Beryllium Copper

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Copper Development Association

Copper Development Association is a non-trading organisation sponsored by the copper producers and fabricators to encourage the use of copper and copper alloys and to promote their correct and efficient application. Its services, which include the provision of technical advice and information, are available to those interested in the utilisation of copper in all its aspects. The Association also provides a link between research and user industries and maintains close contact with other copper development associations throughout the world.

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Foreword

The unique combination of strength, hardness and resistance to corrosion offered by beryllium copper has given it an important place in modern industry. Enquiries continually reach the Copper Development Association for a summary of reliable information on the alloy, and this booklet has been prepared in response to the demand.

It is addressed to the user and potential user of beryllium copper rather than to the student of metallurgy, and for this reason attention is focussed more upon the properties and practical manipulation of the material than upon underlying scientific principles. Nevertheless, the nature of precipitation hardening, to which beryllium copper owes its high strength and hardness, is described in sufficient detail to provide the general reader with a basis for the intelligent interpretation of practical problems with which he may be confronted.

Normal Beryllium Copper - *(Note added, January 1962)*

Extensive investigations have now established that more consistent properties can be obtained in normal beryllium copper by reducing the beryllium content range from 1.8 to 2.0 per cent to 1.7 to 1.9 per cent without significantly affecting the mechanical properties attainable. The present publication refers to the former range but the lower beryllium content has now been generally adopted commercially. This slight adjustment of composition, however, does not materially affect the ageing process.

For the alloy containing 1.7 to 1.9 per cent beryllium, it is recommended by the principal British manufacturers that precipitation hardening for a period of two hours at a temperature within the range 315°C. to 350°C. will give properties acceptable for all commercial purposes. To develop the optimum properties, the lower end of this range should be used for heavily work-hardened material, whilst for softer grades the higher temperatures should be employed. The most suitable heat treatment can be determined from a few trial experiments, but since most beryllium copper components are in a partially work-hardened condition, the lower part of this temperature range is usually preferred.

A further recommendation made by the manufacturers is that users requiring a standard heat treatment for all their material are advised to employ two hours at 335° ±5°C. Use of this temperature ensures that the resulting properties of the alloy fulfil the minimum requirements of British Standurds and that the properties are in many cases the optimum obtainable.

Up to the present time there has been no British Standard Specification covering beryllium copper, but new British Standard Schedules for Copper and Copper Alloy Sheet, Strip and Foil (B.S. 2870) and for Copper and Copper Alloy Wire (B.S. 2873), include the new composition referred to above.

1 – Introduction

The technological importance of beryllium copper rests mainly on the fact that it can be softened or hardened at will by a pair of simple heat treatment processes.

In the fully heat treated condition beryllium copper is the hardest and strongest of the known copper-rich alloys. Indeed, few if any other non-ferrous materials equal it in these respects, and it is similar to many high-grade alloy steels. Compared with steels, however, it has several distinct advantages, among which may particularly be mentioned its greater resistance to corrosion, its considerably higher electrical and thermal conductivities, its non-sparking qualities which make it suitable for tools under conditions where there is risk of explosion, and its lower modulus of elasticity which, for instrument springs, permits greater deflections for similar loads. A further important advantage of beryllium copper over steel for springs is that it can be formed from strip or wire in the soft condition and afterwards hardened by heat treatment at a conveniently low temperature. Unlike spring steel, beryllium copper is non-magnetic and can, therefore, be used in instruments for which steel would be inadmissible on this account.

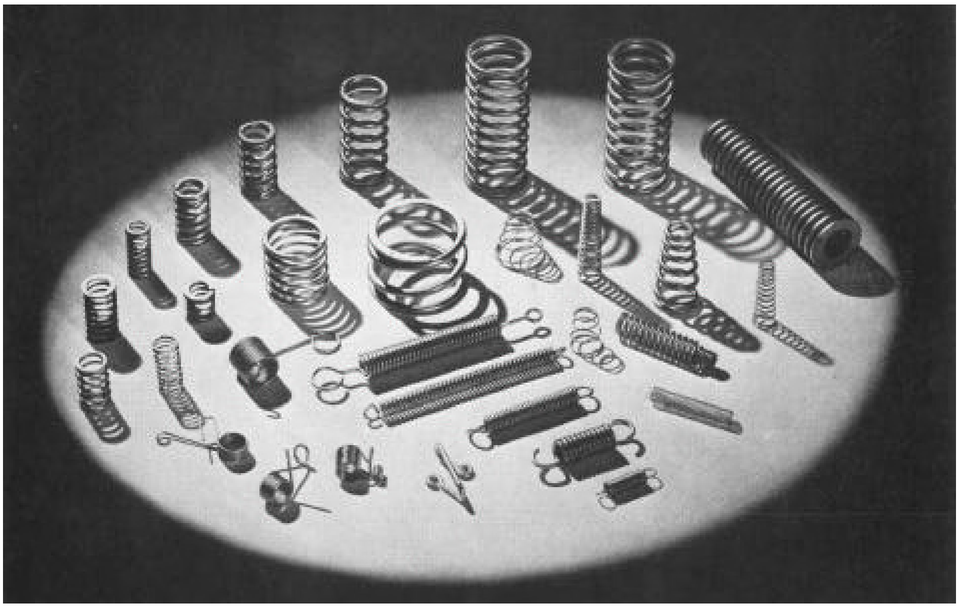
Beryllium is neither abundant in nature nor easily extracted from its ores. Although beryllium copper rarely contains more than about 2% of the element, the commercial alloys are sufficiently expensive to confine their use to applications in which their unique properties can be exploited to the full. This does not mean that beryllium copper fails to compete with cheaper materials or that it is applied in exceptionally high-grade products alone. For example, cases have arisen in which beryllium copper springs have been substituted for much cheaper steel springs in inexpensive mass-produced instruments, because the ease with which they can be manufactured effects a substantial diminution of rejects and signal economy in production time.

Beryllium copper is available in the normal wrought forms of sheet, strip, wire, tube, rod, bar and forgings, and also as castings made by sand moulding or by one or other of the modern precision techniques.

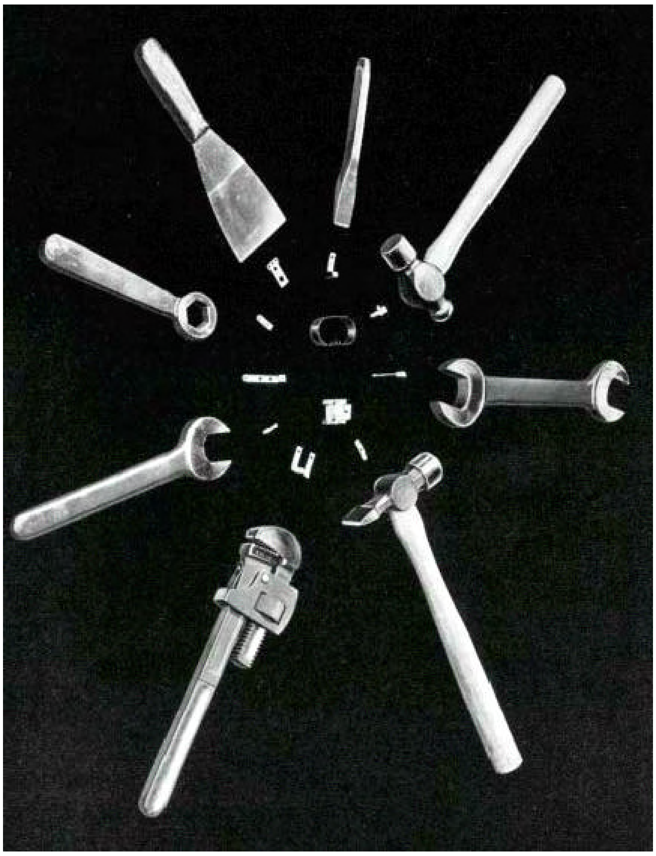
By far the greatest amount of beryllium copper is used for small springs, pressure-responsive diaphragms, flexible bellows, Bourdon tubes and components of measuring instruments for electrical, barometric and similar purposes. The high elastic limit coupled with low modulus of elasticity and good resistance to corrosion are special advantages in this direction, while fatigue resistance is high, even in relatively corrosive environments.

Beryllium copper castings and forgings are employed for purposes which call for high strength combined with good electrical and thermal conductivity, such for instance as electrodes for resistance welding appliances and dies for the moulding of plastics. Castings and forgings are also used for non-sparking tools, including cutting implements, and for highly stressed components which are subjected to fatigue, as, for example, in aircraft.

