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Chapter

Introductory Chapter: An Insight into Fascinating Potential of Magnesium

Sravya Tekumalla and Manoj Gupta

1. Evolution of magnesium

The name, magnesium (Mg), was derived from an ancient city in Greece called "Magnesia" where magnesium carbonate was first discovered. It was first isolated in its elemental form by English chemist Sir Humphry Davy in 1808 [1]. In the earth's crust, magnesium is the sixth most abundant element and occurs in over 60 different minerals with at least 20% of Mg within them. Most commercially important of these minerals include dolomite, magnesite, brucite, and carnallite. Principally, magnesium is extracted from its minerals using a thermal reduction process [2]. Magnesium is also the third most abundant metal ion in seawater. Despite magnesium being only 0.13% of seawater, seawater remains an almost inexhaustible source for its extraction. Magnesium is extracted from seawater or brine using the electrolytic process of magnesium chloride [2]. Of the two extraction processes, the thermal reduction process is known to yield a higher purity of 99.99%, while the electrolysis process can achieve purity limited to 99.8%. Until the 1990s, the USA and Canada dominated the production of magnesium; however, the industrial revolution in China in the late 1990s turned the tables for magnesium production due to its lower operational (energy and labor) costs. It is estimated that 85% of the global magnesium production is currently done by China, and most of the remainder is produced by Russia, Turkey, Spain, Austria, etc. [3].

2. Factsheet of magnesium

The salient characteristics including atomic and crystalline and chemical characteristics and physical, thermal, biological, and mechanical properties of magnesium are shown in **Figure 1**.

3. Past, current, and potential applications of magnesium

Among metallic materials, aluminum is currently the most widely used lightweight material with a density of 2.7 g/cc. Titanium (Ti) and steels are heavier and are used very strategically in the transportation sector. Being abundantly available with price only marginally higher than that of Al (**Table 1**), magnesium-based materials are the present emerging materials in multiple sectors after a gap of about 70 years when they were used initially in aerospace and automobile sectors. This is because magnesium offers multidimensional properties which can be harnessed in a

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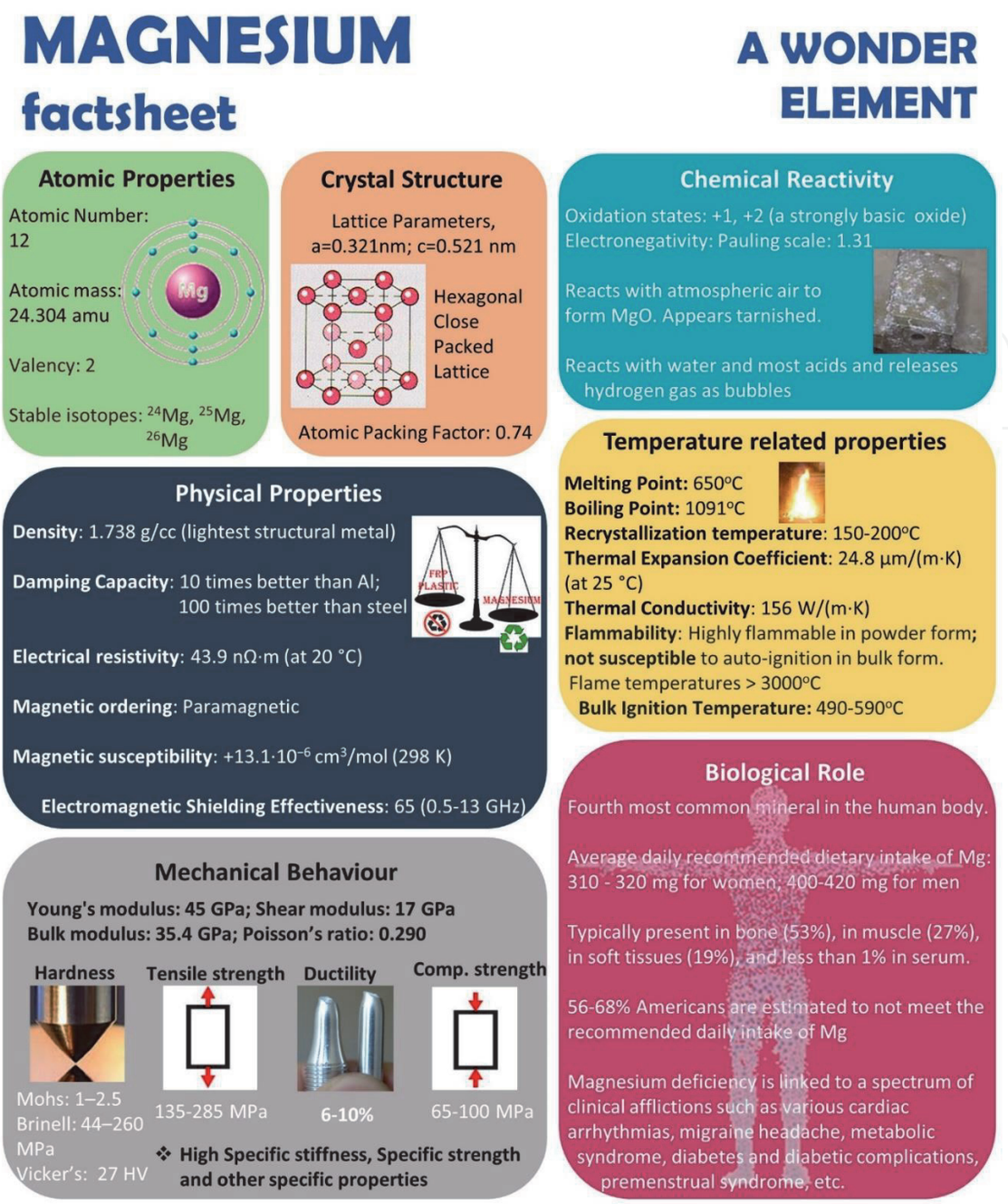

