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Trend of Research and Development for Magnesium Alloys
— Reducing the Weight of Structural Materials in Motor Vehicles —

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1 Introduction

According to information[1] provided by the Agency for Natural Resources and Energy in 2004, passenger transport accounted for about 60% of total energy consumption in the transport sector, and in particular the use of private cars contributed significantly to annual energy consumption, which rose by 64% between 1990 and 2001. 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.

Today, magnesium (Mg) alloys are recognized alternatives to iron and aluminum to reduce the weight of structural materials. In recent years, Mg alloys, previously used only in a limited range of applications, have served as automobile parts and cases for portable electronic devices such as notebook-type personal computers (PCs), as well as portable telephones, thanks to improved corrosion resistance and the development of new technologies to form and work the alloys. In addition, the alloys' improved heat resistance and strength have extended their possible range of application. In particular, given the desirability of minimizing energy consumption and creating and developing a new industry, it is expected that Mg alloys may be used as structural materials for motor vehicles.

This article describes what Mg alloys are, and what applications they are expected to have in automobiles, and indicates where our R & D efforts should be aimed, based on the existing R & D picture both in Japan and other countries.

2 Description of magnesium alloys

2-1 Magnesium as a pure metal

(1) Natural resources and refining methods

Among all the elements, magnesium (Mg) has the 8th highest Clarke number (the amount of an element in the surface layer of the Earth), which is 1/4 that of aluminum, 2/5 that of iron and 190 times higher than those of nickel and copper. The abundance of Mg in the Earth is considered to be the 4th highest, following iron, oxygen and silicon. The raw ores of Mg are dolomite ($MgCO_3 \cdot CaCO_3$) 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.

The methods for manufacturing Mg can roughly be divided into electrolysis and thermal reduction. Electrolysis method involves extracting magnesium chloride from Mg ores and then reducing the magnesium to the 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.

(2) Properties of pure Mg metal

Magnesium is the lightest of all metals in practical use, and has a density (1.74g/cm^3) of about 2/3 that of aluminum and 1/4 that of iron. This material has useful properties such as shielding against electromagnetic waves,

Table 1 : Comparison of physical properties of magnesium and other metals

Metal name	Specific gravity	Melting point (°C)	Boiling point (°C)	Latent heat of melting (kJ/kg, J/cm³)	Specific heat (kJ/kg·K, J/cm³·K)	Coefficient of linear expansion x 10⁶	Tensile strength (MPa)	Elongation	Hardness HB
Mg	1.74	950	1110	368, 640	1.05, 1.84	25.5	98	5	30
Al	2.75	660	2486	398, 1088	0.88, 2.43	23.9	88	45	23
Fe	7.86	1535	2754	272, 213	0.46, 3.68	11.7	265	45	67

Source: Provided by Prof. Kamado, Nagaoka University of Technology

vibration damping, dent resistance, machinability, and low toxicity in humans.

On the other hand, magnesium has shortcomings such as insufficient strength, elongation and heat resistance, as well as being subject to corrosion. Its readiness to corrode has been found to be due to its 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.

2-2 Properties of magnesium improved by alloying

Pure magnesium possesses a variety of excellent properties. To put it to practical use, however, it is necessary to deal with its shortcomings and improve its performance. Alloying may be the answer. 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 aluminum (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. AZ91-based Mg alloys have excellent mechanical properties and castability. In particular, AZ91D-based Mg alloys with high purity for high corrosion resistance are used in car parts, notebook PCs, portable telephones and other products. AZ31C-based Mg alloys, which have high formability and weldability, are most often used as elongating materials for plates, pipes, rods and other products. ZK60A-based Mg alloys produced by adding zinc (Zn) and zirconium (Zr) have a higher hot-workability than other materials. Mg alloys produced by adding rare earth elements such as cerium (Ce) and neodymium (Nd) have high strength at 200 to 250°C and excellent creep resistance and heat resistance[2]. The improved performance characteristics realized by recent R & D efforts will be described in Chapter 4.

2-3 Working methods

The use of Mg alloys has recently increased in applications such as cases for notebook PCs and portable electronic devices because the methods for working these materials have improved rapidly. Mg alloys, which have crystal structures different from those of structural materials such as iron, steel, aluminum and copper alloys, are so difficult to roll at ambient temperatures that it is necessary to work at higher temperatures. Mg alloys may be extruded in almost the same way as aluminum alloys because they have almost the same hot deformation resistance. Forging with a hydraulic press is also used to produce parts for transport equipment such as motor vehicles, helicopters and other aircraft. Die casting (forming molten materials in dies) is mainly used to form parts for motor vehicles because it can form any material in near net shape (nearly the final desired shape) as well as thin products, and is therefore well suited to mass production. In addition, the use of injection molding is behind the recent increase in the use of Mg alloys in the cases of portable electronic devices. Thixotropic molding (or thixo-molding), a combination of injection molding and die casting often used to form plastic products, is in practical use as a semi-melt working method.

The surface treatment techniques used to provide highly corrosion resistant Mg alloy products have already advanced to the same level as die casting methods for carbon steel plates and aluminum alloy products. Mg alloys are generally submitted to a chemical conversion treatment using a chemical reaction. If they are used in severe conditions that may cause wear and stray current corrosion, however, they are generally given an anodic oxidation treatment. Mg alloys may be welded with the same techniques as other metals, including fusion welding. Recently, however, friction stir welding (FSW), a technique useful for metals having low melting points, has attracted much attention because it has several advantages.

