Copper – Magnesium – Nickel

Hans Leo Lukas, Lazar Rokhlin

Literature Data

Many research groups dealt with the constitution of the Cu-Mg-Ni system [1951Koe, 1952Lie, 1956Mik1, 1956Mik2, 1972Feh, 1972Kom1, 1983Dar, 1983Kar, 1986She, 1995Ips]. Reviews were published by [1939Vos, 1949Jae, 1977Ray, 1979Cha, 1979Dri, 1995Ips]. Early work in this ternary system was based on the assumption of continuous solid solutions among the corresponding pairs of binary compounds [1939Vos, 1951Koe, 1956Mik1, 1956Mik2]. A major breakthrough was achieved when the section Cu_2Mg-Ni_2Mg was recognized as a pseudobinary peritectic system [1949Jae, 1952Lie, 1972Feh, 1983Dar, 1983Kar, 1995Ips]. Detailed crystallographic inspection established a ternary compound $(Ni_{0.45}Cu_{0.55})_2Mg$ as a new stacking variant of the Laves phases [1972Kom1, 1972Kom2, 1974Kri]. There is, however, still some lack of information on the complete incorporation of this compound into the phase diagram.

[1949Jae] reported solid solubilities of about 15 mol% Cu_2Mg in Ni_2Mg and about 8 mol% Ni_2Mg in Cu_2Mg, but later works considered these data not as reliable. [1951Koe] investigated the phase relations in three isopleths for Cu:Ni = 3:1, 1:1 and 1:3 by thermal analysis of 40 alloys. He used the results for a basic construction of the liquidus surface, which shows three monovariant troughs, directed from the Mg-Ni to the Cu-Mg side, so that in pairs the binary eutectic transformations $L \rightleftharpoons Ni+Ni_2Mg$ with $L \rightleftharpoons Cu+Cu_2Mg$, the peritectic transformation $L+Ni_2Mg \rightleftharpoons NiMg_2$ with the eutectic transformation $L \rightleftharpoons Cu_2Mg+CuMg_2$, and the eutectic transformations $L \rightleftharpoons NiMg_2+(Mg)$ and $L \rightleftharpoons CuMg_2+(Mg)$ continuously turn one into the other without any invariant reaction. He was aware, that this form of the liquidus surface is a simplification, neglecting the non-isomorphous lattices of the corresponding pairs of compounds Ni_2Mg-Cu_2Mg and $NiMg_2$-$CuMg_2$.

[1952Lie] used thermal analysis, microscopic and X-ray methods for a construction of the polythermal section Cu_2Mg-Ni_2Mg, which was shown to be a pseudobinary peritectic system: $L+Ni_2Mg \rightleftharpoons Cu_2Mg$. The solubility limits of the Ni_2Mg- and Cu_2Mg- based solid solutions were determined. [1956Mik1] constructed the liquidus surface of the Cu-Mg-Ni phase diagram from thermal analysis and microscopic observations. These authors, like [1951Koe] treated the two phases Ni_2Mg and Cu_2Mg as a continuous solid solution. In the Mg-rich part of the system [1956Mik1] reported two invariant four-phase reactions, $L+(Ni,Cu)_2Mg \rightleftharpoons NiMg_2+CuMg_2$ at 540°C and $L \rightleftharpoons (Mg)+NiMg_2+CuMg_2$ at 480°C. For the first one the composition of liquid is given as $Cu_{33.5}Mg_{65}Ni_{1.5}$, however, this is incompatible with Raoult's law, which gives an initial slope of the liquidus of about 5 K/at.% Ni starting at the binary $CuMg_2$ compound, congruently melting at 568°C, whereas the values given by [1956Mik1] correspond to 18 K/at.% Ni. As furthermore $CuMg_2$ dissolves about 1 at.% NI, this slope should be related to the difference of the Ni contents of liquid and $CuMg_2$ and thus the temperatures of congruent melting of $CuMg_2$ and a liquidus point of the $L+CuMg_2$ equilibrium at this Ni content must be even closer. [1956Mik1] furthermore supposed a ternary compound NiCuMg, based on electric resistivity measurements on alloys of the Cu_2Mg-Ni_2Mg section by [1956Mik2]. This compound may be identified with the stacking variant of the Laves phases found by [1972Kom1, 1972Kom2].

[1972Feh] investigated the Cu corner of the Cu-Mg-Ni phase diagram along the monovariant eutectic line starting at the binary eutectic $L \rightleftharpoons (Cu)+Cu_2Mg$ using thermal analysis, electron microprobe analysis, microscopic and X-ray methods. They established the invariant four-phase reaction $L+Ni_2Mg \rightleftharpoons (Cu,Ni)+Cu_2Mg$. [1972Feh], like [1952Lie], considered the Cu_2Mg-Ni_2Mg section to be a pseudobinary system of two solid phases Cu_2Mg and Ni_2Mg. However, they assumed the solubility of Cu_2Mg in the Ni_2Mg phase to decrease rapidly with decreasing temperatures. About 4 to 7 at.% Cu were measured by microprobe analyses of this phase in alloys homogenized 70 h at 700°C. [1972Feh] tentatively outlined a reaction scheme taking into account the liquidus temperatures and invariant reactions reported by [1956Mik1]. They also constructed an isothermal section at 475°C revealing the phase equilibria in solid

state, however the later detected large solubility of $CuMg_2$ in $NiMg_2$ was not yet considered. In addition [1972Feh] constructed four partial isothermal sections at 850, 808, 800, and 750°C from the Cu-Ni side up to the Ni_2Mg-Cu_2Mg line. These sections must be taken as sketches to explain the four-phase reaction, rather than as quantitative diagrams, especially regarding the Mg solubility in the (Ni,Cu) solid solution. The limits at the Cu-Mg binary are about 0.5 at.% larger than in the accepted binary Cu-Mg phase diagram. For digitizing a small figure this may be taken as good agreement, but the limiting solubility of Mg in (Ni,Cu) at the (Ni,Cu)+Ni_2Mg two-phase field at 40 at.% Ni is drawn to increase with decreasing temperature from about 4 at.% Mg at 850°C to 5 at.% Mg at 730°C. This is not likely and no evidence of experimental support for these values is given in the paper. For the Mg-rich part of the system with more than 33 at.% Mg [1972Feh] constructed a tentative reaction scheme accepting the four-phase equilibria published by [1956Mik1].