Figure 1.
Factsheet of magnesium.

Metal	Density (g/cc)	Price/kg (US$) (in 2016) [4]
Magnesium	1.738	4.71
Aluminum	2.7	2.13
Titanium	4.506	8
Steel	7.75–8.05	0.64

Table 1.
Price of the most commonly used metals.

variety of applications. These applications of magnesium are primarily classified into three categories: (i) structural, (ii) nonstructural, and (iii) miscellaneous applications. They are discussed briefly in this chapter.

3.1 Structural applications

About 40% of magnesium produced globally is directly used in the form of its alloys in structural applications [5] in different sectors described below in text as well as shown in **Figure 2**.

3.1.1 Automotive sector

The first automobile in the world (1885–1886) was made up of steel, a dense alloy, in most of its parts. With increasing efforts to improve fuel efficiency and energy efficiency as well as to reduce the cost of the vehicles, there was a shift from usage of steel to aluminum (owing to its lower density) that substantially reduced the weight of the automobiles. However, in recent years, driven by lower density of magnesium (33% lighter than Al), car manufacturers such as Porsche, Suzuki, and General Motors are increasingly using magnesium-based materials primarily due to their excellent specific mechanical and physical properties. Among several magnesium alloys, Mg-Al-based alloy series such as the AZ and AM alloys; Mg-rare earth-based alloys, i.e., WE43 and E21; and ZK alloys demonstrate good strength and ductility combination at room temperature along with good resistance to corrosion (salt spray) and superior castability [6]. Hence, they are predominantly being used in the automobile sector as sheets or even engine blocks and other automobile components such as in steering wheels, boot area, etc. Further, for robust and elevated temperature applications such as engine blocks, newly developed high-strength magnesium alloys and alloy nanocomposites can be used as they demonstrate good thermal and dimensional stabilities [7–11].

3.1.2 Aerospace sector

Historically (in the 1950s), magnesium was a dominant material in the aviation industry as a structural material. In fact, an aircraft (XR56) with all-magnesium was

