

Chapter 2

Magnesium Alloys for Sustainable Weight-Saving Approach: A Brief Market Overview, New Trends, and Perspectives

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Abstract

In the transportation sector, weight-saving strategies emphasize greenhouse gas reductions by improving fuel efficiency. Furthermore, it is a fact that consumers appreciate less-consuming vehicles. Lighter battery electric vehicles (BEV) mean higher travel distance covered with the same battery charge. Still, the fuel range of BEV is today not a secondary issue for choosing an e-vehicle as a unique family vehicle. Weight-saving strategies are also a priority for hydrogen gas-fuelled vehicles. Until hydrogen fuel for the transport sector is not produced at affordable costs in fully renewable pathways, increased fuel efficiency is critical for the product appeal. Magnesium is an environmentally compatible and biodegradable material with a similar density to structural plastics. On the contrary, plastics are responsible for nonbiodegradable microplastics in deep-marine environments when not recycled or correctly treated at their end of life. Due to the costly usage of lightweight materials, priority is given to activities to reduce costs by developing new materials and increasing the affordability of manufacturing costs. In this chapter, magnesium is presented from much perspective point of view: we will base it on comprehension of the past, considering the present, but with some ambition to propel hearts over today's obstacles.

Keywords: magnesium, automotive, weight-saving, carbon footprint, lightweight, electrolytic, Pidgeon

1. Introduction

The need for weight-saving in the automotive and mass transportation sector, like trains and civil airplanes, has historically pushed the usage of magnesium, which, for shared knowledge, is the metallic material at the lowest density, nearly to dense polymers. But, much more effectively, magnesium alloys are characterized by very high specific strength. A long tradition and past knowledge of the magnesium industry accumulated from the 1970s till its Golden Age in the early

1980s. In those years, you could buy primary magnesium at its lowest price on the marketplace, and many bet that the turn against rival aluminum was just around the corner. However, the forecast high growth rate of the magnesium market has not succeeded yet.

Today, you can hear about big worries about magnesium:

- It could be an unsafe material, susceptible to easy burning and explosion.
- It has a high cost and poor availability on the market.
- It has a high carbon footprint in the extractive, refining, and casting processes.

You could also add to the list a poor knowledge of the wrought alloys and their deformation processes and concerns about their poor corrosion and creep resistance. Those barriers prevented magnesium from competing with its main rival in weight-saving strategies in the transport sector, the aluminum metal. In the following, we try to give readers a more detailed view, considering that we have to know what we were in the past to get a keen comprehension of today's concerns.

Most concerns about the magnesium market do not depend on geographical lack of raw material. Still, trade issues, production base, and export policies made primary production in Europe not competitive. The last primary production plant in Europe shut down in 2001 since European-based smelters could not compete with low-cost Chinese production. As a result, the availability of primary material is a genuine concern, as European demand depends mainly on China's imports. Therefore, one main drawback for broader use in the automotive industry is the lack of a solid supply base with stable prices over a medium-term period combined with competitive magnesium production outside China. The last primary production plant in Europe shut down in 2001 since European-based smelters could not compete with low-cost Chinese production. As a result, the availability of primary material is a genuine concern, as European demand depends mainly on China's imports. Therefore, one main drawback for broader use in the automotive industry is the lack of a solid supply base with stable prices over a medium-term period combined with competitive magnesium production outside China. But few people know which milestones were in the history of the magnesium market. Why did magnesium growth not meet reasonable expectations? Why did the material price increase and fluctuate after prolonged stability at the lowest price level targeted in the 1980s, the years of maximum Western production? What shaped today's market structure based on perilous dependency on Chinese producers? In the following, we'll try to give you a compass to never get lost in such a multifaced and complex market.

2. Magnesium demand in the transportation industry: learning from the past about historical barriers to magnesium growing demand

During First World War, Americans noticed the importance of magnesium for its strategic pyrotechnics application. Magnesium was the base of flares incorporated in rocket devices that, fired into the air, descended with a parachute, lighting the

enemy's corridor for several minutes. During the Interwar period, 1919–1939, the interest in strategic magnesium for national armaments industries rose worldwide (**Table 1**). The rise in the magnesium demand was pushed by lightweight structural applications. Alliances were surprised by the German Luftwaffe supremacy of the burning European skies. German airplanes were faster and capable of carrying unexpected bomb shipments. By studying some German planes that crashed, the British discovered that they contained a large percentage of magnesium alloys, the “Elektron metal” as the Germans called it. The weight-saving in German aircraft was the key to such a significant advantage in the European skies. Magnesium was instantly proclaimed as a strategic metal for the second time. The U.S. Government allocated

Starting year	Process	Sources	Company	Region	Type
1895	I.G. Farbenindustrie	Seawater/brine	I.G. Farbenindustrie	Germany	Electrolytic
1915	Dow process	Seawater/brine	Dow Chemical	Midland, Michigan (USA)	Electrolytic
1920	Dow process	Fluoride material and magnesium oxide	American Magnesium Corporation (Alcoa)	California (USA)	Electrolytic
1920	Dow process	Seawater/brine	De Norske Saltverker AS	Bergen, Norway	Electrolytic
1931	I.G. Farbenindustrie's technology	Dolomite/FeSi	National AluminiumMagnesium Institute (VAMI) USSR	Leningrad	
1933	I.G. Farbenindustrie's technology	Dolomite/FeSi	Riken Metal Manufacturing Co.	Ube (Japan)	Thermal
1935	I.G. Farbenindustrie's technology	Dolomite/FeSi	Government plant	Zaporozhye and Solikamsk (USSR)	Electrolytic
1936	I.G. Farbenindustrie's technology	Dolomite/FeSi	Magnesium Electron Company (MEL)	United Kingdom	Electrolytic
1941	Dow process	Seawater	Dow	Freeport, Texas (USA)	Electrolytic
1945	I.G. Farbenindustrie's technology	Brucite Mg (OH) ₂	Aluminum Company of Canada (Alcan)	Arvida (Quebec)	Electrolytic
1951	I.G. Farbenindustrie's technology	Seawater	Norsk Hydro	Porsgrunn, Norway	Electrolytic
1959	Pidgeon	Dolomite/FeSi	Alabama Metallurgical Corp.	Selma, Alabama (USA)	Thermal

Starting year	Process	Sources	Company	Region	Type
1960	Pidgeon	Dolomite/FeSi	Furukawa Magnesium Corp.	Oyama (Japan)	Thermal
1964	Magnetherm	Dolomite/FeSi	Pechiney	Marignac (France)	Thermal
1964	Pidgeon	Dolomite/FeSi	Ube Kosan	Ube (Japan)	Thermal
1969	Modified IG I.G. Farbenindustrie's technology	Brine	National Lead Industries (From 1980, facility operated by Amax Inc.; from 1989, facility operated by Magnesium Corp. of America. MagCorp)	Great Salt Lake, Utah (USA)	Electrolytic
1970	Modified IG I.G. Farbenindustrie's technology	Dolomite/FeSi	AM Magnesium	Texas (USA)	Electrolytic
1972	Dow process	seawater	Dow Chemical	Texas (USA)	Electrolytic
1974	Amati-Ravelli	Dolomite/FeSi	Magnesium do Brasil	Ceara (Brasil)	Thermal
1975	Magnetherm	Dolomite/FeSi	Alcoa's Northwest Alloys	Washington (USA)	Thermal
1992	Norsk Hydro	Magnesite	Norsk Hydro	Quebec (Canada)	Electrolytic
1993	VAMI/ UTI Technology (Russian)	Brine	Dead Sea magnesium	Israel	Electrolytic
1994	Alcan	Asbestos	Noranda	Canada	Electrolytic
1997	Alcan	Magnesite	Queensland Metals Corporation Limited	Australia	Electrolytic

Table 1.
History of worldwide magnesium plants before 2000s.

all of the U.S. nation's total production (at that time produced by Dow Chemical) to national defense. At the beginning of the Second World War, the production of magnesium was 33,500 tons, whereas 5 years later, magnesium production reached a peak of 426,000 tons [1].

Americans developed their own wrought and cast magnesium alloys. Enormous quantities of magnesium were put on military aircraft to curb the weight of liquid and air-cooled engines, wheels, oil tanks, frame structures, instrument housings, gyro frames, and many others. The jet-propelled prototype "Flying Wing" airplane was an aircraft bomber, designed for high speed and maneuverability, made primarily of magnesium (**Figure 1a**). It never entered service in favor of the B-36 bomber (**Figure 1b**) that used a total of 3800 kg of magnesium in castings, forgings, and sheets for airframe parts and fuselage skin. At the same time, for civilian scope, commercial truck vehicle, body, and motor engine parts, benefited as well from the light-weighting that was made possible by magnesium. Magnesium alloys were extensively used in the airframe skin of the large airplane Convair XC-99 built by the U.S. Air force that remained in activity from the 1940s to 1950s. By 1948, the military aircraft Lockheed F-80C

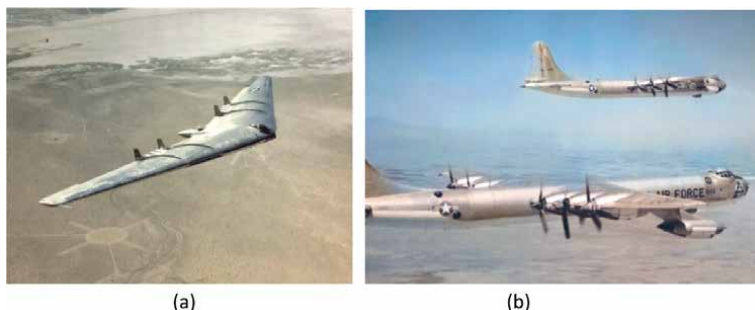


Figure 1.
(a) The “Flying Wing” airplane and (b) the B-36 bomber airplane.



Figure 2.
The Lockheed F-80C is constructed of magnesium throughout, today visible at the United States Air Force Museum, Ohio.

“Shooting Star” was the first American project for constructing a combat-ready jet fighter capable of exceeding 500 mph in level flight. One F-80C (47-171) constructed magnesium throughout, redesignated NF-80C-LO, is today visible at the United States Air Force Museum, Ohio (**Figure 2**).

However, following the end of the Second World War, military applications of magnesium lost their strategic importance. The magnesium extractive industry contracted to register a new peak demand in the early ‘50s because of the Korean War.

The production peak registered during Second World War drawn by U.S. national production was not surpassed until the ‘70s. Widespread post-war applications of magnesium would be expected in automobiles and civil aircraft to reduce engine weight and dynamic masses. Still, magnesium demand finally decreased till the ‘70s, not being sustained by aggressive market growth strategies. Magnesium soon revealed losing in front of the prominence of aluminum alloys. The significant factor restricting the growth of magnesium after wartimes can be researched—as a comparison—looking to a good lesson taught by the rival aluminum industry. The primary aluminum industry had a long tradition of cooperation. A group of pioneers in the European aluminum industry set up an “Aluminum Association” way back in 1901,

just 15 years after the modern electrolysis smelting process patents of Charles Martin Hall and Paul Héroult. It was created to promote the widespread use of aluminum (at that time, aluminum was a pioneering material for few applications) to provide economic governance to the nascent aluminum market [2]. The Aluminum Association shared information on markets, feedback from customers on applications, on the quality of the metal. All those information was necessary to align demand requirements and supply features and to encourage the private sector's investments. It was an observatory to analyze the market trends to make the use of aluminum alloys easier. Moreover, the Aluminum Association directed specific actions toward pricing policy based on stable selling prices to promote demand growth. This stability consolidated a nonspeculative market, and it allowed to plan a gradual and programmable extension of the productive capacities of big plants.

