, and magnesium cannot perform well between hot and cold temperatures. The magnesium strength is increased by doping the different reinforcement and deformation process to get the required strength and ductility [16, 17].

4.3 Electronics applications

Magnesium and its composites are being opted for by the electronics industry owing to its mass reduction. These materials are most commonly used in audio/video players, computers, mobile phones, radar detectors, and many more. Magnesium makes the electronics industry smarter and lighter due to high strength and durable to protect highly sensitive technology. Alloys and composites should be developed to improve the mechanical properties by precipitation hardening [18].

Alloy	Applications	Alloy	Application
ZE41	Sikorsky UH60 Family	WE43A	Sikorsky S92 main transmission
AZ92A	Boeing 737, 747, 757 and 767	WE43	Pratt & Whitney F119 auxiliary casing
ZE41	Pratt & Whitne Canada	ZRE1	Rolls-Royce tray

Table 2.
Common applications of magnesium in aerospace.

VW engine	Halibrand racing wheels	Buick car of the future	GM production wheels
Alfa Romeo seat	Ford radiator support	BMW engine block	BMW door inner
Mercedes transmission case	Interior	Body	Chassis

Table 3.
Common applications of magnesium in automotive.

5. Biomedical applications

Magnesium is present in the form of the mineral is 65% in bones and teeth, and the remaining 35% is present in body fluids and tissues. The biocompatibility and biodegradability make magnesium more suitable for biomedical applications. The researchers are paying much attention to influence the interactive mechanism of biodegradable materials. The magnesium strength has approached the bone strength and is used in orthopedic implants. The magnesium can also be used in other orthopedic surgeries such as screws, plates, and fasteners. The magnesium shows nominal changes in blood composition with six months of implantation without damage to the liver and kidneys [19].

The magnesium is a major alloying element used in biodegradable implant in vivo and in vitro conditions. It has excellent biocompatibility and is the fourth most abundant element present in the human body, and it is an essential nutrient element. Magnesium has a high corrosion rate and releases H₂ gas in human body fluid. Modern techniques have been adopted to control the corrosion rate and heal the fractured tissues without the need for secondary surgery to remove the implants. The fraction of the component must be selected as per biocompatibility to avoid toxicity. Thus, extreme concerns must be taken to choose the reinforcement with magnesium to control biomechanical properties and corrosion rate under biological conditions. The selection of bioceramics is very important as they may cause some severe body fluid issues, and some are mentioned in **Table 4** [20, 21]. The pure magnesium implant is degraded much earlier than the tissue heals. Therefore, mechanical and degradation properties are intended to increase.

The addition of alloying elements in pure magnesium improves the grain refinement and strengthen the composites. The most commonly used bioceramics and their effects are presented in **Table 5**. These ceramics are added in magnesium and its alloys to fabricate the magnesium-based composites with excellent strength and biodegradable properties. The biocompatibility of composite in the biological environment is based on strengthening ability degradation and toxicity [22].

The alloying elements can be classified as toxic, nutrient, and allergic, which are present in the human body. The bioinert and bioactive ceramics are significant reinforcements to achieve required biocompatibility and strength. The properties of

Toxic	Allergic	Nutrient
Ba, Pb, Be, Th, Cd	Al, Ce, Cr, Co, Cu, La, Ni, Pr, V	Ca, Mn, Sn, Sr., Zn

Table 4.
Bioelements and their effects on biofluids.

Ceramic type	Characteristics	Applications
Alumina (Al ₂ O ₃)	Biocompatible and bioinert, good strength, high hardness, the non-advocate tough membrane at the interface	Permeable coatings for stems, screws, and plates, knee prosthesis
Zirconium (ZrO ₂)	Elevated fracture toughness, flexural strength, bioinert, biocompatible, non-toxic	Artificial knees, bone screws and plates, etc.,
Hydroxyapatite (HAP)	Bioresorbable, bioactive and biocompatible, similar composition to the bone, good osteoconductive properties	Femoral knee, femoral hip, tibial components, the acetabular cup

Table 5.
Commonly used bioceramics and their characteristics.

common bioceramics are given in **Table 5**, and the selection of specific bioceramic is important for outstanding performance in toxicity and immunological environment.