[1972Kom1] investigated details of the crystal structure of Ni_2Mg-Cu_2Mg alloys within the range 50 to 55 mol% Cu_2Mg by single crystal X-ray photographs. The alloys were annealed at temperatures between 500 and 800°C. The authors revealed a hexagonal ternary phase at 55 mol% Cu_2Mg: $(Ni_{0.45}Cu_{0.55})_2Mg$ as a new stacking variant of the Laves phase structures. [1972Kom2, 1974Kri] explained the formation of this ternary phase as a function of the electron concentration. The conclusions of [1972Kom1, 1972Kom2] eventually correspond to the suggestions of [1956Mik1, 1956Mik2] about the compound "NiCuMg".

The reviews by [1977Ray, 1979Cha, 1979Dri] essentially accepted the limiting solubilities of the Laves phases from [1972Feh] and rejected those of [1952Lie].

[1983Dar] investigated alloys along the line $NiMg_2$-$CuMg_2$ by X-ray powder diffraction and established the formation of an extended $NiMg_2$-based solid solution (up to 85 mol% $CuMg_2$ at 600°C) with linear variation of the unit cell parameters. At higher Cu concentrations the $NiMg_2$ solid solution coexists with practically pure $CuMg_2$.

[1983Kar] used microscopic and X-ray analyses for the construction of an isothermal section at 400°C in the 40-100 mass% Mg area. The investigation was based on a number of prepared alloys which showed only the phases $NiMg_2$ and $CuMg_2$ in equilibrium with the Mg solid solution. No measurable solubility of Cu and Ni in solid magnesium was found. The solubility of Cu in solid $NiMg_2$ along the $NiMg_2$-$CuMg_2$ line was reported to be quite high whilst the solubility of Ni in solid $CuMg_2$ was reported to be quite small. These conclusions of [1983Kar] agree with the results of [1983Dar]. The extensions of the $NiMg_2$ and $CuMg_2$ homogeneity areas across the $NiMg_2$-$CuMg_2$ line were reported by [1983Kar] to be rather narrow (at least less than 1 at.%).

[1986She] prepared the ternary alloy $Ni_{0.75}Cu_{0.25}Mg_2$ by chemical reaction at 560-580°C without fusion resulting in a dark grey powder. X-ray powder diffraction proved solid solution of Cu in $NiMg_2$. This result confirms once more the high solubility of Cu in $NiMg_2$.

[1995Ips] reinvestigated experimentally the whole Cu-Mg-Ni phase diagram employing differential thermal analysis, X-ray powder diffraction and isopiestic vapor pressure measurements. Four polythermal sections were constructed: isopleths with constant x_{Cu}/x_{Ni} ratios of 2.0, 1.0 and 0.5 and at constant magnesium content of 71 at.%. [1995Ips] confirmed the invariant reactions U_1, U_2 and E_1 reported by [1972Feh] and accepted U_3. They assessed a table giving temperatures and compositions of the phases participating in all invariant four-phase reactions. These data, however, disagree to some extent with the liquidus surface constructed by [1956Mik1], especially in the Mg corner.

Thermodynamic investigations were performed by [1991Gna, 1993Gna1, 1993Gna2, 1994Gna, 1995Feu, 1995Ips].

Thermodynamic assessments were reported by [1995Feu, 1995Jac, 2002Gor]. The first two are restricted to modeling of the liquid phase, ignoring the ternary solubilities in the solid phases. [2002Gor] reported a complete ternary dataset, but there seem to be errors in the reported values. An attempt to reproduce the published calculated diagrams by these data resulted in significantly deviating diagrams.

Three papers [1995Cho, 1996Gon, 1997Gan] constructed formulas to predict ternary thermodynamic properties from the binary ones and applied them to the Cu-Mg-Ni system.

Binary Systems

The three binary systems Cu-Mg, Cu-Ni, and Mg-Ni are accepted from [Mas2]. Thermodynamic assessments of the three binary systems were prepared in the COST 507 action [1998Ans]. The phase diagrams calculated from these assessments agree very well with those of [Mas2].

Solid Phases

One ternary phase was established [1972Kom1, 1972Kom2] in the Ni_2Mg-Cu_2Mg section close to 50 mol%, but its range of stability was not fully determined, neither with respect to temperature nor to composition. [1998Tsu] confirmed an alloy molten from equiatomic parts Cu+Mg+Ni to consist of this phase.
(Cu) and (Ni) form a continuous solid solution. Three of the four binary phases form solid solutions of substantial extensions along the sections Ni_2Mg-Cu_2Mg and $NiMg_2$-$CuMg_2$. The mutual solubility limits of Ni_2Mg and Cu_2Mg are accepted from [1952Lie]. These data were obtained from lattice parameter measurements by X-ray diffraction and may be considered as quite reliable. [1972Feh] reported only 5-7 mol% solubility of Cu_2Mg in Ni_2Mg, derived from microprobe analysis of Ni in this phase in three-phase samples of compositions $Cu_{48}Mg_{17}Ni_{35}$ and $Cu_{39}Mg_{15}Ni_{46}$, annealed at 800°C and quenched. The binary Laves phases exhibit slightly extended homogeneity ranges: 4.3 at.% for Cu_2Mg and about 0.7 at.% Mg for Ni_2Mg. The width across the 33.3 at.% Mg line in the ternary system was not investigated.
The solubility of $CuMg_2$ in $NiMg_2$ was reported as 28 at.% Cu at 600°C [1983Dar], 24 at.% Cu at 400°C [1983Kar] or 25 at.% Cu at 450°C [1995Ips]. These data agree fairly well, also with [1986She]. The solubility of $NiMg_2$ in $CuMg_2$ is negligible, [1983Kar] estimated it to be 1 at.% Cu at 400°C, whereas [1983Dar] did not reveal it at all. The widths of the homogeneity ranges of $NiMg_2$ and $CuMg_2$ across the $NiMg_2$-$CuMg_2$ line are practically zero [Mas, 1983Kar]. The solubility of Cu and Ni in solid (Mg) is very small. In the binary Cu-Mg system it is less than 0.013 at.% Cu, for Ni no value was reported. All solid phases are listed in Table 1.

