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Effect of Samarium on the Properties of Mg–Y–Gd–Zr Alloys

E. A. Luk'yanova, L. L. Rokhlin*, T. V. Dobatkina, I. G. Korol'kova, and I. E. Tarytina
Baikov Institute of Metallurgy and Materials Science, Russian Academy of Sciences, Moscow, 119991 Russia
**e-mail: rokhlin@imet.ac.ru*

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Abstract—The microstructure, the aging kinetics, and the strength properties of Mg–Y–Gd–Zr cast alloys, in particular, a samarium-alloyed IMV7-1 alloy, at room and high (250, 300°C) temperatures after homogenization without and with subsequent aging are studied. Alloying with samarium accelerates the decomposition of the supersaturated magnesium solid solution and enhances the properties of the Mg–Y–Gd–Zr alloys.

Keywords: magnesium alloys, rare-earth metals, strength properties, solid solution decomposition

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INTRODUCTION

Magnesium alloys have a low density, high strength properties, and good absorption of mechanical vibrations and, hence, are widely used in light-weight products. Recently, the mechanical properties of magnesium alloys, especially those at high temperatures, were increased and the field of their application was broadened. This became possible due to alloying of magnesium with rare-earth metals (REMs) [1]. Mg–Y–Gd–Zr alloys demonstrate high strength properties [2–4]. These alloys include an IMV7-1 alloy developed at the Institute of Metallurgy and Materials Science [5]. Earlier studies showed that the strength properties of magnesium alloys can be enhanced by alloying with the REMs that belong to different periodic table groups [6, 7]. The present work continues to study magnesium alloys with REMs from various groups and the effect of samarium on the properties of Mg–Y–Gd–Zr alloys to enhance the properties and to reduce the aging time of the alloys during heat treatment.

EXPERIMENTAL

Investigations were carried out on cast Mg–Y–Gd–Sm–Zr alloys, which were heat treated under various conditions. The contents of yttrium, gadolinium, and zirconium were close to those in the IMV7-1 alloy (Mg–5% Y–5% Gd–0.5% Zr) [5].[1] The content of samarium addition did not exceed its maximum solubility in the magnesium solid solution in binary alloys [8] and was 1–5% Sm. The alloys to be investigated were melted in an electric resistance furnace in steel crucibles using a protecting VI-2 flux containing 38–46% $MgCl_2$, 32–40% KCl, 3–5% CaF_2, 5–8% $BaCl_2$, 1.5% MgO, and <8% (NaCl + $CaCl_2$). The starting materials were Mg-95 magnesium (>99.95% Mg), Sm-1 samarium (>99.83% Sm), ItM-1 yttrium (>99.83% Y), and GdM-1 gadolinium (>99.85% Gd). All alloying elements were introduced into a melt as preliminarily prepared master alloys Mg–43.6% Sm, Mg–39.15% Gd, Mg–42% Y, Mg–47.7% Y, and Mg–9.6% Zr.

A melt was poured from a crucible into a mold made of a corrosion-resistant steel heated to ~750°C, which was then slowly immersed in cold water. This method of casting provided directional solidification of the melt to form ingots with a dense homogeneous structure.

Chemical analysis was performed on a Jobin-Yvon Ultima 2C Inductivity Coupled Plasma-Atomic Spectrometer using atomic emission spectroscopy and an induction plasma. Alloy ingots were homogenized at 515°C for 6 h and, then, were water quenched at room temperature to form a supersaturated magnesium solid solution. The ingots were cut into samples, which were isothermally aged at 200°C for 128 h in order to trace hardening during decomposition of the supersaturated magnesium solid solution by measuring the hardness at room temperature and to establish the optimum aging time for the alloys. An aging temperature of 200°C was chosen, since it hardened the alloy to the largest extent according to [6]. The hardness at room temperature and at 250 and 300°C was measured by the Brinell method by pressing a ball 5 mm in diameter at a load of 2.45 kN using a TSh-2M hardness tester. Tensile properties were investigated on an Instron 3382 universal testing machine at a loading rate of 1 mm/min using standard samples with a gage portion

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[1] Hereafter, the element contents are given in wt %.