The foregoing remarks are sufficient to indicate the wide range of purposes to which beryllium copper can be put. For further information on typical uses of the alloy, attention is directed to the section on Applications, and also to certain of the accompanying illustrations.



Beryllium Copper Springs



Some applications of Beryllium Copper. These range from small springs to non-sparking safety tools

2 - The Commercial Beryllium Copper Alloys

The most important of the beryllium copper alloys contains approximately 2 per cent of beryllium, but in proprietary materials the beryllium content may range from about 1.5 per cent to as much as 2.7 per cent, depending on the properties desired and the purpose to which the material is to be put. For springs and pressure-sensitive appliances, the tendency is to control the beryllium content towards the lower end of the range mentioned, while for dies the extra hardness attained at the upper end of the range is exploited. All such materials normally contain a relatively small amount of cobalt or nickel in addition to the beryllium, mainly to improve the response to heat treatment. In spite of their appreciably different compositions, this group of alloys can conveniently be classed together as "normal beryllium copper", or simply "beryllium copper".

On the other hand, a somewhat different class of materials is typified by the alloy containing approximately 2.6 per cent of cobalt with only about 0.4 per cent of beryllium. In some cases nickel is used instead of cobalt, but the distinction remains that the beryllium content is relatively low. Though less hard and strong than the materials richer in beryllium, these alloys have appreciably higher conductivity, and better retain, during service at moderately elevated temperatures, the strength and hardness imparted by heat treatment. For present purposes, the designation "low beryllium copper" will be taken to mean alloys of this type, as distinct from those previously mentioned.

A third type of commercial alloy, carrying about 1 per cent of beryllium, represents a compromise between normal and low beryllium copper, the properties being intermediate between those of the two grades just described. As these are usually proprietary alloys, containing various unspecified additions, they have not been considered in detail in the present review.

Both normal and low beryllium copper are obtainable in the usual wrought forms, and as castings. Wrought forms, particularly strip, are marketed in four different tempers, known as solution-annealed, quarter hard, half hard and hard respectively. The solution-annealed grade is the softest and most ductile condition available, while the harder tempers are produced by cold work and not by a final heat treatment. All types can, however, be further hardened by heat treatment after forming to the desired shape.

3 - Principles of the Heat Treatment of Beryllium Copper

All commercial grades of beryllium copper are typical precipitation hardening alloys; they can be softened by quenching from a high temperature and afterwards hardened by heating to a moderate temperature. In order to use the material effectively and to control the heat treatment intelligently it is essential to understand the nature of the changes which occur.

Solid metals and alloys are crystalline bodies, the atoms within each crystal being arranged in space on a definite pattern or lattice, the form of which depends on the composition of the material and its temperature. Each different lattice represents a separate physical entity or 'phase' characterised by properties which are peculiar to it alone. In Figure 1, which shows part of the equilibrium diagram of the beryllium-copper system[1], no less than four such solid phases appear, marked respectively a, ß, ? and d. The diagram indicates their distribution in respect of the two variables, composition and temperature, after sufficient time has been allowed at any particular temperature for the attainment of equilibrium. In the upper part of the diagram a fifth phase, namely liquid, makes its appearance, and it will be seen that the temperatures at which the material starts to melt and becomes completely molten vary considerably with composition.

In the attainment of equilibrium, time is an important factor. The higher the temperature, the more rapidly is equilibrium achieved. Thus if an alloy is maintained at a particular temperature until equilibrium is reached and is then cooled with sufficient rapidity, as by quenching, it is generally possible to suppress the changes which would occur at lower temperatures during slow cooling, as so to retain the structure and properties appropriate to the quenching temperature.

Applying these principles to beryllium copper, it is evident from Figure 1 that, if an alloy containing less than 2.7 per cent of beryllium is brought into equilibrium at, and quenched from, any temperature to the left of the boundary ABLOP, it will consist of the a phase alone. The crystal lattice is then similar to that of copper itself, and the material will consequently remain, Iike copper, relatively soft and ductile. The temperature range within which this result can be achieved depends on the beryllium content; for the usual 2 per cent beryllium alloy it is comparatively narrow, Iying between about 780°C on the boundary BL and about 890°C on AB, where incipient melting takes place. The practical solution heat treatment temperature for normal beryllium copper is kept well within this range, and is usually about 800°C.

It is apparent from the diagram that the alloy so quenched is unstable at lower temperatures, and would revert to the a + ? structure should favourable conditions arise. At room temperature the reaction, if it occurs at all, is so sluggish that the quenched condition can be retained almost indefinitely, but it becomes increasingly rapid as the temperature is raised. Moreover, increase of temperature favours diffusion, and consequent agglomeration of the precipitated ? into particles of larger size. After moderate times at the normal hardening temperature of from 300°C to 350°C, the particles of precipitated ? are exceedingly minute and are well distributed throughout the a matrix. The regularity of the a crystal lattice is consequently disturbed, and it becomes difficult to push layers of atoms over one another by externally applied forces. The result is a great increase in the mechanical strength and hardness of the alloy. At somewhat higher temperatures and longer times, however, the sub-microscopic particles of ? can coalesce to form larger entities, leaving the a crystals in much the same condition as before precipitation occurred. Thus the strength and hardness tend to fall, and the material is said to be 'over-aged'.

[1] G V Raynor, Annotated Equilibrium Diagram No 7, Institute of Metals, 1949

As will be seen later, a controlled degree of over-ageing is often exploited in practice, in order to obtain special combinations of properties.

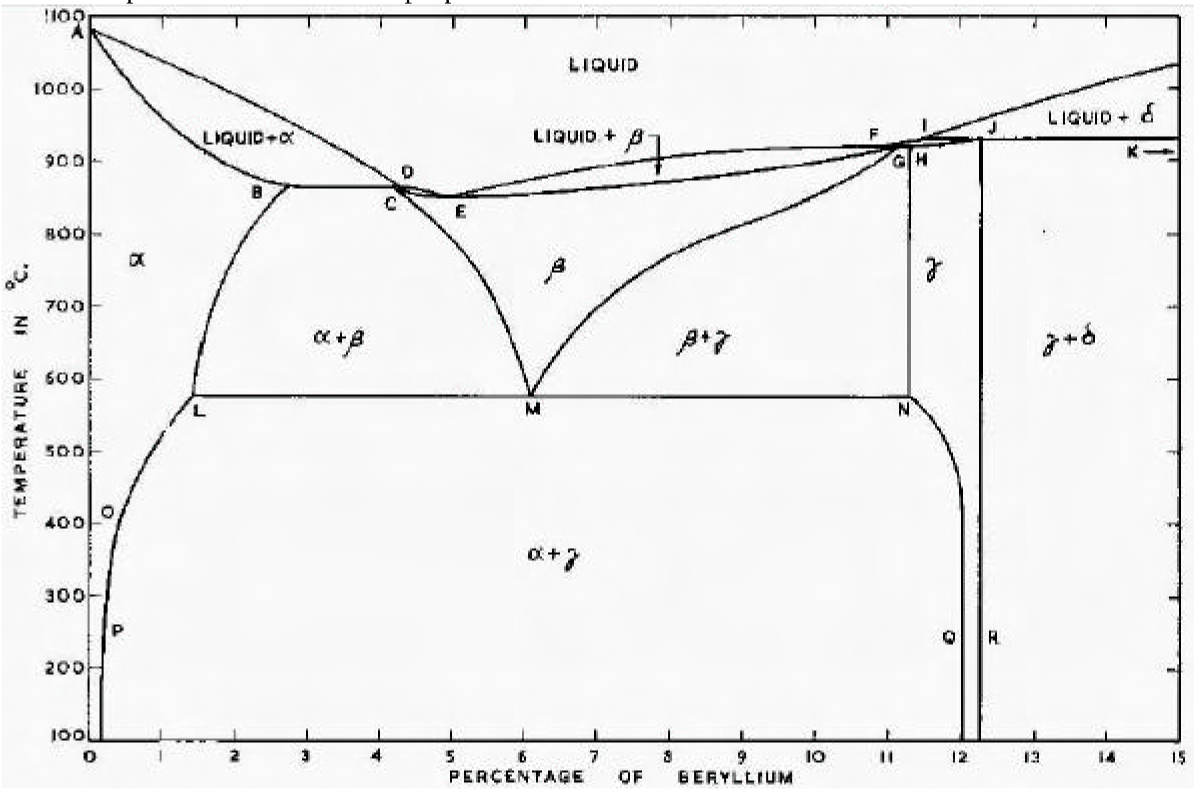


Figure 1 - Equilibrium diagram of the copper-beryllium system (copper-rich alloys)

