Investigation of the mg supersaturated solid solution decomposition in the Mg-Dy-Sm alloys

Lazar Rokhlin, Tatiana Dobatkina, Irina Tarytina, Elena Lukyanova, Olga Ovchinnikova
Institution of Russian Academy of Sciences. A.A. Baikov Institute of Metallurgy and Material Science RAS, Russia

Abstract: *Kinetics and phase transformations during decomposition of the supersaturated Mg solid solution in the Mg-Dy-Sm alloys at different Dy/Sm content ratios were investigated in this work. The solid solution decomposition occurs upon aging at a temperature of 200°C, at which strengthening of the alloys was expected to be highest. With increasing Dy/Sm ratio, the solid solution decomposition gradually decelerates. Addition of Dy to the Mg-Sm alloys intnsifies the age hardening, and the addition of Sm to the Mg-Dy alloys also promotes the hardening. The Mg solid solution decomposition in the ternary Mg-Dy-Sm alloys is accompanied by the formation of the GP-zones, ordering, and the precipitation of plate-like particles in certain planes of the Mg crystal lattice. Such processes are typical of solid solution decomposition in the binary Mg-Re (Nd, Sm, Y, Gd, Tb, Dy) alloys.*

***KEYWORDS**: MAGNESIUM ALLOYS, RARE-EARTH METALS, SOLID SOLUTION DECOMPOSITION, PHASE TRANSFORMATION*

1. Introduction

Magnesium alloys attract a great attention now as the structural materials of low density. They are advantageous for various applications, especially in aerospace and automotive industries, where the weight saving of the constructions is very important [1-3]. As all other structural materials, magnesium alloys should have high strength, which is generally increased by using various alloying additions. Recent investigations show that the highest strength of magnesium alloys at near room and elevated temperatures can be obtained by alloying with certain rare-earth metals [4,5]. In particular, the rare-earth metals belonging to different subgroups such as the cerium subgroup including elements from La to Eu of the lanthanum row and the yttrium subgroup including Y and the elements from Gd to Lu of the lanthanum row apparently differ in the action on magnesium. The Mg-Dy-Sm alloys attract interest because the strength properties of the Mg alloys with rare-earth metals are greatly determined by the decomposition of supersaturated Mg solid solution upon heat treatment. The binary Mg alloys with Sm (cerium subgroup) and Dy (yttrium subgroup) are characterized by high strengthening upon such process, but differ in some important specific features [4]. The aims of this work were as follows:

1) Determination of the decomposition kinetics of the supersaturated Mg-based solid solution in the ternary Mg-Dy-Sm alloys, especially the kinetics of the alloy strengthening upon the decomposition.

2) Establishment of the effect of dysprosium to samarium concentration ratio on the decomposition rate of supersaturated Mg solid solution and the maximum strengthening, which can be achieved upon this process.

2. Materials and methods

The alloys were prepared by melting the initial metals taken in certain proportions in the electrical resistance furnace in crucibles of low-carbon steel under flux preventing Mg melts from burning at air. The prepared melts of the alloys were cast into mould of stainless steel to ingots of 15 mm in diameter and 90 mm in length.

The alloy compositions and their heat treatment regimes were chosen with allowance for the equilibrium Mg-Dy-Sm phase diagram [6]. The ingots of the prepared alloys were solution treated by annealing at 520ºC for 6 hours and quenched in room-temperature water for obtaining supersaturated solid solutions of Mg-based alloys. The decomposition of Mg solid solution upon aging at 200^{o}C was monitored by the measurements of hardness and electrical resistivity. The structure was examined by optical microscopy and transmission electron microscopy (TEM).

3. Results and discussion

The results of the hardness measurements upon isothermal aging of the Mg-Dy-Sm alloys are shown in Fig.1. Analysis of the data indicates the certain specific features of the age hardening of the ternary Mg-Dy-Sm alloys as compared with that of the binary Mg-Dy and Mg-Sm alloys.

The first feature is that the addition of Dy to the Mg-Sm alloys and increase in the Dy content generally increase the hardness of the alloy. The hardness maxima reached upon aging of the alloys become higher with increasing Dy content and, correspondingly, with increasing Dy/Sm ratio. The second feature of the age-hardening of the Mg-Dy-Sm alloys is that this process occurs by two stages differing in kinetics. At the first stage, the hardness changes slowly and insignificantly, but at the second stage the hardness increases abruptly and reaches maximum. The existence of the two stages manifests itself differently in different alloys. In the binary Mg-Sm alloy and in the ternary alloys with the smallest Dy contents they are virtually absent.

