**Effect of Samarium on the Properties of Hot-Extruded Mg–Y–Gd–Zr Alloys**

Elena Lukyanova 1, Natalia Martynenko 1, Olga Rybalchenko 1, Tatiana Dobatkina 1, Irina Tarytina 1, Natalia Tabachkova 2,3, Georgy Rybalchenko 4, Nadezhda Andreeva 1 and Sergey Dobatkin 1,*

1 A.A. Baikov Institute of Metallurgy and Materials Science of the Russian Academy of Sciences, Leninskiy Prospect, 49, 119334 Moscow, Russia; helenelukyanova@gmail.com (E.L.); nataliasmartynenko@gmail.com (N.M.); rybalch@mail.ru (O.R.); dobat@imet.ac.ru (T.D.); tarytina@yandex.ru (I.T.); randreeva@imet.ac.ru (N.A.)

2 Department of Physical Materials Science, National University of Science and Technology “MISIS”, Leninskiy Prospect, 4, 119049 Moscow, Russia; ntabachkova@gmail.com

3 A.M. Prokhorov General Physics Institute of the Russian Academy of Sciences, Vavilova st., 38, 119333 Moscow, Russia

4 P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Leninskiy Prospect, 53, 119991 Moscow, Russia; rybalchenkogv@lebedev.ru

* Correspondence: sdobatkin@imet.ac.ru

**Abstract:** The effect of such an additional promising alloying element as samarium on hot-extruded Mg–Y–Gd–Zr alloys is investigated. The microstructure, kinetics of aging during the decomposition of a supersaturated Mg solid solution, and the mechanical properties of the alloys are studied. The differences of the recrystallization processes that occur in hot-extruded alloys with various contents of samarium (0, 1.7, 2.5%) are demonstrated. After hot extrusion, Mg–Y–Gd–Zr and Mg–Y–Gd–Sm–Zr alloys are additionally hardened during aging due to the decomposition of a supersaturated Mg solid solution. At the same time, samarium changes the nature of this hardening. The alloys with samarium are hardened faster, and the maximum hardness is achieved with shorter aging exposures. The mechanical properties of hot-extruded Mg–Y–Gd–Zr alloys with samarium addition are determined at room and elevated up to 300 °C temperatures. The efficiency and expediency of using samarium both as a separate alloying element and as a partial replacement of more expensive rare-earth elements in alloys with yttrium and gadolinium are shown.

**Keywords:** magnesium alloys; rare earth metals; hot deformation; microstructure; aging; precipitation; hardness; electrical resistivity; tensile tests; mechanical properties

**1. Introduction**

Magnesium alloys remain one of the most widely used structural materials due to their high specific strength, low density, and damping ability. The use of magnesium alloys has led to a decrease in fuel consumption and an increase in the dynamic characteristics of cars and aircraft due to increasing the weight efficiency. It is especially important in such industries as automotive and aerospace engineering, where the magnesium alloys became most widely used. Heat-resistant magnesium alloys find application in creating components of engines, including turbine housings, ventilation louvers, transmissions, and various other parts exposed to elevated temperatures and mechanical strains. These alloys are used in the manufacturing of equipment that operates at high temperatures and in aggressive chemical environments, for instance, in drilling operations and oil and gas processing [1–6]. In addition, recently magnesium alloys have been considered as bioreabsorbable medical materials [7–9]. For the effective use of magnesium alloys, it is necessary to improve their mechanical and functional properties by varying their compositions and processing technologies [10–12]. High strength of magnesium alloys both at room and at...
elevated up to 300 °C temperatures is achieved by additions of rare earth elements (REEs) to magnesium [5]. REEs have a different solubility in solid magnesium [13–15]. The solubility of REEs in solid Mg goes down with decreasing temperature. The difference in room and high temperature solubility predetermines the dispersion mechanism of hardening because of decomposition of a supersaturated Mg solid solution during aging.

Basically, modern developments and studies are focused on alloys containing yttrium and gadolinium as the main alloying components [16–28]. Yttrium and gadolinium belong to the same yttrium subgroup of the REEs and both significantly improve the strength properties of magnesium in a similar way. Due to the high maximum solubility of yttrium (12%, here and below wt. %) and gadolinium (23.3%) in magnesium [5], in order to increase strength, it is necessary to add a significant amount of REEs. As a result, the high content of these expensive REEs increases the cost of alloys. One of such Mg–Y–Gd–Zr alloys with high strength in the hot-pressed state is the IMV7–1 alloy containing 5.0–6.5% yttrium, 3.5–5.5% gadolinium, and 0.15–0.7% zirconium [29,30]. The properties of such alloys might be improved by additional alloying with other REEs, whose effect on magnesium is different from that of yttrium and gadolinium. Samarium can be considered as such an element since it has a lower maximum solubility, about 5.8% [5], in solid Mg than yttrium and gadolinium. Sm is also a good reinforcing element for it [31,32]. Earlier, the phase equilibrium was studied in the magnesium-rich region of the Mg–Y–Gd–Sm system [33].