These efforts were not completely replicated in the nascent magnesium market to sustain post-war demand. It is true that a prominent American producer, the Dow company, broadened civilian markets by the '1950s. Precisely, the date 1954 was when the Dow company started the mass production of Samsonite Ultralite luggage bag, 20% lighter than other luggage bags, entering in operativity a mammoth large-scale magnesium sheet mill. At that time, several advancements in magnesium alloys were made. New coatings (anodic, electroless-Ni, and Cr-plating) were produced in the 1950s to protect the magnesium alloys from corrosion; viable ceramic and porcelain coatings for magnesium were developed, processes for cladding magnesium sheet and plate alloys with other magnesium alloys and aluminum.

At Dow company, people frequently told that Dow's metallurgists within the 1960s probably had alloyed magnesium with any possible element with good wettability like Li, Al, Si, Ca, Mn, Cu, Zn, Sr, Y, Zr, Ag, and Rare Earth [3]. Researchers soon focused on the overall properties of a fabricated Mg-alloy component as a result of microstructure [4] finally realized by alloy chemistry and processing parameters to promote beneficial solid solution distribution, dispersoids, intermetallic precipitation by heat treatments, grain refining.

Corrosion behavior of Mg alloys developed was enormously improved by limiting impurities Fe, Ni, and Cu that largely influence corrosion resistance of Mg because of the formation (and dispersion) of micro-galvanic cells. New Mg-RE, Mg-Th, and Mg-Th-Zr high-temperature alloys were developed at the beginning of the '60s for use at temperatures of 200–350°C but were limited to their high costs to jet aircraft and military missiles. Following the first hot chamber die-casting process developed at Dow Chemical Company [5], further die-casting techniques were improved and widely used to make engine-driven tools (chain saws, post hole diggers, etc.). Researchers and metallurgy laboratories at magnesium companies provided many answers to questions about phase equilibria, alloying effects, and the relationship of structure and properties for their potential customers (casters, forgers, extruders). During the 1960s in Europe, 20,000–25,000 tons, supplied mainly by Norwegian Norsk Hydro, were being used in the Volkswagen Beetle's air-cooled engine and gearbox. Those components were installed above and behind the rear wheels, and this required the German engineers to produce a drive system as light as possible so that the front wheels gripped the road adequately. The 1960s were also the Cold War years, and several magnesium sheets were used in the lightweight intercontinental ballistic missiles. A machined magnesium-lithium alloy LA 141 was chosen for its high stiffness, low weight, and sound vibration damping characteristics for manufacturing the chassis of the Launch Vehicle Digital Computer (LVDC) that provided the autopilot for the Saturn V, the liquid-fueled rocket developed under the Apollo program for human



Figure 3.
The Gemini spacecraft with the centered, white-painted portion in magnesium alloy.

exploration of the Moon. High-temperature magnesium-thorium alloys in sheet and extrusion form constituted a large part of the large conical structure of the Retro-Rocket Modules of the Gemini spacecraft (the white-painted portions in **Figure 3**, just near the black-painted cone).

However, it was symbolic of what president Roger Wheeler said at the 23rd Annual Meeting of the Magnesium Association (still, International Magnesium Association) in 1966. He said that the magnesium industry had failed in the previous 15 years to take its place as a fundamental industrial commodity metal in the U.S. [6]. At that time, magnesium consumption was one order less than forecast one decade earlier. The Magnesium Association recognized that the future of magnesium growth in North America could depend on the automotive market, and automotive engineers needed to lose their concerns about magnesium, following the example of Germans [7]. In Germany, likewise the air-cooled Volkswagen Beetle die-cast engines, in 1967 Porsche developed the 166 kg crankcase for their six-cylinder 911 series (**Figure 4a**), following visionary forecast in the post-wartime (**Figure 4b**).

By the 1970s, developments were extended to new composite magnesium-based materials, new high-temperature magnesium alloys, new fluxing methods, squeeze casting, recycling methods, and new anodizing processes for magnesium [8]. They were good news for the magnesium industry, but, in reality, in the middle 1970s, world demand for magnesium was about not more than 2% of the aluminum. Economic uncertainties by the oil crisis caused the rapid decrease in sales of the Beetle caused German automakers to curtail magnesium consumption [9]. Despite aluminum pricing that remained steady, the rising magnesium price made aluminum much more competitive. Whether during the late 1970s and beginning 1980s, the need for cutting fuel cost of automobiles could represent an opportunity for the magnesium industry, desulphurization and deoxidation of steel were (unfortunately) still considered the most favorable growth market for magnesium [10]. Magnesium for aluminum alloying was expanding market sector as it consumed almost half of the magnesium production, and it was expected to grow at about 5% per year, while some other markets such as desulphurization and die casting were expected to grow more rapidly [10]. Many efforts were made by researchers to develop high-performance alloys for automotive applications to curb as much weight as possible from massive

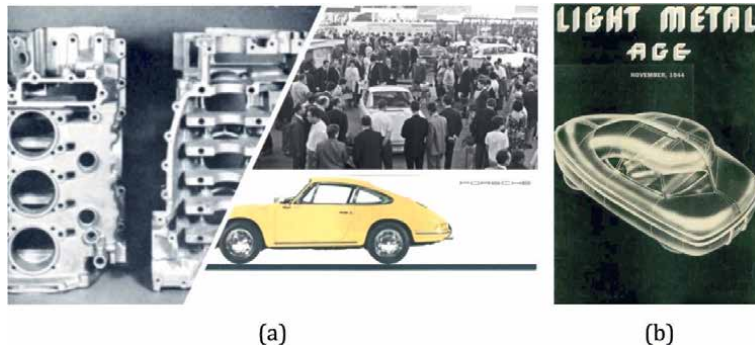


Figure 4. (a) The Porsche 166 kg crankcase for the six-cylinder 911 series; (b) the November 1944 issue of *Light Metal Age* presented an image of “Tomorrow’s light metal car.” In the associated article, the writers talk about the use of aluminum and magnesium in the sleek-lined, spaced-aged cars of the future.

engine blocks, including advanced rapidly solidified magnesium alloys [11] and magnesium alloy composites [12].

Over the second half of the 1980s and early 1990s years, the period was a time of great ferment for magnesium potentialities in the automotive sector [8]. The dominant technology for magnesium production was still electrolysis with giant plants, and the leading producer countries were the United States, Canada, and Norway. Die casting consumption with different magnesium die-cast components in automobile sectors drove the significant annual growth rate of North America—thus more or less the total world magnesium demand at that time. General Motors die-casted in a single-shot, a large part an instrument panel beam for the GMC Savana and Chevrolet Express van. It was a 12 kg part 4 mm thick, which provided 32% mass saving compared to the steel design with improved crashworthiness and high vibration damping. It was less costly thanks to a few parts assemblies, 25 parts in the magnesium design compared to the 67-parts in the steel-made product [13]. To shape much more complex parts made of magnesium, in 1991, the Dow Company registered the Patent for a method and apparatus for the injection molding of magnesium metal, a process based on the foundation of the fundamental discoveries on semi-solid metals by Flemings and his students at Massachusetts Institute of Technology, MIT [14].

During that golden age for magnesium, the US Dow Company increased its almost monopolistic control of the magnesium market thanks to the economy of scale of its giant and old electrolytic plants powered by low-cost power sources available in Texas. In 1991 Dow could produce 109,000 tons per year, namely around 35% of the world’s entire output. But the cost of making magnesium in Texas began to rise gradually as the time of cheap natural gas ended. With almost 20 kW-h of electricity to produce a kilogram of magnesium, a lot of power was available, but all that power had been contracted for by the big aluminum producers like Alcoa, Kaiser, and Reynolds [3]. The old Dow plant became soon antiquated, and to stay in business at a competitive level, the most significant World producer would have had to build a new efficient plant, as planned at the Great Salt Lake, a project that never started. Factors leading to Dow’s success, and that driven till the early 1990s all magnesium market, have been: early entry, cost efficiency, and strategic deterrence behavior [3]. The biggest world’s magnesium producer started to hand over its 60 years of harvests by the early 1970s when Dow began to reap the benefits of its magnesium business rather than investing beyond its old plants in Texas. Dow company switched from a

“limit pricing” strategy originally designed to deter entry to a “skim pricing” type of strategy that ultimately sacrificed the firm’s viability as a magnesium producer [15].

Unlike Dow, other dominant firms have opted to expand tactically in related industries (e.g., DuPont in titanium dioxide and Alcoa in aluminum before 1945). One potential explanation is that Dow’s cost advantage was not sustainable. Dow’s production process benefited from years of incremental improvements but was not fundamentally different from the technology potentially available to others [15]. The Dow big electrolytic plants worked at an efficient scale in the decades after wartime characterized by modest demand for magnesium, and there were substantially no further opportunities for new efficient-scale plants until the U.S. But a radical change, as depicted, started with an automotive interest in magnesium at the beginning of the 1990s. Magnesium would switch its position in the marketplace from a specialty material with one dominant producer with considerable knowledge accumulated in 60 years into a commodity product with a competitive global market [15].

The rest of the story is like what happened to dominant Western countries firms in similar markets for commodity products. As the Cold War ended around 1990 and as the Chinese economic reform entered its Second Stage (the establishment of the Socialist Market Economy), individual Chinese enterprises were allowed to exist and to be protected by the law of the People’s Republic of China. The primary market forces began to shift very rapidly in Western countries. In China, a multiplicity of low-investment production plants with the Pidgeon process were building at the minor technology scale. Hundreds of those plants based on a very high labor-intensive process were set up and ramped up very rapidly, in a few months, producing per capita just a few hundred metric tons per year. There was no Chinese knowledge at that time about magnesium alloying and alloys applications; those plants needed just to sell primary magnesium to the Western countries at almost their marginal cost. This new situation created confusion in the not-stabilized marketplace [3]. However, it is a fact that the Pidgeon process produced a significant amount of World War II magnesium. Those Pidgeon plants during wartime could not compete with the electrolytic process.

On the contrary, in the 1990s, when small Chinese plants started to supply 4% of the world’s magnesium, Chinese labor cost was very low. In that period, Chinese-made magnesium was sold at about 0.72 USD/lb. while Dow’s production cost was not less than 1.08 USD/lb. That magnesium price had been starting to crush the marketplace, a problem that never ended till that time. By far, the principal use of magnesium, almost 50%, that year was recorded in alloying the large numbers in the aluminum beverage cans sector, in which magnesium was (and is) used as a strengthening agent instead of in structural alloys for engineering applications.

