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Materials Science and Engineering A302 (2001) 37–45
MATERIALS SCIENCE & ENGINEERING A
www.elsevier.com/locate/msea

Magnesium
Properties — applications — potential

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Abstract

Magnesium is the lightest of all metals used as the basis for constructional alloys. It is this property which entices automobile manufacturers to replace denser materials, not only steels, cast irons and copper base alloys but even aluminium alloys by magnesium based alloys. The requirement to reduce the weight of car components as a result in part of the introduction of legislation limiting emission has triggered renewed interest in magnesium. The growth rate over the next 10 years has been forecast to be 7% per annum. A wider use of magnesium base alloys necessitates several parallel programs. These can be classified as alloy development, process development/improvement and design considerations. These will be discussed briefly and followed by some examples of the increasing uses of magnesium and future trends.

Keywords: Magnesium; Alloy; Automobile

1. History and properties of magnesium alloys

In the past, magnesium was used extensively in World War I and again in World War II but apart from use in niche applications in the nuclear industry, metal and military aircraft, interest subsequently waned. The most significant application was its use in the VW beetle but even this petered out when higher performance was required. The requirement to reduce the weight of car components as a result in part of the introduction of legislation limiting emission has triggered renewed interest in magnesium. In 1944 the consumption had reached 228 000 t but slumped after the war to 10 000 t per annum. In 1998 with renewed interest it has climbed to 360 000 t per annum at a price of US$3.6 per kg. The growth rate over the next 10 years has been forecast to be 7% per annum [1]. The advantages of magnesium and magnesium alloys are listed as follows,

- lowest density of all metallic constructional materials;
- high specific strength;
- good castability, suitable for high pressure die-casting;
- can be turned/milled at high speed;
- good weldability under controlled atmosphere;
- much improved corrosion resistance using high purity magnesium;
- readily available;
- compared with polymeric materials:
  - ○ better mechanical properties;
  - ○ resistant to ageing;
  - ○ better electrical and thermal conductivity;
  - ○ recyclable.

One of the reasons for the limited use of magnesium has been some poor properties exacerbated by a lack of development work. The disadvantages of magnesium are presented based on the following:

- low elastic modulus;
- limited cold workability and toughness;
- limited high strength and creep resistance at elevated temperatures;
- high degree of shrinkage on solidification;
- high chemical reactivity;
- in some applications limited corrosion resistance.

It is not possible to use conventional alloying techniques to improve some of the properties, e.g. elastic constants. Here one must resort to fibre reinforcement. The solubility of alloying elements in magnesium is limited, restricting the possibility of improving the mechanical properties and chemical behaviour. The crystal

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PII: S0921-5093(00)01351-4

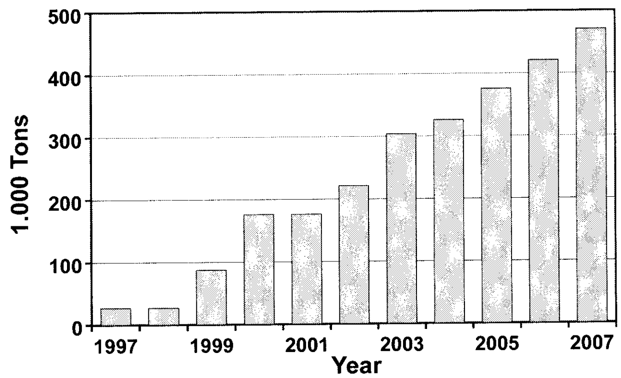


Fig. 1. Capacity primary magnesium [2].

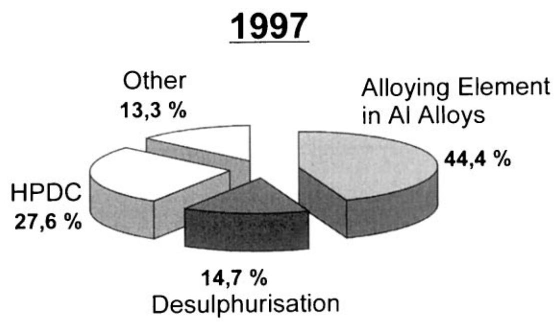


Fig. 2. Magnesium apportioned to metallurgical applications [2].

structure of magnesium is hexagonal which limits its inherent ductility. The only alloying element, which causes a useful phase change to bcc, in this respect, is lithium.

The lack of large-scale applications of magnesium alloys in the past has resulted in limited research and development. Consequently, there are few optimised casting alloys available and even fewer wrought alloys. The production techniques have been adapted from those for other low melting point alloys, e.g. aluminium. No experience is available on new production and working techniques and the know-how accumulated in the past has largely disappeared. The renewed demand has recently started to change this. The number of primary producers has increased and it is hoped that, when demand increases further, magnesium will be available at reasonable prices. Figs. 1 and 2 show the magnesium apportioned to metallurgical applications.