The results of the electrical resistivity measurements of the alloys upon isothermal aging are presented in Fig.2. The resistivity increases successively with increasing total content of the rare-earth metals in the alloys in accordance with the possibility to have more quantities of the soluble atoms in the supersaturated Mg-based solid solutions. Decrease in the electrical resistivity with increasing aging time exhibits the depletion of the Mg-based supersaturated solid solutions since the rare-earth atoms go out of them. Meanwhile, the electrical resistivity curves display kinks reflecting the certain stages of this process. In general, the stages of the solid solution depletion illustrated by the electrical resistivity curves correspond to the above mentioned two stages of the solid solution decomposition traced by the hardness measurements. Optical microscopy was found to be insufficiently informative for investigation of the alloy structures

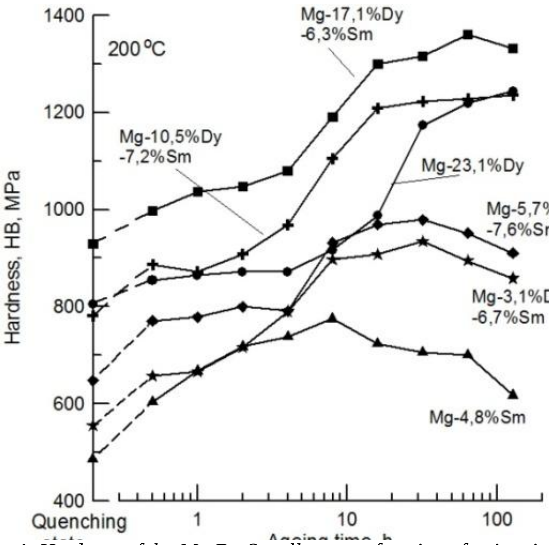

Fig.1. *Hardness of the Mg-Dy-Sm alloys as a function of aging time at 200°C*

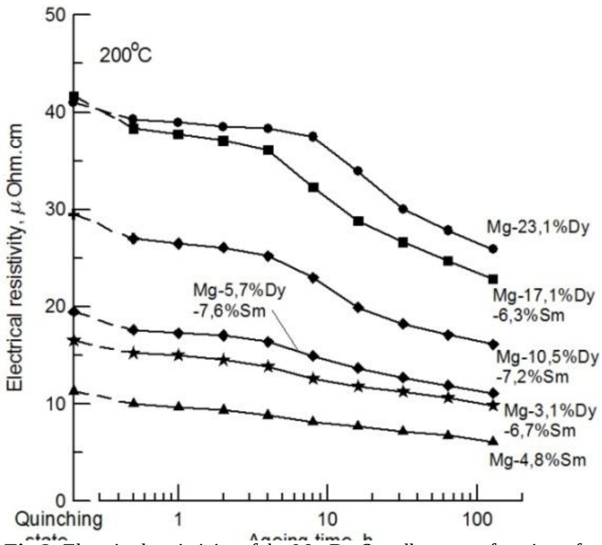

Fig.2. *Electrical resistivity of the Mg-Dy-Sm alloys as a function of aging time at 200°C*

The TEM examination revealed some precipitated particles, but no signs of the initial stage of the solid solution decomposition were exhibited by the solid solution grains of the ternary Mg-5.7%Dy-7.6%Sm alloy with small Dy content after solution treatment. Such signs are usually represented by lines of two-dimensional diffraction and superlattice reflections. The typical structure of the alloy and its diffraction pattern are shown in Fig. 3. Separate extinction lines are seen in the TEM structure image (Fig.3a) and the isolated large reflections of the Mg-based solid solution are seen in the corresponding diffraction pattern (Fig. 3b).

