

## The $p$ – $T$ – $x$ Phase Diagram of the Cu–Mg System

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### Abstract

The phase equilibria in the copper-magnesium system with participation of the gaseous phase were analyzed. Various graphic variants of the equilibria image, the line projections of the maximal solubility on the plane temperature-composition, isobar and isotherm sections of the  $p$ – $T$ – $x$  phase diagram and  $p_{\text{Mg}}$ – $T$  phase diagram were proposed.

The findings of the analysis can be useful during optimization of the melting, casting, heat treatment and operation processes of the copper-magnesium system alloys.

### Keywords

Phase equilibria; phase diagrams; copper-magnesium alloys; intermetallics.

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Alloys of copper and magnesium – magnesium bronzes – find technical applications, in particular, slip rings, collector plates, cables are made from them [1–4]. When melting, casting, and heat treating articles made of magnesium bronze, it is necessary to take into account the evaporation of them having high vapor pressure of magnesium. In this regard, the analysis of equilibrium in the copper-magnesium system acquires importance not only taking into account temperature, but also pressure.

The purpose of this article is to build phase diagrams of the copper-magnesium system at various temperatures and pressures.

Two phases are formed in the copper-magnesium system:  $\text{Mg}_2\text{Cu}$  (Pearson symbol oF48, space group Fddd) and  $\text{MgCu}_2$  (Pearson symbol cF24, space group Fd-3m). The projection of curvilinear lines of maximum solubility located in three-dimensional  $p$ – $T$ – $x$  space onto the temperature-composition plane is shown in Fig. 1 [5].

The equilibrium gas above the pairs of Cu–Mg alloys consists mainly of magnesium atoms. The total vapor pressure above the alloys, with the exception of very dilute copper solutions, can be taken equal to the partial vapor pressure of magnesium. The equilibrium pressure of magnesium vapor over the melts in a wide

range of concentrations and temperatures is given in Table 1 according to the data of [6–8]. The extrapolation of the temperature dependences of the magnesium vapor pressure given in Table 1, before intersecting with the liquidus lines in the diagram in Fig. 1, determines the parameters of three-phase equilibria:  $(\text{Cu} \rightleftharpoons \text{L} \rightleftharpoons \text{G})$ ;  $(\text{Cu}_2\text{Mg} \rightleftharpoons \text{L} \rightleftharpoons \text{G})$ ,  $(\text{CuMg}_2 \rightleftharpoons \text{L} \rightleftharpoons \text{G})$  and  $(\text{Mg} \rightleftharpoons \text{L} \rightleftharpoons \text{G})$ .

The diagram in Fig. 1 is a projection of the lines of maximum solubility located in the  $p$ – $T$ – $x$ -space of the lines of non-invariant equilibria on the temperature-composition plane. At pressures above 500 Pa, this diagram coincides with the basal section.

Taking these parameters and the data of [5–8] into account, Fig. 2 shows the  $p$ – $T$  phase diagram of the copper-magnesium system, which is the projection of the spatial lines of three-phase equilibria of this system on the pressure-temperature plane.

In this diagram, curves 1–10 and 10–17 represent the evaporation and boiling of pure magnesium, respectively, and curves 10–15 represent its melting.

Four-phase equilibria are indicated by points 5, 6, and 7. The parameters of these points and the phases involved in them are given in Table 2.

At each point of the invariant four-phase equilibria, four curves of univariate three-phase

