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**SUPER-LIGHT CONSTRUCTION ALLOYS
(CHAPTERS I, III, IX)**

M. E. Drits, et al

**Foreign Technology Division
Wright-Patterson Air Force Base, Ohio**

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CHAPTER I

PHYSICOCHEMICAL AND MECHANICAL PROPERTIES OF MAGNESIUM AND LITHIUM

Properties of Magnesium

Magnesium is a chemical element of Group II of the Mendeleyev periodic system; it is a silvery white metal with specific gravity of 1.74 g/cm^3 in the solid state and 1.54 g/cm^3 as a liquid (at 700°). The melting temperature is 650° and the boiling temperature is 1107° . The electrical conductivity of magnesium is 38.6% of that of copper.

Distilled water has no effect on magnesium. Magnesium is destroyed in seawater and mineral water. Magnesium dissolves in aqueous solutions of the majority of mineral acids and salts. It is resistant to solutions of hydrofluoric and chromic acid, soda, strong alkalies, and also benzene, kerosine, and mineral oils; therefore it can be used to manufacture conduits, tanks, and cisterns for the transportation and storage of these liquids.

Thanks to its high chemical activity with oxygen, magnesium is used as a deoxidizer in the production of steel and nonferrous alloys; it is also used to obtain hard-to-reduce metals (titanium, zirconium, uranium, vanadium, chromium, etc.) by separating them from compounds.

Magnesium is also used to obtain high-strength inoculated cast iron. It is introduced into molten cast iron in a quantity of 0.3-1.2%.

In the chemical industry powdered magnesium is used to dehydrate organic substances (alcohol, analine, etc.) and also to obtain organomagnesium compounds. In powdered form and as strip magnesium burns with a dazzling white flame; this fact is utilized in pyrotechnics, in high-speed photography, and in military engineering (signal flares, incendiary bombs, etc.).

Magnesium is used in alloying of aluminum alloys and also for the creation of alloys of magnesium itself [1, 2].

Magnesium is a valuable structural material for broad utilization in the national economy, since it falls in the class of elements which are most widely distributed in the Earth's crust. Magnesium comprises about 2.4% of the weight of the crust, while the values for other metals are as follows: titanium, 0.6%; copper, 0.01%; zinc, 0.005%; nickel, 0.008%; lead, 0.0016%, etc. However, magnesium is 4.5 times lighter than iron, 5 times lighter than copper, 2.6 times lighter than titanium, and 1.5 times lighter than aluminum. Thanks to their low specific weight magnesium alloys are of particular interest for structures whose weight must be small (aeronautical, space, and rocket engineering, transport equipment, etc.). They are nonmagnetic and do not give off sparks under impact and friction; these materials are easily worked by machining and by pressure and can be welded by gas and arc welding.

Ingot magnesium and also articles made from magnesium alloys do not represent a danger of fire. Magnesium in the form of rods, powder, or dust can represent a fire danger. The reaction of water with hot and molten magnesium is accompanied by explosion due to the intensity of the combustion of hydrogen which is liberated during the reaction.

The first effort to obtain magnesium in free form was made by Davy in 1800. However, his efforts were unsuccessful. Not until 1828 did Bussy succeed in obtaining magnesium in pure form. Later St. Clair-Deville and Caron first accomplished the production of magnesium by reduction of molten magnesium chloride by metallic sodium, using CaF_2 as a flux. However, the application of magnesium as an engineering metal is connected with the development of the electrolytic production method. In our country the first experiments on the production of magnesium were carried out in 1914-1915 by P. P. Fedot'yev and N. K. Voronin [3, 4].

The first ton-scale lots of industrial magnesium were produced in the 1930's. At present the Soviet magnesium industry occupies a leading place in the world production of magnesium [5].

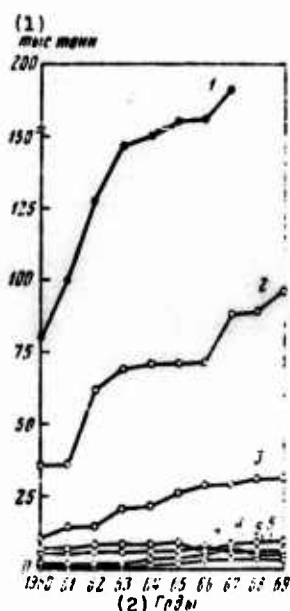


Fig. 1. Production of primary magnesium. 1 - world production; 2 - USA; 3 - Norway; 4 - Canada; 5 - Italy; 6 - Japan; 7 - France. KEY: (1) 1000 tons; (2) Years.

Recent years have seen provision made for a substantial increase in the production and application of magnesium in various branches of technology. This is due, on the one hand, to the possibility of obtaining a wide variety of magnesium-based alloys with high specific strength characteristics and, on the other hand, with the availability

of substantial resources for the production of magnesium. Magnesium is significant in our country not only as a valuable technical material, but also as a substitute for scarce and expensive metals.

A survey of the foreign literature in recent years attests to the significant growth in magnesium production in the capitalist countries. It is clear from the data in Fig. 1 that the major producer of magnesium in the capitalist world is the USA; its share of total production is about 60%. Norway is in second place [6].

Magnesium is supplied in the form of ingots weighing 8 ± 1 kg. Each ingot should be stamped with the trademark of the manufacturer, the magnesium symbol Mg, and the number of the melt. The content of sodium as an impurity should not exceed 0.01%, and that of potassium 0.005%; the sum total of impurities as controlled by GOST 804-62 should not be more than 0.1%, with the following contents of individual elements (% , no more than): 0.04 Fe; 0.01 Si; 0.001 Ni; 0.005 Cu; 0.02 Al; 0.04 Mn and 0.005 Cl.

Table 1. Mechanical properties of magnesium at 20°C.

State of material	$\sigma_{0.2}$ kgf/mm ²	σ_b kgf/mm ²	δ , %	ψ , %	HB, kgf/mm ²
Cast	2.5	11.5	8.0	9.0	30
Deformed	9.0	20.0	11.5	12.5	36

Designation: $\text{kgf/mm}^2 = \text{kgf/mm}^2$.

Table 2. Mechanical properties of cast magnesium at elevated temperatures (stabilized at test temperature for 50 hours).

Temperature, °C	$\sigma_{0.2}$ kgf/mm ²	δ , %	Temperature, °C	$\sigma_{0.2}$ kgf/mm ²	δ , %
100	9.3	18	350	1.40	72
200	5.6	28	400	0.85	80
250	4.1	40	450	0.50	78
300	2.5	58	500	0.35	81

Table 3. Mechanical properties of deformed (pressed) magnesium at elevated temperatures.

Temperature, °C	$\sigma_{0.2}$, kgf/mm ²	σ_b , kgf/mm ²	δ , %	ψ , %	σ_{-1} , kgf/mm ²
200	2,5	6,0	42,5	36,5	2,3
250	2,0	3,0	41,5	32,5	5,0
300	1,6	2,0	58,5	35,5	12,5
350	1,2	1,8	95,0	38,0	17,0
400	0,5	1,0	60,0	33,5	10,3
450	0,4	0,6	65,5	35,5	13,5

Tables 1-3 show the mechanical properties of magnesium in the cast and deformed states at room and elevated temperatures. Data which characterize the modulus of normal elasticity for pure magnesium at various temperatures are given below:

Temperature, °C	20	100	200	300	400	450
Modulus E, kgf/mm ²	4500	4300	4100	3900	3600	3400

The physicochemical properties of magnesium are characterized by the following data:

Atomic number	12
Valence	2
Atomic weight	24.323
Atomic volume, cm ³ /g-atom	13.99
Poisson number.	0.33
Speed of sound in solid magnesium, m/s	4800
Conductivity at 0°C, m/ohm·mm ²	23
Temperature coefficient of electrical resistance (0 to 100°C)	$3.9 \cdot 10^{-3}$
Resistivity (at 20°C), ohm·mm ² /m.	0.047
Thermal conductivity, cal/cm·s·deg.	0.376
Temperature of beginning of recrystallization (minimum, °C.	150
Melting temperature, °C	650 ± 1
Coefficient of volume expansion in the liquid state (at 651-800°C)	$380 \cdot 10^{-6}$
Latent heat of fusion (99.93 Mg), cal/g	~70

Boiling temperature, °C	1107 ± 3
Latent heat of vapor formation during boiling, cal/g.	1350
Entropy at 25°C, cal/g-atom·deg	7.76
Specific heat of vapors, cal/g·deg. . .	0.208
Heat of MgO formation, cal/g-atom . . .	145.8
Electrochemical equivalent, g/amp-hrs .	0.454
Compression during crystallization, % .	3.97-4.2
Shrinkage in the solid state. (from 650 to 20°C), %	2.0
Specific magnetic susceptibility. . . .	$+0.55 \cdot 10^{-6}$
Normal potential with respect to electrode:	
hydrogen, V	-1.55
calomel, V	-1.83

The crystal structure of magnesium is hexagonal close-packed. The coordination number is 6 + 6. Lattice parameters at 25°: $a = 3.2030 \text{ Å}$, $c = 5.2002 \text{ Å}$, $c/a = 1.6235$. The interatomic distance $d_1 = 3.1906 \text{ Å}$ and $d_2 = 2.030 \text{ Å}$. The atomic diameter for coordination number 12 equals 3.20 Å .

The specific weight of deformed magnesium is reduced with an increase in content of admixtures; this is clear from the following data:

Purity, % Mg	99.99	99.95	99.94	99.90
Specific weight (20°C), g/cm ³	1.7388	1.7387	1.7386	1.7381 (1.7370*)
*Die-cast.				

Data on the resistivity and the atomic and specific heat as functions of temperature are presented in Table 4.

The change in the linear expansion of magnesium as a function of temperature, reduced to 1 m of length at 20°C, is as follows:

Temperature, °C from -190 to 0	0-100	0-200	0-300	0-400	0-500
Linear expansion, mm	-4.01	2.59	5.39	8.36	11.53 14.88

Table 4. Resistivity and heat capacity of magnesium at various temperatures.

(1) Температура, °C	(2) Удельное электро- сопротивление, ом·мм ² /м	(3) Атомная теплос- кость, кал/г-атом·град	(4) Удельная теплоемкость, кал/г·град
-192	0,01233	—	—
from -186 to	—	4,598	0,169
-79	—	—	—
-78	0,03053	—	—
0	0,04312	5,648	0,232
18-99	—	5,983	0,246
100	0,05915	6,241	0,256
200	0,07576	6,525	0,268
300	0,09536	6,755	0,278
400	0,11893	6,945	0,285
500	—	7,117	0,295
600	—	7,271	0,299
Above 650	—	7,296	0,300

KEY: (1) Temperature, °C; (2) Resistivity, ohm·mm²/m; (3) Atomic heat, cal/g-atom·deg; (4) Specific heat, cal/g·deg.