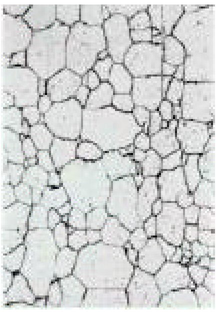
Point	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
°C	1083	864	864	864	850	920	920	920	933
Be, %	0	2.7	4.2	4.3	5.0	11.0	11.15	11.3	11.5
Point	**J**	**K**	**L**	**M**	**N**	**O**	**P**	**Q**	**R**
°C	933	933	575	575	575	400	250	250	250
Be, %	12.3	19.4	1.4	6.1	11.3	0.4	0.2	12.05	12.3

G V Raynor, Institute of Metals (Annotated Equilibrium Diagram Series, No 7), 1949

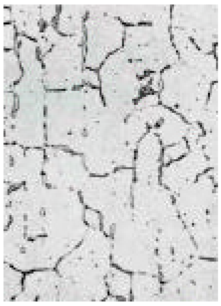
In order to obtain the greatest degree of hardening, it is important that both stages in the heat treatment should be correctly controlled. If the solution temperature is not above the boundary BL in Figure 1, or if the quenching is insufficiently rapid, some of the beryllium may be ejected prematurely as ß, and less will be available to harden the alloy during subsequent precipitation. On the other hand, if the solution temperature is too close to the solidus AB in the diagram, objectionable grain growth, or even incipient melting may take place. These boundaries, particularly BL, are quite steep, and small variations of beryllium content, as well as the presence of added elements like cobalt and nickel, make a considerable difference to the optimum solution temperature. In the second stage of heat treatment, the times and temperatures which give maximum hardness and strength do not as a rule lead to maximum conductivity and freedom from elastic drift, and a compromise is often required in controlling the process. These points are dealt with more fully later.

It must be emphasized that commercial alloys usually contain other elements, either as intentional additions or as impurities, and that the analytical figure for beryllium may not accurately represent the effective beryllium content, because the element is easily oxidised and, unless due care is exercised in the melting and casting processes, some may be present as entrapped oxide which plays no part in the heat treatment. For such reasons, the equilibrium diagram should be regarded as no more than a useful guide to the probable behaviour of the material, and as an indication of the nature of the changes which can be brought about by heat treatment. Though a valuable yardstick, it cannot be expected to apply with quantitative precision in all cases.

It is important to distinguish between the hardening effect of precipitation heat treatment and that brought about by cold work. Material supplied in the commercial tempers called quarter hard, half hard and hard has merely been cold-worked to progressively greater degrees after solution heat treatment, and will respond to subsequent precipitation hardening. The effect of precipitation hardening can, in fact, be superimposed upon that of cold work to give exceptionally high strength.



A. Solution heat-treated



B. Precipitation hardened

Microstructure of beryllium copper (x250)

4 - The Properties of Normal Beryllium Copper

So many factors influence the physical and mechanical properties of beryllium copper that the information included in this section should be regarded as an indication of the probable behaviour of the material, rather than as a factual pronouncement. Proprietary alloys differ somewhat in composition from one another, and response to the final heat treatment depends to a considerable extent on the hot and cold working schedules, and on the exact conditions of the preliminary solution heat treatment. Such factors are generally outside the control of the ordinary user, who is concerned mainly with forming processes and precipitation hardening. Optimum conditions for the production of any particular component can best be found by practical trial, guided by the information about to be given and by the principles outlined in Section III. The makers will generally afford helpful advice.

Physical Properties

The chief physical properties of normal beryllium copper of average commercial composition are given in Table I. Except in the case of conductivity, they are not subject to appreciable variation with the conditions of heat treatment. Precipitation hardening is accompanied by a marked increase in the electrical and thermal conductivities as indicated in the table. The conductivity of heat-treated beryllium copper is greater than that of any other material of comparable mechanical properties. It is important to note that the precipitation heat treatment which results in the maximum hardness does not correspond with that which gives maximum conductivity, for which purpose a moderate degree of over-ageing to agglomerate the precipitate is desirable. This matter will be discussed in more detail when dealing with the effects of heat treatment on the mechanical properties.

The elastic moduli are only about two-thirds of those for spring steel of otherwise similar properties. For the manufacture of instrument springs this is an important advantage, since, for springs of similar design, a smaller load will produce a greater deflection, with a consequent improvement in the sensitivity of the instrument. The temperature coefficients for the elastic moduli have small negative values, which means that beryllium copper springs become very slightly stiffer as the temperature is reduced.

Table 1 - Physical properties of normal beryllium copper

Density	8·25 gm./c.c. 0·298 lb./cu. in.
Coefficient of thermal expansion	17×10^{-6} per °C. $9 \cdot 5 \times 10^{-6}$ per °F.
Electrical conductivity	
Solution heat-treated	16 to 18 per cent. I.A.C.S.
Heat-treated to maximum hardness ..	20 to 25 per cent. I.A.C.S.
Heat-treated to maximum conductivity	32 to 38 per cent. I.A.C.S.
Electrical resistivity at 20°C.	
Solution heat-treated	9·6 to 10·8 microhm cm.
Heat-treated to maximum hardness ..	6·9 to 8·6 microhm cm.
Heat-treated to maximum conductivity	4·6 to 5·4 microhm cm.
Temperature Coefficient of electrical resistance, from 0° to 100°C.	
Heat-treated to maximum conductivity	0·0013 per °C.
Thermal conductivity	
Solution heat-treated	0·20 cal./$cm.^2$/cm./sec./°C.
Precipitation hardened	0·25 cal./$cm.^2$/cm./sec./°C.
Specific heat	0·1
Modulus of elasticity	
Tension (Young's modulus)	18 to 19×10^6 lb./sq. in.
Torsion (Bulk or shear modulus) ..	6·5 to 7×10^6 lb./sq. in.
Temperature coefficient of elastic modulus	
Tension, from −50° to 50°C. ..	−0·00035 per °C.
Torsion, from −50° to 50°C. ..	−0·00033 per °C.

Mechanical Properties

Over a long period of years Gohn and Arnold[2] examined the mechanical properties of numerous samples of beryllium copper strip containing from 1.85 per cent. to 2.25 per cent. beryllium with and without minor additions of cobalt, nickel and iron. Their results provide a comprehensive view of the properties which may be expected for the normal run of commercial materials, though figures for individual alloys may differ considerably. Table II records, firstly, the average values obtained by Gohn and Arnold for the tensile, hardness and fatigue properties of 26 samples under six different combinations of heat treatment and cold work, and, secondly, the standard deviations from these averages, calculated according to ordinary statistical methods. The figures for standard deviation indicate the variations from the mean values which may be expected in normal circumstances, and the table can be regarded as a useful synopsis of fairly extensive data.

[2] *Proc Amer Soc Tes. Mat*, 1946, vol 46, p741

Table 2 – Summary of Mechanical tests by Gohn and Arnold on beryllium copper strip

Condition	**Tensile Strength tons/sq in**	**Limit of Propor-tionality Tons/sq in**	**Proof Stress for 0.01% extension † tons/sq in**	**Young's Modulus lb/sq.in. x 10^6**	**Elongation on 2 in per cent**	**Diamond Pyramid Hardness**	**Fatigue Strength for 10^8 cycles tons/sq in**
Fully Softened (Solution heat-treated)							
Mean Value	31.9	8.0	10.9	17.0	48.1	110	14.5
Standard Deviation	1.6	3.4	1.6	0.9	7.2	10	0.4
Softened and Precipitation hardened							
Mean Value	72.8	27.7	33.9	18.7	6.7	328	15.4
Standard Deviation	8.2	5.2	5.6	1.0	1.9	13	3.0
Softened and rolled to "half hard" condition							
Mean Value	41.4	20.0	26.8	17.7	14.8	172	14.8
Standard Deviation	4.8	5.4	3.6	1.2	5.2	14	2.6
Rolled to "half hard" and precipitation hardened							
Mean Value	89.5	34.5	43.8	19.3	5.5	387	16.6
Standard Deviation	6.1	7.3	7.0	0.6	3.0	44	2.5
Softened and rolled to "hard" condition							
Mean Value	48.5	25.0	31.0	17.2	3.6	214	15.5
Standard Deviation	1.5	3.3	2.0	0.6	1.7	5	2.1
Rolled "hard" and precipitation hardened							
Mean Value	81.7	31.5	41.0	19.6	4.6	376	18.4
Standard Deviation	8.1	4.7	6.0	0.4	2.4	38	2.5

† using an extensometer reading to 0.00002 in on a 2-in gauge length

Manufacturers of proprietary alloys not infrequently claim properties which differ appreciably from the figures given in Table 2. This is particularly true of the limit of proportionality, proof stress and fatigue strength, for which higher values are sometimes quoted. Representative data compiled from trade literature are outlined in Table 3. It should be noted that the proof stress figures given in Table 2 are for 0.01 per cent extension, whereas those in Table 3 are for 0.1 per cent extension.

