

Copper – Hydrogen – Nickel

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Introduction

The dissolution of hydrogen in the Cu–Ni alloys has been investigated since [1910Sie]: the first experiments indicated an increasing hydrogen solubility at 1225°C and $p(H_2) = 0.1$ MPa in the Cu–Ni melts with increasing Ni content up to 21 at.% [1910Sie, 1929Sie, 1950Him]. Some of these results were included in the review [1938Kub]. All Cu–Ni alloys had a greater solubility for hydrogen than that of Cu [1933All]. Later investigations of the Cu–H–Ni ternary system are indicated in Table 1.

The hydrogen solubility in the solid and liquid Cu–Ni alloys was investigated mainly using Sieverts' method [1936Fuk, 1966Bag, 1966Sch1, 1966Sch2, 1970Deg, 1971Jon, 1974Lin, 1976Ger, 1976Str, 1979Tel, 1980Bar, 1982Sak1, 1982Sak2, 1983Str] and cathodic saturation [1968Bar, 1968Bau1, 1969Lip, 1970Lip, 1975Bar1]. Solubility isobars at a pressure of 0.1 MPa have been measured by [1993Ko] for hydrogen in the Cu–Ni solid solutions in the entire range of compositions. The solubility data gave the values for the partial molar enthalpy and excess entropy of the dissolved H atoms.

It was established that under hydrogen pressures lower than 0.01 MPa, the Cu–Ni alloys are only able to adsorb hydrogen [1969Lip, 1970Lip]. The behavior of hydrogen in Cu–Ni alloys is affected by nickel in a complicated manner: 1) a quick decreasing of solubility up to ~10 at.% Cu is observed; 2) the sorption properties change very slowly at 10–30 at.% Cu; 3) a new quick decreasing of solubility is again observed within the interval from 35 to (60–63) at.% Cu. The hydrogen dissolution in the Cu–Ni melts, containing up to 8.5 at.% Ni, obeys the Sieverts' law [1974Lin].

Calculation of the hydrogen solubility in the Cu–Ni alloys at 830 and 1050°C, using the method of cluster components without the correlation in the solution [1977Kar], well coincides with the experimental data of [1936Fuk, 1971Jon].

Absorption of hydrogen by the Cu–Ni alloys at $p(H_2) = 80$ –120 kPa decreases when the Cu content increases [1934Bau]. [1939Ger] noted that the hydrogen dissolution in the Cu–Ni alloys leads to a decrease of lattice parameter which can be explained by the hydrogen diffusion in the alloys.

Thermodynamic properties of the Cu–H–Ni alloys were investigated by [1966Bag, 1966Sch2, 1970Deg, 1971Jon, 1974Lin, 1974Sig, 1979Tel, 1985Tka, 1993Ko].

Binary Systems

Cu–Ni is taken from MSIT Binary Evaluation Program [2002Leb]. The solubility of H in solid and liquid metals are given by the following expression taken from [1984Fro], which may be used up to 50 MPa of hydrogen pressure:

$$\log_{10}(c_H / \text{at.}\%) = 0.5 \log_{10}(p_{H_2} / \text{Pa}) - 2.77 - 2426 / T \text{ (Cu solid, } 770 < T / \text{K} < 1356)$$

$$\log_{10}(c_H / \text{at.}\%) = 0.5 \log_{10}(p_{H_2} / \text{Pa}) - 2.35 - 2250 / T \text{ (Cu liquid, } 1356 < T / \text{K} < 1823)$$

$$\log_{10}(c_H / \text{at.}\%) = 0.5 \log_{10}(p_{H_2} / \text{Pa}) - 3.00 - 870 / T \text{ (Ni solid, } 620 < T / \text{K} < 1670)$$

$$\log_{10}(c_H / \text{at.}\%) = 0.5 \log_{10}(p_{H_2} / \text{Pa}) - 2.48 - 1176 / T \text{ (Ni liquid, } 1670 < T / \text{K} < 1970 \text{ K})$$

The hydrogen solubility in solid and liquid copper given above is in a good agreement with the Cu–H diagram given by [Mas2] under 50 MPa of hydrogen pressure. The solubility of H in solid nickel given by [1984Fro] is affected by a typing error which has been corrected in the expression given above (2.00 has been replaced by 3.00). It must be pointed out that the H–Ni diagram given by [Mas2] under 50 MPa of hydrogen pressure cannot be accepted, because it gives a eutectic composition of 0.036 at.% H at 1406°C whereas the actual composition would be 2.14 at.% H at the same temperature. The solubility of hydrogen in liquid Ni has also been reviewed by [1987Sch]. The best H–Ni phase diagram available to date is that given in [2002Shi] experimentally determined up to 800°C and 5 GPa of hydrogen pressure. The solid solution H–Ni presents a miscibility gap, with a critical point evaluated by [2004Fuk] around 360°C, 1.4 GPa and 50 at.% H.