2. Alloy development

The property profiles demanded by automobile and other large-scale potential users of magnesium have revealed the need for alloy development. A straight transfer of 'high performance' aircraft alloys is not possible not only on economic grounds but often the property profiles do not coincide. Fig. 3 shows the different trends in alloy development depending on the main requirement.

3. Specific strength

The vast majority of magnesium applications are covered by AZ91, a die-casting alloy. This alloy has insufficient creep resistance for many desirable applications at temperatures above 130°C. The aluminium system forms the basis albeit with much lower Al contents for the development of high specific strength wrought alloys. A binary alloy of 6% Al provides the optimum combination of strength and ductility. Fig. 3shows further development of Mg–Al for die-casting Mg–Al–Mn and for wrought alloys Mg–Al–Zn and for sand casting alloys with Mg–Si, Mg–Al–Ca–(RE). The development of Mg–Li–X is a development of super light alloys. Addition of Li decreases strength but

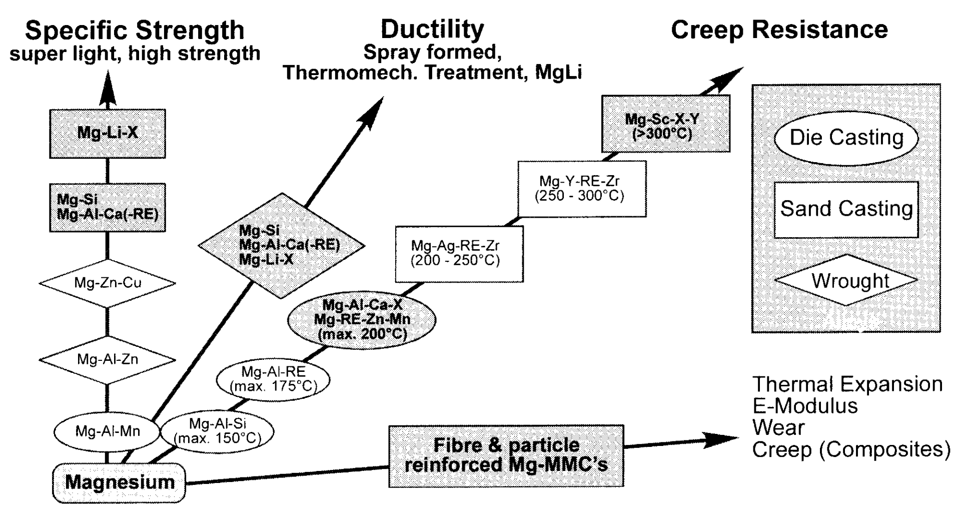


Fig. 3. Directions of alloy development.

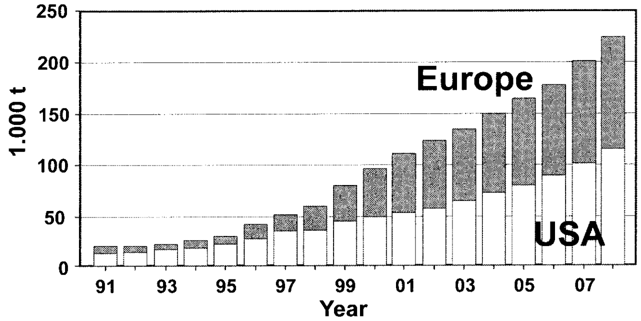


Fig. 4. Increase in pressure die-cast components in USA and Europe from 1991 to1997 [2].

increases ductility. Mg–Li alloys can be aged hardened, although they tend to average at about 60°C. Alloy additions aim at improving the strength and delay overaging. There are numerous applications for high specific strength materials as automobile constructional parts, components and machine tool parts undergoing rapid acceleration and retardation.

4. Ductility

The previous section emphasised the need for improving ductility but concentrated on a combination of high strength with reasonable ductility. There is a need for a series of alloys with very high ductility capable of being formed by thermomechanical treatment. Ductility is determined by the number of operative slip systems. Mg being hexagonal slips at room temperature on the base plane $(0001)\langle 11\bar{2}0\rangle$ and secondary slip on vertical face planes $(10\bar{1}0)$ in the $\langle 11\bar{2}0\rangle$ direction. This limits ductility at low temperatures. At elevated temperatures slip also occurs in the $\langle 11\bar{2}0\rangle$ direction on the $(10\bar{1}1)$ pyramidal planes. This behaviour is influenced by alloying, but as long as the structure remains hexagonal the effect is limited. In addition to the development of new alloys based on Mg–Si and Mg–Al–Ca–(RE) and Mg–Li–X, which offer the possibility of having a phase mixture of bcc and hcp phases, there has been punch work into the development of fine grain material. One such technique, which has been proved successful in the case of aluminium and copper based alloys and steels, is spray forming fine grain material. This has the additional advantage of being homogeneous and can be further worked at high temperatures by forging or extrusion. It was possible to extrude Al–25Si alloys in this state without difficulties [3].