Pseudobinary Systems

The section Ni_2Mg-Cu_2Mg is recognized as a pseudobinary system. It is shown in Fig. 1, which reproduces in general the findings of [1952Lie]. The range, where the ternary Laves phase may be stable is indicated as hatched area according to [1972Kom1]. Corrections were made to meet the melting points of Ni_2Mg and Cu_2Mg reported for the Mg-Ni and Cu-Mg binary phase diagrams [Mas2]. The liquidus and solidus lines as well as the existence of a peritectic in this pseudobinary system, constructed by [1952Lie], have to be considered as quite reliable. They were not disputed and were supported by [1972Feh, 1977Ray]. For the extension of the two-phase field Cu_2Mg+Ni_2Mg the rather precise X-ray data of [1952Lie] were preferred over those of [1972Feh], who gave a solubility of Cu_2Mg in Ni_2Mg decreasing much more with decreasing temperature.

Invariant Equilibria

There are four invariant four-phase equilibria in the system and most probably two maxima of three-phase equilibria. Their temperatures and phase compositions are given in Table 2. The reactions U_1 and U_2 were first reported by [1972Feh] and experimentally verified by [1995Ips]. The compositions of the Ni_2Mg phase in Table 2 are adjusted to the data of [1952Lie]. Reaction U_3 was first reported by [1956Mik1] as $L+Cu_2Mg \rightleftharpoons NiMg_2+CuMg_2$ at 540°C. This reaction implies a three-phase field $L+NiMg_2+CuMg_2$ going to lower temperatures and the authors located it about 1 at.% Ni behind the binary melting point maximum of $CuMg_2$ at 568°C. This is a severe contradiction to Raoult's law, which predicts for 1 at.% Ni about 5 K freezing point depression, using the melting enthalpy of $CuMg_2$ from the accepted binary system [1998Ans] and assuming zero solubility of Ni in $CuMg_2$. With some solubility of Ni in $CuMg_2$ an even smaller temperature difference is expected. Therefore here this reaction is taken from a tentative calculation described below in section Thermodynamics as $L+NiMg_2 \rightleftharpoons Cu_2Mg+CuMg_2$ at 553°C with composition of L near the binary eutectic e_4. The three-phase field $L+NiMg_2+CuMg_2$ passes by a maximum e_3 at about

1 at.% Ni distance the binary $CuMg_2$ phase and then goes to E_1. [1972Feh, 1995Ips] did not investigate U_3 and adopted it from [1956Mik1]. From their calculation [2002Gor] reported very similar phase compositions as given in Table 2, but a temperature of 559°C. E_1 was first reported by [1956Mik1] and experimentally verified by [1972Feh, 1995Ips], except the composition of $NiMg_2$, which is taken from [1983Dar, 1983Kar]. The data on the maximum p_2 are accepted from [1952Lie], those for the maximum e_3 are taken from the calculation described below in section thermodynamics. The reaction scheme is presented in Fig. 2. Figure 3 shows the projection of the invariant equilibrium planes together with the lines of double saturation of liquidus and solidus, calculated from the data of Table 3.

Liquidus Surface

Figure 4 shows the liquidus surface, calculated from the dataset given in Table 3. At lower Mg contents it deviates slightly from the best experimental data, but, as the experiments cover only some restricted areas, it seems to be not possible to construct a better self-consistent diagram of the whole liquidus surface.

Isothermal Sections

Figure 5 shows the calculated isothermal section at 475°C. It differs from that constructed by [1972Feh] by the concentrations of the solid phases, especially $CuMg_2$ and $NiMg_2$ where the data of [1983Dar, 1983Kar] are taken into account. The solubilities of the Laves phases across the 33.3 at.% Mg line must be taken as tentative. They are extrapolations from the binary assessments of these phases. The (Ni,Cu) corner of the (Ni,Cu)+Cu_2Mg+Ni_2Mg field was drawn by [1972Feh] more near to Cu and with higher Mg content.

Temperature – Composition Sections

Figure 6 displays a vertical section of the phase diagram, constructed after [1972Feh]. It follows the eutectic groove from the binary eutectic point L⇌Cu+Cu_2Mg to the counterpart L⇌Ni+Ni_2Mg. Figure 7 displays the vertical section for the constant ratio Cu:Ni = 1:1 (at.%), and Fig. 8 displays the vertical section for a constant Mg content of 71 at.%. The diagrams in Figs. 7 and 8 are calculated using Table 3. Figure 7 above 50 at.% Mg and Fig. 8 agree well with the experimental points of [1995Ips], The extension of the three-phase field L+$NiMg_2$+$CuMg_2$ by [1995Ips] was drawn much smaller, but, by dashed lines the authors themselves indicated that as tentative. Figure 7 below 50 at.% Mg shows somewhat higher temperatures than [1995Ips] and there it has to be taken as tentative.