Solid Phases

No ternary compound exists in the Cu-H-Ni system. All unary and binary phases are listed in Table 2. The first results on the hydrogen solubility in the Cu-Ni alloys were obtained by [1910Sie, 1929Sie, 1933All, 1936Fuk, 1950Him]. Solubility has been investigated both in liquid and solid states at 350, 700 and 1050°C by [1936Fuk, 1957Lie], 1500 and 1600°C by [1966Sch2], 1600°C by [1966Bag, 1966Sch1], 430, 730 and 1030°C by [1968Bla1], 830, 920, 1000, 1070, 1160 and 1220°C by [1971Jon] and 25, 35, 45 and 55°C by [1982Sak1]. The calculation of hydrogen solubility at 1500 and 1600°C using a model of microheterogeneity of metal melts [1971Pet] are in a good agreement with the experimental data of [1966Sch2]. Some isotherms of the hydrogen solubility in the Cu-Ni alloys, obtained by [1966Bag, 1966Sch2, 1971Jon, 1983Str] are shown in the Fig. 1. The experimental results of [1910Sie, 1929Sie, 1950Him] practically coincide with those given in Fig. 1 and the data of [1968Bla1] are consistently lower than that presented across the entire range of alloy compositions. According to the data of [1968Bla1] the solubility of hydrogen increases approximately by a factor of 2.8 when the pressure increases from 0.1 to 0.89 MPa. The hydrogen solubility in Cu-Ni alloys at the temperature 25-55°C is given in Fig. 2 according to the experimental data of [1982Sak1]. At low temperatures, the behavior of hydrogen seems very peculiar: its solubility increases with the copper content of the alloy up to a maximum around 75 at.% Cu, then decreases sharply down to the solubility of H in pure Cu, which is several orders of magnitude lower than its solubility in pure Ni. At high temperature, the atomic ratio H/Ni decreases approximately linearly with the composition when the Ni content in the alloy decreases from 85.0 to 33.4 at.% Ni [1968Bar]. At 100 at.% Ni the lattice parameter of Ni hydride is about 6% larger than the lattice parameter of pure Ni. A continuous decrease of the difference between the hydrogen charged and uncharged specimens is observed when the Cu concentration increases. The fcc lattice of such Cu-H-Ni alloys remains unchanged. No difference between the lattice parameters of charged and uncharged alloys could be detected for alloys containing ~36.8 at.% Ni. Since the lattice parameter of charged specimens differs in a discontinuous way from values characteristic for uncharged alloys, a new hydride phase could form in the Cu-H-Ni system [1968Bar].

The interstitial dissolution of hydrogen gives rise to a reversible lattice expansion by few percent without change of structure [1968Bau1]. During the hydrogen desorption, two different values of lattice parameters appear simultaneously on Cu-Ni alloys containing 10 to 35 at.% Cu. This is due to the transition between two CuNi-H phases of different hydrogen concentrations (α and β phases). With increasing Cu content a decreasing lattice expansion of hydrogen-rich non-ferromagnetic phase is observed: up to 35 at.% Cu, this expansion is proportional to the mean magnetic moment per atom of the corresponding hydrogen-free alloy [1968Bau1]. The comparison with the quantity of absorbed hydrogen suggests further proportionality between lattice expansion of the β phase (as a function of the Cu content) and the corresponding H/Me atomic ratio.

According to the measurements of magnetization, an increase of the Ni content in the (Ni,Cu) solid solutions leads to a decrease of the critical segregation temperature of Cu-H-Ni solutions: for Cu₂₀Ni₈₀-H and Cu₄₀Ni₆₀-H such temperatures are equal respectively 200 and 100°C, but no segregation was observed using XRD for the composition Cu₄₀Ni₆₀-H [1982Ant].

Investigation by thermoemf of Cu-Ni alloys up to 100 MPa of hydrogen pressure shows that alloying of Ni with Cu displaces weakly the pressure of the $\alpha \rightleftharpoons \beta$ transition in the H-Ni system at room temperature and decreases its hysteresis, which achieves ~30 MPa for Ni, 5 MPa for Cu₃₈Ni₆₂ and is absent in the case of the Cu₅₅Ni₄₅ alloy [1982Ant].

[1983Str] noted that the solubility of hydrogen in the Cu-Ni alloys, containing 3.7, 7.3, 11.0 and 14.6 at.% Ni could be expressed under 0.1 MPa of hydrogen pressure respectively by the following equations:

$$\log_{10} (s / \text{at.}\%) = (0.56 \pm 0.16) - (2767 \pm 290)/T \quad (1150 - 1310^\circ\text{C}, 3.7 \text{ at.}\% \text{ Ni})$$

$$\log_{10} (s / \text{at.}\%) = (0.40 \pm 0.17) - (2444 \pm 230)/T \quad (1150 - 1310^\circ\text{C}, 7.3 \text{ at.}\% \text{ Ni})$$

$$\log_{10} (s / \text{at.}\%) = (0.07 \pm 0.13) - (1738 \pm 180)/T \quad (1200 - 1310^\circ\text{C}, 11.0 \text{ at.}\% \text{ Ni})$$

$$\log_{10} (s / \text{at.}\%) = (0.32 \pm 0.13) - (2074 \pm 180)/T \quad (1200 - 1310^\circ\text{C}, 14.6 \text{ at.}\% \text{ Ni})$$

where T is the temperature in K.

Isothermal Sections

It is known that in the H-Ni system two fcc phases α and β with different hydrogen contents can be in equilibrium at room temperature under suitable conditions of electrolytic charging or under high hydrogen pressure [1982Sak2]. In the Cu-H-Ni system, although the width of the two-phase region decreases gradually with the Cu content down to 50 at.%, there is no critical composition for the disappearance of the miscibility gap: two-phase region appears to continue up to pure Cu as shown in Fig. 3. The β hydride phase is stable only under very high hydrogen pressure at compositions above ~60 at.% Cu.

The absorption-desorption isotherms at 25 and 67°C for the Cu-Ni alloys containing up to 50 at.% Cu have been investigated by [1975Bar1, 1980Bar]. The isotherm at 25°C for the Cu₁₀Ni₉₀ alloy within the pressure range 0.15-0.9 GPa is shown in Fig. 4 [1975Bar1]. The plateau of absorption occurs at higher pressure than the desorption one due to hysteresis. The width of the hysteresis loop in Fig. 4 is about 0.25 GPa and the minimum pressure necessary to form β phase is about 0.34 GPa [1975Bar1]. The alloy Cu₅₀Ni₅₀ exhibits no hysteresis and no two-phase region [1980Bar]. It can be concluded that between the alloys Cu₃₈Ni₆₂ and Cu₅₀Ni₅₀ the miscibility gap ($\alpha + \beta$) at 25°C is closed (at 67°C this happens at a lower Cu content).