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. To produce or cast alloy composites (alloy metals) by melting, it is necessary to melt and mold the materials at a high temperature. For Mg, it is essential to prevent the materials from reacting with oxygen in the air. Currently, this is mainly accomplished with sulfur hexafluoride (SF6) gas, but this is a potential greenhouse gas so alternatives that do not use SF6 are now under investigation. Chapter 4 provides more detailed information on recent research aimed at improved fire resistance.

2-4 Pricing

Import prices for magnesium are still higher than for aluminum, but they have dropped to less than twice the price of aluminum. At present, import prices are 180 to 190 yen/kg for Mg and about 280 yen/kg for Mg alloys. The prices for Mg and Mg alloy products depend on the type of product, such as billets and plates. Worked material for automobile bodies is now on the order of 1,000 to 3,000 yen/kg. To use Mg alloys in a wider range of applications, it is generally felt that prices need to be lower than about 500 to 1,000 yen/kg for cast parts and 1,000 to 2,000 yen/kg for thin rolled plates. The prices for Mg and Mg alloys are so much higher than those for Al and its alloys because the production of Mg and Mg alloy products, worked and formed, is about 100 times smaller than that of Al metal and alloy products, and because high-efficiency working processes for Mg metals and alloys are still being developed[3].

2-5 Applications and examples

The development of magnesium alloy products for nongovernmental use 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, telecommunication equipment and sporting goods. Some products have been commercialized, though few of them saw steady use for very long. Recently, Mg alloys have begun to be used for the cases of notebook PCs and portable electronic devices. At present, there are more active moves toward the future utilization of Mg alloys for transport equipment including motor vehicles, motorcycles and aircraft. The domestic demand for Mg alloys in 2002 was greatest for portable telephone cases, followed by notebook PCs, parts for automobiles and two-wheeled vehicles, and digital video cameras. Very recently, some Mg alloys have been used for the housings of large-sized plasma display panels as well.

The use of Mg alloys is greatest for portable electronic devices because the materials have several advantages: they are light, but being metallic they conduct and radiate heat better than plastic; they maintain a metallic texture, but they are non-magnetic; they can block electromagnetic waves and minimize the influence of noise. 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.

2-6 Recyclability

Generally, metals are more recyclable than plastics because they can be melted and reused. 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, and work is underway on the technologies required for recycling wastes from relatively clean factories[10]. In the future, it may be necessary to review the material flow in order to ensure that recycled materials will account for about tens percent of total Mg alloy production.

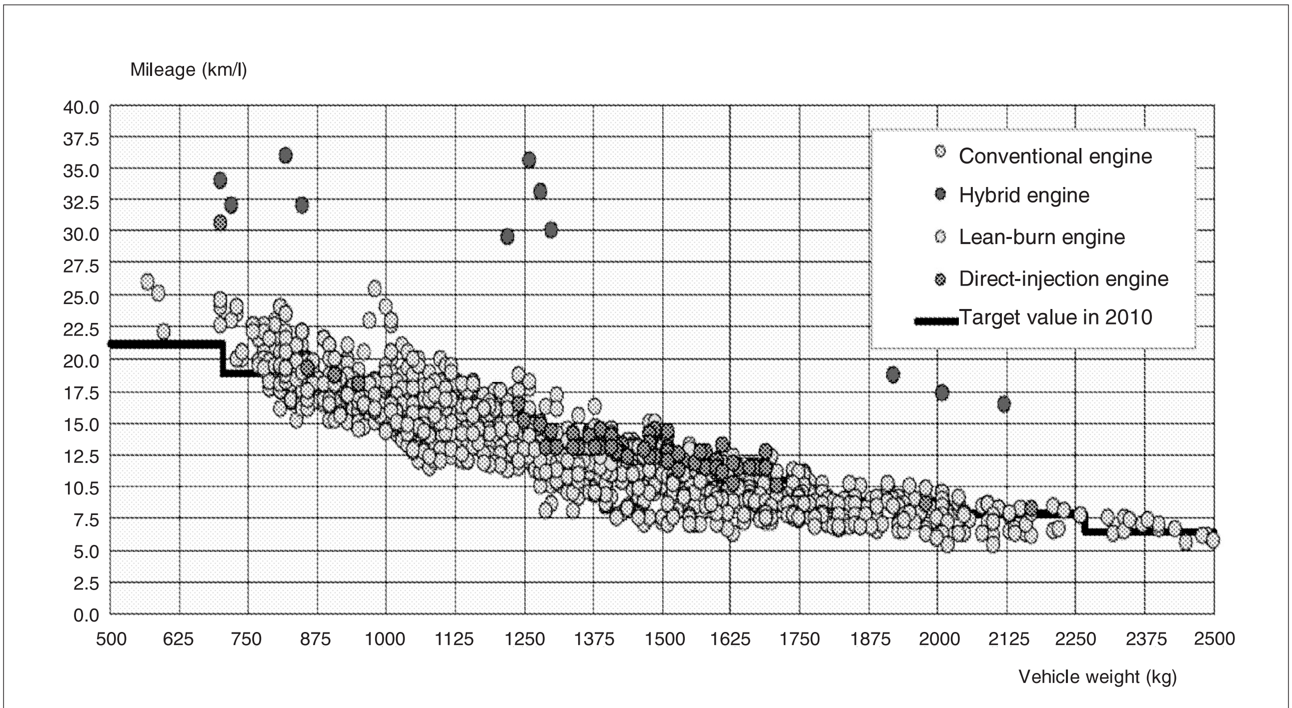
3 Expectations for and problems in the wider application of Mg alloys to motor vehicles

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.