Thermodynamics

Thermodynamic properties of ternary Cu-Mg-Ni alloys were determined from isopiestic magnesium vapor pressure measurements in the temperature range from 777 to 1077°C along three isopleths with x_{Cu}/x_{Ni} = 2.0, 1.0 and 0.5 between about 20 and 90 at.% Mg. Thermodynamic activities and partial molar Gibbs energies of magnesium were derived for the liquid phase and integral Gibbs energies of formation were calculated by Gibbs-Duhem integration. The composition dependence of the activities is reported for the three isopleths [1991Gna, 1993Gna1, 1993Gna2, 1995Ips].
[1972Pre] determined the enthalpy of formation of solid alloys along the section Cu_2Mg-Ni_2Mg within 0 to 40 mol% Ni_2Mg. Behind a minimum at 10 mol% the enthalpy increases with increasing Ni_2Mg content.
Enthalpies of liquid Cu-Mg-Ni alloys were studied by [1995Feu] using various types of calorimeters to determine the integral enthalpies of mixing and heat capacities.
[1995Jac] performed a thermodynamic calculation of the ternary system and reported a partial diagram of the isopleth at x_{Cu}/x_{Ni} = 0.5, compared with experimental points determined by [1995Ips]. These authors used the thermodynamic datasets of the binary systems of the COST 507 action [1998Ans] and added a ternary term to the Gibbs energy of liquid. They did not consider the ternary solubilities in the solid phases. Also [1995Feu] calculated the thermodynamic functions of the ternary liquid using an association model and compared with their measurements. A complete dataset for thermodynamic calculation of the whole ternary system was reported by [2002Gor]. However, the reported dataset seems to contain errors more

severe than a single typing error. An attempt to recalculate the published diagrams from this dataset resulted in diagrams significantly different from the published ones.
A tentative set of ternary terms for the Gibbs-energies of liquid and the ternary solid solutions of the binary intermediate phases is given in Table 3. It has to be used together with the three binary assessments from the COST 507 action [1998Ans]. The fictitious term for the Ni_2Mg type phase in the Cu-Mg system (Cu occupation on Ni sites) is taken from the assessment of Cu-Mg-Zn [1998Ans]. All the interaction parameters for the Laves phases tentatively are set independent on the occupation of the other sublattice, thus, except the Cu-Ni interaction parameters, they were already evaluated in the binary assessments. The ternary parameter for liquid stems from a transformation of Toop's formula, modified by Hillert, into the Muggianu formalism. Calculations by this dataset reproduce fairly well the all experimental points in the Mg-rich part (> 50 at.% Mg) of the system, and may be taken as good approximations in the Mg-poor part.
A generalization of the Miedema model for the estimation of formation enthalpies of ternary and higher-order intermetallics was developed by [1996Gon] and was successfully tested with respect to the experimental data for alloys $MgCu_{2-x}Ni_x$. The estimated enthalpy values increased to some extent with increasing Ni content.
A general solution model for the prediction of ternary thermodynamic properties from the binary subsystems was proposed by [1995Cho] and tested successfully for several alloys of the Cu-Mg-Ni system. Another such model, called parabolic model, was constructed by [1997Gan] and also tested successfully at the Cu-Mg-Ni system.

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Table 1: Crystallographic Data of Solid Phases

Phase/ Temperature Range [°C]	Pearson Symbol/ Space Group/ Prototype	Lattice Parameters [pm]	Comments/References
(Ni,Cu)	*cF*4		Complete solid solution
Cu	*Fm*$\bar{3}$*m*	*a* = 361.48	pure Cu at 25°C [Mas2, V-C]
< 1084.87	Cu		
Ni		*a* = 352.40	pure Ni at 25°C [Mas2]
< 1455			
(Mg)	*hP*2	*a* = 320.94	pure Mg at 25°C [Mas2]
< 650	*P*6$_3$/*mmc*	*c* = 521.07	
	Mg		
$(Ni_xCu_{1-x})_2Mg$	*cF*24		$0 \le x \le 0.45$ at 930°C [1952Lie]
	Fd$\bar{3}$*m*	*a* = 692.8	at *x* = 0.4 [1952Lie]
	Cu_2Mg		
Cu_2Mg		*a* = 704.8	at *x* = 0 [Mas2, V-C]
< 797			
$CuMg_2$	*oF*48	*a* = 907.0	[Mas2, V-C]
< 568	*Fddd*	*b* = 528.4	
	$CuMg_2$	*c* = 1825.0	
$(Ni_{1-x}Cu_x)_2Mg$	*hP*24		$0 \le x \le 0.49$ at 930°C [1952Lie]
	*P*6$_3$/*mmc*	*a* = 486.1	at *x* = 0.39 [1952Lie, V-C]
	Ni_2Mg	*c* = 1594	
Ni_2Mg		*a* = 482.4	at *x* = 0 [Mas2, V-C]
< 1147		*c* = 1582.6	
$(Ni_{1-x}Cu_x)Mg_2$	*hP*18		$0 \le x \le 0.85$ at 600°C [1983Dar]
	*P*6$_2$22	*a* = 525	at *x* = 0.85 [1983Dar]
	$NiMg_2$	*c* = 1355	
$NiMg_2$		*a* = 519.8	at *x* = 0 [Mas2, V-C]
< 760		*c* = 1321	
* $(Ni_{1-x}Cu_x)_2Mg$	*hP*36	*a* = 491.7	$0.5 < x < 0.55$
at least < 800	*P*6$_3$/*mmc*	*c* = 2404.0	[1972Kom1, V-C]
	$(Ni_{1-x}Cu_x)_2Mg$		

Table 2: Invariant Equilibria

Reaction	T [°C]	Type	Phase	Composition* (at.%)		
				Cu	Mg	Ni
L + Ni_2Mg ⇌ Cu_2Mg	930	p_2 max	L	50.0	33.3	16.7
			Ni_2Mg	32.7	33.3	34.0
			Cu_2Mg	36.7	33.3	30.0
L + Ni_2Mg ⇌ Cu_2Mg + (Ni,Cu)	808	U_1	L	(71)	19	(10)
			Ni_2Mg	29	31	40
			Cu_2Mg	42	31	27
			(Ni,Cu)	(78)	(3)	(19)
L + Ni_2Mg ⇌ Cu_2Mg + $NiMg_2$	658	U_2	L	33	58	9
			Ni_2Mg	24	34	42
			Cu_2Mg	42	34	24
			$NiMg_2$	(11)	67	(22)
L ⇌ $NiMg_2$ + $CuMg_2$	567	e_3 max	L	32.3	66.7	1.0
			$NiMg_2$	26.5	66.7	6.8
			$CuMg_2$	32.5	66.7	0.8
L + $NiMg_2$ ⇌ Cu_2Mg + $CuMg_2$	553	U_3	L	39	60	1
			Cu_2Mg	63	35	2
			$NiMg_2$	26	67	7
			$CuMg_2$	32	67	1
L ⇌ (Mg) + $NiMg_2$ + $CuMg_2$	480	E_1	L	14	84	2
			(Mg)	0.013	100	0
			$NiMg_2$	25	67	8
			$CuMg_2$	32	67	1

* Values given in parentheses are uncertain by several at.%.

