UDC 669.721.5:621.86.05

# NEW MAGNESIUM ALLOYS FOR TRANSMISSION PARTS

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Translated from *Metallovedenie i Termicheskaya Obrabotka Metallov*, No. 11, pp. 10 – 18, November, 2006.

Metallurgical aspects of the development of new magnesium alloys for the production of transmission parts and assemblies with the use of sand mold casting, chill casting, and high-pressure die casting are considered. The approach suggested has been used for creating new alloys with elevated creep resistance. The properties of the alloys are presented and compared with the properties of known commercial magnesium alloys.

## INTRODUCTION

Magnesium alloys have the lowest density of all commercial alloys and this makes them attractive for the automotive industry. The use of such alloys for transmission parts not only reduces considerably the total mass of a car but also makes it possible to change considerably the balance of the car, primarily due to lowering the mass of the front part, which improves the dynamics of the car. It is expedient to use magnesium alloys in the production of cars in such transmission parts and assemblies as the housing, the oil pan, the transfer box, the crankcase, the oil pump casing, the starter, the intake manifold, etc. All these parts operate at elevated temperatures and therefore should have an elevated creep resistance and high strength of bolted joints under load for normal operation. Unfortunately, the conventional alloys of the Mg – Al – Zn and Mg – Al – Mn systems are inapplicable for the production of transmission parts operating at a temperature exceeding 130°C [1 – 3].

When various casing parts are produced from conventional magnesium alloys, their insufficiently high creep resistance can lead to an abrupt decrease in the strength of all bolted joints, which causes weakening of the contact between the casing and the bearing insert. This results in oil leakages and enhancement of noise and vibrations.

The veteran magnesium alloys AS21 and AS41 developed in the 1970s and the AS42 alloy created in the late 1980s had an elevated creep resistance but did not meet the requirements on transmission parts due to the poor casting properties, low corrosion resistance, and insufficiently high ultimate rupture strength and fatigue limit [4, 5].

Most transmission parts of ordinary cars are mass-produced by pressure die casting. Thus the cost of the alloy is dominant in the cost of the ready part. This makes the cost of the alloy a decisive factor in the development of new compositions; the alloy should be competitive with respect to the known commercial magnesium and aluminum alloys where the cost is concerned. Moreover, the method of pressure die casting is not recommended in the production of especially large and heavy parts such as the cylinder block. As a rule, such parts are produced by sand casting or casting into metal molds as well as sand and chill casting under low pressure. In these cases the decisive factor is the process of fabrication of the part, and the cost of the part is not treated as the main parameter.

The aim of the present work consisted in developing new magnesium alloys with high creep resistance for the production of automotive transmission parts with the use of sand mold casting, chill casting, and pressure die casting.

## RESULTS AND DISCUSSION

### Metallurgical Considerations for Choosing the Composition for Magnesium Alloys with High Creep Resistance

***Alloys for high-pressure die casting.*** The requirement of acceptable cost and appropriate casting properties of the new alloy restrict the choice of alloying elements for systems containing Al or Zn as the main alloying elements, low amounts of Mn, Si, Ca, and Sr, and a Ce-base mish metal.

When developing magnesium alloys for high-pressure die casting it is desirable to alloy them with aluminum in order to ensure good casting properties. Consequently, the alloy should contain a sufficient amount of aluminum before hardening. However, the presence of aluminum causes formation of a $Mg_{17}Al_{12}$ eutectic intermetallic (β-phase) that lowers the creep resistance. Thus, in order to eliminate the formation of β-phase an alloy of the Mg – Al system should

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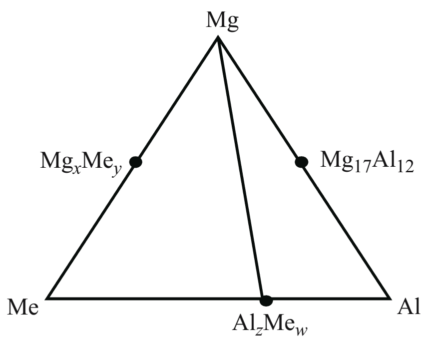


