Cobalt – Copper – Samarium

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Introduction

Since the discovery of hard magnetic properties in the $SmCo_5$ phase, the following investigations were conducted to improve the magnetic characteristics using the various methods of synthesis, doping with other elements, *etc*. The interest in the Co-Cu-Sm alloys is due to excellent hard magnetic properties that can be obtained in copper-containing alloys lying between the $SmCo_5$ and Sm_2Co_{17} compounds. In spite of this, practically all investigations were performed in the Sm concentration range up to 20 at.% in this system. The studies of this system have been conducted mainly in two directions - phase and structural characterizations and investigations of magnetic properties (Curie temperature, coercive force, *etc*.).
The phase, structural and microstructural characterization of the ternary alloys in the Co-Cu-Sm system are presented in [1973Kam, 1974Nis, 1976Zak, 1976Oes, 1976Mel, 1977Mel, 1977Per, 1979Gla, 1979Arb, 1979Mag, 1979Oes, 1981Ter, 1981Gla, 1982Arb1, 1983Arb, 1987Mey, 1989Tur, 1989Der, 1998Tel, 1999Zai, 1999Est1, 1999Est2, 2000Alo, 2000Che, 2002Ven, 2003Gop, 2003Luo, 2005Gjo]. Investigations of magnetic properties have been made by [1973Kam, 1973Sav, 1976Oes, 1976Nag, 1978Nag, 1979Arb, 1979Mag, 1979Oes, 1982Arb2, 1983Arb, 1986Lhy, 1998Tel, 1999Zai, 1999Est1, 1999Est2, 2000Alo, 2000Che, 2002Ven, 2003Gop, 2003Luo, 2003Zha, 2005Gjo]. An extended discussion of recent investigations has been made in [2005Sta] including a detailed review of the permanent magnet alloys based on the Sm_2Co_{17} phase.
Some works are devoted to the thermodynamic properties of alloys. [1987Mey] investigated the crystal structures and enthalpies of formation of alloys with compositions $Sm(Co_{1-x}Cu_x)_5$ ($0.2 \le x \le 0.8$). [1989Tur] calculated the integral enthalpies of mixing of the Co-Cu-Sm system by an isopotential method. [1981Gla] studied the solidification path of a $Sm_{10}Co_{70}Cu_{20}$ alloy using electron probe microanalysis (EPMA) on cross-sections made along the quenched interface. The results are discussed using the ternary phase diagram and a simple theoretical analysis based on the Scheil equation. This approach is a powerful tool for the prediction of microsegregation in complex alloys. Microsegregation leads to the formation of Cu rich zones which are detrimental to the magnetic properties and need to be eliminated by a homogenization heat treatment.
During the last decade, many investigations were conducted on the study of alloys obtained by new methods of synthesis. [2000Che] studied the crystal structure and magnetic properties of a milled $Sm_2(Co_{0.98}Cu_{0.02})_{17}$ alloy, [2002Ven] investigated the phase composition and magnetic properties of a $SmCo_{6.7}Cu_{0.3}$ alloy sintered by different methods (arc-melting, milling). The ball-milled alloy shows a greater coercive force. [2003Gop] studied a mechanically milled $Sm(Co_{0.9}Cu_{0.1})_{4.8}$ alloy. It has been established that milling decreases the coercivity. [2003Zha] studied the effect of Cu substitution on microstructure and magnetic properties of $SmCo_{7-x}Cu_x$ ($0 \le x \le 4.5$) ribbons.
Information relating to investigations of phase relations, structures and thermodynamics is summarized in Table 1.

Binary Systems

The Cu-Sm binary system has been taken from [1996Zhu, 1998Oka]. The phase diagram given in [Mas2] is based on thermodynamic calculations carried out by [1988Sub]. However, it disagrees with several experimental data and therefore is not accepted here. It should be mentioned that experimental studies in the ternary system [1979Gla] indicated narrow homogeneity ranges for the $SmCu_5$ and $SmCu_6$ phases. The phase diagram for the Co-Sm system is accepted from [1995Oka]. It is based on experimental data from [1993Ge]. The accepted diagram is different from [Mas2]. The major differences are: a) an absence of polymorphic transformations in the phases Sm_2Co_{17}, $SmCo_5$, Sm_5Co_{19} and Sm_2Co_7, b) Sm_5Co_{19} is stable over a wide temperature range, c) $SmCo_5$ melts incongruently. The thermodynamic assessment of [1998Su] reproduces the phase diagram given by [1995Oka] very well. However, it is not accepted here because the homogeneity ranges of the Sm_2Co_{17} and Co_5Sm phases are not taken into account by [1998Su]. The Co-Cu system is accepted from [2006Ans].