5. Creep resistance

Magnesium melts at 650°C. Consequently, it is to be expected that there will be problems preventing creep in stressed components. Alloys containing Thorium, e.g. HZ22 show at 623K the highest service temperatures of magnesium alloys and, incidentally, compared to melting point, the highest of any material. The radioactivity of thorium has however resulted in its exclusion as an alloying element. There are various upper limits for service requirements, e.g. max. 150°C, 175°C, 200°C etc. as shown in Fig. 3. This problem can be reduced by achieving creep resistance without room temperature strength and ductility at an acceptable price and without making fabrication difficult. The castability (fluidity) of die-casting alloys, for example, is impaired by using rare earth (RE) elements to improve the creep resistance. In all probability some solutions will be found in the paths suggested for the lower temperature applications, otherwise replacing die-casting by other methods, e.g. squeeze casting will be necessary. The development with scandium containing alloys is proving to be successful but despite reducing the amount of scandium required, a dramatic fall in the price of the alloys remain expensive.

6. Fibre and particle reinforced magnesium (MMCs)

Conventional alloying practice can not ensure certain properties and for these fibre and particle reinforcement must be used. The reinforcement material is usually Al_2O_3, SiC or carbon. The aim is to improve the elastic modulus but perhaps also wear resistance or creep-resistance. It is also possible to modify the thermal expansion. Problems arise from the reactivity of magnesium — the reinforcement can be attacked — which can impair the reinforcement. The aim of developments in this area is to identify an appropriate matrix alloy and fabrication procedure.

7. Process development

Although pressure die casting dominates the techniques currently used, magnesium can be produced by virtually all other gravity and pressure casting methods viz. sand, permanent and semi-permanent mould and steel and investment casting. The choice of a particular method depends upon many factors, e.g. the number of castings required, the properties required, dimensions and shape of the part and the castability of the alloy. Nevertheless, there is a need to develop conventional techniques further and also develop new techniques. At present, the use of pressure die cast alloys is increasing rapidly (Fig. 4). Of all casting techniques in 1997, 81% was pressure die cast AZ91D. As a result of alloy development this will be reduced to 67% by 2002. The properties of AM alloys will increase from 19 to 28% and AS21–AE42 from 0.1 to 5%. The advantages of pressure die cast Mg alloys are:

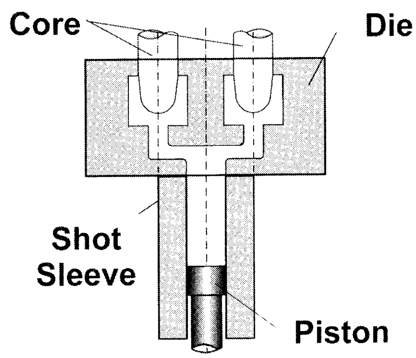


Fig. 5. Principle of indirect squeeze casting.

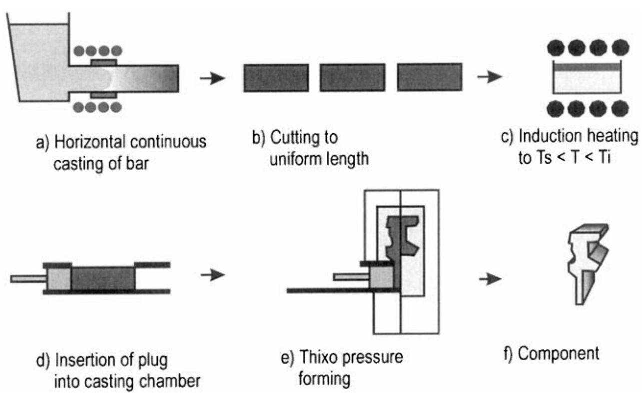


Fig. 6. Principle of thixoforming [4].

- high productivity;
- high precision;
- high quality surface;
- fine cast structure; and
- thin wall and complex structure possible.

In comparison to aluminium:

- 50% higher casting rate;
- can use steel ingots — longer life;
- lower heat content — energy saving;
- good machineability;
- requires 50% of tooling costs; and
- high fluidity of melt.

