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ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
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COPPER-BERYLLIUM ALLOYS FOR TECHNICAL APPLICATIONS

W. Heller

GENEVA

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ABSTRACT

Data of physical properties are compiled for the most commonly used copper-beryllium alloys (CuBe 2, CuBe 1.7, CuCoBe, and CuCoAgBe), with emphasis on their temperature dependence and their variation with particular annealing and hardening treatments. The purpose is to provide a reference source and to indicate the versatility of these materials with respect to other copper alloys and to pure copper. The special features of CuBe alloys include high mechanical strength with reasonably high electrical conductivity, as well as good wear and corrosion resistance. For example, CuBe 2 has a yield strength of up to 1200 N/mm^2, about three times that of pure copper, whilst the electrical conductivity of CuCoBe can be as high as 28 MS/m, nearly half that of pure copper. Typical applications are springs and electrical contacts. The importance of a proper heat treatment is discussed in some detail, notably the metallurgy and effects of low-temperature annealing (precipitation-hardening). A chapter on manufacturing processes covers machining, brazing, welding, and cleaning. This is followed by some remarks on safety precautions against beryllium poisoning. CuBe alloys are commercially available in the form of wires, strips, rods, and bars. Typical dimensions, specifications, a brief cost estimate, and addresses of suppliers are listed.

CONTENTS

1. INTRODUCTION

Solutions to many problems concerning development, construction, and application are limited by technological reasons, especially by those of material technology. Thus it is necessary to derive the knowledge from many different sources of information and to collect new results from scientific investigations into specific applications and details. Therefore it is important to have as much information as possible on these technologies. It is equally important to keep a general view of the subject matter and to have an introduction to the technical details.

This report on copper-beryllium (CuBe) alloys is based on information taken from handbooks, catalogues, and publications, or from industrial experience and other sources. It is intended to provide some knowledge of an interesting material for mechanical applications, and it is hoped that it will be of use in deciding on the correct utilization of CuBe alloys.

A summary of the properties and applications of CuBe alloys is given, and a comparison is made with pure copper and, where necessary and desirable, with other commonly used non-ferrous or copper-based alloys. Particular importance is given to properties, heat treatment, manufacturing processes, and applications. This is important for physical and technical applications in large research laboratories such as CERN.

CuBe alloys combine a range of properties that meet the exacting requirements in many applications in the electronics, aeronautical, automotive, electro-chemical, and instrumentation industries. Some of their particular properties are[1-6]:

- high strength and hardness;
- good electrical and thermal conductivity;
- good wear and corrosion resistance.

Very high mechanical strength and a better electrical and thermal conductivity can be obtained through age-hardening by low-temperature heat treatment[5-9]. This is a fundamental characteristic in the use of CuBe alloys.

These alloys are available as wrought products such as strips, rods, bars, and wires, or as casting ingots for foundry work[10]. Owing to their properties and easy manufacture by machining or forming, CuBe alloys are more versatile in their use than other copper alloys[11,12]. In recent years they have become more and more widely employed.

2. ALLOYING OF COPPER WITH BERYLLIUM

Beryllium can be alloyed with copper to form solid solutions. The copper-beryllium equilibrium diagram is shown in Fig. 1 [1,3,13]. The normally used alloys contain three different phases in solid solution:

- α-phase: maximum solubility 2.1% Be at 864°C
  (face-centred cubic structure, copper-rich phase);
- β-phase: 4.2-11% Be in a temperature region between 920-575°C
  (body-centred cubic structure);
- γ-phase: 11.3-12.3% Be at temperatures lower than 933°C
  (body-centred cubic structure).

The industrially available, and therefore most commonly used, CuBe alloys are listed in Table 1; CuBe 2 and CuCoBe are the most important[5,14-16]. The minimum composition of all additional elements Cu + Be + Co + Ni + Fe + Ag is min 99.5%. The outstanding characteristics of these alloys are:

- CuBe 2, CuBe 1.7: high strength
  wear resistance
  good conductivity
- CuCoBe, CuCoAgBe: high conductivity
  good strength.

The alloy CuCoAgBe can be considered as an alloy for special applications. CuBe prealloys, normally of 4% Be, are used as base materials, which are then diluted with oxygen-free Cu to the desired composition[3]. Additions can be the elements:

- Co, to reduce the grain growth and regulate the hardening process;
- Ag, to prevent surface oxidation and to increase the conductivity;
- Pb (or Te), to improve machinability.

Generally, the result of alloying Cu with Be is to reduce the conductivity and to increase its strength. The physical data compared with those of Cu (oxygen-free high-conductivity min 99.99% Cu) are shown in Table 2 [1,3,5,16-19]. The range of mechanical values given depends on the heat treatment and workability.

Specifically, the alloying of Cu with Be

- decreases the electrical and thermal conductivity γ, λ, and the elongation δ;
- increases the mechanical properties: yield strength $\sigma_{0.2}$, tensile strength σ_B, hardness HV, and fatigue strength σ_D;
- has hardly any effects on density ρ, elastic modulus E, shear modulus G, linear expansion coefficient α, and specific heat c.

Already, very small additions of Be change some properties of Cu in a significant way.

3. PROPERTIES

3.1 General properties

CuBe alloys are used because of their electrical and mechanical properties; mostly in a similar way to Cu or other Cu alloys. The special properties of CuBe alloys are the following:

- *Good electrical conductivity.* The values correspond to 22-60% of those of pure Cu. This depends on the composition of the alloy and the heat treatment given.
- *Great hardness.* In the age-hardened condition they are the hardest of all Cu alloys.
- *High strength.* This is the most important factor. Because of the high strength of the CuBe alloys and the high ratio between strength and weight, it is possible to construct with smaller dimensions than is usual when Cu and Cu alloys or other non-ferrous alloys are employed. CuBe alloys can be as strong as some steels.

- *Age-hardening alloys.* CuBe alloys can be hardened by low-temperature annealing. By a simple age-hardening process, the strength can be increased by a factor of 2 and the conductivity by a factor of 1.5, as shown in Fig. 2 [1,20] and Fig. 3 [10]. The addition of cold-working and hardening (both processes are caused by energy) produces the maximal possible hardness, as can be seen in Fig. 4. The mechanical properties, together with the electrical conductivity of the most commonly used CuBe alloys, are listed in Tables 3, 4, and 5 for strips, rods, and wires[5,7,16,21]. As can be seen, the properties vary according to
    - alloy composition;
    - delivery condition;
    - heat treatment.
- *High fatigue strength.* CuBe alloys have an outstanding fatigue strength, and an excellent resistance to fatigue under vibration or under reverse bending, as shown in Fig. 5 [11].
- *Good mechanical properties at low temperatures.*
- *Good strength at high temperatures up to 300°C.*
- *Extreme wear resistance.* CuBe alloys, when lubricated, have a high wear resistance when in contact with steel and other materials, but have no self-lubrication.
- *Good corrosion resistance.* These alloys can thus be used for applications in seawater and in the chemical industry. The corrosion resistance is similar to that of high-purity Cu; it is markedly reduced in some instances by the presence of oxidizing agents[22].
- *Internal friction.* CuBe alloys present a good resistance to inelastic behaviour under elastic deformation. They therefore have a wide application as spring material.
- *Useful over a wide range of temperatures.* CuBe alloys can be used over a wide temperature range. They do not become brittle at low temperatures. Temperature has less effect on their properties than is the case for most Cu alloys; therefore they are useful over a wider temperature range than most Cu alloys.
- *Non-magnetic.* Because they are non-magnetic, they are used in magnets, calibrating instruments, and in electronics.
- *No sparking.* These alloys are therefore used in the manufacture of tools for use in areas where sparking may produce an explosion.
- *Small relaxation.* Because of their small elastic hysteresis they have a small relaxation.
- *Good machinability.* Because the CuBe alloys have a large percentage of Cu, they are easy to machine, with little tool wear.

All these excellent properties characterize the CuBe alloys and are a result of the solubility of Be in Cu.

3.2 Properties at low and at elevated temperatures

CuBe alloys have good mechanical properties at low and at high temperatures, compared with those of other alloys. Data for tensile and yield strength of CuBe 2, measured at lower and higher temperatures than room temperature, are shown in Fig. 6 [23,24]. The stress is higher at low temperatures and in the harder delivered condition. The elongation varies already a little with the temperature, more in the harder delivered conditions than in the annealed condition, as can be seen in Fig. 7 [23,24]. Between 300°C and -250°C, Young's modulus has already a small variation for CuBe 2 in all conditions, as shown in Fig. 8 [23,24]. In Fig. 9 the toughness of CuBe 2 measured by impact energy shows a decrease to a hardened condition, also at low temperatures[23,24]. The values of thermal expansion, measured by change in length, increase with the temperature, as shown in Fig. 10 [23,24]. The fatigue tensile strength of CuBe 2 in the annealed and tempered condition is shown for four temperatures in Fig. 11 and decreases with a long fatigue life[23,24].

At temperatures above room temperature, good mechanical properties are given for CuBe 2 alloys. The high tensile strength of CuBe alloys is obtained in the region between room temperature and 300°C, as can be seen in Table 6, for cold-worked and hardened conditions[1].

4. WORKABILITY

The delivery program of CuBe alloys includes semi-finished products in the different conditions:

- hot-rolled;
- cold-rolled;
- cold-drawn;
- extrusion cast.

CuBe alloys, like pure Cu or other Cu alloys, are easy to machine. Bending of these materials is easier perpendicular to the direction of rolling than it is parallel to the direction of rolling. Generally, the softer the material, the more it should be cold-worked to obtain a good stability in form. Therefore, for bending work the hardest condition should be chosen, which will permit the forming of the smallest radius desired. Cold-working should be uniformly distributed especially when using small bending radii.

CuBe alloys can be cold-worked by various methods, such as drawing, bending, shearing, punching, and rolling. The local stresses created by the processes can be released by hardening. Particular care must be taken to release internal stresses and remove burrs formed by cutting, since they damage the fibres, thus reducing the fatigue strength. The fatigue strength of a faulty piece can be increased by etching, sand-blasting, or electro-flash trimming.

The rate of cold reduction of thickness in the different delivered conditions is shown in Table 7 [7].

5. METALLOGRAPHY

5.1 Age-hardening process

CuBe alloys are age-hardening alloys. This means that

- the solubility of Be in the Cu matrix increases with increasing temperature;
- the solid solution of CuBe must be obtained at low temperatures by quenching from a high temperature;

- by means of a low-temperature treatment of the solid solution of CuBe, one is able to produce precipitations;
- the precipitation phase in the Cu matrix changes the properties of the alloy.

The precipitation process of hardening a normal CuBe 2 alloy (with 1.9% Be content) is shown in the equilibrium diagram Fig. 12. By annealing this alloy between 774°C and 880°C, the Be is dissolved in the Cu matrix to form the α-phase. At temperatures lower than 575°C, a compound of CuBe, known as the γ-phase, is formed in addition to the α-phase. Between 774°C and 575°C the β-phase exists as well as the α-phase[17).

By quenching the alloy from 780°C-800°C, the Be may be retained in the α-phase as a supersaturated solution. In equilibrium at low temperatures the α- and γ-phases do not exist separately from each other, since the diffusion energy at room temperature is not high enough to precipitate Be atoms out of the α-phase. The good ductility of the α-phase is also retained, but the strength, hardness, and conductivity are relatively low.

Subsequent annealing at temperatures below 575°C (precipitation-hardening) precipitates the Be-rich γ-phase by shifting Be atoms progressively out of the α-lattice. The lattice strains between the ductile α-phase and the brittle γ-phase which has occurred result in maximum strength at room temperature. The α-phase becomes poor in Be concentration owing to the formation of the γ-phase, whilst the ductility and the conductivity increase.

In the temperature range from 200°C to 500°C the phenomenon of discontinuous precipitation is observed in CuBe alloys and leads to the precipitation of the equilibrium phase γ 25-27). In agreement with new investigations the following sequence is described28):

- local zone;
- intermediate phase γ″ (ordered phase, coherent);
- intermediate phase γ′ (tetragonal body-centred, partially coherent);
- equilibrium phase γ (cubic body-centred, incoherent).

The discontinuous precipitation only starts at original grain boundaries in deformed samples. With greater deformation, between 30% and 60%, additional nucleation of cellular precipitation occurs at locations of high inhomogeneous deformation in the matrix of CuBe 1.5 28). New particles are also formed by repeated nucleation in the reaction front. The spacing of the particles increases with annealing time and temperature, owing to a reduced growth velocity. Because discontinuous precipitation in the homogeneous α-phase is not desired (lower strength and corrosion resistance), small additions of third elements such as Co or Cr are added.