Very soon, China, with its low prices, supplied 50% of World magnesium demand (**Figure 5**), becoming the world’s largest supplier of primary magnesium. Between 2000 and 2010, magnesium production in China tripled, mainly due to the high costs of the process in the USA, Canada, France, and Norway. Most of the big magnesium plants in those countries were closed due to lower competitiveness. Despite the establishment of duties that could reduce imports, U.S. producers of magnesium began to exit the market. In 1998, Dow Chemical decided to leave the magnesium business, contracting a licensing deal for its technology to Samaj, a Pima Mining’s subsidiary, for the South Australian magnesium project. Northwest Alloys Inc. closed its plant in Washington by 2001. Renco Metals Inc., the Magnesium Corporation of America parent, filed for chapter 11 bankruptcy in August 2001. In the same year, Norsk Hydro ended magnesium production in Norway, and after 6 years, in 2007, it ended its

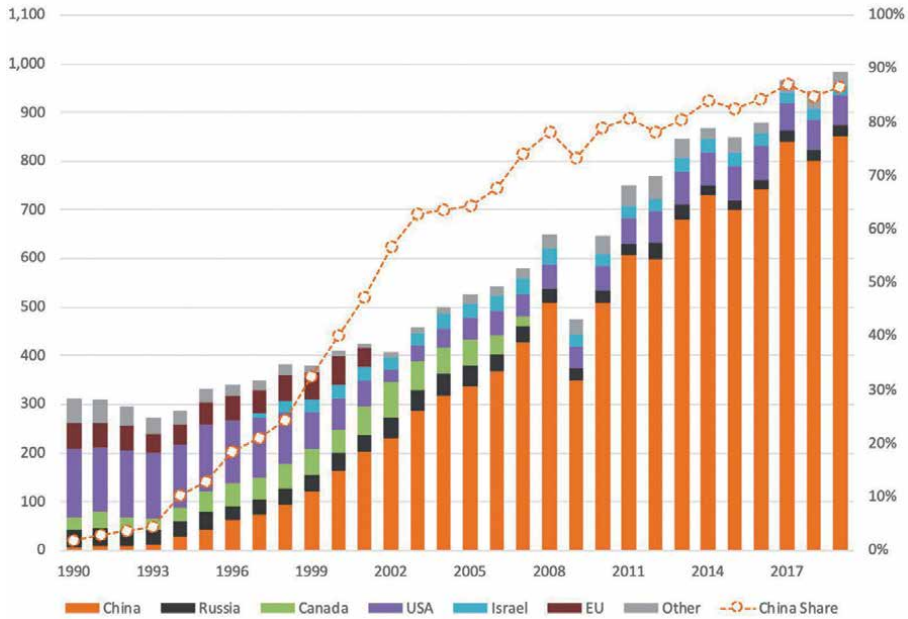


Figure 5. Evolution of magnesium production per region (1990–2017) [16].

operation at Becancour, Canada. Noranda, which operated in Quebec the Magnolia electrolytic magnesium plant relied on serpentinite tails from nearby asbestos mines, closed the smelter in 2003.

By 2015, more than 80% of the world’s magnesium production took place in China, followed by Russia, Israel, and Kazakhstan, with only a few percent market share. In 2021, due to curbs in domestic power consumption, Chinese production of magnesium had been halted or curtailed to such an extent that deliveries to Europe have drastically dropped since 20 September 2021. In the second half of 2021, in the world’s main magnesium production hubs, Shaanxi and Shanxi Provinces, 25 magnesium plants would have to shut down. Five other plants had to cut production by 50% amid China’s power curbing rollout. With an 87% global share in magnesium production, the Chinese supply shortfall has already resulted in record prices, reaching the never recorded price of 6 Eur per kg and a worldwide global distortion in the supply chain.

The dependency on Chinese producers has created magnesium users worldwide a deadly embrace. Fluctuant prices over the 2000s depend on Chinese supplies. From the end of 2007 to the end of the first quarter of 2008, the average U.S. spot Western price increased significantly, as in China and Europe. Several factors contributed to these price escalations. In the United States, a decline in imports from Russia and Canada, two of the leading import sources, caused a supply shortage on the spot market. In China, increased prices for ferrosilicon, power, and transportation were causes for the rapid price increase [1]. In addition, environmental crackdowns by the Government of China may have led to shutdowns at some smaller and highly pollutant Pidgeon plants. In the United States, the Platts Metals Week U.S. spot Western price range reached a peak of USD 3.50 to USD 3.70, while in China, the magnesium price range reached a high of USD 5950 to USD 6250 per metric ton. The increased production cost of Chinese magnesium is firmly attributed to higher prices for raw

	Electrolytic reduction (Western) (%)	Thermal reduction (China Pidgeon, coal-powered) (%)
Materials	6	50
Capital	37	20
Energy	18	8
Labour	16	5
Other	24	17
Total	100	100

Table 2. *Cost shares breakdown of primary magnesium and significant differences existing among the old Western big electrolytic plant and the small Pidgeon plants.*

material (main ferrosilicon), decreased production due to stricter environmental regulations at smelters and coal mines, increased labor costs, and an increase in coal power cost. **Table 2** represents the cost-shares breakdown of primary magnesium and significant differences between the old Western big electrolytic plant and the small Pidgeon plants powered by coal, primary actors of national magnesium production expansion in the first decade of the 2000s.

Though the raw material cost is essential, price stability is a much more relevant factor. For this reason, several projects are currently being developed to increase primary magnesium production capacity worldwide. In Nevada, United States, one company has obtained permission to build a pilot plant to test magnesium production from a dolomite deposit. In Quebec, Canada, a company started the construction of a secondary magnesium smelter. A company in Australia with a 3000 ton per year plant is going to be completed; it will recover magnesium from coal fly ash [17].

Now, let us go a bit in-depth about price concerns.

On the one hand, manufacturers are under the constant pressure of product costs that must be affordable; on the other hand, they cannot easily justify the use of bright material characterized by a (historical) uncertainty of supply over a medium-term period. **Figure 6** shows the price history of magnesium metal (US Market spot price) relative to magnesium and aluminum [USGS Bulletins]. On that source, it is crucial to notice that the ratio between magnesium and (primary) aluminum price has been over the ratio of 1.6, which is generally considered the affordable price ratio for magnesium versus aluminum, usually calculated by the inverse ratio densities of the two materials.

On the other hand, it would be more appropriate to consider the switching cost for each kg of steel that you would substitute with the alternative light metal for the same function. **Table 3** represents a viability study on the structural application of light metal alloy for manufacturing the automobile outdoor body panel that shall guarantee equal (or higher) stiffness and denting capability. To evaluate whether it is technically convenient to replace galvanized mild steel with lighter aluminum and magnesium metal alloys for stamping an outer door panel of a road vehicle, we need to know for alternative lightweight scenarios the substitution factors that are defined as the mass ratio between the lightweight (aluminum and magnesium) and the baseline (steel) component. The mass is obtained by multiplying the material density by the volume of the panel. Otherwise, the outer door panel volume is obtained by the front area of the panel that is usually fixed due to geometry constraints (e.g., the perimetral geometry defined by screen and center pillars) and the thickness of the panel sheet cold drawn.

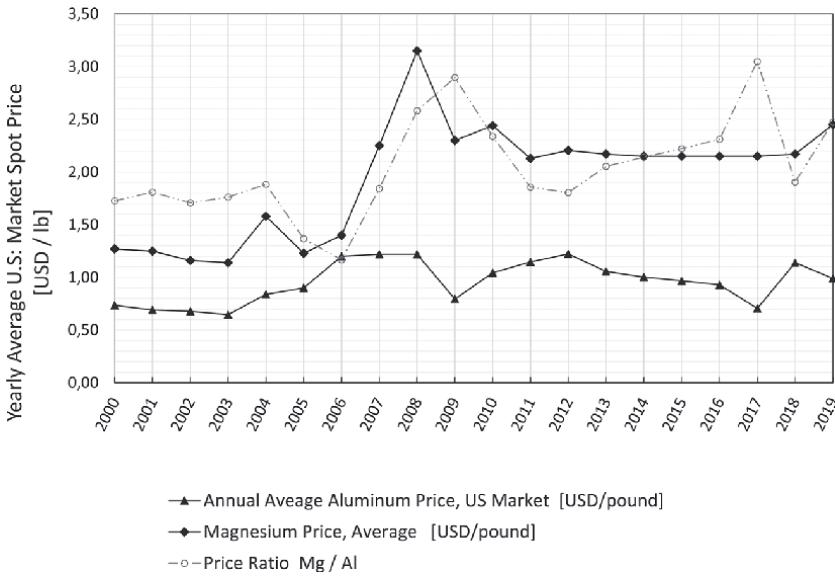


Figure 6. Yearly average U.S. market spot price for aluminum and magnesium [18].

	Baseline	Lightweight solutions	
	AISI 1045 steel	Aluminum 6061	AZ31D twin rolled cast sheet, warm formed
Density [g/cm ³]	7.8	2.7	1.8
Yield strength (minimum) [N/mm ²]	350.0	250.0	135.0
Elastic modulus	210.0	70.0	45.0
thickness for bending load parity and stiffness [mm]	0.8	1.2	1.3
Strength-to-weight ratio (kNm/kg)	44.9	91.2	75.0
Minimum thickness to achieve bending load parity with galvanized steel [mm]	—	1.2	1.3
Minimum thickness to achieve stiffness parity to galvanized steel [mm]	—	0.9	1.3
Panel mass [kg]	15.9	8.1	6.2
Substitution factor (SF)	1.0	0.5	0.4
Weight saved in percentage with lightweight solution	0%	49%	61%
Current production cost (Eur/kg)	0.9	3.3	6.5
Elastic module [GPa]	210.0	70.0	45.0
Switching cost per each kg steel substituted with an alternative metal for the same function, equivalent stiffness, and load (denting) capability, calculated as (price of 1 kg material) × SF: [Eur]	0.9	1.7	2.5
Material unitary cost for steel parity, calculated as (unitary steel price)/SF: [Eur/kg]	0.9	1.8	2.3

Table 3. Feasibility study about the affordability of lightweight solutions with aluminum and magnesium alloy for an outdoor body panel for the automobile; comparison with baseline steel scenario.

Furthermore, it is a multiple constraints problem: it is a strength-limited design problem with constraints in terms of the same (or higher) dent resistance and same (or higher) flexural stiffness of the panel. Under these circumstances, substitution factors for an aluminum alloy AA 5083 sheet cold drawn ranges 0.5–0.6, for a magnesium alloy AZ31D twin rolled cast sheet warm stamped ranges 0.4–0.5 (refer again to **Table 3**).

Thus, by calculating the material substitution factor for each light metal considered, we would evaluate how much is the switching cost of each kg of steel when it is substituted with 0.6 kg aluminum alloy or with 0.4 kg magnesium alloy. **Table 3** shows the switching costs per kg of steel in the case of both aluminum and magnesium solutions. Much more interesting is the line indicating the “steel parity” unitary material price (Euro/kg) for the outdoor panel: it represents how much it should be the unitary price for an alternative material to manufacture the body panel at the exact cost of the baseline case, the steel made pan.

Hence, the big question: is the steel parity cost the unique parameter to consider if magnesium is attractive as light material?

3. Magnesium for weight-saving and lowering energy for transportation

Nowadays, the transportation sector impacts around 25% of direct CO₂ emissions from fossil fuel combustion. Among the variety of transportation means, road vehicles, particularly passenger cars and freight vehicles such as heavy trucks, busses, and two-wheelers, are estimated by the International Energy Agency (IEA), accounting for nearly three-quarters of transport CO₂ emissions. Although CO₂ emissions from aviation and shipping have been increasing in the last decade, the road share of total transport sector emissions has fluctuated around 75% of total transport emissions for two decades. If several efforts and advancements have been made in road-vehicle electrification, otherwise larger (and heavier) vehicles are still preferred by lots of consumers. The worldwide market share of SUVs has increased in the last two decades, and in 2019, before the pandemic crisis, it represented nearly half of the global light-duty vehicle market in several countries. Growing demand for the urban transport of goods is rising, adversely affecting air quality, noise, safety, and liveability in the city. The automotive sector has been putting efforts for reversing CO₂ emissions growth by several strategies; one of those strategies focuses on energy efficiency countermeasures that would be implemented in the form of:

- managing/rationalizing travel habits to reduce the frequency and/or distance switching from high-energy-intensity modes (e.g., private car and or air) to most efficient methods (i.e., train for traveling long distances plus rented new efficient vehicles on local base).