The formation pressures of hydrides in the Cu-H-Ni system increase from 0.500 GPa to 0.612 GPa at 25°C and from 0.520 GPa to 0.635 GPa at 67°C at the decreasing Cu content from 38 to 5 at.% [1980Bar]. The decomposition pressures of these hydrides lie between 0.342 and 0.495 GPa.

Thermodynamics

The enthalpy changes in Cu₂₀Ni₈₀-H₂ system under high hydrogen pressure were measured by [1985Tka]. It was established that $\Delta_f H = 7950 \pm 209 \text{ J} \cdot (\text{mol H}_2)^{-1}$ ($p = 0.560 \pm 0.005 \text{ GPa}$) and $\Delta_{\text{dec}} H = -5146 \pm 209 \text{ J} \cdot (\text{mol H}_2)^{-1}$ ($p = 0.380 \pm 0.005 \text{ GPa}$). These values were used for the calculation of the reaction enthalpies under normal pressure ($\Delta_f H = 13703 \pm 418 \text{ J} \cdot (\text{mol H}_2)^{-1}$ and $\Delta_{\text{dec}} H = -8535 \pm 293 \text{ J} \cdot (\text{mol H}_2)^{-1}$). The considerable difference between the decomposition and formation enthalpy of the hydrides is connected with the hysteresis, observed in this system, but so far no unique and generally accepted interpretation can be offered.

The heat of hydrogen dissolution in the Cu-Ni solid alloys is equal 19.2, 13.4 and 6.7 kJ·(0.5 mol H₂)⁻¹ at 10, 20 and 50 at.% Ni, respectively and 35.6, 27.6, 25.1, 25.9 and 19.2 kJ·(0.5 mol H₂)⁻¹ for the liquid alloys containing respectively 5, 13, 15, 26 and 52 at.% Ni [1976Fro]. It was shown that the partial molar entropy of dissolved hydrogen does not depend on the Cu-Ni alloys composition [1979Tel].

The enthalpy of solution of hydrogen is plotted as a function of concentration for the Cu-Ni system in Fig. 5 [1971Jon]. This system exhibits a “quasi-regular” behavior with constant entropy of solution of hydrogen. At low temperature (25-55°C), the enthalpy of solution of hydrogen presents the behavior shown in Fig. 6. The hydrogen solutions in the Cu-Ni alloys obey the Sieverts’ law in the α (low hydrogen content) domain [1970Deg]. The interaction parameters defined by

$$\varepsilon_{\text{H}}^{(\text{Ni})} = \partial \log_{10} f_{\text{H}} / \partial (\text{mass\% Ni}) \text{ or } \varepsilon_{\text{H}}^{(\text{Ni})} = \partial \ln \gamma_{\text{H}} / \partial (x_{\text{Ni}}),$$

with $f_{\text{H}} = (\text{mass\% H in alloy}) / (\text{mass\% H in pure Cu})$ and $\gamma_{\text{H}} = (x_{\text{H}} \text{ in the alloy}) / (x_{\text{H}} \text{ in pure Cu})$

measure the influence of Ni on the solubility of H in copper. A positive interaction parameter means that Ni increases the hydrogen activity coefficient in Cu, thus decreases its solubility. There is a large discrepancy between the interaction parameters measured by various authors, $\varepsilon_{\text{H}}^{(\text{Ni})}$ being negative between 1150 and 1240°C for [1970Deg, 1974Lin, 1974Sig], negative at 1500-1600°C for [1966Sch2] and positive at 1600°C for [1966Bag].

According to the data of [1976Ger, 1976Str] the temperature dependence of the interaction parameter $\varepsilon_{\text{H}}^{(\text{Ni})} = (-123 \pm 34)/T + (0.0640 \pm 0.0011)$, where T is the temperature in K (up to 15 at.% Ni and within the interval of temperature from 1150 to 1300°C). The interaction parameter of Cu has been measured by [1966Sch2] which proposes $\varepsilon_{\text{H}}^{(\text{Cu})} = \partial \ln \gamma_{\text{H}} / \partial (x_{\text{Cu}}) = +0.33$ at 1500-1550°C, which means that Cu decreases the solubility of H in liquid Ni.

Notes on Materials Properties and Applications

Hydrogen dissolution has detrimental effect on the exploitation and mechanical properties of the Cu-Ni alloys [1974Lin]. All the alloys of the Cu-Ni system dissolve hydrogen, and, if chill-cast when saturated with the gas, produce unsound ingots [1933All]. In every case the hydrogen can be removed by degassing with nitrogen.

The shrinkage of surface with increase of reduction temperature is smaller for Cu-Ni catalyst than for pure Cu catalyst [1957Tak]. The rates of H₂ adsorption on Cu and Cu-Ni catalysts are much smaller than that of Ni, and the adsorption amount per unit area is the greatest for Cu-Ni catalyst, while that of Ni catalyst is the smallest among the three.

Ferromagnetic Cu-Ni alloys can be charged with cathodic hydrogen in high concentrations whereby they loose their ferromagnetic behavior [1968Bau1, 1968Bau2]. Measurements of magnetization of these alloys show a quicker absorption of H₂ compared to Ni. By measuring the temperature dependence on saturation magnetization in different states of hydrogen desorption [1968Bau2] established that two ferromagnetic phases exist in the hydrogenated Cu-Ni alloy with 30 at.% Cu. The influence of magnetization on the magnetic properties of Cu-Ni disordered alloys containing 20 and 40 at.% Cu was also investigated by [1982Ant].

