

Copper – Lead – Tin

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Introduction

The nature of the phase relations in the Cu–Pb–Sn system has been of interest for many years, in particular, because Cu rich Cu–Pb–Sn alloys make excellent bearing metal for use in adverse conditions. More recently, interest in the phase relations of this system is due to the reaction between Pb–Sn alloys and copper through the soldering process; it being one of the oldest metallurgical processes for joining metal parts, in particular owing to the wide possibilities of the use of solder in modern microelectronic technology. For example, in circuit board manufacturing, solder is used to connect the leadframe of a chip to the circuit board. In flip chip technology, solder joins the chip directly to the board [2001Tu]. The constitution of the Cu–Pb–Sn system was first investigated by [1910Gio]. They determined a miscibility gap in the Cu rich corner by extrapolation of the isotherms for the separation of two liquids. Their results were in accordance with a later study of [1931Bri] but differed from the data of [1929Gue]. [1963Dav] conducted an investigation of lead rich alloys and presented the liquidus surface projection for the Pb corner. A similar study was conducted by [1983Mar] in conjunction with a determination of the temperature dependence of the monovariant process $L + \text{Cu}_3\text{Sn} \rightleftharpoons \text{Cu}_6\text{Sn}_5$ in the ternary system. [1983Pik] investigated the liquidus surface in the range of compositions bordering the Pb–Sn system. Critical assessments of the publications relating to the constitution of the system were carried out by [1932Blu, 1970Hof, 1979Cha, 1994Cha]. A review of studies of interfacial reactions was carried out by [2000Kat]. Thermodynamic calculations of isothermal sections were carried out by [1997Lee, 2001Tu, 2002Zen], and of the liquidus surface by [2001Her] and [2001Tu]. Experimental details of different studies are presented in Table 1. Information concerning the phase equilibria in this system is so far incomplete. In particular, the liquidus surface in the Sn corner, the solidus surface over the whole concentration range and also, isothermal and polythermal sections need further experimental investigation. Acquiring this knowledge would extend the practical application of the Cu–Pb–Sn alloys.

Binary Systems

The Cu–Pb system is accepted from [2006Sch]. Data relating to the Cu–Sn and Pb–Sn systems are taken from [Mas2].

Solid Phases

No ternary phases have been reported. Crystallographic data concerning the known unary and binary phases are listed in Table 2.

Invariant Equilibria

Temperatures, types of reactions and compositions of the phases taking place in the invariant equilibria are listed in Table 3. This table is compiled on the basis of [1931Bri, 1963Dav, 1979Cha, 1983Mar] and [1983Pik] with the conversion of compositions from mass to atomic per cent. [1979Cha] assigned E type for the invariant reactions U_3 , U_4 , U_5 in his table. However, in the drawing of the liquidus surface these reactions were shown as U type, which were retained in the present evaluation. [1983Pik] also reported the existence of a transition reaction $L + \varepsilon \rightleftharpoons \eta + (\text{Pb})$ at 250°C, with a composition of the liquid of about 0.79Cu–54.40Pb–44.81Sn (at.%). However, these data are in doubt because the authors indicated the position of the primary crystallization of the ε phase in conflict with the binary diagrams accepted in this assessment. According to the constitution of the Cu–Sn binary system, the η' phase (instead of the η phase) seems to take part in the invariant equilibrium $L \rightleftharpoons (\beta\text{Sn}) + (\text{Pb}) + \eta'$. A partial reaction scheme is presented in Fig. 1. However, it should be considered as tentative only, in particular in the Pb corner, where the

presence of the δ phase primary crystallisation field at the liquidus surface seems to be very doubtful, because it does not exist in equilibria with the liquid phase in the binary system; and there is no data concerning the formation of this phase in the ternary system.

Liquidus, Solidus and Solvus Surfaces

The liquidus surface projection and isotherms of the miscibility gap of the system are shown in Figs. 2 and 3, respectively. They are based on the results of experimental investigations by [1910Gio], [1931Bri], [1983Mar] (as quoted by [1986Zak]) and [1983Pik] as well as the reviews of [1932Blu], [1970Hof], [1979Cha] and [1994Cha]. The miscibility gap in the ternary system is wider than in the binary Cu–Pb system, and it extends to high temperatures - from 980.5°C in the binary system up to ~1130°C for the c_1 critical point in the ternary. The results of [1931Bri] indicate that the miscibility gap closes around 1130 to 1140°C and that the critical point lies at a composition of 60Cu–26Pb–14Sn (at.%). As quoted in the review of [1932Blu], the authors of [1913Bor] and [1929Bau] predicted a much higher temperature of closing, probably due to misinterpretation of their electrical conductivity measurements of the melt at high temperatures.

Liquidus and solidus temperatures of lead rich alloys were determined by [1983Mar] using thermal analysis. Liquidus temperatures for alloys up to about 3.2 at.% Cu are listed in Table 4. These data qualitatively agree with the steep liquidus surface in Fig. 2. The reported solidus temperature of the alloys is quite consistent with the eutectic temperature E_1 (Fig. 2). The liquidus surface projection was calculated from thermodynamic parameters by [2001Her] and [2001Tu]. The positions of the fields of primary crystallization of the γ , ε and η phases need further experimental verification. Also, the existence of the δ primary crystallisation field needs experimental verification. The calculated position of the $L' + L''$ region in the ternary system is shifted to the Pb corner in comparison with experimental data.

Isothermal Sections

Figure 4 presents the isothermal section at 955°C which is close to the monotectic temperature in the Cu–Pb binary system (952.7°C), compiled by [1994Cha] on the basis of experimental results from [1910Gio] and [1931Bri] and the review of [1932Blu]. The miscibility gap and the monotectic temperature (952.7°C compared with 955°C in [1994Cha]) are consistent with the Cu–Pb binary phase diagram [2006Sch]. Isothermal sections for the whole composition range at temperatures of 400, 350, 283°C (Figs. 5 to 7 respectively) and 200, 170°C (Figs. 9 and 10 respectively) were calculated from thermodynamic parameters by [2001Tu]. The isothermal section at 250°C calculated by [1997Lee] is presented in Fig. 8. The isothermal section for 100°C proposed by [1994Cha] is shown in Fig. 11. Figure 12 shows the partial isothermal section in the Sn rich corner at 220°C, calculated by [2002Zen]. All of these sections are in a good agreement with accepted binary systems. On comparing with figures from the original work, compositions were converted from mass to atomic per cent (Figs. 5, 6, 7, 9, 10, 12), and some stretching of narrow phase fields is marked (for example, $\varepsilon + (\text{Cu})$, $\eta + \varepsilon$ etc). The (Pb) solid solution takes part in equilibria with all phases and components of the Cu–Sn binary system at temperatures of 250°C and below, but at higher temperatures equilibrium between (Pb) and the η phase does not occur because this phase is in equilibrium with the liquid of the Pb–Sn system.

Thermodynamics

Using the transpiration method, [1970Aza] (as quoted by [1979Cha]) measured the vapor pressure of Pb over Cu–Pb–Sn melts at 1100°C. Isoactivity plots of Cu, Pb and Sn, as well as the excess Gibbs energy, also shown by [1970Aza], are derived from these data (probably by Gibbs–Duhem integration) and shown in Figs. 13 to 16, respectively. The approximate position of the $L' + L''$ region at 1100°C is presented in Fig. 13 (by a dotted line), on the basis of the experimentally determined temperature dependence of the liquid miscibility gap (see Fig. 3). Comparing this with the data presented by [1970Aza], the position of the $L' + L''$ loop is somewhat shifted. However, there is an inconsistency in the original data of [1970Aza]

because the smoothly curved isoactivity lines were also shown inside the gap; thermodynamics require straight (tie) lines. The slope of these tie lines, estimated from the entry and exit points to the gap are also inconsistent with the location of the critical points in Fig. 2.