**Fig. 1.** Hypothetical ternary diagram of the Mg – Al – Me system.

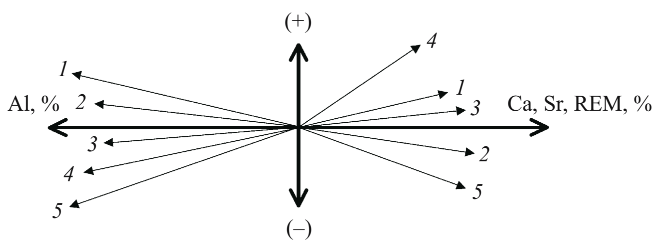


**Fig. 2.** Diagram reflecting the effect of Al, Ca, Sr, and REM on the properties and cost of magnesium alloys for high-pressure die casting: *1* ) strength at room temperature; *2* ) casting properties; *3* ) cost; *4* ) creep resistance; *5* ) ductility, impact toughness.

contain elements that would interact with aluminum forming specific intermetallics.

Let us consider a hypothetical ternary diagram for the Mg – Al – Me system (Me is the third element) and assume that three intermetallic compounds, i.e., $Mg_{17}Al_{12}$, $Mg_xMe_y$, and $Al_zMe_w$ can form in this system (Fig. 1). In order to suppress the eutectic reaction of formation of β-phase ($Mg_{17}Al_{12}$) the element Me should react with aluminum and form an $Al_zMe_w$ intermetallic. In this case the pseudobinary Mg – $Al_zMe_w$ region of the diagram will be active only if the affinity of the element Me for Al is higher than its affinity for Mg; then the formation of $Al_zMe_w$ will be preferred to $Mg_xMe_y$. Analyzing the known diagrams of binary Mg – Me and Mg – Al systems [6] we will see that only rare-earth metals (REM), alkaline-earth elements, and transition elements of the third group of the Periodic System possess such an affinity.

Another way for preventing the appearance of β-phase consists is reducing the content of aluminum to a relatively low value and simultaneously introducing elements possessing a high affinity for magnesium and capable of forming stable phases that hinder grain slip. Such an approach has been used for creating alloys AS21, AS21X, and AS41 [4, 7], in which the formation of a $Mg_2Si$ intermetallic promotes growth in the creep resistance as compared with the same characteristic of the AZ and AM alloys, and for developing an MEZ alloy [8] based on the Mg – Mn – REM system and bearing no aluminum.

Alternative variants for creating new alloys with high creep resistance are based on the idea of suppressing the formation of β-phase in alloys bearing 5 – 9% Al. The task has been solved by alloying the metal with alkaline-earth elements and REM, which bond the excess aluminum into stable intermetallics. As a result, several new alloys for high-pressure die casting that possess enhanced creep resistance have been obtained in the last 10 years. The goal consisted in ensuring an acceptable combination of service parameters, casting properties, and cost [9 – 12]. Unfortunately, such a goal is hard to achieve and most of the alloys mentioned meet the requirements on the properties and service characteristics of transmission parts only partially.

All the new alloys for high-pressure die casting contain Ca, Sr, and REM individually or in different combinations. The final cost of the new alloys depends on the concentration of the alloying elements and on their cost. As a mater of fact, the introduction of these elements in a specific proportion can improve some properties of the alloys and worsen other ones.

Figure 2 presents a diagram of the effect of aluminum and alloying elements on the casting and mechanical properties and on the cost of magnesium-base alloys designed for high-pressure die casting. It can be seen that growth in the content of aluminum in magnesium alloys improves the casting properties and increases the ultimate rupture strength, the compressive strength, and the fatigue limit. At the same time, such properties as the creep resistance, ductility, and impact toughness decrease noticeably. Alloying with aluminum virtually does not affect the cost of the alloy. On the contrary, alloying with alkaline-earth elements (Ca, Sr) and with a mish metal based on REM worsens the casting properties and lowers the ductility and the impact toughness, but the cost of the alloy increases. The positive effect of such alloying is mostly connected with considerable growth in the creep strength and some increase in the strength at room temperature.

The atomic weight of Ca is twice lower than that of Sr and thrice lower than that of REM. Consequently, in order to obtain one and the same volume fraction of the second phase we should add much less Ca than Sr and REM (Table 1).

Thus, at an equal volume fraction Ca provides the highest (as compared to Sr and REM-base mish metal) growth in the ultimate rupture strength, in the compressive strength, and especially in the creep resistance. Being a relatively cheap element, calcium improves the properties to a maximum degree and is optimum with respect to the cost. However, it should be noted that when contained in an amount exceeding 0.3%, calcium worsens the casting properties and decreases the ductility of magnesium alloys. Thus, the creation of new magnesium alloys involves determining the optimum proportion of components (Al, Ca, Sr, REM) ensuring the best service properties at a reasonable cost.

