

The Structural Diagram of the Al–Mg System in Pressure–Temperature–Composition Coordinates

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Abstract

As a result of the analysis of thermodynamic, metallographic, and structural data, various types of aluminum-magnesium system structural diagrams were constructed: the projections of the maximum solubility lines on the temperature- composition plane; P – T -structural diagram; isobaric section of the P – T – x -structural diagrams at the pressure of 100 Pa and isothermal at the temperature of 420 °C; structural diagram in P_{Mg} – T coordinates. The presented variants of the equilibrium image can be used when choosing the conditions for obtaining and operating of the aluminum-magnesium system alloys.

Keywords

Phase equilibria; structural diagrams; aluminum-magnesium alloys; intermetallic compounds.

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Aluminum and magnesium are the basis of many multipurpose industrial alloys. Due to the expansion of these alloys application, including under vacuum and high temperatures conditions, it is of interest to consider the effect of these parameters on the phase equilibria in alloys based on these metals. To the fullest extent, this problem is solved by constructing structural diagrams in the pressure-temperature-composition coordinates (P – T – x -structural diagrams). The first attempt to construct such a diagram for the aluminum-magnesium system is presented in [1]. Since the time of this work publication, in this system additional equilibrium data has appeared. The purpose of this article was to build a new version of the P – T – x phase diagram of the Al–Mg system.

In the Al–Mg system, the β (Al_3Mg_2), ϵ ($\text{Al}_{30}\text{Mg}_{23}$), ξ ($\text{Al}_{52}\text{Mg}_{48}$), and γ ($\text{Al}_{12}\text{Mg}_{17}$) phases are formed [2, 3]. It is assumed that other phases found in a number of works [2–6] are metastable. The composition and structure of the stable phases of the Al–Mg system are presented in Table 1.

The projection of the maximum solubility lines of the Al–Mg system according to [2] is shown in Fig. 1. As will be shown below, the same diagram practically

coincides with the isobar section of this system at a pressure of 1 atm.

The equilibrium gas over the Al–Mg alloys consists of magnesium and aluminum atoms. Since the vapor pressure over solid and liquid magnesium is several orders of magnitude higher than that over aluminum, the total pressure over all alloys can be taken equal to the partial pressure of magnesium. The exceptions are very dilute aluminum based solid solutions.

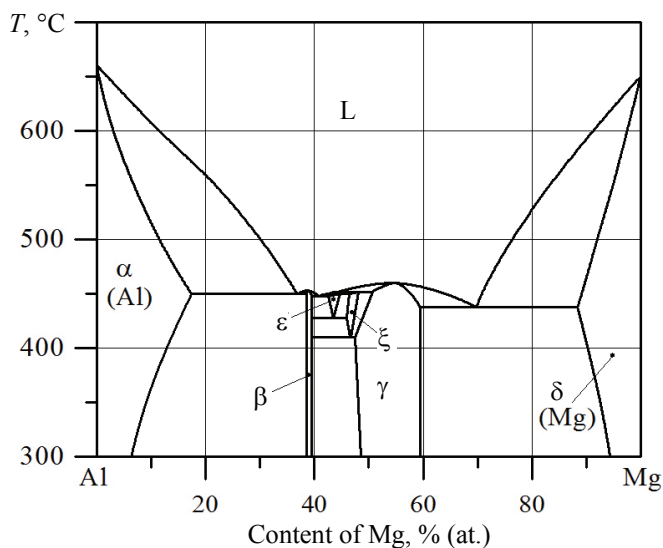
The equilibrium composition and gas pressure above the solid and liquid phases at different temperatures are given in Table 2 in accordance with the data of [4, 5].