The values for the activity coefficient of Pb and its compositional dependence in the Cu corner at 1100°C, reported by [1970Aza] as well as the values of the Pb vapor pressure over Cu rich alloys containing up to 10 at.% Sn and 10 at.% Pb obtained by [1974Hay] using the Knudsen effusion technique at 1130°C are listed in Table 5. It was noted in [1974Hay], that the activity of Pb in binary dilute solutions showed a remarkably positive deviation from Raoult's law and obeyed Henry's law to at least 0.05 at.% of Pb. The calculated Pb isoactivity curves in the Pb rich liquid phase at 1100°C show good consistency with the experimental data of [1974Hay].

The influence of Sn on the activity of Pb in dilute solid solutions has been measured by [1987Ryc1, 1987Ryc2] using an improved isopiestic method. The technique of [1987Ryc2] involved total minimum error in the temperature range 1100 to 1200°C. The first-order interaction parameter is given by [1987Ryc2] as:

$$\varepsilon_{\text{Pb}}^{\text{Sn}} = 8720/T - 1.42$$

based on their experimental results, combined with a value of

$$\ln (\gamma_{\text{Pb}(\text{Cu})}^0) = 3360/T - 0.6$$

for the activity coefficient of Pb at infinite dilution derived from data for binary liquid Cu–Pb alloys. An analysis of the temperature dependence of the $\varepsilon_{\text{Pb}}^{\text{Sn}}$ interaction parameter calculated by [1987Ryc1] on the basis of experimental results and using Krupkowski's method, has shown that the parameter value decreases with increasing temperature.

Indirectly derived activity data on the basis of analysis of the phase relations in the Pb rich corner over the temperature interval from 327 to 527°C, have been reported as activity coefficients of Cu and Sn [1963Dav]. Thermodynamic calculations of the liquidus surface [2001Her, 2001Tu] and of isothermal sections at 250°C [1997Lee], 400, 350, 283, 200 and 170°C [2001Tu] as well as at 200°C [2002Zen] were conducted using Calphad type calculations with a description of the liquid solution phase without ternary interactions. The calculations of [2001Her] show also a comparison with the activity data [1970Aza], misprinted as [1974Hay], however, a comprehensive Calphad assessment including all of the experimental thermodynamic and phase diagram data is still missing.

Notes on Materials Properties and Applications

Information relating to the investigation of properties of the Cu–Pb–Sn alloys is listed in Table 6. Cu–Pb–Sn alloys are applied, in particular, to cases where a metal is exposed to friction (and therefore to wear) under high specific pressure, with shocks and vibrations and at elevated temperatures. So, friction bearings made of copper alloys are used in automotive applications on a large scale, and the Cu–Pb–Sn alloy system is one of the most common [1992Boe]. New trends in development in this area involve high-strength alloys such as Cu–Ni–Sn bronzes, in particular, by the alloys (mass%) 79Cu–20Pb–1Sn and 84Cu–15Pb–1Sn (in at.% they are 92.2Cu–7.2Pb–0.6Sn and 94.2Cu–5.2Pb–0.6Sn, respectively). Another important aspect of the application of Cu–Pb–Sn alloys is related to the reactions between Pb–Sn alloys and copper [2001Tu, 2002Zen] during soldering. Solders are widely used to connect chips to their packaging substrates in flip chip technology as well as in surface mount technology.

Miscellaneous

In the review of [1991But], two models were proposed which can be used to predict the occurrence of liquid immiscibility in ternary metallic alloys. The Cu–Pb–Sn system is denoted as type III in their classification, where liquid immiscibility first appears at elevated temperatures within the ternary diagram, and as the

temperature decreases, the region of liquid immiscibility expands until eventually it intersects one or more of the constituent binaries.

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Table 1: Investigations of the Cu-Pb-Sn Phase Relations, Structures and Thermodynamics

Reference	Method/Experimental Technique	Temperature/Composition/Phase Range Studied
[1910Gio]	Thermal analysis	810 - 1084°C, 75 to 100 at.% Cu, 0 to 28 at.% Pb, 0 to 43 at.% Sn
[1913Bor]	Electrical conductivity measurements	> 1140°C, Cu rich corner
[1929Bau]	Electrical conductivity measurements	> 1140°C, Cu rich corner
[1929Gue]	Thermal analysis	0 to 72 at.% Sn
[1931Bri]	Chemical analysis of the samples from the melt, thermal analysis, metallography	800 - 1200°C, 0 to 63 at.% Sn
[1959Har]	Determination of Cu and Sn solubility in liquid Pb	Pb rich corner
[1963Dav]	Determination of Cu and Sn solubility in liquid Pb. Metallography, thermal analysis	325 - 625°C, Pb rich corner (< 2 at.% Cu, < 2 at.% Sn)

Reference	Method/Experimental Technique	Temperature/Composition/Phase Range Studied
[1970Aza]	Transportation method	1100°C
[1974Hay]	Knudsen effusion-mass loss analysis	0 to 10 at.% Pb, 0 to 10 at.% Sn
[1983Mar]	Thermal analysis, metallography, electronic microprobe analysis	270 - 610°C, Pb rich corner, the alloys containing Cu ₆ Sn ₅ phase
[1983Pik]	Thermal analysis, metallography	180 - 500°C, 0 to 3.8 at.% Cu
[1987Ryc1]	Modified isopiestic method, chemical analysis, thermodynamic calculation (Krupkowski's method)	1100 - 1200°C, 0 to 10 at.% Sn, 0 to 10 at.% Pb
[1987Ryc2]	Modified isopiestic method, thermodynamic calculation (Krupkowski's method)	1100 - 1200°C, 2 to 10 at.% Sn, 2 to 10 at.% Pb
[1989Fel]	Laser reflowed Cu/Pb-Sn solder joints investigation, scanning electron microscopy, energy dispersive X-ray analysis, X-ray diffraction	Room temperature, whole range of compositions
[1995Dae]	Diffusion in soldered microelectronic contacts between Cu and Sn/Pb solders, ion beam etching	150 - 500°C
[1997Lee]	Thermodynamic calculation (Calphad-type)	Whole range of compositions
[2001Her]	Thermodynamic calculation (Calphad-type)	Whole range of compositions
[2001Hir]	Interfacial reactions of quad flat packages (QFP) joints, exposure test	125°C, 37 at.% Pb
[2001Lee]	Redeposition kinetics of intermetallics at the solder Au/Ni/Cu interface during the aging treatment, under bump metallurgy (UBM) structure	≤ 230°C, 2.9Cu-34.3Pb-62.8Sn (at.%)
[2001Tu]	Thermodynamic calculation (Calphad-type)	Whole range of compositions
[2002Li]	Interfacial microstructure of eutectic PbSn solders on Al/Ni(V)/Cu thin films, under bump metallurgy (UBM) structure	220°C

Reference	Method/Experimental Technique	Temperature/Composition/Phase Range Studied
[2002Pra]	Growth kinetics of the Cu–Sn intermetallic compounds at the molten Pb–Sn solder/Cu interface, X-ray diffraction	193 - 310°C, whole range of compositions
[2002Zen]	Thermodynamic calculation (Calphad-type)	Sn rich corner (< 9 at.% Cu, < 47 at.% Pb)