5.2 Microstructure

The influence of initial conditions on a precipitation-hardened CuBe 2 alloy (with Co addition) is shown in Figs. 13a-c 29). A photomicrograph of the structure of only solution-treated CuBe 2 alloy is shown in Fig. 13a. Compared with this sample, the same alloy, delivered in the half-hard state, is shown in Fig. 13b. A third sample of the same alloy, delivered in the hard state, is shown in Fig. 13c. In the solution-treated photomicrograph (Fig. 13a), the grain of the α-matrix can be seen together with small precipitations. Co is added to CuBe 2 to produce small grain size on solidification, and as a consequence to prevent rapid softening during the ageing cycle.

The compound CoBe precipitates out of the supersaturated α-phase and can be seen as uniformly distributed black dots (Fig. 13a). The few light-coloured rings are the β-phase, which formed during solidification of the alloy. This very hard β-phase is unaffected by thermal treatment and must be restricted to a minimum so as not to interfere with machining. Many of the grain boundaries are well defined by the dark γ-phase, which was selectively transformed from the β-phase at temperatures lower than 575°C. If the solution-treatment temperature is too low or if the sample is over-aged, the amount of the γ-phase in the grain boundaries is greatly increased. This lowers the strength and increases the ductility and the conductivity.

The photomicrographs in Figs. 13b and 13c, compared with Fig. 13a, show the amount of deformation due to cold-rolling. This is about 21% in the half-hard condition and 37% in the hard condition. The higher the amount of cold-working, the more the grains are flattened and the more dislocations are formed. Both samples show deformation bands of dislocations and distortion of the twins within the α-grains. Subsequent hardening again produces the desired few precipitations of the γ-phases. Figures 13a-c show the microstructure of the correct annealing processes.

The effect of deformation and of solution heat treatment on the grain structure is shown in Figs. 14a and 14b [10]. Figure 14a shows the material CuBe 2 in the cold-worked state (fully hard condition). Many deformation bands caused by dislocations can be seen. The structure of the same material, after solution-treating at 780°C, is shown in Fig. 14b. The specimen was water-quenched from 780°C. The solution heat treatment is necessary to maintain the structure of the material from 780°C to room temperature. Then the cold-worked material is recrystallized by thermal treatment, and the grains, now free of strains, are of the α-phase with precipitations of the CoBe-phase (to produce many nuclei for small grain size).

The microstructure of solution heat-treated and precipitation-hardened samples are shown in a bad condition in Fig. 15a and in a good condition in Fig. 15b [29]. The sample shown in Fig. 15a was heated to the correct temperature of 800°C, but allowed to cool into the second phase (α + β-region) before water-quenching. The α-grains contain β and CoBe precipitations. At precipitation-hardening temperature the β-phase has been transformed into the γ-phase by precipitation-hardening at the grain boundaries (solid transformation phase) and additionally the β-phase precipitates out of the α-phase. Figure 15b shows (like Fig. 13a) a correct heat-treated CuBe 2 alloy. The small β and CoBe precipitations in the α-grains can be seen, as well as the darkly etched γ precipitations along the grain boundaries.

If the annealing temperature was above the solidus melting point, partial melting would occur. A photomicrograph of a sample, overheated to 870°C, is shown in Fig. 16 [10,29,30]. The "burned" CuBe 2 alloy precipitates the primary β-phase out of the α-phase at the grain boundaries and in small pools within the grains. The same β-phase (also seen as small rings in Figs. 13a, 15a, and 15b) contains about 4% Be and cannot be redissolved. Because the β-phase is brittle and massive, the ductility of the alloy is lost. Material in this condition cannot be salvaged.

All specimens were etched by swabbing with 3 g ammonium peroxodisulfate $(NH_4)_2S_2O_8$ and 1 mℓ ammonium hydroxide NH_4OH in 100 mℓ water H_2O [10,29,30].

6. HEAT TREATMENT

After having explained the metallographic processes involved, some interesting details will be given concerning the correct heat treatment.

The heat treatment of CuBe alloys is a two-stage process comprising:

- solution heat treatment:
  short solution annealing, followed by quenching in water;
- hardening by precipitation treatment:
  low-temperature annealing for several hours.

6.1 Solution heat treating

Generally, solution heat treatment indicates a softening operation, while precipitation-hardening denotes a hardening operation. The solution heat treatment is usually done in the α-phase region of CuBe alloys to produce a homogeneous distribution of the alloying elements. The energy introduced must be high enough to form a solution and to equalize the concentration according to the equilibrium. This process is initiated by diffusion. The important factors are time and temperature. The recommended solution heat treatment for CuBe alloys is[10,11,30]:

- CuCoBe : 1-3 h 900-925°C/water-quenched;
- CuBe 1.7 : 1-3 h 775-805°C/water-quenched;
- CuBe 2 : 1-3 h 785-805°C/water-quenched.

In rare cases where an unduly high degree of deformation is included in the alloy during fabrication, it may be necessary to resoften (recrystallize) the metal by a solution heat treatment in order to make it possible to continue cold-working. This is a recrystallization process, where new grains will be formed and the alloying elements will again be dissolved.

The higher the temperature the better the solution, but a coarse grain will be formed. At lower temperatures a weaker solution is reached with a finer grain.

6.2 Precipitation-hardening

The treatment by precipitation-hardening is a low-temperature annealing process; it can be divided into three classes:

- hardening to maximum strength;
- hardening to less than maximum strength, using lower temperatures and shorter time;
- over-ageing for a slightly longer time, and at higher temperatures than those required to give the maximum strength.

The selection of the correct method depends on the properties required in the finished metal. The three most important properties to be considered when making this choice are: tensile strength, conductivity, and elongation.

Generally the precipitation process can be considered as a two-part transformation, the formation of nuclei of a new phase and their growth. Both reactions are regulated by diffusion and again are dependent upon the energy introduced by heat treatment.

Precipitation-hardening gives a higher strength and a better conductivity as the amount of γ precipitation increases.

The effect of the heat treatment depends on the variation of the temperature and the time. The influence of temperature on the properties has already been shown in Fig. 2 and is plotted again as a function of tensile strength in Fig. 17 11). As Fig. 17 shows, the harder the delivered condition, the higher the maximum tensile strength, and the lower the treatment temperature needed to achieve this.

The alteration of some of the principal properties due to annealing time are shown in Fig. 18 31). Hardness, strength, and elastic modulus have maximum values, and elongation becomes a minimum value, according to the optimal size and distribution of γ and CoBe precipitations in the material due to annealing time and temperature. The conductivity increases due to the decrease of the Be concentration in the α-matrix. Precipitations are varied by controlling the temperature and time of annealing.

The influence of cold-rolling and precipitation-treatment temperature and time on the four important properties of CuBe 2 (tensile strength, elongation, hardness, and conductivity) is shown in Fig. 19 1,3,22) for the four delivered conditions. At lower temperatures the formation of precipitations takes a longer time, whilst at higher temperatures the optimum conditions are reached in a shorter time. The same influence can be seen in Figs. 2, 17 and 18.

More detailed values of the tensile strength are shown in Fig. 20 30). For example, for the quarter-hard condition of CuBe 2, the same strength (1220 N/mm^2) can be achieved by annealing at 343°C for either half an hour or for seven hours. With the longer treatment time, however, one finds that the elongation and conductivity increase (compare Figs. 18 and 19) at the cost of a little reduction in hardness32). This is the difference between the over-ageing process with well-defined properties, and the low-hardening process. The formation and distribution of precipitation is better attained by over-ageing than by the low-hardening process. When undergoing the phenomenon of over-ageing, where the strength decreases after maximum, the structure of the alloy is near equilibrium at hardening temperature and the precipitated particles become coarse33). Most of the curves exhibit only a slight slope and a pseudoplateau, so that over-ageing with extended treatment time of about three hours is preferable.

Figure 21 shows the effect of cold reduction on "as delivered" and on heat-treated samples3,6). The elongation is reduced and the strength increased more in the non-treated sample than in the treated sample. This is due to the prevention of dislocation slide (produced by cold deformation) by precipitations in the treated samples.

The exact values of electrical conductivity plotted as a function of treatment time and temperature are shown in Fig. 3 for CuBe 2 and in Fig. 22 11) for CuCoBe (the CuBe alloy with the best conductivity). This increase in conductivity can be explained as being due to the production of Be precipitations, thus reducing the Be content in the α-matrix.

The influence of precipitation heat treatment on the fatigue strength of CuBe 2 in various delivered conditions is shown in Table 8 8). For the same conditions of hardness, a comparison of various precipitation heat treatment on the fatigue strength of CuBe 1.7 and CuBe 2 is made. As can be seen, the fatigue strength shows an increase of approximately 20% through a harder delivery condition.

6.3 General remarks on heat treatment

While the combinations of time and temperature are highly critical, preliminary test runs are recommended. The tolerances of furnace temperature should be about ±5°C for annealing and ±10°C for solution heat treatment[30]. Metallographic tests are the best temperature control.

For short duration age-hardening with precise time control at precipitation temperatures, salt baths are often used. However, CuBe alloys should not be solution heat treated in salt baths.

The use of vacuum furnaces or the heat treatment in an inert atmosphere is desirable but not essential, except for pieces which must have bright surfaces. If air furnaces are used there will be a drop in the fatigue strength unless the oxidized surface layer can subsequently be removed by mechanical or chemical means[32]. Hardened pieces can be quenched in air or in water, depending on the thickness of material and on the rate of cooling required.

Shrinkage of up to 0.2% and brazing are the main sources of distortion. Some preventive measures are:

- use a harder grade;
- no hardening treatment, use only mill-hardened material;
- short over-ageing heat treatment (2 hours at 340-370°C);
- long low-hardening heat treatment (6 hours at 260-290°C);
- stress relief;
- clamping (in a jig).

If the above measures do not prevent distortion, then the critical parts of the piece may be reinforced with steel, or may have to be redesigned.

The selected heat treatment is dependent upon the severity of cold-forming to which the piece has been subjected, and the mechanical properties required. One should choose the hardest temper condition from which one can form the part, and after forming, the piece should be precipitation-hardened to give the desired properties. It should be noted that the material will shrink by approximately 0.2% during heat treatment[10].

7. MANUFACTURING PROCESSES

The advantage of CuBe alloys is the ease of manufacture and the simple heat treatment needed to obtain the desired physical properties. To select the best alloy and temper for a given application:

- first select the alloy that will give the desired strength and conductivity;
- next choose the hardest delivered condition from which the piece can be formed or manufactured;
- finally select the precipitation-hardening treatment which will give the desired properties.

7.1 Machining

Virtually all standard production methods are applicable to CuBe alloys. An index of machinability is given as 40% for CuBe alloys, if free-cutting brass has one of 100% [22]. Machining with correct tool geometry is simple and highly efficient[34]. Lathe tools may be made of

- carbon steel (rarely);
- high-speed steel;
- carbide-tipped tools (sintered carbide).

Tipped tools are recommended, depending on the quantity, form, and manufacturing process required as summarized in Tables 9 and 10 [35,36]. The tool life is the number of pieces machined for each tool regrind. The angles of cutting tools are explained in Table 10 and Fig. 23.

The tapping of threads in CuBe alloys needs a special tap as described in Table 11 [35,36]. Cutting oil must always be used. When working with Be materials, care must be taken to avoid inhaling the dust produced by machining, since Be is poisonous.

7.2 Brazing and welding

For joining CuBe alloys with CuBe or steel parts, the following methods can be commonly used[37,38]:

- Low-temperature brazing at 620-650°C (brazing with a brazing material composition of Cu 24%, Ag 61%, In 15%).
- High-temperature brazing at 780-790°C (brazing with a brazing material composition of Cu 28%, Ag 72%; mostly recommended).
- Brazing in vacuum for large pieces at 645-835°C (brazing with a brazing material composition of Ag 20%, Au 60%, Cu 20%; in particular for cast material).
- Welding CuBe with CuBe, Cu, Cu alloys, or steel (MIG- and TIG-welding).
- Electrical resistance welding.
- Electron beam welding.