- deploying energy-efficient technologies for vehicles and fuels.

- more stringent requirements on vehicle efficiency, namely, power consumption per km.

The latter strategy is thought a valuable approach for accompanying market migration from heavy vehicles powered by combustion engines fueled by gasoline toward cleaner electrified cars that could be likely powered by near-zero-emission electricity. During vehicle operation, the fuel consumption rate can be approximated as the sum of a linear function of the vehicle mass and—as a second contribution—the loss in aerodynamic drag; both of them through coefficients that depends on several vehicle characteristics. Strategies approaching weight reduction are actually most effective during transient driving cycles; instead, during constant speed traveling, the

vehicles' fuel efficiency mostly depends on aerodynamic drag forces. Global average fuel consumption of new cars has been too slowly decreased, less than 2% per year, setting around 7 L gasoline equivalent per 100 km (Lge/100 km). To get on track with 2030 targeted 4.5 Lge/100 km, expected standards will become significantly more stringent to achieve efficiency goals. In 2021 the European Commission proposed new CO₂ emissions targets for 2030 and 2035 that require CO₂ emissions reductions of half actual emissions for cars and vans.

Despite wide literature on life cycle assessment of on-road vehicles considers fossil fuel-powered vehicles, a similar approach is being deployed in the case of electric motor-powered vehicles (considering the energy efficiency of kWh per km traveled) or hydrogen-gas fueled road vehicles (considering hydrogen gas supplied to fuel cell unit per km traveled). Precisely for fully electric cars, the weight of full-electric vehicles is a sum of the mass of the vehicle's architecture and the mass of battery packs. Thus, its common sense considering that the travel range represents for the consumers the independence from the plug-in commences with battery size. That's the Achille's heel of plugged-in vehicles for fossil-fueled vehicle buyers. On the one hand, travel range increases with battery capacity, but on the other hand, larger battery capacity means a heavier vehicle to travel.

While vehicle downsizing improvements in fuel efficiency could be achieved, it appears in contrast with buyers' needs; thus, reducing size for reducing mass could not target a competitive strategy for automakers.

For this reason, a weight-saving strategy primarily implemented by extensive use of lightweight materials—better to say, by higher specific strength—is, therefore, most promising for pursuing consumers' satisfaction. Meanwhile, environmental aspects are successfully addressed, as they cannot be deferrable. It has been estimated that a 10% of vehicle weight curbing increases the vehicle's fuel efficiency by nearly 7%. But the ability to introduce new lightweight materials into vehicles is not a simple remove-and-replace process. Concerns about the impact of material changes on manufacturing lines, supplying network reliability, material cost stability, secure material availability in the marketplace are the main drivers in the material-shift decision process as they all could be more important for automakers than the percentage of weight saved. The potentiality of any lightweight scenarios steered by material replacement rates is based on the actual capability of lighter but weaker materials to safely replace heavier but stronger ferrous alloys, like steels and cast irons. As shown in **Table 3**, the weight-saving potentialities of lighter material depends on the specific substitution factor for the specific function, and it's a fact that the materials substitution factor strongly depends on: the physical properties of the material (e.g., its density and its elastic module as key-factor impacting on stiffness-limited design), the shaped part mechanical properties that are strongly dependent on the shaping process employed (e.g., fatigue limit obtained by cold pressure die-casting operations is different from fatigue limit obtained with low-pressurized die-casting), the geometrical constraints fixed by design (e.g., limited space of fixed boundaries to frame architecture).

As it is usual for any comparative analysis, we need a baseline and parameter to use in the calculation of data output to compare. The fuel consumption reduction coefficient is conventionally used as a measure of fuel-mass correlation. It provides the saving in specific consumption achieved through a 100 kg weight-saving. Recent literature set in the range 0.3–0.5 L/(100 km × 100 kg), varying with modeling assumptions, such as vehicle class, car model, driving cycle, the fuel consumption reduction coefficient for internal combustion engine vehicles [19], and values in the range of 0.47–1.17 kWh/(100 km × 100 kg) for electric vehicles [20].

But there is always a “but”; light-weighting is not a stand-alone measure whether its motivation is pollution curbs [21]. The extractive metallurgy (mining and refining) of nonferrous structural metals that are highly reactive toward oxygen like aluminum, titanium, and magnesium is complicated due to their low grade. The high complexity of the ore extraction and the energy-intensive pyrometallurgical or hydrometallurgical processes employed for pure metal refining are critical stages for the potential release of gas, liquid, and solid emissions (i.e., direct pollutant emissions) and for a large amount of CO₂ emissions correlated to lots of energy consumed (i.e., indirect pollutant emissions). In the next sections, we’ll go into details, but for the moment, we can summarize by this way:

- light nonferrous alloys are the cleaner solution in their usage phase in the transport sector because they can target a consistent weight curb capable of reducing direct emissions at the tailpipe of fossil-fueled vehicles. For internal combustion engine vehicles with average tailpipe emissions near 120 gCO₂/km, assuming 2.4 KgCO₂ emitted at tailpipe per liter gasoline burned, it can be calculated to reduce by 100 kg onboard vehicle mass, nearly 1.2 kgCO₂ is the pollution cut per 100 km traveled.
- The direct CO₂ curb obtained in the usage phase could be reduced (sometimes nullified) by the sum of pollution (direct and indirect) emitted during the extractive phase, the refining process, and the manufacturing of the lighter products. For example, on average, the greenhouse gases emitted as equivalent CO₂ per kg of product manufactured can vary from 2.0 to 2.5 kgCO₂eq per each kg of steel made products and 12.0–16.0 kgCO₂eq per each kg of aluminum products.

Therefore, a broad vision must encompass the net CO₂ emissions over the road vehicle lifespan.

A qualitative scheme representing the green ability of light alloys against heavier metal, such as steel, is depicted in **Figure 7**. The baseline case (1) represents a reference, for example, a body panel made of galvanized plain carbon steel. For the steel-made product, the total CO₂ emitted over the product’s lifespan is the sum of the CO₂ (direct and indirect) emitted during the manufacturing stage and the usage phase (traveling). By replacing steel-made products with lighter metal alloy (2), we shall consider more pollutant emissions in the fabricating stage. For this reason, the break-even point T1 versus the baseline scenario (1) could be targeted at the T1 traveled distance. The beneficial effect of weight saving is visible by the gray shaded area from T1 to the expected vehicle lifespan representing the net CO₂ curb by lightweight solution. Case (3) represents the use of much lighter material (due to the reduced slope of the line), but with higher CO₂ emitted in the manufacturing stage as per the higher linear coefficient of the line (3). In this second scenario, the break-even point switches to the higher T2 mileage. The difference between the two shaded areas represents the net CO₂ cut for alternative weight-saving scenarios (2) and (3) compared to the baseline scenario (1).

We refer again to **Table 3**. On average, you may consider 0.5 the aluminum substitution factor applicable in structural engineering applications, thus 100 kg of steel (that accounts for around 230 kgCO₂ for the manufacturing stage) would be potentially replaced by approximately 50 kg of aluminum, which accounts for about 700 kgCO₂eq emitted in the manufacturing phase. On the other hand, referring to the schematic representation in **Figure 7**, aluminum onboard would potentially save 50 kg. Now you

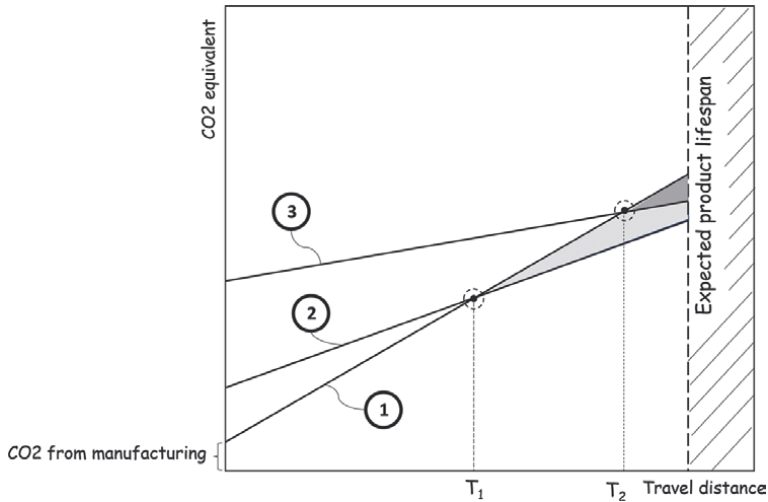


Figure 7. Three qualitative scenarios for addressing the environmental impact of automotive body panels over the product lifespan.

can account for nearly 0.2 gramCO₂, the pollution cut per kg of weight saved and per each km traveled. Putting onboard an internal combustion engine-powered vehicle 50 kg aluminum to replace steel, we would cut around 5.95 gCO₂ per km traveled.

Now, we can proceed with a further step.

The net CO₂ emissions from the aluminum-steel switch account for around 470 kgCO₂eq emitted in the “cradle-to-gate” phase (including extractive, refining, alloying, and manufacturing stages). Aluminum bodies shall travel onboard around 78,000 km to achieve the break-even point, namely the traveling distance necessary to offset the 470 kgCO₂ extra emissions over the steel-made bodies (the baseline scenario). The environmental sustainability of the lighter solution is therefore strongly influenced by the environmental impact of the raw material fabrication phase, mostly the extractive stage. For that reason, intensive use of recycled patterns to limit the use of primary (virgin) metal for such energy-intensive lightweight alloys is the key to excellent sustainable use of light alloys on-road vehicles. And what about magnesium products? Former data about the carbon footprint of magnesium production have indicated an extensive range of 37–47 kgCO₂eq/kg of magnesium [22]. With such numbers, many still consider magnesium from a technical point of view an exciting opportunity to implement lightweight strategies but an unsound option for a cross-cutting greening approach. It would be effortless to calculate whether 37 kgCO₂eq is the carbon footprint per kg of magnesium to put onboard for replacing 1.6 kg of steel, the CO₂ emitted for the manufacturing phase could be “absorbed”, traveling for a lot, above 200,000 km. What are the reasons for such a high carbon footprint of magnesium metallurgy? And shall we consider those numbers still valid today? We’ll try to get an answer to those questions in the following sections.

4. Safety and environmental concerns about magnesium

There are two primary sources of direct and indirect pollutant emissions in the magnesium industry. The first source is correlated to high reactivity with the oxygen of

magnesium when molten. In the air, molten magnesium is coated with an oxide layer, which, in contrast to the aluminum oxide layer, cannot protect highly reactive magnesium from oxygen. It is true that molten aluminum, too, is highly reactive with oxygen. However, the alumina layer that instantaneously forms on liquid metal in oxygen is dense and not permeable to further oxygen. The magnesium oxide layer formed during melting is characterized by low density. The Pilling–Bedworth number (PBR) explains the high-temperature oxidation behavior of different metals and their oxides [23] by the ratio between the molar volume of oxide and the molar volume of metal. This volume change is responsible for varying types of surface stress in the oxide layer.

For $PBR < 1$, tensile stress on the oxide layer promotes the layer to crack: that's what happens in molten magnesium metal. When the PBR is equal to 1 (the better situation with PBR above 1), it represents a safe condition. Sound compressive stresses develop in the thin dense, and stable oxide layer, protecting the molten metal from the outer atmosphere. This happens for iron, aluminum, titanium, and other metals. Unfortunately, this does not apply to magnesium. Emley [24] found that up to 450°C, magnesium forms a protective magnesium oxide layer, but it becomes porous and non-protective over 450°C. The high reactivity with oxygen causes magnesium to easily ignite and endangers the workers and the production line.