Solid Phases

Crystallographic data of the unary, binary and ternary phases of the Co-Cu-Sm system are listed in Table 2. The formation and range of solid solutions based on the binary phases, the existence of the ternary compounds and the crystal structures of the phases is strongly dependent on the synthesis method and annealing temperature. The ternary phase X, $SmCo_{3.3}Cu_{1.7}$ ($CaCu_5$ type) was reported to be stable at 900°C by [1981Ter]. However, later investigations did not confirm the stability of this phase and thus its existence is doubtful. The ternary phase $Sm(Co_{1-x}Cu_x)_7$ ($TbCu_7$ type), stable at $0.114 \leq x \leq 0.57$ and 600°C, was reported by [2003Luo]. A phase with the same structure was reported by [2000Alo] at $0 \leq x \leq 0.1$ and by [2002Ven] at $0 \leq x \leq 0.043$. In both studies, [2000Alo] and [2002Ven], at $x = 0$, the $SmCo_7$ phase formed together with Sm_2Co_{17}. It was shown by [2002Ven] that $Sm(Co_{1-x}Cu_x)_7$ decomposed into a two-phase mixture of $Sm(Co_{1-x}Cu_x)_5$ and $Sm_2(Co_{1-x}Cu_x)_{17}$ after annealing. Probably the solid solutions obtained by [2000Alo] were metastable. According to [2000Alo], the $Sm(Co_{1-x}Cu_x)_7$ phase cannot be formed at $x > 0.1$ contradicting the data of [2003Luo]. Other investigations indicated only solid solutions based on binary phases. [1974Nis] studied the $Sm(Co_{1-x}Cu_x)_5$ ($0 \leq x \leq 0.8$) alloys at 800°C and discovered the formation of solid solutions with the $CaCu_5$ structure. At $T > 800$°C, [1974Nis] observed the separation of the $Sm_2(Co,Cu)_{17}$ phase. This result is in conflict with later investigations. For example, [1977Per] found that $Sm(Co_{1-x}Cu_x)_5$ decomposed at temperatures below 730°C at $x = 0.1$ and below 615°C at $x = 0.2$. According to [1976Zak], the $Sm(Co,Cu)_5$ alloys (24.9-36.4 at.% Cu) are single-phase at 1100°C and decompose at 600°C into two phases. [1979Gla] found a complete mutual solubility between the $SmCo_5$ and $SmCu_5$ phases at 850°C. [1979Arb] investigated the crystal structure of the $Sm(Co_{0.81}Cu_{0.19})_{5.5}$ alloy. It has been established that this alloy contains two phases: $Sm_2(Co_{1-x}Cu_x)_{17}$ (Th_2Ni_{17} or Th_2Zn_{17} type) and $Sm(Co_{1-x}Cu_x)_5$ ($CaCu_5$ type). The annealing of the alloy was in the range 900 to 1200°C. [1979Mag] also studied an alloy of composition $Sm(Co_{0.65}Cu_{0.35})_{5.6}$ at different annealing temperatures and found a three-phase mixture, coherently bonded on (0001) planes. [1989Der] indicated that the $Sm_{1-s}(Co_{1-x}Cu_x)_{5+2s}$ phase is stable up to $x = 0.98$ at 850°C. However, this statement contradicts the binary Cu-Sm diagram and the data for the ternary system from [1979Gla] (see more details in the section Isothermal Sections). The Sm_2Cu_9 phase found by [1989Der] was not confirmed by any other investigations and is therefore doubtful. [1989Der] measured lattice parameters for $Sm(Co_{1-x}Cu_x)5$ alloys and showed that they do not deviate from Vegard's law. At Sm deficient compositions, the a parameter increases and c decreases with increasing x. [1999Zai] investigated the $Sm(Co_{1-x}Cu_x)_2$ alloys and established that the solid solubility limits for Cu in $SmCo_2$ and Co in $SmCu_2$ are 14 and 11%, respectively. [2003Luo] investigated the structural stability of $Sm(Co_{1-x}Cu_x)_7$ alloys. According to the results obtained, Cu doping can stabilize the $TbCu_7$ type structure in $Sm(Co_{1-x}Cu_x)_7$ alloys at Cu contents ranging from $0.114 \leq x \leq 0.571$ at 600°C.

Invariant Equilibria

[1979Gla] presented details of some transformations in the ternary system. These are given in Table 3.

Liquidus Surface

The liquidus surface of the Co-Cu-Sm phase diagram presented in Fig. 1 is taken from [1979Gla] with slight modifications made to ensure correct intersection angle between the monovariant lines in the U_1 point.

Isothermal Sections

Isothermal sections of the Co-Cu-Sm system (up to 20 at.% Sm) were studied experimentally at different temperatures by [1977Per] at 1200°C and 800°C, by [1979Gla] at 850°C and by [1981Ter] at 900°C. The data of these investigations are slightly different in relation to the homogeneity ranges of the solid solutions based on the binary phases. The results of [1989Der] for 850°C disagree with the accepted Cu-Sm binary diagram and the data of [1979Gla] for the ternary system. According to accepted binary diagram, the $SmCu_5$

phase should be stable at 850°C and there is no phase Sm_2Cu_9. The tie lines obtained by [1979Gla] at 850°C are different from those of [1989Der]. For example, the three-phase equilibrium (Co)+(Cu)+$SmCu_6$ was indicated by [1979Gla], whilst [1989Der] indicated equilibrium between (Co), (Cu) and $Sm(Co_{1-x}Cu_x)_5$ solid solutions. The tie lines obtained by [1979Gla] at 850°C agree with the data of [1981Ter] and [1977Per] obtained at 900 and 800°C, respectively. That is why the isothermal section of [1979Gla] for 850°C is accepted. It is presented in Fig. 2 after modifications made to ensure agreement with the accepted binary diagrams. Namely: homogeneity ranges of $Sm(Co,Cu)_5$, Sm_2Co_{17}, $SmCu_6$, (αCo) and (Cu) phases have been reduced, violation of the Schreinmaker rule has been eliminated at the Sm_2Co_{17} triangle-tip of the (αCo) + Sm_2Co_{17} + $Sm(Co,Cu)_5$ tie triangle.

Temperature – Composition Sections

Isoplethal sections at 10.5 and 16.7 at.% Sm are shown in Figs. 3 and 4, respectively [1979Gla]. The liquidus at 10 and 30 at.% Cu was also determined by [1979Gla]. Some limited data for isopleths at 10 and 20 at.% Cu were obtained by [1977Per].