6. Hydrogen storage applications

6.1 Role of magnesium in hydrogen storage

In the recent decade, rapid advancement in nanostructuring techniques brought a new confidence in hydrogen storage applications. The hydrogen gas has been stored in metal hydride in the new generation technology in solid-state hydrogen storage. The physical and chemical properties of materials could be fundamentally varied with nano parameters. The research focused on nano-microstructures, which can play a vital role in hydrogen storage materials [23, 24]. To attain the maximum hydrogen storage capacity, Mg-based hydride materials are considered the most promising metallic content based on materials. Even though Mg has a higher storage capacity, the magnesium hydride's practical applications are still not reached because of its high working temperature and low kinetics. Besides, the high thermo-stability of bulk MgH_2 , such as Entropy (ΔS), Enthalpy (ΔH) with the decomposition, is $130JK^{-1}mol^{-1}H_2$ $75 kJ/mol H_2$ respectively, which means the temperature needed to reach $300^\circ C$ at the equilibrium pressure of 1 bar. So, it is required to optimize the stability between magnesium and hydrogen molecules that could increase the thermodynamics and kinetics properties. Reducing the particle size (nanoscale) and adding various catalyst materials are two critical factors in enhancing hydrogenation properties. The following factors that influence the absorptions rate are the physisorption rate of hydrogen gas on the magnesium alloy's surface, dissociation capacity, and nucleation growth of magnesium to the magnesium hydride [25, 26].

6.2 Mechanism of hydrogenation in magnesium-based materials

The pure magnesium, which has a hexagonal structure reacts with hydrogen molecules reversibly to form magnesium hydride in which the parametric details are presented in **Table 6**—the reversible reaction presented in Eq. (1).



The crystal structure of MgH_2 transformed into tetragonal β - MgH_2 . At the same time, the pressure is increased with the high hydrogen pressure at the ambient temperature. The β - MgH_2 transformed into a metastable orthorhombic γ - MgH_2 phase. The schematic illustration of the mechanisms is presented in **Figure 3**.

The following reaction mechanism is composed of five different intermetallic processes.

1. hydrogen physisorption at the surface
2. dissociation of the hydrogen molecule/chemisorption
3. surface penetration of the hydrogen into the material
4. diffusion through the hydride layer to the interface with the metallic phase
5. conversion of metal into metal hydride [29].

Magnesium (Mg)	Magnesium hydride (MgH ₂)
Crystal structure: Hexagonal	Crystal structure: tetragonal rutile -type
Space group: p63/MMC	Space group: p42/mnm
Lattices parameters: a = 3.2075 Å, c = 5.2075 Å, α = 90°, β = 90°, γ = 120°	Lattices parameters: a = 3.025 Å, c = 4.5198 Å, α = 90°, β = 90°, γ = 90°
Atomic coordination: Mg (c) (1/3, 2/3, 1/4)	Atomic coordination: H (f) (0.30478, 0.30478, 0) Mg (a) (0, 0, 0)

Table 6.
 Magnesium and magnesium hydride crystallographic data [27].

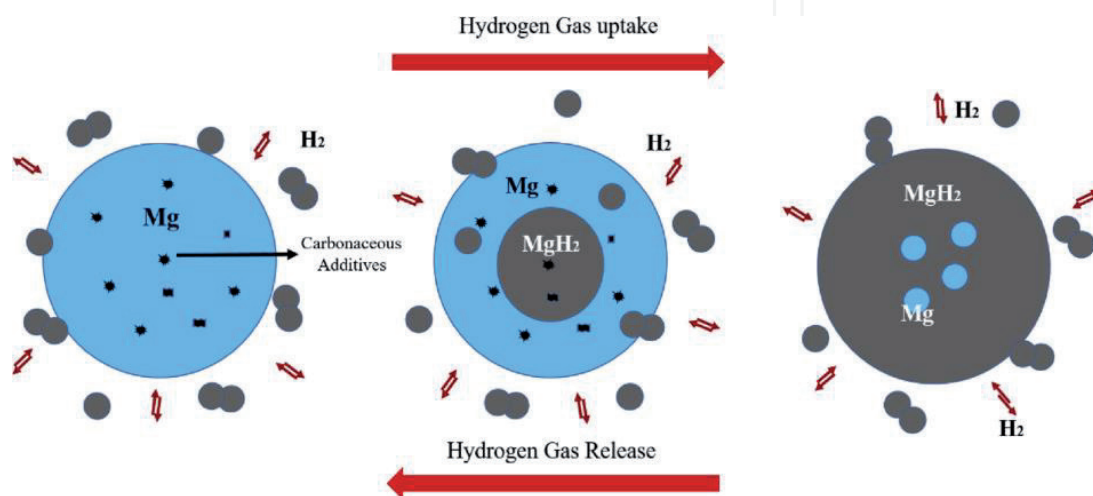


Figure 3.
 The hydrogen gas ab/desorption mechanisms in magnesium [28].