Table 2: Crystallographic Data of Solid Phases

Phase/ Temperature Range [°C]	Pearson Symbol/ Space Group/ Prototype	Lattice Parameters [pm]	Comments/References
(Cu) < 1084.62	<i>cF4</i> <i>Fm$\bar{3}m$</i> Cu	$a = 361.46$	pure Cu at 25°C [Mas2]
$\text{Cu}_{1-x-y}\text{Pb}_x\text{Sn}_y$			at 798°C $x = 0, 0 \leq y \leq 0.077$ [1944Ray, 1994Sau] at 700°C $x = 0, 0 \leq y \leq 0.087$ [1970Tok, 1997Boc] at 250°C $x = 0, 0 \leq y \leq 0.057$ [1970Tok, 1997Boc] at 200°C $x = 0, 0 \leq y \leq 0.007$ [1944Ray, 1994Sau] at 952.7°C $y = 0, 0 \leq x \leq 0.004$ [1991Tep] at 326.5°C $y = 0, 0 \leq x \leq 0.000046$ [1991Tep] at 183°C $x + y = 1, 0 \leq x \leq 0.013, 0 \leq y \leq 0.281$ [Mas2] $a = 361.46$ to 370.46 at $x = 0, 0 \leq y \leq 0.091$ [1994Sau]
(α Pb) < 327.502	<i>cF4</i> <i>Fm$\bar{3}m$</i> Cu	$a = 495.02$	at 25°C [Mas2]
$\text{Cu}_x\text{Pb}_{1-x-y}\text{Sn}_y$			at 183°C $x = 0, 0 \leq y \leq 0.293$ [1954Tyz] at 173°C $x = 0, 0 \leq y \leq 0.264$ [1960Cah] at 25°C $x = 0, 0 \leq y \leq 0.02$ [1960Cah] at 326.5°C $y = 0, 0 \leq x < 0.0002$ [1991Tep]
(β Pb) HP	<i>hP2</i> <i>P6$_3$/mmc</i> Mg	$a = 326.5$ $c = 538.7$	at 25°C, 10.3 GPa [Mas2]
(β Sn) 231.9681 - 13	<i>tI4</i> <i>I4$_1$/amd</i> β Sn	$a = 583.18$ $c = 318.18$	at 25°C [Mas2]
(β Sn), $\text{Cu}_x\text{Pb}_y\text{Sn}_{1-x-y}$			at $y = 0, 0 \leq x \leq 0.0001$, [1939Hom, 1994Sau]

Phase/ Temperature Range [°C]	Pearson Symbol/ Space Group/ Prototype	Lattice Parameters [pm]	Comments/References
(α Sn) < 13	<i>cF8</i> <i>Fd$\bar{3}m$</i> C (diamond)	$a = 648.92$	[Mas2]
β , Cu _{1-x-y} Pb _x Sn _y 798 - 586	<i>cI2</i> <i>Im$\bar{3}m$</i> W	$a = 297.81$ to 298.71 $a = 298.1$ to 299.1	$x = 0, 0.131 \leq y \leq 0.165$ [1994Sau] $x = 0, 0.134 \leq y \leq 0.157$ [1994Sau] $x = 0, 0.152 \leq y \leq 0.172$ [1939Isa, 1994Sau]
γ , Cu ₃ Sn 755 - 520	<i>cF16</i> <i>Fm$\bar{3}m$</i> BiF ₃	$a = 606.05$ to 611.76 $a = 611.6 \pm 0.6$	15.5-27.5 at.% Sn at 0 at.% Pb [1994Sau] 16.6-25.0 at.% Sn at 710°C [1994Sau] at 25 at.% Sn, 700°C [1957Kno]
δ , Cu ₄₁ Sn ₁₁ 590 ~ 350	<i>cF416</i> <i>F$\bar{4}3m$</i> Cu ₄₁ Sn ₁₁	$a = 1798.0$	20-21 at.% Sn at 0 at.% Pb [1994Sau] labelled as “Cu ₃₁ Sn ₈ ” [1979Cha] at 20.5 at.% Sn, single crystal selected from the alloy subsequently annealed at 710°C (2 d) and 560°C (5.5 d) and then quenched in water [1977Boo]
ζ , Cu ₁₀ Sn ₃ 640 - 582	<i>hP26</i> <i>P6₃</i> Cu ₁₀ Sn ₃	$a = 733.0$ $c = 786.4$	20.3-22.5 at.% Sn at 0 at.% Pb [1994Sau] at 23.1 at.% Sn, single crystal selected from the alloy annealed at $602 \pm 2^\circ\text{C}$ (6 d) and rapidly quenched [1975Bra]
ϵ , Cu ₃ Sn < 676	<i>oC80</i> <i>Cmcm</i> Cu ₃ Sn	$a = 552.9$ $b = 477.5$ $c = 432.3$	24.5-25.9 at.% Sn at 0 at.% Pb [1994Sau] at 25 at.% Sn [1983Wat, 1994Sau]
η , Cu ₆ Sn ₅ (h) 415 - 186	<i>hP4</i> <i>P6₃/mmc</i> NiAs	$a = 419.0$ $c = 508.6$ $a = 419.2 \pm 0.2$ $c = 503.7 \pm 0.2$	43.5-45.5 at.% Sn at 45.45 at.% Sn [1994Sau] single crystal with 45.45 at.% Sn selected from the alloy annealed at 210°C (49 d) and quenched into iced water [1973Gan]

Phase/ Temperature Range [°C]	Pearson Symbol/ Space Group/ Prototype	Lattice Parameters [pm]	Comments/References
η' , Cu ₆ Sn ₅ (r) < 186	h^*	$a = 2087.0$ $c = 2508.1$	~ 45.45 at.% Sn at 0 at.% Pb; superlattice based on NiAs-type structure [1994Sau] single crystal with 45.45 at.% Sn selected from the alloy annealed at 210°C (49 d) and at 175°C (49 d) and then cooled to room temperature for 14 d [1973Gan]
α' (Cu–Sn)	$hP2$ $P6_3/mmc$ Mg	$a = 2087.0$ $c = 2508.1$ $a = 2087.0$ $c = 2508.1$	metastable ~8–11.5 at.% Sn at 0 at.% Pb [1963Der, 1967Deb, 1994Sau] at ~ 8 at.% Sn [1963Der] at 11.5 at.% Sn in the alloy with 16.5 at.% Sn heated to 570°C for 10 min, and then aged at 100°C and 130°C [1984Sau, 1994Sau] labelled as “ δ' ” [1973Van]
ω (Cu–Sn)	$hP12$	$a = 421$ $c = 1110$	metastable, 15–16 at.% Sn at 0 at.% Pb [1971Van, 1973Van, 1980Zak] in single-crystal with 15.5 at.% Sn quenched from 700°C [1980Zak]
X (Cu–Sn)	$hP9$	$a = 728$ $c = 258$ $a = 740$ $c = 260$	metastable on tempering of a quenched β single-phase alloy [1932Isa, 1934Bug, 1957Bag] at ~15 at.% Sn [1932Isa, 1957Bag] in a 15 at.% Sn alloy with memory of shape, annealed at 100°C and quenched into water; labelled as “L” [1983Kuw]
β_2 (Cu–Sn)	ordered rhombic	$a = 1273$ $b = 424$ $c = 600$	metastable in a 15.5 at.% Sn alloy quenched from 700°C and aged during 15 years [1980Zak]
γ' (Cu–Sn)	ordered cubic	$a = 899$	metastable in a 19.5 at.% Sn alloy, vapor quenched, below 200°C [1984Sau, 1994Sau]

Table 3: Invariant Equilibria

Reaction	T [°C]	Type	Phase	Composition (at.%)		
				Cu	Pb	Sn
L, L', L''	~1130	c ₁ , critical	L	~60	~26	~14
$L' + (\text{Cu}) \rightleftharpoons L'' + \beta$	772 [1979Cha]	U ₁	L'	~ 83.33	~ 3.29	~ 13.38
			(Cu)	-	-	-
			L''	~ 6.15	~ 90.56	~ 3.29
			β	-	-	-
$L' + (\text{Cu}) \rightleftharpoons L'' + \gamma$	734 [1979Cha]	U ₂	L'	~ 80.22	~ 1.84	~ 17.94
			(Cu)	-	-	-
			L''	~ 3.08	~ 88.69	~ 8.23
			γ	-	-	-
L', L'', γ ?	~600	c ₂ , critical	L	~29	~22	~49
$L + \beta \rightleftharpoons \gamma + (\text{Cu})$	577 [1979Cha]	U ₃	-	-	-	-
$L + \gamma \rightleftharpoons \delta + (\text{Cu})$	500 [1979Cha]	U ₄	-	-	-	-
$L + \delta \rightleftharpoons \varepsilon + (\text{Cu})$	> 350 on the basis of [1963Dav]	U ₅	-	-	-	-
$L \rightleftharpoons (\text{Pb}) + \varepsilon + (\text{Cu})$	326 [1963Dav]	E ₁	L	0.19	99.78	0.03
$L \rightleftharpoons (\beta\text{Sn}) + (\text{Pb}) + \eta'$	182.2 [1963Dav] or 180 [1983Pik]	E ₂	L	0.45	26.60	72.95