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. It is thought that mileage might be 5 - 10% higher if cars weighed 10% less, as shown in Figure 1. For example, a weight reduction of 1 kg per 1,000 kg of car weight could increase mileage by about 0.016 km/l. For enhanced energy saving in motor vehicles, therefore, weight reduction technology for structural materials is indispensable, so it is necessary to use large quantities of materials having a high specific strength (strength (in kg/cm^2) divided by specific gravity).

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. To meet the standard in 2014, it will be necessary to attain the high mileage of 20 km/l. Figure 2 shows how much improvement will be needed for domestic small passenger cars to meet the mileage standard in 2010. According to this analysis, it will be necessary to reduce the mass of vehicles by about 10% (100 to 150 kg). To attain such a great reduction in mass, it will

Figure 1 : Mileage vs. weight for a gasoline-powered passenger car

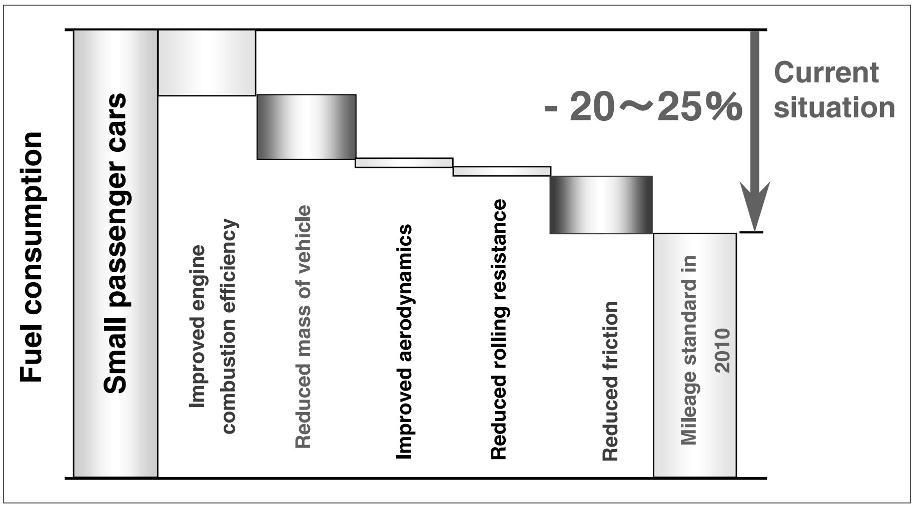


Source: The home page of the Ministry of Land, Infrastructure and Transport[5] probably be necessary to replace steel with Mg alloys as the structural material. For this reason, much attention is now focused on Mg alloys as structural materials or parts for motor vehicles.

Figure 3 shows a car and the places where Mg alloys have been used or where their application continues to be considered.

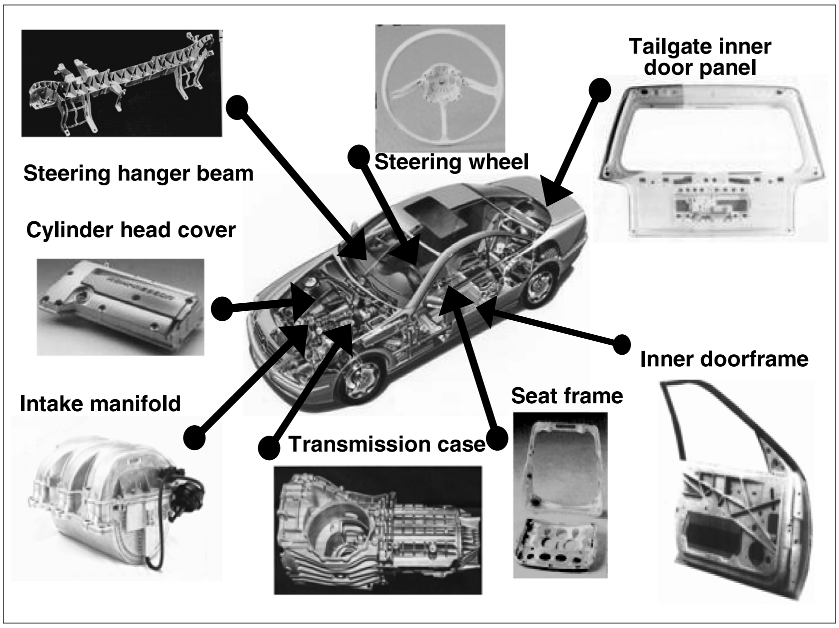
In Germany, Mg alloys have been used as die cast parts, and Volkswagen used 42 thousand tons of Mg alloys in 1971. In the U.S.A., Mg alloy parts have been used in motor vehicles since the 1970s. General Motors and Ford started to use Mg alloys in steering columns in 1973 and 1978, respectively. In Japan recently, the use of Mg alloys has increased incrementally each time a new car is developed. The general-purpose Mg alloy AZ91D is used in various types of covers and cases. Mg alloys AM50 and AM60, with higher ductility and impact resistance, are used for steering wheel cores. Mg alloys that contain additives such as rare earth elements and calcium (Ca) to provide high heat resistance are used for transmission cases and oil pans. Japanese companies have already used Mg alloys in more than 10 types of parts. Other applications include, but are not limited to, steering wheel cores, engine head covers, air bag plates, electronic control part cases, seat frames, and transmission