Thermodynamics

[1987Mey] determined the heat of dissolution in liquid tin for pure elements and compounds in a Tian-Calvet calorimeter at 900°C and deduced the enthalpies of formation of alloys with compositions $Sm(Co_{1-x}Cu_x)_5$ ($0.2 \le x \le 0.8$) at 25°C for the measured values. The enthalpies of formations of $Sm(Co_{1-x}Cu_x)_5$ alloys are presented in Table 4. The x dependences of enthalpies of formation and lattice parameters indicate an ideal behavior for the mixing of $SmCo_5$ and $SmCu_5$. [1989Tur] calculated the integral enthalpies of mixing of Co-Cu-Sm system by isopotential method. These are reproduced in Fig. 5.

Notes on Materials Properties and Applications

[1973Kat] studied magneto-crystalline anisotropy in $Sm(Co_{1-x}Cu_x)_5$ alloys. It was shown that the magneto-crystalline anisotropy constant decreases monotonically with increasing x. A characteristic feature of the high-coercivity $Sm(Co,Cu)_5$ compound is the magnetic after-effect. It was studied in a $SmCo_{3.5}Cu_{1.5}$ alloy by [1973Sav]. [1976Oes] investigated the saturation moments (at 4.2 K) and coercive force for a $Sm_{0.167}Co_{0.683}Cu_{0.15}$ alloy. The measured value of the saturation moment is 0.75 μB and the coercive force is ${}_IH_C$=12.5kOe. [1976Mel] found a correlation between the observed microstructure and the corresponding magnetic parameters for alloys of compositions $Sm(Co_{0.65}Cu_{0.35})_{5.6}$, $Sm(Co_{0.84}Cu_{0.16})_{6.9}$ and studied the effect of aging on the microstructure. [1977Mel] used electron microscopy to study $Sm(Co_{0.87}Cu_{0.13})_z$ ($7.5 \le z \le 7.8$) aged at 400 and 800°C. It was shown that the coercivity of these materials with the Sm_2Co_{17} structure is due to the presence of very fine precipitates of the $Sm(Co_{1-x}Cu_x)_5$ phase. [1976Nag, 1978Nag] investigated the hard-magnetic properties of $Sm(Co,Cu)_z$ alloys at composition ratios of the rare-earth to the transition metal of 1:5 and 2:17 with copper contents up to 35% of the transition metal fraction. The coercivity ${}_IH_C$ showed a maximum along a tie line from the off-stoichiometric $Sm(Co_{0.65}Cu_{0.35})_{5.6}$ to the Sm_2Co_{17} phase. The investigations showed that alloys have useful hard-magnetic properties in the bulk form. Coercivity and microhardness were measured for $Sm_2(Co_{1-x}Cu_x)_{17}$ alloys by [1986Lhy]. It was shown that the hardness maximum corresponds to the peak of coercivity. [1982Mag] studied the coercive force of $Sm(Co_{0.65}Cu_{0.35})_z$ with z = 4.5, 5.6, 6 and found that eutectoid decomposition does not contribute to the rise in the coercive force very much, while the main process responsible for its rise is the decomposition of the supersaturated solid solution with the formation of a non-equilibrium $Sm_2(Co_{1-x}Cu_x)_{17}$ phase. [1979Arb] investigated the coercive force of a $Sm(Co_{0.81}Cu_{0.19})_{5.5}$ alloy. Annealing the alloy from 900 to 1200°C increases the coercive force. [1979Oes] studied the magnetic properties of $Sm(Co_{1-x}Cu_x)_5$ ($0.3 \le x \le 0.9$) alloys and showed that the coercivity is intrinsic in nature, and not dependent on pinning by second phases. [1986Mit] studied magnetic properties, microstructure and domain structure of a cast and annealed alloy of $SmCo_{3.25}Cu_{1.75}$ using magnetometry, the Kerr magneto-optic effect, SEM and EPMA. The magnetic properties, in particular the mechanism of magnetization reversal, were found to be related to the microstructure and domain structure. [1999Est1]

performed microstructural studies of $Sm(Co_{1-x}Cu_x)_5$ ($0 \le x \le 0.5$), determined the crystal structures of the alloys and measured magnetic properties. Coercivity increased with Cu content, while the Curie temperature decreased. The highest pinning field is observed in the $Sm(Co_{0.5}Cu_{0.5})_5$ alloy. [1999Est2] performed a more detailed investigation of $Sm(Co_{0.5}Cu_{0.5})_5$. The as-cast state showed long elongated regions with a solidification texture. The sample annealed at 1000°C showed a more homogeneous composition. Two slightly different regions were observed. The pinning mechanism is associated with structural disorder introduced by an excess of Sm in the otherwise $CaCu_5$ type structure. [2000Alo] investigated the structural and magnetic properties of $Sm(Co_{1-x}Cu_x)_7$ alloys. These samples have uniaxial anisotropy. The maximum value of T_C is 852°C. [2000Che] studied the crystal structure and magnetic properties of milled $Sm_2(Co_{0.98}Cu_{0.02})_{17}$ alloy. The coercive force $_IH_C$ measured by [2000Che] is 9.0 kOe. The coercive force of the permanent magnet $Sm(Co_{1-x}Cu_x)_7$ was studied by [1982Arb2] as a function of the heat treatment program. Magnetization variation during recovery was measured for a $Sm(Co_{0.84}Cu_{0.16})_{6.9}$ alloy in a low and a high-coercivity state by [1989Lil]. [2003Luo] investigated the structural stability and magnetic properties of $Sm(Co,Cu)_7$ alloys. It was shown that $Sm(Co_{1-x}Cu_x)_7$ exhibits ferromagnetic order. A strong uniaxial anisotropy at fields higher than 20 T is obtained with $x = 0.114$ at 5 K. Saturation magnetization and Curie temperature decrease with increasing Cu content. [2003Zha] studied the effect of Cu substitution on the microstructure and magnetic properties of $Sm(Co_{1-x}Cu_x)_7$ ($0 \le x \le 0.643$) ribbons. Cu substitution is helpful to enhance the degree of preferred orientation of the *c*-axis of the columnar dendrite grains parallel to the longitudinal direction of the ribbons. [2005Gjo] studied the structure and magnetic properties of $Sm(Co_{1-x}Cu_x)_5$ alloys and established that the Curie temperature decreases with increasing Cu content.
The information relating to the investigations of materials properties is summarized in Table 5.

