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# RECENT GROWING DEMAND FOR MAGNESIUM IN THE AUTOMOTIVE INDUSTRY

## RAST POVPRAŠEVANJA PO MAGNEZIJU V AVTOMOBILSKI INDUSTRIJI

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This article summarizes the importance of magnesium and magnesium alloys in the automotive industry. The resources and properties for magnesium, as well as for magnesium alloys, in manufacturing are concisely treated, taking the $SF_6$ emissions from magnesium production into account. Moreover, the possibilities of recycling magnesium and magnesium alloys are considered, ending with the expectations and problems in the wider application of magnesium in motor vehicles.

Keywords: Automotive industry, Mg Alloys, emission SF6, recycling, motor vehicle.

V članku je poudarjen pomen magnezija in magnezijevih zlitin v avtomobilski industriji. Viri in lastnosti magnezija in njegovih zlitin so na kratko predstavljeni z upoštevanjem emisije SF6 pri proizvodnji magnezija. Analizirane so tudi možnosti recikliranja magnezija in magnezijevih zlitin. Predstavljena so tudi pričakovanja in problemi večje uporabe magnezija v motornih vozilih.

Ključne besede: avtomobilska industrija, Mg-zlitine, emisija SF6, recikliranje, motorna vozila

## 1 INTRODUCTION

Although a small amount of magnesium has been used in automobiles for many years, its low density and the constant search for weight savings are encouraging subjects to evaluate more potential applications. The ease with which die castings can be produced makes it a favoured manufacturing route for most applications [1]. Current applications include seat frames, transmission system casings, air-bag housings and lock bodies. **Table 1** summarises the benefits of using magnesium die castings for seat frames.

**Table 1:** Benefits of using magnesium die castings for seat frames
**Tabela 1:** Prednosti pri uporabi tlačnih ulitkov magnezija za okvirje sedežev

Material choice:
- Lower specific weight than other options
- Better elongation than other die-casting metals
- 20–30 % shorter cycle times than aluminium die casting
- Longer die life (about double) than aluminium die casting
- ability to produce thinner walls than aluminium die casting

Economic choice:
- Magnesium price stability
- Investment cost reduction in comparison to current seats

Pure magnesium is about one-third lighter than aluminium, and two-thirds lighter than steel. A lighter weight translates into greater fuel efficiency, making magnesium-alloy parts very attractive to the auto industry. And these lighter parts come with good deformation properties, giving the products good dent and impact resistance, as well as fatigue resistance. The alloys also display good high-speed machinability and good thermal and electrical conductivity [2].

Magnesium is a silvery-white metal that is principally used as an alloying element for several non-ferrous metals (Al, Zn, Pb, etc.). Magnesium is among the lightest of all the metals and also the sixth most abundant on earth. The variety of applications of magnesium alloys in the automotive industry, aerospace engineering, chemical industry, etc. contribute to a rapid increase in the production of magnesium in the world [3].

The production of magnesium in the world increased from 20 000 t per year in 1937 up to 400 000 t per year in year 2000, of which China produced 170 000 t of magnesium in 2000. Magnesium alloys are predicted to continue to grow in popularity (about 15 % per year in the automotive industry alone), but the world's supply of magnesium, like every other natural resource, will be not

**Table 2:** US consumption of primary magnesium in 2007 by use
**Tabela 2:** Poraba proizvodov iz primarnega magnezija v ZDA v letu 2007

| USE | kt |
|---|---|
| Magnesium casting | 25.9 |
| Magnesium wrought products | 2.7 |
| Alloying element with aluminium (specially in aluminium cans) | 28.9 |
| Iron and steel desulfurization | 9.3 |
| Others | 5.4 |
| Total | 72.3 |

be unlimited forever. The solution is, logically, to recycle. Especially since anywhere between 30 % to 50 % of the metal handled by die casters ends up as scrap. For the end of life, a consequential approach is used: recycling the metal will significantly avoid the need to produce primary metal. To optimize the recycling of magnesium, an understanding of the current market of primary magnesium is essential [4]. **Table 2** is based on a publication of the US Geological Survey.