In the fully heat-treated condition, tensile strengths of between 70 and 90 tons/sq. in. can be expected, depending on the degree of cold work applied before the heat treatment. This strength is associated with elastic limits up to nearly 50 tons/sq. in., and with diamond pyramid hardness values upwards of 350. As might be expected, the corresponding tensile elongation figures are comparatively low, being of the order of 2 per cent on 2 inches. The form in which the material is supplied has relatively little influence on the mechanical properties, though wire tends to be somewhat stronger than strip or rod, because of the greater degree of cold work which is normally imposed upon it before the final heat treatment. On the other hand, the beryllium content is an important factor; if the beryllium content is appreciably below 2 per cent., the strength and hardness values will approach the lower limits given in Table 3, while for beryllium contents exceeding 2 per cent. the higher figures are likely to be attained. The properties are, moreover, influenced by the actual degree of cold work applied, for the terms "quarter hard", "half hard" and "hard" are by no means rigidly defined, and individual manufacturers may well put different interpretations upon them. When applied to beryllium copper, "quarter hard" generally means about 10 per cent cold reduction in sectional area, "half hard" about 20 per cent, and "hard" about 35 per cent reduction.

Table 3 –Representative mechanical properties of normal beryllium copper compiled from manufacturers' literature

Condition	Tensile Strength tons/sq.in.	Elastic Limit or Limit of Propor-tionality tons/sq.in.	Yield Point or Proof Stress for 0.1 % Extension tons/sq.in.	Percentage Elongation	Diamond Pyramid Hardness
Solution heat treated	30 - 35	6 - 9	12 - 16	40 - 60	90 - 130
Solution heat treated and precipitation hardened	73 - 85	44 - 56	62 - 76	2 - 10	345 - 400
Cold worked, ¼ hard	33 - 40	18 - 27	27 - 36	20 - 35	130 - 180
Cold worked, ¼ hard and precipitation hardened	78 - 89	49 - 61	67 - 81	2 - 6	360 - 420
Cold worked, ½ hard	38 - 50	24 - 31	33 - 40	10 - 20	180 - 220
Cold worked, ½ hard and precipitation hardened	89 - 95	63 - 65	71 - 87	2 - 5	380 - 440
Cold worked, hard	45 - 55	31 - 38	42 - 50	2 - 10	220 - 240
Cold worked, hard and precipitation hardened	85 - 100	55 - 69	73 - 95	1 - 3	390 - 460
Casting, fully heat treated	67 - 77	47 - 56	51 - 69	1 - 3	360 - 430

Under alternating stress, the endurance limit of fully heat-treated beryllium copper is about ±19 tons/sq. in. for 108 cycles, and this figure is but little impaired by moderately corrosive environments. For example, when tested in a salt spray solution, beryllium copper retains over 90 per cent of its endurance limit in the ordinary atmosphere. The good resistance of beryllium copper to corrosion fatigue commends it for service under conditions which would prohibit the use of most other materials of comparable mechanical properties.

Table 2 indicates that the fatigue strength is not greatly affected by heat treatment. From the point of view of resistance to cyclic stresses, there would appear to be some advantage in avoiding the very hard conditions in which the material is likely to be more sensitive to notches or to minor surface imperfections and more prone to retain locked-up stresses which are normally detrimental to fatigue life.

In spite of its hardness and comparatively low ductility, heat-treated beryllium copper is not dangerously brittle under impact loading. The Izod value normally lies between about 4 and 12 ft. lb.

The Erichsen cupping test value for beryllium copper prior to the final heat treatment varies with the degree of cold work and also with the thickness of the material. Some typical figures are given in Table 4. Cupping tests, which purport to reflect the deep-drawing properties of the material, are not applied to beryllium copper in the precipitation hardened condition.

Table 4 – Typical Erichsen cupping test results for normal beryllium copper prior to precipitation hardening

Thickness of Strip in.	**Solution-Annealed**	**Depth of Cup in mm.**		
		¼ Hard	**½ Hard**	**Hard**
0.01	9	6	5	4
0.02	10.5	7.5	6.5	5
0.03	11	8.5	7.5	6
0.04	12	9.5	8	7
0.05	12	9.5	8	7
0.06	12.5	10	8.5	7.5
0.07	12.5	10	8.5	7.5

The maximum resolved shear stress associated with the tensile strength of beryllium copper in the solution heat-treated condition, is about 25 tons/sq. in. In all harder conditions, whether achieved by cold work or by heat-treatment, the strength in shear may be taken to be approximately half the ordinary tensile strength.

Except for a few special applications, such for instance as moulds for plastics and plunger tips for die casting machines, beryllium copper is rarely required to withstand elevated temperatures, and no authentic information on the elevated temperature properties is available. At 300°C. over-ageing would take place in a period measured in hours or days at most, depending on the exact composition and degree of cold work, and the practical upper limit of temperature to which heat-treated beryllium copper could be exposed for prolonged periods without detriment to the properties would be unlikely to exceed 250°C, with 200°C as a conservative estimate. A few test results have been reported showing that exposure to 200°C for 500 hours caused a reduction in tensile strength from 93 tons/sq. in. to 85 tons/sq. in., after the material had cooled. When actually tested at this temperature, the mechanical properties would not be greatly inferior to those at normal temperature. Under conditions involving creep, however, beryllium copper, like other precipitation hardening materials, might well be prone to sudden failure with little or no extension.

In contrast, the mechanical properties of beryllium copper, in common with those of all copper alloys, are considerably improved as the temperature is reduced below normal. Table 5 gives a few typical values. It is clear that, if room temperature properties are used for design purposes, there will be an enhanced margin of safety when beryllium copper is put into service at low temperatures. In particular, there need be no fear of brittleness, for the ductility increases together with the strength properties as the temperature is reduced, meaning that there is an effective improvement in toughness. This is confirmed by the slight but distinct increase in the Charpy impact values shown in Table 5. As previously mentioned, the modulus of elasticity tends to increase as the temperature is reduced: consequently beryllium copper springs become slightly stiffer at low temperatures. This fact must be taken into consideration in the design of calibrated springs for instruments operating at low temperatures.

Table 5 **-** *Low Temperature Properties of Normal Beryllium Copper*

(Richards and Brick, *Trans. Amer. Inst. Min. Met. Eng.*, 1954, vol. 200, Pt. 5, pp. 574-580.)

Condition		**Temperature ^oC**				
		Room	**-50**	**-100**	**-150**	**-200**
Solution heat treated and precipitation hardened						
Tensile strength	tons/sq.in.	85	86	87	89	94
Proof stress, 0.2% extension	tons/sq.in.	64	71	72	74	78
Elongation	per cent on 1 in.	5	6	8	9	9
Young's Modulus	lb/sq in x10^6	17.6	17.9	18.2	18.8	19.2
Charpy impact test	ft.lb.	4	5	5	6	7
Solution heat treated, cold drawn to "half hard" condition and precipitation hardened						
Tensile strength	tons/sq.in.	87	88	90	94	99
Proof stress, 0.2% extension	tons/sq.in.	76	80	84	88	89
Elongation	per cent on 1 in.	4	5	4	5	6
Young's Moldulus	lb/sq in x106	18.11	18.5	18.5	18.4	19.0
Charpy impact test	ft.lb.	5	5	5	6	7

5 - The Properties of Low Beryllium Copper

Though considerably less hard and strong than the normal alloy, low beryllium copper is distinctly more ductile in the fully heat-treated condition, and has a higher conductivity of both electricity and heat. Moreover, its precipitation hardening temperature is about 100°C. above that of normal beryllium copper, and it follows that it can be used at higher temperatures without risk of over-ageing.

Physical Properties

Typical physical properties for low beryllium copper are given in Table 6. The chief point of interest is the relatively high electrical conductivity which reaches about 50 per cent I.A.C.S. in the appropriately heat treated condition.