The time to ignition depends on the magnesium alloy composition [23, 25]. The real big problem of flame ignition in magnesium is that the oxidation reaction is highly exothermic. Magnesium oxide, white powder, creates a net release of energy in the form of heat. Magnesium ignited burns with flame at more than 2000°C; thus, no crucible can resist if the flame is not extinguished. Furthermore, magnesium atoms are also capable of reducing water to the highly flammable hydrogen gas by the reaction $Mg(s) + 2H_2O \rightarrow Mg(OH)_2(s) + H_2(g)$; meanwhile, hydrogen gas could be easily ignited by the excess heat given by the magnesium reduction reaction. Magnesium metal can also react with carbon dioxide when present in the atmosphere to promote and sustain magnesium oxide formation accordingly with the following: $Mg(s) + CO_2 \rightarrow 2MgO(s) + C(s)$. For this reason, conventional carbon dioxide fire extinguishers cannot be used for extinguishing magnesium fires (required Class D dry chemical fire extinguisher or covering the fire with sand to remove air source).

This hazardous behavior of magnesium metal is therefore historically correlated to conditions that lead to flame ignition of molten magnesium or magnesium in the form of powder, ribbon, thin strips, and foils, namely those fine structure forms that can be quickly heated up just by relatively low heating source, for example by friction. The highly exothermic oxidation reaction could bring explosive hazards in the presence of moisture when flame ignition is not adequately managed by specific knowledge and expertise. For these reasons, particularly in the presence of molten magnesium (for example, during cast shaping), fluorine-based compounds, such as SF₆, for protection of molten magnesium have been used since the 1930s [26]. Before introducing SF₆, magnesium was protected with alkali metal halide fluxes, sulfur dioxide (SO₂), or even elemental sulfur. The decomposition and following reaction between the fluorine and liquid magnesium keeps separate highly reactive molten magnesium from oxygen. On the one hand, these reactions are thought capable of creating on the molten metal surface an elastic, nonporous protective film containing MgO and MgF₂ with a Pilling–Bedworth ratio larger than 1 [27]. On the other hand, significant impact is ascribable to the use of SF₆ as a cover gas. The SF₆ environmental impact has been calculated to be 22,800 kg CO₂eq/kg of SF₆ used (in other words, 22,800 times greater than 1 kg of CO₂ emitted). Usually, 1 kg of SF₆ is required as cover gas per ton of melting magnesium, resulting in a 22,800 kg CO₂ equivalent per kilogram of melt

magnesium. In Europe, SF₆ is banned, while in the United States, its use is optional for the industry.

To present date, banded SF₆ has been substituted by less impacting hydrofluorocarbons such as HFC-134a, however, considered a greenhouse gas but much less impacting. A much lower impact is for sulfur dioxide, but it presents limits for its toxicity and its corrosive properties. Usually, a specific blend of them is used. Recently the Novec 612 fluid—registered by the 3 M Company—promises a meager global warming potential (GWP, expressed as kgCO₂eq/kg product) of 1, equivalent to CO₂. Furthermore, to limit the intense use of protective substances, an old approach recently proposed consists of adding unique alloying elements to improve the ignition resistance of magnesium alloys. In the past, Emley [24] claimed that additions of small amounts of Be, Al, and Ca enhanced the oxidation resistance of solid Mg alloy near the melting point. Such magnesium alloys could be melted in the air if the oxide skin on the ingot was not broken. Sakamoto et al. [28] verified the oxide film on the Mg-Ca consists of a CaO surface thin layer, and just below this layer, a mixture of MgO-CaO exists. To date, the main reason for this protective effect from Ca-O is not clarified. One prominent hypothesis embraces the PBR rule. The higher thermodynamic stability of Ca-O added oxide layer and the kinetics of the diffusion and reaction of Mg ion at and through the oxide layer formed by a mixture of MgO and CaO. When the oxide layer consists of a combination of MgO and CaO, the large volume of CaO might compensate for the shrinkage due to MgO formation. Phenomena involved in retarding flame ignition in Mg alloys systems when alloyed with Ca, Be, and Y has been studied for years but not wholly clarified today.

To summarize, reasonable and sustainable practices are available today in the marketplace to safely treat magnesium and significantly reduce the pollutant emissions in handling molten magnesium in foundries.

But the second source of pollution for the magnesium industry, much more relevant and challenging to control, depends on the vast amount of energy necessary for the magnesium extractive and refining phase, namely the primary magnesium fabrication. There are only a few processes available for the primary magnesium fabrication as they are based on sources of the raw materials by which magnesium can be extracted: raw materials ores (such as dolomite, magnesite, hydroxide mineral brucite, halide mineral carnallite) and brine, which is a mainly a highly concentrated water solution of common salts like hydrated magnesium chloride, magnesium sulfate and magnesium bromide, whose preferred reservoirs are the higher concentrated seawater such as the Great Salt Lake and the Dead Sea. By the way, magnesium raw material sources are considered practically inexhaustible, as magnesium is the 4th abundant metal in the Earth crust, following iron, aluminum, and silicon. Moreover, inexhaustibility is properly true for seawater reservoirs of magnesium chloride salts. Depending on the type of magnesium source employed, we can distinguish two prominent process patterns to produce magnesium metal: (a) the electrolysis of fused anhydrous magnesium chloride obtained by various refining upstream processes (e.g., dehydration of magnesium chloride brines or chlorination of magnesium oxide) and (b) the thermal reduction of magnesium oxide by ferrosilicon derived from carbonate ores. Today's electrolytic processes are mainly based on the oldest and original Dow process employing seawater as a primary magnesium source.

The Dow process was developed in the first decade of the twentieth century, as the USA started an extensive magnesium production for military scopes. Electrolytic cells are vessels equipped with multiple steel cathodes and graphite anodes partially submerged in the dehydrated molten salt electrolyte. They generally operate to

temperatures from 680 to 750°C to develop the basic reaction: $\text{MgCl}_2 \rightarrow \text{Mg}$ (liquid metal) + Cl_2 (gas). While the Dow process was starting and ramping up US national production, Germans continued investigating carbo-chlorination of magnesite to produce liquid anhydrous magnesium chloride. During those years, when the second peak of magnesium demand rose, Canadian scientist Lloyd Montgomery Pidgeon developed the thermal process for reducing magnesium oxide with silicon in externally heated retorts. Silicon is generally obtained by ferrosilicon ores, and it is produced in an arc furnace, mixed with calcined dolomite, and then briquetted. The briquettes are placed in a retort and heated to extract magnesium vapors condensed at the cold end of the retort with a relatively small diameter. The process is a batch process. It requires metal to be removed from the condensers, slag to be evacuated as a solid, and finally, it is possible to recharge the retort. Thus, the Pidgeon process has reduced the productivity of magnesium per day compared to big electrolytic cells plants. We would simplify the basic reaction as: $2\text{CaO} + 2\text{MgO} + \text{Si} \rightarrow 2\text{Mg} + \text{Ca}_2\text{SiO}_4$. It is an endothermic reaction, and a large amount of heat must be applied to initiate it and continue.

Therefore, the Pidgeon main environmental problem is the combustible used for firing furnace; oil or gas are commonly used for the scope. Former literature ascribed to oil firing the high environmental impact of polluting emissions, ranging from 37 to 47 kgCO₂eq/kg of Mg extracted [22].

Another thermal process, the Bolzano process, like the Pidgeon process, employs the dolomite-ferrosilicon briquettes. Briquettes are stacked on a unique charge support system through which internal electric heating is conducted to the charge. In that case, most carbon emissions are drawn by the indirect carbon emissions of the energy mix used. Depending on the electricity carbon footprint on a local base, the Bolzano process ranges from 13 to 33 kgCO₂eq/kg of Mg depending on the local electricity share produced by hydropower [29].

In brief, we can summarize. On the one hand, the Pidgeon process advantage consists of low investments to recoup, fewer constraints on the minimum size to be profitable, short time for facility construction, equipment installation, and plant ramp-up, flexible production. On the other hand, it suffers from low productivity, high labor requirement, and high energy consumption.

But to reply to the big question: Are the environmental concerns about magnesium extractive processes still valid today? It is necessary to ponder data from the most recent life cycle assessment studies committed to an in-depth investigation of magnesium green ability. In 2013, the International Magnesium Association (IMA) published the study “Life Cycle Assessment (LCA) of Magnesium Components in Vehicle Construction” which analyzed the entire life cycle of magnesium components for transport applications [30]. The study addressed primary magnesium production, alloying, component production, use phase, and the end-of-life of magnesium components, particularly for passenger vehicles comparing differences in emissions among Pidgeon process employed in small factories during the first decade of the 2000s with the most recent Pidgeon process practiced in larger plants. The worst numbers in former LCA studies before 2011 addressed massive emissions from small Pidgeon process plants developed in China from the 1990s to 2011. Pollution emissions from small plants significantly decreased following the imposed shutdown of several high pollutant firms, including small magnesium plants, ordered by the Chinese Government 1 month before starting the Beijing Olympic Games to improve air quality. Small factories in the primary magnesium business would have targeted more stringent environmental prescriptions before they could resume production,

but several small factories had not restarted production. Survived small plants restarted, at higher operating costs, improving the energy Efficiency with substitution of coal by gaseous fuels, with more efficient re-use of waste heat, and installing additional air treatment equipment.

Therefore, the 2013 LCA analysis published by the International Magnesium Association downscaled the overall average emissions from the Pidgeon process under the improvements mentioned above to 28 kg CO₂eq, including all upstream processes [30]. It is worth noticing the magnesium production plant located in Brazil uses a silicothermic process, a modified type of the Bolzano Process. It targeted an excellent result of 10.1 kgCO₂eq/kg magnesium.

Alternatively to the Pidgeon process, the big electrolytic plants could have a meager environmental impact, depending on the primary energy source. The Dead Sea Magnesium plant, which produces magnesium from the Dead Sea evaporite deposits in Israel, uses natural gas as an energy supply. The global warming potential of this process is accounted for 17.8 kg CO₂eq/kg Mg [30]. As in this electrolysis plant, two main by-products are produced, liquefied chlorine (Cl₂) and KCl-rich salt. They can have a wide range of potential uses; thus, they are used as raw materials for other sectors. Credits for their re-use, therefore, contribute to decreasing the global warming potential to 14.0 kg CO₂eq/kg magnesium [30].

Since 2017 a new electrolysis plant with a capacity of 100,000 metric tons per annum has been operating in China by the Qinghai Salt Lake Magnesium Co. (QSLM). The QSLM electrolytic magnesium smelter is located at Golmud in Qinghai Province. This process produces pure magnesium from magnesium chloride (MgCl₂) brine, an adjacent potash production waste product. The smelter produces low CO₂ embedded magnesium metal thanks to energy power used for the complex supplied from regional hydro facilities (75%), solar (9%), and wind, as well as a local thermal power station. With support from the Qinghai Provincial Government and the national Government in Beijing, QSLM has plans to expand the production of pure magnesium alloys from current levels to 150,000 mtpa soon and then to 450,000 mtpa. Adjacent to the electrolytic magnesium smelter, Magontec has constructed a new primary magnesium alloy cast house facility with an output capacity of 60,000 metric tons per annum that will take pure liquid magnesium from the adjacent smelter. Magontec's plant benefits the QSLM's energy supply of 75% hydro and nearly 10% solar. The overall greenhouse gas emissions of the electrolysis amount to 8.5 kg CO₂eq/kg magnesium. Apart from pure magnesium, the electrolysis of magnesium chloride produces gaseous chlorine. The amount of chlorine produced cannot finally be predicted at this stage of the project, but a chlorine yield of around 2.5 kg per kg of magnesium can be assumed. This by-product is used as feedstock for the nearby PVC plant. Producing 2.5 kg of chlorine usually leads to greenhouse gas emissions of about 3.2 kg CO₂eq [30]. Thus, crediting these emissions, which the magnesium electrolysis has saved, leads to overall emissions of 5.3 kg CO₂eq/kg of magnesium ingot [30]. The Qinghai plant has not reached its total capacity but is still ramp-up.