There are several disadvantages of pressure diecasting Mg alloys:

- entrapped gas pores as a result of high fill-up-rate and thus solidification;
- thick walls castable only to limited degree;
- limited mechanical properties with cheaper die-casting alloys;
- limited range of alloys available;
- poor creep resistance due to fine grain size cast microstructure;
- limited castability (and high cost) of creep resistant Mg–Al–RE alloys;
- heat treatment not possible; and
- unsuitable for welding.

The conventional technologies must be improved such that there is an improvement in the cast microstructure, microstructural homogeneity and process reliability. The problem of porosity in pressure die-casting has been addressed by the development of vacuum pressure die-casting. In addition developments are well advanced with squeeze casting and thixotropic casting. In squeeze casting metal is filled into a steel mould under high pressure but with a much slower flow rate. The indirect form is similar to bottom feeding of an ingot. The feeder system remains attached to the form and ensures full filling of the form (Fig. 5). Squeeze cast components do not show porosity and can be welded and heat-treated. This method is also suitable for thick and thin sections. Further development is however necessary to increase production rates. The principle of thixoforming is illustrated in Fig. 6. A bar is produced by continuous casting such that the structure is microstructurally homogenous and fine grained. It is then cut into billets of uniform length for subsequent insertion into the die-casting chamber. It is then heated inductively to a temperature between the solidus and liquidus to give 'mushy' billet. This is then press formed. The resultant component has a much more uniform microstructure than conventional die cast components and does not suffer from porosity to the same extent. This technique has been researched and investigated for several metals. It is yet to be taken up for magnesium although its feasibility has been demon-

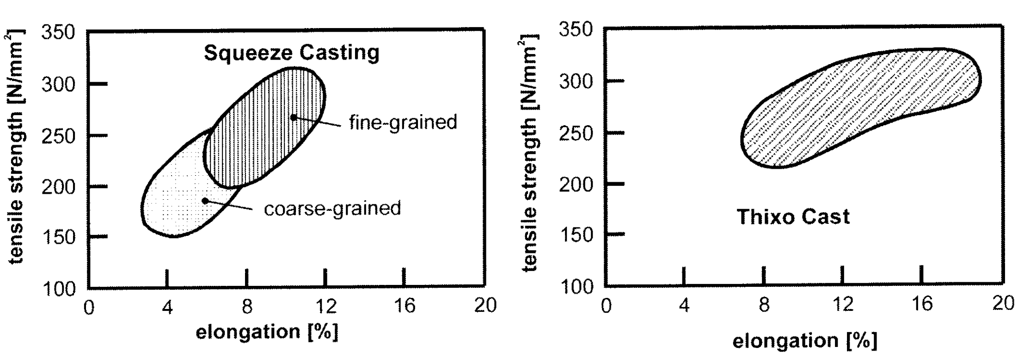


Fig. 7. Relationship between tensile strength — elongation areas for squeeze cast and thixo cast AZ91 T4 material [5].

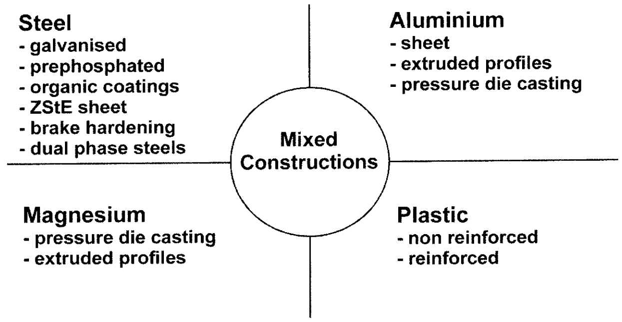


Fig. 8. Material trends in car body building.

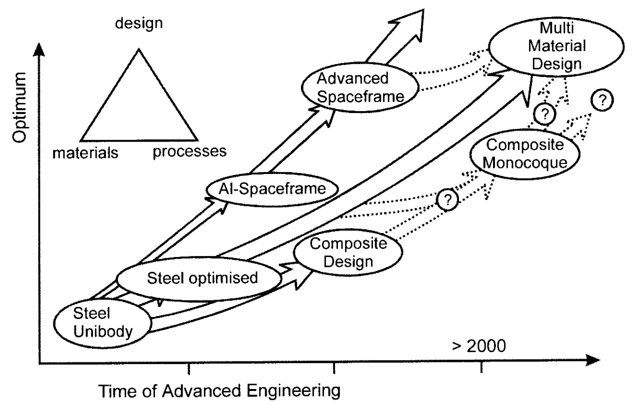


Fig. 9. Development of constructional materials in car manufacturing [6].

strated. Fig. 7 shows a comparison of the tensile strength–elongation areas for coarse grained and fine-grained squeeze cast AZ91 T4 and thixocast AZ91 T4 with elongation.