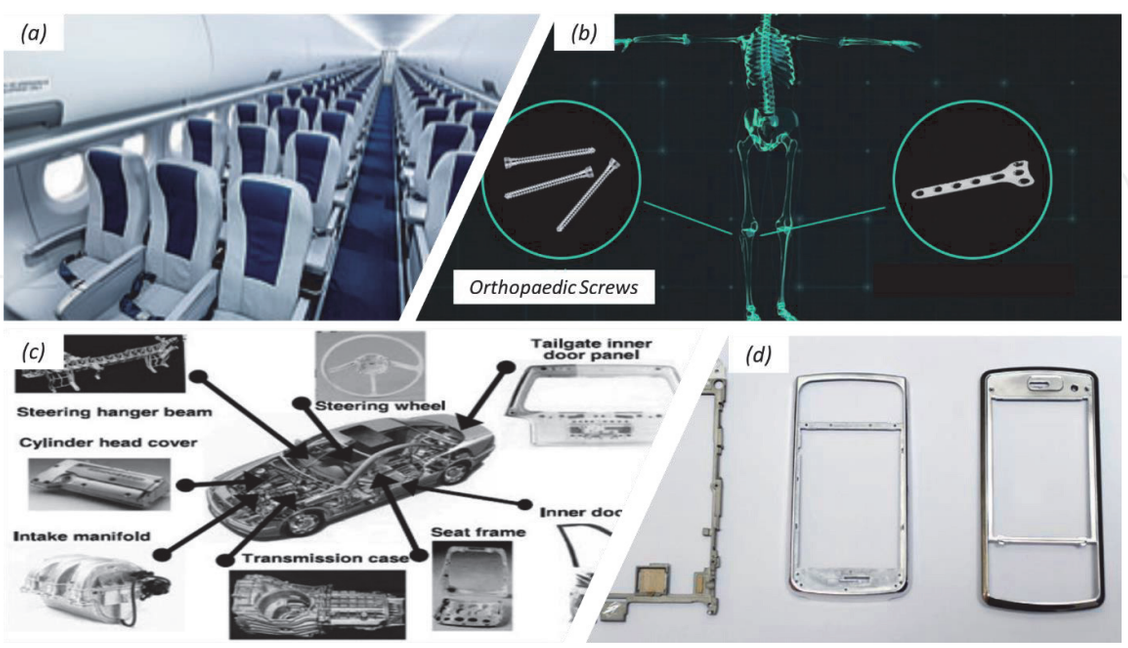

Figure 2.
Potential applications of Mg in (a) aerospace sector in the form of passenger seats (image taken from [25]); (b) biomedical sector where biodegradable magnesium alloy products can be used as implants, assist in fracture fixation, etc. (image taken from [26]); (c) automobile applications (image extracted from [27]); and (d) electronic applications such as mobile handset panels and casings (image used from [28]).

built by Northrop in 1943 during the World War period, similar to the Lockheed F-80C in 1950 [12]. With the "traditional" challenges such as reactivity and perceived flammability, magnesium usage was limited. Ever since upliftment of the ban on magnesium by FAA [13], there is an ever-increasing demand for high-performance magnesium alloys for reducing weight in aircraft structures such as interior components, fuselage structures, gearboxes, aero engine frames, helicopter transmissions, covers and components, flight control systems, electronic housings, and aircraft wheels [14]. With advancement in the alloy design and material development, for the abovementioned as well as other applications in both commercial and military aircrafts, advanced higher-performance magnesium alloys and composites that are also ignition-resistant or ignition proof and corrosion-resistant suit the requirement of the aviation industries and can help in achieving sustainability and protecting the environment [8, 15–17].

3.1.3 Electronic sector

In consumer electronic industries, due to the shortcomings of plastics that do not shield the electromagnetic radiations, have poor stiffness, and generate enormous scrap of electronic equipment, there is a need for nontoxic lightweight materials that can match the density of the commonly used plastics and perform better than that of plastics. These attributes are the reason that makes magnesium-based materials very lucrative as magnesium can be remelted, reused, and recycled. Its electromagnetic shielding capacity (65–66 in 0.5–13 GHz frequency range) is the same or even superior to that of aluminum alloys (59–65 in 0.5–13 GHz frequency range) [18–20]. Magnesium is currently one of the most sought-after materials for making the casings, frames, panels, and other parts in the electronic items such as mobile phones, laptops, cameras, etc. [21].

3.1.4 Biomedical sector

Mg is the fourth most abundant ion in the human body and assists in several functions like aiding bone health and multiple metabolic processes in the body besides being antibacterial and attracts attention as an excellent biomaterial [22]. Since magnesium is both biocompatible and biodegradable, it is the best fit to be used in the body as a nonpermanent biodegradable implant as it (i) reduces patient trauma; (ii) requires no revision surgery; (iii) reduces doctor's time; and (iv) reduces medical costs [23]. Further, it is also required by the body as it is instrumental for about 300 enzyme systems and assists in energy production and synthesis of nucleic acid in the body [24]. Further, there is good evidence for the use of supplemental Mg in various cardiac arrythmias, preeclampsia/eclampsia, migraine headache, diabetes and related complications, metabolic syndrome, premenstrual syndrome, asthma, and hyperlipidemia [24], indicating the significance of magnesium in human bodies and biomedical sectors.