It is a fact that government policies of the country in which plants operate play an essential role in the environmental impact of magnesium. The national electricity mix used for plant operations, disposal, and recycling routes and the grade of technical solution development drastically reduce electrolytic routes' effects. Under the updated LCA data, the following **Table 4** recalculates the GWP for the body panel case study (refer to **Table 3**). GWP for the three options refers to average updated data published in [30]. Finally, since GWP are expressed per unit mass of material used, it is necessary to consider the actual usage of light material for the specific application.

	Baseline	Lightweight solutions	
	AISI 1045 steel	Aluminum 6061	AZ31D twin rolled cast sheet, warm formed
Substitution factor (SF)	1.0	0.5	0.4
KgCO ₂ eq emitted for substituting 1 kg of steel with alternative metals for same function, equivalent stiffness, and load (denting) capability (kgCO ₂ eq emitted per kg of material) × SF [kgCO ₂ eq]	2.3	4.9 ¹	2.0 ²
			10.8 ³
Steel parity GWP calculated as (GWP _{steel})/(SF): [kgCO ₂ eq/kg]	2.3	4.7	3.7

¹Average value for Hall-Heroult, primary aluminum globally [31].

²Average value for electrolytic process powered by high share renewable energy (QSLM plant) [30].

³Average value for Pidgeon process revised [30].

Table 4.

Recalculated GWP data for comparative scenarios in manufacturing a lightweight outdoor body panel with light metal alloys.

Table 4 estimates the kgCO₂eq emitted by aluminum and magnesium solution for substituting each kg of steel in the inner door panel for the same function, at equivalent (or higher) stiffness, and equivalent (or higher) denting capability. The calculation method follows:

$$\text{kgCO}_2\text{eq emitted per kg of material} \times \text{substitution factor (SF)} \quad (1)$$

The last line of **Table 2** shows the recalculated GWP for aluminum and magnesium light solutions to the “steel parity” calculated as:

$$\text{GWP for steel parity} = \text{GWP of steel} / \text{substitution factor (SF)} \quad (2)$$

The (2) represents the GWP of metal alloys give parity to body panel made of steel at equal (or higher, as for magnesium solution) stiffness and load capability.

5. Recycling capability of magnesium alloys

Recycling metals is critical to their overall sustainability. Magnesium retains most of the necessary physical integrity when recycled if it is not contaminated. Remelting and forming of ingots are the main energy requirement for recycling, but generally, secondary production of magnesium ingots requires substantially less energy than primary production [32]. Otherwise, this process’s greenhouse gas emission mainly depends on the selected cover gas; generally, a cumulative 3.6 kgCO₂eq/kg of secondary magnesium produced could be released [33].

Today the recycling of magnesium is technologically feasible. Currently, the primary source of magnesium alloy scrap comes from the magnesium die-casting industry (the most common method of fabricating new magnesium alloys parts). Die casting foundries can manage the amount of process scrap in three different ways:

- The scrap can be sold on the open market and downgraded for recycling in other sectors, such as steel desulphurization.
- The scraps can be recycled internally or externally within a closed-loop system; this could optimize the demand for primary raw material saving up to 50% primary magnesium in casting automotive parts, rising to 85% for electronic die-cast products. Among factors that influence the number of recycled scraps and recycling ratio optimization we should consider: the amount of material lost in the melting cycle, the number of different components that are cast, the percentage of cast parts that must be rejected during production, the end quality of process scrap, and the recycling operation efficiency all affect the amount of process scrap, and primary magnesium utilized [34].
- Remelting of magnesium chips from machining of die castings, considering that, due to high magnesium susceptibility to oxidize and fine forms of chips, chips remelting could produce further dross quantity. For this reason, preliminary treatments are required to eliminate possible lubricants (e.g., aqueous washing treatment, steam treatment). The second treatment in liquid acid pickling solution (deoxidizer) specific for magnesium alloys helps to reduce oxide contamination.
- Recent studies [35] successfully validated the no-melting route for recycling magnesium chips by hot forging and extrusion as it is done for aluminum chips.

On the other hand, the processing of end-of-life vehicles is today still not easily practicable and needs technological improvement. Shredded magnesium can be contaminated with iron, nickel, and copper from coatings and fasteners, all of which are detrimental to the corrosion resistance of the metal. Although the low-value markets mentioned above (aluminum alloys and steel desulphurization) can absorb low-quality post-consumer magnesium, options for separating it from other metals are necessary for magnesium structural alloys applications. The main viable option is melting magnesium in contact with molten salt to remove oxides from the liquid metal. This process is today not fully capable of separating magnesium from other metals. Another possibility is metal vapor distillation: due to higher vapor pressure and low boiling point of magnesium compared to aluminum and many other metals.

On the other hand, a too high magnesium-aluminum chemical affinity results in poor separation. A much more viable route is collecting and separating magnesium from the high-quality scraps made of aluminum-magnesium alloys: the beverage can stock (e.g., the aluminum 3xxx series alloys employed for the body, the aluminum 5xxx series used for edge), and the aluminum 5xxx series today preferred for body panels of automobiles. To separate magnesium, chlorine gas bubbling through the liquid alloyed metal can remove magnesium by reaction, but such a hydrometallurgy process requires large amounts of chlorine and energy. Further recent advancements in magnesium separation from aluminum alloy scraps focus on electrorefining. It is a process in which metals are purified in an electrolytic cell where the anode is the impure metal, and the cathode is a very pure sample of the metal [36]. To summarize, an efficient recycling route for magnesium by automotive scraps is still an issue. Broad approaches based on the design for corrosion-free assembling and easy disassembling of magnesium parts in the multi-material structure are on track.

6. Magnesium solution in the automotive sector: the present

One significant value that manufacturers usually give to magnesium is its excellent die-castability resources, compared with aluminum. It is mainly due to very low viscosity in the molten state and reduced (or absent) die-soldering phenomena with steel mold-die that broadly extend mold-dies lifespan. The high castability is one metallurgy factor that allows die-casters to realize large, thin-walled, and complex casting shapes. It is due to a less costly manufacturing process that would replace steel-made components by assembling numerous steel stamped pieces or heavily reinforced plastic members [37]. As magnesium alloys can be cast with thinner walls than aluminum, the lower elastic modulus of magnesium alloys can be compensated using located ribs of thin wall thickness that allow restoring stiffness at required values. Secondly, the lower latent heat for solidification of magnesium compared to aluminum leads to considerably shorter casting cycle times, compensating for the lower heat conductivity of magnesium. For a comprehensive overview of die-casting processes and recent advancements, you may refer to [38], here in the following, shortly resumed. Two main casting processes are available for magnesium, the pressure-assisted cold, and hot-chamber injection, with an alternative represented by low-pressure die casting. In pressurized injection casting processes, high pressure is exerted after the liquid metal injection to compensate for metal shrinkage and remove as much possible air entrapped during the shot sleeve movement that accelerated to pressurize liquid metal into the die. The metal solidifies at high cooling rates (higher for the cold chamber than the hot chamber), leaving a fine-grained material (more satisfactory for the cold-chamber process) with secondary dendrite arm spacing in the range of 5–10 μm . As it is usual for any metal, particularly for magnesium alloys, grain refinement is one primary strengthening mechanism capable of saving good ductility and though properties, generally lower for the common magnesium-aluminum alloys containing more than 3–4% of aluminum. If, on one hand, aluminum promotes a strengthening mechanism based on a solid solution, on the other hand, an excess of aluminum (it is limited up to 9%) produces an almost continuous secondary phase of aluminum enriched—the magnesium aluminide, $\text{Mg}_{17}\text{Al}_{12}$. The magnesium aluminide decreases local plastic resources at the alpha-solution grain boundaries, where magnesium aluminide precipitates.

The long tradition of magnesium automotive part die-casting is proper for magnesium manufacturers, as shown in **Figure 8**, where an example of Meridien's timeline for automobile products is summarized. Magnesium die-casting is evolving in Mercedes-Benz automatic transmission cases, from the first seven-speed automatic transmission case developed in 2003 (**Figure 9**) to the current eight-speed transmission case, still manufactured by magnesium alloy.

Figure 10a shows the recent magnesium die-cast liftgate inner for the 2017 Chrysler Pacifica Mini-Van realized by Meridian Company with Fiat-Chrysler Automobiles. The liftgate assembly consists of:

- Magnesium alloy die-cast internal structure, around 80% of the liftgate at the nominal.
- Wall stock of 2.3 mm, 20% with localized ribbing and thick patches.
- Aluminum wiper bracket.
- Two-piece aluminum outer skin.

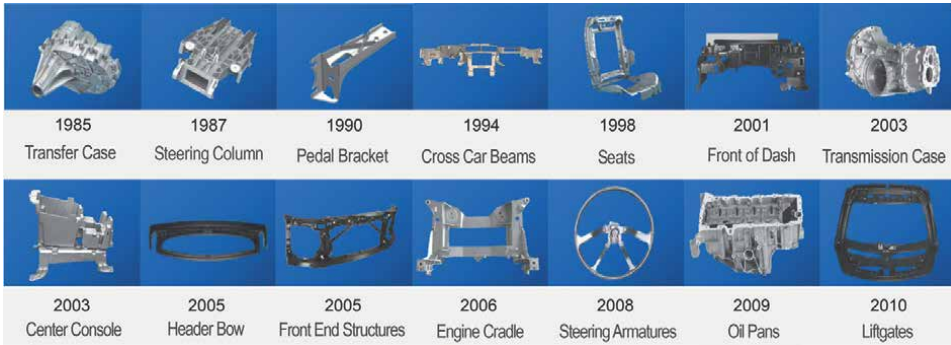


Figure 8.
Meridian product development timeline (courtesy of IMA).



Figure 9.
The 2003 case of the 7G-TRONIC, the world's first seven-speed automatic transmission.



Figure 10.
(a) Diecast liftgate inner by Meridien (courtesy of IMA), 1450 mm wide, 1210 mm in height, the mass of 6.9 kg, (b) Strut bar Audi A8 (courtesy of IMA).