## 2 RESOURCES AND PROPERTIES OF PURE MG METAL. MANUFACTURING

The abundance of Mg in the Earth is considered to be the 4$^{th}$ highest metal, following iron, aluminium and silicon. The raw ores of Mg are dolomite ($MgCO_3$. $CaCO_3$) and magnesite ($MgCO_3$), and Mg is the second most abundant metal in seawater, following sodium. Therefore, it can be said that magnesium is an almost inexhaustible resource, and is distributed all over the world.

Magnesium is the lightest of all metals in practical use, and has a density (1.74 g/cm$^3$) of about 2/3 that of aluminium and 1/4 that of iron.

On the other hand, magnesium has shortcomings, such as insufficient strength, elongation and heat resistance, and a corrosion propensity. Its readiness to corrode has been found to be due to trace content of metals such as iron (Fe), nickel (Ni) and copper (Cu). The problem of corrosion has to be solved if the purity of the Mg is improved. However, its electrochemical potential indicates that magnesium will corrode by contact corrosion whenever it is in contact with any other metal. Therefore, magnesium is generally surface-treated before it is used.

The methods for manufacturing Mg can roughly be divided into electrolysis and thermal reduction. The electrolysis method involves extracting magnesium chloride from Mg ores and then reducing magnesium to its metallic form by electrolysis. Thermal reduction involves extracting magnesium oxide from Mg ores, adding a reducing agent such as ferro-silicon to it, and refining the resulting material by heating it to a high temperature under reduced pressure.

## 3 PROPERTIES OF MAGNESIUM IMPROVED WITH ALLOYING

The development of magnesium-alloy products has a long history that dates from 1945. Research has been conducted on the manufacture of various products, such as office goods, agricultural machines and tools, telecommunications equipment and sporting goods. Mg alloys have not yet been used as light structural materials for aircraft. However, they have been used for the gearbox housings of helicopters and other aircraft because they are good vibration dampers, a characteristic that has also brought them into use in the steering wheel cores of motor vehicles.

Alloying means altering a pure metal by melting it and adding other elements to it. This method is applied to almost all metals. Alloying magnesium improves its strength, heat resistance and creep resistance (creep is defined as deformation at a high temperature and under load). For example, AZ-based Mg alloys are well known materials produced by adding aluminium (Al) and zinc (Zn) to pure Mg. The appropriate amounts of additives may improve the strength, castability, workability, corrosion resistance and weldability of these alloys in a well-balanced way [5].

## 4 $SF_6$ EMISSIONS FROM MAGNESIUM PRODUCTION

The use of Mg alloys has recently increased. The surface-treatment techniques used to provide highly corrosion resistant Mg alloy products have already advanced on the same level as the die casting methods of some carbon steel plates and aluminium alloy products [6]. To put Mg alloy products to practical use, however, it is necessary to solve the critical problem that magnesium has a high activity in the presence of oxygen. For Mg, it is essential to prevent the formation of products of reaction with oxygen in the air. Currently, this is mainly accomplished with sulphur hexafloride ($SF_6$) gas, but is a potential greenhouse gas so alternatives that do not use $SF_6$ are now under investigation. The magnesium metal production and casting industry uses sulphur hexafluoride ($SF_6$) as a cover gas to prevent the violent oxidation of molten magnesium in the presence of air. $SF_6$ is a colourless, odourless, non-toxic, and non-flammable gas. The industry adopted the use of $SF_6$ to replace sulphur dioxide ($SO_2$), which is toxic and requires careful handling, to protect worker safety.

Historically, more than half of $SF_6$ emissions from the US magnesium industry have come from the primary magnesium industry, and the magnesium recycling industry, for the most part, continues to employ sulphur dioxide as a cover gas.

In 1999, EPA began the voluntary $SF_6$ Emission Reduction Partnership for the Magnesium Industry. $SF_6$ was introduced to replace $SO_2$, which corrodes casting equipment also. However, safer $SO_2$ handling procedures and the relatively low cost of $SO_2$ compared to $SF_6$ makes $SO_2$ more attractive [7].

## 5 MAGNESIUM TODAY

The magnesium industry is now experiencing a time of change with the die-casting segment characterized by rapid growth, both in the European and the North American markets. On the supply side, newcomers have started production, several projects are under consideration or at the pilot stage, while other suppliers have withdrawn from the business [8].