The domain of temperatures over which serrated yielding occurs for the hydrogenated Cu-Ni alloys at the strain rate $1.37 \cdot 10^{-4} \text{ sec}^{-1}$ is shown in Fig. 7 for three H₂ concentrations [1968Bla2]. In addition, the effect of increasing the strain rate is shown in Fig. 7, where the results of a series of static strain-aging experiments are also plotted. It can be seen from Figs. 7 and 8 that the region of serrated yielding is strongly dependent on hydrogen level, but under no circumstances were yield points noted in alloys containing >58 at.% Cu, even in the more critical static tests. The increase in the lower critical temperature with increasing Cu content implies that the diffusion coefficient of hydrogen in Ni is lowered by the addition of Cu [1968Bla2]. At the same time, the upper critical temperature is falling.

Increase of hydrogen content in the α phase leads to monotonous decrease of T_C [1982Ant]. The β phase of the Cu₂₀Ni₈₀-H ingot and both α and β phases of the Cu₄₀Ni₆₀-H solution are paramagnetic at the temperature above 27°C. Alloy containing 40 at.% Cu is characterized by $T_C \approx 162 \text{ K}$. Magnetization of the Cu₂₀Ni₈₀-H ingots in the $\alpha + \beta$ two-phase region decreases approximately linearly when the hydrogen content increases. These solutions have no spontaneous magnetization at the temperatures above 4.2 K in the β phase domain [1982Ant].

Miscellaneous

The activation energy of the hydrogen diffusion in the Cu-Ni solid solutions is equal to $146.4 \text{ kJ} \cdot \text{mol}^{-1}$ [1939Ger].

The differential heat of hydrogen adsorption at near zero coverage of the Cu-Ni catalyst, containing 1 at.% Ni, was calculated as $44.4 \text{ kJ} \cdot \text{mol}^{-1}$ [1957Tak].

The temperature dependence of hydrogen diffusion coefficient in the Cu-Ni alloys has been investigated by the electrochemical permeation method [1982Sak1]. The concentration dependence of activation energy for hydrogen diffusion in Cu-Ni alloys is shown in Fig. 9. Figure 10 plots the diffusion coefficient of hydrogen at different temperatures.

Solid solutions Cu-H-Ni are kinetically unstable under atmospheric pressure and $T > 250 \text{ K}$ and decompose forming metals and hydrogen [1982Ant]. After interruption of the cathodic saturation an intensive desorption of hydrogen from the Cu-H-Ni alloys is observed at room temperature [1968Bar].

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Table 1: Investigations of the Cu-H-Ni Phase Relations, Structures and Thermodynamics

Reference	Method/Experimental Technique	Temperature/Composition/Phase Range Studied
[1910Sie, 1929Sie]	Sieverts' method	1225°C / (Cu-Ni) + H ₂ up to 21 at.% Ni
[1933All]	MSA, density measurements	(Cu-Ni) + H ₂
[1934Bau]	Sieverts' method	(Cu-Ni) + H ₂
[1936Fuk]	Sieverts' method	(Cu-Ni) + H ₂
[1939Ger]	XRD	(Cu-Ni) + H ₂ at 15, 25 and 75 at.% Ni
[1950Him]	Sieverts' method	642-944°C / (Cu-Ni) + H ₂ at 5, 10 and 20 at.% Ni
[1957Tak]	Pressure measurements	100-130°C / (Cu-Ni) + H ₂ at 1 at.% Ni
[1966Bag]	Sieverts' method	(Cu-Ni) + H ₂
[1966Sch1]	Sieverts' method	1600°C / Cu-H-Ni
[1966Sch2]	Sieverts' method	1500 and 1600°C / Cu-H-Ni
[1968Bar]	XRD, electrolytic saturation	25°C / Cu-H-Ni
[1968Bau1]	XRD	(Cu-Ni) + H ₂ at 10-35 at.% Cu
[1968Bla1]	Pressure measurements	430, 730 and 1030°C / (Cu-Ni) + H ₂
[1969Lip]	Cathodic saturation	20°C / Cu-H-Ni
[1970Deg]	Sieverts' method	1240°C / (Cu-Ni) + H ₂ up to 9.7 at.% Ni
[1970Lip]	Cathodic saturation	20°C / Cu-H-Ni
[1971Jon]	Sieverts' method	830-1220°C / (Cu-Ni) + H ₂ at 21-88.8 at.% Ni
[1974Lin]	Sieverts' method	1250°C / (Cu-Ni) + H ₂ up to 8.6 at.% Ni

Reference	Method/Experimental Technique	Temperature/Composition/Phase Range Studied
[1975Bar1]	High pressure apparatus	25°C / Cu ₁₀ Ni ₉₀ + H ₂
[1975Bar2]	Measuring of thermoemf	(Cu-Ni) + H ₂ at 38 and 55 at.% Cu
[1976Ger, 1976Str]	Sieverts' method	1150-1300°C / (Cu-Ni) + H ₂ up to 15 at.% Ni
[1979Tel]	Sieverts' method	400-700°C / (Cu-Ni) + H ₂
[1980Bar]	Sieverts' method	25 and 67°C / (Cu-Ni) + H ₂ at 5-50 at.% Cu
[1982Ant]	XRD, measurements of magnetization	250°C / Cu-Ni-H
[1982Sak1]	Cathodic saturation	24-56°C / (Cu-Ni) + H ₂
[1982Sak2]	Cathodic saturation	25°C / Cu-H-Ni
[1983Str]	Modified Sieverts' method	1150-1310°C / (Cu-Ni) + H ₂ at 3.7, 7.3, 11.0 and 14.6 at.% Ni
[1985Tka]	Twin calorimeter method	25°C / Cu ₂₀ Ni ₈₀ -H
[1993Ko]	Equilibrate-quench-analyze technique	441-1157°C / Cu-H-Ni