***Alloys for sand and chill casting.*** All magnesium alloys with high creep resistance used for sand casting and chill

**TABLE 1.** Effect of Calcium, Strontium, and REM on the Formation of Intermetallics [13]

| Element | Expected compounds | ρ, tons/$m^3$ | $Q_{rel}$ |
|---|---|---|---|
| Ca | $Al_2Ca$ | 2.35 | 1/1 |
| Sr | $Al_2Sr$ | 2.98 | 2.2/1.8 |
| | $Al_4Sr$ | 2.85 | 1.1/1.1 |
| REM | $Al_{11}REM_3$ | 4.02 | 1.90/2.35 |
| | $Al_2REM$ | 4.95 | 3.50/3.55 |

**Notations:** ρ) density; $Q_{rel}$) relative amount of alloying element required for bonding an equal amount of aluminum (calculated in terms of the relative mass fractions of the elements in the numerators and in terms of the relative volume fractions in the denominators).

casting are alloyed with zirconium and hence do not contain aluminum. Zirconium is a unique refiner of grains in magnesium. It also increases the corrosion resistance and contributes to the prevention of porosity in the castings [14, 15]. Zirconium can work as a powerful refining additive only under the condition that the melt has been saturated with this metal at a temperature of 750 – 780°C. This regime causes strong oxidation of the surface of the melt and losses in magnesium and expensive alloying elements (Y, Gd, Dy, Yb, Nd, etc.). Moreover, modern commercial technologies commonly involve one heat in a crucible designed for 300 – 400 kg of metal. The economic efficiency of the process is relatively low, because a considerable amount of metal should be left in the crucible in order to avoid penetration of nonmetallic inclusions and excess zirconium compounds into the final casting. Thus, the conventional process and the use of relatively expensive alloying elements make the sand cast and chill cast commercial alloys with high creep resistance relatively expensive (both ingots and ready castings). These alloys are chiefly used for fabricating parts with complex geometry and high operating properties for the aerospace industry and exclusive and racing cars, when the required operating properties are of primary importance and cost is secondary.

The principles of creation of alloys sand cast and chill cast under high pressure differ considerably. The main mechanisms determining the properties of alloys cast under high pressure are the hardening of the solid solution created by specially chosen alloying elements and hardening of the grain boundaries as a result of rapid cooling during the hardening. Stable eutectic intermetallics in the form of rather coarse segregations form in the cooling process. The main mechanisms affecting the creep resistance of alloys cast into sand and metal molds are precipitation hardening and strengthening of grain boundaries. Thus, design of magnesium alloys with a high creep resistance cast into sand and metal molds and subjected to heat treatment in mode T6 should be performed with allowance for the following alloying principles and rules. The main alloying elements should have a high range of solubility in magnesium in solid state and this range should be narrowed markedly upon a decrease in the temperature to the room value. This feature determines the effective capacity of the alloys for aging. Data on the solubility ranges of binary magnesium alloys are presented in [4, 6].

The dissolved atoms should have a low diffusivity in the matrix in order to form interatomic bonds and a solid solution that will not age under conditions differing from the operating ones. In order to ensure high properties of the alloy at elevated temperatures the alloying elements should form thermally stable intermetallics that are coherently bonded with the matrix, reinforce the grain boundaries, and efficiently resist strain. The melting temperature of such compounds is a good indicator of their thermal stability.

The first nucleating particles are usually unstable and coherently bonded with the matrix and ensure effective occurrence of precipitation hardening. In the course of the aging process the metastable phases transform into stable equilibrium ones. Their morphology is a determining factor that affects both the strength and the creep resistance. Basing ourselves on the data of [4, 6] and taking into account the availability and the commercial attraction of alloying elements, we can consider some of them (for example, Nd, Ce-base mish metal, Y, Gd, and Ca) as expedient for the development of new alloys. A cerium-base mish metal is the least expensive alloying alternative. However, it cannot promote active aging due to the very limited solubility of cerium and especially of lanthanum in solid magnesium. Neodymium seems to be the chief alloying element of the mentioned four due to the optimum combination of its wide solubility range in solid magnesium, availability, and cost. Yttrium and especially gadolinium possess the highest solubility in magnesium. However, they are relatively expensive. In addition, Gd has a high atomic weight, which means that its mass fraction should be higher than that of Y and Nd at the same atomic fraction.