Table 1. Compositions of alloys Mg–Y–Gd–Sm–Zr (alloys 1–7) and Mg–Y–Gd–Zr (IMV7-1, alloy 8)

Alloy	Component content,* %			
	Y	Gd	Sm	Zr
1	7	7	5	0.5
2	6	6	4	0.5
3	5	5	3	0.5
4	4	4	2	0.5
5	3	3	1	0.5
6	7	7	1	0.5
7	3	3	5	0.5
8	5	5	–	0.5

*Magnesium for balance.

Table 2. Maximum hardness achieved upon aging and incubation times τ for the hardness variation in alloys 1–8

Alloy	$HB_{\max}$, MPa	τ, h
Mg–Y–Gd–Sm–Zr alloys		
1	1469	2
2	1403	2
3	1317	4
4	1069	8
5	982	8
6	1354	4
7	1165	2
Mg–Y–Gd–Zr alloy (IMV7-1)		
8	1210	8

5 mm in diameter. Metallographic polished sections for microstructural examination were prepared by polishing on a woolen cloth using a chromium oxide suspension in water. Samples were etched in a 0.5% solution of nitric acid solution in alcohol or a 30% solution of orthophosphoric acid in alcohol to reveal their microstructure. The microstructure was examined by optical microscopy on an M-24 Reichert metallographic microscope.

RESULTS AND DISCUSSION

The compositions of the investigated alloys (Table 1) were taken to be the same as in the charges, since chemical analysis showed insignificant deviations of the experimentally determined compositions from the calculated ones. The compositions were chosen as follows. Alloy 8 (IMV7-1 alloy) used for comparison included the optimal content of alloying elements, namely, yttrium, gadolinium and zirconium; i.e., this composition could be considered as nominal. Alloys 2, 3, and 4 were found to contain the expected maximum, average, and lowest REM contents, respectively, including additionally introduced samarium. Alloy 1 comprised the maximum amount of all REMs at which high strength properties but low ductility were expected. Alloy 5, on the contrary, contained the lowest amount of all three REMs at which low strength properties were expected. The remaining two alloys should characterize the mechanical properties at extremely high yttrium and gadolinium contents and at an extremely low samarium content (alloy 6) and extremely low yttrium and gadolinium contents at an extremely high samarium content (alloy 7). The zirconium content was the same in all alloys, namely 0.5%, which corresponds to the standard content in magnesium alloys with REMs.

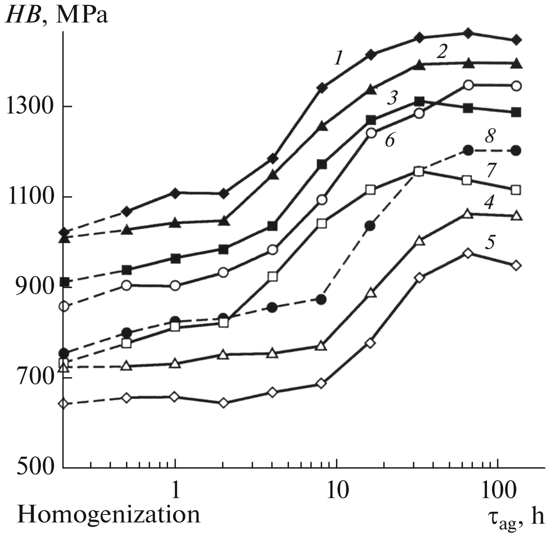

Fig. 1. Change in the hardness *HB* of alloys Mg–Y–Gd–Sm–Zr (*1*–*7*) and Mg–Y–Gd–Zr (*8*) during isothermal aging at 200°C.

The study showed that the IMV7-1 alloy with samarium and the IMV7-1 alloy with the nominal composition were hardened upon aging. Figure 1 shows the hardnesses of the IMV7-1 and Mg–Y–Gd–Sm–Zr alloys measured during isothermal aging. The hardness of all alloys changes similarly to that of magnesium alloys with REMs of the yttrium subgroup: a certain incubation time takes place. However, the incubation time and the time when the hardness begins to increase sharply were different depending on the alloy composition. Table 2 lists the maximum hardness achieved during aging and incubation times τ for all alloys.