Table 6 - Typical Physical Properties of Low Beryllium Copper

Density	8.8 gm./c.c. 0.318 lb./cu.in.
Coefficient of thermal expansion	17×10^{-6} per °C 9.5×10^{-6} per °F
Eletrical Conductivity	
Solution heat-treated	20 to 25% I.A.C.S.
Heat-treated to maximum hardness	45 to 48% I.A.C.S.
Heat-treated to maximum conductivity	48 to 52% I.A.C.S.
Electrical resistivity at 20°C.	
Solution heat-treated	6.9 to 8.6 microhm cm.
Heat-treated to maximum hardness	3.6 to 3.8 microhm cm.
Heat-treated to maximum conductivity	3.3 to 3.6 microhm cm.
Thermal conductivity	
Solution heat-treated	0.3 cal./cm.^{2}/cm./sec./°C.
Precipitation hardened	0.5 cal./cm.^{2}/cm./sec./°C.
Thermal capacity (specific heat)	0.1 cal./gm./°C.
Modulus of elasticity	
Tension (Young's Modulus)	16 to 17 x 10^6 lb./sq.in.
Torsion (Bulk or shear modulus)	5.5 to 6.5 x 10^6 lb./sq.in.

Mechanical Properties

The range of mechanical properties to be expected for low beryllium copper is indicated in Table 7. In the fully heat-treated condition the tensile strength is in the neighbourhood of 50 tons/sq. in. with elongation values of about 10 per cent. Low beryllium copper has a higher electrical conductivity than any other material of comparable strength and toughness.

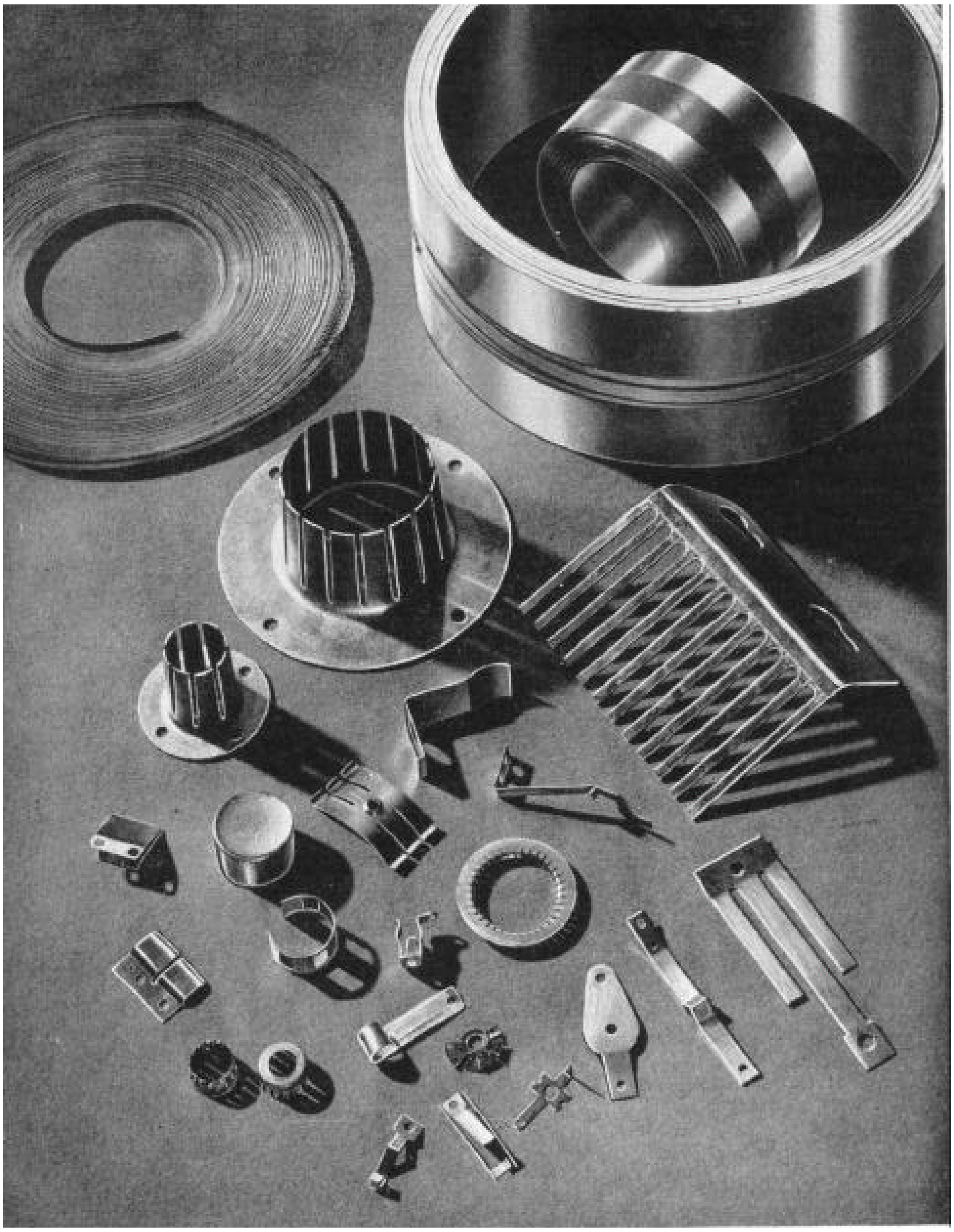
As in the case of normal beryllium copper, the tensile strength increases as the temperature is reduced, the improvement being about 7 tons/sq. in. for a drop in temperature of 200°C. This is accompanied by a slight increase in elongation, and an improvement of several ft. lb. in the Charpy impact value, which at room temperature is about 10-12 ft. lb.

No publication on the mechanical properties of low beryllium copper at elevated temperatures has been traced, though applications involving exposure to raised temperatures have been cited, such for instance as resistance welding electrodes and oil burner nozzles. In such circumstances the high thermal conductivity helps to keep the material relatively cool. The upper limit of temperature at which low beryllium copper could be used for long periods without risk of over-ageing is probably in the neighbourhood of 350°C. or 400°C.

Some proprietary alloys of the low beryllium type contain other elements besides cobalt. In general, the properties of these materials can be expected to be within the ranges given in Tables 6 and 7, though individual values may differ somewhat from the stated figures.

Table 7 - Representative Mechanical Properties of Low Beryllium Copper

Condition	Tensile Strength tons/sq.in.	Elastic Limit or Limit of Propor-tionality tons/sq.in.	Yield Point or Proof Stress for 0.1 % Extension tons/sq.in.	Percentage Elongation	Diamond Pyramid Hardness
Solution heat treated	17 - 25	4 - 9	9 - 14	20 - 35	65 - 85
Solution heat treated and precipitation hardened	44 - 54	24 - 34	35 - 45	8 - 15	190 - 230
Cold worked, ½ hard	27 - 36	15 - 29	24 - 34	10 - 15	100 - 140
Cold worked, ½ hard and precipitation hardened	49 - 58	31 - 40	44 - 54	8 - 20	210 - 240
Cold worked, hard	31 - 38	18 - 29	27 - 36	5 - 8	115 - 145
Cold worked, hard and precipitation hardened	49 - 58	33 - 43	47 - 54	5 - 12	210 - 240
Casting, heat treated	34	-	27	10	250
Forgings, heat-treated	48	-	42	15	250
Forgings, heat-treated and cold worked	50 - 55	-	46	10	270



Typical springs and similar products made from beryllium copper strip

6 - Resistance to Corrosion

In most normal environments the resistance to corrosion of beryllium copper, whether of the normal or low beryllium type, is comparable with that of copper itself. In particular, beryllium copper is far more resistant to corrosion than most of the steels with which it competes in the manufacture of springs and pressure-sensitive appliances. In this respect it is similar to phosphor bronze.

Beryllium copper is claimed to be quite as resistant as copper to sea water, and its resistance to corrosion fatigue in this medium has been shown by Gough and Sopwith[3] to be outstandingly high. Beryllium copper was regarded by the investigators as superior to the stainless steel which they also tested.

Aqueous solutions of salts which are neutral in their reaction do not, as a rule, attack beryllium copper, though superficial discolouration, usually greenish in hue, may be expected. On the other hand, salts like ferric chloride which hydrolyse in solution cause considerable corrosion on all copper alloys, including beryllium copper.

Gaseous halogens and halogen acids as well as strong acids such as nitric and chromic which are oxidising in character attack beryllium copper, but sulphuric acid is less harmful unless the conditions are oxidising. The same remark applies to the common organic acids, the action of which is greatly accelerated in oxidising environments.

Beryllium copper is moderately resistant to aqueous solutions of sodium hydroxide, but should on no account be exposed to ammonium hydroxide or to ammonia vapour.