Figure 2 : Target by function to meet the mileage standard in 2010



Source: Provided by Prof. Kamado, Nagaoka University of Technology

Figure 3 : Applications of Mg alloys in motor vehicles



Source: Provided by Prof. Kamado, Nagaoka University of Technology

Table 2 : Demand for Mg alloys from automobile manufacturers

Formed materials	Metals	• Stable supply and price reduction (including recycling technologies) • Development of low-cost and high-performance alloys (with high heat resistance, strength, toughness, etc.) • Establishment of infrastructure for recycling
	Plates	• Attainment of high formability and good surface quality • Widening and low-cost technologies (for thin plates, continuously cast materials, etc.)
	Extruded materials	• Large-sized materials, irregular sections, low-cost technologies (high-speed extrusion)
Processing technologies	Pressing	• High-speed super-plasticity pressing technologies for large-sized parts
	Forging	• Die casting technologies for large-sized and thin products with decreased defects such as gas and nests
	Welding & joining	• Welding technologies to deal with corrosion protection and resistance to stress corrosion cracking (SCC) • Mechanical joining and solid-phase welding technologies including the joining of different materials
	Surface reforming	• Low-cost surface treatment, easy to recycle products

Source: Prepared by STFC based on a lecture by Prof. Kamado at NISTEP

cases. In particular, steering parts made from Mg alloys are used in many car models because these materials have a good vibration damping effect.

In the U.S.A., three automobile manufacturers (GM, Ford and Daimler-Chrysler), generally called 'the Big 3', jointly established the United States Council for Automotive Research (USCAR) in 1992. The Council worked out a plan for strengthening their competitiveness and taking environmental measures, and has since made efforts to implement the plan. As part of this, the Magnesium Powertrain Cast Components Project was started in 2001 under the direction of the United States Automotive Materials Partnership (USAMP). This project aims to increase the use of Mg alloys in a motor vehicle to about 100 kg by 2020[6].

To bring about the extensive use of Mg alloys in motor vehicles, however, it will be necessary to achieve a stable supply of Mg ore, improve the heat resistance of Mg alloys, improve high-speed forming, welding, joining, surface reforming and other technologies for large-sized parts and members, and reduce the cost of these technologies. Table 2 summarizes the technical problems pointed out or requests made by automobile manufacturers as Mg alloy users.

4 Trend of research and development for magnesium alloys in Japan

4-1 Development of high-performance alloys

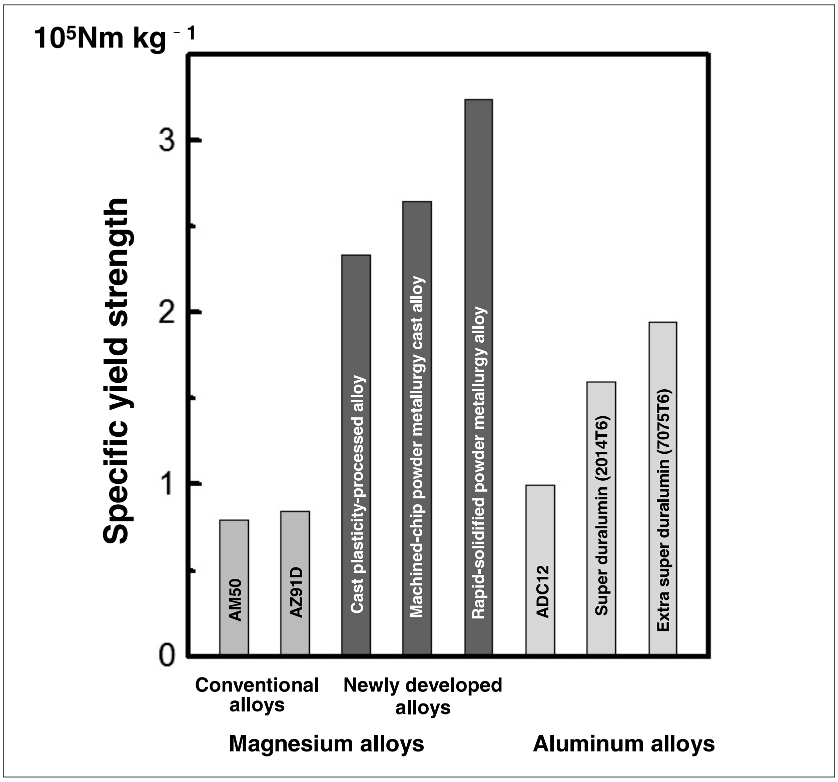
(1) Development of magnesium alloy having the highest strength in the world and a long-period multilayer structure

The development of a new high-performance magnesium alloy as a result of targeted research funded by the Ministry of Education, Culture, Sports, Science and Technology that began in September 1999 is generally considered a breakthrough. This R & D effort produced new Mg-Zn-, Mg-Al-Ca-, and Mg-Y-Zn-based alloys with high strength, creep resistance and heat resistance.

Prof. Yoshihito Kawamura et al. at Kumamoto University succeeded in developing the high-strength and fast-solidifying alloy Mg97Zn1Y2 using powder metallurgy[7] and showed that this alloy has the special atomic configuration called a long-period multilayer structure. It can also be manufactured by casting, and the substitution of dysprosium (Dy), holmium (Ho) or erbium (Er) as a rare earth element can give almost the same properties as the use of yttrium (Y). In addition, they found ways to process the alloy to improve both its strength and ductility.