The content of zinc should be reduced to 0.3 – 0.8%, because it interacts with REM and yttrium forming eutectic intermetallics and thus neutralizing the contribution of REM and Y to the process of precipitation hardening.

We have already mentioned that the refinement of grains is a very important factor in the development of sand cast and chill cast alloys. It is well known that when added to magnesium zirconium promotes considerable refinement of grains and thus lowers the porosity of the castings [14, 15]. Alloys of the Mg – Zr system have better density in thin and thick sections and are insusceptible to through porosity of the walls, which can be a cause of leakage of lubrication, for example. A low amount of dissolved zirconium is primarily responsible for the small grain size typical for zirconium-bearing alloys [14 – 16].

As compared to alloys of the Mg – Al system, all Mg – Zr alloys have a high purity. This is connected with the high natural reaction capacity of zirconium, which ensures its interaction with all impurities commonly encountered in

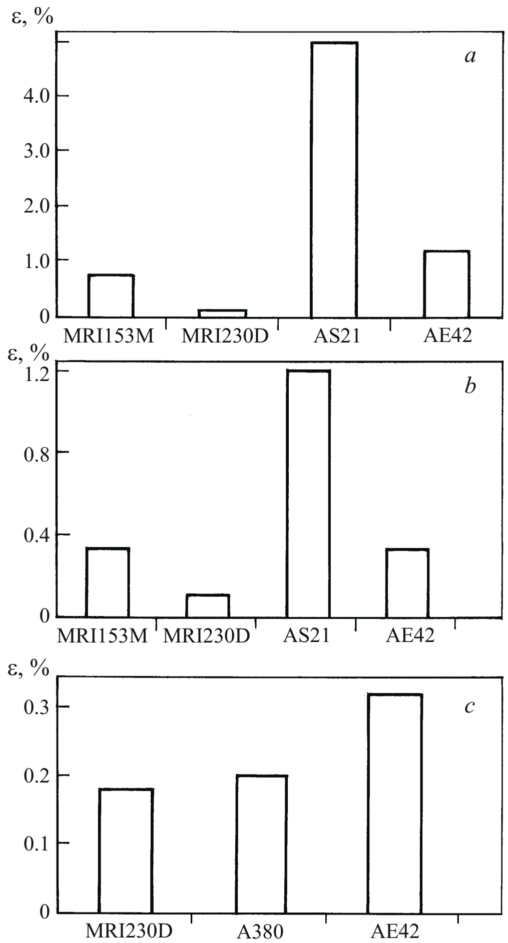


**Fig. 3.** Creep strain ε of magnesium alloys MEI153M and MRI230D, commercial alloys AS21 and AE42, and aluminum alloy A380. The test for creep strength lasted for 200 h: *a*) at a temperature $t = 135°C$ and a stress $\sigma = 100$ MPa; *b* ) $t = 150°C$, $\sigma = 70$ MPa; *c*) $t = 175°C$, $\sigma = 70$ MPa.

molten magnesium alloys and segregation of the formed compounds in the form of disperse particles. Such compounds precipitate prior to zirconium dissolution in molten magnesium (the maximum solubility of zirconium in molten magnesium is 0.6%). This makes it possible to keep the content of impurities (Si, Cu, Fe, and Ni) at a level lower than 50 ppm, commonly within 10 – 20 ppm.

Such elements as Zn, Y, Ag, and REM (La, Ce, Pr, and Nd), which are compatible with zirconium, are the most suitable for practical use.

Heat treatment is very important for ensuring the required combination of operating characteristics. The mode of heat treatment should be chosen so as to obtain the required mechanical properties at commercially acceptable duration of the hold during the treatment for solid solution and especially during aging. Treatment for solid solution should be performed at the highest practically possible temperature for dissolution of coarse inclusions of the eutectic intermetallic compounds formed in the casting process. In actual practice the treatment for solid solution is conducted at a temperature 20 – 30°C lower than the solidus temperature of the given alloy. The greatest difficulties are commonly connected with the choice of the temperature and the duration of aging, because these parameters determine the properties of ready products to a considerable degree.