The maximum equilibrium information in a two-component system involving the gas phase contains a three-coordinate P – T – x -structural diagram. However, its image and use presents serious difficulties. Most of the P – T – x -diagram information is transmitted by the P – T diagram, which is a projection of the three-phase equilibrium spatial lines on the pressure- temperature plane. Such a P – T diagram of the aluminum-magnesium system is shown in Figs. 2a and 2b. In these Figures, all lines of three-phase equilibria of

Table 1

**Composition and crystal phase structure
of Al-Mg system**

Phase	Magnesium content, % at.	Pearson Symbol	Source
Al ₃ Mg ₂ (β)	38.5 – 40.3	cF1192	[7]
Al ₃₀ Mg ₂₃ (ε)	42.5 – 44.7	hR53	[8]
Al ₅₂ Mg ₄₈ (ξ)	46.4 – 48.1	–	–
Al ₁₂ Mg ₁₇ (γ)	45.0 – 60.5	C158	[9]



**Fig. 1. Projection of Al-Mg system maximum solubility
lines on the temperature-composition plane**

Table 2

**Activity and equilibria magnesium partial pressure
of P_{Mg} phases of Al-Mg system**

Phases	Temperature, °C	a_{Mg}	$\lg P_{\text{Mg}}$	Source
$\alpha + \text{L}$	583	0.104	1.05	[5]
	523	0.202	0.58	
	481	0.290	-0.19	
	456	0.340	-0.09	
$\alpha + \beta$	387	0.300	-1.17	[4]
	437	0.350	-0.80	
β	451	0.391	-0.11	[5]
$\beta + \gamma$	387	0.440	-1.00	[4]
	437	0.420	-0.22	
γ	462	0.582	0.23	[5]
$\gamma + \beta$	387	0.910	-0.68	[4]
	437	0.900	0.10	
$\delta + \text{L}$	455	0.910	0.32	[5]
	545	0.950	1.51	

condensed phases and two-phase equilibria of congruently melting phases are almost vertical, since in the intervals indicated in these diagrams, the pressure does not noticeably affect the phase transition temperature [9].

In Figs. 2a and 2b transformations of pure magnesium are represented by curves 4–17 (evaporation), 17, 18 (melting), and 17, 16 (boiling). Melting of pure aluminum corresponds to the line 14–15, which ends at the triple point of aluminum, located, as well as the curves of evaporation and boiling of aluminum at pressures several orders of magnitude lower than indicated in Figs. 2a and 2b.

Each horizontal of the three-phase equilibria in Fig. 1 corresponds to a point of four-phase equilibria in Figs. 2a and 2b. The coordinates of these points with an indication of presented temperature, pressure and the phases are summarized in Table 3.

Three curves of three-phase equilibria fit each point of the four-phase equilibria. The position of these curves indicating the equilibrium with the participation of the gas phase as well as the position of the points of the four-phase equilibria are determined taking into account the experimental data [4, 5] and their agreement with the rules of geometric thermodynamics [10]. When determining the position of the 7–14 curve of the three-phase equilibrium $\alpha \leftrightarrow \text{L} \leftrightarrow \text{G}$, it is taken into account that as it approaches the triple point of aluminum, the composition of the equilibrium gas is enriched with aluminum atoms. Thus, the equilibrium curve 7–14 passes through a maximum at a temperature of 621 °C.

The P – T structural diagram shown in Figs. 2a and 2b makes it possible to represent isobaric and isothermal sections of the Al–Mg system at any pressure and temperature. The method of constructing these sections can be found in [1, 10].

From the P – T structural diagram in Figs. 2a and 2b, it follows, in particular, that isobar sections at pressures above 10^3 Pa will be the same and will not depend on pressure, since all lines of three-phase equilibria involving gas are located below these pressures. It follows that the diagram representing the lines of maximum solubility in Fig. 1 can be considered as an isobaric section at any pressures above 10^3 Pa. However, it should be noted that at very high pressures of the order of 10^6 Pa, when the pressure starts to noticeably affect the condensed phase equilibrium [10], the vertical lines of these equilibria on the P – T diagram will begin to bend.