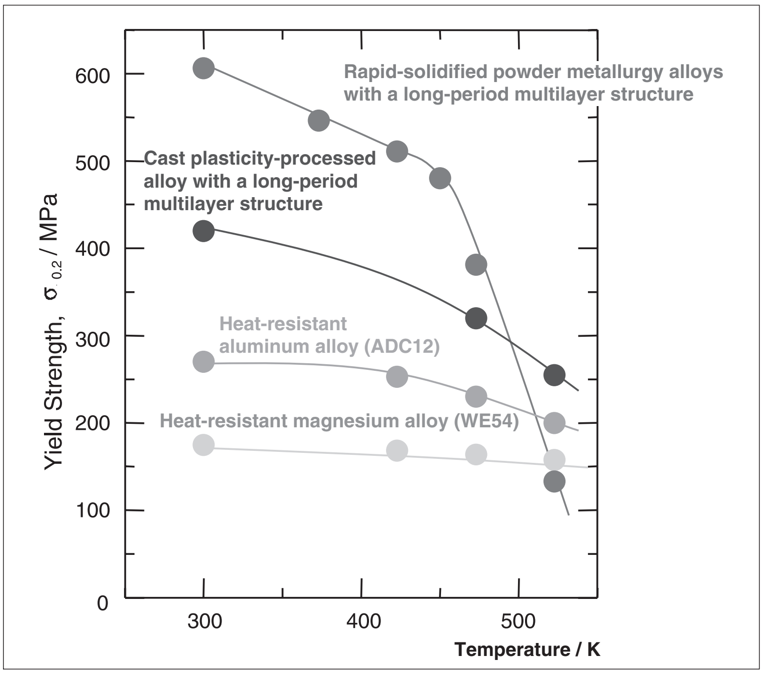
Figures 4 and 5 show the characteristics of the new alloys. The new alloys' specific strength is about 3 times higher than that of commercial high-strength Mg alloys, and higher than commercial titanium alloys and extra super duralumin. Even at high temperatures, they retain high strength and rapid superplasticity (superplasticity is defined as a tensile elongation of 200% or more at a distortion rate of 10-2 to 10-1/sec or more).

Figure 4 : Specific yield strength of Mg alloy with a long-period multilayer structure



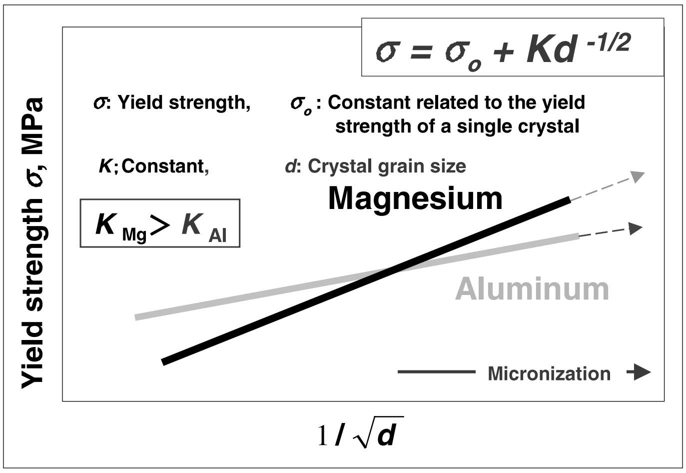
Source: Provided by Prof. Kawamura, Kumamoto University

Figure 5 : Yield strength vs. temperature of new alloys with a long-period multilayer structure



Source: Provided by Prof. Kawamura, Kumamoto University

Figure 6 : Crystal grain size vs. yield strength



Based on these R & D efforts to create new alloys, Development of Next-Generation Powder Metallurgy Magnesium Alloys and Members was started in 2003 as a part of the Project "Civil Aviation Fundamental Technology Program-Advanced Materials & Process Development for Next Generation Aircraft Structures" set up by the Ministry of Economy, Trade and Industry.

(2) Improvement in heat resistance

Prof. Shigeharu Kamado et al. at Nagaoka University of Technology are now developing Mg alloys with high die-castability and high heat resistance, for use in automotive drive systems under a project set up by the NEDO (New Energy and Industrial Technology Development Organization)[7]. These alloys contain aluminum and a rare earth element as additives and show high creep resistance (which should be restrained if they are used at a high temperature). Furthermore, R & D efforts were made to improve Mg-Zn-Al-Ca-RE (RE = rare earth element)-based alloys, with the aim of giving them characteristics comparable to those of heat-resistant aluminum alloy ADC12. To put the improved alloys to practical use, transmission cases were also experimentally manufactured.

(3) Mechanical performance improved by micronization of crystal grains

A metal's mechanical strength depends on its crystal grain size, as quantified in the Hall-Petch relationship (Figure 6). It is generally known that micronizing their crystal grains improves the strength of Mg alloys more than Al alloys.