Correctly chosen alloying elements can ensure good casting properties of magnesium alloys (enhanced flow, low susceptibility to cracking, reduced porosity, and improved denseness of the castings) in combination with elevated corrosion resistance and acceptable cost. In fact, the creation of a new alloy is always a compromise between the wanted operating characteristics and the cost. Thus, the main task is reduced to determining the optimum combination of the factors mentioned.

## Results of Development of Magnesium Alloys with High Creep Resistance

Dead Sea Magnesium (DSM) Ltd. has worked on creation of new magnesium alloys with elevated creep resistance for sand mold casting and pressure die casting. The results of these works are presented below.

***Alloys for high-pressure die casting.*** We have already mentioned that it is very difficult to create a new alloy for high-pressure die casting that would have an adequate combination of casting properties, creep resistance, mechanical properties at room temperature, and corrosion resistance simultaneously meeting the high requirements of the automotive industry to transmission parts. In order to ensure the required characteristics DSM and Volkswagen AG have launched a joint program on development of new inexpensive magnesium alloys with high creep resistance for high-pressure die casting. Two such alloys, i.e., MRI153M and MRI230D, have been created as a result of the joint venture [13, 17 – 21]. MRI53M is an inexpensive alloy without beryllium and with a high creep resistance. The parts produced from this alloy serve at a temperature of up to 150°C for a long time under high pressure. The casting properties of alloy MRI153M are similar to those of alloy AZ91D. This has been confirmed by experimental high-pressure die casting of complex-configuration castings for transmission housing, oil pans, bearing plates, oil pumps, and other parts.

The properties of alloy MRI153M and, for comparison, of commercial alloys AZ91, AE42, and AS21used for pressure die casting are presented in Table 2 and in Fig. 3. It can be seen that the corrosion resistance and the mechanical properties of alloy MRI153M correspond to (or even exceed) those of commercial AZ91D and the other compared alloys.

The creep resistance of alloy MRI153M at $t = 100$ – 150°C and $\sigma = 50$ – 110 MPa is also much higher than that of commercial alloys. These results show that alloy MRI153 can be recommended for fabricating such parts as transmission housing, oil pump, valve cup, inlet manifold, etc.

Alloy MRI230D was designed for high-pressure die casting of such car parts as cylinder blocks operating at a tempe-

**TABLE 2.** Mechanical and Corrosion Properties of Alloys MRI153M and MRI230D and of Commercial Alloys

| Alloy | $t_{test}$, °C | $\sigma_{0.2}$, MPa | $\sigma_r$, MPa | δ, % | $\sigma^c_{0.2}$, MPa | $A_i$, J | $\sigma_{-1}$, MPa | $v_{cor}$, mg/cm$^2$/day |
|---|---|---|---|---|---|---|---|---|
| MRI153M | 20 | 170 | 250 | 6 | 170 | 8 | 120 | 0.09 |
| | 150 | 135 | 190 | 17 | 135 | – | – | – |
| MRI230D | 20 | 180 | 235 | 5 | 180 | 6 | 110 | 0.10 |
| | 150 | 150 | 205 | 16 | 150 | – | – | – |
| AZ91D | 20 | 160 | 260 | 6 | 160 | 8 | 100 | 0.11 |
| | 150 | 105 | 160 | 18 | 105 | – | – | – |
| AE42 | 20 | 135 | 240 | 12 | 115 | 12 | 80 | 0.12 |
| | 150 | 100 | 160 | 22 | 85 | – | – | – |
| AS21 | 20 | 125 | 230 | 16 | 110 | 14 | 75 | 0.34 |
| | 150 | 87 | 120 | 27 | 80 | – | – | – |

**Notations:** $t_{test}$) test temperature; $\sigma^c_{0.2}$) ultimate compressive strength; $A_i$) impact energy, $\sigma_{-1}$) fatigue limit (the tests were performed by rotating a bent specimen for $5 \times 10^7$ cycles); $v_{cor}$) corrosion rate (the tests were performed in salt vapor for 200 h in accordance with B-117 ASTM).

rature exceeding 190°C. The alloy possesses a high creep resistance combined with good casting properties, high strength, and very high corrosion resistance. The typical properties of alloy MRI230D and, for comparison, of commercial magnesium alloys and of aluminum alloy A380 are presented in Table 2 and in Fig. 3. These data show that alloys MRI230D and A380 have close values of creep resistance at $t = 150 - 175$°C and $\sigma = 70$ MPa.