In today's marketplace, magnesium die-casting means the production of parts in compliance with the stringent requirements of high-purity alloy standards. This is the basis for the successful applications of die-cast parts for use in corrosive environments without complicated and cost-adding surface treatments. It is a paradox that magnesium die-cast alloys are melted in steel crucibles, when we know that iron is an impurity with a strong negative influence on corrosion. This can only be done when the whole production sequence, including the processing of ingots, is performed with close attention to the thermodynamic principles involved in keeping iron at an acceptable level throughout the process.

A number of applications, especially in the automotive field, require the ability to absorb energy without the formation of a fracture. Typical examples are provided by steering-wheel cores, instrument panels/cross-car beams, seat parts and door parts. These are typical examples where material properties, processing and design interact strongly in determining the properties of the product. The safe handling of magnesium requires an understanding of the basic processes that can cause hazardous events. The most common reactions involved are the following:

1) Burning/oxidation
   $2Mg + O_2 = 2MgO$
2) Rapid evaporation (expansion) of water entrapped by liquid magnesium
   $Mg(liq.) + H_2O(liq.) = H_2O(vap.) + Mg$
3) Water reaction/hydrogen explosion
   $Mg + H_2O = MgO + H_2$
   $2H_2 + O_2 = 2H_2O$
4) Thermite reaction
   $3Mg + Fe_2O_3 = 3MgO + 2Fe$
5) Silica reaction
   $2Mg + SiO_2 = 2MgO + Si$

There is a growing emphasis on environmental aspects when materials are selected. Magnesium, like aluminium, is an energy-intensive material to produce, and it is not obvious that use of this material will be beneficial. With a full analysis of the environmental impact of production, use and recycling, a life-cycle assessment (LCA) can be performed. Hydro magnesium has issued a comprehensive life cycle inventory (LCI) for the production of magnesium die-casting alloys. This inventory has been used to make a comparative analysis of the parts produced in die-cast magnesium alloys and other alloys. It follows that recyclability is a necessary prerequisite to release the full environmental benefits of using magnesium. Another important factor is to reduce or eliminate the consumption of the potent greenhouse gas $SF_6$. Recent research has shown that applying a dilute mixture of $SO_2$ in dry air is a viable method for replacing $SF_6$. $SO_2$ must be added as a 0.5–1.5 % mixture in dry air by using a well-designed gas distribution system supplied from a special mixing unit.

The rapid growth of magnesium alloy die-casting has triggered numerous developments of post-casting treatments. Equipment is readily available for trimming, vibratory finishing, blasting and machining. New, environmentally friendly conversion coatings have been developed, as well as improved painting and anodizing processes.

## 6 MAGNESIUM ALLOYS

Due to their low density (1.8 g/cm$^3$), magnesium alloys offer distinct advantages for weight saving in automotive applications [9]. It is fair to say that the 1990s have seen a growth of magnesium applications, among which are found steering-column assemblies, steering wheels, instrument panels, seat frames, valve covers and even a manual transmission-case application. The need for further weight reduction is extending the future use of magnesium to critical components such as transmission and engine parts. Magnesium faces a challenge in meeting the performance requirements of these components, for elevated-temperature (150 °C) strength and creep resistance, as well as adequate corrosion resistance. The most economic use of Mg in the automotive industry at the moment is in die-cast applications and this is because of the high productivity of the die-casting process, which upsets the cost of the magnesium metal.

The 1990s have seen renewed activity in the development of elevated-temperature Mg die-casting alloys. In 1994–1997 there have been patent applications on rare-earth and calcium containing alloys. These alloy systems have very good creep properties, such as creep-resistance and bolt-load retention, but contain the expensive rare-earth additions and their die-castability is not known. Also, in 1994-95 a cost-effective Mg-Al-Ca alloy system was developed and a patent application was filed.

There is presently an ongoing worldwide effort to develop more optimum elevated-temperature Mg alloys. Work is underway on the development of new alloys with a potential application in automotive parts requiring elevated temperature performance, such as engine components and automatic transmission cases. The commercial success of these alloys will require Mg producers to focus their efforts and address issues related to cost and recyclability. In collaboration with part producers and end users they will also need to address die-castability and manufaturability.