Figure 1 shows the following behavior of hardness. First, the hardness of the initial homogenized alloys and after aging at any temperatures increases when the total content of yttrium, gadolinium, and samarium is increased via a certain increase in the content of each of them. Aging also increases the maximum hardness. This is evident when comparing the hardnesses of alloys 1–5. The incubation time of the decomposition of the supersaturated magnesium solid solution

Table 3. Hardness *HB* (MPa) of the alloys IMV7-1 alloy (8), ML5, and Mg–Y–Gd–Sm–Zr (1–3, 6) at 20, 250, and 300°C in various states

Alloy	State					
	homogenization at 515°C, 6 h			aging at 200°C, 32 h		
	test temperature, °C			test temperature, °C		
	20	250	300	20	250	300
8	755	625	481	1165	760	491
ML5	675	276	144	853	307	142
1	1022	988	666	1457	1015	713
2	1011	742	628	1399	980	680
3	912	695	580	1317	940	636
6	858	742	621	1292	954	699

decreases with increasing total REM content in these alloys.

Second, the introduction of samarium into Mg–Y–Gd–Zr alloys increases the hardness and accelerates hardening during the decomposition of the supersaturated magnesium solid solution. This can be seen from a comparison of the hardness curves upon aging of alloys 8 (IMV7-1 alloy without samarium) and 3 (3% Sm and the same content of yttrium, gadolinium, and zirconium) and 6 and 1 (1 and 5% Sm and the same content of yttrium, gadolinium, and zirconium, respectively). A comparison of the hardness curves upon aging of alloy 8 (IMV7-1 without samarium) and alloys 1–3 with 3–5% Sm also suggests that samarium alloying of Mg–Y–Gd–Zr alloys accelerates the decomposition of the supersaturated magnesium solid solution and the related hardening (see Fig. 1).

Third, the total hardness of the alloys in the investigated content range of the REMs is mainly determined by the content of yttrium and gadolinium in them. The role of samarium in the hardness and the hardening on aging is weak as compared to other elements. This conclusion can be made from a comparison of alloys 7 and 1, which contain the same amount of samarium (5%) and different amounts of yttrium and gadolinium (3% in 7 alloy and 7% in 1 alloy).

The advantage of the Mg–Y–Gd–Zr alloys is their higher strength properties (higher high-temperature strength) at elevated temperatures up to 300°C as compared to other magnesium alloys. The effect of samarium on the high-temperature strength of the Mg–Y–Gd–Zr alloys was estimated by measuring the hot hardness at high (250, 300°C) temperatures after homogenization and subsequent hardening aging. Alloys bearing REMs were homogenized at 515°C for 6 h and then aged at 200°C for 32 h.

For comparison, a widely used commercial magnesium cast ML5 alloy (Mg–8% A1–0.3% Mn–0.8% Zn) was prepared according to Russian Standard GOST 2856–79 and tested under the same conditions. This alloy was subjected to heat treatment, which includes homogenization at 415°C for 8 h and aging at 200°C for 8 h.

Table 3 lists hardness *HB* of several Mg–Y–Gd–Sm–Zr alloys and the IMV7-1 and ML5 alloys at room temperature, 250, and 300°C after homogenization and subsequent hardening aging.

It is seen that the hardness of samarium-bearing alloy 3 at all temperatures is higher than that of the IMV7-1 alloy (alloy 8 without samarium) containing the same amount of yttrium and gadolinium as alloy 3 does. The hot hardness of the alloys 2 and 1 grows when the content of samarium, yttrium, and gadolinium is increased and turns out to be higher at all temperatures of tests in both states compared to both alloy 8 containing no samarium and the commercial magnesium ML5 alloy. The hardness of the alloys after aging at 200°C is high for all test temperatures (20, 250, 300°C).

As a result, this study suggests that samarium alloying of the IMV7-1 alloy enhances its hardening and decrease the time it takes for the maximum hardening to be achieved. Samarium alloying of the alloys containing yttrium and gadolinium hardens them at room temperature, which also retains at elevated temperatures (up to 300°C). Reducing the aging time to achieve the maximum hardening makes hardening heat treatment of samarium-containing alloys energetically favorable.