These results promise widening of the range of application of MRI alloys and confirm that their characteristics meet the requirements on various car parts.

***Alloys for sand mold and chill casting.*** The Magnesium Electron Company developed alloys WE43 and WE54 in the 1980s and since that time few works have been devoted to the creation of new alloys for sand and chill casting [15, 24]. The alloys have a favorable combination of creep and corrosion resistances and are assumed to be the best high-temperature magnesium alloys where operating characteristics are concerned. However, the exceptionally high cost of alloys of the WE series and some problems arising in working with molten metal limit their use. Today most of the parts cast into sand molds are produced from alloy ZE41 [14, 25] that has lower characteristics of strength and creep resistance and good casting properties. Though the corrosion resistance of this alloy is low (especially in marine water) it is widely used for parts of helicopter transmission.

The unhappy combination of high operating properties and exceptionally high cost of alloy WE43 and of the moderate cost but low creep and corrosion resistances of alloy ZE41 became especially obvious in the last three years. The situation stimulated design of high-temperature magnesium alloys for sand mold and chill casting [22, 26]. The many-sided research performed at the Dead Sea Magnesium and Volkswagen AG resulted in the creation of three alloys with high creep resistance named MRI201S, MRI202S, and NRI206S [22]. All the three alloys can be sand and chill cast or be an alternative for low-pressure sand mold casting. The alloys are recommended for use only after heat treatment by mode T6, which makes it possible to implement all the advantages of the mechanism of precipitation hardening and ensures an optimum combination of strength, ductility, and creep resistance. Typical mechanical properties of the new MRI alloys at room and elevated temperatures are presented in Table 3 in comparison with the properties of alloys WE43, ZE41, and EZ33. It can be seen that alloy MRI201S-T6 has the same combination of properties as alloy WE43-T6. Thus, analyzing the chemical composition of these alloys we can state that MRI201S is a less expensive alternative to alloy WE43. MRI202S possesses high creep and corrosion resistances at a moderate strength. The characteristics of creep and corrosion resistances of this alloy under operating conditions exceed those of all commonly used sand cast alloys except for WE43 and WE54.

Sand cast and chill cast alloy MRI206S does not have a high strength but possesses an elevated ductility; the level of its creep and corrosion resistances is similar to those of alloys EZ33 and ZE41. Since the cost of production of alloy MRI206S is close to those of ZE41A and EZ33, it can be recommended for replacing EZ33 and ZE41A.

All MRI alloys preserve high strength at a temperature of up to 250°C (maximum test temperature). On the contrary, the strength of aluminum alloy A319-T6 (with segregated fine particles of $AlSi_6Cu_{3.5}$) commonly used for transmission housings produced by sand mold casting or chill casting deteriorates considerably at a temperature exceeding 150°C [23]. It can be seen from the data of Fig. 4 that all the new MRI alloys are superior to alloy A319 with respect to the creep strength at 150 – 200°C.

Characteristics important for transmission parts include not only creep resistance but also relaxation effects that may

**TABLE 3.** Typical Properties of MRI Alloys and Commercial Alloys

| Alloy | $t_{test}$,°C | $\sigma_{0.2}$, MPa | $\sigma_r$, MPa | δ, % | $\sigma^c_{0.2}$, MPa | $\sigma_{-1}$, MPa | $v_{cor}$, mg/cm$^2$/day | Creep test | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | $t_{test}$, °C | $\sigma^t_{0.2/200}$ |
| MRI201S-T6 | 20 | 185 | 265 | 6 | 190 | 110 | 0.10 | 185 | 185 |
| | 150 | 180 | 250 | 11 | 190 | – | – | 200 | 170 |
| | 175 | 175 | 245 | 12 | 185 | – | – | 250 | 75 |
| MRI202S-T6 | 20 | 165 | 270 | 9 | 145 | 95 | 0.12 | 175 | 155 |
| | 150 | 160 | 245 | 15 | 140 | – | – | 200 | 120 |
| | 175 | 155 | 230 | 16 | 135 | – | – | 250 | 40 |
| MRI206S-T6 | 20 | 125 | 225 | 12 | 130 | – | 0.14 | 175 | 120 |
| | 150 | 120 | 195 | 18 | 125 | – | – | 200 | 110 |
| | 175 | 115 | 180 | 21 | 120 | – | – | 250 | 35 |
| WE43-T6 | 20 | 180 | 260 | 6 | 190 | 100 | 0.10 | 175 | 190 |
| | 150 | 178 | 210 | 7 | 185 | – | – | 200 | 160 |
| | 175 | 175 | 205 | 11 | 185 | – | – | 250 | 60 |
| ZE41-T5 | 20 | 140 | 220 | 5 | 140 | 95 | 3.10 | 175 | 70 |
| | 150 | 120 | 170 | 22 | 115 | – | – | 200 | 50 |
| | 175 | 110 | 150 | 25 | 110 | – | – | 250 | 20 |
| EZ33-T5 | 20 | 100 | 165 | 3 | 97 | – | 1.40 | 175 | 75 |
| | 150 | 95 | 150 | 9 | 95 | – | – | 200 | 65 |
| | 175 | 89 | 140 | 16 | 90 | – | – | 250 | 27 |