(i)Micronization of crystal grains by ECAP method

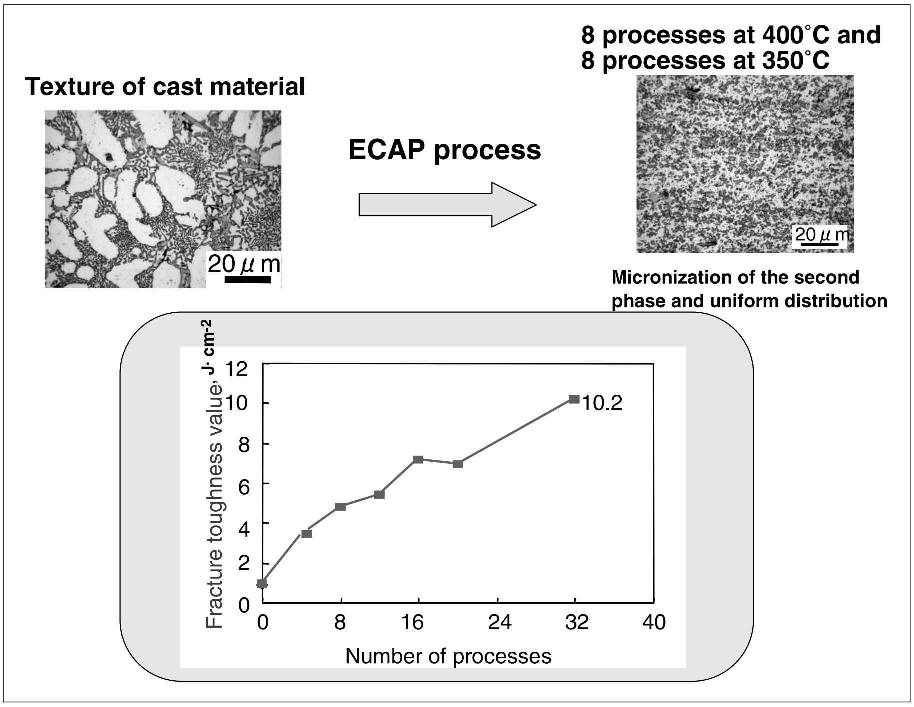
In 1981, Segal et al. in Russia published a method called ECAP or ECAE (Equal-Channel Angular Pressing or Extrusion) for micronizing crystal grains by combining a high working stress (shear distortion) and recrystallization. If this process is repeated several times, the size of crystal grains will be decreased to the level of 2 to 3 μm. Mg alloys subjected to the process repeatedly become excellent materials, with higher strength, higher elongation and an improved fracture toughness value (value expressing the stress that starts to expand cracks in a material). Figure 7 shows a case where the repeated ECAP process decreases the crystal grain size of a material and increases the fracture toughness value of the material.

(ii) Micronization of crystal grains by precipitation

It is considered desirable to form conventional Mg alloys at a high temperature of 200°C or more. To enlarge the range of applications, it will be necessary to reduce the cost of processing[14], and the other method, which can micronize crystal grains at a lower temperature and a higher speed, is preferable.

It was reported that processing Mg alloys around 175°C produced great quantities of fine precipitates on the order of 50 to 100 nm, and that Mg alloys were recrystallized from the precipitates to provide alloys with a crystal

Figure 7 : Fracture toughness improved by rotary ECAP method



Source: Provided by Materials Research Institute for Sustainable Development, National Institute of Advanced Industrial Science and Technology

size of 0.5 μm and both high strength and high elongation. Mg alloys with higher strength and higher extensibility were obtained from the alloys introduced in Section 4-1 (2) with the “Repeated Plastic Working method” developed by Katsuyoshi Kondoh, Associate Professor, Research Center for Advanced Science and Technology, the University of Tokyo[14].

4-2 Development for forming and welding technologies

(1) Forming technologies

Among the different Mg alloy forming methods, a great deal of attention is focused on die-casting, thixo-molding (injection molding) and press forging techniques as described in Section 2-3[8]. These techniques are selected according to the desired application, and continue to be further improved.

In the die casting technique, molten metal is poured into a set of dies; a mobile die and a fixed die. It can be used for mass production, has good dimensional accuracy, and can produce parts that are thin and have complicated shapes. The thixo-molding technique uses thixotropy (the phenomenon of having lower viscosity and higher fluidity when shear force is applied in the semi-molten and granulated solid phase) and injection molding (the conventional plastic molding method in which a heat-melted material is injected into molds and solidified by cooling). This technique, which can be used in an enclosed space, has the great advantage that harmless Ar gas can be used as an alternative to SF6, a gas with adverse environmental effects. This method is used to produce cases for portable electronic devices and production is increasing rapidly. The press forging technique is a method of forging, bending, pressing and finishing thin Mg alloy plates at 300°C to provide thin products of high quality. This method is used in the mass production of cases for electronic devices such as MD players and digital cameras. This method has advantages in that it can be used to manufacture Mg alloy products with a better surface quality than conventional cast Mg alloy products without requiring processing such as polishing, and it improves the rigidity of products.

(2) Welding technologies

It has been felt that it was difficult to weld Mg alloys. However, the use of the friction stir welding (FSW) method will probably attract a great deal of attention. This method is applicable to light metals having a relatively low softening point.

FSW was developed in the United Kingdom about 15 years ago. As shown in Figure 8, it involves simultaneously rotating and pushing a cylindrical tool with a projection on its lower end so as to drive the projection into the parts of base materials to be welded and produce friction heat that softens the base materials; and stirring and mixing the plastic material around the welded parts by the rotation of the tool to weld different base materials together. This welding method has the advantages that it is unlikely to produce deformation, pores and cracks, that no sealing gas is required, and that no harmful radiation such as infrared is produced. The FSW method is now used to manufacture all the Shinkansen trains of Series 700 that use aluminum car bodies. This technology is expected to become very important in the manufacture of large-sized Mg alloy parts.