Beryllium copper can safely be exposed to most organic liquids, such as petroleum products, refined oils, industrial solvents and refrigeration media. This includes halogenated compounds such as trichlorethylene and freon provided that no free halogen acids are present. Certain copper-rich alloys, including beryllium copper, should not be brought into contact with pure acetylene, as there is risk of forming explosive copper acetylide.

Beryllium copper is attacked by sulphur and certain of its compounds, particularly those which, like sulphur dioxide and sulphuretted hydrogen, are gaseous. Crude oil and town gas are potentially dangerous to beryllium copper, especially at elevated temperatures, because of the sulphur compounds which they usually contain.

It is undesirable to expose beryllium copper to molten metals, including mercury, though the latter is less detrimental to beryllium copper than to brass. The resistance of beryllium copper to molten sodium and potassium at moderate temperatures is, however, said to be good.

Under oxidising conditions, especially at elevated temperatures, the film of beryllium oxide formed on the surface of the material is protective and greatly retards progressive oxidation. Since, however, the temperatures at which such protection becomes apparent are those at which over-ageing occurs, the use of beryllium copper merely as an oxidation-resisting material would hardly be economical.

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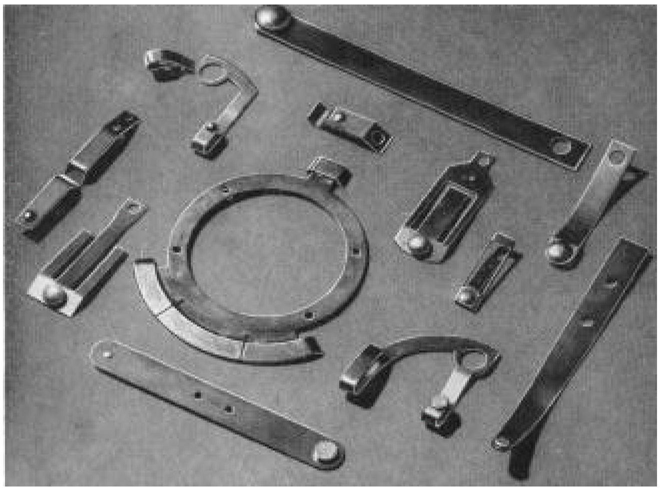
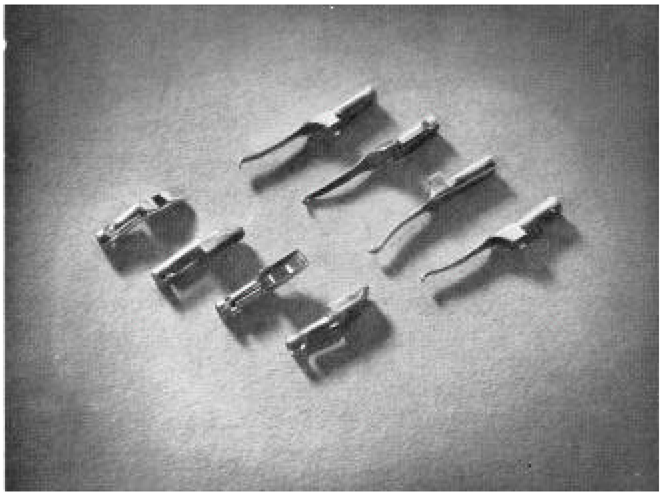
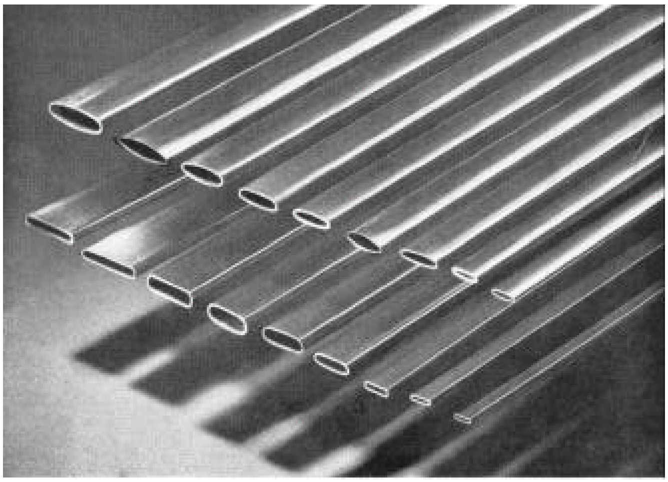
[3] *J. Inst. Metals*, 1937, 60, 143.



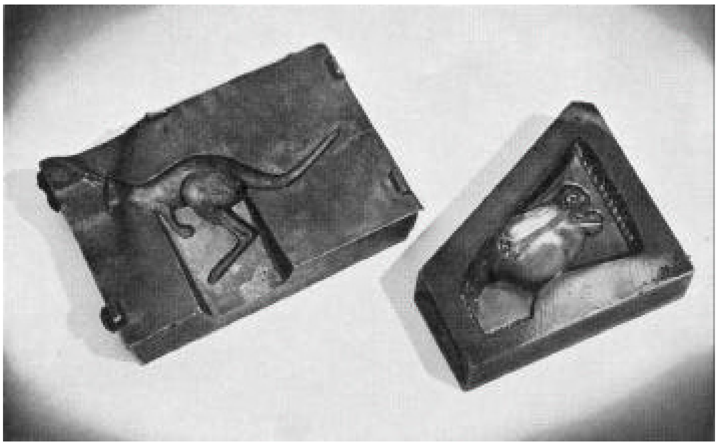
Beryllium copper spring contacts for electrical purposes



Small spring connectors made from beryllium copper

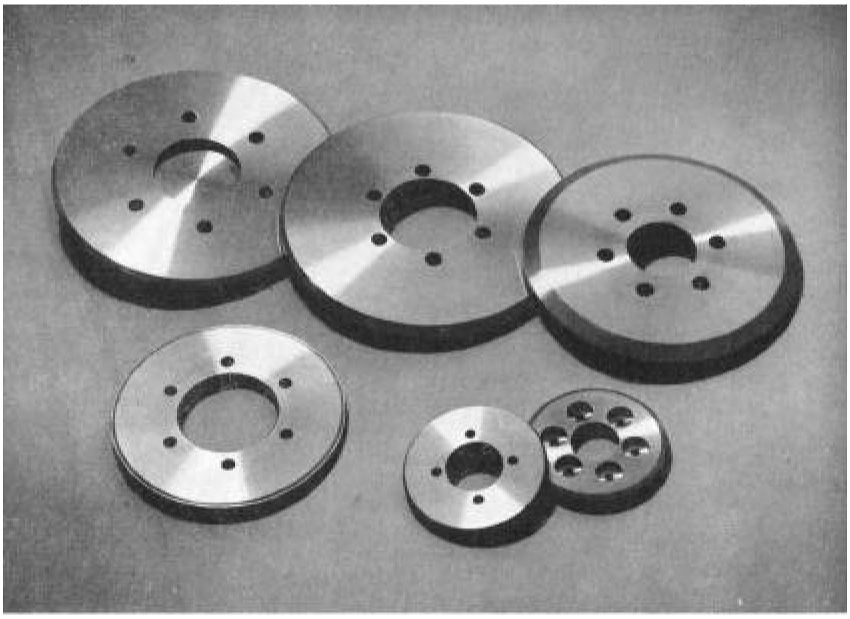


Beryllium copper tubes for Bourdon pressure gauges

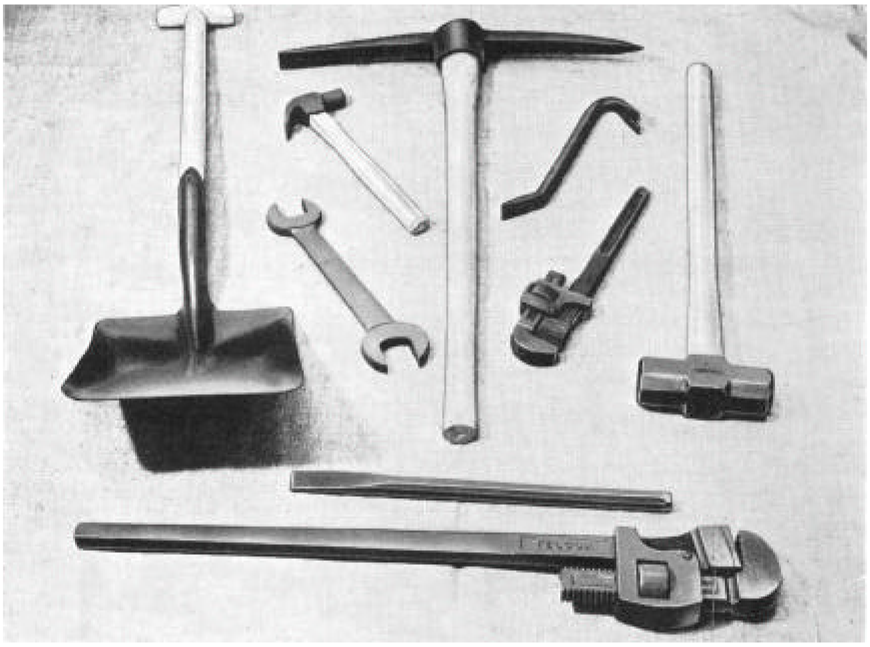


Beryllium copper dies for the moulding of plastics

Die casting plunger tip in low beryllium copper



Seam-welding electrodes of low beryllium copper



Some large beryllium copper safety tools

7 – Applications

The applications of beryllium copper are primarily those in which its special properties of high strength and hardness, elasticity, conductivity and resistance to corrosion can be exploited to the full. They fall into four main groups, namely:

(1) Springs of many kinds, including diaphragms for pressure-sensitive instruments.
(2) Dies for deep drawing and forging metals and for moulding plastics.
(3) Resistance welding electrodes and their holders.
(4) Non-sparking tools.

The primary advantage offered by beryllium copper in the first of these groups is the ease with which the alloy can be fabricated into complicated shapes and afterwards hardened to spring temper by heat treatment. Moreover, the conductivity is much higher than that of any other material of comparable spring properties, and this fact coupled with the non-magnetic qualities of the alloy commends it particularly to the electrical industry, not only for multitudinous spring contacts of various types but also for calibrated springs in electrical measuring instruments. Delicate items, like the hair springs of clocks, are relatively easy to make in beryllium copper and yet are comparatively robust to handle on the assembly benches, with the result that the proportion of rejects is low. For this reason beryllium copper springs are finding favour among manufacturers engaged in the mass production of such articles, in spite of the rather high cost of the alloy. For pressure-sensitive instruments such as aneroid capsules, tubes of Bourdon gauges and metal bellows, beryllium copper offers excellent resistance to corrosion, while its high elastic limit, low modulus and freedom from zero drift spell sensitivity and reliability.

The use of beryllium copper for dies in the forging, deep drawing and plastics industries is a comparatively late development, but has become important. Dies of intricate shape can readily be produced by machining, hobbing or more usually by one or other of the modern processes of precision casting, and can subsequently be hardened. The high thermal conductivity and good resistance to wear make for long life, the first-named property being of particular value in the moulding of plastics, where heat must be transmitted through the die; it results in a markedly shorter operating cycle than that obtainable with steel dies of similar dimensions. The high cost of the material is balanced by the fact that worn dies can always be remade, either by softening, remachining and rehardening or, if necessary, by recasting. For the deep drawing of stainless steel, dies made from beryllium copper offer long life combined with freedom from galling. For most applications in this category, the alloy favoured is of the normal type, but carries a distinctly higher beryllium content, namely about 2.5 to 2.7 per cent, than that used for the manufacture of springs. This has the effect of increasing the hardness, strength and resistance to wear under the exacting conditions of service. Nevertheless, low beryllium copper has proved exceptionally satisfactory for the plunger tips of cold chamber die-casting machines operating on zinc and aluminium alloys. Even in the precipitation hardened condition, low-beryllium copper retains sufficient malleability to enable the peening action of the molten metal on the nose of the plunger to compensate for wear, and so to preserve an accurate fit in the sleeve.

Electrodes and electrode holders for resistance welding machines call for high electrical and thermal conductivity combined with sufficient strength and hardness to resist deformation under moderate pressure at elevated temperatures. In this field of application low beryllium copper, in the form of forgings or castings, has proved its merit. Some of the proprietary alloys specially designed for this purpose contain approximately 1 per cent of silver in addition to the usual quantities of cobalt and beryllium. It is claimed that this modification diminishes the

contact resistance without detriment to the mechanical properties or to the response to heat treatment.
Other applications of low beryllium copper involving the transfer of heat include nozzles for gas and oil burners, as well as the plunger tips of die casting machines already mentioned.

A complete range of safety tools including hammers, screwdrivers, spanners, pliers, chisels, hacksaw blades, knives, scissors, shears, picks, shovels and scrapers of all kinds, is available in beryllium copper for use in mines, arsenals, aerodromes and factories handling inflammable or explosive materials. Normal beryllium copper is generally used for the purpose, and the articles may be produced as castings, forgings or from rolled or drawn metal according to their shape and size. Cutting tools take and retain a good edge, and such items as cold chisels and hacksaw blades are well able to cope with the cutting of ordinary steels. A word is necessary concerning the nature of sparks produced by concussion. Almost invariably they are due to minute particles of iron which are sufficiently heated by the energy of impact to become incandescent and to burn to iron oxide as they fly through the air. Similar particles of beryllium copper, if formed at all, do not oxidise so violently and no sparks are produced when tools of the alloy are struck against hard solids such as rock or concrete. Nevertheless, it is conceivable that sparks could result from a glancing blow of beryllium copper against an iron object. Ordinary care should always be exercised in using beryllium copper implements where impact with iron or steel is possible, and they should not be regarded as providing complete immunity from danger under such conditions, though the risk is very much reduced.

8 - The Manufacture and Manipulation of Beryllium Copper

Melting and Casting

As with most other alloys, beryllium copper is made by melting the constituent metals together in the required proportions and pouring into suitable moulds, which may be either of simple shapes to facilitate subsequent fabrication by such processes as rolling and drawing or in the form of castings to be used as such.

Copper-beryllium master alloys, usually containing about 4 per cent of beryllium, are available commercially for addition to copper. Even though almost equal amounts of copper and master alloy are required for the production of beryllium copper, it is expedient to melt the copper first and to add the master alloy to it, allowing for a loss of about 0.1 per cent beryllium. Alternatively various proprietary compositions are marketed, particularly in America, in ingot form for the production of castings. A proportion of beryllium copper scrap can be incorporated with due discretion.

As with other copper alloys, care should be taken to avoid the introduction of hydrogen during melting. Though molten beryllium copper is not abnormally prone to absorb gas, cases have been reported in which wet or oily scrap, or the addition of damp charcoal, has led to unsoundness in the castings. Charcoal is normally used during melting, but it should be carefully dried and preferably added in the incandescent condition.

A suitable flux for dealing with small scrap or turnings is barium chloride. Fluxes like cryolite, which can react with beryllium should be avoided; not only do they lead to loss of beryllium but they may also evolve fumes which, laden with beryllium compounds, are detrimental to health.

To minimise loss of beryllium it is desirable not to overheat the melt. For normal purposes a pouring temperature of about 1100°C should not be exceeded, this being approximately 100°C above the melting point of the alloy.

Ingots and billets for subsequent fabrication are normally poured into cast iron moulds, and oily mould dressings of the type used for brass and similar alloys give satisfactory results. The molten metal is very fluid and, provided that the melt is not gassy, it sinks well during solidification, necessitating adequate feeding. Care should be taken not to expose too long a stream of molten metal to the air during pouring, in order to avoid oxidation with consequent loss of beryllium and the possibility of entrapping dross in the casting.

Moulding procedure for the production of sand castings is essentially similar to that for other copper-base alloys such as bronzes and gunmetals, and the same sands and core materials may be used. Good permeability is advantageous, and, to avoid hot tears, cores should not be too strong. The moisture in green sand moulds should be restricted, and for large castings skin drying is desirable. The metal should enter the moulds as quietly as possible through a choke followed by a gently widening gate to slow down the stream. A skim riser to collect dross should be located behind the choke. Such precautions are recommended because beryllium, like aluminium, tends to form a tenacious film of refractory oxide on the surface of the molten alloy.

The pattern shrinkage allowance for beryllium copper is approximately the same as that for phosphor bronze or gunmetal, and may be taken to lie between about 1/8 in and 3/16 in per linear foot.

In addition to the normal sand moulding technique, beryllium copper castings can be produced without difficulty by such specialised processes as investment casting and shell moulding, the first-named being particularly suitable for small objects of intricate design where good surface finish and close dimensional tolerances are required. Semi-permanent moulds of the ceramic or gypsum type can also be used. In the production of dies and die inserts for the plastics industry it is not unusual to apply pressure during solidification, either by means of compressed air or by a steel die ("hob") inserted into the mould, in order to ensure the accurate reproduction of fine detail on the surface of the casting.