Table 3: Ternary Parameters for the Cu-Mg-Ni System. To be Used Together with the Binary Parameter Datasets Cu-Mg, Cu-Ni and Mg-Ni of the COST 507 Action [1998Ans]

Parameter	T-range [K]	Value
$L_{Cu,Mg,Ni}^{liq}$	298-6000	+7500. -9.2 · T
${}^0G_{Mg:Ni}^{Laves\text{-}C15}$ - ${}^0G_{Mg:Ni}^{Laves\text{-}C36}$	298-6000	+4000
${}^0G_{Ni:Mg}^{Laves\text{-}C15}$ - ${}^0G_{Ni:Mg}^{Laves\text{-}C36}$	298-6000	-4000
${}^0L_{*:Cu,Mg}^{Laves\text{-}C15}$	298-6000	+13011.
${}^0L_{Cu,Mg:*}^{Laves\text{-}C15}$	298-6000	+6599.
${}^0L_{*:Cu,Ni}^{Laves\text{-}C15}$	298-6000	+25100. -8.0 · T
${}^0L_{Cu,Ni:*}^{Laves\text{-}C15}$	298-6000	+25100. -8.0 · T
${}^0L_{*:Mg,Ni}^{Laves\text{-}C15}$	298-6000	+50000.
${}^0L_{Mg,Ni:*}^{Laves\text{-}C15}$	298-6000	+50000.

Parameter	T-range [K]	Value
${}^0G_{\mathrm{Mg:Cu}}^{\mathrm{Laves\text{-}C36}} - {}^0G_{\mathrm{Mg:Cu}}^{\mathrm{Laves\text{-}C15}}$	298-6000	+4000.
${}^0G_{\mathrm{Cu:Mg}}^{\mathrm{Laves\text{-}C36}} - {}^0G_{\mathrm{Cu:Mg}}^{\mathrm{Laves\text{-}C15}}$	298-6000	-4000.
${}^0L_{\mathrm{*:Cu,Mg}}^{\mathrm{Laves\text{-}C36}}$	298-6000	+13011.
${}^0L_{\mathrm{Cu,Mg:*}}^{\mathrm{Laves\text{-}C36}}$	298-6000	+6599.
${}^0L_{\mathrm{*:Cu,Ni}}^{\mathrm{Laves\text{-}C36}}$	298-6000	+25100. -8.0 · T
${}^0L_{\mathrm{Cu,Ni:*}}^{\mathrm{Laves\text{-}C36}}$	298-6000	+25100. -8.0 · T
${}^0L_{\mathrm{*:Mg,Ni}}^{\mathrm{Laves\text{-}C36}}$	298-6000	+50000.
${}^0L_{\mathrm{Mg,Ni:*}}^{\mathrm{Laves\text{-}C36}}$	298-6000	+50000.
${}^0G_{\mathrm{Ni:Mg}}^{\mathrm{Laves\text{-}C36}} - {}^0G_{\mathrm{Ni}}^{\mathrm{SER}} - 2 \cdot {}^0G_{\mathrm{Mg}}^{\mathrm{SER}}$	298-6000	-30000. +8.0 · T
${}^0G_{\mathrm{Cu:Mg}}^{\mathrm{NiMg_2}} - {}^0G_{\mathrm{Cu}}^{\mathrm{SER}} - 2 \cdot {}^0G_{\mathrm{Mg}}^{\mathrm{SER}}$	298-6000	-26000. +0.5 · T