The resulting tensile properties (Table 4) of the Mg–Y–Gd–Sm–Zr alloys as compared to those of the IMV7-1 alloy confirm the usefulness of samarium alloying of the IMV7-1 alloys to enhance their

Table 4. Mechanical tensile properties of the IMV7-1 and Mg–Y–Gd–Sm–Zr alloys

Alloy, state	Test temperature 20°C			Test temperature 250°C		
	σ_u	$\sigma_{0.2}$	δ, %	σ_u	$\sigma_{0.2}$	δ, %
	MPa			MPa		
8 (IMV7-1, Mg–Y–Gd–Zr):						
homogenization at 515°C, 6 h	225	158	9.1	185	114	10.3
the same + aging at 200°C, 32 h	243	164	3.2	193	136	7.2
1 (Mg–Y–Gd–Sm–Zr):						
homogenization at 515°C, 6 h	260	176	3.9	223	137	5.6
the same + aging at 200°C, 24 h	299	267	1.5	260	245	2.4
4 (Mg–Y–Gd–Sm–Zr):						
homogenization at 515°C, 6 h	245	170	13.8	–	–	–
the same + aging at 200°C, 24 h	284	261	1.7	243	204	2.8

strength properties (especially the yield strength) at room temperature and high-temperature strength.

Microstructural examination exhibited gray crystals in the structure of the cast alloys, which consisted of magnesium and REMs and formed as a result of nonequilibrium crystallization (Fig. 2a). The number of these crystals in the structure increased when the REM content increased. These crystals dissolved almost completely during homogenization even in the most complex alloys (Fig. 2b). Individual fine black crystals of the zirconium phase (αZr) were also observed. Optical microscopy shows no noticeable changes in the structure of the alloys after aging. The electron microscopic examination of the Mg–Y–Gd–Zr alloys aged at 200°C [9] in the studied content range showed the formation of the metastable β'' and β' phases, hardening these alloys on aging. The hardening of the Mg–Y–Gd–Sm–Zr alloys can be also explained by the precipitation of the metastable phases from the solid solution.

These results were used to propose a composition for a new REM-contaning cast magnesium alloy [10].

CONCLUSIONS

(1) Samarium alloying of IMV7-1 (Mg–Y–Gd–Zr) alloys resulted in the acceleration of the decomposition of the supersaturated magnesium solid solution and aging-induced hardening. The general kinetics of decomposition and hardening remained the same during aging.

(2) Samarium alloying enhanced the strength properties (hardness, yield strength, tensile strength)

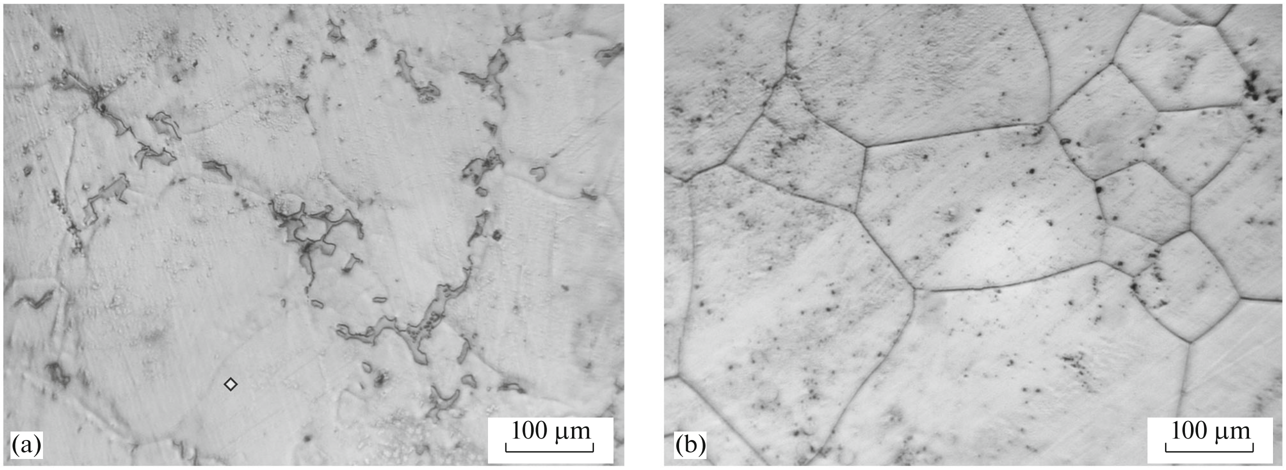

Fig. 2. Microstructures of alloy 3 (Mg–5% Y–5% Gd–3% Sm–0.5% Zr) in (a) as-cast state and (b) state homogenized at 515°C for 6 h.

of the Mg–Y–Gd–Zr alloys, which retained their high-temperature strength.

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