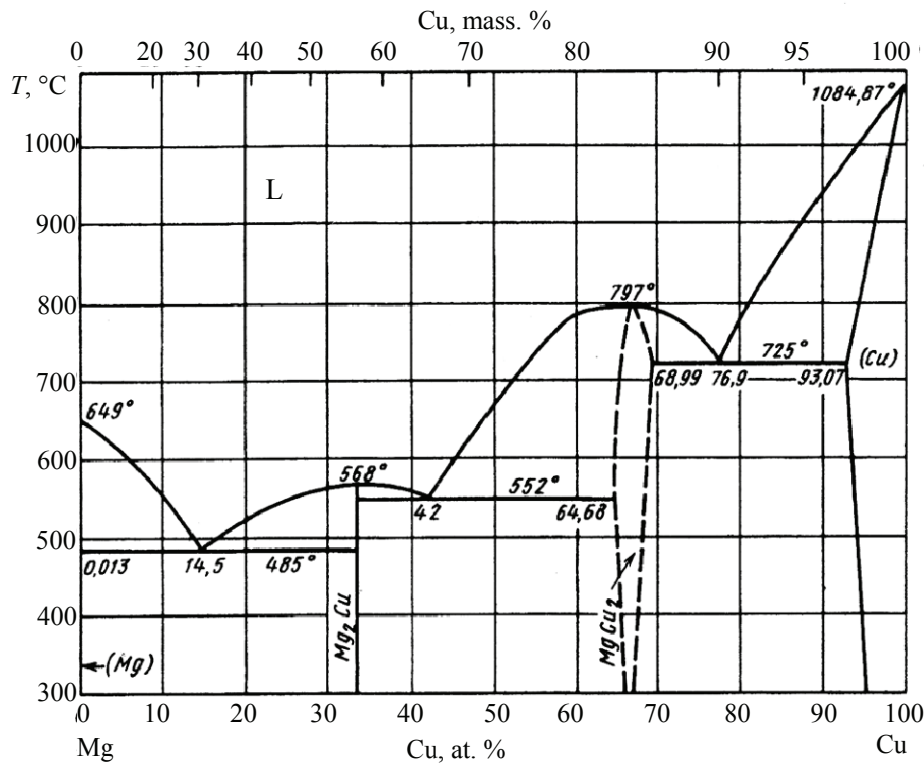


Fig. 1. The projection of the lines of maximum solubility of the copper-magnesium system on the temperature – composition plane [5]

Table 1

Temperature dependence of the partial vapor pressure of Mg over equilibrium melts Cu–Mg [ $\lg P_{Mg}(Pa) = -A/T + B$ ]

Composition, Mg at. %	A	B	Temperature, °C	Source
22.4	7760	9362	815 – 927	[6]
33.0	7630	9705	823 – 888	
52.1	6910	9607	669 – 781	
58.1	6850	9609	652 – 729	
66.7	6760	9682	618 – 683	
76.5	6670	9710	608 – 687	
85.7	6630	9726	599 – 668	
93.6	6590	9728	592 – 667	
11.0	8720	9460	900 – 1069	[7]
18.0	8520	9736	875 – 959	
22.0	8420	9896	740 – 948	
29.0	8260	10127	800 – 915	
37.0	8000	10202	812 – 866	
42.0	7830	10159	775 – 837	
50.0	7630	10123	776 – 837	
66.0	7390	10213	572 – 749	
76.0	7260	10228	640 – 730	[8]
90.0	7190	10279	619 – 730	
17.29	8337	9550	900 – 974	
23.36	8097	9570	886 – 957	
30.07	7867	9709	829 – 963	
37.04	7670	9733	809 – 870	
44.49	7463	9794	789 – 876	
50.53	7299	9902	833 – 848	
67.28	7004	9920	707 – 800	
65.52	6905	9936	683 – 778	
90.05	6840	9964	706 – 783	