Table 4: Liquidus temperatures of the Pb rich alloys [1983Mar, 1986Zak]

Composition (at.%)			Liquidus Temperature [°C]
Cu	Pb	Sn	
0.32	98.81	0.87	481
1.60	96.70	1.70	555
1.58	94.18	4.24	562
1.55	90.13	8.32	560
3.16	95.15	1.69	592
3.08	88.68	8.24	800

Table 5: Thermodynamic Properties of Pb in the Cu rich Corner. Standard State Pb (liquid)

Thermodynamic Quantity	Data of [1970Aza], at 1100°C	Data of [1974Hay], at 1130°C
γ_{Pb}^0	6.7	4.3
$\varepsilon_{\text{Pb}}^{\text{Pb}}$	−3.6	0.0
$\varepsilon_{\text{Pb}}^{\text{Sn}}$	3.3	7.0
$\rho_{\text{Pb}}^{\text{Sn}}$	0	−15

Table 6: Investigations of the Cu-Pb-Sn Materials Properties

Reference	Method/Experimental Technique	Type of Property
[1913Bor]	Electrical conductivity measurements	Electrical conductivity
[1929Bau]	Electrical conductivity measurements	Electrical conductivity
[1995Dae]	Ion beam slope cut method, scanning electronic microscopy	Specific electric resistance, growth constants of the ε and η' phases
[1999Mor]	Review	Young's modulus, yield stress, tensile stress, elongation, electrical conductivity

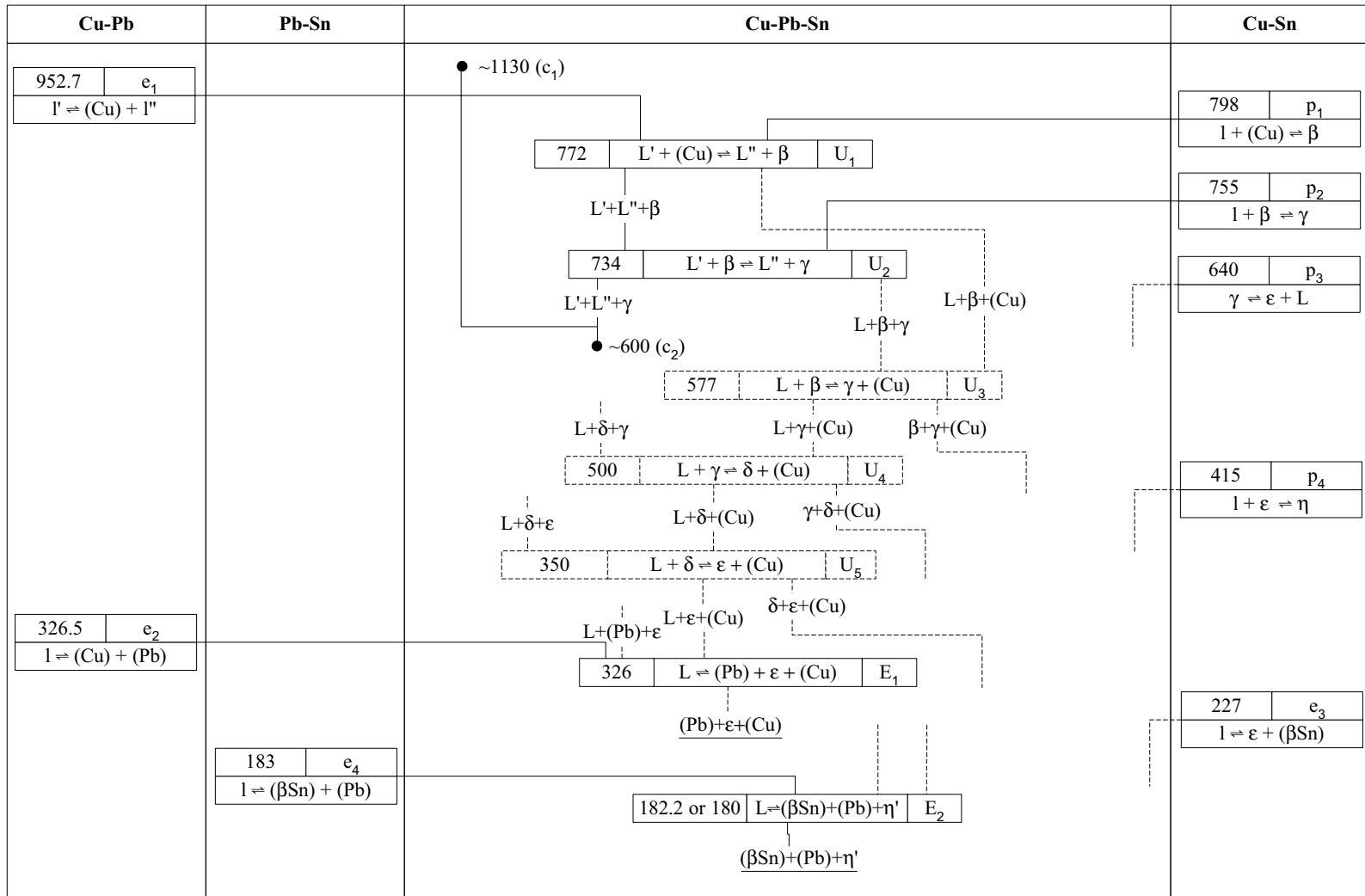


Fig. 1: Cu-Pb-Sn. Partial reaction scheme (tentative)