**Notations:** $\sigma^t_{0.2/200}$) stress ensuring creep strain of 0.2% after 100-h testing at $\sigma$ = 70 MPa at various temperatures. Other notations are as in Table 2.

arise under compressive stresses especially in zones of bolted joints. The data of Table 4 illustrate the results of loading tests of bolted joints of MRI alloys at 175 and 200°C at an initial load $\sigma_0$ = 70 MPa. The ratio of the final test load after cooling to room temperature ($\sigma_f$) to the initial load at room temperature ($\sigma_0$) was chosen as a measure of preservation of load in the zone of bolted joint. For comparison we present in Table 4 the results of tests of bolted joints from alloys A380 (for high-pressure die casting) and A319 (for chill casting). It can be seen from the data of the table that the new alloys are superior to aluminum alloys with respect to the parameter of preservation of load in bolted joints.

The operating experience of alloy WE54 [15, 24] has shown that the long-term stability of properties at a temperature of up to 200°C, and especially in the vicinity of 150°C, is one of the most important requirements that is met by high-temperature magnesium alloys used for fabricating

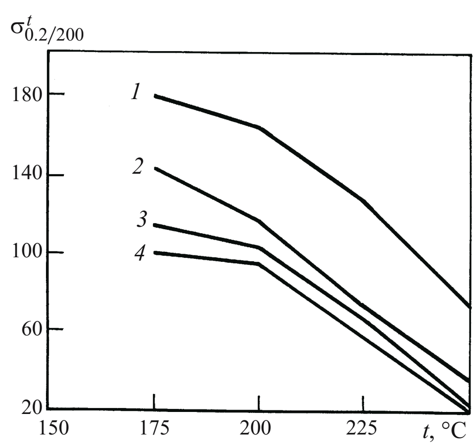


**Fig. 4.** Dependence of the creep resistance $\sigma^t_{0.2/200}$ (the stress ensuring a creep strain of 0.2% after a 200-h hold at an elevated temperature) on the test temperature of alloys: *1* ) MRI201S-T6; *2* ) MRI202S-T6; *3* ) MRI206S-T6; *4* ) A319-T6.

**TABLE 4.** Residual Stresses in Bolted Joints of MRI Alloys and of Commercial Aluminum Alloys after Testing at Elevated Temperatures under Load

| Alloy | $\sigma_f/\sigma_0$, % | |
|---|---|---|
| | 175°C | 200°C |
| MRI201S-T6 | 97 | 85 |
| MRI202S-T6 | 96 | 81 |
| MRI206S-T6 | 92 | 77 |
| A319-T6 | 76 | – |
| A380 | 82 | 72 |

**Notations:** $\sigma_f/\sigma_0$) fraction of residual stresses at room temperature after 100-h testing under load ($\sigma_0$ = 70 MPa) at 175 and 200°C.