Miscellaneous

The coercivity mechanism of magnetic materials in Co-Cu-Sm system was discussed in a number of works [1973Kat, 1976Per, 1977Mel, 1978Nag, 1980Laz, 1983Arb, 1986Mit, 2004Yam]. [1973Kat] presented evidence of spinodal decomposition. [1983Arb] found a mixture of two macroscopic phases (one with an ordered Th_2Zn_{17}, another with the $CaCu_5$ structure). [1986Mit] revealed the existence of two phases; $SmCo_5$ rich and $SmCu_5$ rich. Theoretical interpretation of the hard-magnetic properties of $Sm(Co,Cu)_z$ compounds with $5 < z < 8.5$ was presented in [1976Per]. [1980Laz] evaluated critical fields for the pinning of a narrow domain wall in materials with high magnetocrystalline anisotropy, such as $Sm(Co,Cu)_z$ compounds, with $5 < z < 6$. [2004Yam] calculated the crystal field parameter at each Sm site using a point charge model. The temperature dependence of the coercivity in $SmCo_{3.5}Cu_{1.5}$ at low temperatures was interpreted in terms of a physical model in the framework of the quantum regime by [1991Su]. [1999Zai] investigated the effect of hydrogenation on phase composition and magnetic properties of $Sm(Co_{1-x}Cu_x)_2$ alloys. First-principle calculations [2005Gab] demonstrated that $Sm(Co_{1-x}Cu_x)_5$ alloys are unstable with respect to decomposition into two phases of the same structure with different x values. The calculations also suggest that the magnetic state of the alloys affects the stable x values and the Cu atomic site preferences. SEM and thermomagnetic studies confirmed the two-phase structure of the as-cast $Sm(Co_{1-x}Cu_x)_5$ alloys. High-temperature homogenization eliminates the chemical microsegregation and slightly increases the coercivity of the alloys.

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Table 1: Investigations of the Co-Cu-Sm Phase Relations, Structures and Thermodynamics

Reference	Method/Experimental Technique	Temperature/Composition/Phase Range Studied
[1973Kam]	DTA	920°C/Sm(Co,Cu)$_5$ 16-66 at.% Cu/ hypothetical isothermal section
[1974Nis]	X-ray analysis, X-ray microanalysis, metallographic examination / X-ray powder diffractometer	800-1000°C / Sm(Co$_{1-x}$Cu$_x$)$_5$, $0 \le x \le 0.8$
[1976Zak]	X-ray diffraction, optical microscopy / Debye camera	500, 700, 1100°C / SmCo$_{5-x}$Cu$_x$: SmCo$_{4.4}$Cu$_{0.6}$, SmCo$_4$Cu$_{0.8}$, SmCo$_4$Cu, SmCo$_{3.5}$Cu$_{1.5}$
[1976Oes]	X-ray analysis / Debye-Scherrer	Sm$_{0.167}$Co$_{0.683}$Cu$_{0.15}$
[1976Mel]	X-ray analysis, Electron microscopy / Siemens powder diffractometer, Phillips EM300 electron microscope	400-800°C / Sm(Co$_{0.65}$Cu$_{0.35}$)$_{5.6}$, Sm(Co$_{0.84}$Cu$_{0.16}$)$_{6.9}$
[1977Per]	DTA, metallographic examination, EPMA	800, 1200°C / SmCo$_5$-Sm$_2$Co$_{17}$ up to 20 at.% Cu / partial isothermal section
[1979Gla]	DTA, metallographic examination, EPMA / ARL, SEMQ microanalyser	850°C / isothermal section, liquidus surface
[1979Arb]	X-ray analysis	400-1000°C / Sm(Co$_{0.81}$Cu$_{0.19}$)$_{5.5}$
[1979Mag]	X-ray analysis / RKU-114M, RKV-86	420-1100°C / Sm(Co$_{0.65}$Cu$_{0.35}$)$_{5.6}$
[1979Oes]	X-ray analysis / GE XRD-5 diffractometer	800°C / Sm(Co$_{1-x}$Cu$_x$)$_5$, $0.3 \le x \le 0.9$
[1981Ter]	X-ray analysis, metallography, EPMA	Phase relations
[1981Gla]	EPMA	Solidification path
[1982Arb1]	X-ray analysis	800-1220°C / Sm(Co$_{0.86}$Cu$_{0.14}$)$_7$
[1983Arb]	X-ray analysis	500-1250°C / Sm(Co$_{0.8}$Cu$_{0.2}$)$_5$, Sm(Co$_{0.7}$Cu$_{0.3}$)$_5$ / phase composition
[1987Mey]	X-ray analysis, calorimetric measurements / X-ray focusing camera, Tian-Calvet calorimeter	400, 950°C / Sm(Co$_{1-x}$Cu$_x$)$_5$, $0.2 \le x \le 0.8$
[1989Tur]	Calculation of enthalpies of mixing by isopotential method	Co-Cu-Sm
[1989Der]	X-ray analysis, EPMA, DTA	850°C / 0-20 at.% Sm / partial isothermal section
[1998Tel]	X-ray analysis / X-ray powder diffractometer	1000°C / Sm(Co$_{1-x}$Cu$_x$), x = 0.2, 0.3, 0.4, 0.5, 0.6, 0.8
[1999Zai]	X-ray analysis / DRON-4U, DRON-2 powder diffractometers	800°C / Sm(Co$_{1-x}$Cu$_x$)$_2$, x = 0, 0.2, 0.4, 0.6, 0.8, 1
[1999Est1]	X-ray analysis, metallographic microscopy, SEM / X-ray powder diffractometer, polar Kerr microscopy, SEM	1000°C / Sm(Co$_{1-x}$Cu$_x$)$_5$, x = 0.0, 0.2, 0.3, 0.4, 0.5

