In this paper we study the recrystallization of magnesium and alloys containing about 0.05-0.09 and 9 at. % Mn, Al and Ca.

The alloys were made from MG1 magnesium (99.91%), AV000 aluminum (99.98%), sublimated calcium and an Mg-Mn hardener. Ingots weighing 0.5 kg were cast into metal molds and then rolled twice. The final rolling with 60% deformation was carried out after the ingots had been heated to 300°. The deformation conditions were selected in such a way that crystallization did not have time to take place during the treatment, and that high-grade metal, without cracks was obtained. Subsequent annealing was carried out at 65-275° for periods lasting one minute to 40 hours.

The beginning of recrystallization in the alloys was determined from the microstructure. To relieve work hardening the surfaces of the specimens were etched to a depth of 0.1 mm in a 50% aqueous solution of HNO₃.

The microstructure was studied after further polishing and etching in a 5% solution of HNO₃ in alcohol.

To study the mechanics of recrystallization of magnesium we used the method described in [1]. It consists in the following: an annealed specimen is locally deformed (indented by a ball in a hardness tester) and then annealed at different temperatures. The recrystallization is observed from the appearance of new, very fine grains in the indentation zone. Sheet magnesium specimens rolled with a 60% reduction was subjected to recrystallization annealing at 450° for one hour, as a result of which there formed a coarse-grain structure, after which they were locally deformed in a Brinell press (load of 3,000 kg, ball diameter 5 mm) and annealed at 65-100° for 20 minutes to 10 hours.

Figure 1 shows the different times at which the recrystallization of magnesium began in the alloys in question. As can be seen, the time required for recrystallization to begin decreases appreciably as the annealing temperature is stepped up in all the materials in question. For example, in the case of magnesium, as the annealing temperature rises from 65 to 1050°, the time prior to recrystallization is reduced from 10 hours to several minutes. In the case of magnesium alloys containing 0.1% weight Mn or Al (Fig. 1a) the time prior to recrystallization at 75 and 150° falls from 13 and 18 hours to 3 minutes.

Thus, at 150° the recrystallization of the magnesium and its alloys containing small amounts of manganese and aluminum begins within several minutes. When the same amount of calcium is added to the magnesium, recrystallization is greatly inhibited, and at 150° the time required is increased to 13 hours, i.e., by a factor of approximately 150. In the alloy containing a larger amount of calcium no recrystallization is observed at this temperature, even after prolonged periods, and it is only after heating for 15 hours at 200° that we find the first recrystallized grains.

Figure 2 shows how the recrystallization process develops with time at 200° in the case of a magnesium alloy containing 2% weight Mn (0.9 at. %). As can be seen recrystallization begins after the alloy has been soaked for 5 minutes (Fig. 2a); after 10 minutes the number of recrystallized grains increases appreciably (Fig. 2b) and 5 hours later recrystallization is completely over (Fig. 2c).

The activation energy for the beginning of recrystallization of magnesium and its alloys was calculated from the slope of the experimental lines shown in Fig. 1 using the equation given in [2].

The activation energy is shown in the table, which also gives data for the mechanics of recrystallization of alloys at 150°. There are no published data on the activation energy or the recrystallization temperature of magnesium. The activation energy we obtained for pure magnesium is 17.5 kcal/g at, i.e., almost half the activation energy for self-diffusion (32 kcal/g at) [3]. Taking into account what has been said, plus the data contained in [4] - [6], we can say that the mechanism of recrystallization differs from the mechanism of self-diffusion.

As can be seen from the table, when the amount of alloying element is small (0.1% weight or 0.05 at. %) an increase in the time prior to the start of recrystallization corresponds to a higher activation energy. The maximum increase in activation energy for recrystallization (17.5 - 36 kcal/g at.) occurs when magnesium is alloyed with calcium, which inhibits the recrystallization process to the greatest extent.

An increase in the alloying component either has no effect at all on the activation energy (Mg-Al alloys) or only slightly reduces it (Mg-Mn and Mg-Ca alloys). The different effects of the alloying elements studied on the recrystallization process of magnesium is evidently due to the
Alloy

<table>
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<tr>
<th>Amount of alloying component</th>
<th>Time prior to recrystallization at 150° in minutes</th>
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<tbody>
<tr>
<td>In % weight</td>
<td>In at. %</td>
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<tr>
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<tr>
<td>Mg - Ca</td>
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**Table**

**Fig. 3.** Relationship between atomic dimensions of alloying elements and increase in time prior to commencement of recrystallization of magnesium at 150°; 1) 0.06 - 0.09 at. %; 2) 0.9 at. %

Figure 3 shows the relationship between time required for initiation of recrystallization of magnesium containing 0.06 - 0.09 and 0.9 at. % additive and the atomic diameter of the alloying element.

Calcium, which has a larger atomic diameter than magnesium, hampers recrystallization to a greater extent than manganese and aluminum, which have smaller atomic dimensions. For example, despite the close absolute values of the dimensional factor (-23.2 and -19.7% for calcium and manganese, respectively), the time required for the start of recrystallization at 150°, compared with manganese, is increased by a factor of almost 800, and in the second case by only 3. A similar regularity is valid for higher concentrations of these elements. More than 30,000 minutes are required for magnesium with 0.9 at. % Ca to begin recrystallizing, but only one hour for magnesium containing the same amount of manganese.

Aluminum, with a smaller atomic diameter than magnesium (dimensional factor from 10.6%), is the least effective of the elements studied. As can be seen from the table and from Fig. 3, in the magnesium alloy containing 0.9 at. % Al the recrystallization is detected after only 5 minutes at 150°.

The dimensional factor also determines the interaction between components, particularly the maximum solubility of the alloying additive in the base metal in the solid state. If we analyze the data obtained, it seems that the less the solubility of the element in solid magnesium, the more inhibited the recrystallization process. Calcium, which has very limited solubility (0.58 at. % at 517°) has the greatest effect on an increase in the recrystallization time for magnesium at the temperature studied.

Manganese, which has a very high maximum solubility in magnesium (1.03 at. % at 653°), affects the recrystallization process to a much less extent.

Aluminum shows a wide range of solid solutions (11.6 at. % at 437°) and slows down the recrystallization of magnesium to a far lesser extent than manganese.