Properties of Lithium

In recent decades lithium has attracted ever greater attention from researchers and engineers. Lithium (discovered in 1817 in Sweden by Arfvedson) falls in group I of the periodic system and heads the subgroup of alkali metals. After hydrogen and helium it has the third smallest atomic weight (6.940); the system number of lithium is 3; the nucleus of the atom consists of three protons and four neutrons and therefore lithium is monovalent. It possesses the smallest atomic radius of all the alkali metals (1.57 Å) and leads with the greatest ionization potential (5.37 eV); this makes lithium chemically less active than the other alkali metals [4, 7, 8]. Thanks to its low atomic radius lithium possesses a simpler crystal lattice than the remaining alkali metals. At normal temperature lithium has a bcc lattice with a lattice constant of

3.5023 Å, coordination number 8, interatomic distance 3.0331 Å, and an atomic diameter for coordination number 12 equal to 3.14 Å.

Thanks to the bcc lattice lithium possesses very high ductility and can be easily deformed at room temperature; during deformation no hardening occurs, since the recrystallization temperature of lithium lies below 20°. In the negative temperature region (minus 190-200°) lithium takes on, in part, a close-packed hexagonal structure, which can be converted into an fcc structure by deformation.

Lithium is a silvery white metal with a melting temperature of 186° and a boiling temperature of 1336°. It does not burn in dry air; the ignition temperature is about 640°. At a low temperature in air it is corroded (it tarnishes and a dark-brown coating appears in separate spots). Lithium corrosion products can be ignited at 200°; therefore lithium can only be stored in airtight covered vessels or in an inert medium.

The electrical resistivity of lithium at 0° equals $8.9285 \cdot 10^{-6}$ ohms. The conductivity of lithium is about 20% of that of silver. The normal potential of lithium equals 3.02 V; it heads the series in voltage.

Lithium is the lightest metal on Earth, with a specific weight of 0.534 g/cm³; it is 15 times lighter than iron, 5 times lighter than aluminum, and 3.5 times lighter than magnesium. It has the highest heat capacity of all metals - 0.784-0.905 cal/g·deg (for 20-100°).

The content of lithium in the Earth's crust amounts to 0.0065%. In terms of reserves in the crust it exceeds such metals as zinc (0.005%), tin (0.004%), lead (0.0016%) and other widely used metals. It is present in the crust in amounts 130 times greater than that of cadmium and 160 times greater than that of antimony. The output

of metallic lithium and various compounds of it is growing steadily, having increased about 100 times in the last 20 years in the capitalist countries.

Lithium is not found in free form. The basic minerals from which lithium is obtained are spodumene and lepidolite. Lithium is produced by electrolysis of molten lithium chloride and also by reduction of the oxide or the carbonate of lithium.

Table 5 gives brands and chemical composition of metallic lithium.

Table 5. Chemical composition of lithium (per GOST 8774-58).

(1) Марка	(2) Литий, % (не менее)	(3) Примеси, % (не более)							(4) Кремни- кислота	(5) Азот (нит- риды)
		K	Na	Mg	Ca	Al	Fe	Mn		
(6) ЛЭ-1	98	0,2	0,8	0,3	0,05	0,03	0,01	0,005	0,2	0,05
ЛЭ-2	97	0,3	1,0	0,5	0,10	0,05	0,03	0,020	0,4	0,20

KEY: (1) Brand; (2) Lithium, % (no less than); (3) Impurities, % (no more than); (4) Silicic acid; (5) Nitrogen (nitrides); (6) LE-1, LE-2.

Metallic lithium is cast in the form of flat pigs weighing 100-250 g. Lithium containing no more than 0.01% each of sodium and potassium is used for the manufacture of magnesium/lithium alloys.

The mechanical properties of lithium are close to those of lead. Certain properties of lithium differ from those of other alkaline metals and are analogous to properties of elements in Group II, in particular magnesium. In terms of its ability to combine with other metals and its participation in chemical reaction lithium is closer to magnesium than to the alkali metals.

Lithium reacts slowly with dry air. It reacts with many organic compounds and their halide derivatives. It reacts vigorously with dilute mineral acids, hydrochloric acid, and nitric acid; it reacts slowly with concentrated nitric acid. Lithium is easily alloyed with virtually all metals except iron. At elevated temperatures lithium enters into reaction energetically with chlorine, bromine, iodine, carbon, etc.

Lithium is widely used as a deoxidizer and degasifier for various metals and alloys. Usually 2% alloys with those metals subjected to deoxidation are used for this purpose.

The application of lithium for alloying various metals and alloys is of major interest, since the use of lithium during alloying is facilitated by the fact that it has high reactivity and possesses a broad region of the liquid state (melting temperature 186°C, boiling temperature 1336°C) [8, 9].

Below is a listing of certain physicommechanical properties of lithium:

Number in the periodic system	3
Atomic weight	6.94
Atomic volume, $\text{cm}^3/\text{g-atom}$	13.1
Coefficient of linear expansion at 20°	$56 \cdot 10^{-6}$
Specific weight (at -273°), g/cm^3	0.562
Melting temperature, °C	186
Rate and heat of fusion, cal/g	32.81
Boiling temperature, °C	1336
Coefficient of thermal conductivity (0-100°), $\text{cal/cm} \cdot \text{s} \cdot \text{deg}$	0.17
Specific heat, $\text{cal/g} \cdot \text{deg}$	
at 0°	0.784
at 100°	0.905
Electrical conductivity (0°), $\text{ohm}^{-1} \cdot \text{cm}^{-1}$	$16.7 \cdot 10^{-4}$

Ohmic resistance (20°), $\text{ohm}\cdot\text{mm}^2/\text{m}$. . .	0.093
Temperature coefficient of electrical resistance	
at $t = 0-100^\circ$	$4.58\cdot 10^{-3}$
above 100°	$4.35\cdot 10^{-3}$
Specific magnetic susceptibility (18-20°)	$+0.50\cdot 10^{-6}$
Electron work function, V	2.34-2.38
Tensile strength, kgf/mm^2	11.8
Relative elongation, %	50-70
Normal elasticity modulus, kgf/mm^2 . .	500
Coefficient of compressibility, cm^2/kgf	$8.8\cdot 10^{-6}$
Coefficient of volume expansion	
at $0-178^\circ$	$0.92\cdot 10^{-7}$
at $182-235^\circ$	$1.06\cdot 10^{-7}$
Thermal neutron capture cross section, barn	
natural lithium	67 ± 2
isotope Li^6	910
isotope Li^7	0.033

The most important area of application for lithium and its compounds is in nuclear power engineering. First of all in this case there is the preparation of tritium during bombardment of the isotope Li^6 with neutrons for thermonuclear reactions [8].

Lithium deuteride is used as a solid combustible in hydrogen bombs, while liquid Li^7 is used as a heat exchange agent in nuclear reactors.

A number of lithium compounds are used as propellants for rockets, guided missiles, etc. [7, 8].

Lithium compounds have found broad application in the silicate industry for the production of ceramics, enamels, special glasses, etc. In military production (tanks, aircraft, etc.) broad use is made of greases containing lithium. It is applied in welding of

aluminum and magnesium alloys. Lithium and its compounds find application in the chemical industry, in refrigeration, radio electronics, etc.

Table 6 gives properties of alloying elements included in the composition of magnesium-lithium alloys.

Table 6. Physicochemical properties of the major alloying components included in highly alloyed magnesium alloys.

(1) Элемент	(2) Атомный вес	(3) Атомный диаметр, Å	(4) Кристаллическая решетка	(5) Удельный вес, г/см ³	(6) Температура, °C	
					(7) плавления	(8) кипения
Al	26,98	2,86	(9)	2,7	660	2060
Ag	107,88	2,88	(Кубическая гранецентриро- ванная	10,49	960,8	2210
Cd	112,41	3,04	(10)	8,65	320,9	767
Ce	140,13	3,62	Гексагональная компактная	6,88	640	1400
Mn	54,94	3,2	(11)	7,4	1250	2150
Si	28,09	2,52	Кубическая сложная	2,4	1415	2360
Sn	118,7	2,8	(12)	7,3	231,9	2360
Zn	65,38	2,74	Типа алмаза	7,14	419,5	907
			Тетрагональная (13)			
			(10)			
			Гексагональная компактная			

(1) Элемент	(14) Удельная теп- лопроводность (0-100°), кал/см·с·град	(15) Удельное со- противление при 0°C, 10 ⁻⁶ ом·см	(16) Удельная теп- лоемкость при 20°, кал/г·град	(17) Коэффициент линейного рас- ширения, 10 ⁻⁴ /град	(18) Модуль уп- ругости 10 ⁴ кг/мм ²
Al	0,502	2,83	0,214	0,231	0,72
Ag	1,00	1,50	0,0559	0,197	0,82
Cd	0,23	10,6	0,0552	0,316	—
Ce	—	78,0	0,05	0,08	—
Mn	0,0119	710,0	0,1147	0,221	—
S	0,2	(2-3) 10 ⁴	0,168	0,43	1,15
—Sn	0,157	11,5	0,0541	0,0695	0,415
Zn	0,269	5,7	0,0926	0,465	1,3
				0,222	
				0,395	

KEY: (1) Element; (2) Atomic weight; (3) Atomic diameter, Å; (4) Crystal lattice; (5) Specific weight, g/cm³; (6) Temperature, °C; (7) Melting; (8) Boiling; (9) Cubic face-centered; (10) Hexagonal close-packed; (11) Cubic complex; (12) Diamond type; (13) Tetragonal; (14) Specific heat conductivity (0-100°), cal/cm·s·deg; (15) Resistivity at 0°C, 10⁻⁶ ohm·cm; (16) Specific heat at 20°, cal/g·deg; (17) Coefficient of linear expansion, 10⁻⁴/deg; (18) Young's modulus, 10⁴ kgf/mm².

CHAPTER III

EFFECT OF LITHIUM ON MAGNESIUM PROPERTIES

Even the first investigations on the nature of the interaction of lithium with magnesium [10-14] showed that lithium may be of practical interest as an alloying element in magnesium alloys. Preparation of alloys with a specific weight less than that of magnesium itself was a very attractive proposition, and the presence of a large region of solid solutions on the magnesium side and on the lithium side as well made this achievable in practice. In addition, the presence of a bcc β phase in the structure of the alloys pointed to the possibility of obtaining alloys which would be extremely ductile and easily worked by pressure at comparatively low temperatures. Therefore, as early as the 1930's the first information appeared on the properties of magnesium-lithium alloys, along with studies of the phase diagram which included lithium.

In the work by F. I. Shamray and P. Ya. Sal'dau [13] it was indicated that alloys of magnesium containing up to 5 wt. % Li possessed adequate corrosion resistance and, with a lithium content up to 15 wt. % they machined well. Haneman and Hoffman [62] studied the effect of lithium on grain refinement of cast magnesium alloys. They determined the concentrations of various alloying elements which would lead to total disappearance of columnar crystallization in the macrostructure of the magnesium. Investigation of magnesium-lithium alloys containing 0.4 to 1.6 wt. % Li indicated that, along

with aluminum and zinc, lithium is an element which is extremely effective in obtaining a fine-grain uniaxial structure. The columnar crystallization of pure magnesium disappeared with additions of approximately 1 wt. % aluminum, zinc, and lithium, while substantially greater quantities of lead and cadmium were required.

Table 8. Mechanical properties of cast Mg-Li alloys.

Lithium content in alloy, %	σ_b , kgf/mm^2	δ , %	HB, kgf/mm^2	Lithium content in alloy, %	σ_b , kgf/mm^2	δ , %	HB, kgf/mm^2
0,0	9,2	7,3	36	1,0	13,3	8,4	42
0,1	11,1	4,9	44	1,5	19,8	8,4	42
0,5	14,0	7,2	42	3,0	11,1	3,4	42

Designation: $\text{kgf/mm}^2 = \text{kgf/mm}^2$.