Reference	Method/Experimental Technique	Temperature/Composition/Phase Range Studied
[1999Est2]	X-ray analysis, metallographic microscopy, SEM / X-ray powder diffractometer, polar Kerr microscopy, SEM	1000°C / $Sm(Co_{0.5}Cu_{0.5})_5$
[2000Alo]	X-ray analysis / X-ray powder diffractometer	$Sm(Co_{1-x}Cu_x)_7$, x = 0, 0.014, 0.029, 0.0429, 0.057, 0.071, 0.1
[2000Che]	X-ray analysis, TEM / Phillips X-ray powder diffractometer, JEOL JEM-2000FX	Milling, 500-900°C / $Sm_2(Co_{0.98}Cu_{0.02})_{17}$
[2002Ven]	X-ray analysis / X-ray powder diffractometer	1150, 800°C, as-milling / $Sm(Co_{0.957}Cu_{0.043})_7$
[2003Gop]	X-ray analysis, optical microscopy, SEM, EPMA, DSC / Phillips PW3020 X-ray powder diffractometer, Leo 440i SEM, CAMECA analyser	Milling, 700°C / $Sm(Co_{0.9}Cu_{0.1})_{4.8}$
[2003Luo]	X-ray analysis / Rigaku D/max 2500 diffractometer	600°C / $Sm(Co_{1-x}Cu_x)_7$, x = 0.114-0.571
[2005Gjo]	X-ray analysis / X-ray powder diffractometer	$Sm(Co_{1-x}Cu_x)_5$

Table 2: Crystallographic Data of Solid Phases

Phase/ Temperature Range [°C]	Pearson Symbol/ Space Group/ Prototype	Lattice Parameters [pm]	Comments/References
(αCo) 1495 - 422	*cF*4 $Fm\overline{3}m$ Cu	a = 356.88 a = 354.47	at 520°C [V-C2] [Mas2]
(εCo) < 422	*hP*2 $P6_3/mmc$ Mg	a = 250.71 c = 406.86	at 25°C [Mas2]
(Cu) < 1084.62	*cF*4 $Fm\overline{3}m$ Cu	a = 361.46	at 25°C [Mas2]
(αSm) < 734	*hR*9 $R\overline{3}m$ Sm	a = 362.90 c = 2620.7	at 25°C [Mas2]
(βSm) 922 - 734	*hP*2 $P6_3/mmc$ Mg	a = 366.30 c = 584.48	[Mas2]
(γSm) 1074 - 922	*cI*2 $Im\overline{3}m$ W	-	[Mas2]

Phase/ Temperature Range [°C]	Pearson Symbol/ Space Group/ Prototype	Lattice Parameters [pm]	Comments/References
(δSm)	*hP*4 $P6_3/mm$ αLa	*a* = 361.8 *c* = 1166	at 25°C, 4.0 GPa [Mas2]
$Sm_2(Co_{1-x}Cu_x)_{17}$ < 1347	*hR*57 $R\overline{3}m$ Th_2Zn_{17}	*a* = 842.0 *c* = 1221.0	10.5-12.5 at.% Sm at $x = 0$ [Mas2], [V-C2], [2000Oka] $0 \le x \le 0.1$ at 850°C [1979Gla]
Sm_5Co_{19} < 1270	*hR*72 $R\overline{3}m$ Ce_5Co_{19}	*a* = 503.5 *c* = 4845	[Mas2], [V-C2], [2000Oka]
$Sm_2(Co_{1-x}Cu_x)_7$ < 1241	*hR*54 $R\overline{3}m$ Er_2Co_7	*a* = 504.52 *c* = 3648.6	[V-C2], [1995Oka] $0.2 \le x \le 0.35$ at 800°C [1977Per]
$SmCo_3$ < 1200	*hR*36 $R\overline{3}m$ Be_3Nb	*a* = 505 *c* = 2459	[Mas2] [V-C2]
$Sm(Co_{1-x}Cu_x)_2$ < 1070	*cF*24 $Fd\overline{3}m$ Cu_2Mg	*a* = 726.4 to 727.6	at 800°C, $0 \le x \le 0.14$, [1999Zai], [Mas2]
Sm_9Co_4 < 613	*o**52	*a* = 1115 ± 2 *b* = 946.1 ± 0.8 *c* = 917.3 ± 0.9	[Mas2] [V-C2]
Sm_3Co ≲ 700	*oP*16 *Pnma* Fe_3C	*a* = 706 *b* = 960 *c* = 634	[Mas2] [V-C2]
$Sm(Cu_{1-x}Co_x)_6$ < 967	*oP*28 *Pnma* $CeCu_6$	*a* = 806.0 *b* = 503.4 *c* = 1004.9	[Mas2], [V-C2], [2000Oka] maximal $0.17 \le x \le 0.24$ [1979Gla]
$SmCu_4$ < 880	*oP*20 *Pnnm* $CeCu_4$	*a* = 442 *b* = 801 *c* = 901	[1988Sub]
$Sm(Co_xCu_{1-x})_2$ < 855	*oI*12 *Imma* $CeCu_2$	*a* = 435.2 to 433.8 *b* = 692.3 to 690.5 *c* = 737.7 to 736.3	at 800°C, $0 \le x \le 0.11$, [1999Zai], [Mas2]
SmCu < 785	*cP*2 $Pm\overline{3}m$ CsCl	*a* = 353.4	[1988Sub]