As an example of the isobaric section in Fig. 3 shows a diagram in temperature-composition coordinates at a pressure of 100 Pa. The peculiarity of

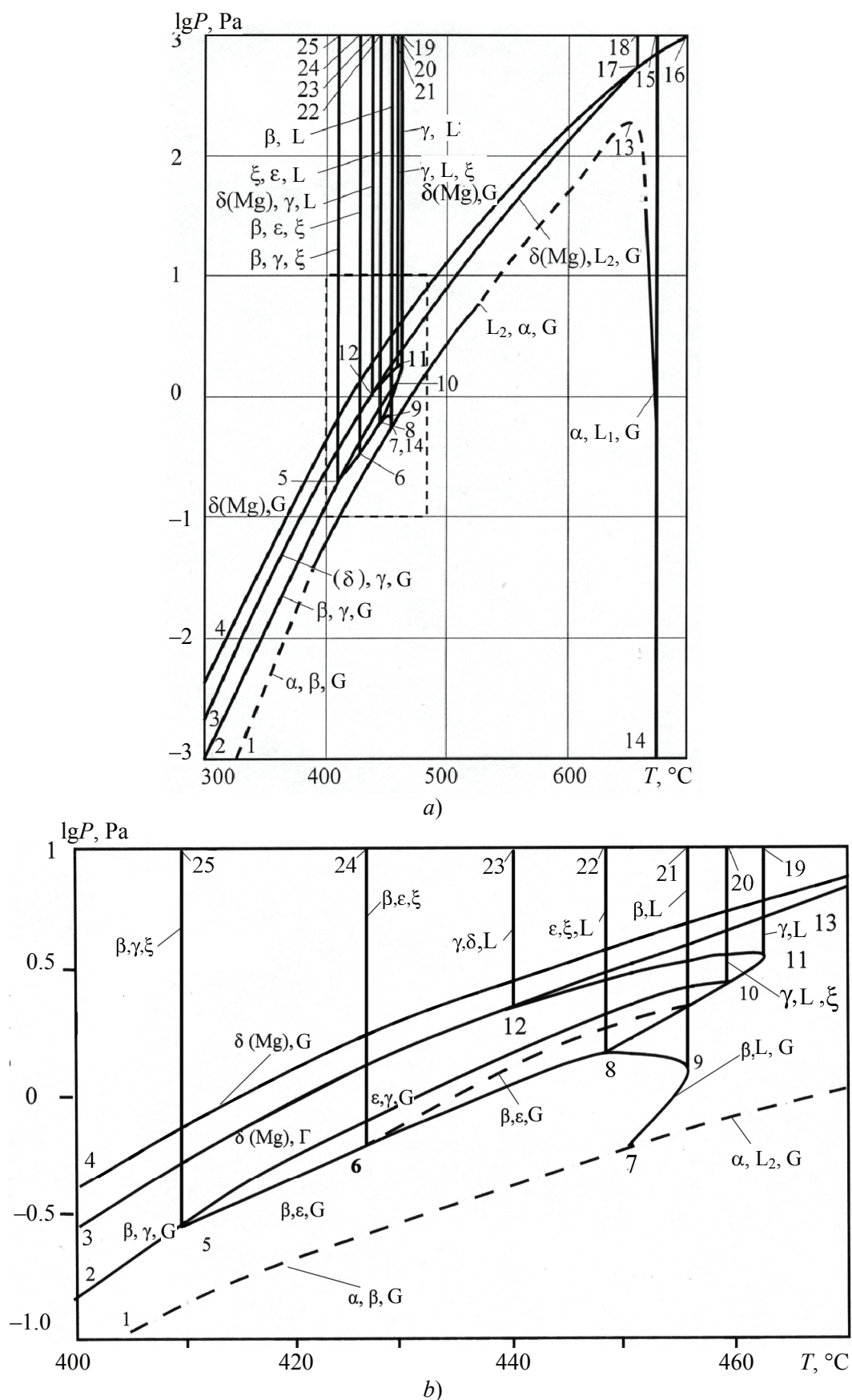


Fig. 2. The P - T structural diagram of Al-Mg system on temperature interval, $^{\circ}\text{C}$:
 a – 300 – 700; b – 400 – 460