Fig. 2: Cu-Pb-Sn.
Liquidus surface
projection

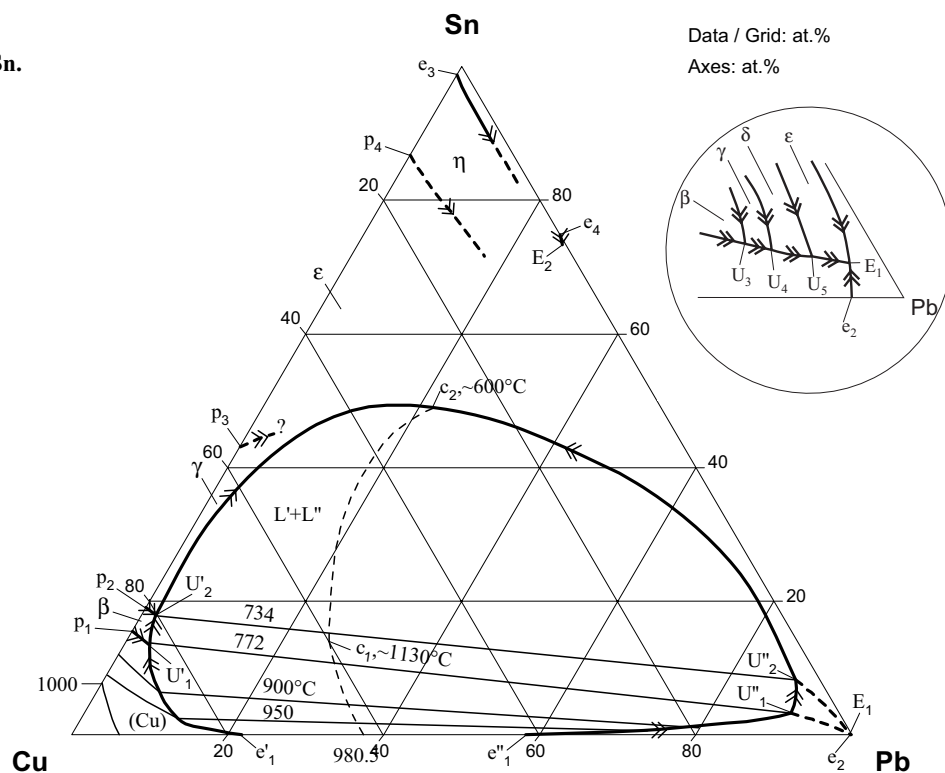


Fig. 3: Cu-Pb-Sn.
The liquid miscibility
gap at various
temperatures

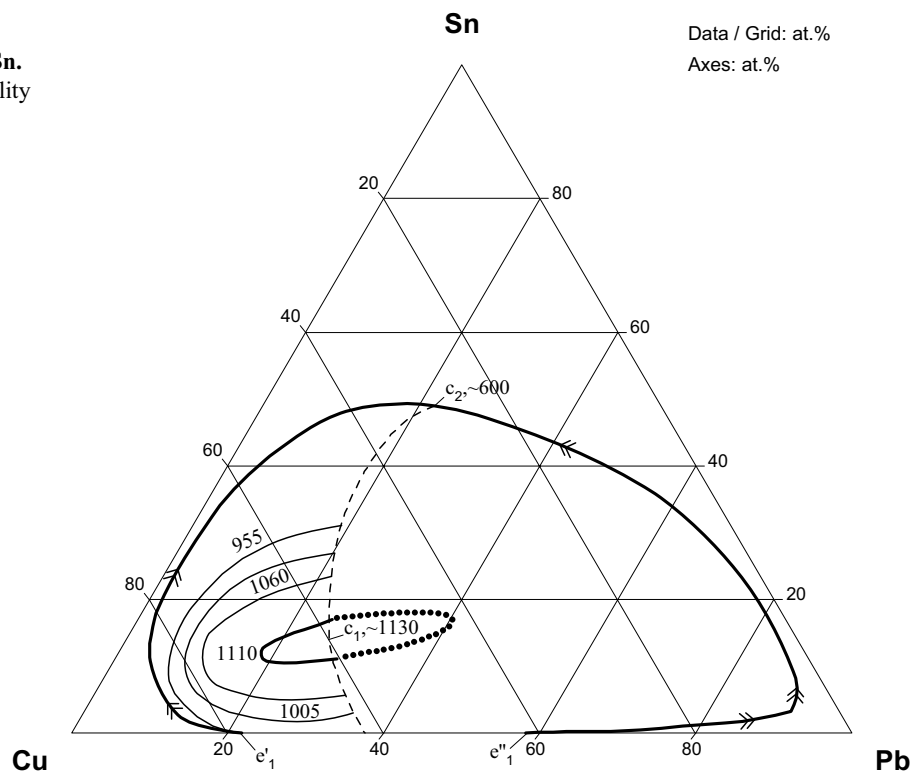


Fig. 4: Cu-Pb-Sn.
Isothermal section
at 955°C

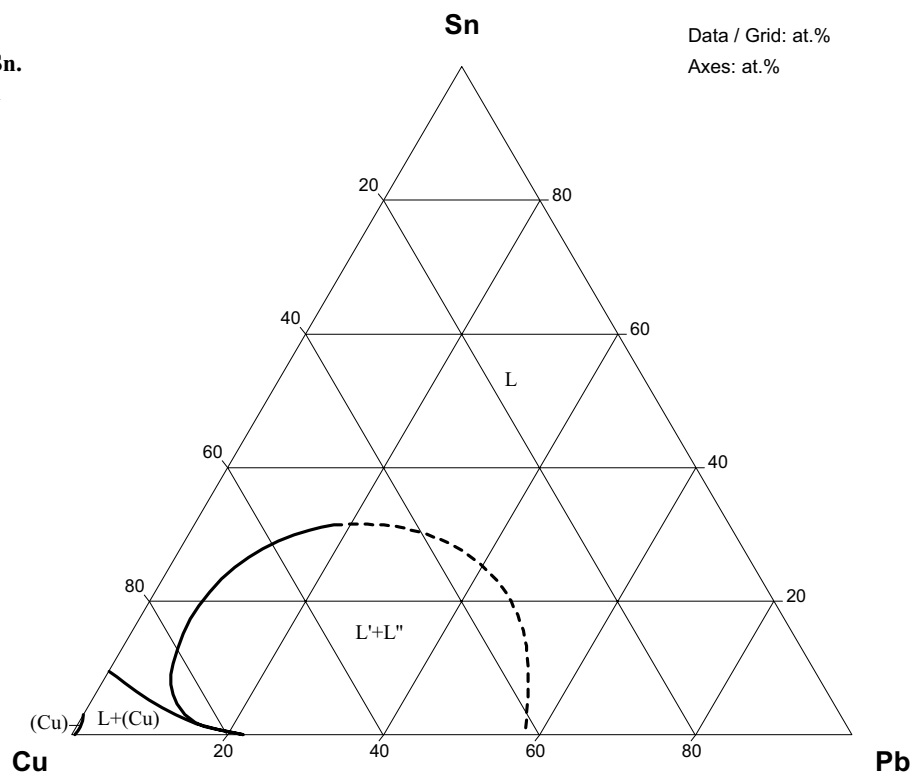


Fig. 5: Cu-Pb-Sn.
Isothermal section
at 400°C

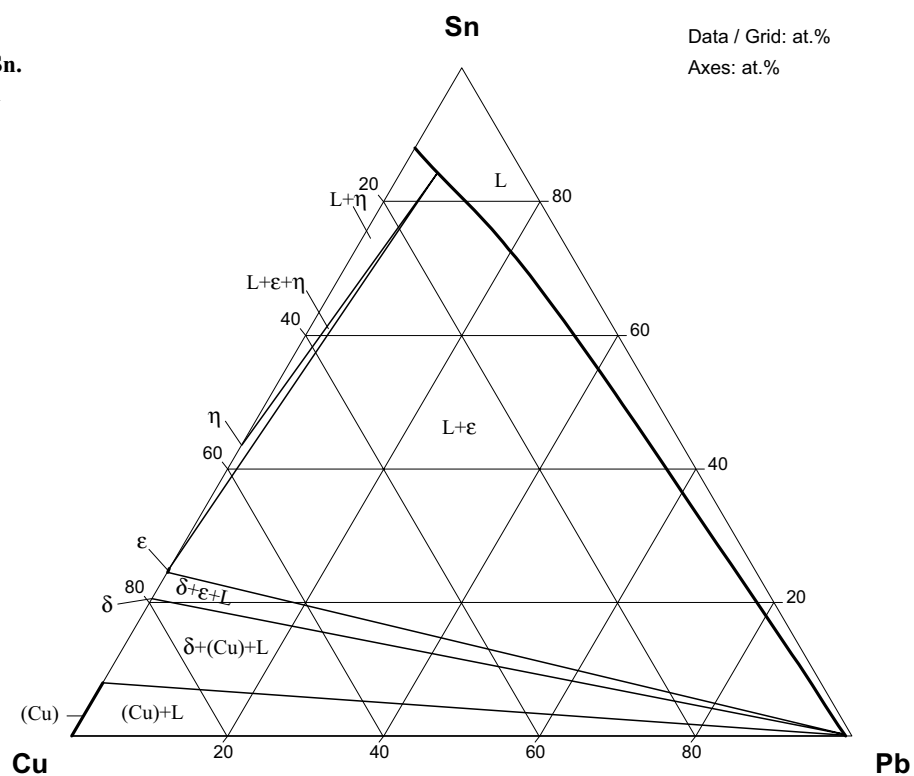