Table 2: Crystallographic Data of Solid Phases

Phase/ Temperature Range [°C]	Pearson Symbol/ Space Group/ Prototype	Lattice Parameters [pm]	Comments/References
α , (Ni,Cu,H)	<i>cF4</i> <i>Fm$\bar{3}m$</i>		α phase: low hydrogen content
β , (Ni,Cu,H)	Cu		β phase: high hydrogen content
(Ni) < 1455		$a = 352.40$	at 25°C [Mas2]
(Cu) < 1084.62		$a = 361.46$	at 25°C [Mas2] melting point [1994Sub]
(β H) < -259.34	<i>hP2</i> <i>P6₃/mmc</i> Mg	$a = 377.6$ $c = 616.2$	[Mas2] triple point
(α H) < -271.9	<i>cF4</i> <i>Fm$\bar{3}m$</i> Cu	$a = 533.8$	[Mas2]
NiH	<i>cF8</i> <i>Fm$\bar{3}m$</i> NaCl	$a = 374.0$	[V-C2]
NiH ₂	<i>hP3</i> <i>P$\bar{3}m1$</i> NiH ₂	$a = 266$ $c = 433$	[V-C2]

Fig. 1: Cu-H-Ni.
Solubility of
hydrogen under 0.1
MPa H_2 pressure in
the Cu-Ni solid
alloys at 350, 700,
920, 1050, 1220°C,
and in the Cu-Ni
liquid alloys at
1500 and 1600°C