6.3 Nanostructuring

Nanostructuring is also one of the important factors that can enhance the kinetics of magnesium-based materials, and it can destabilize the thermodynamics of magnesium hydride formations. The reduction of particle size into nanoscale will decrease the stability of metal hydride. The nanoparticles significantly contribute to the overall surface energy. The total energy required for dehydrogenations on metal hydrides depends on the radius of particle size r and could be as in Eq. (2) [30].

$$\Delta G(r) = \Delta G_o(r) + RT \ln \frac{P}{P_o} + \frac{3V_{M\Delta M \rightarrow MH_2}(\gamma, r)}{r} \quad (2)$$

6.4 Magnesium composites in hydrogen storage application

6.4.1 Mg-carbon composites in hydrogen storage

The novel electronic properties of carbon and exciting interaction between hydrogen and carbon atoms, particularly nanostructured materials, exhibit the prominent catalytic effect on the Mg as the hydrogen storage material. Initial time, graphite has been proposed as one of the anti-sticking agents in the ball milling to improve the efficiency of the process with magnesium and examined its catalytic effect on the hydrogenation characteristics. Later on, the studies investigated

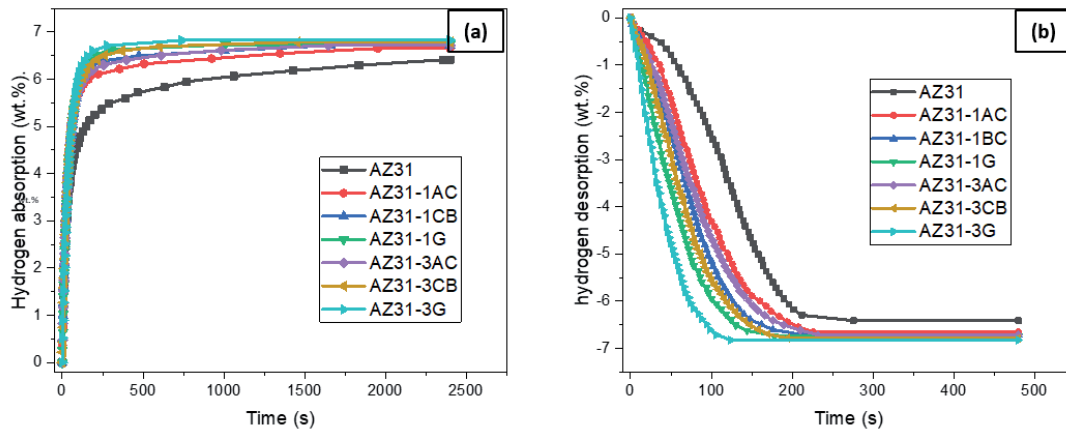


Figure 4. Hydrogenation kinetic curves for AZ31- magnesium alloy/carbon materials, (a) Hydrogen absorption, (b) Hydrogen desorption [28].

Materials	Processing Method	Particle Size	Temperature/ Pressure	Capacity	Kinetics	Ref.
Mg-CB	Ball milling (BM)	5–15 μm	300 °C	6.0 wt.%	Abs: 40 min	[31]
Mg-Ti/ Graphene	BM 600 rpm, (10 hrs)	1.4–2 μm	300 °C/0.08 bar	4.3 wt.%	- (PCT)	[32]
Mg-GNS (Graphene Nano Sheet)	BM 450 rpm, (20 hrs)	<10 nm	300 °C	6.2 wt.%	60 min	[33]
Mg- AC (activated carbon)	BM 300 rpm, (15 hrs)	30–45 nm (crystallite)	300 °C	6.5 wt.%	7 min	[34]
AZ31 ZK60	ECAP (plastic deformation)	—	320 °C	~6.4 wt.%	12 hrs.	[35]
AZ61	ECAP(plastic Deformation)	24.09 μm (grain)	375 °C 35 atm	6.2 wt.%	Abs:2564 s Des: 156 s	[36]
AZ31/ Graphene	ECAP	4.35 ± 0.7 μm (grain)	375 °C 35 atm	6.72 wt.%	Abs:1567s Des: 229 s	[28]
	Ball milling (BM)	39.18 μm				