Fig. 6: Cu-Pb-Sn.
Isothermal section
at 350°C

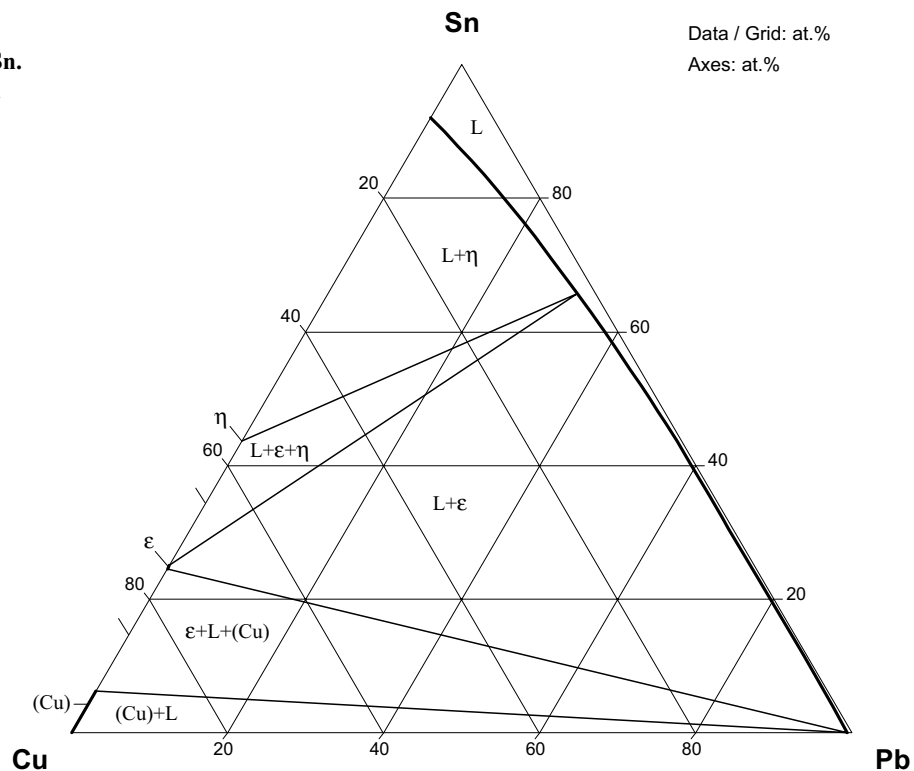


Fig. 7: Cu-Pb-Sn.
Isothermal section
at 283°C

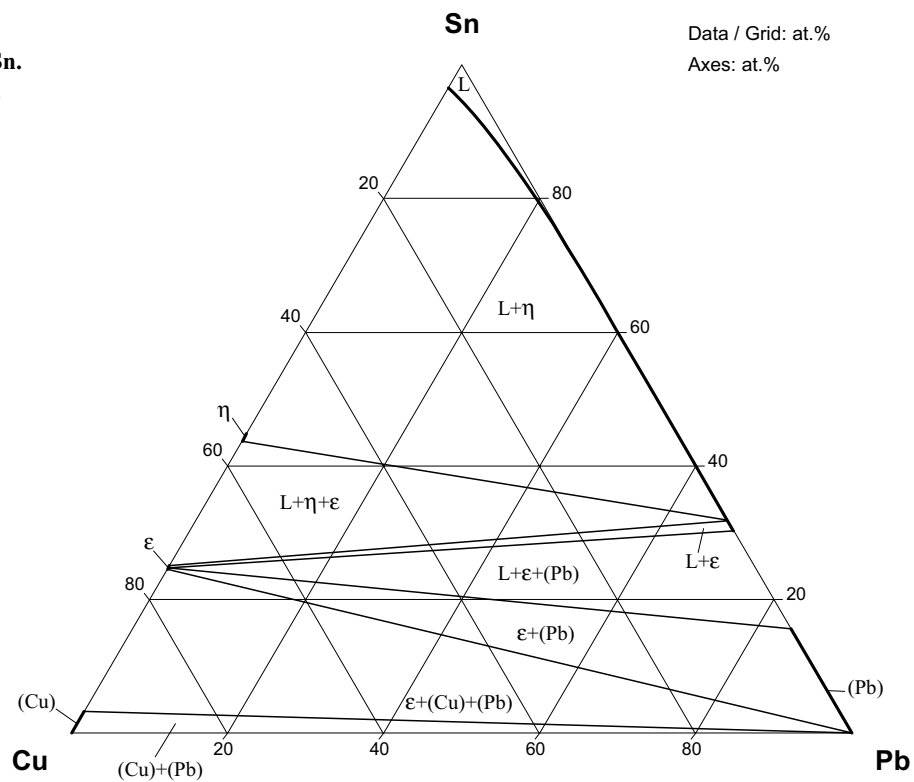


Fig. 8: Cu-Pb-Sn.
Isothermal section at
250°C

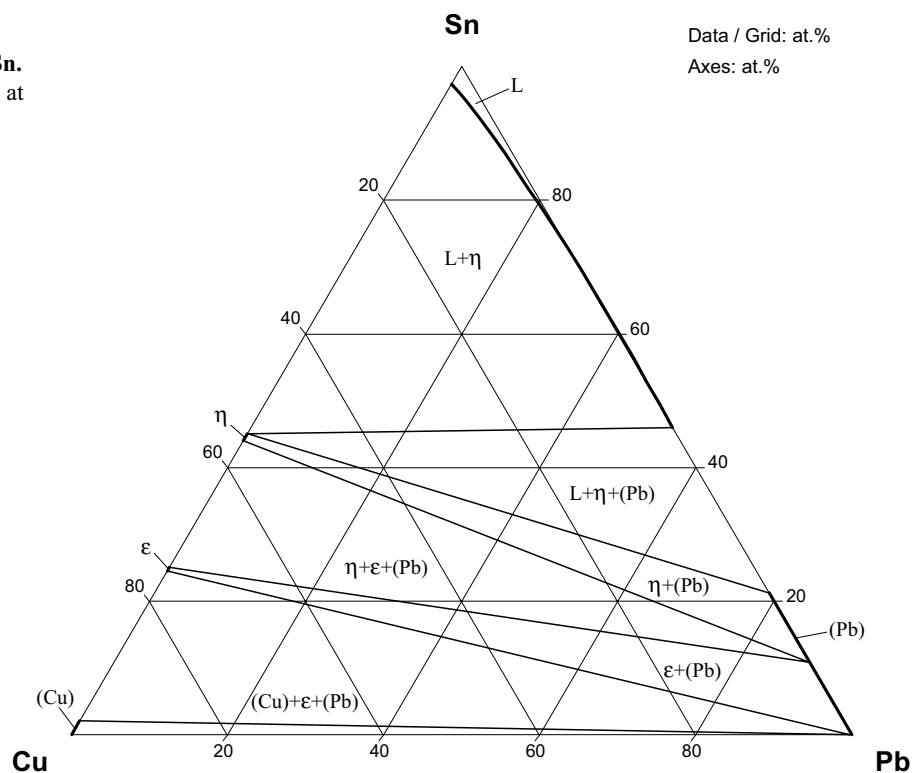


Fig. 9: Cu-Pb-Sn.
Isothermal section at
200°C

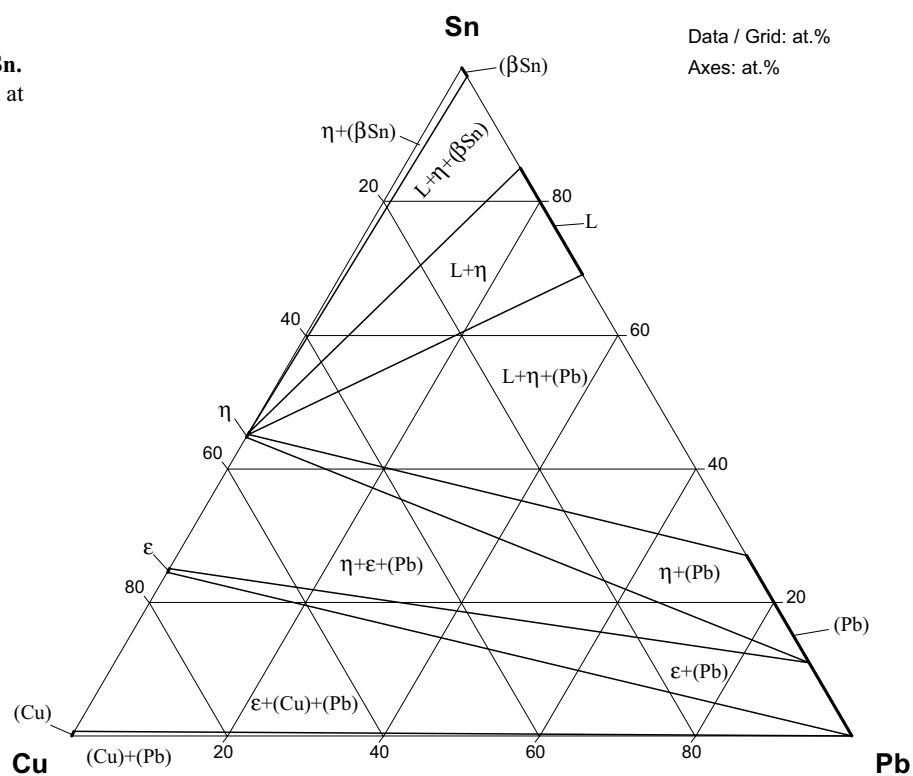