The solubility of samarium in a Mg-based solid solution in the presence of yttrium and gadolinium was determined [34]. It was established that samarium reduces the solubility of yttrium and gadolinium in solid Mg, and the overall solubility of all REEs decreases with decreasing temperature [33,34]. The Mg solid solution is found to be in equilibrium only with the Mg$_{41}$Sm$_5$ and Mg$_{24}$(Y, Gd)$_5$ phases, which belong to the binary Mg–Sm and Mg–Y–Gd systems, respectively. Yttrium and gadolinium dissolve significantly in the Mg$_{41}$Sm$_5$ phase up to 4.4 at.% (~15 mass.%), so the total $\sum$REEs in the compound is 11.9 at.% (~44.3 mass.%). Samarium dissolves in the Mg$_{24}$(Y, Gd)$_5$ phase up to 8.2 at.% (~12.4 mass.%), so the total $\sum$REEs in the compound is 20.2 at.% (~56.8 mass.%).

The effect of samarium on magnesium alloys with yttrium and gadolinium was investigated in [35–39]. In works [35,36], alloys with a high content of gadolinium were considered. Mechanical properties mainly at elevated temperatures and creep resistance of Mg–8%Gd–4%Y–1%Sm–0.5%Zr and Mg–11%Gd–2%Y–3%Sm–0.5%Zr alloys were studied. The effect of samarium on the mechanical properties in tensile and compression tests and the kinetics of hardening during aging were investigated for as-cast Mg–5.5%Y–5.5%Gd–3%Sm–0.7%Zr and Mg–7.5%Y–7.5%Gd–5%Sm–0.7%Zr alloys in [37]. In general, studies [35–37] were focused on sufficiently rich REE compositions (more than 13% $\sum$REEs). It was shown that the alloys had low ductility in tensile tests. Less REEs-doped Mg–6%Gd–3%Y–3%Sm–0.5%Zr and Mg–5.5%Gd–3%Y–1%Sm–0.5%Zr alloys were studied in [38,39]. The authors considered the mechanisms of dynamic recrystallization, microstructure evolution, and the precipitation process during deformation. Unfortunately, the mechanical properties of these alloys were not presented. The aim of this work was to study the effect of small additions of samarium (up to 2.5%) on the microstructure, the decomposition kinetics of a magnesium solid solution during aging, and the mechanical properties at room and elevated temperatures in low alloys of the IMV7–1 type in hot-extruded state.

2. Materials and Methods

In this work, alloys with different contents of yttrium, gadolinium, and samarium were prepared. The Mg–3.2%Y–5.3%Gd–0.4%Zr alloy (1) was close to the IMV7–1 alloy without the addition of samarium. The Mg–3.3%Y–5.4%Gd–1.7%Sm–0.7%Zr alloy (2) has a similar content of yttrium and gadolinium as the alloy (1) and a small addition of samarium within the joint maximum solubility of REEs in Mg solid solution [34]. The Mg–1.9%Y–3.7%Gd–2.5%Sm–0.4%Zr alloy (3) has a lower content of yttrium and gadolinium than that of the IMV7–1 alloy and a larger amount of samarium within its joint solubility in solid Mg.
The alloys were melted using an electric resistance furnace in an iron crucible under coating flux to prevent melt ignition. The flux consisted of 38–46% MgCl$_2$, 32–40% KCl, 3–5% CaF$_2$, 5–8% BaCl$_2$, 1.5% MgO, and <8% (NaCl + CaCl$_2$). High purity metals were used in order to prepare the alloys: Mg (>99.95%), Sm (>99.83%), Y (>99.83%), and Gd (>99.85%). REEs and zirconium were added to melt as master alloys with composition of Mg–43.6%Sm, Mg–39.15%Gd, Mg–47.7%Y, and Mg–9.6%Zr. The melt was cast into a steel mold with a diameter of 52 mm, which was preheated to 350 °C. The nominal compositions of alloys were determined by chemical method on ULTIMA 2C inductivity coupled plasma-atomic spectrometer (HORIBA Jobin Yvon SAS, Palaiseau, France). Then, the ingots were homogenized at 515 °C for 6 h with cooling in air in order to obtain the equilibrium structure and supersaturated solid solution of magnesium. After homogenization, the preforms were extruded on a vertical hydraulic press with a force of 160 tons into bars with a diameter of 14 mm. The total degree of deformation was about 93% (drawing ratio ~13.8). Extrusion was carried out at 430 ± 10 °C. The container temperature was 20–40 °C lower than the ingot heating temperature followed by cooling in air. Since the air cooling rate is sufficient to prevent the decomposition of the Mg solid solution, additional quenching in water was not required.