3.2 Nonstructural applications

3.2.1 Alloying element to aluminum

On par with its direct structural applications, magnesium is used primarily as an alloying element to Al (about 40% of magnesium produced globally is used for alloying with aluminum). Magnesium is alloyed with aluminum up to 30% catering to suit a range of applications including pyrotechnics [29]. Some applications of Al-Mg alloys are as sheets in automobile applications and shipping industry due to

their good mechanical properties, castability, and superior corrosion resistance, owing to the presence of elevated magnesium content [30].

3.2.2 Refining titanium

Magnesium acts as a reducing agent in the production of titanium, beryllium, zirconium, uranium, and hafnium. It is the second largest use of Mg in a nonstructural market. In applications related to organic chemistry, magnesium is also used in industrial synthesis such as the Grignard reaction. Particularly, Mg is important for production of Ti sponges [31].

3.2.3 Steel desulfurization

Sulfur (0.025–0.03% S) is damaging to steel and causes brittleness. Hence, desulfurization of steel is done by exploiting the high affinity exhibited by

Minor applications	Advantages of using magnesium and other remarks
Sacrificial anode [35]	High-resistivity environment that have high current output per unit weight and inherent negative potential are particularly suitable for magnesium anodes. Some applications include underground pipelines, domestic water heaters, storage tanks, and other similar environments, where the galvanic corrosion of steel can be prevented by employing magnesium anodes. With suppressing the corrosion, the safety and resource conservation can be increased as the number of leaks decrease drastically
Magnesium batteries [36, 37]	A range of Mg batteries are under development in recent years for various applications. One such application includes that of military applications where magnesium is used in reserve cell batteries and dry cells. Magnesium batteries have (i) long shelf life (up to 10 years), (ii) high cell voltage and wide voltage range, (iii) high power density capacity, and (iv) lightweight in their inactivated state
Hydrogen storage [38]	Hydrogen is a plentiful yet largely untapped potential energy source. Hydrogen fuel cell prototype engines are 3–4 times more efficient than internal combustion engines. 10 kg of Mg can store roughly 0.67 kg of hydrogen. Mg can absorb about 7.6 wt. % hydrogen, which makes it one of the largest capacities among metal hydride alloys. Recently reported air-stable magnesium nanocomposites assist in nanostructuring, resulting in rapid storage kinetics by eliminating the need for usage of expensive heavier metal catalysts
Flameless ration heater (FRH) [39]	FRH is an exothermic chemical heater activated by water, applied to heat the food (especially in meal, ready-to-eat (MREs)). Ration heat is generated in an oxidation–reduction reaction which involves the transfer of electrons. US military specifications for the heater require it to be capable of raising the temperature of an 8-ounce (226.8 g) entree by 100°F (38°C) in 12 minutes and that it has no visible flame. The ration heater typically contains finely powdered magnesium metal, alloyed with a small amount of iron, and table salt. A little amount of water is to be used to activate the reaction, and the reaction proceeds when the boiling point of water is quickly reached [40]
Alkaline water	Mg alkaline water has a pH of 8.5–10 (vs. pH of water = 7–7.4). Pure Mg, Mg-Zn alloy, and Mg-Ca alloy are potential materials used. Al is not to be used as Al is linked to Alzheimer's disease
Fire starter	Due to its high flammability in fine or powdered forms, it is an ideal choice in this application. The fire starter is composed of an Mg block and flint stone. Typical applications include military, leisure, and emergency [41]

Table 2.
Miscellaneous applications of magnesium-based materials.