Fig. 10: Cu-Pb-Sn.
Isothermal section
at 170°C

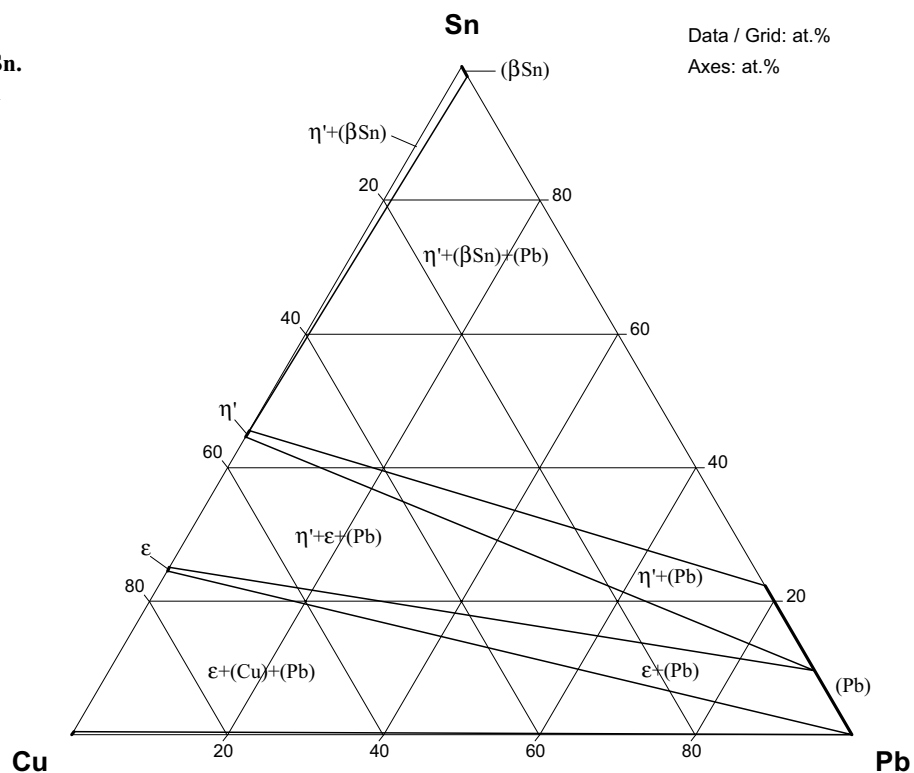


Fig. 11: Cu-Pb-Sn.
Isothermal section
at 100°C

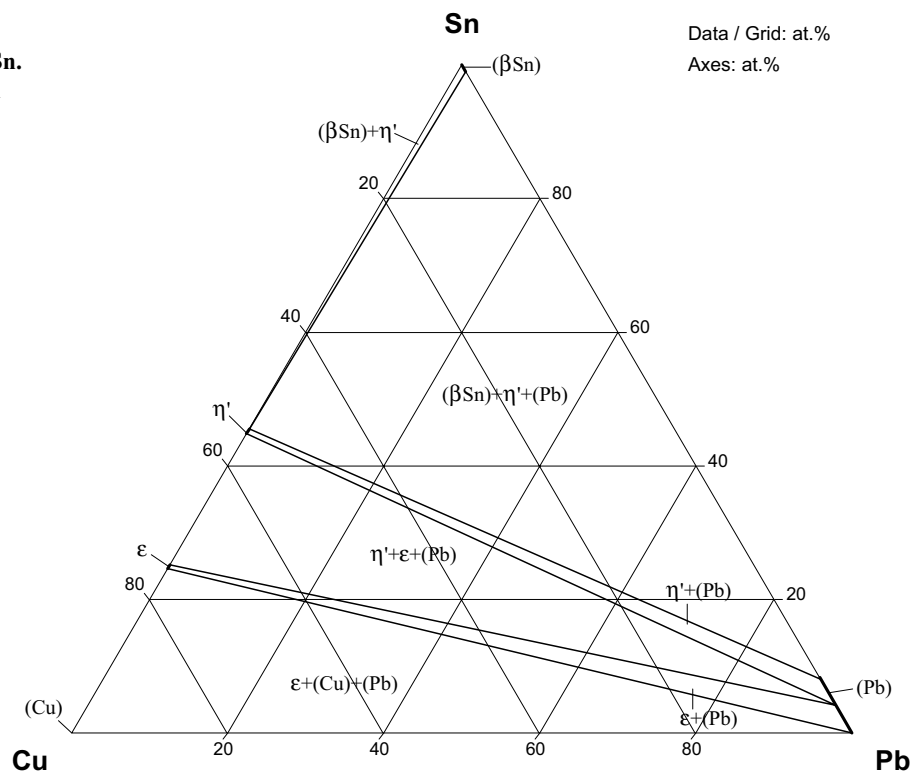


Fig. 12: Cu-Pb-Sn.
Partial isothermal
section at 220°C

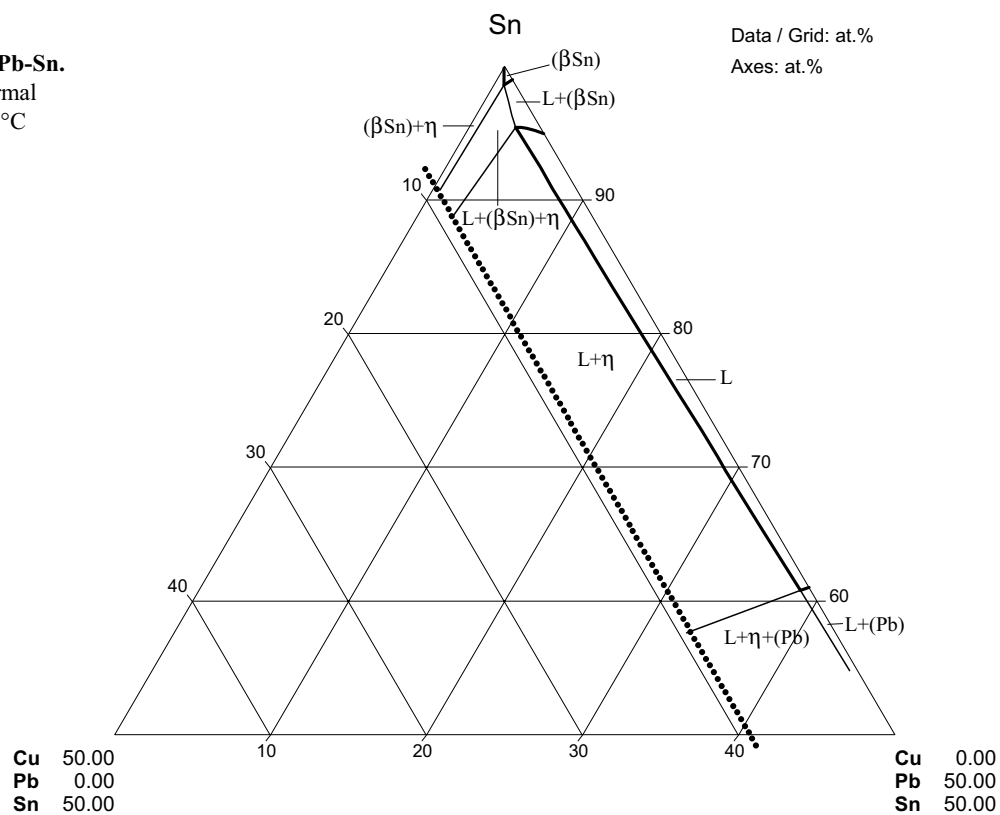


Fig. 13: Cu-Pb-Sn.
Activity of Cu at
1100°C. Standard
state Cu (liquid)