The microstructure was investigated using a Neophot 2, NU–2E optical microscope (VEB Carl Zeis, Jena, Germany) after chemical etching using 60% ethylene glycol, 20% acetic acid, 1% nitric acid, and 19% water to reveal the grain structure. The Image Expert Professional 3 software (Nexsys, Moscow, Russia) was used to calculate average grain size. Transmission electron microscopy (TEM) was performed on a JEM–2100 electron microscope (Jeol, Tokyo, Japan) with an accelerating voltage of 200 kV. The foils for TEM observation were thinned by mechanical grinding followed by ion bombardment on a GATAN 600 machine (GATAN, Pleasanton, CA, USA).

The kinetics of decomposition of the Mg solid solution after hot extrusion was studied by investigating the dependence of hardness and electrical resistivity on time with exposures up to 128 h during isothermal aging at 200 °C. Hardness was determined by the Brinell method on an IT 5010–01M instrument (LLC “ZIP”, Ivanovo, Russia) under a load of 612.9 N using a steel ball of 2.5 mm in diameter as an indenter. The electrical resistivity was studied by a BSZ–010–2 micro-ohmmeter (JSC “NIIEMP”, Penza, Russia) on cylindrical samples of 6 mm in diameter. The distance between the terminals was 21.8 mm. The measurement error did not exceed ±0.7%.

The uniaxial tensile properties of the studied alloys were evaluated immediately after additional aging of hot-extruded samples. The tensile tests were carried out at room and elevated up to 300 °C temperatures using an Instron 3382 universal testing machine (Instron, High Wycombe, UK). The extension rate was 1 mm/min. The cylindrical samples of 5 mm in diameter and 28 mm in working length was used for test.

3. Results

The microstructure of the alloys before extrusion consisted of grains of Mg solid solution with a size of 200–250 µm. Hot extrusion led to the formation of a fine-grained structure. Figure 1 shows the microstructure of the studied alloys after hot extrusion in the longitudinal (parallel to the extrusion) direction. The microstructure of all alloys consisted of light grains of a magnesium solid solution with inclusions of black crystals of the α–Zr% phase. The presence of rich in REEs intermetallic phases such as Mg$_4$Sm$_5$ and Mg$_{24}$(Y, Gd)$_5$ [33,34] could not be observed with an optical microscope. The study of the microstructure showed that recrystallization during deformation depends on the content of samarium in the alloys. The structure of the Mg–3.2%Y–5.3%Gd–0.4%Zr alloy without samarium consisted of completely recrystallized equiaxed grains with an average size of 7.93 ± 0.23 µm. The alloy with 1.7% samarium was also completely recrystallized but had a finer grain of 2.94 ± 0.06 µm in size. The structure of the less alloyed Mg–1.9%Y–3.7%Gd–2.5%Sm–0.4%Zr alloy with the highest content of samarium was partially recrystallized
and consisted of both deformed grains extended along the extrusion direction and fine recrystallized grains with a size of $2.87 \pm 0.08 \mu m$.

**Figure 1.** Microstructures of hot-extruded Mg–3.2%Y–5.3%Gd–0.4%Zr (a), Mg–3.3%Y–5.4%Gd–1.7%Sm–0.7% Zr (b), and Mg–1.9%Y–3.7%Gd–2.5%Sm–0.4%Zr (c) alloys in the longitudinal direction.

An increase in the concentration of alloying elements can complicate the recrystallization process by creating obstacles to grain boundary movement and impeding the growth of new grains. Consequently, recrystallization is expected to decelerate with the increasing in the concentration of the alloying elements. Surprisingly, in the case of the Mg–1.9%Y–3.7%Gd–2.5%Sm–0.4%Zr alloy, which is the least alloyed among the compared alloys, recrystallization occurs more slowly than in two other more heavily alloyed alloys. Given the lower content of yttrium and gadolinium but higher content of samarium in this alloy, it is assumed that samarium has a more significant effect on the rate of recrystallization. Thus, with an increase in the amount of samarium, recrystallization in Mg–Y–Gd–Zr alloys gradually slows down, and after reaching a high content of samarium, it does not proceed completely.

In Figure 2, the curves of hardness (Figure 2a) and electrical resistivity (Figure 2b) of hot-extruded alloys during isothermal aging at 200 °C are presented.