## 7 POSSIBILITIES FOR THE RECYCLING OF MAGNESIUM AND MAGNESIUM ALLOYS

Simultaneously with the increasing applications and consumption of magnesium, significant quantities of new scrap are generated; scrap from production as well as postconsumer scrap. As a result of this anticipated increase in new scrap generation, companies are planning new magnesium recycling plants or they are expanding existing capacity. The principal long-term effect is that after an automobile is scrapped the magnesium-containing parts may be removed from the automobile and recycled. These additional magnesium-containing parts would result in additional quantities of old scrap as a source of supply. The projected increase in the use of magnesium in this application has prompted developed countries such as Germany, Japan, Great Britain, USA and Canada to install additional magnesium recycling capacity. In USA in 1998 the recycling efficiency rate for magnesium was estimated to be 33 %.

New magnesium-based scrap is typically categorized into one of the four types. Type I is high-grade scrap, generally materials such as gates, runners and drippings from die-casting operations that is uncontaminated with oils. Types II, III and IV are lower-graded materials. Type II is oil-contaminated scrap, type III is dross from magnesium-processing operations, and type IV is chips and fines. Old magnesium-based scrap or postconsumer scrap consists of such materials as automotive parts, helicopter parts, lawnmower decks, used tools and the like. This scrap is sold to scrap processors. In addition to magnesium-based scrap, significant quantities of magnesium are contained in aluminium alloys that can also be recycled. In particular, magnesium has a lower specific heat and a lower melting point than other metals. This gives the advantage of using less energy in recycling, with recycled Mg requiring as little as about 4 % of the energy required to manufacture new material. At present, however, recycling procedures are still not fully developed. For example, an experimental investigation of the processing of non oil-contaminated metal scrap based on magnesium and its alloys was carried out. Experimental investigations were conducted on a laboratory scale and the results were verified on an industrial scale. The investigations show that: processing of this kind of scrap is possible with a metal-extraction efficiency rate in range 45–90 %, depending on the quality of the scrap; and for the purpose of achieving satisfactory techno-economical effects it is necessary to have suitable processing technology, which includes the preparation, metallurgical processing, smelting and refining. An electrolytic process to recycle low-grade and post-consumer magnesium scrap was developed to recover magnesium from magnesium oxide, unlike the traditional electrolytic process that uses magnesium chloride as a feed material [10].

## 8 THE RECYCLING OF MAGNESIUM

Magnesium scrap is being melted and refined under strict control. After the removal of oxides and compositional adjustments, magnesium alloys of at least the same quality as primary metal are cast into ingots.

The magnesium die-casting industry has grown significantly over recent years and this growth is projected to continue with automotive applications leading the way. The current consumption of magnesium is about 2 kg per vehicle worldwide, and over the next 20 years, the automotive industry could use almost 100 kg per vehicle, or more than 50 times the current demand. This leads to significant amounts of magnesium scrap. Depending on the die-casting process used, and the design of the part, between 80 % to 100 % of the net weight of the casting can be scrap. To realize this growth, magnesium has to be economically and environmentally acceptable. All options for reusing pre- and post-consumer magnesium scrap in alternative markets, or for recycling, need to be evaluated. The growing demand for magnesium alloys in the automobile industry necessitates increasing recycling capacities. In this respect, the recycling process is today still basically related to the clean casting returns. However, there is an ever greater need to recycle other residual magnesium materials as well. The reuse or recycling of these residual materials continues to be a problem, in particular with regard to environmental issues. The re-melting of painted casting returns results in considerable quantities of dioxin. These must be recorded quantitatively and, using an appropriate filter, must be removed from the waste gases down to a content of 0.1 mg/m$^3$. This demands a relatively large investment in filter technology.

Today, the "dross" arising in the die-casting foundries is also recycled, i.e., the more or less salt-free magnesium scrapings that occur when the crucible surface is skimmed. The chips arising in the production process today are contaminated with either oil or oil-water emulsions. Even with long draining times, it is not possible to reduce the oil content to below 10 %. In this form, the chips cannot be re-melted using any of the melting techniques applied so far. They burn (to a greater or lesser extent), producing black oil-smoke clouds in the melting crucible, resulting in extreme emissions of dioxins, total C, HCl and Mg oxide, as well as scrapings that have to be disposed of in an expensive process. This is a very high-cost method of destroying magnesium chips. A technique was developed, it consists of pressing the magnesium chips in a hot condition at > 300 °C, which not only removes the oil thermally, but also causes the chips to cake in such a way that a re-melting process can be carried out without any major loss during red heat. Until now, this technique has only been applied rarely, and the quantities to be pressed per unit of time are relatively small.