8. Material trends in car body manufacturing

The development of new production techniques, e.g. laser technology and the development of new materials, steels, aluminium, magnesium and plastics is influencing the ways cars are made and the materials used. Fig. 8 shows this diagrammatically. The development of constructive method is shown in Fig. 9. The diagram illustrates actual and possible developments starting from the steel unibody of the 1950's. In the drive to reduce the exhaust emissions it is necessary to reduce the weight of the car, improve design streamlining and improve engine efficiency. Other demands on car designers include power and comfort, air comfort, reduced noise vibration as well as improved safety, environmental protection, and corrosion protection result. This will result in an actual increase in weight as shown in Fig. 10.

The impact of fuel savings (Fig. 11) by minimising weight increases and improving running efficiency can be demonstrated by a simple calculation. Assuming new registrations in Germany in 1997 offer 5% fuel savings over previous models and have an average consumption of 8.5l/100 km an average mileage of 20 000 km, this means a fuel saving of 300 000 000 l per annum. The impact on the environment is self-evident. The introduction of sulphur-free petrol will completely eliminate sulphur dioxide pollution, which at present is not removed by catalytic converters.

Long-term benefits can only be achieved by consistent basic research. Table 1 shows where saving in fuel consumption can be achieved and the relative importance of innovative materials, not only magnesium alloys.

The possible contribution of magnesium is shown in Table 2. The application is indicated together with the development/improvement necessary.

Previous studies [9] on the development of creep-resistant magnesium alloys have resulted in formulation of rules of selection for alloying elements. The low melting point of magnesium sets a natural limit to the

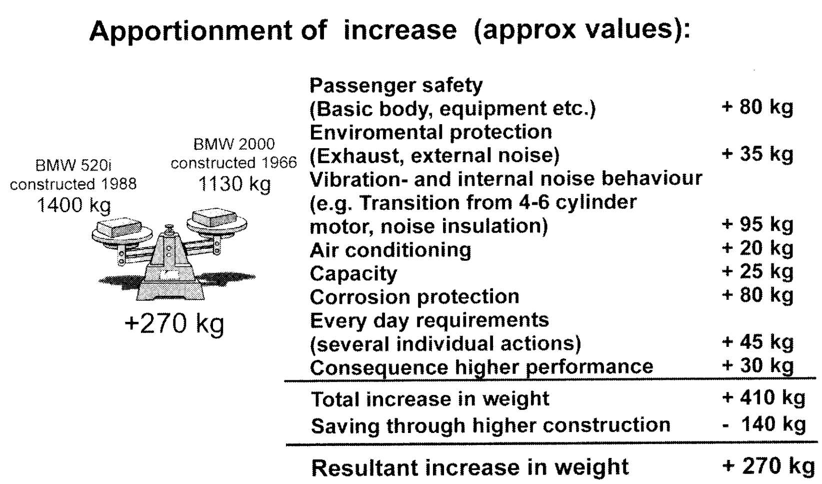


Fig. 10. Increase in vehicle weight as a result of increased requirements [7].

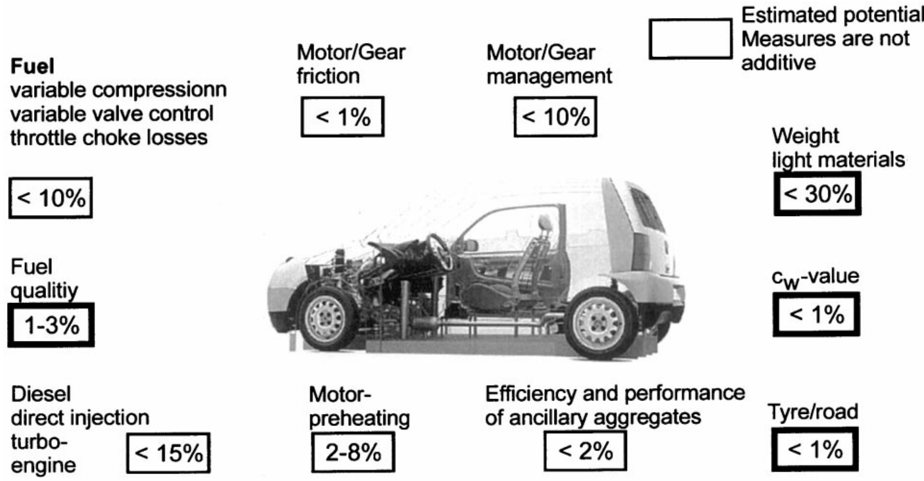


Fig. 11. Effect of technical measures on the CO_2 emission [7].