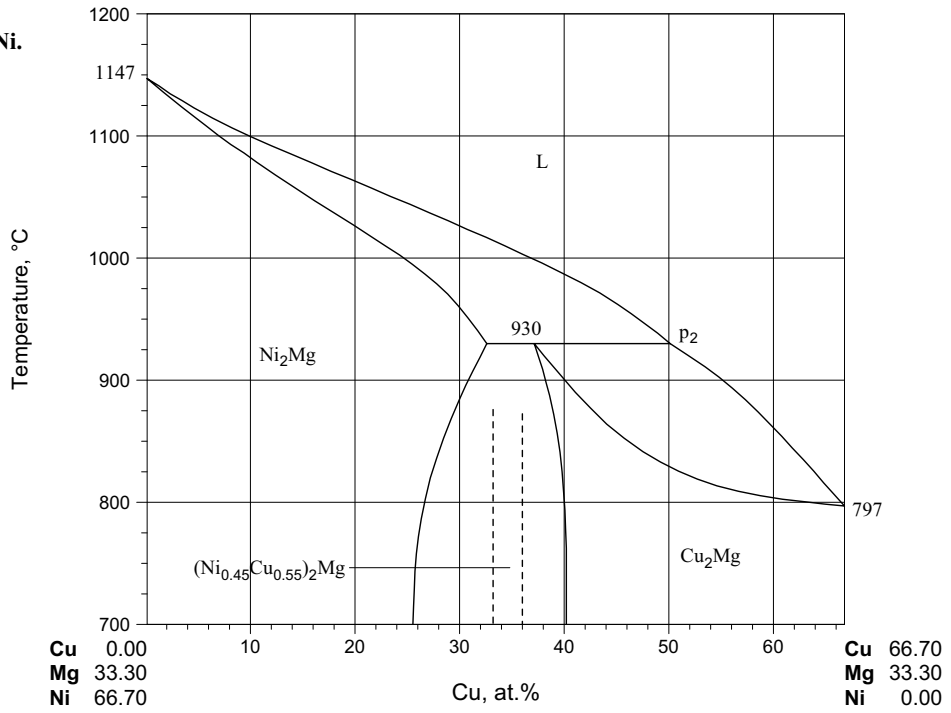

Fig. 1: Cu-Mg-Ni. The pseudobinary system Ni_2Mg-Cu_2Mg

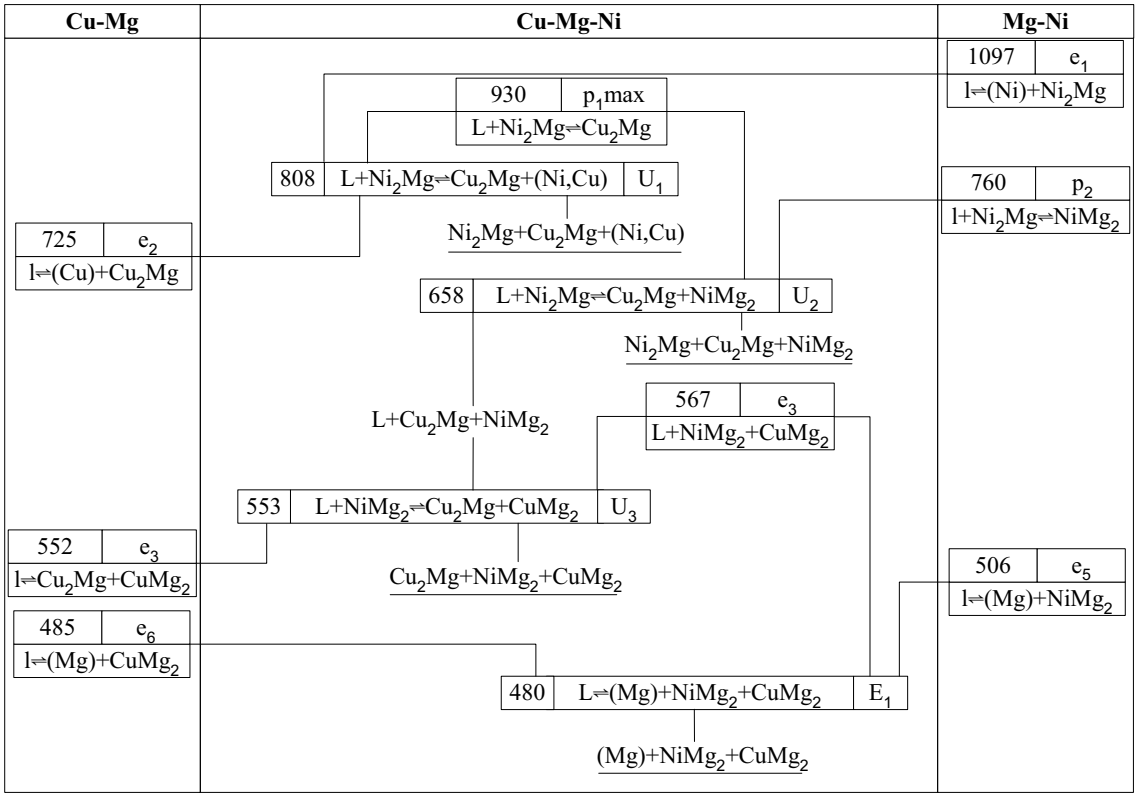

Fig. 2: Cu-Mg-Ni. Reaction scheme

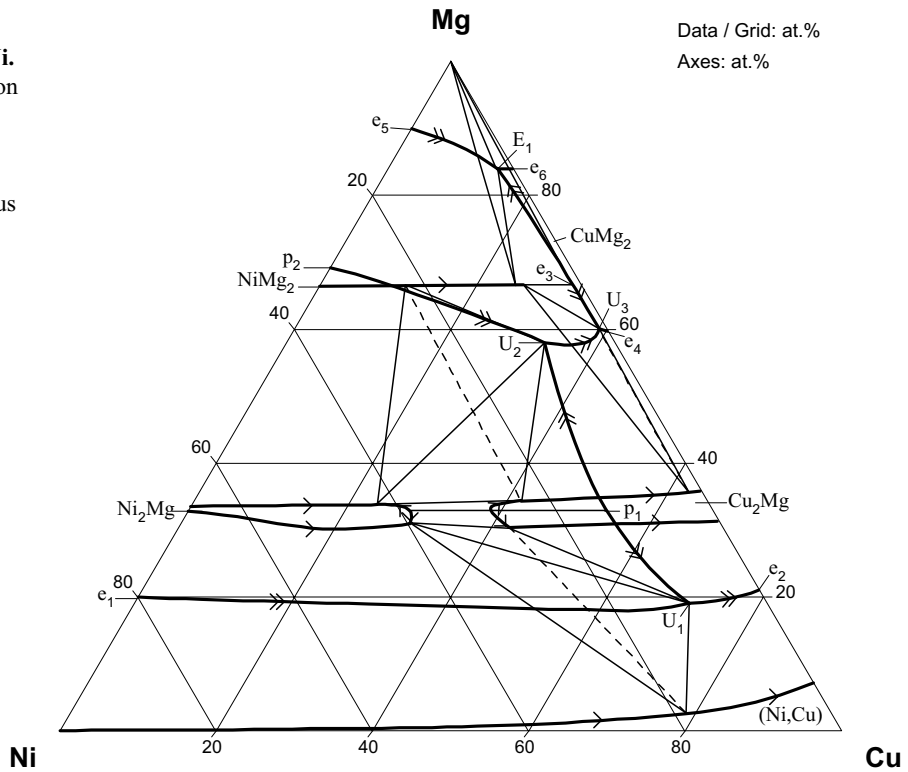

Fig. 3: Cu-Mg-Ni. Calculated projection of the four-phase equilibrium planes and lines of double saturation of liquidus and solidus