K. V. Peredel'skiy reported on the mechanical properties of cast alloys of magnesium with lithium [63]. The results which he obtained during casting of alloys in metallic molds heated to 200° are shown in Table 8.

Addition of 0.5% Li to magnesium increased tensile strength from 9.2 to 14 kgf/mm^2 ; a further increase in lithium content in the alloys led to a reduction in strength. Alloying magnesium with lithium increased the relative elongation, which reached a maximum at 1-1.5% Li. Alloys containing up to 1% lithium cast satisfactorily in both metallic and loam molds, yielding dense castings. The author noted a favorable influence of the lithium (in quantities no greater than 1%) on a reduction in oxidizability during melting and casting. With respect to corrosion resistance it was noted that alloys containing less than 1% Li turned out to be resistant to air. When specimens were stacked for five months under standard conditions they retained a pure metallic surface, while other magnesium alloys (including those now used in practical applications) carried traces of corrosion under similar conditions.

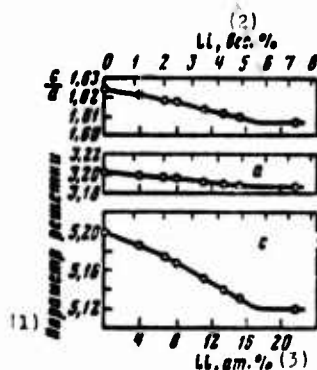


Fig. 21. Change in lattice parameters with the introduction of lithium into magnesium.

KEY: (1) Lattice parameter; (2) Wt. %; (3) At. %.

In a monograph edited by A. Beck [64] data are presented from G. Zibel and H. Vosskühler concerning the effect of lithium on the electrical conductivity of magnesium. According to these data lithium falls in the class of metals which reduce magnesium conductivity most intensively, even with small additions. In this respect it is most similar to such metals as aluminum, antimony, and manganese. According to data from the same authors, the introduction of lithium into magnesium in a quantity of 4.5% reduced the specific weight of the magnesium from 1.74 to 1.60 g/cm³. Figure 21 shows curves which characterize the reduction in the crystal lattice parameter for magnesium when it is alloyed with lithium. Since the parameter was reduced more rapidly for the c-axis than for the a-axis, the ratio of axes c/a dropped with an increase in the lithium percentage and the hexagonal lattice was sharply distorted. The introduction of lithium into magnesium led to an increase in hardness; however, this was not extremely great - the hardness maximum was achieved at a lithium content of 3-5 wt. %, while an increase in lithium content to 7.10% led to a drop in the hardness values.

In work [18], in addition to studies of the nature of interaction of components in the Mg-Li and Mg-Li-Ag systems, experiments were carried out on the corrosion resistance of alloys containing lithium. The action of ordinary atmospheric air over several months did not lead to signs of corrosion to any greater degree

than in the case of the usual magnesium alloys (without lithium). Specimens were also heated in a weak current of air for 40 hours at 200°. As a result of such treatment they were slightly tarnished, but were not crumbled into powder. The authors concluded that magnesium-lithium alloys can serve as the basis for obtaining lightweight materials with required mechanical properties. They noted that to accomplish this it is necessary to use adequately pure lithium, since the presence of sodium and potassium is undesirable, taking into account both the chemical activity of the alloys and the atomic diameters.

Detailed investigation of the properties of magnesium-lithium alloys and conditions for producing and processing them were published by Jackson et al. [34]. The authors indicate that magnesium-lithium alloys can be smelted quite satisfactorily under a flux or in an inert atmosphere. The application as the flux of a mixture of 75% LiCl and 25% LiF salts in a quantity amounting to 25-35% of the charge weight ensures the best properties. Hot pressure working can be carried out in the 190-360°C pressure interval, depending on alloy composition and type of treatment. The authors reported that a binary alloy of magnesium containing 11.5% Li possessed a specific weight of approximately 1.4 g/cm³; however, it possessed low strength and high ductility. Alloying magnesium-lithium alloys to increase their strength made it possible to obtain alloys with a specific weight of 1.45 to 1.65 g/cm³. The binary magnesium-lithium alloys possessed a Brinell hardness of 30-35 points.

In work [34] it was noted that one of the most important effects of lithium on magnesium is an increase in ductility. Although the phase with a body-centered cubic lattice was present in alloys containing more than 5% Li, even with 2% Li there was a noticeable improvement in the plastic characteristics and workability of the magnesium (Fig. 22).



Fig. 22. Ductility and tensile yield strength of pressed magnesium as a function of the content of lithium [34]. 1 - $\sigma_{0.2}$; 2 - δ ;

3 - ψ .

KEY: (1) kgf/mm^2 ; (2) Li, wt. %.

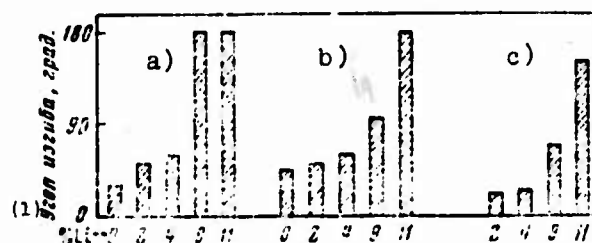


Fig. 23. Plasticity of magnesium during bending as a function of lithium content [34]. a) pressing; b) hot rolling by 50% per pass at 232°C; c) cold rolling by 45% (magnesium was broken up during rolling by 19%).

KEY: (1) Bend angle, deg.

The influence of lithium on the plasticity of pure magnesium during bending is shown on Fig. 23. A very sharp increase in plasticity was observed during transition from the two-phase to the single-phase cubic structure. Thus, a hot-rolled alloy with 9% Li could not be bent by more than 90°, while an alloy with 11% Li withstood bending by 180°. The authors of work [34] noted that in the pressed state the alloy with 9% Li possessed somewhat better plasticity during bending than the one with 11% Li, a matter

explained by their different shape and the arrangement of the α -phase in the microstructure. This work also presents information on the effect of lithium on the rollability of magnesium in the cold. Where magnesium of industrial purity was destroyed during rolling after reduction by 19%, alloys containing lithium could be rolled in the cold with a reduction to 45%. After cold rolling alloys containing lithium retained virtually the same plasticity under bending as in the hot-rolled state. Using an original procedure, studies were made in work [34] of the tendency of magnesium-alloys toward work-hardening; this development was judged by the magnitude of the bending deflections of pressed samples after a determined period of time. The first additions of lithium to the magnesium led to an increase in capacity for work hardening; however, subsequent alloying reduced deformation hardening, which was found to be very minor with Li contents of 11 and 12%.

The authors note that magnesium-lithium alloys consisting wholly of α -phase were capable of deformation hardening and possessed stable mechanical properties at room temperature. Alloys containing lithium in a quantity greater than that required to obtain 100% β -phase in the structure showed improved stability at 66°, although their deformation hardening was very slight. It was concluded that a wt. % ratio of Mg:Li = 6 is the best from the point of view of selecting alloy bases for further alloying.

In work [34] a study was made of the corrosion resistance of binary magnesium-lithium alloys by cyclic immersion of the specimens in a 3% NaCl solution over the course of eight days (1/2 min in the solution and 2 min in air). The average daily weight loss by the specimens is indicated by the following data (relative to the weight loss of pure magnesium):

Mg + 1.26% Mn . . .	0.62	Mg + 9.3% Li . .	0.77
Mg + 2% Li . . .	4.92	Mg + 11% Li . .	0.53
Mg + 4% Li . . .	4.44		

These data indicate that as compared with the most corrosion-resistant industrial alloy M-1 (Mg-Mn), the magnesium-lithium alloy with 11% Li is superior with respect to corrosion resistance, while the alloy with 9.3% Li is not much inferior. Alloys with 2 and 4% Li possess lower corrosion resistance. The authors concluded that magnesium-lithium alloys with 11-12% Li can be used as plating materials for anode protection of the higher-strength magnesium-lithium alloys which possess an elevated tendency toward corrosion. In the opinion of Jackson et al., the primary advantages of using lithium to alloy magnesium arise from the transformation of the hexagonal lattice into a body-centered cubic lattice and they are summed up as an increase in the ratio of yield points under compression and tension, an increase in the modulus of elasticity under compression (comparable with moduli under tension), as an improvement in workability by pressure at room temperature, and as improved deformability during hot and cold rolling and extrusion.

Hibbard et al. [65] compared certain properties of magnesium with properties of solid solutions of lithium and indium in magnesium (Table 9). The alloys were prepared in nitrogen using pure initial materials. The obtained castings were homogenized in four stages with intermediate cold deformation. Heating time was ten days at temperatures from 146 to 480°C for the alloy with indium and 186 to 588°C for that with lithium. Specimens were rolled in the cold up to the appearance of cracks. The percentage elongation was used as the measure of permissible deformation during rolling. After each 5% elongation the hardness was measured. The authors note that although the strength of the magnesium was reduced with the introduction of lithium, the hardness and ductility increased. Cracking during rolling was detected at 20% elongation for the indium alloy, at 25% for pure magnesium, and with 35% elongation for the alloy with lithium.

Table 9. Properties of magnesium alloys.

(1) Металл, сплав	(2) Содержание легиру- ющего элемента, %		(5) Отношение па- раметров ре- шетки c/a	(6) Плотность, г/см ³	(7) Твердость*	(8) Предел проч- ности при растяжении, кг/мм ²	(9) Относитель- ное удлине- ние (l = 25 мм), %
	(3) Весовой	(4) Атомный					
Mg-In	44	14.2	1.633	2.705	712	18.3	0
Mg	—	—	1.624	1.734	275	18.9	1.6
Mg-Li	5.4	16.4	1.606	1.574	427	15.0	3.0

*Per DRN (diamond striker).

KEY: (1) Metal, alloy; (2) Content of alloying element, %; (3) Weight; (4) Atomic; (5) Ratio of lattice parameters c/a; (6) Density, g/cm³; (7) Hardness*; (8) Tensile strength, kgf/mm²; (9) Relative elongation (l = 25 mm), %.

Despite the fact that the addition of 14.2 at. % In to magnesium caused a substantially greater increase in hardness than addition of 16.4 at. % Li, deformation hardening in the latter case was greater. Metallographic study of cold-rolled and hot-rolled specimens showed that the Mg-Li alloy and pure magnesium contained deformation twins, while the Mg-In alloy contained wavy deformation bands, with twins being absent from the structure.

The properties of binary magnesium-lithium alloys, as well as the effect of third alloying components, were studied by Jones [66]. He used a special batch of lithium, guaranteed to contain less than 0.005% Na and less than 0.01% K, to prepare the alloys. The mechanical properties of binary alloys of magnesium with 6.5 and 12 wt. % Li in the cast state are given below (according to data from microstructural studies the alloy with 6.5% Li consisted only of the single phase α , while the alloy with 12% Li consisted only of β -phase):

	HB, kgf/mm ² (10/500/30)	σ_b , кг/мм ²	$\sigma_{0.1}$, кг/мм ²	δ , % (l = 50 мм)	ψ , %
Mg-6.5% Li . . .	.38	13.4	6.3	30	31
Mg-12% Li . . .	.35	9.5	6.3	60	80

Designation: кг/мм² = kgf/mm².