**TABLE 5.** Effect of Long-Term Hold (1000 h) at Elevated Temperatures on Strength Characteristics of New Alloys

| Alloy | $t_h$,* °C | Testing at 20°C | | | Testing at 175°C | | |
|---|---|---|---|---|---|---|---|
| | | $\sigma_{0.2}$, MPa | $\sigma_r$, MPa | δ, % | $\sigma_{0.2}$, MPa | $\sigma_r$, MPa | δ, % |
| MRI201S | 20 | 185 ± 7 | 265 ± 10 | 6 ± 1 | 178 ± 11 | 255 ± 9 | 12 ± 3 |
| | 150 | 182 ± 9 | 272 ± 8 | 5 ± 1 | 175 ± 9 | 242 ± 7 | 11 ± 4 |
| | 200 | 178 ± 10 | 268 ± 9 | 6 ± 1 | 175 ± 7 | 240 ± 9 | 12 ± 3 |
| MRI202S | 20 | 165 ± 8 | 270 ± 9 | 9 ± 1 | 155 ± 3 | 236 ± 9 | 16 ± 3 |
| | 150 | 162 ± 7 | 273 ± 7 | 10 ± 2 | 157 ± 6 | 230 ± 8 | 15 ± 4 |
| | 200 | 164 ± 6 | 268 ± 10 | 9 ± 1 | 154 ± 5 | 232 ± 6 | 15 ± 3 |
| ÌRI206S | 20 | 125 ± 8 | 225 ± 9 | 12 ± 2 | 125 ± 7 | 180 ± 11 | 21 ± 3 |
| | 150 | 120 ± 6 | 220 ± 8 | 11 ± 1 | 127 ± 9 | 177 ± 10 | 20 ± 2 |
| | 200 | 118 ± 5 | 225 ± 8 | 13 ± 1 | 124 ± 4 | 179 ± 8 | 20 ± 4 |

* Temperature of the hold.

transmissions and their housings. For example, alloy WE54 loses ductility considerably at room temperature (less than 2%) after a long-term (over 1000 h) hold at 150°C. For this reason we evaluated the susceptibility of MRI alloys to embrittlement under conditions of long-term hold at elevated temperatures. We established (Table 5) that the mechanical characteristics of the MRI alloys (both at room temperature and at 175°C) after 1000 h of testing at 150°C remained virtually unchanged. It should be noted that the new MRI alloys have excellent mechanical properties after rapid treatment by mode T6. The duration of aging of MRI alloys is much shorter than a hold typical for conventional alloys (6 – 48 h) used for sand and chill casting [14, 15, 24].

From the standpoint of applications it is very important that the new alloys possess high casting properties, tightness in pressure tests, and weldability; this has been shown by testing castings of cylinder blocks and heads under pressure. Producers of aircrafts and cars require acceptable cost of new materials in addition to high properties. It follows from Table 6 that alloys MRI201S and WE43 have close strength characteristics and creep and corrosion resistances. The other two new alloys have lower operating characteristics than WE43 but much better characteristics than ZE41 and EZ33. The data of Table 6 show quite convincingly that all the new alloys have the best combination of operating parameters and cost.

## CONCLUSIONS

We have considered metallurgical aspects of the development of alloys for sand and chill casting and high-pressure die casting. The approach suggested has been implemented in the creation of new creep resistant magnesium alloys MRI153M and MRI230D for casting under high pressure and MRI201S, MRI202S and MRI206S for sand mold and chill casting.

**TABLE 6.** Generalized Rating of MRI Alloys as Compared to Commercial Alloys

| Alloy | Characteristic | Service parameters | | | | Cost | Total score |
|---|---|---|---|---|---|---|---|
| | | creep resistance | yield limit at 150°C | corrosion resistance | total score | | |
| | SP* | 10 | 7 | 9 | – | 10 | – |
| MRI201S | Score (S) | 10 | 10 | 10 | – | 4 | |
| | SP × S | 100 | 70 | 90 | 260 | 40 | 300 |
| MRI202S | Bally | 9 | 8 | 10 | | 7 | |
| | SP × S | 90 | 56 | 90 | 236 | 70 | 306 |
| MRI206S | Bally | 8 | 5 | 10 | | 9 | |
| | SP × S | 80 | 35 | 90 | 205 | 90 | 295 |
| WE43 | Bally | 10 | 10 | 10 | | 2 | |
| | SP × S | 100 | 70 | 90 | 260 | 20 | 280 |
| ZE41 | Bally | 6 | 6 | 3 | | 10 | |
| | SP × S | 60 | 42 | 27 | 129 | 100 | 229 |
| EZ33 | Bally | 7 | 4 | 5 | | 9 | |
| | SP × S | 70 | 28 | 45 | 143 | 90 | 233 |

* Significance of the parameter.

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