4-3 Improved fire resistance

One problem with Mg alloys is their high activity in the presence of oxygen. To reduce the hazard, SF6 is used to prevent Mg alloys in the molten state from coming into contact with air, as described in Section 2-3. However, SF6 has a long lifetime in the atmosphere and is 24,000 times more potent than an equal amount of CO_2 in causing global warming. Therefore, it is necessary to minimize the emission of SF6 and urgently necessary to adopt SF6-free Mg alloy manufacturing methods. To take measures against SF6, the NEDO (New Energy and Industrial Technology Development Organization) started the 3-year "Development of Non-SF6 Melting Process and Micro Structural Control for High Performance Magnesium Alloy" in 2004.

The National Institute of Advanced Industrial Science and Technology has already succeeded in raising the ignition point of Mg alloys by 200 to 300°C by adding calcium (Ca), as shown in Figure 9.

4-4 Strengthening databases

The recent research described above indicates that in Japan the basic technologies for using Mg have advanced remarkably in recent years

Figure 8 : Concept of the friction stir welding method

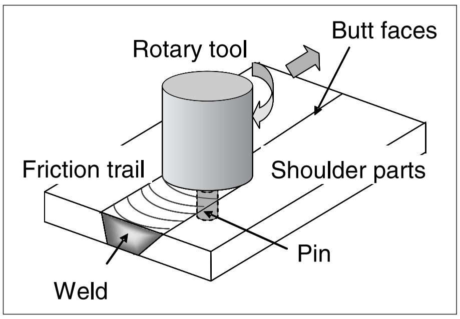
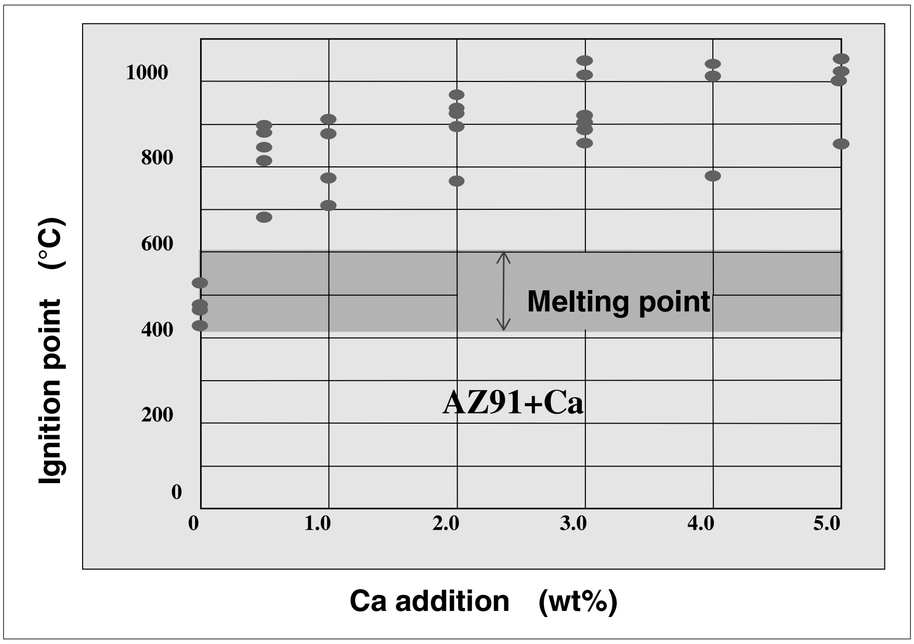


Figure 9 : Ca addition vs. ignition point



Source: Provided by Materials Research Institute for Sustainable Development, National Institute of Advanced Industrial Science and Technology and now rank with the best in the world. In the future, it will be necessary to effectively apply this research, established technologies, and evaluation of the characteristics of Mg alloys to the design of products in order to enlarge the range of applications as soon as possible. One way to promote this is to build up and improve the databases shared by the related organizations. The databases on Mg alloys available in Japan include one prepared by the Japan Magnesium Association[9]. In the future, it will be necessary to further strengthen these databases.

5 Trends of research and development promotion systems in Japan and other countries[4, 6]

5-1 Europe

In Europe, R & D efforts for Mg alloys have been part of the development projects aimed at reducing the weight of motor vehicles for the primary purpose of reducing CO_2 emissions.

The main participant in the EUCAR project being implemented in Europe is the joint research organization established by automobile manufacturers such as Fiat, Volvo, Daimler-Chrysler, Ford, Volkswagen (VW) and BMW; universities, research organizations, and parts suppliers in Europe also participate in this project. For this project, the common themes of research and development are (1) material design guidelines, (2) new welding and joining technologies, (3) the development of new extruded materials, and (4) the development of new heat-resistant Mg alloys.

In Germany, the Federal Ministry of Education and Research has supported the "InMaK-Project" (Innovative Magnesium Compound Structures for Automobile Frames), which is intended to create new material designs by reviewing destruction simulation models. As part of this, research has been conducted on material design methods and welding and joining techniques. Over the period 1996 - 1999, the German government invested about 2 billion yen in research under the MADICA Project (Mg Alloy Die-Casting Project), in which 5 universities and 43 companies including 5 automobile manufacturers participated. This project developed not only die casting technologies, but also mechanical working, welding & joining, and thixo-molding technologies. At present, the Science and Technology Promotion Association, a governmental organization, is implementing the "SFB390 Project" with a total research investment of about 5 billion yen over the 1996 - 2005 period. Under this project, research is being conducted in the areas of metallurgical engineering and microstructure, manufacturing technologies and composite materials.