Heat treatment not only failed to yield any advantages, but actually substantially reduced the mechanical properties of the binary magnesium-lithium alloys. The data given above indicate that the alloys possessed exceptionally high plasticity in the cast state.

During rolling of the magnesium-lithium alloys the rolls were heated to 100°. The alloys were rolled with a sequence of directions, i.e., rotation by 90° before every pass in the rollers, in order to avoid directivity of the structure in the sheets. The anisotropy of the rolled material was insignificant (Table 10). Annealing at 300° substantially lowered the strength characteristics, owing to an increase in plasticity. The author notes that rolling in the cold somewhat increased the properties of both alloys, but in this case plasticity was noticeably reduced.

Tests carried out by Jones [66] on drawing sheets per Erichsen indicated that magnesium-lithium alloys possessed a somewhat greater capacity for drawing than industrial sheet magnesium alloys. The best results were obtained for sheets with the finest grain structure, obtained as the result of annealing after cold rolling in criss-cross directions. After hot rolling the sheets had a coarser grain structure and Erichsen tests were less satisfactory.

Toaz and Ripling [67] studied mechanical properties of three pressed magnesium-lithium alloys which possess structures which are totally hexagonal (4% Li), two-phase hexagonal and cubic (6% Li), and wholly cubic (11% Li), depending upon test temperature and deformation rate. The authors of the work indicated that the content of sodium in the alloys was increased with an increasing degree of alloying with lithium; therefore it was impossible to consider that the obtained results are connected only with a change in the lithium content and with the crystal structure of the alloys.

Table 10. Mechanical properties of magnesium-lithium alloys in the rolled state.

(1) Состояние	(2) $\sigma_{0.2}$ кг/мм ²	(3) $\sigma_{0.1}$ кг/мм ²	(4) $\delta_{0.2}$ (l=50 мм)	(5) ψ, %	(6) Направление вы- резки образца
(4) Сплав Mg-6,5% Li					
(5) Перекрестная прокатка					(7)
(6) при 500° от 25 до 6,3 мм	18,6	13,1	12	30	Долговое
(6a) при 300° от 6,3 до 1,6 мм	17,0	12,4	12	30	Поперечное (8)
(9) То же, плюс отжиг	14,7	8,5	23	30	Долговое (7)
(10) 30 мин при 300°	14,8	8,5	29	42	Поперечное (8)
(10a) Сплав Mg-12% Li					
(11) Перекрестная прокатка в горячем состоянии от 25 до 6,3 мм	14,7	10,0	5,5	14,5	(7) Долговое
(12) Перекрестная прокатка в холодную до 1,6 мм	14,7	10,8	13,0	25,0	(8) Поперечное
(9) То же, плюс отжиг	11,6	6,9	35	50	Долговое (7)
(10) 30 мин при 300°	11,6	6,9	35	45	Поперечное (8)

KEY: (1) State; (2) kgf/mm²; (3) Direction of specimen cut; (4) Alloy Mg-6.5% Li; (5) Cross rolling; (6) at 500° from 25 to 6.3 mm; (6a) at 300° from 6.3 to 1.6 mm; (7) Longitudinal; (8) Transverse; (9) The same, plus annealing; (10) 30 min at 300°; (10a) Alloy Mg-12% Li; (11) Cross rolling in the hot state from 25 to 6.3 mm; (12) Cross rolling in the cold to 1.6 mm.

Figure 24 gives the mechanical properties of three investigated alloys as a function of test temperature and deformation rate. It was shown that additions of lithium to magnesium increase its plasticity and reduce tensile strength. All three alloys revealed the presence of a brittleness threshold; with an increase in deformation rate the temperature of the transition to the brittle state was increased. In those cases in which a body-centered cubic phase was present in the structure an intermittent nature of the stress-strain curves was observed in a definite temperature interval. The authors connect this with strain aging or with the interaction of dislocations with dissolved atoms. Studies of the microstructure of specimens tested for elongation at various temperatures and with a different degree of deformation showed that alloys with a hexagonal structure (4% Li) and with a hexagonal and cubic structure (6% Li) formed transcrystallite cracks during strains amounting to 1/3-1/2 of their relative elongation at rupture. The authors consider that

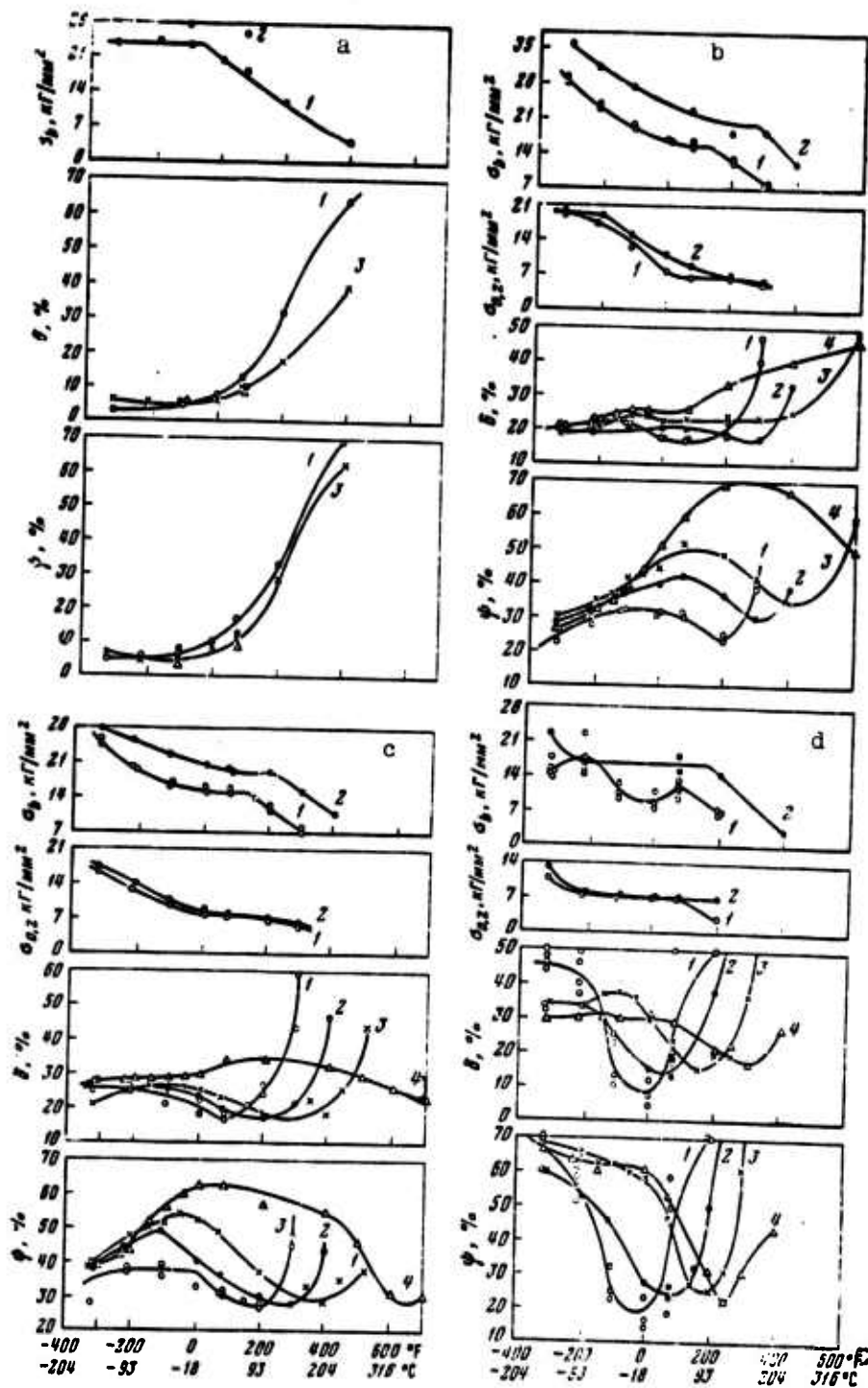


Fig. 24. Mechanical properties of pure magnesium (a) and of its alloys with 4% (b), 6% (c), 11% (d) Li as a function of test temperature and deformation rate. Deformation rate, mm/min: 1 - about 1.3; 2 - 250; 3 - 2500; 4 - about 500 m/min. Designation: $\mu\Gamma/\text{mm}^2 = \text{kgf}/\text{mm}^2$.

these cracks are developed on twins. In an alloy rich in lithium with a wholly cubic structure intergrain cracks were detected under test conditions, causing reduced plasticity. Since this alloy contained a rather substantial quantity of the impurity sodium, the authors consider that the brittleness of the alloy might be connected with diffusion of sodium to grain boundaries.

The question of the effect of sodium on magnesium-lithium alloys was discussed in the work by Payne and Eynon [68] [spelling of names not verified - Translator]. In this work studies were made of binary magnesium-lithium alloys containing 12-13.5% Li, as-cast and after various types of heat treatment, where the content of sodium was monitored (Table 11). It was shown that sodium can weaken the grain boundaries as the result of heat treatment even in those cases when it does not prevent obtaining adequately high values of strength and plasticity in cast material. The authors explained this by a change in the solubility of sodium - i.e., an increase in its solubility with heating up to 200-400°C and a reduction in solubility with cooling to room temperature. A cast alloy with a fairly large quantity of sodium (group A) possessed zero elongation, while after quenching from 400°C it turned out to be fairly plastic. The plastic properties of magnesium-lithium alloys in groups B and C were lowered as a result of heating to fairly low temperatures. Alloys of group E show the influence of different contents of sodium on embrittlement of the alloy under identical conditions of heat treatment.

The authors conclude that embrittlement can be avoided only with a sodium content of 0.002% or less.

They took this quantity as the permissible limit. In work [68] an unfavorable effect of sodium on resistance of magnesium-lithium alloys to atmospheric corrosion is also noted.

Table 11. Effect of sodium on the mechanical properties of cast magnesium-lithium alloys.

(1) Группа	(2) Состав, вес. %		(3) Условия	(4) Свойства при растяже- нии	
	Li	Na		(5) $\sigma_{0.2}$, кг/мм ²	δ , %
A	13,5	0,033	(6) Только что отлит	5,89	0
			(7) Т. о. 24 ч при 400°C, охлаждение в воде	11,0	37
B	13,0	0,0116	Только что отлит (6)	11,23	43
			Т. о. 24 ч при 200°C (7a)	9,0	4
C	12,0	0,0133	Только что отлит (6)	11,0	42
			Т. о. 1 ч при 100°C (8)	11,0	34
			Т. о. 8 ч при 100°C (9)	9,68	19
			Т. о. 64 ч при 100°C (10)	7,36	4
D	12,0	0,017	Только что отлит (6)	11,0	39
			После выдержки 6 мес при обычной температуре (11)	9,68	6
E	13,5	0,0083	Только что отлит (6)	11,0	39
			Т. о. 24 ч при 200°C (7a)	5,89	0
	13,5	0,0070	Только что отлит (6)	11,0	39,5
			Т. о. 24 ч при 200°C (7a)	9,0	9
	13,5	0,0025	Только что отлит (6)	10,9	44
			Т. о. 24 ч при 200°C (7a)	11,0	35
	13,5	0,0010	Только что отлит (6)	10,6	39
			Т. о. 24 ч при 200°C (7a)	10,4	36,5
	13,5	0,00023	Литое состояние (12)	11,0	42
			Т. о. 24 ч при 200°C (7a)	11,0	41

KEY: (1) Group; (2) Composition, wt. %; (3) Conditions; (4) Properties during elongation; (5) kgf/mm²; (6) Immediately after casting; (7) Heat treatment [HT] 24 h at 400°C, cooling in water; (7a) HT 24 h at 200°C; (8) HT, 1 h at 100°C; (9) HT, 8 h at 100°C; (10) HT, 64 h at 100°C; (11) After holding 6 mos at room temperature; (12) As-cast.