Phase/ Temperature Range [°C]	Pearson Symbol/ Space Group/ Prototype	Lattice Parameters [pm]	Comments/References
$Sm(Co_{1-x}Cu_x)_5$	*hP*6 $P6_3/mmm$ $CaCu_5$	*a* = 503 to 505 *c* = 399 to 401	$0.12 \le x \le 0.3$ at 1100-700°C [1976Zak]
		a = 500.1 *c* = 399.7	$x = 0.18$ [1976Oes]
		a = 500.7 to 505.2 *c* = 399.0 to 407.7	at 800°C, $0.3 \le x \le 0.9$, [1979Oes]
		a = 500.6 - 504.8 *c* = 399.9 - 406.6	at 950°C, $0.2 \le x \le 0.8$, [1987Mey]
		a = 500.83 ± 0.02 to 504.10 ± 0.09 *c* = 399.24 ± 0.02 to 405.4 ± 0.1	at 1000°C, $0.2 \le x \le 0.8$, [1998Tel]
		a = 504.8 *c* = 400.9	at 900°C, $x = 0.34$ [1981Ter]
		a =497.8 to 500.5 *c* = 398.4 to 401.5	at 1000°C, $0 \le x \le 0.3$ [2005Gjo]
		a = 499.0 *c* = 403.8	$Sm(Co_{0.65}Cu_{0.35})_{5.6}$ at 400°C [1976Mel]
		a = 503.8 *c* = 402.7	$Sm(Co_{0.65}Cu_{0.35})_{5.6}$ at 800°C [1976Mel]
$SmCo_5$ 1322 - 810		*a* = 500.2 ± 0.5 *c* = 396.4 ± 0.5	at $x = 0$ [Mas2] [V-C2], homogeneity range at $x = 0$ is 15 - 17.5 at.% Sm
$SmCu_5$ < 923		*a* = 507 *c* = 410.4	at $x = 1$ [Mas2] [V-C2], homogeneity range at $x = 1$ is 16 - 17 at.% Sm [1979Gla]
$Sm(Co_{1-x}Cu_x)_7$	*hP*8 $P6_3/mmm$ $TbCu_7$	*a* = 493.5 to 498.1 *c* = 401.0 to 401.1	probably metastable $0 \le x \le 0.1$, [2000Alo]
		a = 493.48 ± 0.01 to 497.36 ± 0.02 *c* = 403.51 ± 0.01 to 406.74 ± 0.01	at 600°C, $0.114 \le x \le 0.571$, [2003Luo]

Table 3: Invariant Equilibria

Reaction	T [°C]	Type	Phase	Composition (at.%)*		
				Co	Cu	Sm
L + $Sm_2(Co,Cu)_{17}$ ⇌ (αCo) + $Sm(Co,Cu)_5$	~1130	U_1	L $Sm_2(Co,Cu)_{17}$ (αCo) $Sm(Co,Cu)_5$	17.9 65.1 92.9 51.3	69.8 23 6.16 34.6	12.3 11.9 0.94 14.1
L + (αCo) + $Sm(Co,Cu)_5$ ⇌ $Sm(Co,Cu)_6$	~995	P	-	-	-	-
L + (αCo) ⇌ $Sm(Co, Cu)_6$ + (Cu)	~910	U_2	-	-	-	-

* - as digitized from Fig. 1.

Table 4: Thermodynamic Data

Reaction or Transformation	Temperature [°C]	Quantity per Reaction [J, mol, K]	Comment
1/5Sm + $(1–x)$Co + xCu = 1/5Sm$(Co_{1–x}Cu_x)_5$	25	$\Delta_f H = –7400$ $\Delta_f H = –8700$ $\Delta_f H = –10400$ $\Delta_f H = –11000$ $\Delta_f H = –12200$	$Sm_{0.166}Co_{0.669}Cu_{0.165}$ $Sm_{0.174}Co_{0.492}Cu_{0.334}$ $Sm_{0.163}Co_{0.33}Cu_{0.507}$ $Sm_{0.168}Co_{0.285}Cu_{0.547}$ $Sm_{0.167}Co_{0.167}Cu_{0.666}$

Table 5: Investigations of the Co-Cu-Sm Materials Properties

Reference	Method/Experimental Technique	Type of Property
[1973Kam]	Magnetic measurements	Magnetic properties
[1973Kat]	Magnetic measurements / Vibrating sample magnetometer	Saturation magnetization, anisotropy field
[1973Sav]	Magnetic measurements, Kerr effect	Magnetic after-affect
[1976Oes]	Magnetic measurements / Foner magnetometer	Saturation moments, coercive force
[1976Nag], [1978Nag]	Bulk-magnetic measurements / Vibrating sample magnetometer, optical metallography	Hard-magnetic properties
[1979Arb]	Magnetic measurements	Coercive force
[1979Mag], [1982Mag]	Magnetic measurements	Coercive force
[1979Oes]	Magnetic measurements / Vibrating sample magnetometer	Magnetic properties
[1982Arb1] [1982Arb2]	Magnetic measurements	Coercive force
[1983Arb]	Magnetic measurements	Coercive force
[1986Lhy]	Magnetic and microhardness measurements / vibrating sample magnetometer	Coercive force, microhardness