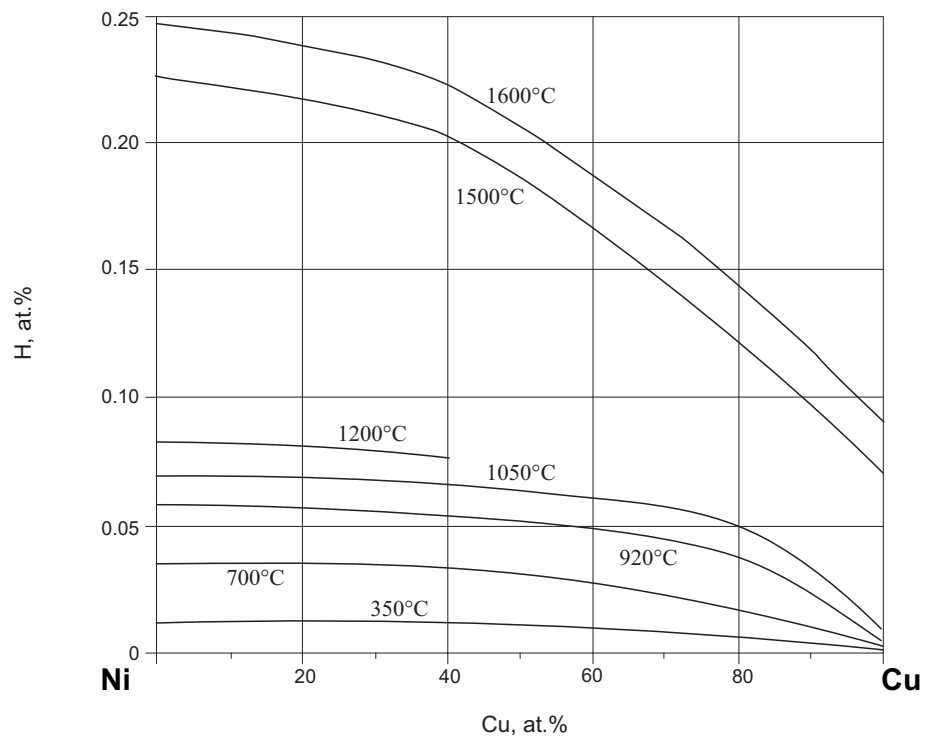


Fig. 2: Cu-H-Ni.
Solubility of
hydrogen in the
Cu-Ni alloys at
25-55°C

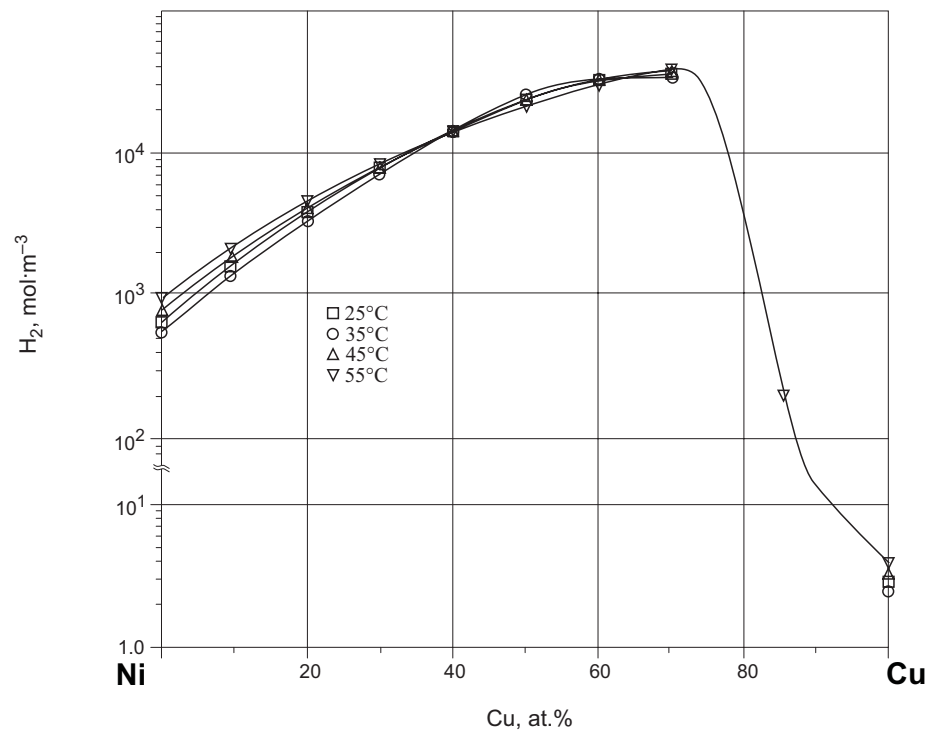


Fig. 3: Cu-H-Ni.
Isothermal section at
room temperature

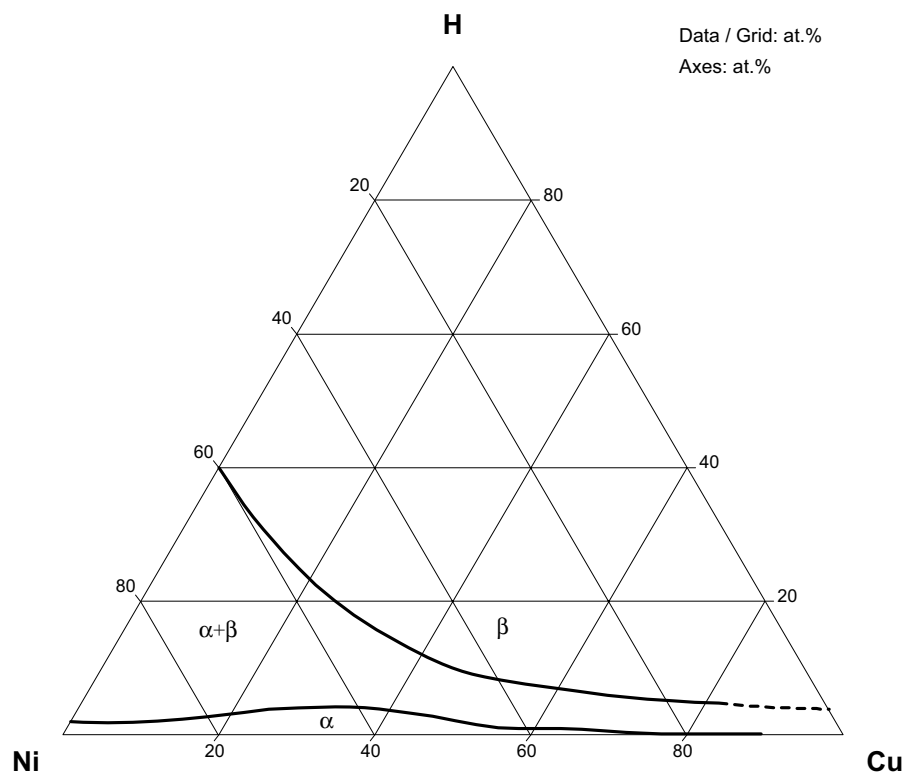


Fig. 4: Cu-H-Ni.
Pressure-compositi
on isotherms for
hydrogen in
 $\text{Cu}_{10}\text{Ni}_{90}$ at 25°C
(the upper and
lower curves
correspond to
formation and
decomposition
conditions
respectively)