N. N. Belousov and V. A. Yegorova [69] carried out a study in order to test magnesium-lithium alloys as casting materials; they studied the binary alloy Mg + 10% Li. An effort to obtain a shaped casting of magnesium-lithium alloys by pouring in a sand mold ended in failure; the alloys were almost entirely burned out. During casting of ingots in a cylindrical cast-iron chill mold fairly strong oxidation of the ingot surface was observed, since the gap which formed between the ingot surface and the wall of the chill mold during shrinkage allowed air to enter. Application of the method of crystallization under piston pressure made it possible to obtain ingots with a good surface quality, a uniform fine-grained structure, and absence of any shrinkage defects in the central zone.

It was noted that magnesium-lithium alloys are not welded to the material of the metal die pressure cast mold, and they fill the mold well during casting under pressure. It was particularly easy to obtain castings of the binary magnesium-lithium alloy. Specimens manufactured by casting under pressure were tested for elongation, hardness, and impact toughness in the cast and heat-treated states. Results from tests of the binary magnesium-lithium alloy as compared with the standard casting alloy ML6 (system Mg-Al-Zn-Mn) are shown in Table 12.

Table 12. Results of mechanical tests of specimens manufactured by casting under pressure.

(1) Сплав, состояние	σ_B , кг/мм ²		δ , %	α_H , кг/см ²	HB, кг/мм ²
	(2) образцы с круг- лым сечением	(3) плоские образцы			
(4) Mg-10%Li, литой	7,8	13,4	2,1	4,5	33
(5) То же, термически обработанный	11,4	10,5	3,1	1,7	24
(6) ML6, литой	15,8	18,1	—	0,34	69
(5) То же, термически обработанный	15,2	21,1	—	0,74	69

KEY: (1) Alloy, state; (2) Specimens with round cross section; (3) Flat specimens; (4) Mg + 10% Li, as-cast; (5) The same, heat-treated; (6) ML6, as-cast.

Designation: кг = kgf.

As is evident, the impact toughness of the magnesium-lithium alloy was found to be substantially higher than that of the standard alloy, although the relative elongation of the former was extremely small; this is apparently connected with the presence of sodium [68]. The fracture face of castings of magnesium-lithium alloy had a much finer crystalline structure than alloy ML6. Figure 25 shows castings of magnesium-lithium alloy manufactured by pressure casting.

The authors conclude that magnesium-lithium alloys can be used for castings manufactured by casting under pressure, especially in those cases when the design requires a material with strength which is equal to that of magnesium alloys but which has a lower specific weight (1.45-1.65 g/cm³).

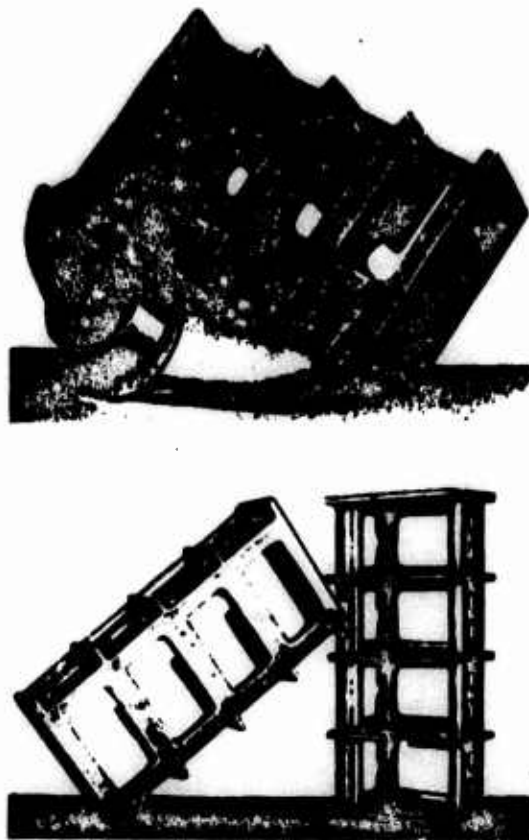


Fig. 25. Magnesium-lithium alloy castings manufactured by casting under pressure (top - before removal of the casting system; bottom - after removal of gate system).

Hauser, Landon, and Dorn [70] made a detailed study of the mechanism of deformation and destruction of binary solid solutions of lithium (0.76-4.6 wt. %) in magnesium with a hexagonal close-packed crystal structure. The alloys were subjected to heat treatment at 300-360°C in order to obtain identical grain size (0.04-0.06 mm). Elongation testing at a constant rate (1% per minute) was carried out at room temperature and at 4.78, 195, and 295°K. After destruction the specimens were investigated metallographically to determine the mechanisms of deformation and fracture. Lattice

parameters were also determined for all of the alloys, in order to compare changes in deformation mechanisms with changes in the ratio c/a .

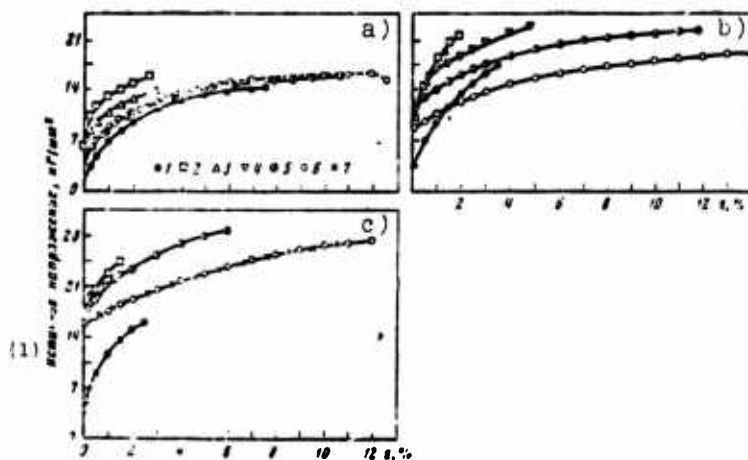


Fig. 26. True stress vs. true strain for various test temperatures as a function of elongation of magnesium-lithium alloys ($\dot{\epsilon} = 1\%/min$). Test temperature, °K: a) 295; b) 195; c) 78. Li content, at. %: 1 - 0; 2 - 2.6; 3 - 4.4; 4 - 7.6; 5 - 10.4; 6 - 14.5; 7 - the same, $\dot{\epsilon} = 50\%/min$.

KEY: (1) True stress, kgf/mm^2 .

Figure 26 shows stress-strain curves for magnesium-lithium alloys tested at various temperatures. Deformation shocks accompanied by a drop in stress were detected on certain curves (intermittent curves). The authors explained this in terms of strain aging.

With small additions of lithium to the magnesium there was an increase in yield point and in the degree of strain hardening, characteristic for alloying of a solid solution. At large quantities of lithium a deflection appeared on the curves in the direction of reduced strain hardening, where the deflection appeared at lower

stresses with an increase in lithium content. Metallographic and X-ray structural studies made it possible to conclude that the increase in plasticity and the reduction in the degree of strain hardening of magnesium-lithium alloys are connected with the appearance of prismatic slip in addition to ordinary base slip, characteristic of magnesium and its alloys. Alloying magnesium with lithium essentially reduces the ratio c/a in the hexagonal lattice; this formed the basis for the proposal that the appearance of the system of prismatic slip is connected with this reduction. The change in the mechanism of strain with a change in lattice parameters is apparently caused by a reduction in interplanar distance d .

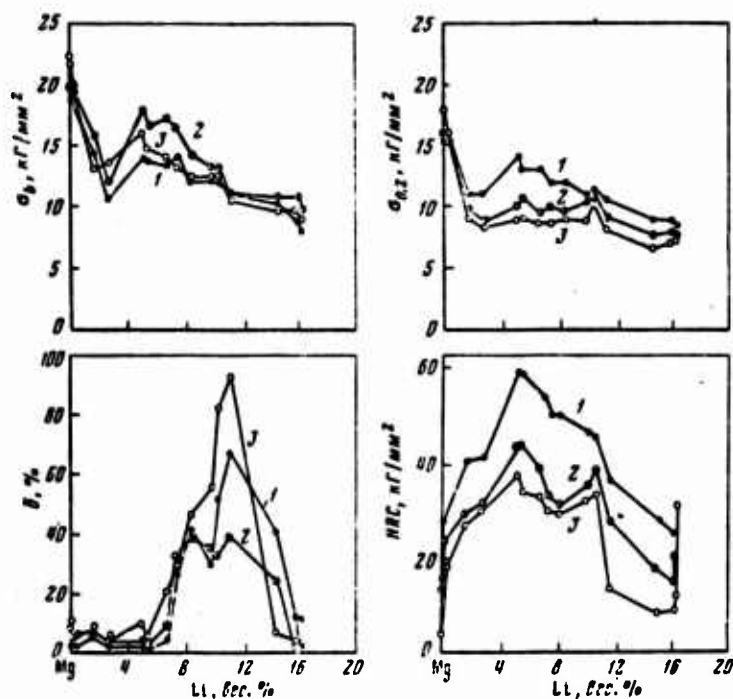


Fig. 27. Mechanical properties of hot-pressed (1), quenched (2), and annealed (3) alloys of magnesium as a function of lithium content.

Designations: kgf = kgf; sec. % = wt. %.

Properties of binary magnesium-lithium alloys in the hot-pressed, quenched, and annealed states were studied in work [71], along with more complex ternary and quaternary alloys containing lithium (Fig. 27).

Tensile strength and yield point were reduced with an increase in the quantity of lithium in the magnesium; relative elongation and hardness varied along a curve with a maximum. This shape of the elongation curves is apparently connected with the use of inadequately pure charge materials (magnesium and lithium) for manufacture of the alloys, since according to data from works [33, 34, 50, 51] the plasticity of alloys rich in lithium should not be so low. Quenching and annealing of hot-pressed alloys reduced their strength characteristics and hardness and increased their plasticity.

Recent years have seen a substantial growth of interest in the study of magnesium-lithium alloys. At the same time substantial differences have been observed in the values of properties obtained by different researchers during study of even the simplest binary alloys of magnesium with lithium. This divergence is apparently connected with the high sensitivity of these alloys to purity of the initial charge materials and to conditions of smelting and casting and subsequent deformation. The existence of disagreements in literature data has hampered comparison of the results obtained by different authors for more complex alloys with lithium as well; this is further complicated by the fact that the conditions under which the alloys were manufactured and the treatment to which they were subjected have not always been reported.