**Figure 2.** Effect of aging duration at 200 °C on hardness (a) and electrical resistivity (b) of hot-extruded Mg–Y–Gd–Zr and Mg–Y–Gd–Sm–Zr alloys.

The aging temperature was chosen based on previous studies of the aging kinetics of a hot-pressed plate of the IMV7–1 alloy, where this temperature provided the maximum strengthening [30]. Measurement of hardness showed that all alloys are significantly...
strengthened during aging, but the behavior of the hardness dependence on the composition of the alloy is different. It is important to note that two stages of hardness can be traced with increasing of aging time for the Mg–3.2%Y–5.3%Gd–0.4%Zr alloy without the addition of samarium. At the first stage, a slight increase in hardness is observed, after which it is established at an approximately constant level with an exposure of up to 8 h. Then, at the second stage, a more significant increase in hardness occurs, reaching a maximum at 64 h with a steep peak, and its subsequent decrease. In the alloy with the addition of 1.7% samarium, the hardness reaches higher values and the curve also has two stages; however, at the first stage, the increase in hardness occurs faster, and there is no area where it has constant values. In this case, the maximum hardness is reached faster and corresponds to a holding time of 32 h. The hardness of the Mg–1.9%Y–3.7%Gd–2.5%Sm–0.4%Zr alloy increases almost continuously up to the maximum at 32 h and then decreases. The peak of the curve looks more smoothed. Thus, with an increase in the content of samarium, the hardness increases faster, and its maximum is shifted towards lower aging exposures.

The electrical resistivity of the alloys only decreases during aging. This indicates that in the hot-extruded alloys, the magnesium solid solution is depleted in REEs as a result of the precipitation process. On the curves of changes in electrical resistivity, two stages are also traced. At the first stage, the electrical resistivity decreases slightly or remains constant in a certain holding time range. For the alloy without the addition of samarium, the electrical resistivity practically does not change up to a holding time of 16 h. Then, at the second stage, a significant decrease in electrical resistivity occurs. In alloys with samarium additives, the decrease begins earlier after holding for 4 h. At the same time, in Mg–3.2%Y–5.3%Gd–0.4%Zr and Mg–3.3%Y–5.4%Gd–1.7%Sm–0.7%Zr alloys at the longest exposure of 128 h the electrical resistivity values are close to each other and tend to an equilibrium state at 200 °C, where the electrical resistivity is constant. In general, the addition of samarium helps to accelerate the decomposition of the Mg-based solid solution in hot-extruded alloys with yttrium and gadolinium. The established patterns of the kinetics of the decomposition of a supersaturated Mg solid solution in hot-extruded alloys, depending on the content and ratio of samarium to yttrium and gadolinium, may be in agreement with the nature of the recrystallization in these alloys.

In the hot-extruded Mg–1.9%Y–3.7%Gd–2.5%Sm–0.4%Zr alloy, the features of structural transformations occurring during the decomposition of the supersaturated magnesium solid solution were analyzed by TEM. They are presented in Figure 3. In the initial hot-extruded state (Figure 3a), within the grains of the Mg solid solution, a dislocation structure was observed without noticeable precipitates of REE-rich phases. In this case, the diffraction pattern (Figure 3b) contained elongated superstructural reflexes. They were located at the midpoints of segments in the reciprocal lattice connecting the central reflex with the reflexes of the prismatic (100) planes of the Mg solid solution. Such a position of superstructural reflexes indicates the formation of ordered $\beta''$-phase of $D0_{19}$ type [5,28,40]. The stretching of the reflexes is considered a sign of short-range ordering. After aging at 200 °C for 64 h, resulting in the achievement of the highest hardness values, the structure contains plate-shaped precipitates located both in the body of the magnesium grain and along its boundaries (Figure 3c). The particles at the grain boundaries of the Mg solid solution were larger (up to 0.1 µm) and had more distinct contours. Zones free from precipitates were observed around them. Within the grains of the magnesium solid solution, the precipitates looked diffuse, and their size did not exceed 50 nm. The electron diffraction pattern taken from the region inside the grain showed that superstructural reflexes were transformed into point reflexes and were located in the basal plane in a certain way in the form of “X” (Figure 3d). This arrangement of superstructural reflexes in the basal plane of the Mg solid solution indicates the formation of a metastable $\beta'$-phase. Aging at a higher temperature of 250 °C for 24 h leads to coarsening of the precipitation products of the magnesium solid solution up to ~1 µm (Figure 3e). The elongation of REEs-enriched particles and their regular arrangement along certain planes of the crystal lattice of the Mg solid solution are clearly manifested. It can be seen on Figure 3e that the precipitated particles are located
along the boundaries of the deformation twin. The presence of superstructural reflexes and strands in the electron diffraction patterns (Figure 3f) suggests that the coherent bond between the lattices of the particles and the Mg solid solution is still retained at a higher aging temperature.