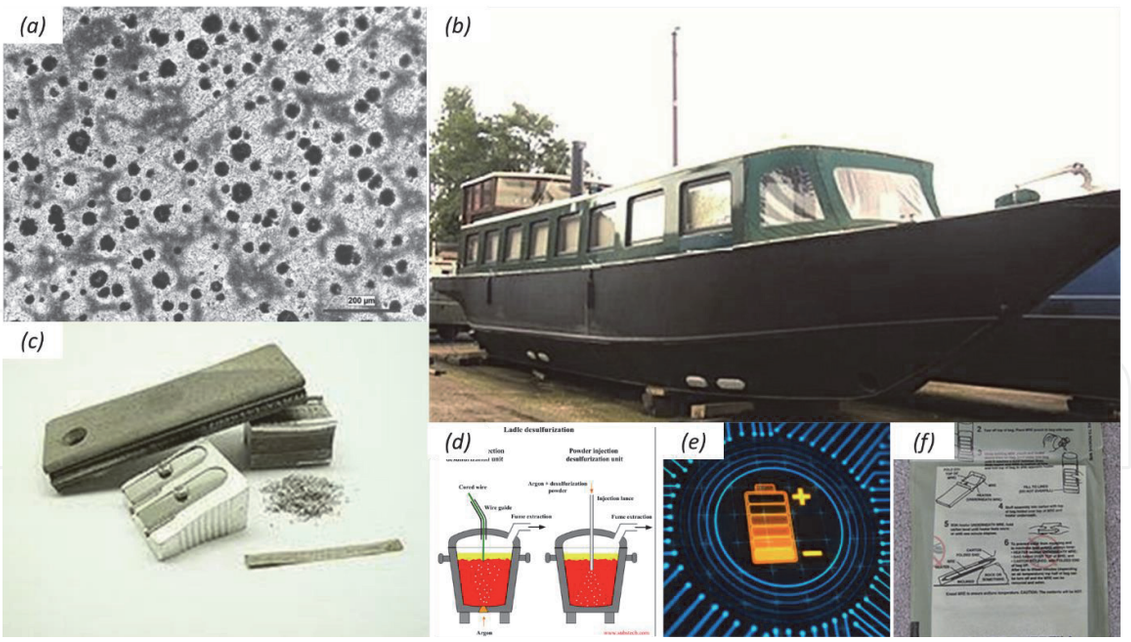

Figure 3.
Miscellaneous applications of magnesium in (a) nodularizing iron (image taken from [42]); (b) anodes, a steel wide-beam canal barge showing a newly blacked hull is protected with the help of new magnesium anodes (image taken from [43]); (c) fire starter, shavings, sharpener, and ribbons (image taken from [44]); (d) desulfurization of steel (image reproduced from [45]); (e) new generation fast magnesium-ion solid-state electrolyte batteries (image taken from [46]); and (f) flameless ration heater (image taken from [47]).

magnesium to sulfur. It is the third largest use of Mg in a nonstructural market. Magnesium is added to molten iron or steel which helps in reacting with sulfur and reduces the sulfur in the steel [32].

3.2.4 Iron nodularization

For nodularizing cast iron, magnesium is used to produce spheroidal graphite cast iron or nodular cast iron. The addition of magnesium to cast material assists in the formation of nodules instead of flakes resulting in improved ductility. Typically, nodular cast iron is used in several components in automotive sector and pipes [33].

3.2.5 Photoengraving

Printing industry uses wrought (plates) of magnesium alloys for photoengraving. This is because Mg etches rapidly, hence creating a sharp impression. Further, it also creates less hazardous by-products as compared to alternative metals [34].

3.3 Miscellaneous applications

Table 2 and **Figure 3** list minor applications where magnesium is currently/can be potentially employed.

4. Concluding remarks

In this introductory chapter, a snapshot on the diverse and multidimensional properties and capabilities of magnesium is introduced. In view of the environmental conservation and lightweighting, and to improve the fuel and cost

efficiency, magnesium is strongly emerging in weight-critical structural applications such as in the automobile, aerospace, space, and defense sectors. Further, as magnesium is light, recyclable, an excellent dampener, and an efficient electromagnetic shielder, it finds a remarkable place in the electronic industry. In addition, with its biodegradability and nontoxicity coupled with its low elastic modulus, almost matching that of the bone, it is a potential material as a nonpermanent implant in the human body. It is also an extremely important element used in several other applications such as alloying element to Al, refining of Ti, desulfurization of steel, fire starter, etc. Thus, magnesium is a potentially a very important eco-friendly metal that is opening multibillion dollar markets in many industrial sectors.

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