Reference	Method/Experimental Technique	Type of Property
[1986Mit]	Magnetometer, Kerr magneto-optic effect	Demagnetization
[1998Tel]	Magnetic measurements / pulsed-field magnetometer	ac susceptibility, coercive force
[1999Zai]	Magnetic measurements / vibrating-sample magnetometer, MPMS-5XL SQUID magnetometer	Magnetic properties of hydrogenated samples $Sm(Co_{1-x}Cu_x)_2$ x = 0, 0.2, 0.4, 0.6, 0.8, 1
[1999Est1]	Magnetic measurements / vibrational magnetometer VSM	Curie temperature, coercive force
[1999Est2]	Magnetic measurements / vibrational magnetometer VSM	Curie temperature, coercive force
[2000Alo]	Magnetic measurements / SQUID magnetometer, vibrating-sample magnetometer VSM	Magnetization, Curie temperature
[2000Che]	Magnetic measurements / vibrating-sample magnetometer Oxford VSM	Magnetization, Curie temperature
[2002Ven]	Magnetic measurements / SQUID magnetometer, vibrating-sample magnetometer VSM	Magnetization, Curie temperature
[2003Gop]	Magnetic measurements / vibrating-sample magnetometer (Digital Measurements Systems)	Coercivity
[2003Luo]	Magnetic measurements / SQUID magnetometer	Magnetization, Curie temperature
[2003Zha]	Magnetic measurements	Magnetic properties
[2005Gab]	Magnetic measurements /MPMS and vibrating sample magnetometer (VSM) Microstructure/SEM	Coercivity
[2005Gjo]	Magnetic measurements / vibrating sample magnetometer	Magnetic properties