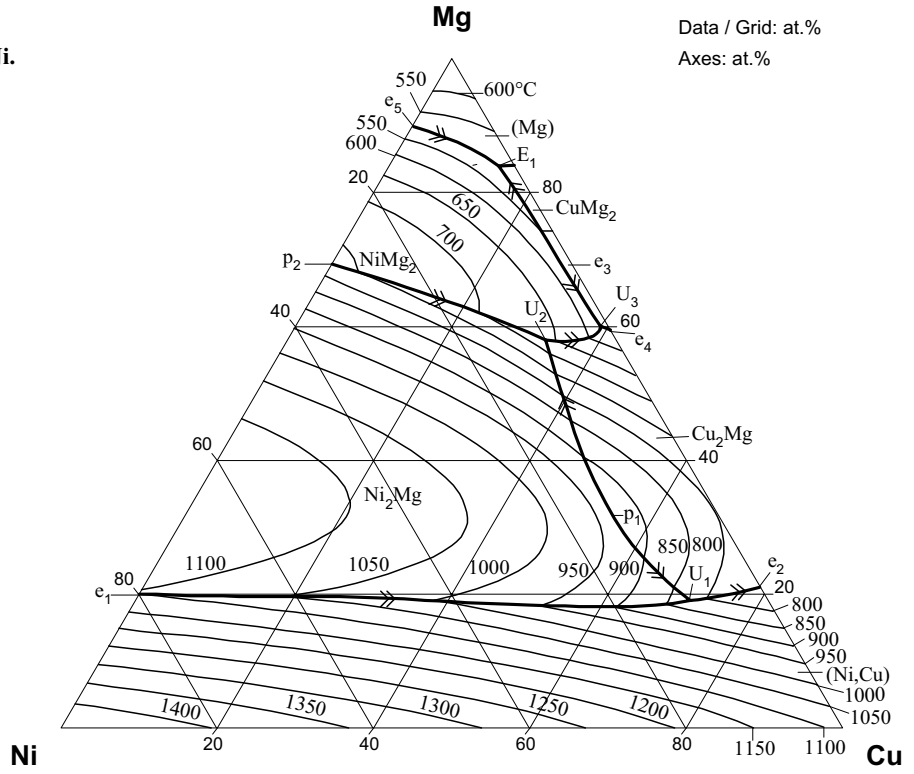

Fig. 4: Cu-Mg-Ni. Calculated liquidus surface

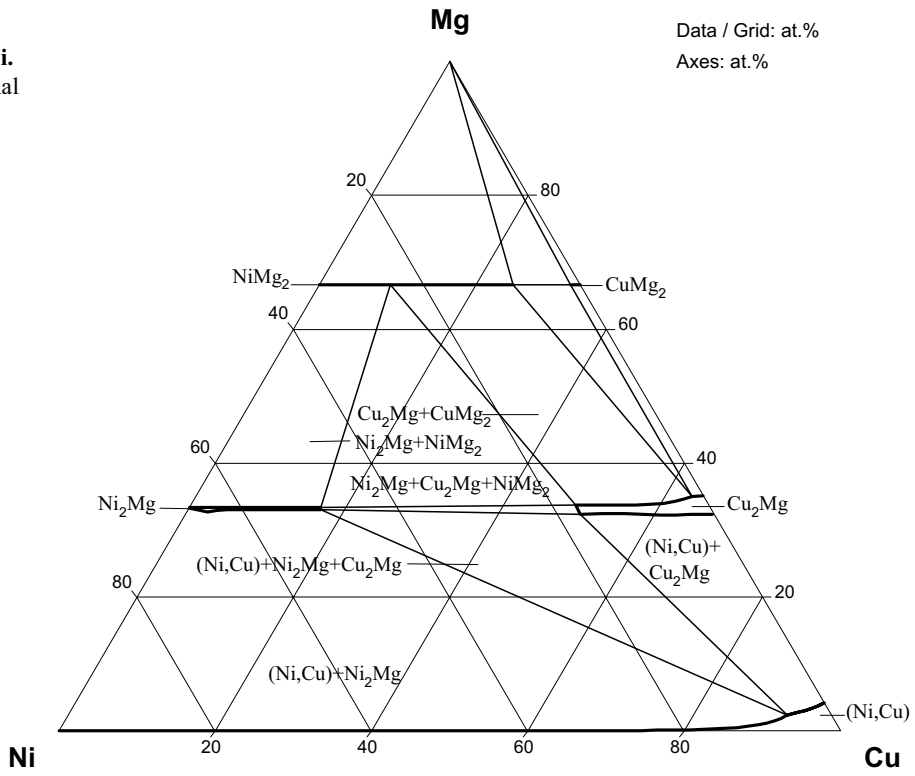

Fig. 5: Cu-Mg-Ni. Calculated isothermal section at 475°C

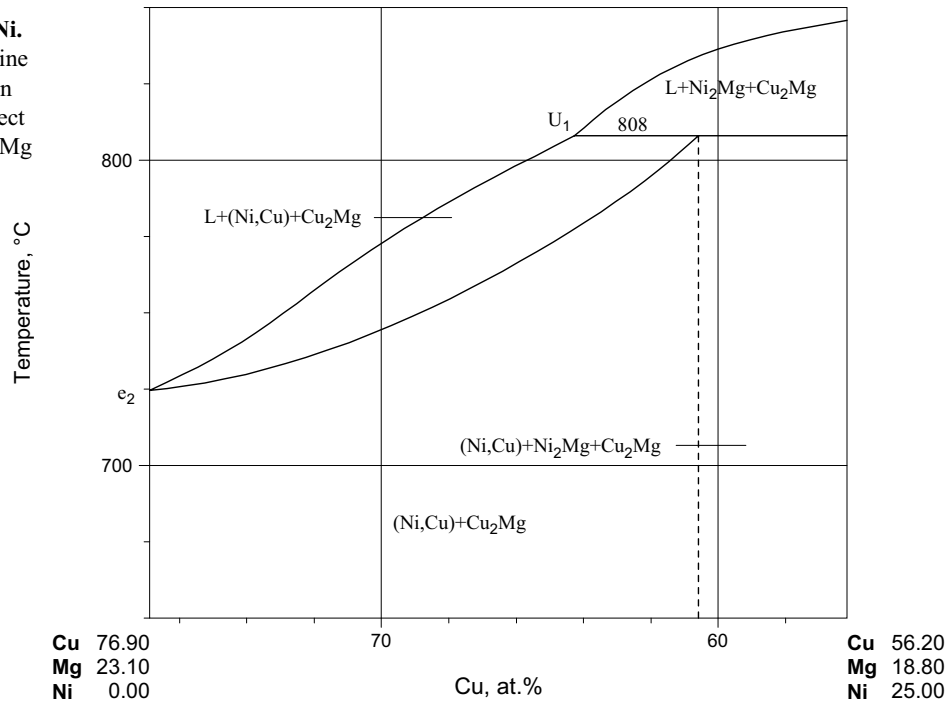