For brazing, a suitable flux is necessary. The area to be joined must be thoroughly cleaned, and any oxide coating should be mechanically removed. Because of the Be oxide it is not generally possible to use any oxyacetylene welding process. The best welding results are obtained with inert gas-shielded arc welding[32]. When the parts to be joined are relatively small the welding can be carried out in the solution-treated condition and immediately quenched into water. This acts as a solution treatment. The sooner the quench begins, the better. If a quenching from welding or brazing temperature to room temperature is not possible, a solution heat treatment (annealing at 760-780°C and quenching) is recommended. It is usually recommended to join the material before hardening. Wherever possible, however, welding or brazing should be carried out in the soft condition, and solution-treated after welding.

While the melting point of CuAg eutectic brazing alloy (780°C) is located in the range of the solution treatment of CuBe alloys, the solder Cu 28%, Ag 72% is recommended. For rapid brazing time it is possible to use the alloy Ag 60%, Cu 27%, In 13% with a melting range of 605-710°C. For coarse pieces and heavy castings a brazing alloy Ag 20%, Au 60%, Cu 20% exists with a melting range of 645-835°C in vacuum. In order to stimulate enough activity in the brazing material to obtain a good joint in a reasonable time, the temperature must be raised to 800°C. The 800°C limit is critical. If exceeded, extreme grain growth or incipient melting will occur in CuBe 2. Parts to be brazed should be clamped with a minimum pressure to avoid distortion.

Low-temperature brazing material melts at about 630°C (e.g. Cu 24%, Ag 61%, In 15%, or Ag 50%, Cu 16%, In 16%, Cd 18%), below the solution treatment range of CuBe alloys[37]. The time at brazing temperature is to be minimized to achieve the best possible properties after precipitation-hardening. In raising the parts to brazing temperature, a rapid heating rate through the range 320-590°C is desirable to restrict rapid γ precipitation, which impairs properties in brazed and hardened parts. The time at brazing temperature must not be sufficient to dissolve the precipitate.

Thermal treatment of heavy plate weldings should include over-ageing at 400°C to decrease the notch effect of the weld[39]. Special heat treatments after brazing or welding are best determined for each application by experimentation. CuBe alloys are at least as weldable with gas-shielded arc welding or electron beam welding as are other high-strength structural materials[40]. The alloys containing greater Be amounts appear to be the most readily welded because of lower thermal conductivities, lower melting points, and a lesser sensitivity to cracks at high temperature.

It is also possible to weld CuBe alloys with other metals or alloys by electrical resistance, as shown in Table 12 [36].

7.3 Cleaning

If a bright surface is desired, the following steps should be observed:

- All machining of the chosen alloy should be finished before hardening.
- All parts to be heat-treated should be absolutely free of grease.
- Heat treatment.
- After heat treatment if there are signs of oxidation, the parts should be pickled for 15-30 minutes in a sulfuric acid (H_2SO_4) bath of 15-25 Vol.% and at 70-80°C. The duration of pickling depends upon the degree of oxidation, and should be continued until the black film has been entirely removed[10,30].
- Rinsing thoroughly in cold water.
- Brightening may be followed by dipping for about 15 seconds in a cold nitric acid solution (HNO_3) of 15-30 Vol.%. When gas is produced, the acid is attacking the CuBe and the parts should be withdrawn from the bath[10,30].
- Rinsing thoroughly in cold water and drying.
- Further manufacturing processes should be continued immediately, or the surface may be plated or coated. Coating with Cu or Cd (1-2 μm) prevents surface oxidation and is an excellent base for welding.

7.4 Manufacturing range

CuBe alloys are obtainable in the form of strips, rods, bars, wires, tubes, and casting ingots.

Table 13 shows the fabrication program of standard sizes available from stock, along with the manufacturing limits. These limits are not definitive and vary from firm to firm. Tolerances on dimensions are respected.

8. COSTS

The cost of a part depends on many factors such as workability, heat treatment, machinability, and processing.

A short comparison of costs[35)] between two common spring materials, for a simple spring manufactured in series, is given in Table 14. This shows that although material costs are high, these alloys are not excessively expensive in comparison with total costs of fabrication and material.

Owing to the fact that CuBe alloys are stronger than other Cu alloys, it is often possible to make thinner constructions, thus saving weight and offsetting the higher price per kilogramme of CuBe. When one considers the ratio of price to quality, the CuBe alloys are very interesting materials.

In Table 15 a comparison is given with approximate values of electrical conductivity, tensile strength, and material cost of some typical Cu alloys. It can be seen that the relation between electrical conductivity and price of CuBe alloys is not as good as that of pure Cu, and the relation between tensile strength and price is better. This is the reason why Cu alloys are often preferred. The higher ratio for strength to price of CuZn and CuSn(P) alloys is dependent mainly on the low material cost. More important for the choice are the absolute high values of the strength and the conductivity. The material price is variable with the daily market price.

In Fig. 24 properties and costs of some typical Cu alloys (Cu, CuZn, CuSn, CuBe 2, CuCoBe, and CuNiZn) are compared and summarized[37)]. For the CuBe alloys the conductivity is second only to pure Cu, whilst strength, spring stability, and heat resistance are noticeably higher. The material costs also are higher, but not excessively so, if specific properties are necessary.

9. REMARKS ON SAFETY

Beryllium is poisonous. There is a danger of poisoning (via the lungs) due to the inhalation of dust and smoke if the Be concentration in the air is uncontrolled. Experience shows that if normal safety precautions such as dust extraction ducting, ventilation, and working in a wet condition[5)], are used when machining, melting, or welding, no safety problems should occur[41,42)].

For pure beryllium the average working concentration is limited to[41,42)]:

- 2 $\mu g/m^3$ air for 8 hours exposure, or
- 25 $\mu g/m^2$ air for 30 minutes exposure in closed rooms, and
- 0.01 $\mu g/m^3$ air for 30 days in the open air.

10. APPLICATIONS

CuBe alloys are mostly used because of their relatively good conductivity and high strength.

Amongst the traditional uses for CuBe alloys are:

- all types of springs (leaf springs, coil springs, spring connectors, torsion springs, Bourdon tubes, etc.);
- electrical connections (contacts, connectors, relays, switches, commutators, sockets, interruptors, etc.);
- all uses of Cu requiring higher mechanical properties;
- diaphragms and bellows;
- ball- and roller-bearings;
- spark-proof tooling;
- resistance welding electrodes;
- in magnets such as antimagnetic material (magnets and precision instruments);
- ordnance (firing pins);
- in the watch industry (gears, etc.);
- in the die-making industry (plastic moulds).

These examples show the wide field of remarkable, common, and frequently unusual applications for the material CuBe.

11. CONCLUSION

Copper-beryllium is the hardest of the copper alloys. It has high mechanical strength, hardness, and good electrical and thermal conductivity. The most important and commonly used alloy is CuBe 2 with the highest yield strength of CuBe alloys of up to 1200 N/mm^2, or about three times that of pure copper. For applications requiring good electrical conductivity, the alloy CuCoBe is most suitable with its conductivity up to 28 MS/m or about 50% that of pure copper.

These alloys are therefore chosen for electrical contacts and for all types of springs. Because CuBe alloys are age-hardenable, the mechanical and electrical properties can be varied by heat treatment over a wide range by a factor of about 2. The low-temperature annealing processes produce precipitation of small particles in the material, which results in a change of properties.

The success of the application depends upon the correct choice of the alloy, its condition, and the careful realization of the correct treatment. Therefore, some aspects are treated from a general point of view, whilst references are also made to fine details and special engineering applications.

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Table 1

Most commonly used CuBe alloys (composition in weight %)

Name	Specification	Be	Co	Co + Ni + Fe	Cu + other additions
CuBe 2	SAE CA 172 CDA 172 DIN 17666 Wnr. 2.1247 BS 2870-CB 101 ISO DR 546	1.8-2.0	min. 0.2	max. 0.6	Rest Cu
CuBe 1.7	SAE CA 170 CDA 170 DIN 17666 Wnr. 2.1245 BS 2870-CB 101 ISO DR 546	1.6-1.8	min. 0.2	max. 0.6	Rest Cu
CuBe 2 automat		1.8-2.0	min. 0.2	max. 0.6	Rest Cu 0.2-0.3 Pb
CuCoBe	SAE CA 175 CDA 175 DIN 17666 Wnr. 2.1285 ISO DR 546	0.4-0.7	2.4-2.7	-	Rest Cu
CuCoAgBe	SAE CA 176 CDA 176	0.25-0.50	1.4-1.7	-	Rest Cu 0.9-1.1 Ag

SAE = Society of Automotive Engineers
CDA = Copper Development Association
DIN = Deutsche Industrie-Norm (Deutscher Normenausschuss)
BS = British Standard
ISO = International Organization for Standardization

Table 2

Physical data of CuBe alloys (in the hardest condition after precipitation-hardening) compared with Cu (oxygen-free high-conductivity).

Property	Sign	Dimension	Cu (OFHC)	CuBe 2	CuCoBe
Melting point (solidus)	T_S	°C	1083	865	1030
Density	ρ	kg/m^3	8960	8250	8750
Elastic modulus	E	N/mm^2	125000	130000	133000
Shear modulus	G	N/mm^2	46000	51000	52000
Electrical conductivity at 20°C	γ	MS/m % IACS	59 101.7	12.7 22	27.5 47.5
Electrical resistivity at 20°C	ρ	$\mu\Omega m$	0.017	0.078	0.038
Thermal conductivity at 20°C	λ	W/mK	393-460	113-126	209-239
Linear expansion coefficient at 20-200°C	α	1/K	16.2×10^{-6}	17.0×10^{-6}	17.6×10^{-6}
Specific heat at 20°C	c	kJ/kgK	0.385	0.418	0.418
Yield strength	$\sigma_{0.2}$	N/mm^2	40-430	200-1200	140-900
Tensile strength	σ_B	N/mm^2	150-450	450-1500	390-1000
Elongation	δ	%	40-2	35-1	35-2
Hardness (Vickers)	HV	N/mm^2	400-1000	900-4000	700-2600
Fatigue strength for 10^8 cycles	σ_D	N/mm^2	< 180	250-340	210-250

Table 3

Mechanical and electrical properties of CuBe strips

Condition	Treatment time and temperature [°C]	Tensile strength [N/mm^2]	Yield strength [N/mm^2]	Elastic limit [N/mm^2]	Elongation [%]	Rockwell hardness	Vickers hardness [N/mm^2]	Electrical conductivity [MS/m]
CuBe 2: as delivered + age-hardenable								
A	-	420-550	200-250	100-140	35-60	B 45-78	900-1500	9.7
¼ H	-	530-620	420-560	280-420	15-35	B 68-90	1300-1850	9.1
½ H	-	600-700	530-630	390-490	5-25	B 88-96	1800-2200	8.6
H	-	700-840	670-790	490-600	2-8	B 96-102	2200-2500	8.6
age-hardened								
AT	3 h 315	1160-1340	980-1190	700-880	3-10	C 36-41	3500-4000	12.5
¼ HT	2 h 315	1230-1400	1050-1260	770-950	2½-6	C 38-42	3700-4150	12.5
½ HT	2 h 315	1300-1480	1120-1340	840-1020	1-5	C 39-44	3800-4400	12.5
HT	2 h 315	1340-1510	1150-1370	880-1090	1-3	C 40-45	3900-4500	12.5
as delivered + mill-hardened								
AM	-	700-770	530-630	390-490	18-23	C 18-23	2200-2500	11.4
¼ HM	-	770-840	600-700	460-560	15-20	C 21-26	2400-2800	11.4
½ HM	-	840-950	670-810	530-670	12-18	C 25-30	2600-3000	11.4
HM	-	950-1050	770-950	600-740	9-15	C 30-35	3000-3450	11.4
XHM	-	1120-1230	950-1120	700-880	4-10	C 35-39	3450-3800	11.4
XHMS	-	1230-1340	1050-1200	770-910	3-9	C 37-41	3600-4000	11.4
CuBe 1.7: as delivered + age-hardenable								
A	-	420-550	200-250	100-140	35-60	B 45-78	900-1500	9.7
¼ H	-	530-620	420-560	280-420	15-35	B 68-90	1300-1850	9.1
½ H	-	600-700	530-630	390-490	5-25	B 88-96	1800-2200	8.6
H	-	700-840	670-790	490-600	2-8	B 96-102	2200-2500	8.6
age-hardened								
AT	3 h 315-330	1050-1270	910-1120	600-810	3-12	C 33-38	3300-3700	12.5
¼ HT	2 h 315-330	1120-1300	950-1160	670-840	2½-8	C 35-39	3450-3800	12.5
½ HT	2 h 315-330	1190-1370	1020-1230	740-910	1-6	C 37-40	3600-3900	12.5
HT	2 h 315-330	1270-1410	1090-1300	770-980	1-5	C 39-41	3800-4000	12.5
as delivered + mill-hardened								
AM	-	700-770	490-630	350-490	18-23	C 18-23	2200-2500	11.4
¼ HM	-	770-840	560-700	420-560	15-20	C 21-26	2400-2800	11.4
½ HM	-	840-950	670-810	490-670	12-18	C 25-30	2600-3000	11.4
HM	-	950-1050	770-950	560-740	9-15	C 30-35	3000-3450	11.4
XHM	-	1120-1230	950-1120	700-880	3-9	C 34-38	3400-3700	11.4
CuCoBe: as delivered + age hardenable								
A	-	max. 390	140-210	70-140	20-35	B 20-45	700-900	11.4
½ H	-	420-530	350-490	210-350	5-10	B 65-76	1200-1450	14.2
H	-	490-600	420-560	280-420	2-8	B 78-88	1500-1800	14.2
age-hardened								
AT	3 h 480	700-840	560-700	420-560	8-15	B 92-100	1900-2500	25.6
½ HT	2 h 480	770-910	670-840	490-630	5-12	B 95-102	2050-2600	27.4
HT	2 h 480	770-910	700-840	530-670	5-12	B 95-102	2050-2600	27.4
as delivered + mill-hardened								
HTC	-	530-630	350-530	210-420	5-15	B 78-88	1500-1800	34.4
HTR	-	840-1050	770-980	560-770	1-5	B 97-104	2350-2700	27.4