5-2 United States

The USCAR project, as described in Chapter 3, started in 1992 to develop a 3-liter car with 6 seats. In 1995, the United States Automotive Materials Partnership (USAMP) was established to undertake research and development projects for various materials. As one of these projects, the federal government, research organizations and the Big 3 automobile manufacturers initiated a development program for an environmentally friendly Supercar for the 1993 - 2004 period. Ford is implementing the development program "P2000 Mondeo Contour", in which 103 kg of Mg alloy parts would be used in an effort to develop a car that gets 29km/l.

Furthermore, the "FreedomCAR Project" in which the federal government, research organizations and the Big 3 automakers participated has been integrated into the huge automobile project called the "FreedomCar and Vehicle Technology Program". The Department of Energy (DOE) was, is and will be responsible for promoting and managing the implementation of this project from 2002 to 2010. Under this project, magnesium power train parts will be developed to reduce the weight of the trains for which aluminum alloys were and are mainly used, and tests have been conducted on Mg alloys for use as engine parts with the goal of improving creep resistance and corrosion resistance and also improving casting technologies and recyclability while reducing costs. The Argonne National Laboratory is responsible for carrying out the R & D for the project. In 2003, it was expected that a cast Mg alloy developed in this project would be used in a front engine cradle, and the replacement of cast aluminum with this new material reduced the weight of the cradle by 35%, from 15.8 kg to 10.3 kg. The participants in this project have an open working attitude that enables them to actively make use of the results of R & D efforts undertaken in other countries.

5-3 China

At present, China is rapidly emerging as one of the largest magnesium ore producers in the world. It has increased its share of the global production of Mg ore since 1995. In China, abundant coal can be used as a heat source, and many plants using the Pidgeon method have been established. The Pidgeon method is a refining process that uses the reduction of MgO•CaO by silicon. Even relatively small plants can be operated economically, which is why China could easily enter the refining industry.

While material manufacturing technologies improve with the expansion of markets for the base materials, great efforts are also being made in developing new casting and forming technologies to improve the value-added of products. Under China's 10th 5-year Plan, a total investment of about 40 million dollars for 5 - 10 years was initiated in 2001, and R & D projects for magnesium refining and processing technologies began to be implemented in cooperation with foreign automobile manufacturers operating in China as well as Chinese universities and colleges. Academic organizations such as Tsing Hua University, Shanghai Jiao Tong University, and ChongQing University have already started to conduct research on the commercialization of Mg alloy die casting technologies.

5-4 Korea

In the second half of the 1990s, the Korean government started to invest in academic and industrial projects to develop technologies necessary to commercialize large-sized Mg alloy parts and members. These projects have since been implemented. The government intends to participate in the projects until the results of the R & D efforts are transferred to corporations. The projects focus on the improvement of heat resistance and the cost reduction of plate materials. It is reported that R & D efforts are being made to put large-sized parts and members to practical use, for example, to manufacture the systems that can produce rolled materials in 2m widths.

5-5 Japan

As one of the recent projects set up jointly by industrial, academic and government agencies, the "Ibaraki Magnesium Project" started to be implemented on a full scale in July 2005. The prefecture of Ibaraki appropriated 17 million yen for this project in its fiscal year 2005 budget. In this prefecture, companies established a partnership organization to implement joint research and development projects in cooperation with the Ibaraki Industrial Technology Center and Ibaraki University, and to outsource research projects to research organizations such as the National Institute of Advanced Industrial Science and Technology. This project gives priority to three areas: machining, plastic molding and recycling technologies. In the prefecture of Niigata, the Niigata Industrial Creation Organization is launching a development project for next-generation Mg alloy products by outsourcing research to educational institutions such as Nagaoka University of Technology, Niigata Institute of Technology and Nagaoka National College of Technology. However, these projects are not oriented towards the development of automobile materials as described in this article.

6 Conclusions and recommendations

To work towards a sustainable society, it is absolutely necessary for future R & D projects 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 R & D 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 application 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. At present, Japan leads the world in this basic research. However, it is far behind the U.S.A. and Europe in terms of the applications to passenger cars that are expected to have the greatest impact. Recently, the Chinese and Korean governments have also begun programs to develop Mg alloys. It is necessary for the Japanese government to settle the direction of its support so that the basic technologies developed in this country will be of practical use in the fields where they have the greatest impact. From this point of view, two recommendations are made herein as follows:

(1) It is necessary to integrate all the results of development activities that have been carried out separately on basic Mg technologies, set up a national project to apply these results, and take active measures to make practical and efficient use of them in the fields where they can be expected to have the greatest impact. To do so, it is now necessary to:
 - (i) Prepare a road map for each application of Mg alloys and share the knowledge; and
 - (ii) Strengthen the fundamentals of our database on Mg alloys in order to perform part design more efficiently.

(2) In the near future, it may be necessary to:
 - (i) Improve the performance characteristics of Mg alloys through further R & D efforts, enlarge the range of application of the current technologies, and promote cost reduction by increasing the use of Mg alloys.
 - (ii) Establish standard specifications for the quality of materials in cooperation with the U.S.A and European countries and require Mg ore producing countries to meet the specifications in order to ensure reliable quality. To achieve this, industrial, academic and government agencies must work together to establish standards for Mg materials that take into account the entire relevant body of accumulated knowledge and information.
 - (iii) If the use of Mg alloys increases in applications such as motor vehicles and the cases for portable electronic devices, it is expected that the recovery of recyclable Mg alloys from the general markets will increase. To respond to the increasing recovery of materials, it is necessary to build up an appropriate recycling system and develop recycling technologies.

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