Figure 3. Electron micrographs (a,c,e), microdiffraction patterns (b,d,f) of the hot-extruded alloy Mg–1.9%Y–3.7%Gd–2.5%Sm–0.4%Zr in the initial state (a,b), after aging at 200 °C, 64 h (c,d), and after aging at 250 °C, 24 h (e,f).

The mechanical properties of the alloys were investigated using tensile tests. The studies were performed along the pressing direction both at room temperature and elevated temperatures up to 300 °C in order to assess the possibility of their application at high temperatures. The results of mechanical testing of alloys at room temperature in the
hot-extruded and additionally aged states are shown in Figure 4. The average values of mechanical properties obtained after testing of three samples for each condition are summarized in Table 1.

In the alloy without samarium, the ultimate tensile strength (UTS) was 270 ± 4 MPa, the yield strength (YS) was 194 ± 2 MPa, and the elongation (EL) was 12.2 ± 2.3%. The addition of 1.7% samarium to the alloy with ~3% yttrium and ~5% gadolinium slightly increased its strength characteristics after hot extrusion, but significantly reduced ductility to EL = 5.2 ± 1.2%. However, the alloy with a lower content of yttrium (~2%) and gadolinium (~3.5%) with the addition of 2.5% of samarium retained the strength properties at the same level as the alloy without the addition of samarium, but had a higher ductility with an EL 18.9 ± 1.2%.

Aging at 200 °C with an exposure of 24 h practically did not increase the strength properties of the Mg–3.2%Y–5.3%Gd–0.4%Zr alloy but led to a significant decrease in ductility to El = 3.5 ± 0.2%. This is consistent with the fact that during aging for 24 h in the alloy without samarium, the hardness does not yet reach high values, although the decomposition of a supersaturated magnesium solid solution already occurs in it. In Mg–3.3%Y–5.4%Gd–1.7%Sm–0.7%Zr and Mg–1.9%Y–3.7%Gd–2.5%Sm–0.4%Zr alloys after aging for 24 h, on the contrary, there is a noticeable increase in UTS up to 386 ± 6 and 360 ± 6 MPa, respectively, together with a decrease in ductility. While in the alloy with the addition of 1.7% samarium, the EL drops to a very low value of 1.9 ± 0.6%, in a less
alloyed alloy with 2.5% samarium the ductility retains sufficient for structural materials (6.6 ± 0.7%).

Long-term aging for 64 h in the alloy without samarium provides the highest hardening up to UTS = 333 ± 7 MPa and a minimum ductility corresponding to EL = 2.5 ± 0.9%. The strength properties of the Mg–3.3%Y–5.4%Gd–1.7%Sm–0.7%Zr alloy is retained during longer aging time. At the same time, the loss of the ductility is also observed to an even greater extent up to EL = 1 ± 0.1%. The Mg–1.9%Y–3.7%Gd–2.5%Sm–0.4%Zr alloy had almost the same mechanical properties as with a shorter holding time of 24 h. Thus, in an alloy with a lower content of more expensive yttrium and gadolinium and with the addition of 2.5% of samarium, the best mechanical properties are provided. It is important to note that they are achieved with a more appropriate short-term aging exposure of 24 h.

Hot-extruded alloys after aging were also tensile tested at elevated temperatures of 200, 250, and 300 °C (Figure 5). Table 2 shows the average values of mechanical properties obtained after testing of three samples for each condition.

![Figure 5](image-url). Engineering stress–strain response of the hot-extruded Mg–Y–Gd–Zr and Mg–Y–Gd–Sm–Zr alloys after aging at 200 °C for 64 h in tensile tests at elevated temperatures.
Table 1. Mechanical properties of Mg–Y–Gd–Zr and Mg–Y–Gd–Sm–Zr alloys in tensile tests at room temperature.

<table>
<thead>
<tr>
<th>Alloy Composition</th>
<th>Hot Extrusion</th>
<th>Hot Extrusion + Aging</th>
<th>Hot Extrusion + Aging</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>UTS, MPa</td>
<td>YS, MPa</td>
<td>EL, %</td>
</tr>
<tr>
<td>Mg–3.2%Y–5.3%Gd–0.4%Zr</td>
<td>270 ± 4</td>
<td>194 ± 2</td>
<td>12.2 ± 2.3</td>
</tr>
<tr>
<td>Mg–3.3%Y–5.4%Gd–1.7%Sm–0.7%Zr</td>
<td>278 ± 7</td>
<td>223 ± 5</td>
<td>5.2 ± 1.2</td>
</tr>
<tr>
<td>Mg–1.9%Y–3.7%Gd–2.5%Sm–0.4%Zr</td>
<td>273 ± 1</td>
<td>186 ± 3</td>
<td>18.9 ± 1.2</td>
</tr>
</tbody>
</table>

Table 2. Mechanical properties of hot-extruded Mg–Y–Gd–Zr and Mg–Y–Gd–Sm–Zr alloys after aging at 200 °C for 64 h in tensile tests at elevated temperatures.