Explanation of designations:

A = solution heat treated (annealed)
H = hard
T = age-hardened at standard time and temperature
M = mill hard
X = extra
S = special
C = high conductivity
R = high strength

Table 4

Mechanical and electrical properties of CuBe rods

Condition	Treatment time and temperature [°C]	Tensile strength [N/mm^2]	Yield strength [N/mm^2]	Elastic limit [N/mm^2]	Elongation [%]	Rockwell hardness	Vickers hardness [N/mm^2]	Electrical conductivity [MS/m]
CuBe 2, CuBe 2 Automat: as delivered + age hardenable								
A	-	420-600	140-210	100-150	35-60	B 45-80	900-1550	9.7
H under 25.4 mm Ø	-	630-920	530-740	250-460	10-20	B 88-103	1800-2600	8.6
H over 25.4 mm Ø	-	600-810	530-740	250-460	10-20	B 88-103	1800-2600	8.6
	age-hardened							
AT	3 h 315	1160-1340	1020-1230	770-880	3-10	C 36-41	3500-4000	12.5
HT under 25.4 mm Ø	2 h 315	1300-1510	1160-1410	840-1050	2-5	C 39-44	3800-4400	12.5
HT over 25.4 mm Ø	2 h 315	1200-1510	1050-1410	770-1050	2-5	C 39-44	3800-4400	12.5
CuCoBe: as delivered + age-hardenable								
A	-	250-370	140-210	70-140	20-35	B 25-45	750-900	11.4
H	-	460-560	390-530	250-460	10-15	B 60-75	1100-1400	11.4
age-hardened								
AT	3 h 480	700-840	560-700	380-530	10-25	B 92-100	1900-2500	25.6
HT	2 h 480	770-910	700-840	490-630	8-20	B 95-102	2050-2600	27.4
CuCoAgBe: as delivered + age-hardenable								
A	-	250-370	140-210	70-140	20-25	B 25-45	750-900	11.4
H	-	460-560	390-530	250-460	10-15	B 60-75	1100-1400	11.4
	age-hardened							
AT	3 h 480	700-840	560-700	380-530	10-25	B 92-100	1900-2500	28.5
HT	2 h 480	770-910	700-840	490-630	8-20	B 95-102	2050-2600	28.5

Table 5

Mechanical and electrical properties of CuBe wires

Condition	Treatment time and temperature [°C]	Tensile strength [N/mm^2]	Yield strength [N/mm^2]	Elastic limit [N/mm^2]	Elongation [%]	Electrical conductivity [MS/m]
CuBe 2: as delivered + age-hardenable						
A	-	400-550	140-250	100-160	35	9.7
1/4 H	-	630-810	490-670	280-460	10	8.6
1/2 H	-	770-950	630-770	420-560	5	8.6
3/4 H	-	910-1090	770-950	560-740	2	8.6
H	-	980-1160	840-980	740-980	1	8.6
age-hardened						
AT	~~3 h 315~~	1160-1330	1020-1230	770-950	3	12.5
1/4 HT	2 h 315	1230-1440	1120-1330	840-1050	2	12.5
1/2 HT	2 h 315	1300-1510	1190-1400	910-1160	1	12.5
3/4 HT	2 h 315	1330-1620	1230-1440	950-1190	1	12.5
HT	2 h 315	1370-1620	1260-1510	980-1230	1	12.5
as delivered + mill pre-tempered						
1.29-1.89 mm Ø	-	980-1160	-	-	-	12.0
1.90-2.53 mm Ø	-	840-980	-	-	-	12.0
2.54-2.89 mm Ø	-	800-910	-	-	-	12.0

Table 6

High-temperature tensile strength σ_B [N/mm^2] of CuBe alloys

Condition	Temperature of specimen [°C]				
	20	100	200	250	300
Cold worked	950	950	930	900	850
Hard + hardened	1390	1350	1320	1230	1110

Table 7

Delivery condition and cold reduction of CuBe alloys

Condition	Cold reduction of thickness [%]	Deformability
A	0	Deep drawing, pressing, highest deformation
¼ H	11	High deformation
½ H	21	Middle deformation
H	37	Mainly for flat pieces, low deformation

Table 8

Influence of precipitation heat treatment
on the fatigue strength σ_D [N/mm^2] of CuBe 1.7
and CuBe 2 in various delivered conditions

Condition		Precipitation heat treatment [°C]			
		316	330	343	375
CuBe 1.7	A	246	259	257	257
	¼ H	298	306	302	288
	½ H	295	298	302	298
	H	341	302	302	301
CuBe 2	A	253	249	239	255
	¼ H	271	293	295	274
	½ H	309	296	293	291
	H	313	300	316	300

Table 9

Comparison between cutting tools

Tool material	Relation of cost	Relation of tool life
Sintered carbide	├──────────┤ 2.5	├────────────────────┤ 5
High-speed steel	├──────┤ 1.5	├──────────┤ 2.5
12% Cr steel	├──┤ 1	├──┤ 1

Table 10

Carbide-tipped cutting tools for free machining CuBe alloys

Angle	CuBe 2 (Pb addition)	CuCoBe (Te addition)
α Front clearance	6-12°	4.4-8°
β Wedge angle	80-66°	74-84°
γ Top rake	4-12°	2-10°
κ Relief angle	45-90°	45-90°
ε Nose angle	90°	90-105°
λ Side rake angle	0-8°	0.5°
χ Side clearance	6°	6°
δ Cutting angle ($\alpha + \beta$)	-	-
ν Side cutting angle	-	-
r Nose radius	0.6 mm	0.6 mm
Cutting speed	50-80 m/min	60-100 m/min
Feed	0.03-0.15 mm/revolution	0.05-0.20 mm/revolution

Table 11

Screw taps for alloy CuBe 2

Angle	Condition: A-½ H σ_B = 420-700 N/mm^2	Condition: H-HT σ_B = 700-1500 N/mm^2
Tapped hole, blind:		
Rake angle	14-16°	Standard
Tapped hole, through:		
Rake angle at the first thread	8-10°	3-5°
Other angle	6-8°	6-8°
Cutting speed	3-4 m/min	3-4 m/min

Table 12

Resistance welding of CuBe alloys with other materials

Good welding	Satisfactory welding	Poor welding
Braze 70-30	Copper	Carbon steel
Copper-nickel	Braze 95-15	Stainless steel
Silver-nickel	Aluminium	Magnesium
Copper-silicium	Nickel	Zinc
Copper-phosphor	Monel	Tin

Table 13

Manufacturing ranges and dimensions

Form	Profile	Dimensions [mm]	Specifications
Wires	Round	(0.2-0.5 diameter) 0.5-9.5 diameter (9.5-12 diameter)	ASTM B 197 QQ-C 530 (AIR 9075) (DIN 17677) AMS 4725
	Rectangular	Available	
	Square	Available	
Strips		0.025-0.124 thickness × 1.4-1.53 width to to 3.175-4.775 thickness × 25.4-305 width	ASTM B 194 QQ-C 533 BS 2870-CB 101 DIN 17670 AIR 3370 AMS 4530
Rods, bars	Round	Cold drawn 1.4 - 63.5	ASTM B 196 ASTM B 441 DIN 17672 QQ-C 530 AMS 4650
		Hot worked 19.1 -203.2	
		As cast 101.6 -254.0	
	Hexagonal	Cold drawn 3.0 - 38.1	
	Square	Cold drawn 2.0 - 50.8	
		Hot worked 10.7 -133.3	
	Rectangular	Cold worked 4.76- 25.4 × 12.7-305	
		Solution heat-treated 4.76- 25.4 × 12.7-305	
		Hot worked 6.35- 63.5 × 31.7-355	
		Cold drawn 0.5 - 20 × 0.5- 20	
		Cold drawn 20 - 50.8 × 6.3- 50.8	

Table 14

Comparison of costs for a simple spring

Costs	CuSn 8 (FB 440) [SF]	CuBe 2 (FB 930) [SF]	Factor
Costs of material	1.40	5.20	1:4
Costs of fabrication	4.30	4.30	1:1
Total	5.70	9.50	1:1.7

Table 15

Comparison of electrical conductivity γ, tensile strength σ_B, and material price of Cu alloys

Compared values	Cu	CuZn	CuSn(P)	CuBe 2	CuCoBe	CuNiZn
γ	1	0.33	0.14	0.33	0.67	0.08
σ_B	1	1.5	2.5	4.5	2.5	1.6
Material price	1	0.6	0.8	2.4	1.8	1.3
γ/price	1	0.55	0.18	0.14	0.37	0.06
σ_B/price	1	2.5	3.1	1.9	1.4	1.2

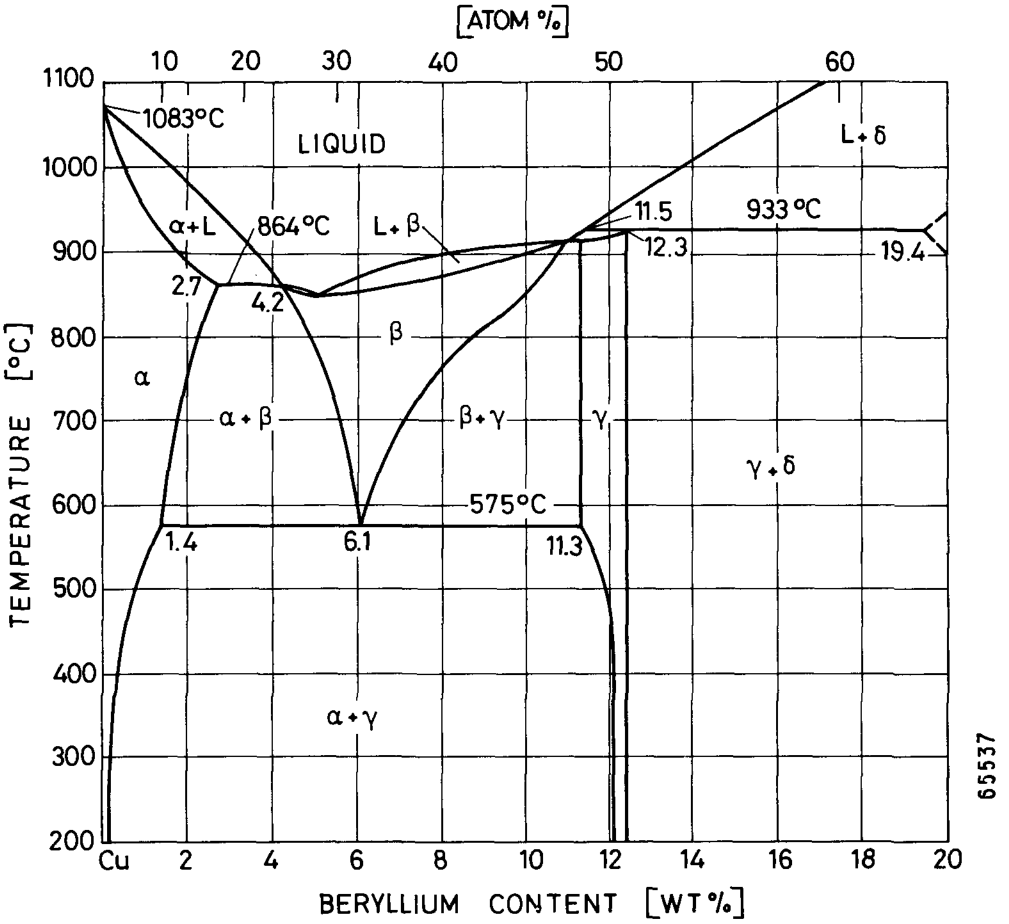

Fig. 1 Equilibrium binary system copper-beryllium (CuBe)