Works [72-74] present information on properties of binary magnesium-lithium alloys manufactured from metallic lithium and magnesium of industrial purity.

Z. A. Sviderskaya and V. F. Trokhova studied the effect of lithium (up to 9 wt. % - 25 at. %) on the recrystallization

temperature of magnesium and on the kinetics of the recrystallization process for magnesium-lithium alloys [72]. Magnesium of brand Mgl (99.91%) and lithium LE1 (99.7%), with a sodium impurity content of 0.15%, were used in the investigation. A mixture of salts consisting of 75% LiCl and 25% LiF was used during smelting as a covering and refining flux. Ingots were produced by immersing ingot molds filled with molten metal in water and, after mechanical treatment, they were pressed into rods 10 mm in diameter (degree of deformation 90%). Billets 20 mm long were cut from the rods and upset on a forge in two stages. First the blanks were upset to 50% deformation at 300-320° (in a direction perpendicular to the direction of extrusion), and then the specimens were annealed to a uniform coarse-grain structure in all melts (annealing temperature 200-300°, time 1-10 hours). Then the specimens were upset again on the forge at room temperature to a thickness of 2 mm. The degree of cold deformation corresponded to 60%. To determine the temperature of the beginning and end of recrystallization, annealing was carried out for 1 hour at temperatures ranging from 50 to 250° (at every 50°, and in certain cases every 5-10°, in order to define more precisely the recrystallization temperature). A 50% solution of nitric acid in water was used to remove the surface layer; about 0.2 mm was etched off. Temperatures of the beginning and end of recrystallization of the process were determined by microscope and X-ray methods. To identify the microstructure the specimens were polished and etched with a 0.5% solution of nitric acid in alcohol. X-ray photographs were taken from flat specimens (6 × 8 × 2 mm) in an RKSO camera on copper radiation; the slope of the specimen with respect to the beam of X-rays was 30°.

Results of recrystallization temperature determinations are presented on Fig. 28, along with the appropriate part of the Mg-Li phase diagram. Data from the microscope and X-ray methods coincide well. Lithium rendered a comparatively weak influence on the temperature of the beginning of recrystallization for magnesium.

The first additions of lithium, right up to 3.3 at. % (1 wt. %), caused virtually no increase in the temperature of the beginning of recrystallization. A noticeable increase in this temperature was observed only with 6-7 at. % (1.5-2 wt. %) lithium, but even for the alloy richest in lithium (25 at. % and 9 wt. %) the temperature of the beginning of recrystallization for the alloy exceeded that of pure magnesium by only 55°. Up to 2 at. % (0.6 wt. %) the lithium had no effect on the temperature of the end of recrystallization of the process; an increase in lithium content to 3.3 at. % (1 wt. %) led to a noticeable drop in the temperature of the end of recrystallization. With a further increase in lithium concentration this temperature grew, reaching the value of $t_{\text{рекр}}$ or pure magnesium at 18 at. % (6 wt. %) lithium; at 25 at. % (9 wt. %) it was 50° higher than the temperature of the end of recrystallization for magnesium.

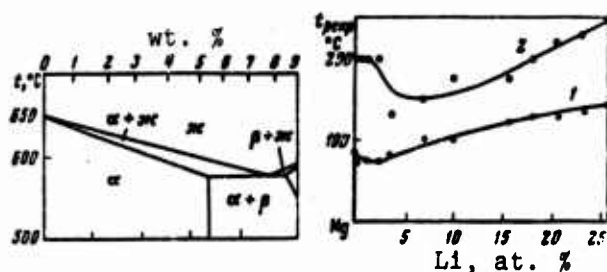


Fig. 28. Temperature of the beginning (1) and end (2) of recrystallization of magnesium alloys as a function of lithium content.

The kinetics of the recrystallization process were studied for certain alloys by the microscope method. Specimens were annealed in the 50-150°C interval with a hold time ranging from 1 min to 5 hours. Logarithmic lines are depicted on Fig. 29. The line for pure magnesium was constructed from data in work [75]. The time required for the beginning of the recrystallization process diminished noticeably with an increase in annealing temperature. The rectilinear nature of the curves confirmed the presence of an exponential relationship between the time of the beginning of recrystallization and the absolute temperature. This made it possible to use the tangent of the slope of the lines to calculate the magnitude of activation energy for the process of the beginning of recrystallization. The data given below show that the introduction of lithium

into magnesium in amounts up to 6.8 at. % slightly reduce the magnitude of the activation energy - i.e., alloying with lithium favored the recrystallization process. An increase in lithium concentration to 23-25 at. % led to a small increase in activation energy; however, on the whole, all of the obtained values were adequately close:

Lithium content

at. %	.0	0.2	3.3	6.8	23.3	25.7
wt. %	.0	0.06	1.0	2.0	8.0	9.0
U, kcal/g-atom	17.5	15.1	14.9	16.2	18.6	18.9

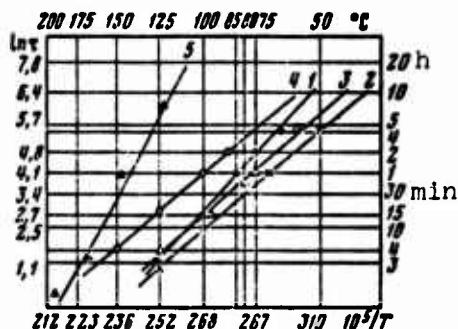


Fig. 29. Kinetics of recrystallization of magnesium and of magnesium-lithium alloys. Li content, at. %: 1 - 0; 2 - 0.2; 3 - 3.3; 4 - 6.8; 5 - 25.7.

Thus, the change in activation energy also indicates a weak influence of lithium on the recrystallization of magnesium. From the point of view of the ratio of atomic dimensions, alloying magnesium with lithium is characterized by a positive dimensional factor, since the atomic diameter of magnesium is somewhat greater than that of lithium and, as is known [75, 76], in this case the effect of the dissolved element on recrystallization of the base is less effective. In terms of its influence on the recrystallization of magnesium, lithium is clearly similar to such elements as zirconium, aluminum, etc. [75].

The absence in the Mg-Li system of any change in solubility with a change in temperature also indicates the negligible role played by particles of the second phase in the inhibition of the recrystallization process; this is in contrast to the situation which occurred in alloys with a large dispersion decay effect. The high activity and diffusion mobility of lithium could obviously have affected the strong development of recrystallization processes to a certain degree.

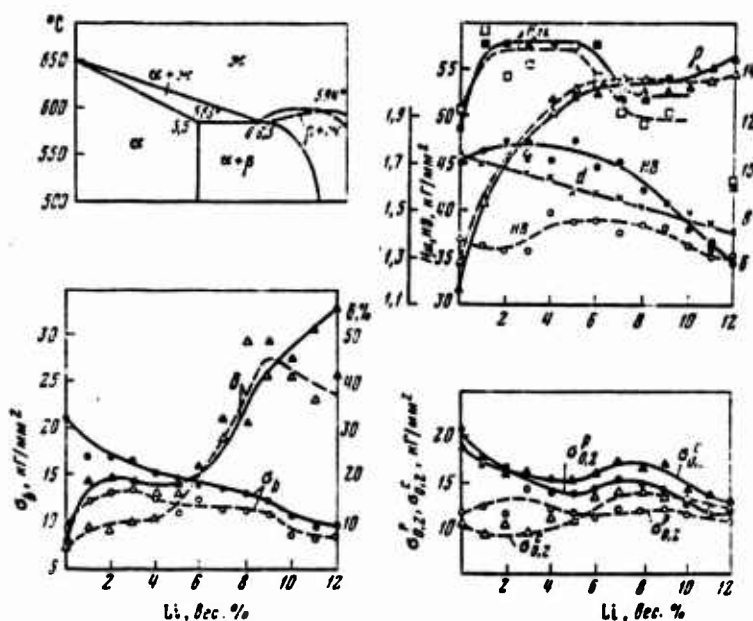


Fig. 30. Mechanical properties (tension $\sigma_{0.2}^P$ and compression $\sigma_{0.2}^C$) of hot-extruded (solid lines) and annealed (broken lines) alloys of magnesium as a function of lithium content.

M. Ye. Drits, Z. A. Sviderskaya, and V. F. Trokhova studied the mechanical and certain physical properties of binary magnesium-lithium alloys in the hot-pressed and annealed states [73, 74]. Lithium of various degrees of purity with sodium contents of 0.04 and 0.14% and Mg1 magnesium (99.91%) were used for the investigations.

The alloys were smelted in an electric resistance furnace in steel crucibles under a layer of flux (75% LiCl + 25% LiF) in a massive ingot mold with a graphite adapter. Rods 10 mm in diameter were extruded from the ingots. The degree of deformation was 88%. The alloys were annealed at 500° for 50 hours with cooling in air (heated in quartz ampules in an atmosphere of SO₂).

Figure 30 shows graphs which characterize the effect of lithium on the properties of magnesium in the case of alloying with lithium of highest purity.

The introduction of lithium into magnesium led to a reduction in specific weight and to a substantial increase in resistivity of the alloys. The most intensive growth in electrical resistance occurred in the region of solid solution α enriched with magnesium; with transition to the two-phase $\alpha + \beta$ region the curves became smoother. With an increase in lithium content to 12 wt. % the resistivity of the alloy grew from 4.6 to 14.4 $\mu\text{ohm}\cdot\text{cm}$. Annealing of the alloys did not have a noticeable influence on the magnitude and nature of the change in electrical resistivity. Specific weight was reduced from 1.74 g/cm³ for pure magnesium to 1.32 g/cm³ for the alloy with 12% Li. The first additions of lithium (1-2%) sharply reduced microhardness of the solid solution enriched with magnesium, both in the hot-extruded state and after annealing; with transition to the two-phase region the microhardness was reduced in both states, where the microhardness of the β -solid solution enriched with lithium (points on the ordinate) was 6-8 kgf/mm² lower than that of magnesium. With alloying by lithium the hardness of the alloys was first slightly increased, but then with the appearance of the β -phase in the structure the hardness values dropped. A substantial difference was observed between the hardness of the hot-extruded and of the annealed specimens; this is apparently connected with growth of the grains due to recrystallization occurring during annealing.

An increase in lithium concentration in the alloys led to a reduction in yield point of the hot-extruded alloys and to a growth in relative elongation: at a lithium concentration of 12% - i.e., with transition to the β -region - strength was reduced to less than half of the strength of magnesium, while plasticity grew by eight times. The change in strength of annealed alloys with a change in lithium content had quite a different character: alloys containing less than 10 wt. % Li had strength higher (by 2-7 kgf/mm²) than that of magnesium, but as the concentration of lithium was increased the strength was also reduced; relative elongation of annealed alloys (1-5% Li) was lower than that of the hot-extruded specimens.

The tensile yield point changed in a course virtually analogous to that of tensile strength, with the exception of a small increase for the hot-extruded alloys in the region of two-phase structure. Curves of compressive yield strength followed an analogous course. Values of compressive yield strength for alloys with substantial amounts of lithium exceeded the values of the tensile yield points.