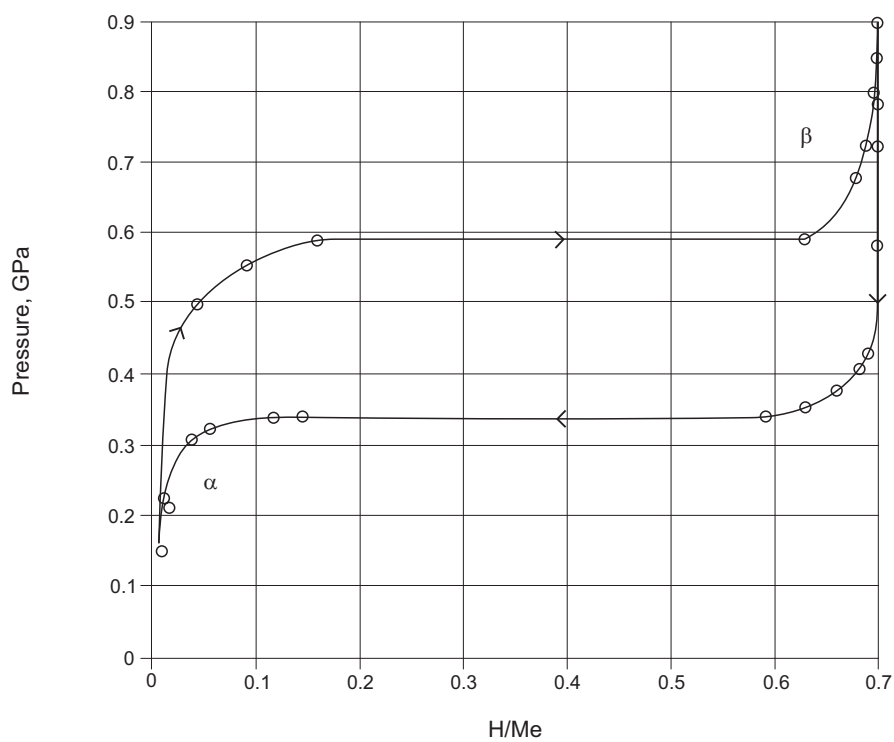


Fig. 5: Cu-H-Ni.
Standard enthalpy
of hydrogen
solutions in the
Cu-Ni alloys

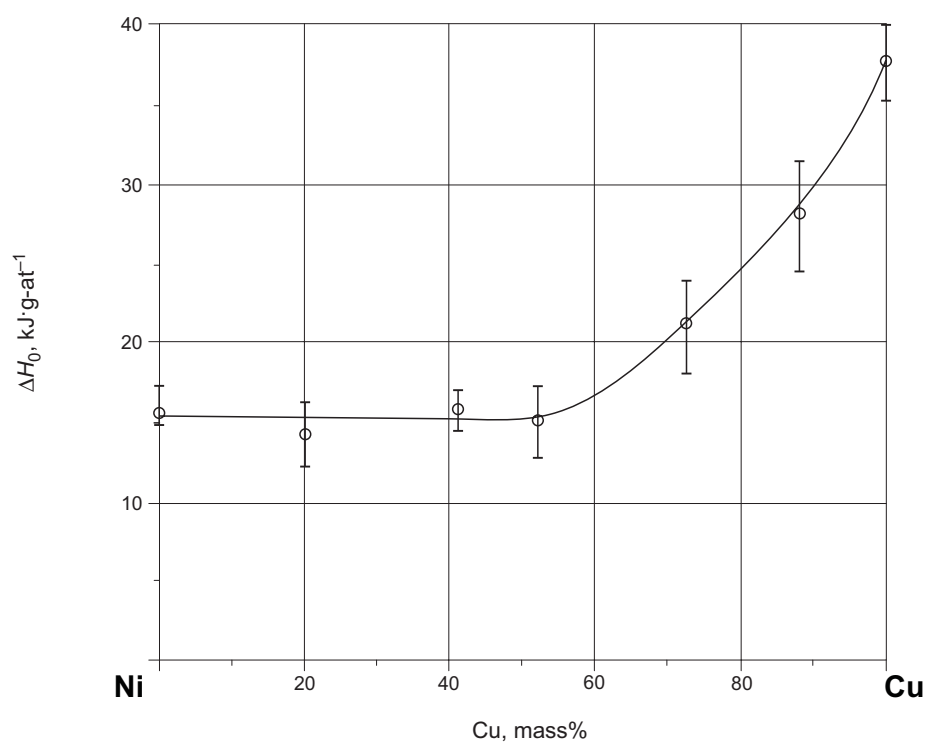


Fig. 6: Cu-H-Ni.
Heat of hydrogen
solution in the Cu-Ni
alloys at 25-55°C

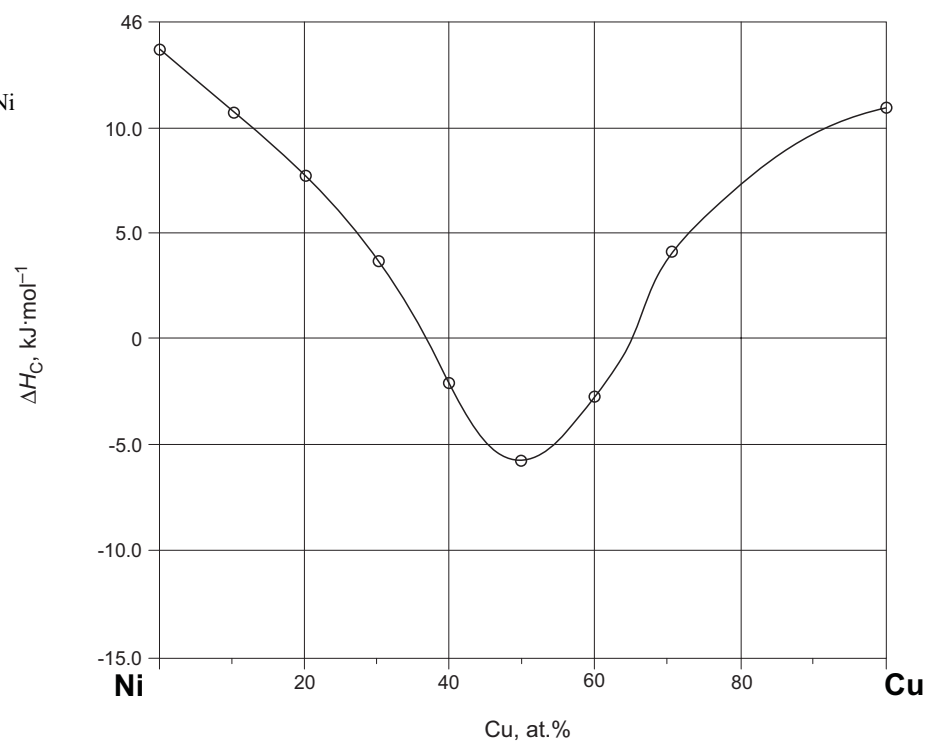
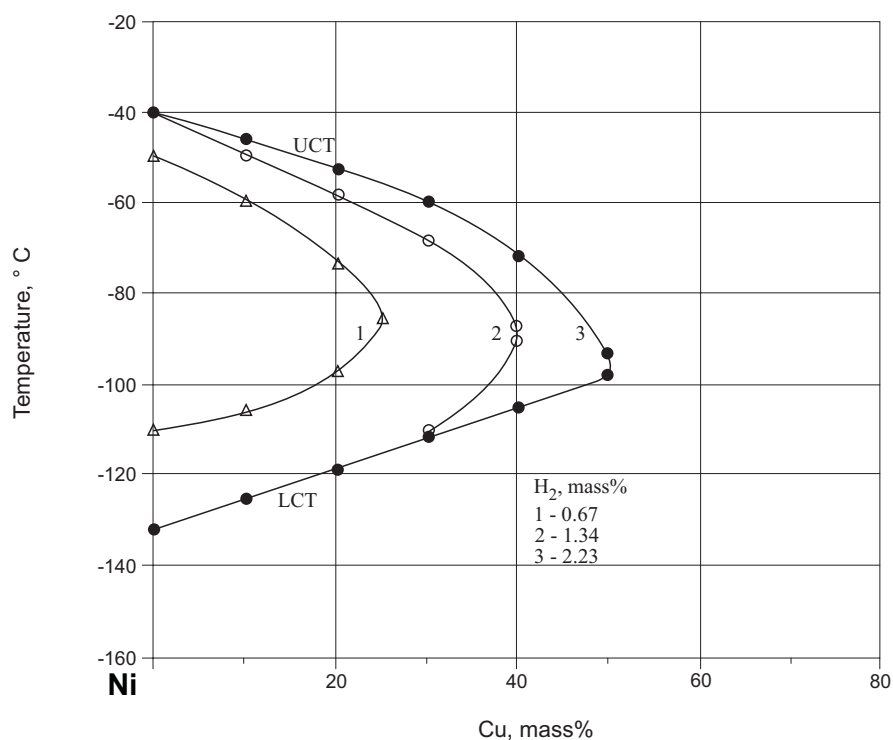


Fig. 7: Cu-H-Ni.