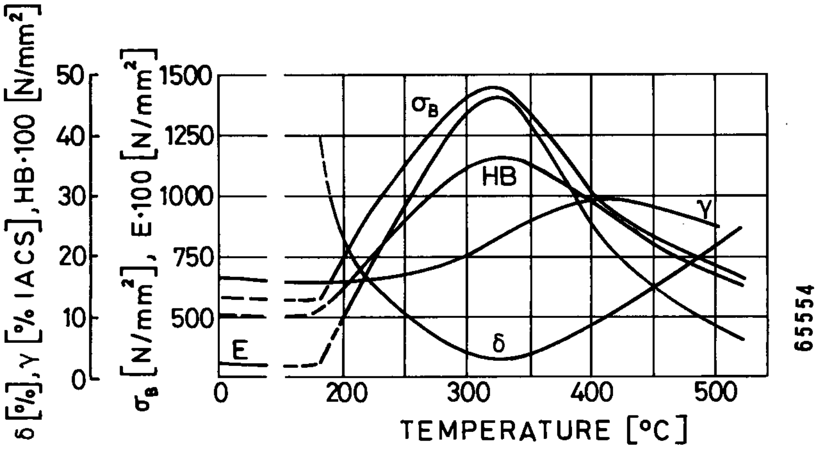

Fig. 2 Influence of annealing on the tensile strength σ_B [N/mm^2], Young's modulus E [N/mm^2], elongation δ [%], electrical conductivity γ [% IACS], and hardness HB [N/mm^2] of cold-rolled and hardened alloy CuBe 2.2. [100% IACS (International Annealed Copper Standard) = 58 MS/m.]

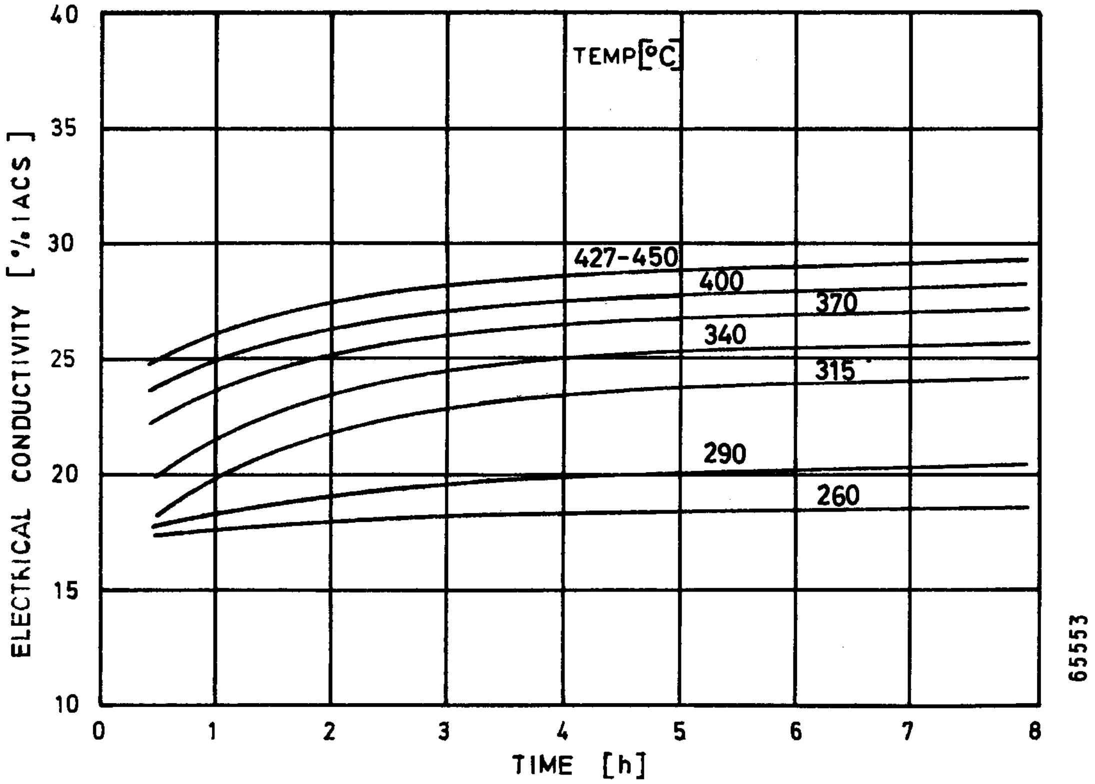

Fig. 3 Effect of ageing times and temperatures on the electrical conductivity γ [% IACS] of CuBe 2. These curves are representative of the four principal conditions: solution heat-treated, 1/4 hard, 1/2 hard, and hard. [100% IACS = 58 MS/m.]

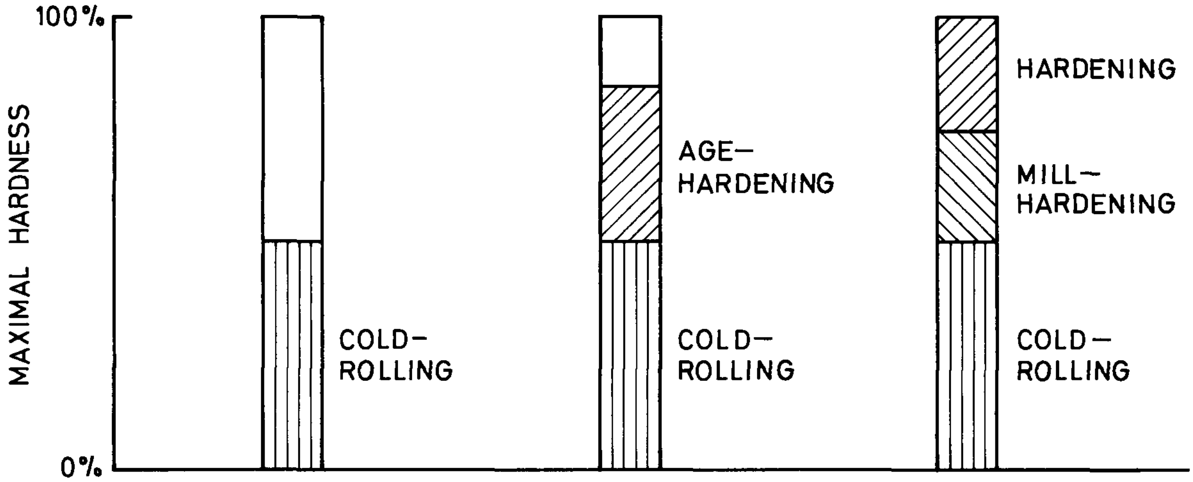

Fig. 4 Influence of cold-rolling and hardening on the maximal possible hardness of CuBe alloys

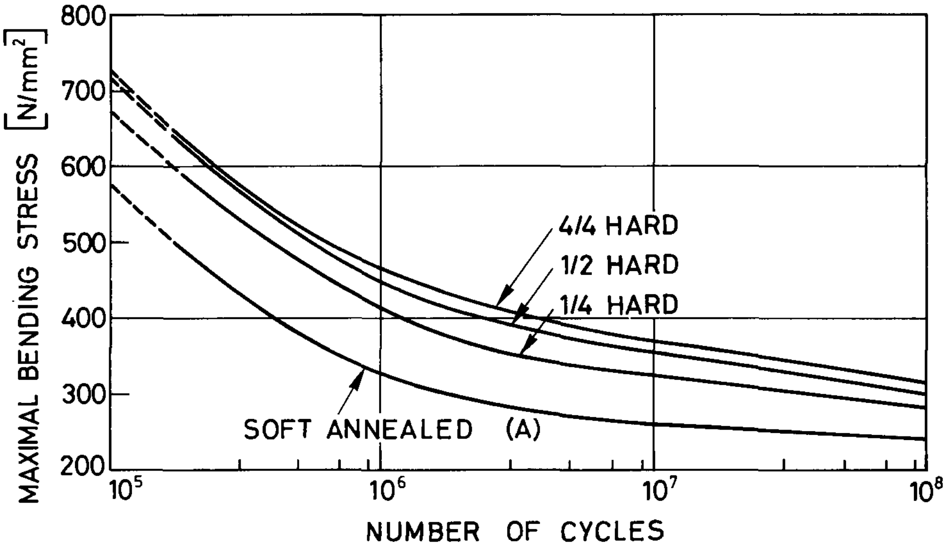

Fig. 5 Fatigue resistance to maximal cyclic bending stress σ_D $[N/mm^2]$ of CuBe 2 after precipitation heat treatment at 320-340°C

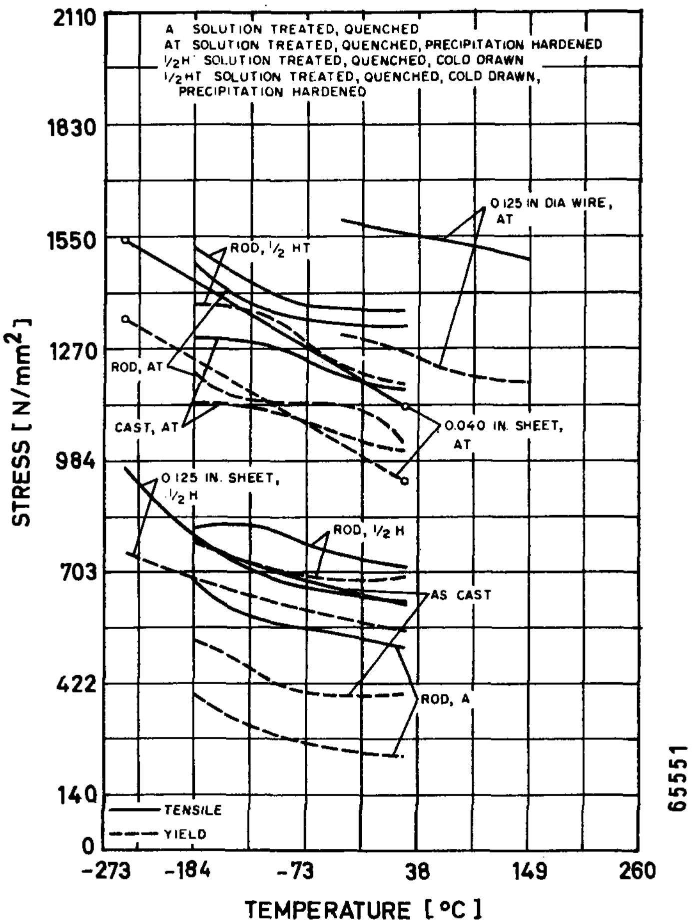

Fig. 6 Tensile and yield strength σ $[N/mm^2]$ at low and elevated temperatures of CuBe 2 in different conditions