An AM60B alloy has been used due to elongation, strength, castability, and energy-absorbing properties. The magnesium casting allows replacing seven steel stampings, including reinforcements in hinge & latch areas, two plastic pieces, joining technologies. In the final assembly, a powder coat was applied to all structures to prevent galvanic corrosion problems. **Figure 10b** shows the new die-cast strut bar of

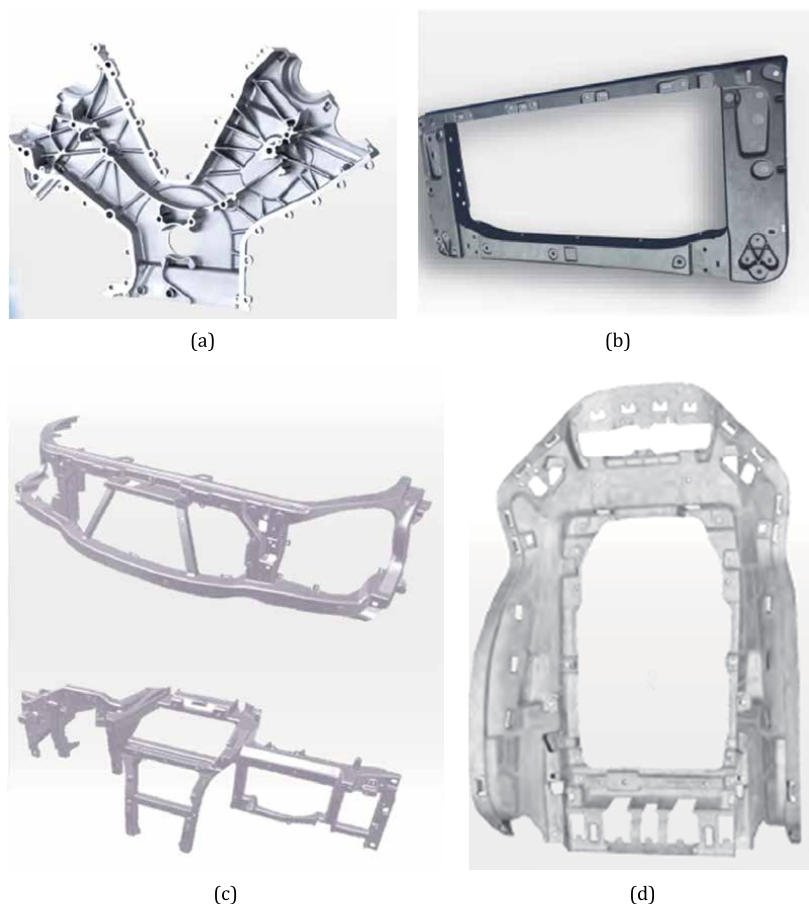


Figure 11. Recent die cast parts from magnesium industry [courtesy of GF Casting Solutions]: (a) Porsche Control Box Cover, made of MgAl₄RE₄ alloy, 2.6 kg weight, realized by multistage process (casting, stamping, machining), then assembled; (b) E-vehicle upper door frame alloy made of AM 50 alloy, 2.9 kg weight, realized by multistage process (casting, punching, machining, e-coating); (c) Ranger Rover Front End & Cross Car beam made of AM60 alloy, 6.0 kg weight realized by the multistage process then assembled (casting, machining, stamping); (d) Daimler SLK 2 seat back frame, AM 50 alloy by die-casting, 2.6 kg weight (courtesy of GF Casting Solution AG).

Strut bar for Audi A8 realized by Stihl Magnesium. In **Figure 11**, several magnesium-made parts have been recently put onboard vehicles.

Magnesium part manufacturers deploy a long-tradition cumulated in warm and hot deformation processes (**Figure 12**). Opposite to the common thought about magnesium deformation resources, wrought magnesium alloys are suitable for sheet forming contributing to weight-saving projects in the automotive sector. Indeed, significant drawbacks in magnesium alloys' sheet forming and deformation processes exist, especially compared to aluminum alloys. Due to its hexagonal structure, to activate enough slip systems for assuring sufficient plasticity, magnesium alloys must be formed above 200°C. Furthermore, the different heat transfer capability compared to aluminum is an issue to consider for optimizing pre and re-heating temperatures in the hot-deformation multistage processes. Extrusion of magnesium alloys is usually carried out in multiple steps, starting with a pre-extrusion of large billets into smaller diameter billets. After the preliminary stage, the billet can be re-heated and subsequently extruded into the final shape. Generally, the pressure per unit volume material

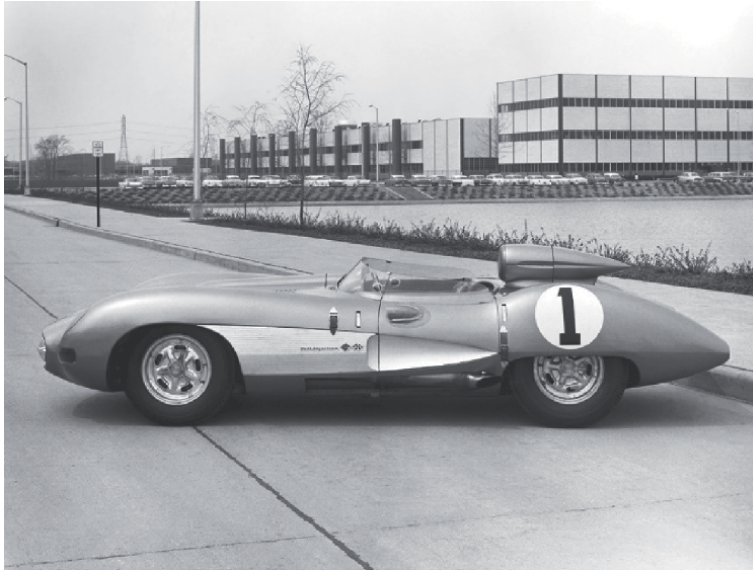


Figure 12.
The Chevrolet Corvette SS Race Car, 1957, made of magnesium-formed panels.

extruded is higher than in aluminum alloys. Thus, extrusion speed shall be carefully controlled and optimized for specific magnesium alloy to avoid local melting and local oxidation phenomena, particularly critical for hollow sections extrusion process by porthole dies, as typically employed for aluminum alloys. These aspects are firm limits for semi-finishing and net-shape forming processes, prominently for affordability.

But on the other hand, warm deep drawing is also possible for magnesium alloys, as for aluminum alloys; in the range of 100–180°C thin sheet of 0.5 mm approximately can be drawn, with precise temperature control and at a lower speed [39]. The recent application of magnesium sheets we can find in the literature illustrates the successful use of a novel Mg-Zn-Ca-Zr alloy in sheet form produced by twin-roll casting. This alloy has been used to manufacture a Volkswagen Passat deklid magnesium-made that saved half 6 kg of the original 12 kg steel weight [40]. Large magnesium components can also be produced by die casting (see **Figure 13**).

Net-shape semi-solid forming has attracted automakers with alternate attention since the middle 1990s. The net-shape semi-solid forming is possible for magnesium alloys thanks to its thixotropic state realized when vigorously sheared in a semi-solid state. Shearing reduces the viscosity of the slurry mass to a similar value of the liquid metal, providing similar (sometimes better) castability of the liquid form. Still, the semi-solid state allows shaping with lower latent heat in the mass; this creates advantages for shorter casting cycles than die-casting (depending on chosen semisolid process) lower metal shrinkage to compensate, and consequently near-net shaping. The industrial application of semi-solid net-shaping in the magnesium industry commenced in the early 1980s with the Dow Chemical Company. Dow Chemical patented the Thixomolding technology based on the architecture of plastic injection molding machinery for injecting magnesium alloys in the semi-solid state into a mold die.

Further advantages of injection molding of magnesium alloys are that this technology's highly complex shaping capability allows for more innovative design concepts and a multi-body-material concept design. Direct assembly of different

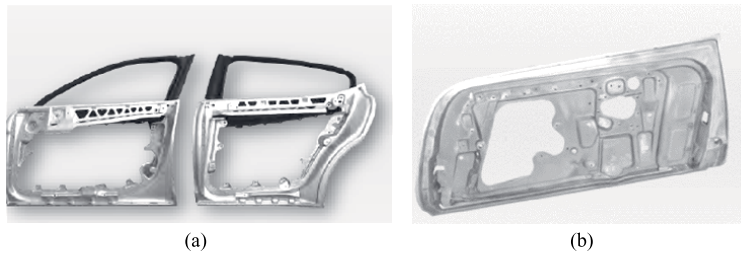


Figure 13. (a) The Porsche window frame realized by AM50 magnesium alloy with multi process stages (casting, laser cutting, machining), finally coated and joined; (b) The Aston Martin cover door made AM50 with multi-stage process (Casting, Stamping, Flattening) [courtesy of GF Casting Solutions AG].

parts during injection molding in a molded-in technique, thanks to inserting aluminum parts directly in the tool. As a semi-solid process, less energy is consumed by the Thixomolding apparatus; the power energy is estimated to be on the order of 12–24% lower than the total energy required by a conventional casting process. An additional benefit is that the Thixomolding product cycle employs inert gas, usually argon, to protect magnesium feedstock from oxidation once introduced in the hopper in particulate and solid forms (pellets or chips) [41]. However, it is worth noticing that current die-casting processes align with the environmental sustainability of the Thixomolding process thanks to much more environmentally friendly cover gases mixtures today used instead of the banded SF₆. With relevant advantages of the Thixomolding process in net-shaping part of high complexity in a single shot, two are the most drawbacks acknowledged by part manufacturers. The high price and the limited number of suppliers of chip or pellet forms of magnesium alloys, namely the material feedstock of Thixomolding machinery, and the maximum clamping force exerted during the metal injection into mold dies. Clamping forces of 2700–6500 kN generally allow the production of thin flat surfaces (0.8 mm, not possible by high pressure die-casting) such as that for tablet terminals, notebook computers, electronics, sports goods. Instead, the interest of the automotive sector is to even thicker and wider structural components with a weight of over 2 kg. This would require more giant machines with increased clamping forces over 8000 kN [41].

7. Conclusions: new trends and perspectives

The historical and current primary market for structural applications of magnesium alloys is high-pressure die-cast parts. We find those components in the automobile's powertrain, chassis, or body areas. Depending on the type of structural part to shape, key technical features that need to target are the safe-at-break behavior avoiding fast-fracture failure modes, sufficient toughness (i.e., minimum impact energy to rupture and fracture toughness), specific strength, corrosion resistance, high-temperature resistance, or creep resistance (for powertrain applications). From the manufacturing point of view, the requirements addressed shall target affordable production cost, which merges fixed and variable costs, derived from the accounting of investment costs (machinery and tools, energy, labor, etc.) and operating costs (raw material cost, trimming, machining, coating costs, etc.) to recoup.

Specifically, in automotive assemblies, corrosion concerns are crucial. Today high purity versions of magnesium alloys show corrosion properties comparable to

aluminum die casting alloys, but galvanic corrosion problems persist when magnesium parts have to be assembled with different materials. Therefore, advancements in coating techniques are the basis for safely combining magnesium parts with other materials. High ductility magnesium alloys are of interest to the automotive sector. Advancements in alloying are crucial for the correct choice of the structural ability of magnesium material. The higher creep resistance of Mg-Al-Si, the AS series, acknowledged by Germans during WWII, is allowed by Si addition which forms fine and hard Mg₂Si particles along the grain boundaries to help retard grain boundary sliding. The remarkable grain-refining ability of zirconium in the Mg-Zn-Zr series alloys allows high strength and ductility for use either at elevated temperatures or for energy-absorbing applications, however at a higher cost due to Zr. The ZE series achieved further mechanical properties in the die-cast part with Mg-Rare Earth-Zn-Zr casting alloys. RE elements (La, Ce, etc.) are added as they are active during aging treatment by promoting high-temperature stable precipitates with a strengthening effect. The costly Magnesium-Yttrium casting alloys, the WE series, containing approximately 4–5 wt.% Y, exhibit high strength with good creep resistance at temperatures up to 300°C and superior corrosion resistance (comparable to some aluminum-based casting alloys). Furthermore, the WE43 and the Elektron 21, a proprietary magnesium-based casting alloy containing neodymium, gadolinium, and zinc developed by Magnesium Elektron (today part of Luxfer MEL Technology), passed stringent flammability tests of Federal Aviation Administration FAA-FAR 25.853 Part 25, Appendix F, Part 2 Modified Seat Cushion Test. Both alloys did not burn when melted, or they are self-extinguished.