Table 1
Saving in fuel consumption[8]

Measure taken	Potential saving (%) fuel		Importance of innovative materials
	Short/medium term	Long term	
Light constructions	3–5	10–15	++
C_w value	2	4–6	+
Motor/gear control	5	10	±
Resistance to rolling	1–2	3	+
Motor preheating	2	4–6	±
Equipment	2	4	±

Table 2
Development trends and main focus for magnesium materials in car bodies[8]

Innovation	Application	Development
Fibre and particle reinforcement	Structural elements	Material dimensioning
Pressure die-casting	Supporting elements, additional components	Fatigue strength, tolerance on size
Squeeze casting, thixoforming	Support columns, module supports	Component size, material development, process parameters
Extrusion	Structural elements, frame profiles	Deformation behaviour, material development, production processes
Gluing	Structural elements	Boundary reactions, surface treatment
Mg sheet	Roof elements	Surface quality, deformation behaviour, production processes

operating temperature. Consequently, if magnesium is to remain competitive with aluminium alloys it is necessary to raise the operating temperature by alloying techniques. The search for suitable alloying elements is based on the following premises. The alloying elements should show sufficient solubility in magnesium at high temperatures, which decreases with decreasing temperature so that age hardening becomes possible through precipitation from the supersaturated solution. The precipitates should contain a high magnesium content thereby increasing the volume fraction of precipitated phase thus reducing the required amount of alloying element. Several alloying additives should be used to increase the number of precipitates and by forming complex precipitates improve the properties of the precipitate. Elements should exhibit a low rate of diffusion in magnesium and thus reduce the tendency to overageing and dislocation climb. Rare-earth metals are partic-

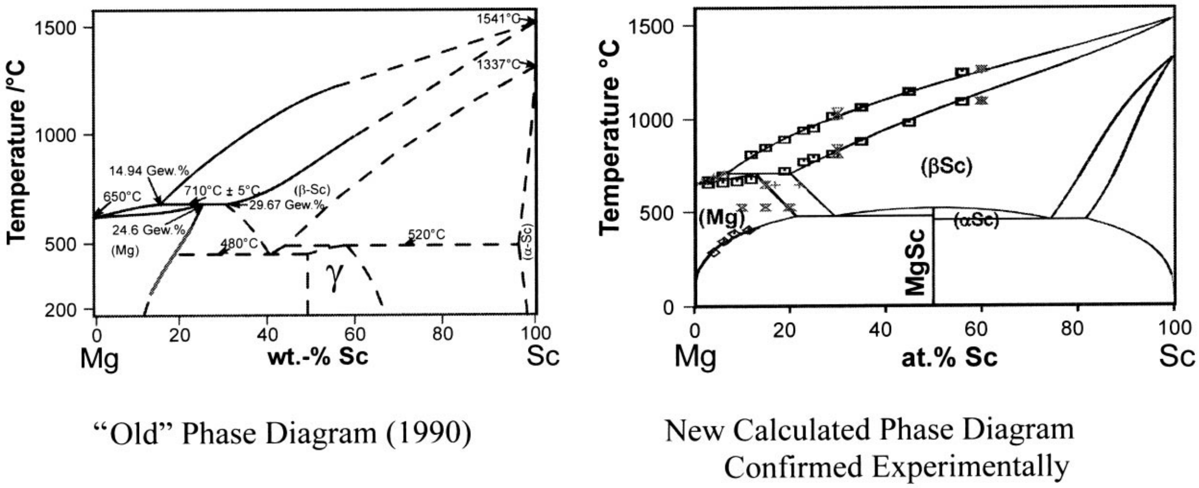


Fig. 12. Old and new phase diagram of Mg–Sc system [10,11].

ularly suitable. The elements Sc, Y, La and the lathanides as well as Nd, Tb, Er, Dy and Gd, with Zr as grain refiner, form the basis for the development of creepresistant alloys. The WE series with Y, Nd additions are in service up to 300°C but could not reach the operating temperatures of Mg–Th alloys. In an attempt to achieve this scandium was chosen. The interesting feature of alloying with scandium is the increase in the melting point of the solid solution. The high melting point of scandium compared with other rare earth indicates a lower diffusivity in magnesium. The density of scandium (3 g cm^{-3}) is lower than alternative alloying elements. Alloying with other elements such as Y, Nd, La and Ce could improve the room and high temperature properties, reduce the solubility of scandium in magnesium and form complex compounds. Initial work on the binary Mg–Sc system showed that the phase diagram was not correct. It was not possible to carry out a proper solution and ageing treatment. The composition of the alloys had been chosen as MgSc12 and MgSc16 based on the presumed phase diagram. The phase diagram was calculated and verified experimentally in Clausthal and Charles University, Prague [10,11]. Fig. 12 shows the old and new phase diagram. It was decided to add Mn and reduce the amount of scandium in an attempt to produce an age hardenable alloy. Fig. 13 shows the calculated isothermal isoplethe sections.