<table>
<thead>
<tr>
<th>Alloy Composition</th>
<th>T = 200 °C</th>
<th>T = 250 °C</th>
<th>T = 300 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>UTS, MPa</td>
<td>YS, MPa</td>
<td>EL, %</td>
</tr>
<tr>
<td>Mg–3.2%Y–5.3%Gd–0.4%Zr</td>
<td>312 ± 1</td>
<td>252 ± 8</td>
<td>8.9 ± 2.2</td>
</tr>
<tr>
<td>Mg–3.3%Y–5.4%Gd–1.7%Sm–0.7%Zr</td>
<td>368 ± 5</td>
<td>292 ± 10</td>
<td>8.5 ± 1.1</td>
</tr>
<tr>
<td>Mg–1.9%Y–3.7%Gd–2.5%Sm–0.4%Zr</td>
<td>323 ± 3</td>
<td>257 ± 2</td>
<td>16.5 ± 0.9</td>
</tr>
</tbody>
</table>
In the Mg–3.2%Y–5.3%Gd–0.4%Zr alloy, which does not contain samarium, at a test temperature of 200 °C, compared with tests at room temperature, the strength characteristics practically remain at the same level, and the EL increases from 2.5 ± 0.9 to 8.9 ± 2.2%. With an increase in temperature up to 250 °C, the mechanical properties of the alloy generally do not change. At the same time, a decrease in strength up to UTS = 230 ± 10 MPa is observed at a higher temperature of 300 °C. In addition, an alloy with 1.7% samarium barely softens up to 250 °C, while its ductility increases. The alloy with a lower content of yttrium and gadolinium and with an addition of 2.5% of samarium only slightly softens when heated to 250 °C. However, it has an increase in ductility to higher values in comparison with alloys without samarium and with an addition of 1.7% of it. In general, at all elevated test temperatures, the alloy without samarium and the alloy with an addition of 2.5% samarium—less alloyed with yttrium and gadolinium—had a similar level of strength characteristics. Although the most alloyed Mg–3.3%Y–5.4%Gd–1.7%Sm–0.7%Zr alloy tested at the room temperature in the aged state turned out to be the least ductile, it achieved the highest properties at elevated temperatures.

4. Discussion

The difference in recrystallization behavior, kinetics of aging, and mechanical properties of Mg–Y–Gd–Sm–Zr alloys are primarily associated with the different solubility of samarium, yttrium, and gadolinium in Mg solid solution. The solubility of these elements determines the degree of saturation of the Mg solid solution, as well as the nature of its decomposition, which, with decreasing temperature, is accompanied by the precipitation of REE-rich phases. Due to its lower solubility than that of yttrium and gadolinium, samarium also limits the joint solubility of all elements in Mg solid solution in Mg–Y–Gd–Sm–Zr alloys, making it more saturated with a smaller total amount of REEs.

This also contributes to a more accelerated decomposition of the supersaturated Mg solid solution during aging. In turn, the accelerated decomposition of the Mg-based solid solution is accompanied by an earlier precipitation of REE-rich phases, which also affect the recrystallization during hot deformation of such alloys. Since the decomposition of the supersaturated Mg solid solution proceeds faster, with an increase in the content of samarium, the presence in the structure of precipitates of phases that are harder than the magnesium matrix can prevent the movement of dislocations and sliding along grain boundaries, and therefore have a restraining effect on the mechanisms of deformation and the development of recrystallization.

Therefore, alloys with samarium additions have a finer-grained recrystallized structure (up to ~3 µm) than alloys without samarium, which directly affects their mechanical properties. In the partially recrystallized structure of the Mg–1.9%Y–3.7%Gd–2.5%Sm–0.4%Zr alloy, D019-type ordering already takes place after directly hot extrusion. The β"-phase formed as a result of ordering has a hexagonal, closed, packed lattice and is completely coherent with the magnesium solid solution matrix. The lattice periods are

\[ a_{\text{β}''} = 2a_{\text{Mg}} \quad \text{and} \quad c_{\text{β}''} = c_{\text{Mg}}, \]

where \( a_{\text{Mg}} \) and \( c_{\text{Mg}} \) are the periods of the magnesium crystal lattice. After reaching the maximum hardening, a metastable phase \( \beta' \) is formed in the structure. It is confirmed by a certain diffraction pattern (Figure 3d) in the basal plane. Figure 6a shows the result of grouping process of the reflexes of the precipitated phase into three superimposed systems with third-order symmetry in reciprocal lattice.