Table 7. Hydrogen storage properties of Mg-alloys with different types of carbonaceous materials.

the advantages of the carbon additives such as single-walled carbon nanotubes (SWNT), activated carbon (AC), carbon black (CB), fullerene (C60), and boron nitrate (BN) nanotubes in the enhancements of practical hydrogenations properties of magnesium and its alloys.

The addition of carbon materials shows significant advantages in hydrogenation kinetics and particularly in the improvement of hydrogenation capacities. Moreover, Huang et al. investigated the hydrogenation kinetics with different carbon materials such as activated carbon (AC), carbon black (CB), and graphene nanosheets. The AZ31- magnesium alloy added with graphene sheets reached the maximum storage capacity of 6.83 wt.%. The AZ31-magnesium alloy reached its maximum capacity in less than 15 minutes and released entire hydrogen in less than 3 minutes, and its kinetic curves presented in **Figure 4**. It clearly shows that carbon

and magnesium-based materials as composites (Mg alloys-carbon composites) produce the prominent catalytic effect for hydrogenation. Moreover, the results illustrate the carbon effects, which are strongly related to the unique electronic- π properties and sheet morphology of nanographene, which can make the high porosity with the high surface area. The sheet-like morphology acts as the nucleation site for the hydrogen molecules penetration into the materials and could increase the hydrogenation kinetics [28].

The theoretical capacities of different materials were calculated by the elemental molecular equation as follows

$$C = \frac{xM_{H_2}}{xM_{H_2} + yM_{Mg} + zM_{Al} + tM_c + \dots} \quad (3)$$

Where C is the theoretical capacity (wt.%); M_{H_2} is the molecular weight of hydrogen; M_{Mg} is the molecular weight of Mg; M_{Al} is the molecular weight of Al; M_{Zn} is the molecular weight of Zn; M_C is the molecular weight of C with its corresponding weightage of the quantity in the reaction (x, y, z, and t). The hydrogen storage properties of Mg-Alloys with different carbonaceous materials were presented in **Table 7**.

7. Materials challenges

A limited number of magnesium alloys are available compared to aluminum alloys. The properties can be significantly improved by introducing micro/nano-sized particles. The reinforcements offer tremendous opportunities to improve the characteristics of the material and tailored the properties. It is very difficult to avoid oxidation while handling the melt casting. Various processes need to be optimized for magnesium alloys and Mg MMCs. New forming processes should be developed to improve formability at a certain temperature and a certain strain rate.

In the hydrogen storage applications, magnesium is one of the promising candidates even though there are many available materials. But poor kinetics and high hydriding, de-hydriding temperature limits its applications. Considerable efforts are dedicated to solving these issues by preparing composites by adding catalytic materials and nanostructuring. However, Mg-based material systems still having the parameters to be optimized. It is needed that the fabrication methods for preparing sub-nano, metric crystals with size will be considered to attain the potential targets to destabilizes the strong bondage between Mg-H. Even though the targets still stay on to be experimentally achieved.

IntechOpen

IntechOpen

Author details

Aqeel Abbas, Veeramanikandan Rajagopal and Song-Jeng Huang*
Department of Mechanical Engineering, National Taiwan University of Science and
Technology, Taipei, Taiwan, R.O.C

*Address all correspondence to: sgjhuang@mail.ntust.edu.tw

IntechOpen

© 2021 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/3.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. 