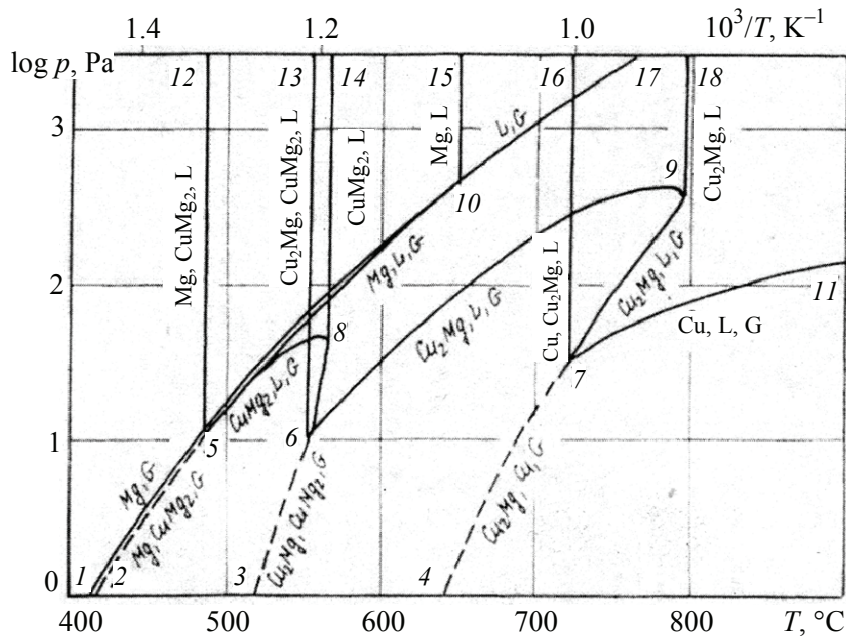


Fig. 2.  $p$ - $T$  phase diagram of the Cu-Mg system

Table 2

#### Four-phase equilibrium points of the Cu-Mg system

Point number in the diagram of Fig. 2	Temperature, °C	Pressure, Pa	Equilibrium phases
5	485	10	Mg, CuMg <sub>2</sub> , G, L
6	552	10	Cu <sub>2</sub> Mg, CuMg <sub>2</sub> , L, G
7	725	30	Cu, Cu <sub>2</sub> Mg, L, G

equilibria end. The phases involved in these equilibria are shown in Fig. 2. In the diagram in Fig. 2, there are two more points of non-invariant equilibria 8 and 9, which correspond to congruent melting of Cu<sub>2</sub>Mg and CuMg<sub>2</sub>.

The isobar  $p = 100$  Pa crosses the curves of three-phase equilibria 5-12, 5-10, 6-13, 6-9, 7-10, 9-7 and 7-11 on the  $p$ - $T$ -diagram (the point of intersection of the isobar with the melting curve of copper is not shown) In accordance with this, eight contour lines of non-invariant equilibria are shown in the isobaric section of Fig. 3. A characteristic feature of this diagram is the presence of three closed regions of the liquid. Of interest is also the heating behavior of mixtures of intermetallic compounds Cu<sub>2</sub>Mg and MgCu<sub>2</sub>. First, when mixtures are heated, they melt at a temperature of 552 °C, then at a temperature of 660 °C, the formed melt solidifies with the release of magnesium vapor, then at a temperature of 700 °C the remaining Cu<sub>2</sub>Mg melts again to form a liquid already rich in copper, which in turn at a temperature of 840 °C hardens again with the release of magnesium vapor and copper-based solid solutions. At an even higher

temperature close to the melting point of copper, these solutions, enriched with magnesium, melt again.

The isotherm  $T = 740$  °C intersects the equilibrium curves 7-11, 7-9, 6-9 on the  $p$ - $T$  diagram. In accordance with this, in the isothermal section at a temperature of 740 °C (Fig. 4) there are three horizontal horizons of unvariant equilibria. As follows from Fig. 4, in the indicated pressure range there is a region of a solid solution of magnesium in copper, a solid intermetallic compound Cu<sub>2</sub>Mg, and two liquid regions, one of which is rich in copper and the other is rich in magnesium.

Of practical interest is the diagram of the first kind [7] for the Cu-Mg system in  $p_{Mg}$ - $T$  coordinates, which is shown in Fig. 5. Taking into account the fact that the total equilibrium pressure of solutions based on copper gas over all alloys, except for very dilute solutions based on copper, can be replaced without partial error by partial pressure of magnesium, the diagram in Fig. 5 can easily be transformed from the diagram in Fig. 2, removing all equilibrium curves involving only condensed phases.