Fig. 1: Co-Cu-Sm.
Partial liquidus surface

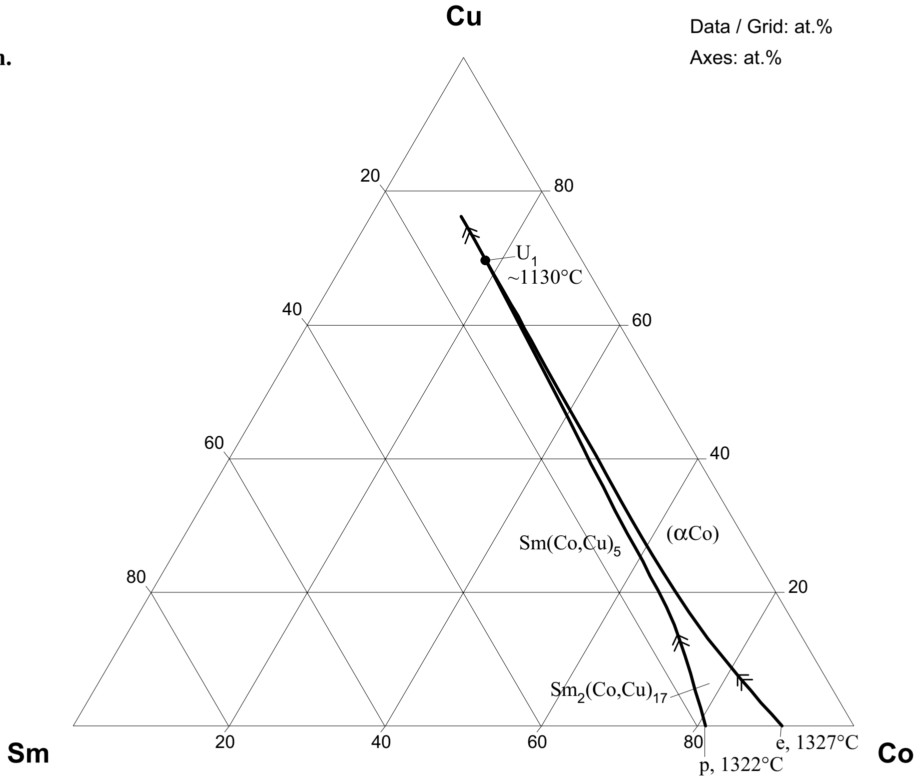

Fig. 2: Co-Cu-Sm.
Partial isothermal section at 850°C

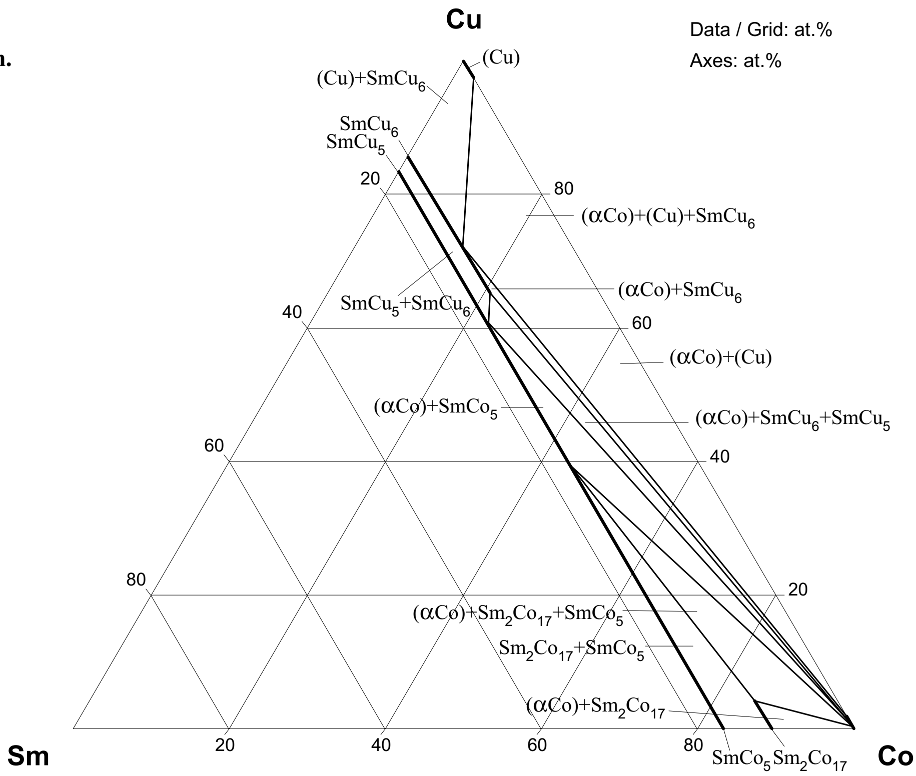

Fig. 3: Co-Cu-Sm. Partial isopleth at 10.5 at.% Sm

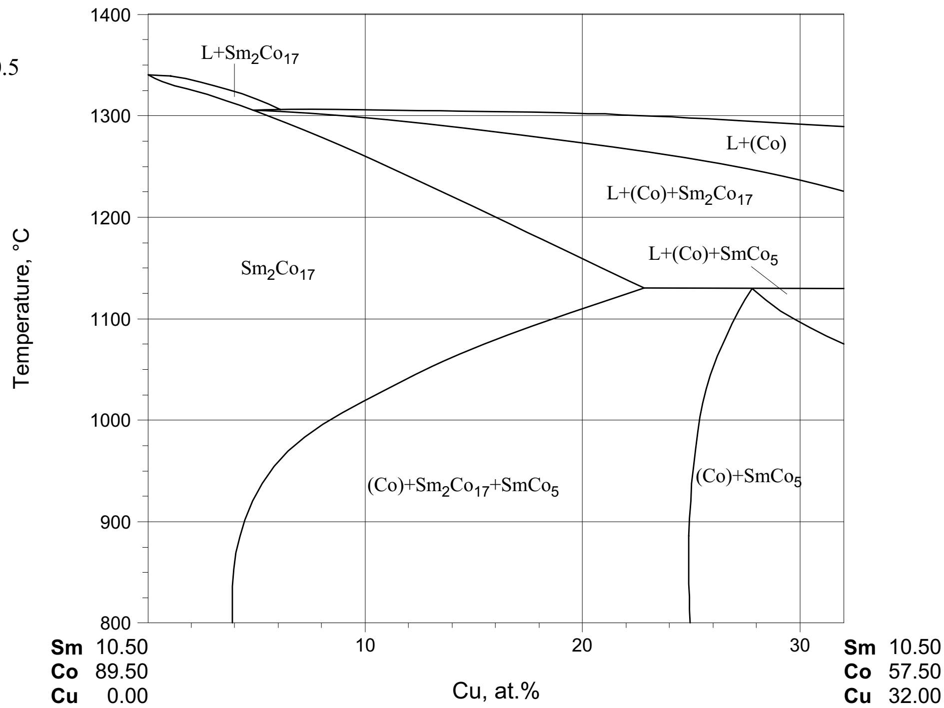

Fig. 4: Co-Cu-Sm. Schematic isopleth at 16.7 at.% Sm

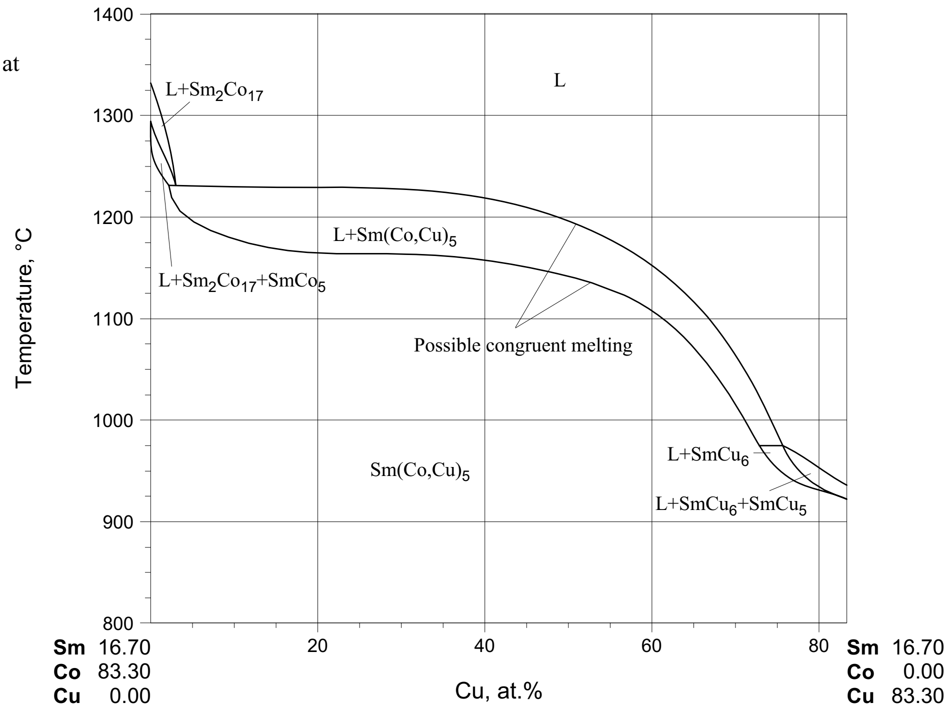

Fig. 5: Co-Cu-Sm. Calculated integral enthalpies of mixing of liquid alloys, in kJ·mol^{-1}