References

- [1] Abbas A, Huang S-J. ECAP effects on microstructure and mechanical behavior of annealed WS₂/AZ91 metal matrix composite. *J Alloys Compd* 2020;155466. doi:10.1016/j.jallcom.2020.155466.
- [2] Rashad M, Pan F, Liu Y, Chen X, Lin H, Pan R, et al. High temperature formability of graphene nanoplatelets-AZ31 composites fabricated by stir-casting method. *J Magnes Alloy* 2016;4:270-7. doi:10.1016/j.jma.2016.11.003.
- [3] Sundaresan R, Froes FH. Mechanical Alloying in the Titanium-Magnesium System. *Key Eng Mater* 1991;29-31:199-206. doi:10.4028/www.scientific.net/KEM.29-31.199.
- [4] Kichigin VI, Shein AB. The kinetics of hydrogen evolution reaction accompanied by hydrogen absorption reaction with consideration of subsurface hydrogen as an adsorbed species: Polarization curve. *J Electroanal Chem* 2020;873:114427. doi:10.1016/j.jelechem.2020.114427.
- [5] Huang S-J, Rajagopal V, Ali AN. Influence of the ECAP and HEBM processes and the addition of Ni catalyst on the hydrogen storage properties of AZ31-x Ni (x=0,2,4) alloy. *Int J Hydrogen Energy* 2019;44:1047-58. doi:10.1016/j.ijhydene.2018.11.005.
- [6] Huang S-J, Abbas A. Effects of tungsten disulfide on microstructure and mechanical properties of AZ91 magnesium alloy manufactured by stir casting. *J Alloys Compd* 2020;817:153321. doi:10.1016/j.jallcom.2019.153321.
- [7] Ward-Close CM, Partridge PG, Gilmore CJ. Precipitation and hardening in titanium-magnesium and titanium-calcium alloys. *Titanium'92 Sci Technol* 1993:651-8.
- [8] Huang S, Ali AN. Materials Science & Engineering A Effects of heat treatment on the microstructure and microplastic deformation behavior of SiC particles reinforced AZ61 magnesium metal matrix composite. *Mater Sci Eng A* 2018;711:670-82. doi:10.1016/j.msea.2017.11.020.
- [9] Zhou E, Suryanarayana C, Froes FHS. Effect of premilling elemental powders on solid solubility extension of magnesium in titanium by mechanical alloying. *Mater Lett* 1995;23:27-31.
- [10] Chen C, Cai G, Chen L, An Y, Xu G, Wang Q. Hydrogen absorption properties of a slurry system composed of a magnesium alloy powder and C₆H₆. *J Alloys Compd* 2003;356-357:409-12. doi:10.1016/S0925-8388(03)00225-1.
- [11] Abbas A, Huang S-J. Investigation of severe plastic deformation effects on microstructure and mechanical properties of WS₂/AZ91 magnesium metal matrix composites. *Mater Sci Eng A* 2020;780:139211. doi:10.1016/j.msea.2020.139211.
- [12] Huot J. Nanocrystalline Metal Hydrides Obtained by Severe Plastic Deformations. *Metals (Basel)* 2012;2:22-40. doi:10.3390/met2010022.
- [13] Luo AA. Magnesium casting technology for structural applications. *J Magnes Alloy* 2013;1:2-22. doi:10.1016/j.jma.2013.02.002.
- [14] Friedrich H, Schumann S. Research for a "new age of magnesium" in the automotive industry. *J Mater Process Technol* 2001;117:276-81. doi:10.1016/S0924-0136(01)00780-4.
- [15] Powell BR, Rezhets V, Balogh MP, Waldo RA. Microstructure and creep behavior in AE42 magnesium die-casting alloy. *JOM* 2002;54:34-8. doi:10.1007/BF02711864.