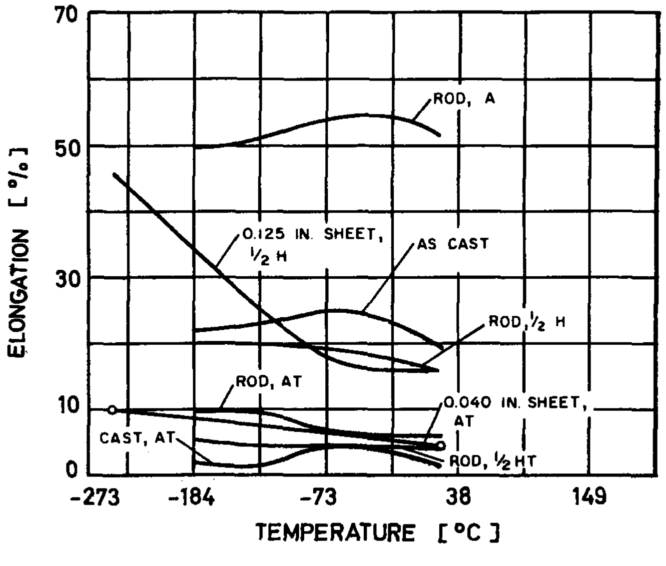

Fig. 7 Elongation δ [%] at low temperature of CuBe 2 in different conditions

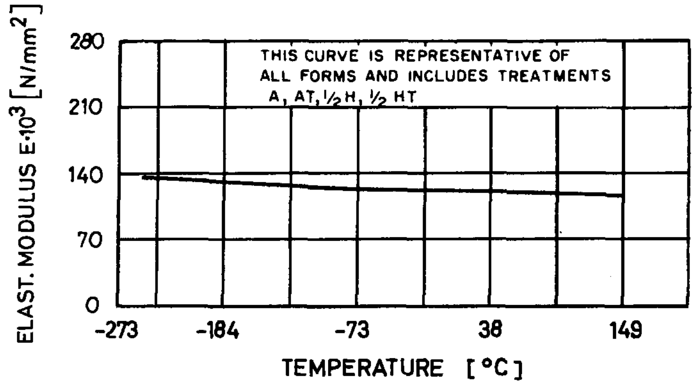

Fig. 8 Modulus of elasticity E $[N/mm^2]$ at low and elevated temperatures of CuBe 2

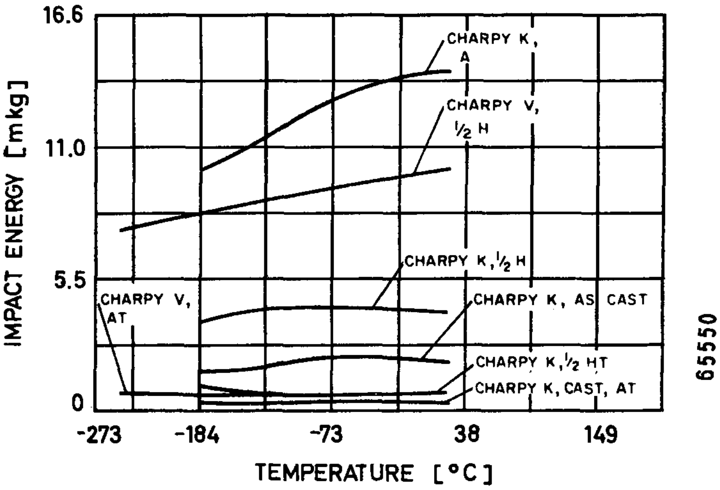

Fig. 9 Impact energy (toughness) [m•kg] at low temperature of CuBe 2 in different conditions

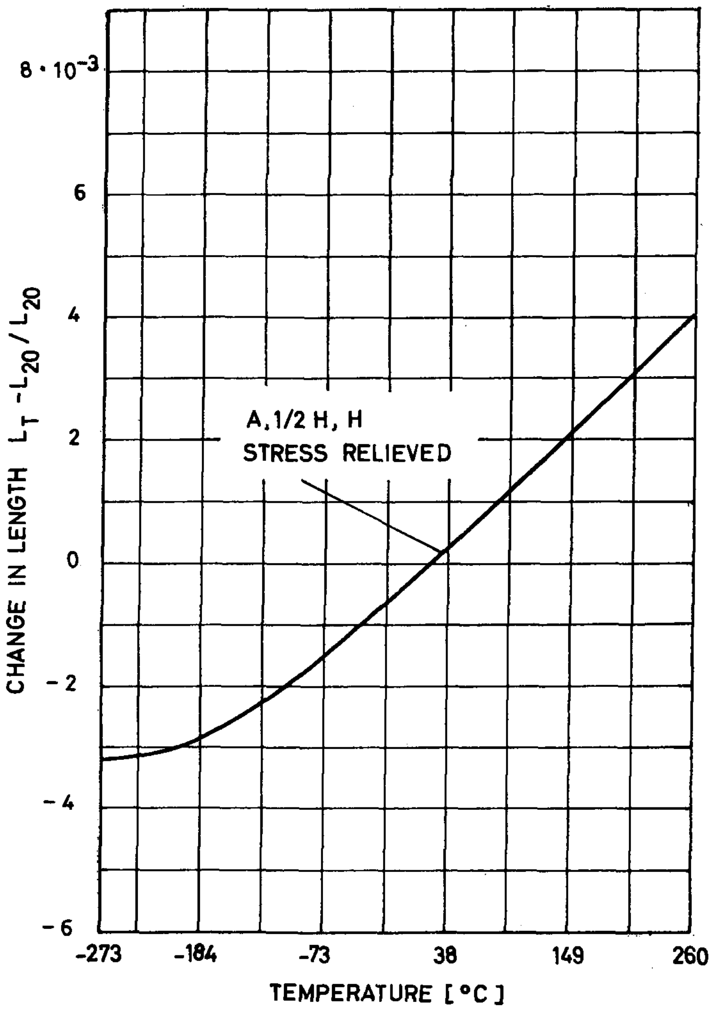

Fig. 10 Thermal expansion (change in length) at low and elevated temperatures of CuBe 2

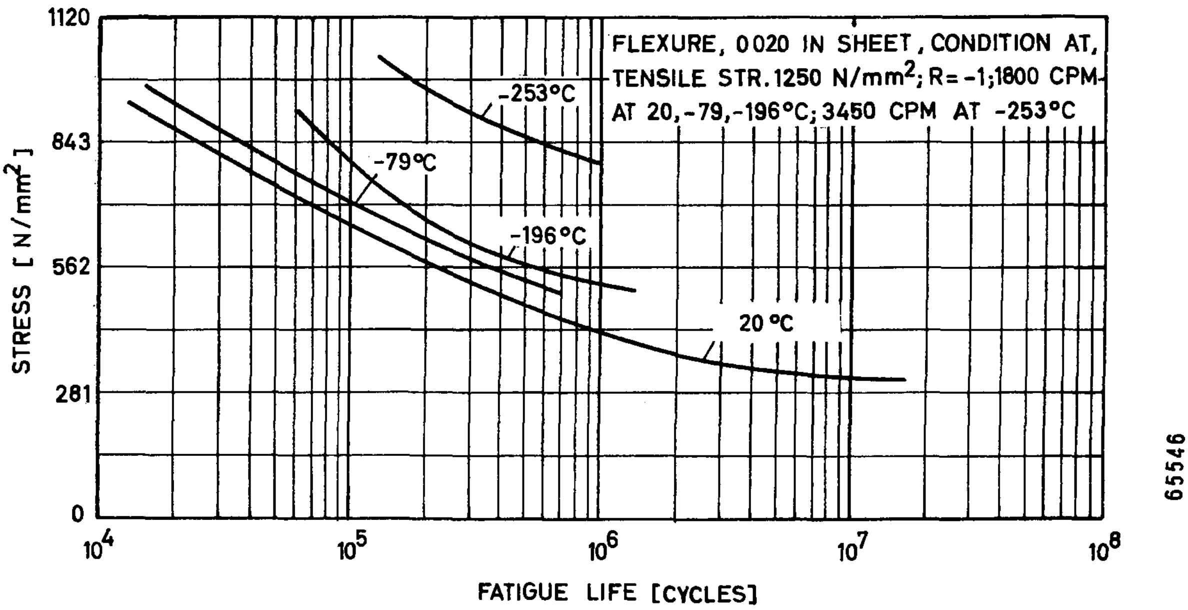

Fig. 11 Fatigue tensile strength σ_D $[N/mm^2]$ at low temperatures of CuBe 2 in solution-treated and age-hardened conditions

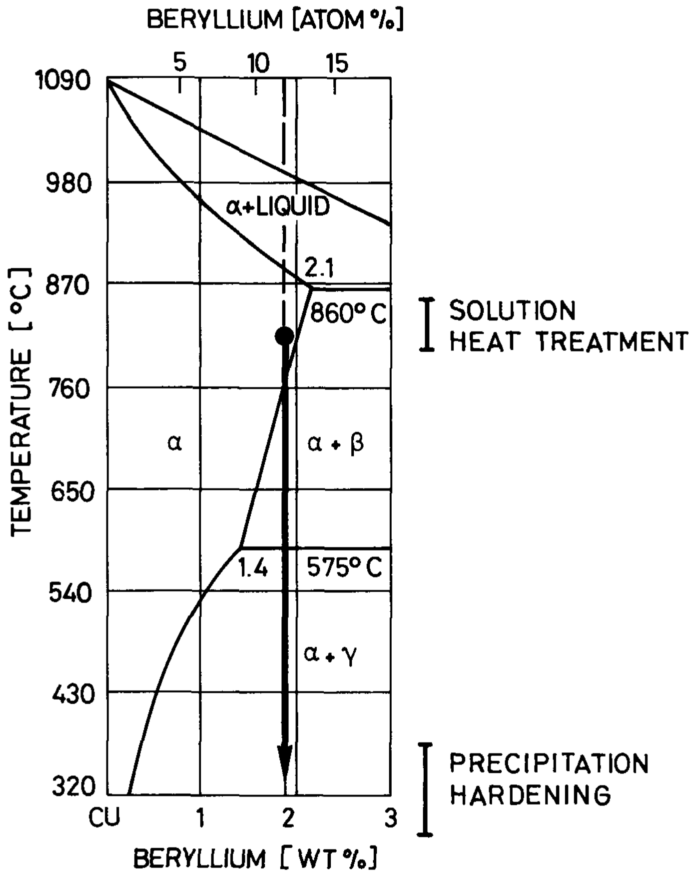

Fig. 12 Annealing of a CuBe alloy with 1.9% Be content

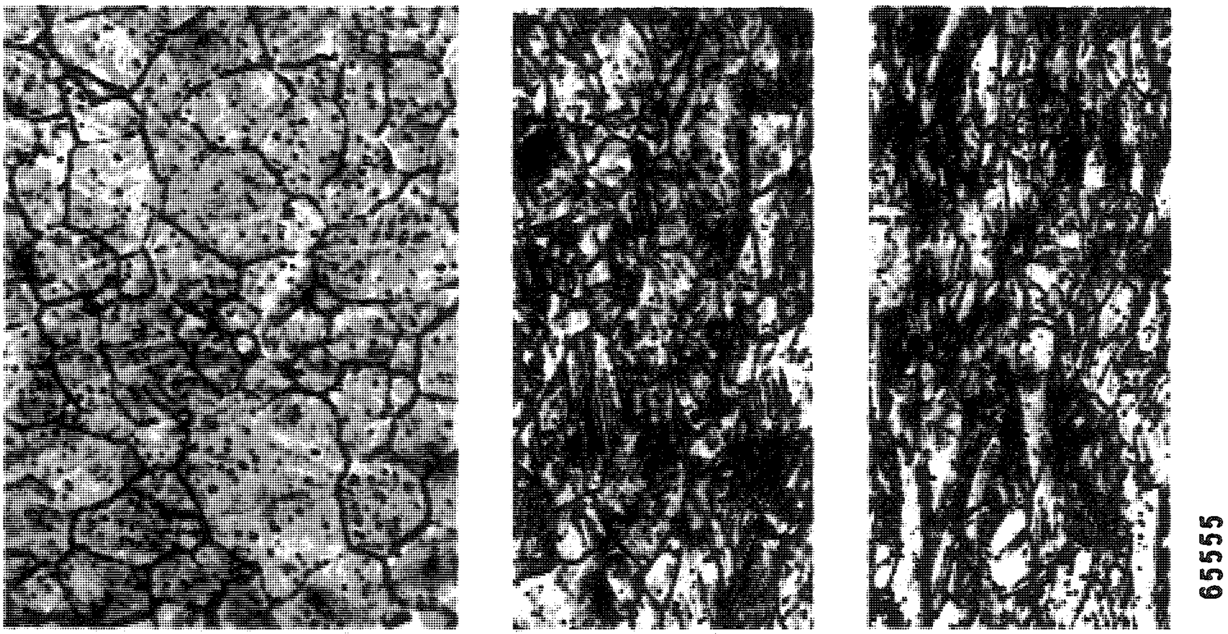

Fig. 13 Microstructure of correctly precipitation-hardened CuBe 2 alloy (with Co-additions). 300 ×.

a) Solution-treated before hardening: α-grains with precipitations of β-phase rings and CoBe-dots and, at the boundaries, defined γ-phase.

b) Half-hard before hardening: deformation structure with same precipitations and twins.

c) Hard before hardening: flattening of grain with precipitations by deformation.