In each system, reflexes are located on lines parallel to [010] *, [410] *, [430] * of the Mg solid solution. They divide the distances to (010) \( d_{\text{Mg}} \) into four equal parts and into eight equal parts to (410) \( d_{\text{Mg}} \) and (430) \( d_{\text{Mg}} \). It means that they are reflections from planes with interplanar distance \( (d) \) 4 times larger than \( d_{\text{Mg}} / 4 \) and 8 times larger than \( d_{\text{Mg}} / 4 \). Phase \( \beta' \) has an orthorhombic crystal lattice with parameters \( a_{\text{β}'} = 8d_{\text{100Mg}} \), \( b_{\text{β}'} = 2d_{\text{Mg}} \) and \( c_{\text{β}'} = c_{\text{Mg}} \). It is oriented in three symmetrical ways. In this case, the symmetry axis coincides with the hexagonal axis of the Mg solid solution (Figure 6b). The large planes of the plates of the precipitated phase are located along the (110) planes of the magnesium solid solution perpendicular to its basal plane (Figure 6c). The formation of
the orthorhombic phase $\beta'$ and its favorable location prevent the basal slip of dislocations, which ensures the hardening of the alloy during aging and determines its high level of strength properties.

Figure 6. Schemes of the basal planes of the reciprocal (a) and atomic (b) lattices of the decomposed Mg solid solution for three systems of reflections with third-order symmetry, corresponding to the orthorhombic $\beta'$-phase, and its location in the hexagonal lattice of the Mg solid solution (c). The red rectangle indicates the particle shape and its location.

Mechanical tensile tests generally showed that the use of samarium as an alloying addition to magnesium alloys containing yttrium and gadolinium promotes their hardening at room and elevated temperatures (up to $300 \, ^\circ\text{C}$) and significantly reduces the aging time required to achieve the highest hardening. This makes the hardening heat treatment of the alloys with samarium additives more energy efficient. According to mechanical testing at room temperature, the loss of ductility of the hot-extruded IMV7-1 type alloy with a small addition of 1.7% of samarium is more significant than the strength effect that is achieved in it during aging. However, such an alloy demonstrates the best mechanical properties after heating to 200–300 $^\circ\text{C}$, determining the possibility of its operation at elevated temperatures. The most effective was the addition of 2.5% of samarium into the alloy with a lower content of yttrium and gadolinium in comparison with the addition of samarium into the IMV7-1 type alloy. This alloy had higher mechanical properties at room and elevated test temperatures. Thus, yttrium-gadolinium magnesium alloys with samarium, having the required level of mechanical properties, can be more economical by reducing the content of more expensive yttrium and gadolinium, and have a shorter aging heat treatment. Table 3 shows the mechanical properties of Mg–Y–Gd–Sm–Zr alloys obtained in this study together with the results of previous studies for comparison.

In the Mg–8%Gd–4%Y–1%Sm–0.5%Zr alloy [35], sufficiently high strength properties were obtained in testing at elevated temperatures. The authors do not give mechanical properties at room temperature, possibly due to low plastic characteristics under these conditions. It should be noted that the amount of samarium in the alloy is too small
compared with the amount of yttrium and gadolinium in order to evaluate the effect of samarium on the mechanical properties. Alloys Mg–11%Gd–2%Y–3%Sm–0.5%Zr [36], Mg–5.5%Y–5.5%Gd–3%Sm–0.7%Zr, and Mg–5.5%Y–5.5%Gd–3%Sm–0.7%Zr [37] with a samarium content of 3% or more also have low ductility and an average level of strength, despite the high total content of REEs. In the alloys with a low content of yttrium and gadolinium and with the additives of samarium within the joint solubility, as shown in the present study, high strength properties are achieved. These strength characteristics are commensurate with the characteristics of high gadolinium alloys, but there is a large margin of ductility.