More cost-efficient production routes for sheet products are believed to create new opportunities for the automotive market segment. Considerable efforts have been directed at innovative developments of global efforts in expanding the manufacturing capabilities of magnesium sheets through the twin-roll casting process route, offering many benefits, including a reduction in the number of processing steps and energy savings [42].

Finally, last but not least, die-casting and semisolid process design strategies are similar to those employed for injection molding of structural plastics. But, in general, plastic designs require thicker sections than magnesium die-castings. Both materials allow complex shapes with ribs to enhance stiffness (**Figure 14**), but magnesium die-castings need more minor material for these features than plastics. As a result, magnesium die-castings can be designed more efficiently (less volume, less weight, more significant feature variation) and offer a higher degree of definition than comparable plastic designs, superior mechanical properties, and the capability to integrate several functional design features, material recyclability. The latter feature is not of minor importance, being automakers sensitive to recyclability resources of material used for car manufacturing. Although the material price-based approach leads to the obvious choice of plastics, complex and large parts could present unforeseen internal costs to the product line, negatively impacting final product marketability. A whole approach cost also considers the impact on a company's internal costs structure and the value-added needs of the next customer in the product chain, up to and including the end-user. In a total system cost strategy, the benefits of using magnesium tend to outweigh the lowest material price strategy. This is typical for products like instrument panel structures. The benefits of higher stiffness, elongation, toughness, and design flexibility allow the magnesium part to readily integrate many features in a one-piece to be fully assembled and quickly installed into the vehicle with weight-saving up to 50% compared to plastic designs.



Figure 14. *Magnesium AM 50 die cast front center console for Audi A8, high stiffness, no machining and all connection and fixing points are intergrated (courtesy of GF Casting Solutions).*

An interesting overlap of cast magnesium's mechanical and physical properties with reinforced plastics, primarily strength, and density, would drive the material switch. In the interior design of automotive vehicles today, large bodies are made of non-fully recyclable plastics. Thus, other potentialities for magnesium die-casting and injection molding could be redesigning today's plastic structural components with recyclable and more robust magnesium metal.

In this chapter, we tried to resume the magnesium for lightweight approach over the past, till today. Hopefully, but not exhaustively, this was tentative to answer where the magnesium industry is going. We must not forget the past, learning lessons that are still valid today. However, we must consider some new factors, mainly based on the magnesium trade, were unknown in the past century or during the golden Age of magnesium peak demand. It is a fact that when going through magnesium history, several articles projected an optimistic future for magnesium.

Forecasting the future of magnesium, especially in current pandemic times, is difficult. Nevertheless, one aspect appears clear by going through past and recent magnesium history: magnesium had survived continuous fluctuating demand;

meanwhile, price volatility registered over time depended on the current (nonstructured and programmed) supply capacity over time and trade issues.

Several concerns about magnesium's potential applications are today derived from false myths. Eighty years ago, Germans and (after) Americans employed magnesium for aircraft weight-saving, but today it is wrongly thought there are few proofs of its capabilities in realizing lightweight bodies. What is clear from the lesson learned in the past (and today) is that it is necessary to dramatically increase the primary magnesium supply with modern low impacting big plants. Looking at recent history, we are probably on the right track. As learned from the past, prices are not volatile once the supply is stable, and the magnesium's demand (driven by automakers primarily) rises.

Acknowledgements

The authors appreciated the input and feedback by members of the International Magnesium Association (IMA) founded in 1943 with the mission of promoting the use of magnesium in material selection and to encourage innovative applications.

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References

- [1] Kramer DA. Introduction and History. Magnesium, Its Alloys and Compounds. Virginia, USA: U.S. Geological Survey; 2001. p. 3. Available from: <https://pubs.usgs.gov/of/2001/of01-341/>
- [2] Bertilorenzi M. Business, finance, and politics: The rise and fall of international aluminium cartels, 1914-45. *Business History*. 2014;**56**(2):236-269. DOI: 10.1080/00076791.2013.771337
- [3] Brandt EN. We Called it Mag-Nificent: Dow Chemical and Magnesium, 1916-1998. Michigan, USA: MSU Press; 2013
- [4] Hanawalt J, Glaza G. New applications and developments of magnesium alloys in the automotive industry. In: SAE Technical Paper 520090. 1952. DOI: 10.4271/520090
- [5] Patent US2660769A. Dow Chemical Co.; 1950
- [6] Wheeler R. Magnesium: What's wrong with it and what to do about it. *Light Metal Age*. 1966;**6**:17-18
- [7] Erickson S. Magnesium: A proven material for light weight automotive die castings. In: SAE Technical Paper 770323. 1977. DOI: 10.4271/770323
- [8] Mezoff JG. Magnesium for automobiles. In: *Perspective*. SAE Transactions. Vol. 89. Pennsylvania, USA: SAE International; 1980. pp. 1617-1630. Available from: <http://www.jstor.org/stable/44633783>
- [9] Hollrigl-Rosta F, Just E, Kohler J, Melzer HJ. Magnesium in the Volkswagen. *Light Metal Age*. 1980;**8**:22-29
- [10] Fisher PA. Desulphurizing iron with magnesium. *Light Metal Age*. 1973;**6**:19-20
- [11] Das SK, Chang CS, Raybould D. High performance magnesium alloys by rapid solidification. *Light Metal Age*. 1986;**12**:5-8
- [12] Mikucki B, Shook S, Mercer W, Green W. Magnesium matrix composites at Dow: Status update. *Light Metal Age*. 1986;**10**:16-20
- [13] Nehan M, Maloney R. Magnesium AM60B instrument panel structure for crashworthiness FMVSS 204 and 208 compliance. SAE Paper No. 960419; Warrendale, PA. 1996
- [14] Patent WO 9009251A1. Dow Chemical Co.; 1990
- [15] Lieberman MB. The magnesium industry in transition. Review of Industrial Organization. 2001;**19**(1):71-79
- [16] CM Group. The Magnesium Report 2017. 2018
- [17] U.S. Geological Survey. Mineral Commodity Summaries, January 2020 U.S. Available from: <https://pubs.usgs.gov/periodicals/mcs2020/mcs2020.pdf>
- [18] USGS. Magnesium Statistics and Information, Annual Publications (2001-2020). Available from: <https://www.usgs.gov/centers/national-minerals-information-center/magnesium-statistics-and-information>
- [19] Fontaras G, Zacharof NG, Ciuffo B. Fuel consumption and CO2 emissions from passenger cars in Europe—Laboratory versus real-world emissions. *Progress in Energy and Combustion Science*. 2017;**60**:97-131. DOI: 10.1016/j.pecs.2016.12.004
- [20] Del Pero F, Berzi L, Antonacci A, Delogu M. Automotive lightweight

design: Simulation modeling of mass-related consumption for electric vehicles. *Machines*. 2020;**8**:51. DOI: 10.3390/machines8030051

[21] Shen D, Phipps A, Keoleian G, Messick R. Life-cycle assessment of a powertrain structural component: Diecast aluminum vs. hypothetical thixomolded® magnesium. In: SAE Technical Paper 1999-01-0016. 1999. DOI: 10.4271/1999-01-0016

[22] Ramakrishnan S, Koltun P. Global warming impact of the magnesium produced in China using the Pidgeon process. *Resources, Conservation and Recycling*. 2004;**42**(1):49-64. DOI: 10.1016/j.resconrec.2004.02.003

[23] Pilling NB, Bedworth RE. The oxidation of metals at high temperatures. *Journal of the Institute of Metals*. 1923;**29**:529-591

[24] Emley EF. *Principles of Magnesium Technology*. Oxford, New York: Pergamon Press; 1966

[25] Kim YM, Yim CD, Kim HS, You BS. Key factor influencing the ignition resistance of magnesium alloys at elevated temperatures. *Scripta Materialia*. 2011;**65**(11):958-961. DOI: 10.1016/j.scriptamat.2011.08.019

[26] Patent US1972317A. Dow Chemical Co.; 1934

[27] Czerwinski F. Oxidation characteristics of magnesium alloys. *JOM*. 2012;**64**(12):1477-1483

[28] Sakamoto M, Akiyama S, Ogi K. Suppression of ignition and burning of molten Mg alloys by Ca bearing stable oxide film. *Journal of Materials Science Letters*. 1997;**16**:1048-1050. DOI: 10.1023/A:1018526708423

[29] Cherubini F, Rauegi M, Ulgiati S. LCA of magnesium production:

Technological overview and worldwide estimation of environmental burdens. *Resources, Conservation and Recycling*. 2008;**52**(8-9):1093-1100. DOI: 10.1016/j.resconrec.2008.05.001

[30] Ehrenberger S. Carbon footprint of magnesium production and its use in transport applications. Update of the IMA Report “Life Cycle Assessment of Magnesium Components in Vehicle Construction (2013)”. 2020. Available from: <https://www.intlmag.org/resource/resmgr/sustainability/2020-LCA-Study-2021-02-09.pdf>

[31] Nunez P, Jones S. Cradle to gate: Life cycle impact of primary aluminum production. *International Journal of Life Cycle Assessment*. 2016;**21**:1594-1604

[32] Sivertsen LK, Haagensen JO, Albright DA. Review of the life cycle environmental performance of automotive magnesium. *SAE Transactions*. 2003;**112**:275-281

[33] Tharumarajah A, Koltun P. Is there an environmental advantage of using magnesium components for light-weighting cars? *Journal of Cleaner Production*. 2007;**15**(11-12):1007-1013. DOI: 10.1016/j.jclepro.2006.05.022

[34] Bell N, Waugh R, Parker D. Magnesium recycling in the EU. IMA Report 2017. Available from: http://www.intlmag.org/resource/resmgr/sustainability/FullRprt_EU-Mg-recycling_201.pdf

[35] D’Errico F, Plaza GG, Giger F, Kim SK. Life cycle assessment of ECO-magnesium® alloy produced by green metallurgy EU project process route. In: Alderman M, Manuel MV, Hort N, Neelameggham NR, editors. *Magnesium Technology*. NY, USA: Springer; 2014, 2014. pp. 7-12. DOI: 10.1007/978-3-319-48231-6_3

[36] Patent US 20150225864 A1. Phinix, LLC; 2015

[37] Ruden T. Replacing plastics with magnesium for structural automotive components. *Light Metal Age*. 2005;4:36-41

[38] Luo AA. Magnesium casting technology for structural applications. *Journal of Magnesium and Alloys*. 2013;1(1):2-22. DOI: 10.1016/j.jma.2013.02.002

[39] Doege E, Dröder K. Sheet metal forming of magnesium wrought alloys—Formability and process technology. *Journal of Materials Processing Technology*. 2001;115(1):14-19. DOI: 10.1016/S0924-0136(01)00760-9

[40] Hernandez JV, Yi S, Letzig D, Kim S, Kim JJ, Seo MH, et al. Magnesium process and alloy development for applications in the automotive industry. In: Joshi V, Jordon J, Orlov D, Neelameggham N, editors. *Magnesium Technology*. NY, USA: Springer; 2019. DOI: 10.1007/978-3-030-05789-3_3

[41] Czerwinski. *Magnesium Injection Molding*. Boston, MA: Springer US; 2008. DOI: 10.1007/978-0-387-72528-4

[42] Javaid A, Czerwinski F. Progress in twin roll casting of magnesium alloys: A review. *Journal of Magnesium and Alloys*. 2021;9(2):362-391. DOI: 10.1016/j.jma.2020.10.003