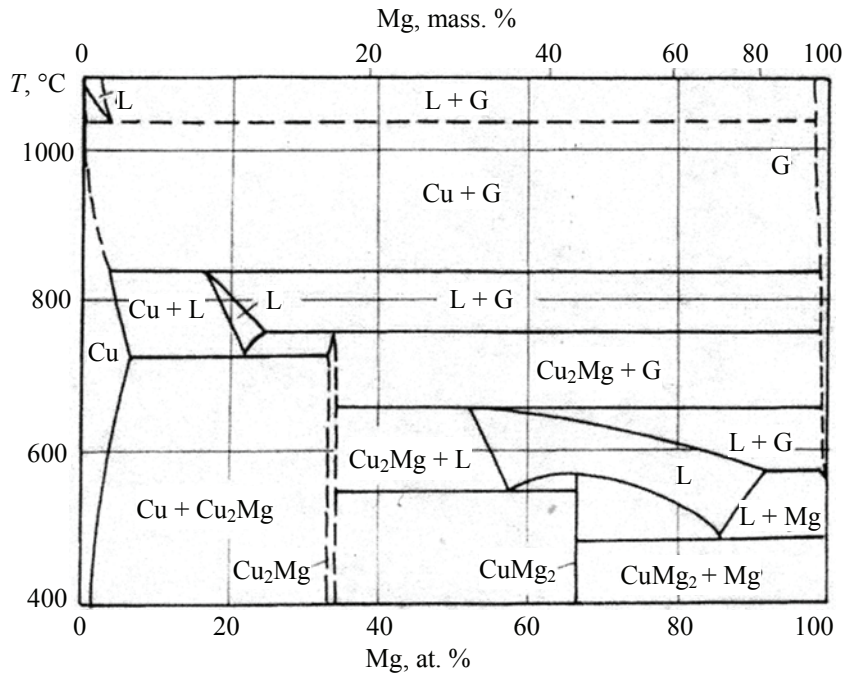


Fig. 3. Isobaric section of the phase diagram of the Cu–Mg system at a pressure of 100 Pa

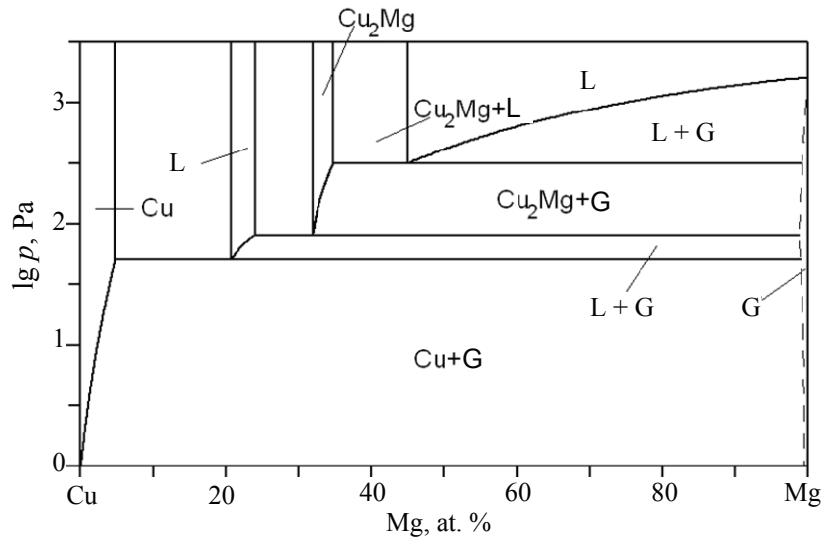


Fig. 4. Isothermal section of the phase diagram of the Cu–Mg system at a temperature of 740 °C

Examples of isobaric and isothermal sections of the phase diagram of the copper-magnesium system are shown in Figs. 4 and 5.

The whole diagram of Fig. 5 is divided into five single-phase regions (two regions of solid solutions based on copper and magnesium, liquid, regions of solid phases  $\text{Cu}_2\text{Mg}$  and  $\text{CuMg}_2$ ), separated by the boundaries of two-phase equilibria. The compositions of the phases located in these equilibria can be determined using the diagram in Fig. 1. To determine the composition of alloys in single-phase regions of

Fig. 5, the presence of isobars or isotherms of solubility of magnesium is necessary. In particular, the compositions of alloys, in particular liquids, in the diagram of Fig. 5, limited by the curve 10–5–6–7–8, can be calculated from the information given in Table 1.

The presented options for graphic equilibrium in the copper-magnesium system can be useful in choosing the optimal conditions for melting, casting, and heat treatment of alloys of the copper-magnesium system.