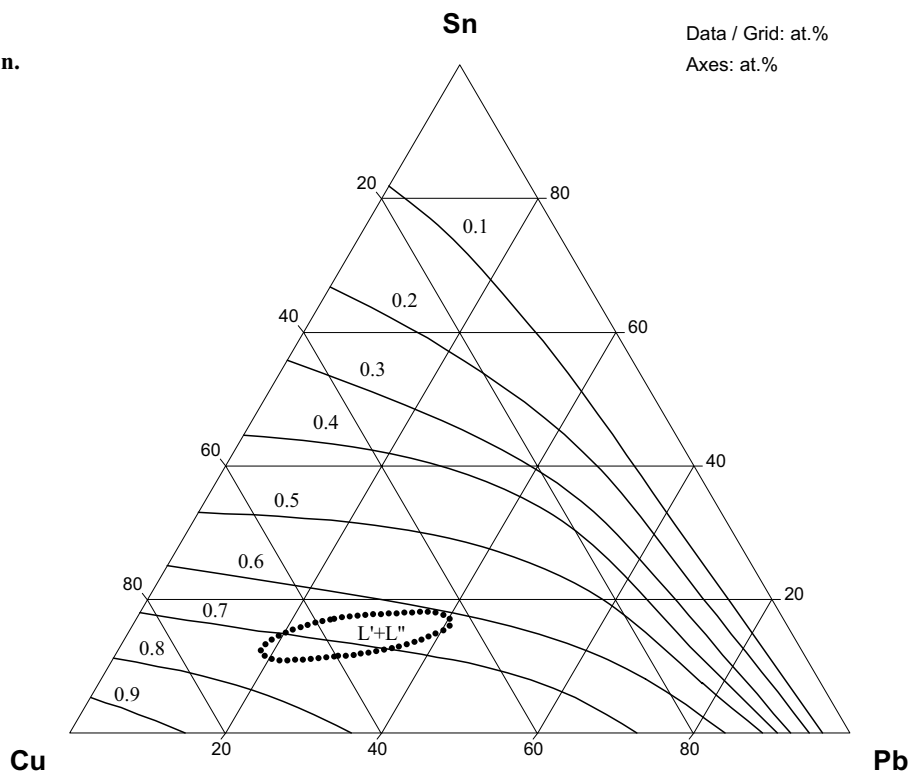
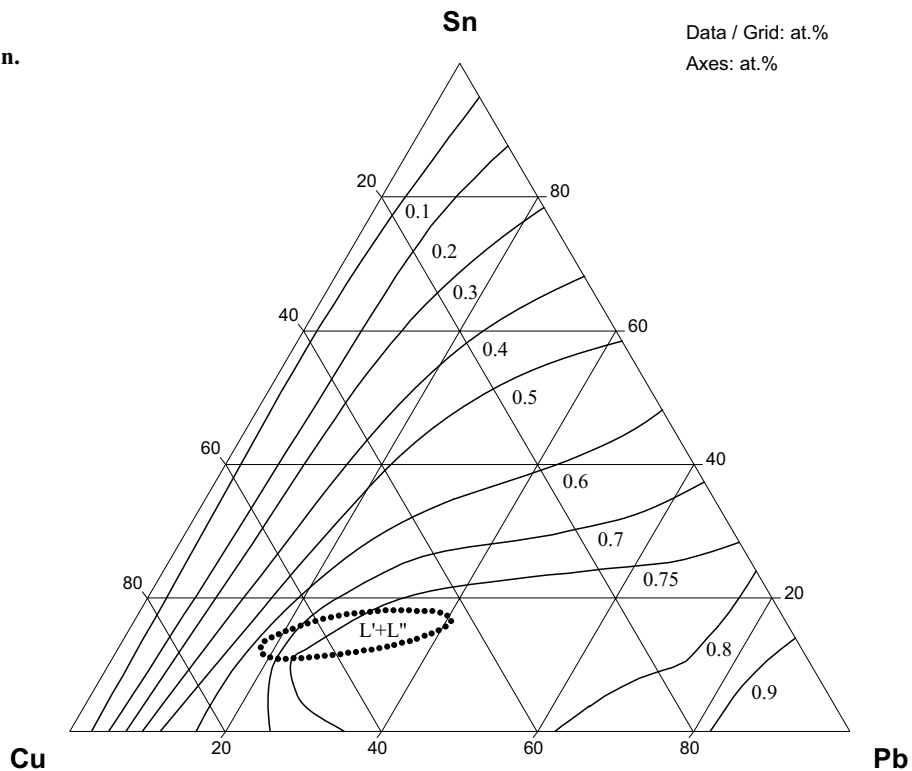


Fig. 14: Cu-Pb-Sn.

Activity of Pb at
1100°C. Standard
state Pb (liquid)

**Fig. 15: Cu-Pb-Sn.**

Activity of Sn at
1100°C. Standard
state Sn (liquid)

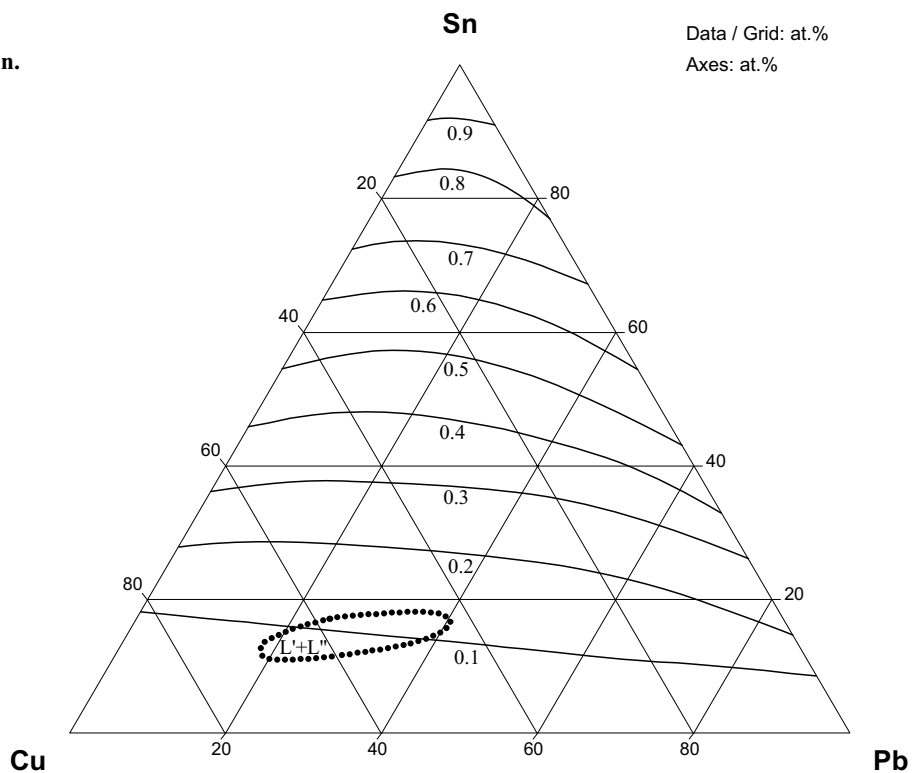


Fig. 16: Cu-Pb-Sn.
Excess Gibbs energy
 G (kJ/mol) at 1100°C.
Standard states are Cu
(liquid), Pb (liquid)