The use of calculated phase diagrams is essential to save material and time to focus on optimisation of more promising systems. Fig. 14 shows creep curves of various magnesium–scandium alloys together with that for WE43 T6. These curves were measured at 350°C and at stress of 30 MPa. It can be seen that the creep resistance of magnesium–scandium–manganese alloys is two orders of magnitude less than WE43 at 350°C. At the accepted upper limit of 300°C for WE54 Mg–Sc alloys can be loaded more or employed at the same load operating at temperatures of 50°C or higher. This approach of combining theoretical predictions

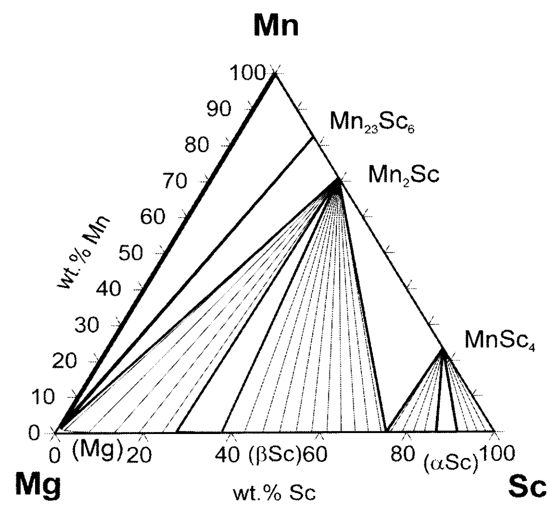


Fig. 13. Calculated isothermal section of ternary system Mg–Sc–Mn [10].

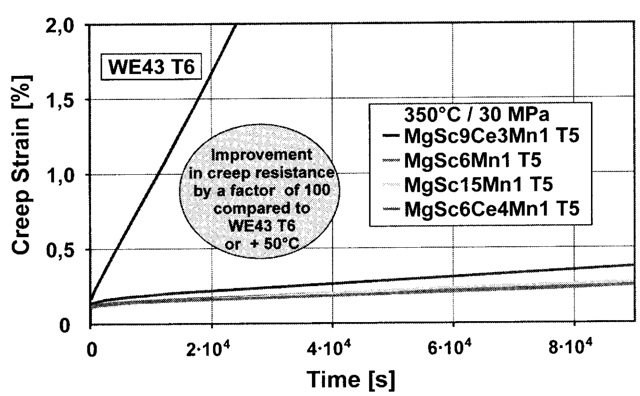
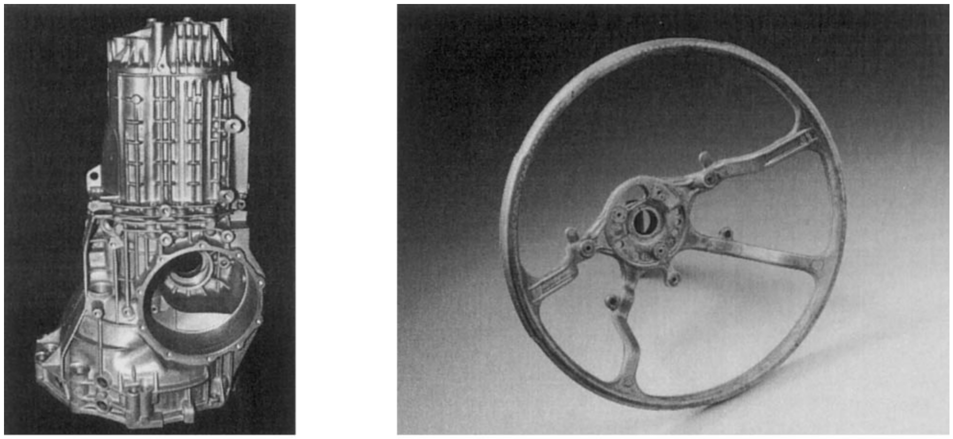
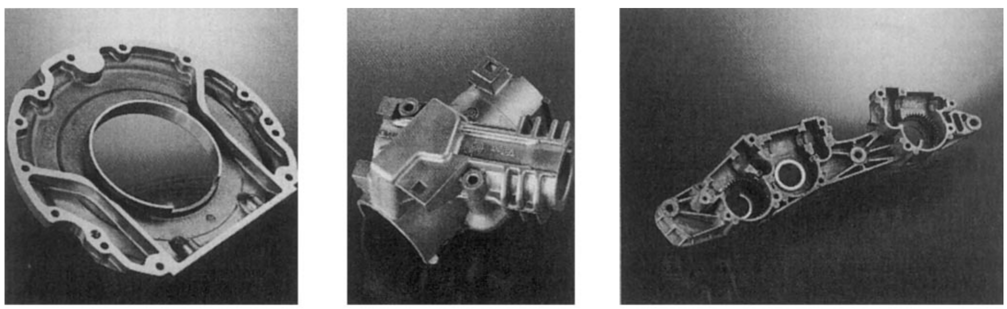