In addition to protecting the environment, the main objective, of course, is to manufacture a clean alloy, which can be reused in the automobile industry and, if possible, has a high-purity (HP) quality. To achieve this it requires a type-specific separation and collection of the casting returns at the die caster's plant, and a fault-free handling/transport at the disposing/recycling company. If these prerequisites are satisfied, the recycling process will result in an alloy that complies with the standards. Today we distinguish between four different recycling categories:

1) "in-cell" recycling
2) "in-house" recycling
3) End of Life Vehicle (ELV) recycling
4) industrial (external) recycling/service.

Depending on the structure of the installation, the annual capacities of the recycling plants vary between 2 000 t per year and 10 000 t per year.

"In-cell" recycling takes place directly at the plant of the die-caster, who immediately puts the clean, initial castings into the melting crucible again. "In-house" recycling may become interesting for die-casters with high throughput quantities. ELV recycling still poses a challenge. By 2015, automobile manufacturers will be forced to reuse 95 percent of the materials used in the car and, what is more, in the same area of applications.

The traditional technology is melting and refining with salt, also called flux refining. The casting returns are melted down in an open steel crucible (heated by gas or electricity) while salt is added.

The Salt Furnace Technology was developed, using super-heated salt to melt the returns and cleaning the melt by settling in a multi-chamber furnace. In the one-furnace version of this technology, ingots are cast directly from the recycling furnace. There will be a constant increase in the demand for the recycling of residual magnesium materials. The statutory regulations will be ever more oriented towards a closed-loop cycle in which all the residual materials are, if at all possible, reused. The utilization of larger quantities of "post-consumer scrap" must be prepared and new applications must be created for the use of "non-HP alloys".

## 9 EXPECTATIONS AND PROBLEMS IN THE WIDER APPLICATION OF Mg TO MOTOR VEHICLES

Passenger transport accounted for about 60 % of the total energy consumption in the transport sector, and in particular the use of private cars contributed significantly to this consumption. To build a sustainable society in the future it will be necessary to reduce the weight of the structural materials used in transport equipment, especially private cars, both to conserve energy and to minimize global warming [11].Today, magnesium alloys are recognized alternatives to iron and aluminium for reducing the weight of structural elements [12]. On the other hand, motor vehicles tend to increase in weight as they are given additional functions, such as safety devices and electronic equipment. The challenge for the future is not only to offset weight increases due to performance enhancements, but also to reduce the overall weight of motor vehicles. Conventional weight reduction technologies have reduced the weight of motor vehicles by improving their structural design and thinning steel materials by increasing their strength. For the future, however, it is generally recognized that drastic changes in structural materials should be considered [13].

For passenger cars, the general rule is that about 86 % of their total lifetime energy use (from the time of production to the time of disuse or scrapping) is consumed by carrying their own weight and persons around. In Europe, the regulation governing $CO_2$ emissions from motor vehicles has been worked out, setting the standard that $CO_2$ emission shall not exceed 140 g/km in 2012 and 120 g/km in 2014. According to previous analysis, it will be necessary to reduce the mass of vehicles by about 10 %. To attain such a great reduction in mass, it will probably be necessary to replace steel with Mg alloys as the structural material. For this reason, much attention is now focused on Mg alloys as structural materials or parts for motor vehicles.

To work towards a sustainable society, it is absolutely necessary to develop energy-saving technologies that contribute to the reduction of $CO_2$ emissions. It is especially important to reduce the amount of energy that is consumed simply to enable a vehicle to carry its own weight around. Therefore, the weight reduction of transport equipment is one of the most important technical challenges. It is anticipated that activities will be accelerated to develop and commercialize Mg alloys that contribute to the weight reduction of structural materials for transport equipment.

Although Mg alloys possess a variety of desirable physical properties, including lightness, they have had a limited range of applications because they also have performance shortcomings, such as low strength, low heat resistance and low corrosion resistance. In recent years, however, advanced basic research on Mg alloys has enlarged the range of applications [14].

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