The next stage of the decomposition of the Mg based solid solution in the Mg-5.6%Dy-7.6%Sm alloy was observed by weakness or disappearance of the straight lines indicating the existence of GP-zones and the appearance of new superlattice reflections typical of the decomposition of the Mg-based solid solution in the binary Mg-Dy alloys [7] and other Mg-based alloys containing the rare-earth metals of yttrium subgroups (Y, Gd, Dy) with the formation of the metastable β′ phase with base-centered orthorhombic lattice (cbco) [8]. The images of the Mg grain fields remained uneven, but rougher than before, without any clearly visible precipitates (Fig.4a). The arrangement of the superlattice reflections become more complex, but all of them are observed within the basal planes or their tracks in the reciprocal Mg lattice. All superlattice reflections are present at all Mg [100]* radius-vectors of the Mg reciprocal lattice, dividing them to four equal parts. One of such diffraction patterns is shown in Fig.4b. The diffraction patterns obtained from the Mg lattice in the Mg-5.7%Dy-7.6%Sm alloy confirmed also the similarity of the alloy structure at this stage of the Mg-based solid solution decomposition to that observed in the binary Mg-Dy and other Mg-based alloys with rare-earth metals of the yttrium subgroup (Y, Gd, Dy), which contain the metastable (cbco) β´ phase. This state of the solid solution decomposition in the Mg-5.7%Dy-7.6%Sm alloy corresponds to the hardness maximum after aging at 200°C for 32 h.

At the latest stage of the solid solution decomposition of the Mg-5.7%Dy-7.6%Sm alloy at 250°C (softening after hardness maximum), coarse plate-like crystals are formed, which are present on three planes in the Mg hexagonal lattice. The micrograph of this structure presented in Fig.5a exhibits the plate-like shape of the precipitated particles. The particles are clearly outlined in the structure. The diffraction pattern taken from the area shown in Fig.5a is presented in Fig.5b. The number of superlattice reflections is smaller, and they are very fine. Nevertheless, the reflections can be distinguished only in the tracks of the basal planes of the Mg reciprocal lattice. (It would be reasonable to suppose that the coarse plate-like precipitates belong to one of the equilibrium phases ($Mg_{41}Sm_5$ or $Mg_{24}Dy_5$ [6])).

Taking into consideration the Mg-Dy-Sm phase diagram [6], two processes of the decomposition of the Mg based supersaturated solid solution could be expected in the ternary Mg-Dy-Sm alloys. Each of them should be completed with the formation of two equilibrium phases existing in the adjoining Mg-Dy and Mg-Sm binary systems, $Mg_{24}Dy_5$ and $Mg_{41}Sm_5$, respectively. Only such binary compounds are in equilibrium with Mg solid solution in the ternary Mg-Dy-Sm system.

4. Conclusions.

1. The decomposition of the Mg based supersaturated solid solution in the Mg-Dy-Sm alloys becomes successively less intense with increasing Dy/Sm concentration ratio.

2. The decomposition of the Mg based supersaturated solid solution occurs by two main stages. At the first stage, the strengthening of the alloys is insignificant and, at the second stage, the hardness abruptly increases, reaches maximum and decreases with increasing aging time.

3. Addition of Dy to the Mg-Sm alloys enhances their age hardening. On the other hand, the addition of Sm to the Mg-Dy alloys also increases their strengthening. The highest hardness of the Mg-Dy-Sm alloys is reached at a Dy/Sm ratio of about 1.5.

4. The decomposition of the Mg based supersaturated solid solution in the Mg-Dy-Sm alloys is accompanied by the formation of precipitates typical of the binary Mg-Sm and Mg-Dy alloys. They include GP-zones in the form of the rods directed along the hexagonal axis of the Mg lattice, ordering of the Mg_3Cd type (β″), formation of the metastable base-centered orthorhombic (cbco) β´ phase, and equilibrium phases. The highest hardness is reached due to the formation of the metastable cbco β´ phase. The precipitation of supposedly equilibrium phase is also observed at the grain boundaries of the Mg based solid solution.

5 The plate-like precipitates formed upon the decomposition of the Mg based supersaturated solid solution in the ternary Mg-Dy-Sm alloys contain both Dy and Sm in different ratios.