- [16] Verma R, Carter JT. Quick Plastic Forming of a Decklid Inner Panel with Commercial AZ31 Magnesium Sheet, 2006. doi:10.4271/2006-01-0525.
- [17] Logan S, Kizyama A, Patterson C, Rama S. Lightweight Magnesium Intensive Body Structure, 2006. doi:10.4271/2006-01-0523.
- [18] Luo A, Sachdev A. Microstructure and Mechanical Properties of Magnesium-Aluminum-Manganese Cast Alloys. *Int J Met* 2010;4:51-9. doi:10.1007/BF03355502.
- [19] Bommala VK, Krishna MG, Rao CT. Magnesium matrix composites for biomedical applications: A review. *J Magnes Alloy* 2019;7:72-9. doi:10.1016/j.jma.2018.11.001.
- [20] Nakamura Y, Sakaki K, Kim H, Asano K, Watanuki T, Machida A. Reaction paths via a new transient phase in non-equilibrium hydrogen absorption of LaNi₂Co₃. *Int J Hydrogen Energy* 2020;45:21655-65. doi:10.1016/j.ijhydene.2020.05.237.
- [21] Nakamura Y. Differences in Behavior among the Chlorides of Seven Rare Earth Elements Administered Intravenously to Rats. *Fundam Appl Toxicol* 1997;37:106-16. doi:10.1006/faat.1997.2322.
- [22] Radha R, Sreekanth D. Insight of magnesium alloys and composites for orthopedic implant applications – a review. *J Magnes Alloy* 2017;5:286-312. doi:10.1016/j.jma.2017.08.003.
- [23] Schneemann A, White JL, Kang S, Jeong S, Wan LF, Cho ES, et al. Nanostructured Metal Hydrides for Hydrogen Storage 2018. doi:10.1021/acs.chemrev.8b00313.
- [24] Huang S, Rajagopal V, Ali AN. ScienceDirect Influence of the ECAP and HEBM processes and the addition of Ni catalyst on the hydrogen storage properties of AZ31-x Ni (x ¼ 0 , 2 , 4) alloy. *Int J Hydrogen Energy* 2018;44:1047-58. doi:10.1016/j.ijhydene.2018.11.005.
- [25] Jia Y, Sun C, Shen S, Zou J, Mao SS, Yao X. Combination of nanosizing and interfacial effect: Future perspective for designing Mg-based nanomaterials for hydrogen storage. *Renew Sustain Energy Rev* 2015;44:289-303. doi:10.1016/j.rser.2014.12.032.
- [26] Bardhan R, Ruminski AM, Brand A, Urban JJ. Environmental Science Magnesium nanocrystal-polymer composites : A new platform for designer hydrogen storage materials 2011:4882-95. doi:10.1039/c1ee02258j.
- [27] Shao H, Xin G, Zheng J, Li X, Akiba E. Nanotechnology in Mg-based materials for hydrogen storage. *Nano Energy* 2012;1:590-601. doi:10.1016/j.nanoen.2012.05.005.
- [28] Huang S, Rajagopal V, Chen YL, Chiu Y-H. ScienceDirect Improving the hydrogenation properties of AZ31- Mg alloys with different carbonaceous additives by high energy ball milling (HEBM) and equal channel angular pressing (ECAP) *. *Int J Hydrogen Energy* 2019;45:22291-301. doi:10.1016/j.ijhydene.2019.10.032.
- [29] Martin M, G C, Borkhart C, Fromm E. Absorption and desorption kinetics of hydrogen storage alloys 1996;238:193-201.
- [30] Radtke G, Dresselhaus M, Chen G, Be V. Size effects on the hydrogen storage properties of nanostructured metal hydrides : A review 2007:637-63. doi:10.1002/er.
- [31] Spassov T, Zlatanova Z, Spassova M, Todorova S. Hydrogen sorption properties of ball-milled Mg-C nanocomposites. *Int J Hydrogen Energy* 2010;35:10396-403. doi:10.1016/j.ijhydene.2010.07.123.

[32] Ye W, Chi Q, Zhou H, Gao P.
ScienceDirect Ball-milling preparation
of titanium / graphene composites and
its enhanced hydrogen storage ability.
Int J Hydrogen Energy 2018;43:19164-
73. doi:10.1016/j.ijhydene.2018.08.166.

[33] Zhao G, Fan J, Zhang H, Zhang Q,
Yang J. Materials Science & Engineering
A Exceptional mechanical properties
of ultra- fine grain AZ31 alloy by the
combined processing of ECAP , rolling
and EPT. Mater Sci Eng A 2018;731:54-
60. doi:10.1016/j.msea.2018.05.112.

[34] David E. Nanocrystalline
magnesium and its properties of
hydrogen sorption 2007;20:87-90.

[35] Skryabina N, Medvedeva N,
Gabov A, Fruchart D, Nachev S, Rango
P De. Impact of Severe Plastic
Deformation on the stability of MgH
2. J Alloys Compd 2015;645:S14-7.
doi:10.1016/j.jallcom.2015.03.128.

[36] Huang S, Chiu C, Chou T, Rabkin E.
ScienceDirect Effect of equal channel
angular pressing (ECAP) on hydrogen
storage properties of commercial
magnesium alloy AZ61 2018;3:0-9.
doi:10.1016/j.ijhydene.2018.01.044.