The photomicrographs on Fig. 31 show the microstructure of binary alloys of magnesium with lithium in the cast, hot-extruded, and annealed states. The presence of a second phase (β) can be detected in the structure of the cast and hot-extruded alloys beginning at 3-4 wt. % Li; it can be seen in the annealed alloys from 5 wt. % Li. Alloys containing 6-9 wt. % Li consisted of light crystals of a solid solution α , enriched with magnesium, and of darker crystals of β . With an increase in the quantity of lithium in the alloys beyond 10% the structure once again became single-phase, consisting wholly of grains of β solid solution enriched with lithium.

In the hot-extruded state additions of lithium up to 1 wt. % somewhat reduced the size of the recrystallized grain. An increase in lithium concentration led to a growth in the recrystallized grains. Recrystallization was also able to occur to a significant

degree for alloys with a two-phase structure. With a lithium content of more than 10% the alloys have a completely recrystallized structure with a fairly large grain.

GRAPHICS NOT REPRODUCIBLE

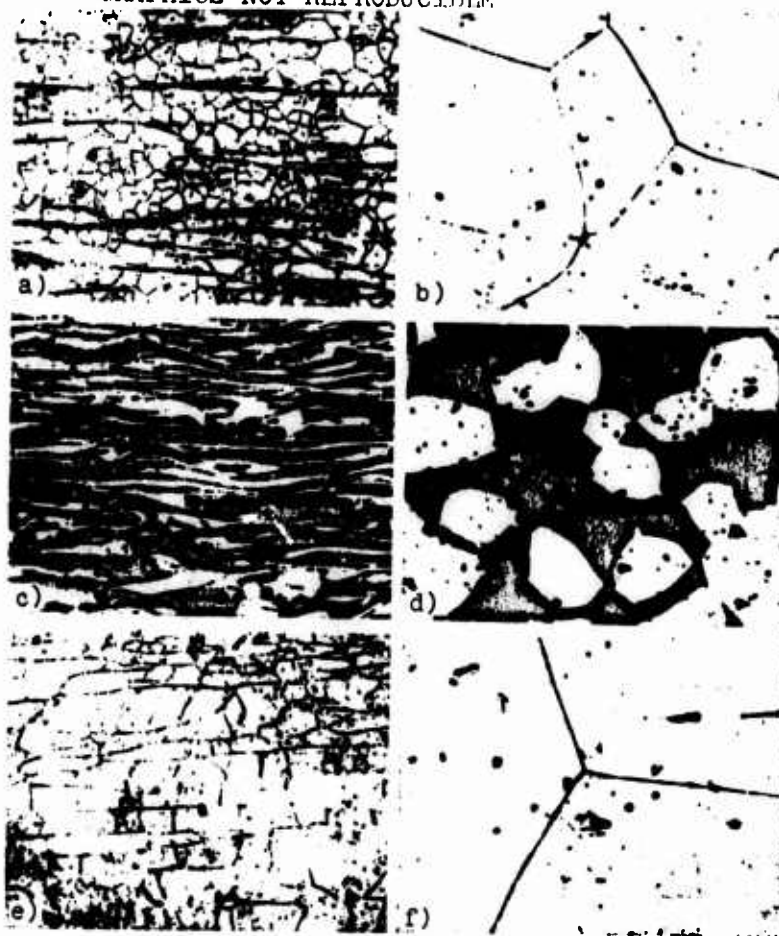


Fig. 31. Microstructure of magnesium-lithium alloys, $\times 160$. Content of Li, wt. %: a) 5 (hot-extruded alloy); b) the same (annealed); c) 8 (hot-extruded); d) the same (annealed); e) 12 (hot-extruded); f) the same (annealed).

As the result of the annealing a substantial growth in grains was observed in all investigated alloys. In addition, the nature of the structure was changed in the direction of achieving a more

equilibrium state. In alloys with 3 and 4% Li it was not possible to detect the presence of β phase after annealing; small thin chains of the second phase could be seen only with 5% Li. Crystals of the α -phase took on a regular form in alloys with a two-phase region.

As was indicated above [70], the drop in strength properties and the increase in plasticity which occur when magnesium is alloyed with lithium are connected with a change in the mechanism of plastic deformation due to the intensive development of prismatic slip. According to data in work [74], the change in the mechanism of deformation for hot-extruded alloys apparently had greater significance, since in the annealed state only minor hardening due to alloying of magnesium with lithium was detected.

Table 13 gives results of determination of mechanical properties for magnesium-lithium alloys manufactured with lithium of various degrees of purity.

Table 13. Mechanical properties of binary Mg-Li alloys.

(1) Содержание Лития, вес. %	(2) В исходном литии 0,14 % Na			(2) В исходном литии 0,04 % Na		
	σ_b , кг/мм ²	$\sigma_{0,2}$, кг/мм ²	δ , %	σ_b , кг/мм ²	$\sigma_{0,2}$, кг/мм ²	δ , %
1	18,0	14,5	10,6	17,1	12,0	18,8
3	15,0	6,5	12,0	16,7	11,1	18,8
5	14,7	8,2	14,0	14,6	8,8	17,2
6	12,7	8,7	38,0	14,0	9,3	32,0
7	12,7	9,7	44,0	13,7	10,3	31,6
10	10,9	8,6	40,0	10,4	8,4	49,6
12	10,3	7,1	42,1	9,7	6,4	55,2

KEY: (1) Lithium content, wt. %; (2) In initial lithium.

Designation: кг = kgf.

The results of chemical analyses showed that in the first case (with 0.14% Na in the initial lithium) the alloys contain 0.01-0.04% admixtures of sodium, while in the second case the values were 0.007-0.015%. As is evident from the data in Table 13 the general character of the change in strength properties is identical; however,

in the case of the purer lithium relative elongation was higher for the majority of the alloys than when lithium with a larger quantity of sodium was used. Besides this, in the second case plasticity grew continuously with an increase in lithium content, while in the first case relative elongation of the alloys remains virtually unchanged after a content of 6-7% Li is reached.

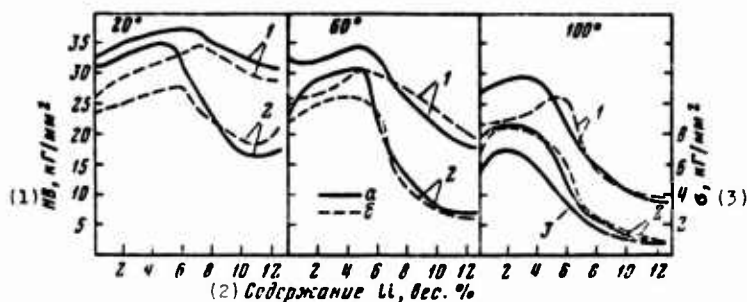


Fig. 32. Softening of hot-extruded (a) and annealed (b) magnesium alloys at temperatures of 20, 60, and 100°C as a function of lithium content. 1 - change in hardness during holding under load, 30 s; 2 - the same, 60 min; 3 - stress-rupture strength after 100 h.

KEY: (1) HB, kgf/mm²; (2) Li content, wt. %
(3) σ , kgf/mm².

The authors of work [74] also studied the effect of lithium on the tendency of magnesium to soften in time at various temperatures. Short-term and prolonged hardness methods were used for this purpose.¹ Specimens were first stabilized at the test temperatures for 100 hours and then held under load for 30 s and 1 hour. Stress-rupture strength of alloys after 100 hours was also determined at 100° by the stretching method. Figure 32 shows that the presence of a substantial quantity of lithium in the alloys

¹Softening was calculated by the formula $\Delta HB (\%) = (HB^{30''} - HB^{60'})100/HB^{30''}$.

caused a tendency towards softening, even under standard temperature conditions. The hardening effect of lithium during short-term application of loads was manifested at contents up to 7% Li, while in prolonged (hour) tests it appeared with contents up to 5-6% Li.

Softening of the alloys containing 8-12% Li at room temperature with a hold time of one hour reached 40-50%. Increasing the temperature to 60-100° led to a substantial reduction in the values of short-term and prolonged hardness; however, the nature of the curves remained as before. With an increase in temperature the curve maximum was shifted toward the side of lower lithium concentrations. Alloys based on a solid α -solution enriched with magnesium were softened to a substantially lesser degree than alloys having the structure of a β -solid solution enriched with lithium. The stress-rupture strength curve (at 100°) was similar in nature to the curve of long-term hardness. The authors note that the presence of more than 3 wt. % Li in magnesium alloys causes a greater tendency toward softening under load, even at such comparatively low temperatures as 60-100°.

A more detailed study of the properties of binary magnesium-lithium alloys in the region of β -solid solution enriched with lithium were carried out by M. Ye. Drits, Z. A. Sviderskaya, F. M. Yelkin [77, 78], who studied the effect of lithium contents of 10 to 20 wt. % on the structure and the mechanical properties of magnesium. Magnesium Mg1 and lithium containing no more than 0.04% sodium were used to prepare the alloys. The procedure of alloy preparation was analogous to that used in work [74]. Mechanical properties were determined in the hot-extruded state and after prolonged (100 hours) stabilization at 60°. The specific weight of the investigated alloys varied from 1.42 to 1.18 g/cm³.

Figure 33 presents curves which characterize the change in mechanical properties with an increase in lithium content in the alloys. As is evident, in the investigated concentration region

the mechanical properties remain virtually unchanged up to a content of 16% Li. Strength properties under tension were not particularly high: $\sigma_b = 8.5-10.5 \text{ kgf/mm}^2$; $\sigma_{0.2} = 6-7 \text{ kgf/mm}^2$; HB = 32-36 kgf/mm²; compressive yield strength was somewhat higher than tensile yield strength (7-8 kgf/mm²). The plasticity of binary magnesium-lithium alloys based on the β -solid solution turned out to be very high: $\delta = 40-50\%$; $\psi = 70-80\%$; $a_H = 2.8-3.2 \text{ kgf}\cdot\text{m/cm}^2$. In alloys containing more than 16% Li a certain reduction in mechanical properties was observed; the reduction of plasticity was most noticeable. Thus, the alloy with 20% Li possessed the following characteristics: $\sigma_b = 7.5-8.5 \text{ kgf/mm}^2$; $\sigma_{0.2} = 5-6 \text{ kgf/mm}^2$; $\delta = 30-35\%$; $\psi = 50-60\%$. The authors explain this by intensification of the effect of impurities (sodium and potassium) on the properties of the alloys, since the quantity of the former increases with an increase in lithium concentration; there is also a noticeable increase in the quantity of oxides during smelting under exposed conditions. The investigated binary alloys were adequately stable; their mechanical properties remain unchanged after prolonged low-temperature annealing (see Fig. 33). Study of hot and long-term hardness at 60° showed that softening of these alloys during heating occurred very intensively. The magnitude of softening (ΔHB) remained virtually unchanged in the 10-16% Li interval, comprising 60-65%. For alloys containing more than 16% Li softening grew to 65-70%. The stress-rupture strength (at 60° after 100 hours) comprised $\sigma_{100}^{60} = 2.0 \text{ kgf/mm}^2$ for the binary alloy 14% Li and $\sigma_{100}^{60} = 1.3 \text{ kgf/mm}^2$ for the alloy with 20% Li.

The microstructure of alloys in the cast state consisted of a uniform β -solid solution with fairly large grains. With an increase in lithium concentration in the alloys the grain size was somewhat reduced. In the hot-extruded state the structure of the investigated alloys was partially recrystallized (segments of fine recrystallized grains occurred along with large grains stretched in the direction of deformation).