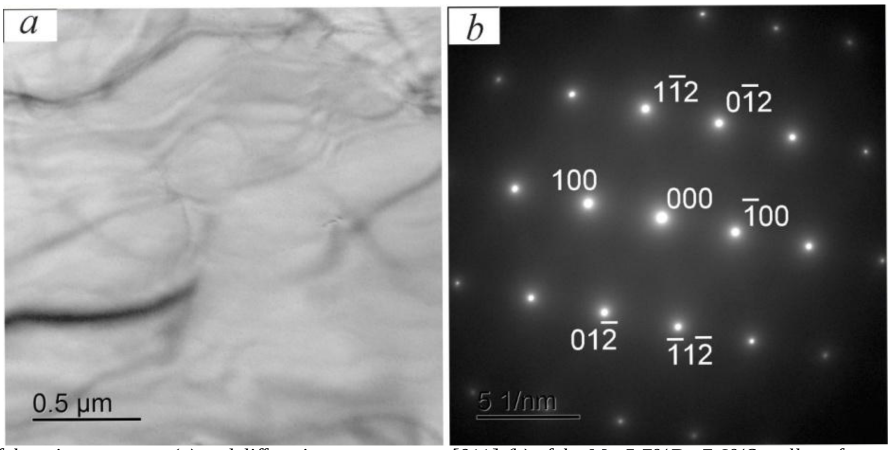

Fig.3. *TEM image of the microstructure (a) and diffraction pattern, zone [011] (b) of the Mg-5.7%Dy-7.6%Sm alloy after solution treatment and natural aging*

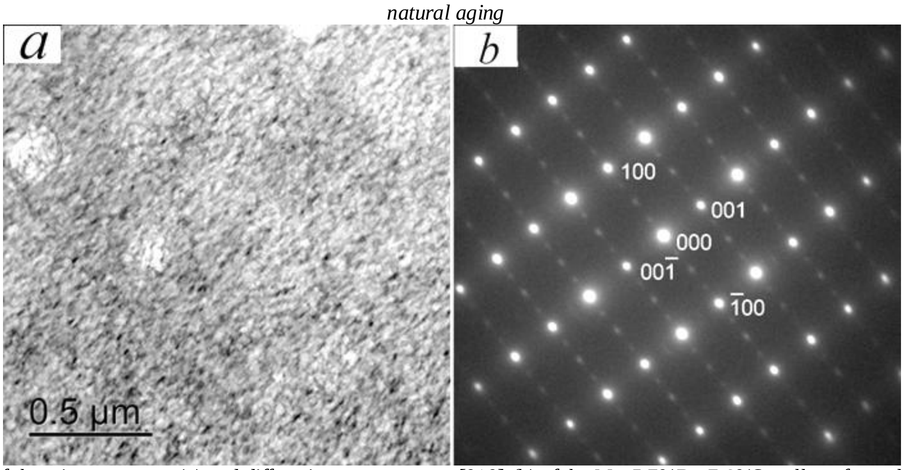

Fig. 4. *TEM image of the microstructure (a) and diffraction pattern, zone [010] (b) of the Mg-5.7%Dy-7.6%Sm alloy after solution treatment and aging at 200°C for 32h*

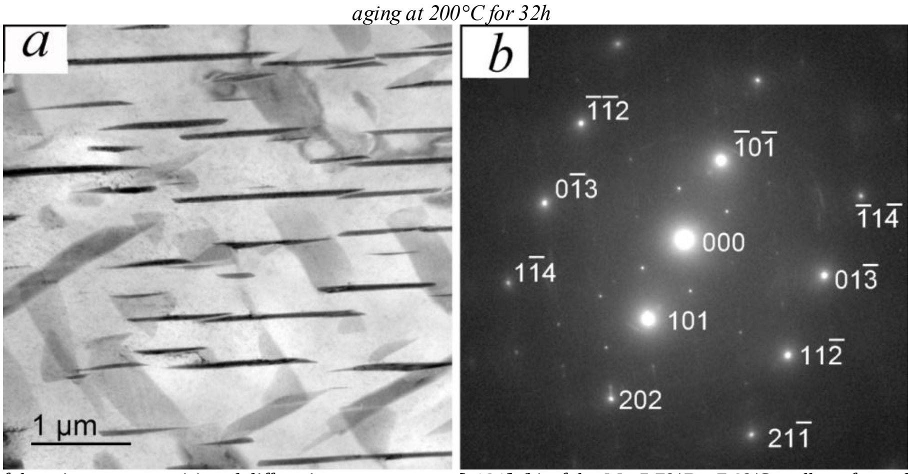

Fig.5. *TEM image of the microstructure (a) and diffraction pattern, zone [-131] (b) of the Mg-5.7%Dy-7.6%Sm alloy after solution treatment and aging at 250°C for 128 h.*

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