Fig. 14. Creep curves of new developed Mg alloys [12].



Gear Box Housing Steering Wheel Frame

Fig. 15. Various Mg automobile parts (Volkswagen AG).



Sealing Flange Steering Column Lock Housing Gear Box – Seat Movement

Fig. 16. Further Mg parts in automobiles (UNITECH).

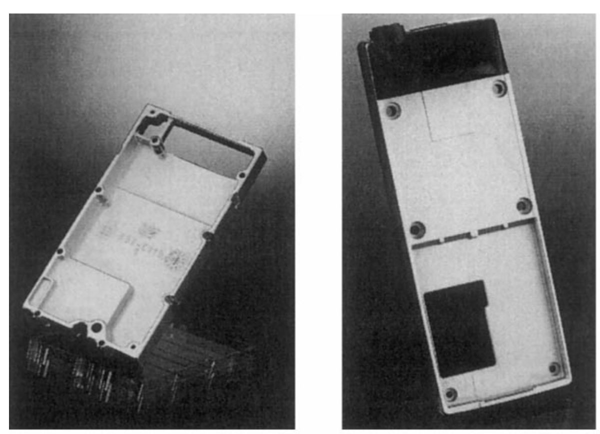
with experience-based selection has been particularly fruitful and is being adopted in the development of other alloys.

9. Applications of magnesium alloys

The use of magnesium alloys in the European automobile industry encompasses parts such as steering wheels, steering column parts, instrument panels, seats, gear boxes, air intake systems, stretcher, gearbox housings, tank covers etc. Some are illustrated in Figs. 15 and 16.

10. Non-automotive applications

Magnesium based alloys have been used for numerous applications in hobby equipment e.g. bicycle frames. Interesting applications in communication engineering are shown in Fig. 17. In this case, light weight



Screen Housing Units For Mobile Handset

Fig. 17. Mg parts used in communication engineering (UNITECH).

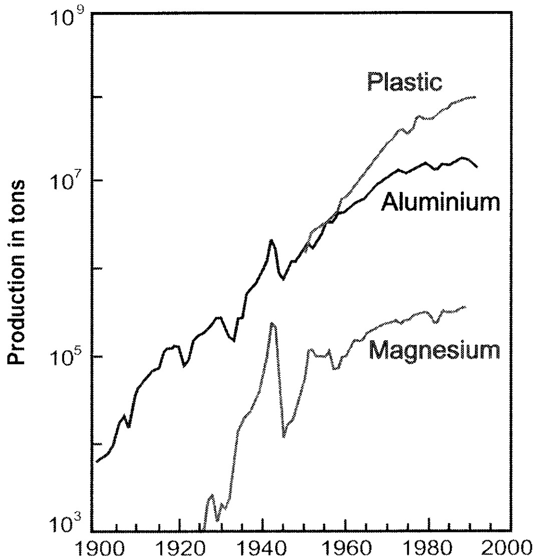


Fig. 18. Production of high strength structural materials in the 20th century.

is required as well as screening against electro–magnetic radiation which plastic materials cannot offer.

11. Outlook

The major driving force for development is the automobile industry. Although some interesting developments have been realised for space, aircraft and other applications we have seen successful applications in automobile industry components such as steering wheels, steering column parts, instrument panels, seats, gearboxes and air intake systems. Future developments will include large body parts, cylinder blocks, door frames and petrol tank covers. Over the period 1998–2000, the increase in die cast components will have been 15–20% and is expected to be a further 10% from 2001 to 2007. Fig. 18 shows a similar development of other light materials, which are competitors for Mg in some applications. As can be seen the use of magnesium is predicted to rise at a similar rate to that of other metals well into the new century. This presumes continued investment in research and development.

Acknowledgements

The author would like to thank members of the Institute of Materials Engineering and Technology at the Technical University Clausthal for discussions and support.

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