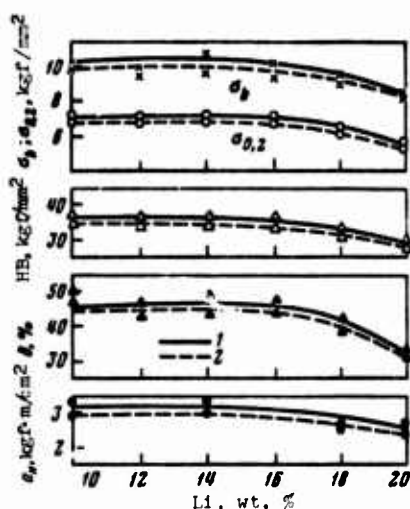


Fig. 33. Mechanical properties of hot-extruded (1) and stabilized (2) alloys of magnesium as a function of lithium content.

Studies of single crystals of magnesium and binary alloys of magnesium with lithium containing up to 16 at. % Li were studied in works [79-81]; the effective lithium on the mechanism of plastic deformation of magnesium as a function of temperature and deformation rate was investigated. The authors of work [79] showed that for pure magnesium and for the alloy with 7.9 at. % Li the critical brittleness temperature comprises 250 and 200°K, where the twinning process was observed in the region of brittle failure. Alloys containing 12.9 and 15.9 at. % Li remain plastic even at 4.2°K and were destroyed along the planes of the prisim after prismatic slip, without the formation of twins. On the basis of determination of critical shear stresses it was established that for magnesium and for the alloy with 7.9 at. % Li prismatic slip is a thermally activated process over the entire temperature range studied. For alloys with larger contents of lithium (12.9 and 15.9 at. %) the critical shear stress depended weakly on temperature in the 300-400°K region.

Schwartz, Mitchell, and Dorn [80] studied creep of single crystals of magnesium alloy with 12 at. % Li at temperatures of 450-850°K. The activation energy of the creep process turned out to be independent of stress. The authors conclude that the magnitude

of activation energy and its independence from stress make it possible to consider that the rate of steady-state creep is controlled not by transverse slip and not by viscous friction, but by the rate of dislocation creep.

The mechanism of base creep (within the temperature limits 500-885°K) for single crystals of Mg alloy with 12 at. % Li was studied later by Chirouze, Schwartz, and Dorn [81] [spelling not verified - Translator]. Single crystals were oriented along the planes (0001) [$\bar{1}210$] for base slip. The results of the study confirmed data from previous works and made it possible to conclude that in this alloy base creep is connected with creep of dislocations, at least in the 600-750°K interval. In a temperature interval lower than the one indicated above (up to 550°K) the deformation rate increases very rapidly with a growth in stress, with microstructural studies indicating the appearance of twins. At temperatures higher than 800°K an extremely significant increase in activation energy was observed. This allowed the authors to propose that some sort of new mechanism is operative close to the melting temperature.

The studies described above [79-81] thus indicated that alloying magnesium with lithium has an essential influence on the change in the mechanism of its plastic deformation, and at the same time influences changes in the mechanical properties of the alloys.

The materials presented in this chapter indicate that in view of their low strength characteristics binary magnesium-lithium alloys are not of themselves of interest for use as structural materials. However, the low specific weight of magnesium-lithium alloys and their high plasticity leads to interest in applying them as bases for more complex alloys.

CHAPTER IX

APPLICATION OF MAGNESIUM-LITHIUM ALLOYS

Recently superlight magnesium-lithium alloys have drawn the attention of flight-vehicle designers. In the USA their development is accomplished under the leadership of the National Aeronautics and Space Administration (NASA). This is understandable, since any reduction in the weight of rockets, spacecraft, and other flight vehicles is an important question. Magnesium-lithium alloys are half the weight of aluminum, 15-25% lighter than standard magnesium alloys, and almost 30% lighter than beryllium alloys. The application of magnesium-lithium alloys in missile technology makes it possible to reduce the weight of rockets by 20-30%. The use of magnesium-lithium alloys in various structures is determined first of all by their advantages, as listed in the introduction.

Table 50 contains data which characterize the specific strength and rigidity of magnesium-lithium alloys as compared with standard magnesium and aluminum alloys and plastics [117, 118]. It is clear from the data in this table that magnesium-lithium alloys are a material which is light as plastics and as strong as the metallic alloys. In ascending order of specific rigidity of bars of identical weight the various alloys fall in the following sequence: steel - aluminum alloy - magnesium alloy - magnesium-lithium alloy.

Table 50. Specific strength and rigidity of various lightweight alloys and plastics.

Material	γ , g/cm ³	σ_b , kgf/mm ²	σ_b , MPa	$\sigma_{0.2}$, kgf/mm ²	$\sigma_{0.2}$, MPa	E , kgf/mm ²	E , MPa
IMV1 (USSR)	1,62	31,5	19,5	23	14,2	4400	2720
MA2-1 (USSR)	1,79	29	16,2	20	11,2	4200	2350
AZ31 (USA)	1,76	29,5	16,7	22,5	12,8	4500	2560
IMV2 (USSR)	1,58	26	20,0	21	12,6	4500	2350
LA2933 (USA)	1,56	22	14,1	15	9,6	4400	2320
IMV3 (USSR)	1,33	19,0	13,7	16,0	11,6	4300	3120
IMV3-1 (USSR)	1,40	23	16,4	20,5	14,6	4200	3000
LA141A (USA)	1,32	14,5	11,0	12,5	9,5	4300	3260
6061-T6 (USA) (aluminum alloy)	2,72	32	11,8	23,5	10,5	7030	2590
AD33 (USSR) (aluminum alloy)	2,71	32	11,8	23	10,3	7100	2620
Polyvinyl chloride plastic	1,30	5,3	4,1	—	—	350	270
Acetal plastic	1,41	7,0	5,0	—	—	290	200
Glass-fiber-reinforced plastic	2,15	56,0	26,0	—	—	2500	1300

Designations: γ = g; σ_b = kgf.

The weights of certain articles manufactured from alloys AZ31B and LA141A are compared in Table 51.

Table 51. Weight of articles (g) made from alloys AZ31B and LA141A.

Parts	AZ31B	LA141A	Reduction in weight, %
Parabolic radar reflector	546	447	25
Protective cover used in electronics	9,5	7,3	23
Radio case	712,8	521,4	27



Fig. 88. Housing of the computer unit for the rocket "Saturn-V."

We will pause briefly to consider individual examples of the application of magnesium-lithium alloys.

Certain firms in the USA use the magnesium-lithium alloy LA141A to manufacture parts for missiles and spacecraft. The use of this alloy in the "Aegena" rocket made it possible to reduce its weight by 22 kg. Magnesium-lithium alloy was used to manufacture the housing for the computer installation in the control system of the "Saturn-V" booster rocket (Fig. 90) [sic] and the frame for an electronic computer [121].

Replacement of aluminum alloys by magnesium-lithium materials in the manufacture of the skin and cover of the instrument bay of the "Saturn 1-B" rocket led to a reduction in shroud weight of approximately 46% [121]. Application of the LA141A alloy for the frame of the computer unit on the "Saturn" rocket reduced the weight of this device by 20 kg. When we consider that reducing the weight of a rocket by 1 kg provides savings of about 22 thousand dollars (thus on one rocket about 500 thousand dollars was saved), the urgency of using magnesium-lithium alloys in rocket and space technology becomes obvious [6, 121].

In addition, magnesium-lithium alloys can find application as armor for the protection of spacecraft from micrometeorites. Magnesium-lithium alloys are also used in other branches of technology; for example they were used to manufacture the housing of the armored personnel carrier M113 (USA), permitting substantial reduction in the weight of the machine and increasing its operational characteristics [121]. Preliminary tests showed that the M113 with a housing of magnesium-lithium alloy ($\text{Mg} + 14\% \text{Li} + 1.5\% \text{Al} + 0.08\% \text{Mn}$) possesses high maneuverability as compared to an APC with an ordinary housing.

It is known [42] that thanks to the low weight and high coefficient of thermal expansion the alloy LA141A was used to

manufacture disks in tracking mechanisms in the launch unit of the antitank guided missile system "TOW."

Figure 89 shows a distributor made from alloy LA141A for the electric power system of a space rocket. In the "Gemini" rocket [sic] magnesium-lithium alloy was used to manufacture stamped-sheet covers for the modulation mechanism of the computer unit (Fig. 90), and also for assembly brackets of the switching device of the rocket [121]. Considering that magnesium-lithium alloys operate well at low temperatures, they can be used in the design of fuel systems and storage units designed for cryogenic fuels, and also as materials for connecting shells in solid missile fuels.



Fig. 89. Distributor for the electric power supply system of a space rocket, manufactured from magnesium-lithium alloy.

Various U.S. firms are manufacturing a large number of articles from magnesium-lithium alloys. Examples are frames, brackets, lining sheets and plates, boxes for electronic instruments, waveguides, space rocket shrouds, thermal grids and screens, gyroscope parts, etc.

There is information that the "Boeing" firm (USA) proposes the use of magnesium-lithium alloys in satellites inserted into lunar orbit, in self-propelled lunar laboratories, and for the manufacture of satellite solar batteries [117].

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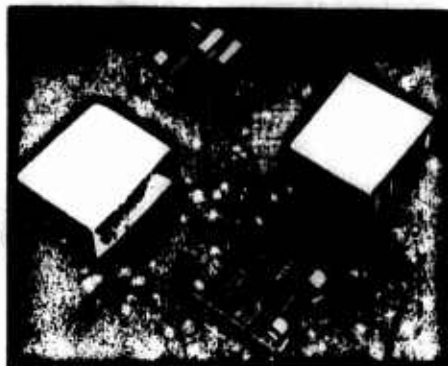


Fig. 90. Covers for the modulation mechanism of the computer unit of the "Gemini" rocket.

Magnesium-lithium alloys can also be used in the manufacture of tanks, fairings, stiffeners, guide tubes for portable starters, and for certain types of missiles of the "ground-to-ground" class, etc.

The electrical and vibration characteristics of magnesium-lithium alloys may attract the attention of designers in those cases when savings in weight are required.

The damping characteristics of magnesium-lithium alloys can, in contrast to aluminum and magnesium, be favorable for the introduction of a change into the resonance frequency in order to reduce instrument vibration [117].

In aeronautical engineering magnesium-lithium alloys can be used to manufacture brackets, emergency ladders, doors, electronic equipment housing, fairings, and other parts which require high machineability of the material and increased specific rigidity. In helicopter design it can be used as supports for special ceramic armored plates [117].

Magnesium-lithium alloys may be of interest also as materials with special physical properties; apparently they can be used in chemical engineering, radio engineering, radio electronics, etc.

It is difficult at present to define all the possible areas suitable for the use of superlight alloys; one thing is clear, they can well be used at present where the question of weight or special properties inherent to magnesium alloys alloyed with lithium is decisive.

Broad application of magnesium-lithium alloys is at present limited mainly by their relatively high cost. This limitation is temporary and due to the low volume of production of the alloys and the high cost of lithium. The high price on lithium of elevated purity with respect to sodium content is due also to the minor scale of metallurgical production, which in the next few years should be substantially increased, since the reserves of ores containing lithium are adequately great.