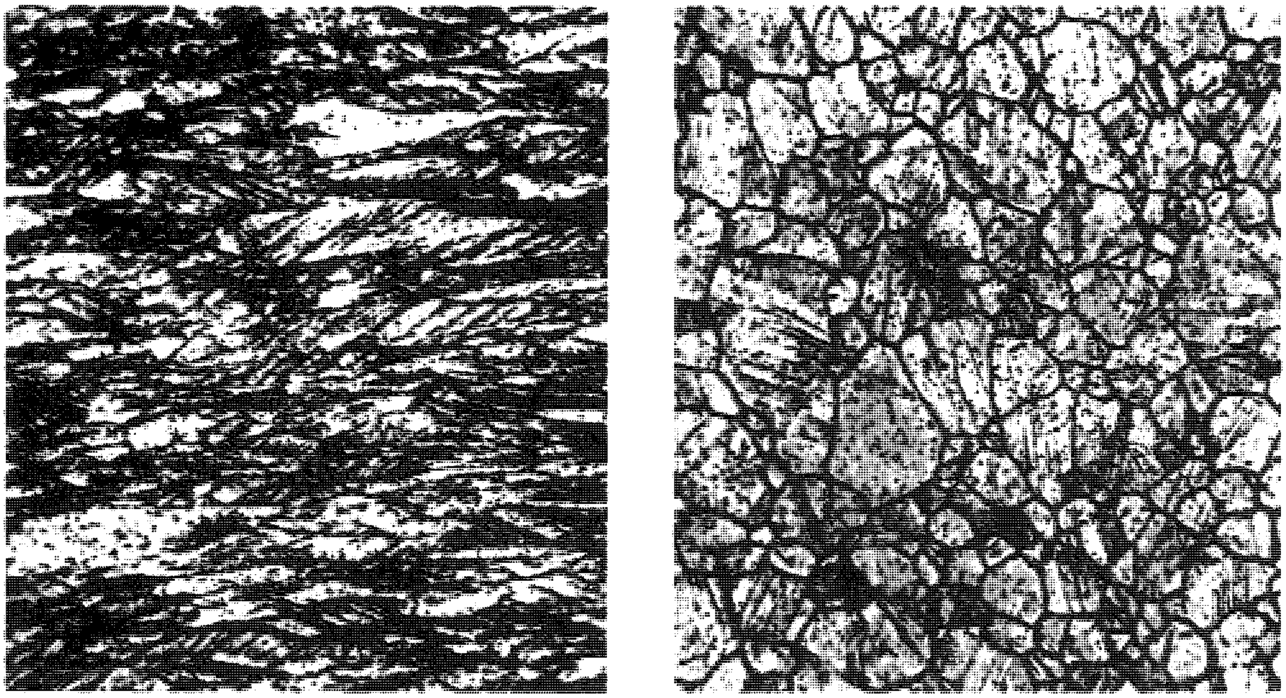

Fig. 14 Effect of deformation and of solution heat treatment on grain structure of CuBe 2. 300 ×.

a) Cold worked: deformation structure.

b) After cold-working, solution treatment at 780°C and water quenching: α-grains with CoBe precipitations.

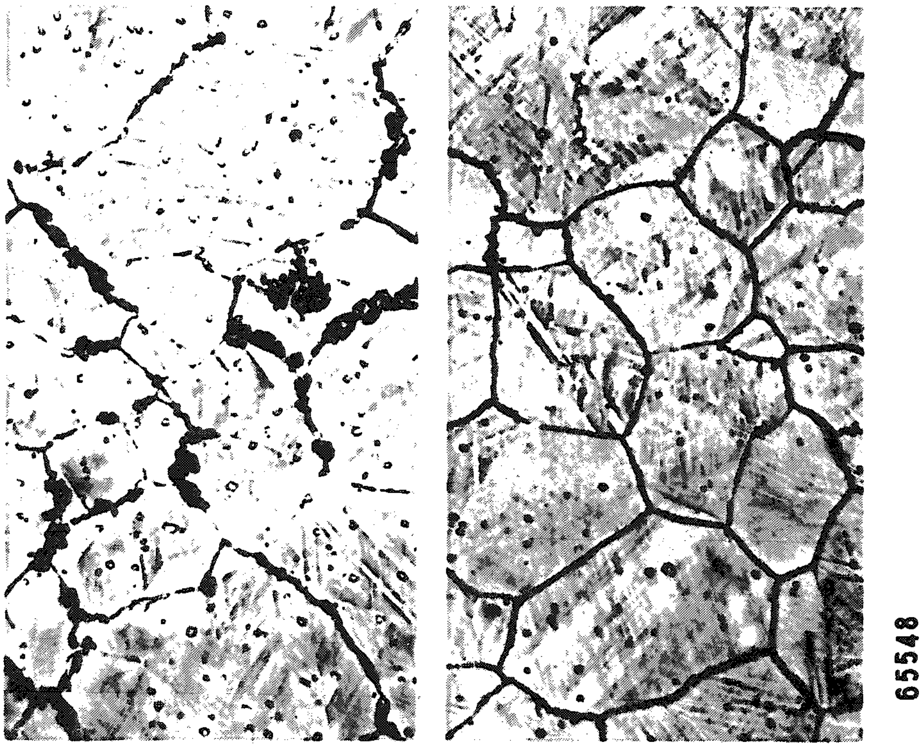

Fig. 15 Microstructure of CuBe 2 alloy, solution heat-treated 15 min at 800°C and precipitation-hardened 3 h at 315°C. 1000 ×.

a) After solution annealing, delayed quenching to 650°C, then water quenching and hardening: α-grains with β- and CoBe-precipitations, γ-precipitations at grain boundaries.

b) After solution annealing, water quenching and hardening: β- and CoBe-precipitations in α-grains and γ-precipitations at grain boundaries.

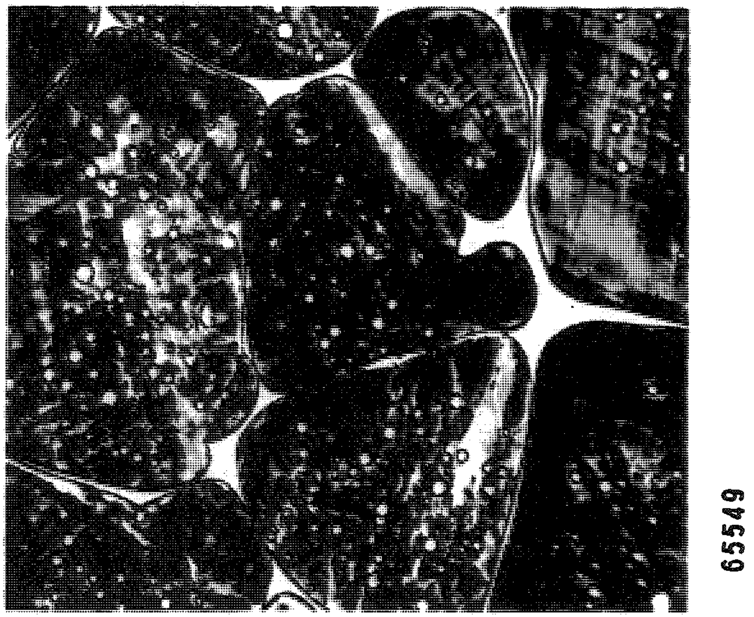

Fig. 16 Microstructure of CuBe 2 alloy, solution heat-treated at 870°C, quenched, and precipitation-hardened 3 h at 315°C. 1000 ×.

"Burned" structure precipitate primary β-phase out of α-phase.

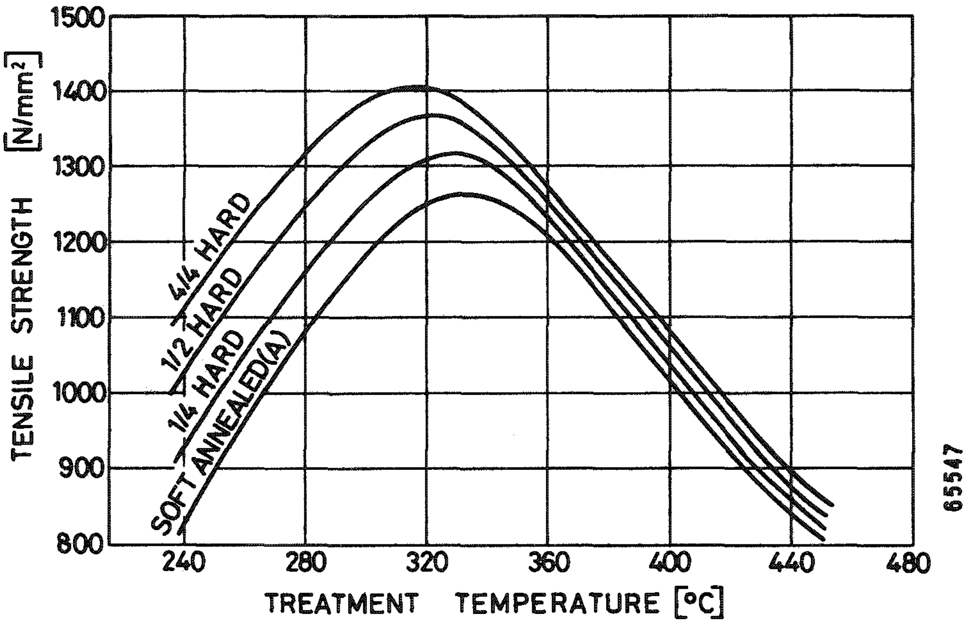

Fig. 17 Influence of temperature on the ultimate tensile strength σ_B [N/mm²] for CuBe 2 after 3 h precipitation treatment according to delivery condition

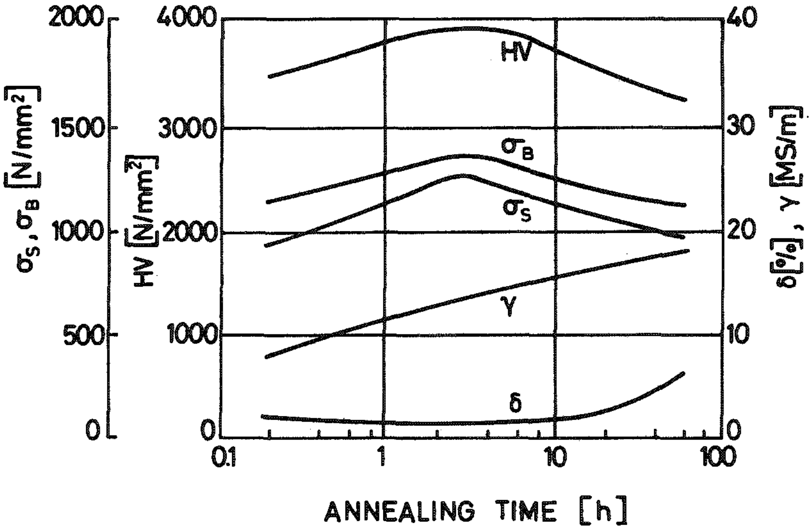

Fig. 18 Alteration of tensile strength σ_B [N/mm²], yield strength σ_S [N/mm²], hardness HV [N/mm²], elongation δ [%], and conductivity γ [MS/m] of CuBe 2 by annealing time at about 315°C

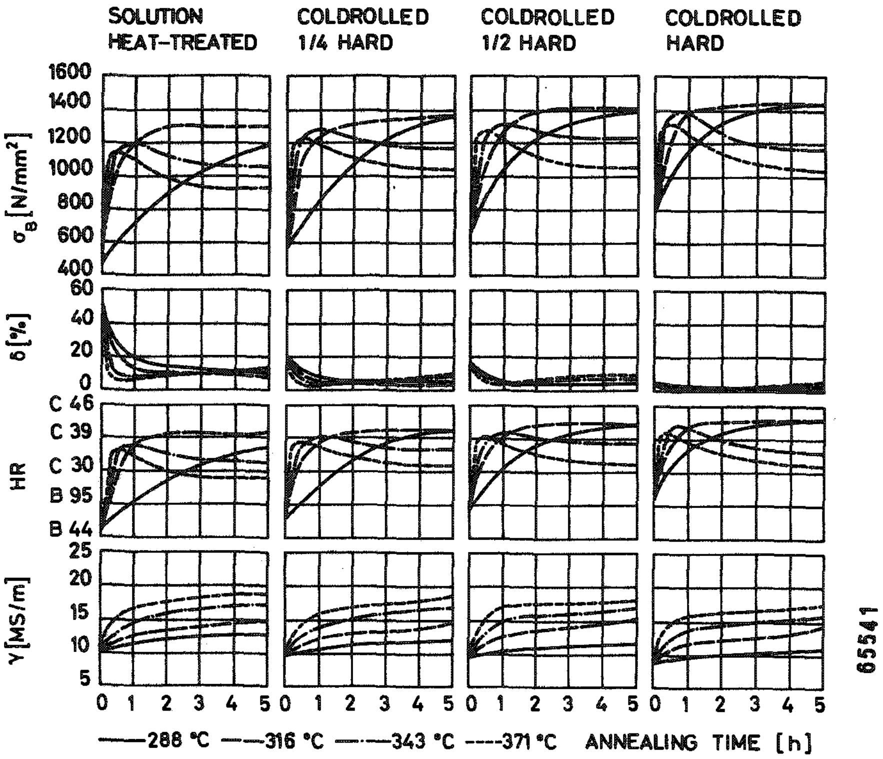

Fig. 19 Influence of cold-rolling and precipitation heat treatment on tensile strength σ_B [N/mm²], elongation δ [%], Rockwell hardness HRB and HRC, and electrical conductivity γ [MS/m] of CuBe 2