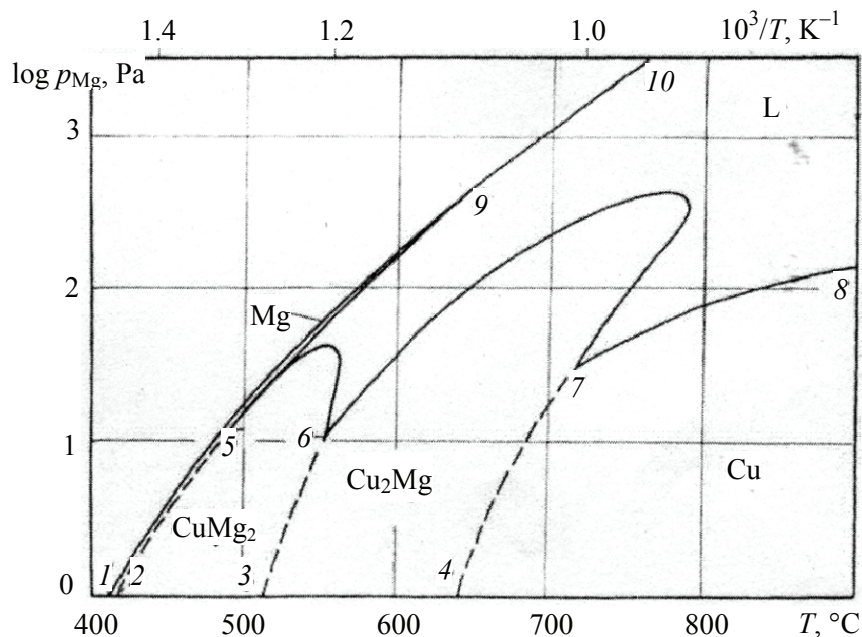


Fig. 5.  $p_{\text{Mg}}-T$  phase diagram of the Cu-Mg system

### Conclusions

Based on the analysis of equilibria involving the gas phase in the copper-magnesium system, a  $p-T$  diagram of this system, examples of isobaric and isothermal sections of a triple  $p-T-x$  phase diagram and a  $p_{\text{Mg}}-T$  phase diagram are presented.

### References

1. Nikolaev A.K., Kostin S.A. *Med' i zharoprochnyye mednyye splavy* [Copper and heat resistant copper alloys]. Moskva: DPK Press, 2012, 720 p.
2. Ten E.B., Badmazhalova I.B. Polucheniye kachestvennykh litykh zagotovok iz Cu-Mg splavov. [Preparing high-quality cast billets from Cu-Mg alloys]. *Izv. VUZov. Tsvetnaya metallurgiya*. 2013, 1, 45-49.
3. Ten E.B., Nam C.U. Nepreryvnaya plavka beskislородnоy medi [Continuous smelting of oxygen-free copper]. *Izvestiya VUZov. Tsvetnaya metallurgiya*. 2000, 6, 22-24.
4. Ten E.B. Nepreryvnoye gorizonta'noye lit'ye beskislородnоy medi. [Continuous horizontal casting of oxygen-free copper]. *Liteynoye proizvodstvo*. 2003, 7, 7-10.
5. Diagrammy sostoyaniya dvoynykh metallicheskih sistem. Spravochnik. [Phase diagrams of binary metal systems. Directory]. Ed. by N.P. Lyakishev. Moscow: Mashinostroyeniye. 1997, 2, 1024 p.
6. Sieben P., Schmal H.G. Vapour Pressure and Activity of Magnesium in the Binary Alloy Systems with Nickel and Vapour Pressure of Some Pure Metals. *Giesserei*. 1966. B. 18 (14), 197-211.
7. Gard S.P., Bhatt Y.J., Sundaram C.V. Thermodynamic Study of Liquid Cu-Mg Alloys by Vapour Pressure Measurement. *Metal. Trans.* 1973, 4, 283-289.
8. Juneja J.M., Iyngar G.N.K., Abraham K.P. Thermodynamic Properties of Liquid (Magnesium + Copper) Alloys by Vapour-Pressure Measurement Made by a Boiling-Temperature Method. *J. Chem. Thermodynamic*. 1986, 18, 1025-1035.
9. Levinsky Yu.V., Lebedev M.P. *R-T-x-diagrammy sostoyaniya dvoynykh metallicheskih sistem* [ $p-T-x$ -state diagrams of binary metal systems]. Moscow, Nauchnyy mir, 2014. 200 p.