Table 3. Mechanical properties of alloys of the Mg–Y–Gd–Sm–Zr system during tensile tests in various sources.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Test Temperature, °C</th>
<th>UTS, MPa</th>
<th>YS, MPa</th>
<th>EL, %</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mg–8%Gd–4%Y–1%Sm–0.5%Zr</td>
<td>20</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Hot extrusion + aging</td>
<td>200</td>
<td>376</td>
<td>325</td>
<td>4</td>
<td>[35]</td>
</tr>
<tr>
<td></td>
<td>250</td>
<td>393</td>
<td>345</td>
<td>6.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>354</td>
<td>300</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Mg–11%Gd–2%Y–3%Sm–0.5%Zr</td>
<td>20</td>
<td>252</td>
<td>201</td>
<td>2.4</td>
<td>[36]</td>
</tr>
<tr>
<td>As-cast</td>
<td>200</td>
<td>303</td>
<td>237</td>
<td>3.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>250</td>
<td>319</td>
<td>246</td>
<td>4</td>
<td></td>
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<tr>
<td></td>
<td>300</td>
<td>273</td>
<td>212</td>
<td>4.7</td>
<td></td>
</tr>
<tr>
<td>Mg–5.5%Y–5.5%Gd–3%Sm–0.7%Zr</td>
<td>20</td>
<td>339</td>
<td>234</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>As-cast + aging</td>
<td>200</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>[37]</td>
</tr>
<tr>
<td></td>
<td>250</td>
<td>304</td>
<td>224</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Mg–7.5%Y–7.5%Gd–5%Sm–0.7%Zr</td>
<td>20</td>
<td>290</td>
<td>285</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>As-cast + aging</td>
<td>200</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td></td>
<td>250</td>
<td>285</td>
<td>282</td>
<td>0.1</td>
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<td></td>
<td>300</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Mg–3.3%Y–5.4%Gd–1.7%Sm–0.7%Zr</td>
<td>20</td>
<td>386</td>
<td>331</td>
<td>1.9</td>
<td>present study</td>
</tr>
<tr>
<td>Hot extrusion + aging</td>
<td>200</td>
<td>368</td>
<td>292</td>
<td>8.5</td>
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</tr>
<tr>
<td></td>
<td>250</td>
<td>356</td>
<td>315</td>
<td>7.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>266</td>
<td>277</td>
<td>6.4</td>
<td></td>
</tr>
<tr>
<td>Mg–1.9%Y–3.7%Gd–2.5%Sm–0.4%Zr</td>
<td>20</td>
<td>360</td>
<td>276</td>
<td>6.6</td>
<td></td>
</tr>
<tr>
<td>Hot extrusion + aging</td>
<td>200</td>
<td>323</td>
<td>257</td>
<td>16.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>250</td>
<td>316</td>
<td>258</td>
<td>10.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>241</td>
<td>211</td>
<td>13.6</td>
<td></td>
</tr>
</tbody>
</table>

5. Conclusions

When studying the effect of samarium on the structure, hardening kinetics during aging, as well as the mechanical properties of low yttrium-gadolinium magnesium alloys, the following main conclusions were obtained:

1. In Mg–Y–Gd–Zr alloys with the addition of samarium 1.7–2.5% and without it, dynamic recrystallization occurs during hot extrusion. Depending on the content of samarium and its ratio to the content of yttrium and gadolinium, recrystallization proceeds differently. With an increase in the samarium content, the microstructure of the alloys changes from completely recrystallized to partially recrystallized with the presence of elongated deformed grains. At the same time, a finer recrystallized grains (up to ~3 µm) are formed in the structure of hot-extruded alloys with samarium than in an alloy without samarium.

2. Hot-extruded Mg–Y–Gd–Sm–Zr alloys are additionally strengthened after isothermal aging at 200 °C due to the decomposition of the supersaturated magnesium solid solution. Samarium accelerates the decomposition of the Mg solid solution of the
Mg-Y-Gd-Zr alloys after hot extrusion, thereby reducing the duration of the heat treatment by aging required to achieve greatest hardening.

3. Strengthening of hot-extruded Mg–Y–Gd–Sm–Zr alloys during aging is due to the formation of a metastable orthorhombic phase $\beta'$ in the structure of plate-shaped precipitates, which is coherently bound to the crystal lattice of the magnesium solid solution. It is oriented with respect to the magnesium matrix in three symmetrical ways with the symmetry axis coinciding with the hexagonal axis of the crystal lattice of the Mg solid solution, and is arranged in large planes along the (110) planes of Mg perpendicular to its basal plane.

4. The addition of 1.7% samarium to the alloy with ~3% yttrium and ~5% gadolinium increases its strength properties at room temperature only after additional hardening aging and significantly reduces its ductility. However, the mechanical properties of the alloy are high at elevated temperatures of 200–300 °C. The addition of 2.5% samarium to the alloy with ~2% yttrium and ~4% gadolinium provides high mechanical characteristics up to 300 °C with a lower content of expensive REEs.


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Conflicts of Interest: The authors declare no conflict of interest.

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