Table 3
Point coordinates of four-phase equilibria
of Al–Mg system

Point number on Fig. 2a diagram	Phases, involved in equilibrium	Temperature, °C	Pressure, Pa
5	β, γ, ξ, G	410	0.55
6	$\beta, \varepsilon, \xi, G$	428	0.80
7	β, ε, L, G	448	0.95
8	ε, ξ, L, G	452	1.10
10	γ, L, ξ, G	462	9.20
12	$\gamma, \delta(\text{Mg}), L, G$	438	5.00
14	α, β, L, G	450	0.90

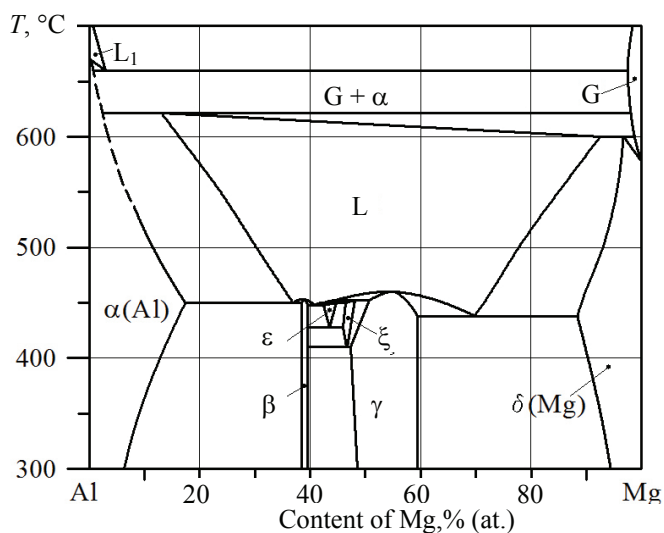


Fig. 3. Isobaric section of the Al–Mg system structural diagram at a pressure of 100 Pa

this diagram is its structure at temperatures above 500 °C. At a lower temperature, this diagram completely coincides with that in Fig. 1.

At a higher temperature the isobaric curve for $P = 100$ Pa on the P – T diagram (Fig. 2a) intersects the curves of three-phase gas equilibria three times, the 13–17 equilibrium curve $\delta(\text{Mg}) \leftrightarrow L_2 \leftrightarrow G$ at a temperature of 600 °C and the $\alpha \leftrightarrow L_2(L_1) \leftrightarrow G$ curve at a temperature of 620 °C and 660 °C twice. In this regard three horizons of the invariant three-phase equilibria appear on the diagram in Fig. 3. At a temperature of 600 °C, the magnesium-based solid solution decomposes into a gas consisting practically of magnesium vapors, and the liquid L_2 , also enriched in magnesium. At a temperature of 620 °C, it is rich in aluminum and is decomposed into an aluminum-based solid solution with the release of magnesium vapors.

At a temperature of 660 °C, solid and liquid solutions of aluminum are in equilibrium with gaseous magnesium.

From the diagram in Fig. 3 follows an interesting peculiarity in the behavior of the melts of intermetallic compounds L_2 upon heating. When heated above 460 °C, the intermetallic compounds melt, and upon further heating up to 620 °C, they re-solidify with evolution of gaseous magnesium and solid solution based on aluminum. The latter is dissolved again only when heated to 660 °C. It is interesting to note that this behavior with alternation during heating of melting and solidification should be observed in all binary systems, in which the curves of three-phase equilibria of $\alpha \leftrightarrow L \leftrightarrow G$ have a maximum.

As an example of an isothermal section Fig. 4 shows the structural diagram of the Al–Mg system at 420 °C. The isotherm $T = 420$ °C intersects in the P – T diagram of Fig. 2a four curves of three-phase equilibria: the 1–14 ($\alpha \leftrightarrow \beta \leftrightarrow G$) at a pressure of $\lg P = -0.75$; 5, 6 ($\beta \leftrightarrow \xi \leftrightarrow G$) at a pressure of $\lg P = -0.5$; 5–10 ($\varepsilon \leftrightarrow \gamma \leftrightarrow G$) at a pressure of $\lg P = -0.2$. In accordance with this, the diagram in Fig. 4 shows four horizontals of three-phase β, ξ, γ , and $\delta(\text{Mg})$ decomposition reactions with the release of magnesium vapors and the formation of less solid magnesium-rich phases.