The upper (UCT) and lower (LCT) critical temperatures for Ni-Cu alloys at three hydrogen concentrations (the stress/strain curve is serrated between these temperatures)

**Fig. 8: Cu-H-Ni.**

The upper (UCT) and lower (LCT) critical temperatures at strain rates $1.37 \cdot 10^{-3}$ (1) and $1.37 \cdot 10^{-4}$ (2) sec^{-1} and at $25 \text{ cm}^3 \text{ H}_2$ per 100 g of alloy

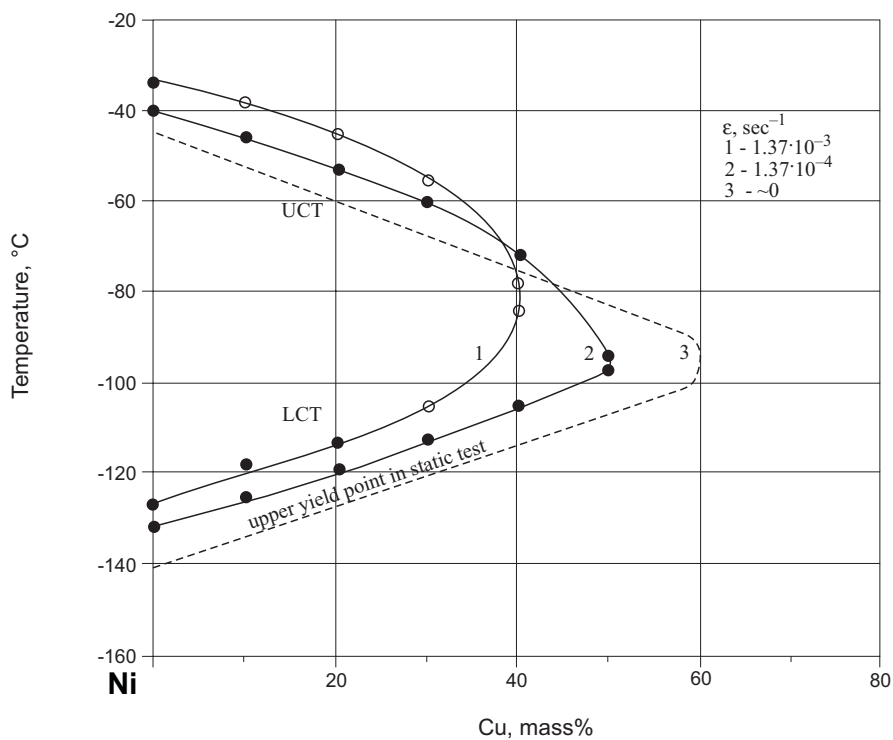


Fig. 9: Cu-H-Ni.
Activation energy for
hydrogen diffusion in
Cu-Ni alloys

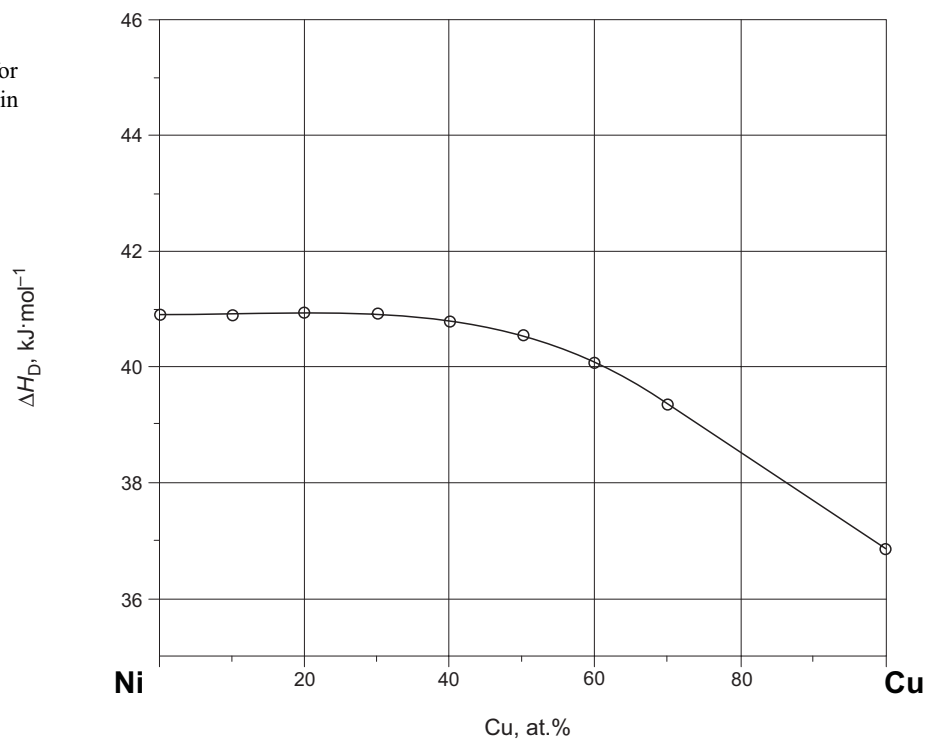


Fig. 10: Cu-H-Ni.
Diffusion coefficient
of hydrogen in Cu-Ni
alloys at 25-55°C