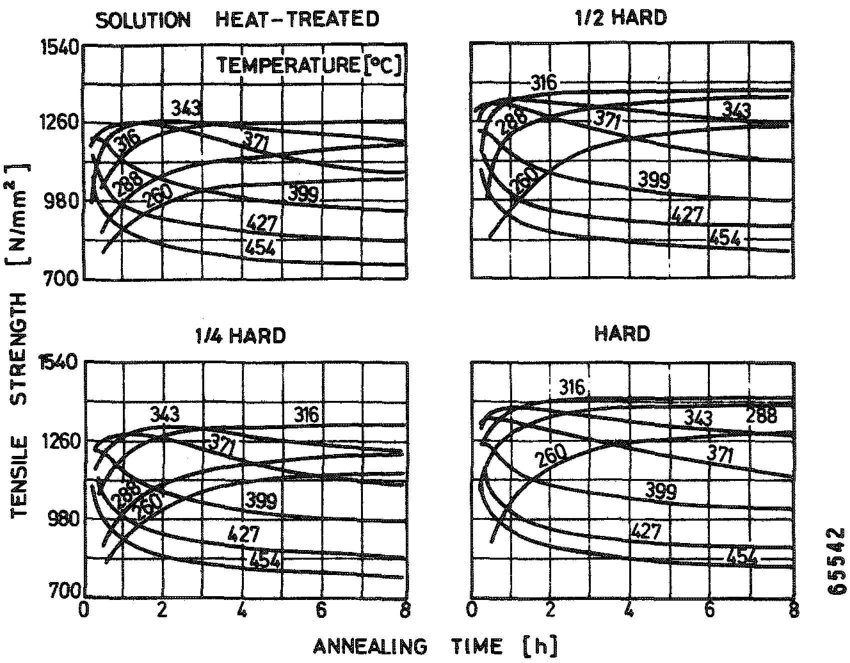

Fig. 20 Influence of heat treatment on the tensile strength σ_B [N/mm²] of the alloy CuBe 2 in condition solution heat-treated, 1/4 hard, 1/2 hard, and hard

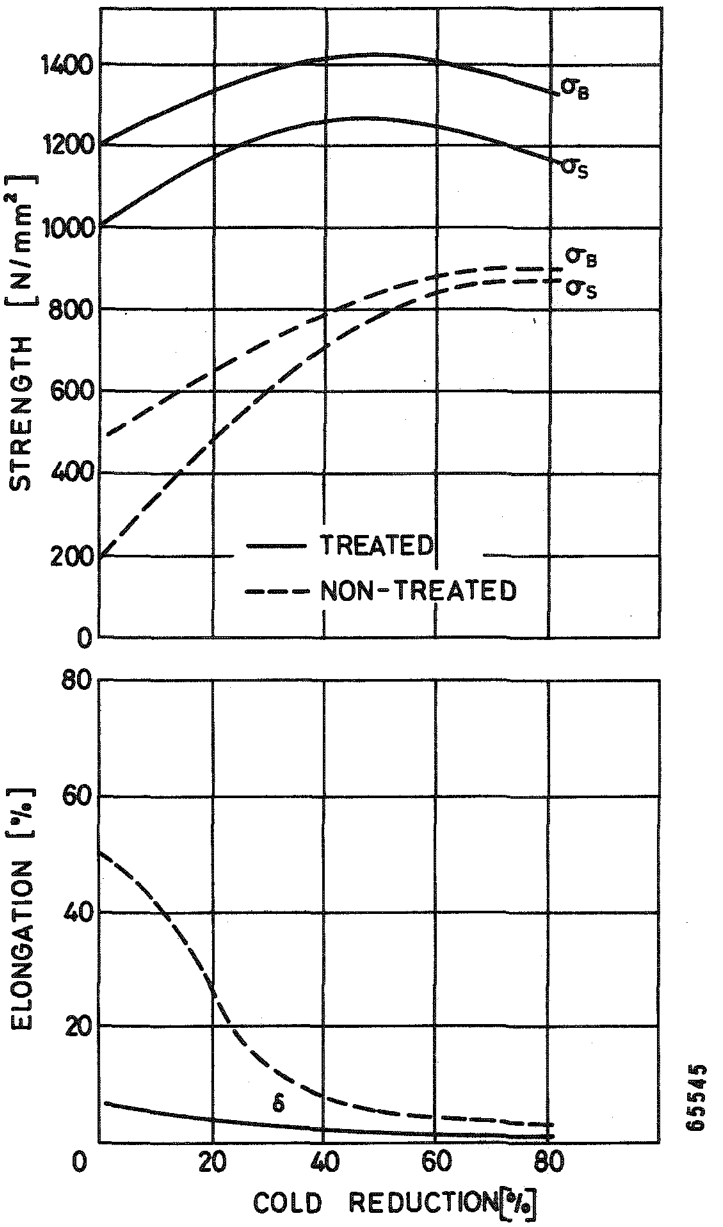

Fig. 21 Influence of cold reduction and additional heat treatment on tensile strength σ_B [N/mm²], yield strength σ_S [N/mm²], and elongation δ [%] of CuBe 2

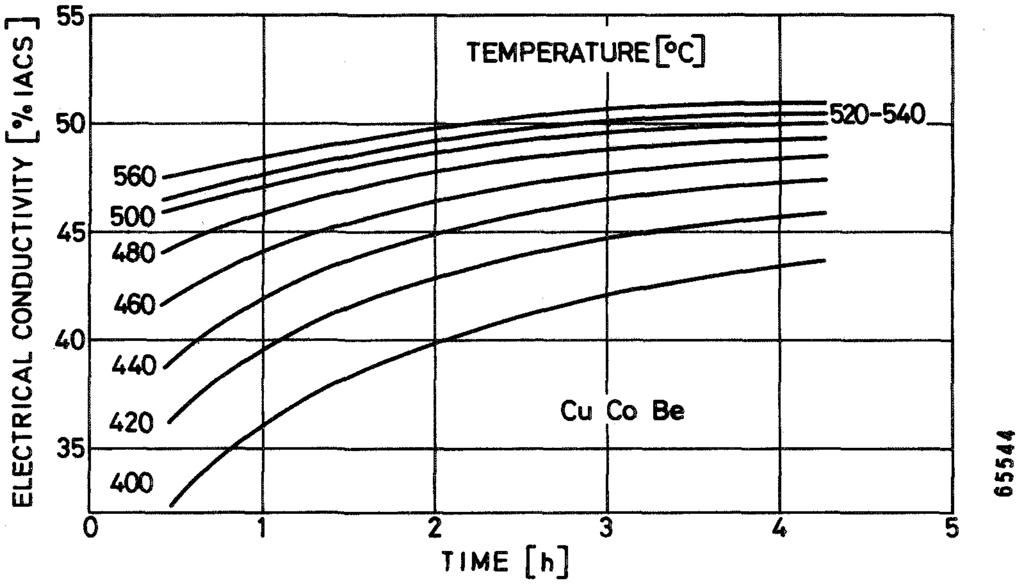

Fig. 22 Effect of precipitation treatment temperature and time on electrical conductivity γ [% IACS] for CuCoBe in 1/4 H, 1/2 H, and H condition. [100% IACS = 58 MS/m.]

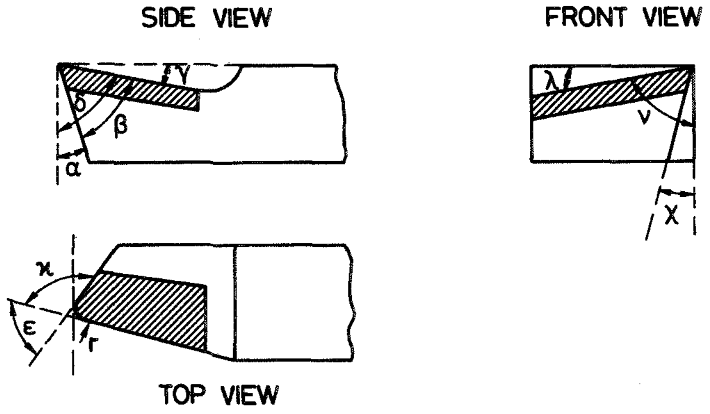

Fig. 23 Angles of cutting tools

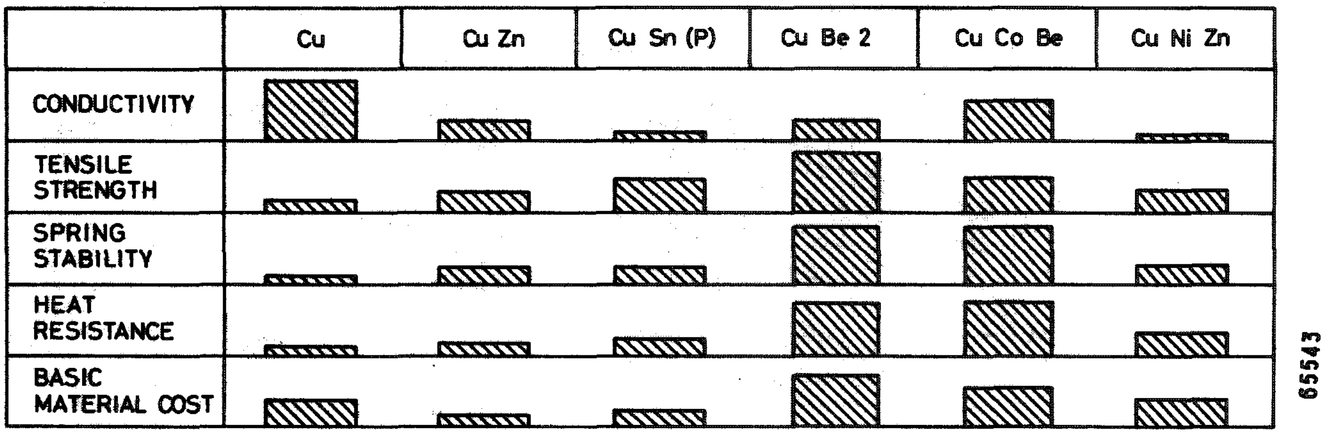

Fig. 24 Comparison between typical Cu alloys

ANNEX

ADDITIONAL SOURCES OF INFORMATION

Switzerland : Glucydur AG,
Gibelinstrasse 13,

CH-4500 Solothurn.

Conseil international pour le développement du cuivre,
100, rue du Rhône,

CH-1204 Genève.

Association métallurgique SA,
Kollerweg 32,

CH-3000 Bern 6.

France : Centre d'information du cuivre, laitons, alliages,
67, boulevard Berthier,

F-75017 Paris.

Tréfimétaux-Berylco SA,
76-78, avenue des Champs-Elysées,

F-75008 Paris.

Stainless SA,
7, rue de Rouvray,

F-92200 Neuilly-sur-Seine.

Germany : Deutsche Beryllium GmbH,
Tabaksmühlenweg 28-30,

D-6370 Oberursel.

Deutsches Kupfer-Institut,
Knesebeckstrasse 96,

D-1 Berlin 12

Kabel- und Metallwerke Gutehoffnungshütte AG,
Vahrenwalderstrasse 271,

D-3 Hannover

Great Britain : Copper Development Association,
55, South Audley Street,

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United States of America : Kawecki Berylco Industries Inc.,
PO Box 1462,

Reading, PA 19603,
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Brush Beryllium Company,
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Cleveland, OH 44110,
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