For systems with a relatively volatile component, structural diagrams of the first type are of practical interest [1, 10]. On both axes of coordinates of such diagrams, the values of two intensive quantities should be plotted. In this case, the entire field of the diagram occupies only single-phase regions separated by two-phase boundaries. For the aluminum-magnesium system, such a diagram in coordinates of magnesium partial pressure-temperature is shown in Fig. 5.

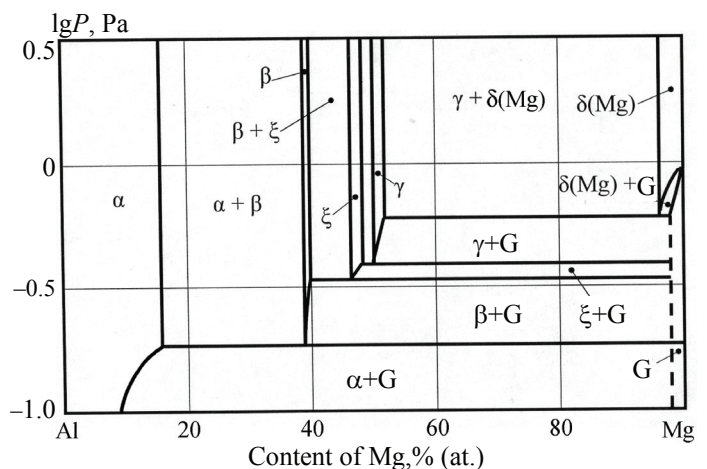


Fig. 4. Isothermal section of the Al–Mg system structural diagram at a temperature of 420 °C

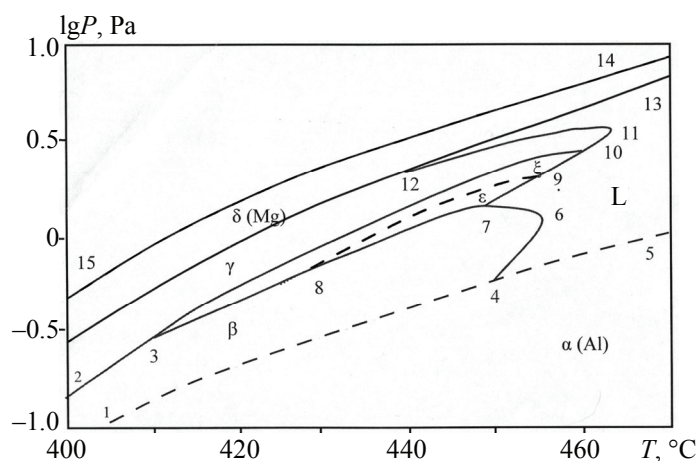


Fig. 5. Al-Mg system structural diagram in $\lg P_{\text{Mg}} - T$ coordinates

Fig. 5 shows the diagram with seven single-phase fields: α (Al), β , ϵ , γ , ξ , δ (Mg), g . This diagram is useful for determining the phase that is in equilibrium at a given temperature and partial pressure of magnesium. The diagram in Fig. 5 is easily transformed from the diagram in Fig. 2b by excluding from the latter all the curves of three-phase equilibria that do not contain gas.

The analysis of equilibria in the Al-Mg system and methods for their graphical representation may be useful when choosing production and operation conditions for aluminum-magnesium system alloys.

Conclusion

Based on the analysis of thermodynamic, metallographic and structural data a generalized version of the graphical image of equilibrium in the aluminum-magnesium system is proposed. It takes into account the influence of pressure, temperature and composition. The projections of the maximum solubility lines on the temperature-composition plane, the $P-T$ diagram, the isobaric and isothermal section of the three coordinate $P-T-x$ -diagram and diagram of the magnesium partial pressure - temperature were considered.

These diagrams may be useful in optimizing the conditions for the production and operation of the aluminum-magnesium system alloys.

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