Fig. 6: Cu-Mg-Ni. Isopleth along the line of double saturation of liquid with respect to (Ni,Cu) and Cu_2Mg

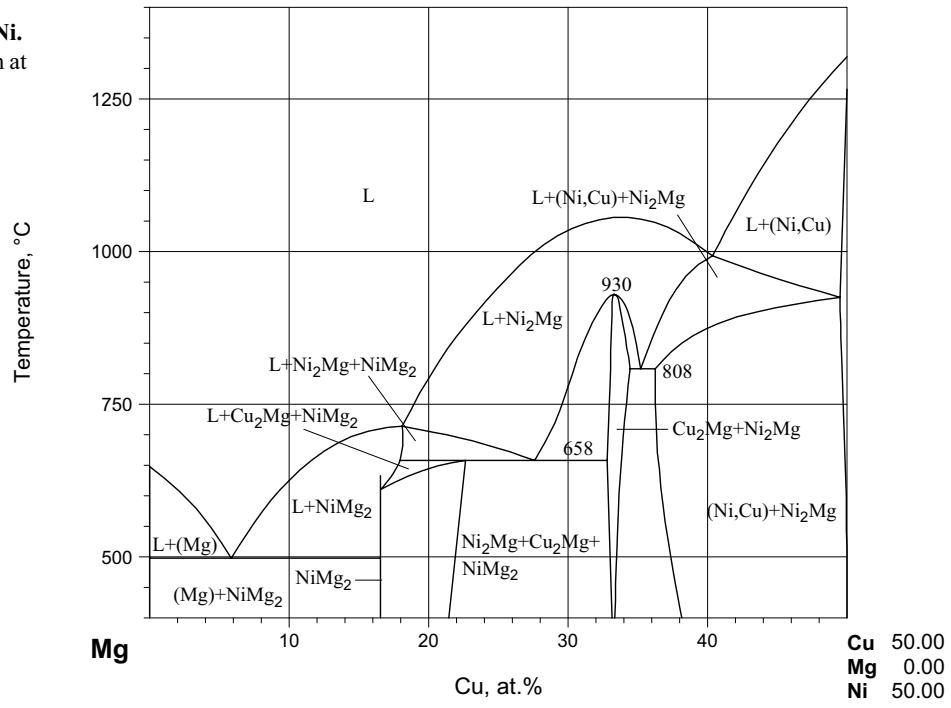

Fig. 7: Cu-Mg-Ni. Calculated isopleth at Cu:Ni=1:1

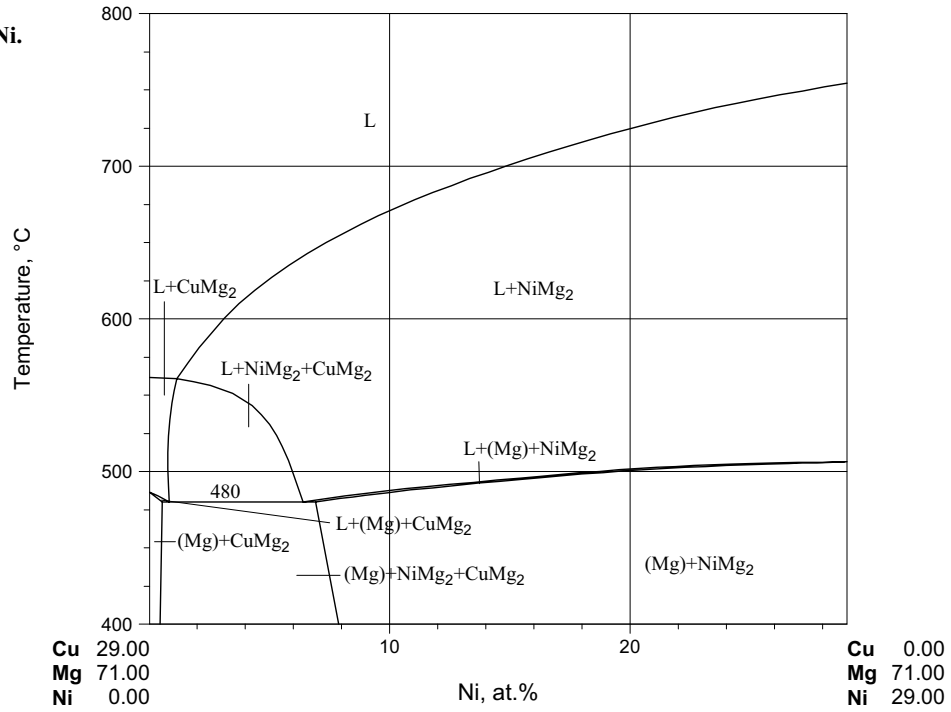

Fig. 8: Cu-Mg-Ni. Isopleth at 71 at.% Mg