No important references to the die casting of beryllium copper on a commercial scale have been traced in the literature, although a few successful experiments have been reported.

Hot Working

Beryllium copper can be extruded and hot forged or pressed at temperatures between about 570°C and 810°C, preferably towards the upper limit of this range. On the subject of hot rolling the literature is curiously silent, but much commercially produced sheet and strip appears to be broken down hot. For optimum response to subsequent precipitation hardening, hot rolling and other hot working operations should be carried out as far as possible at temperatures between about 750°C and 810°C, and it is desirable to cool the metal quickly, preferably by quenching. These recommendations are not, however, always practicable and, as an alternative, a solution heat treatment can be applied at the end of the hot-working schedule.

Cold Working and Press-Shop Practice

Cold working processes can be divided into two groups, namely, those like rolling and drawing, which are generally the responsibility of the manufacturer, and those like press-forming operations. which are more the concern of the user. The same basic principles apply to both groups, and they will be considered together, mainly, however, from the point of view of the user.

In Fig. 2 are typical strain hardening curves for annealed copper and several of its alloys, including normal beryllium copper in the solution annealed condition. The last named lies wholly above its companions and shows a greater overall rise, indicating that beryllium copper is distinctly more difficult to deform than the others. It requires more power and more frequent annealing. Moreover each anneal should, in theory, be carried out at the temperature of solution heat treatment, followed by quenching. This is not, however, necessarily mandatory for intermediate anneals, provided that the ready-to-finish anneal is so accomplished

A true strain (See Note for Figure 2) of about 0.4, corresponding to 33 per cent reduction in sectional area, is generally found to be practicable between anneals. This degree of deformation, usually effected by cold rolling or drawing, brings the material into the "hard" temper, while the "half hard" and "quarter hard" grades correspond to true strains of approximately 0.2 (18 per cent reduction) and 0.1 (10 per cent reduction) respectively. Since a total true strain of about 0.4 represents the practical limit of formability in each case, it is apparent that the formabilities of the four commercial tempers can be assessed roughly as:

Solution-annealed	0.4 - 0	= 0.4
Quarter hard	0.4 - 0.1	= 0.3
Half hard	0.4 - 0.2	= 0.2
Hard	0.4 - 0.4	= 0

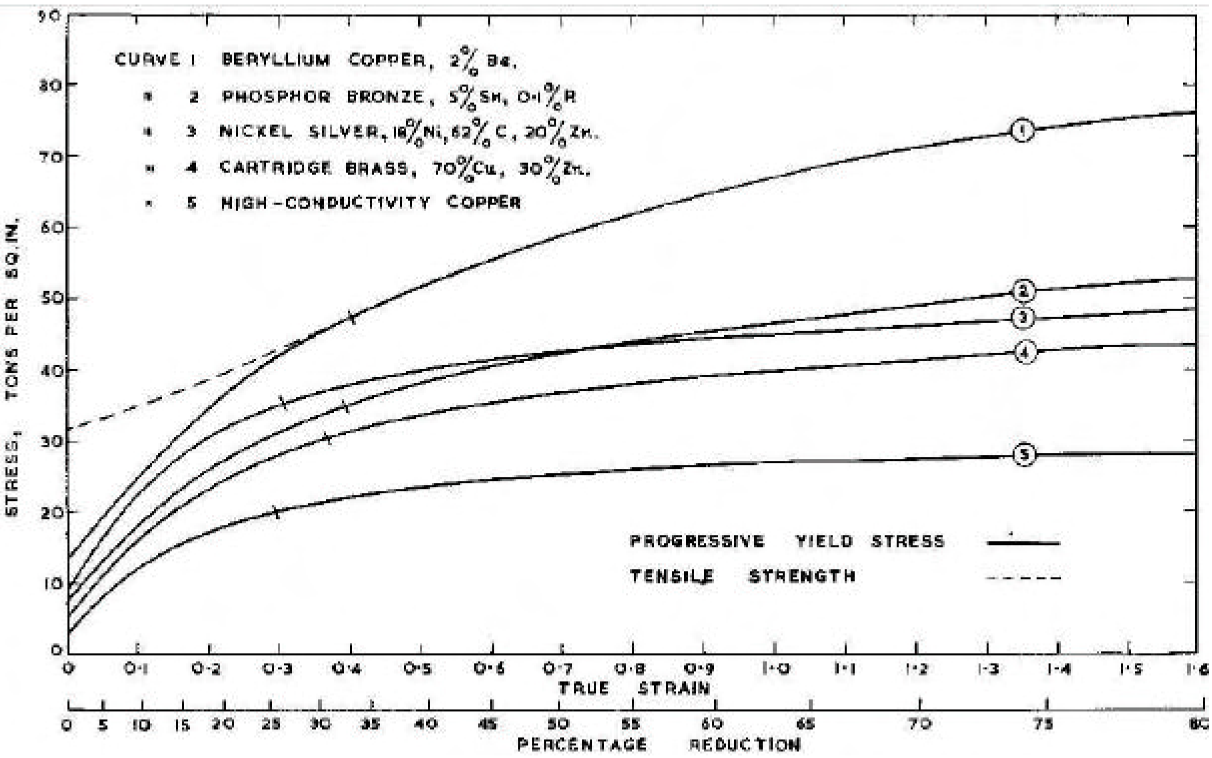


Figure 2 - Typical strain-hardening curves for copper, beryllium copper and several other copper alloys.

Note: The true strain at any particular instant during the reduction of a sectional area of original size A_o, is defined as the minute change of area, -dA, at the instant in question divided by the sectional area, A, from which the change takes place. The actual true strain, obtained by integration is therefore $\log_e A_o/A$. Besides being more fundamental in concept, true strains have the great advantage over percentage reductions that they are directly additive. Thus, if A_1 represents an intermediate stage in the reduction between A_o and A_1 then $\log_e A_0/A_1 + \log_e A_1/A = \log_e A_0/A$, which is clearly the correct answer. In contrast, an attempt to add the corresponding percentage reductions leads to

$100\left(\frac{A_o-A_1}{A}+\frac{A_1-A}{A_1}\right)$ and not to the expected total reduction of $100\frac{(A_o-A)}{A_o}$

These figures give a general indication of the relative degrees to which normal beryllium copper in the different commercial tempers can be bent deep drawn or otherwise formed into useful shapes. Their significance is emphasised by the fact that smooth curves are obtained when the Erichsen values in Table 4 are plotted against them.

Low beryllium copper behaves in much the same way, and, for both types of alloy the fabricating qualities of the various tempers can be broadly described as follows:

Solution-annealed:
For all applications involving severe deep drawing bending or similar forming processes. May give slight burr on blanking.

Quarter hard:
Gives better spring properties and cleaner blanking than solution-annealed material, and is almost as formable.

Half hard:
Good spring properties with formability about half that of solution-annealed material. Can be bent round moderate radii, and has improved blanking characteristics.

Hard:
Gives maximum strength, hardness and spring properties for parts which require little or no forming. Good blanking properties.

Except in the form of finished products, normal beryllium copper is rarely supplied in the precipitation hardened condition, for it is almost unworkable. In contrast, precipitation hardened low beryllium copper retains sufficient ductility to enable light forming operations to be carried out, and stock is sometimes supplied by the manufacturers in the fully hardened condition, thus eliminating the need for heat treatment by the purchaser. No great amount of deformation can be applied to such material, but in the manufacture of flat or moderately bent springs and similar articles, its use represents a considerable convenience. On the other hand, it is more likely to carry locked-up stresses which are undesirable, especially from the point of view of resistance to fatigue.

Because of the comparatively high forces required to deform beryllium copper, proper attention to lubrication is necessary in all cold working processes. Moreover, it is essential to ensure scrupulous cleanliness, and in particular to avoid oxide films which are abrasive in character and lead to unnecessary wear on the tools. For light operations, a lubricant composed of soap and water is generally sufficient and has the advantage that it can be easily removed by washing. For severe deep drawing and similar purposes, however, it is desirable to use extreme pressure lubricants, though lard oil or a heavy soap paste with solid additions to promote film strength may prove satisfactory. Lubricants containing appreciable quantities of sulphur tend to stain beryllium copper unless they are removed immediately after use, and in any case all lubricant should invariably be removed prior to heat treatment in order to avoid discoloration of the product. For particularly severe operations, it is possible to plate the stock with cadmium, which not only protects the surface from atmospheric oxidation, but also acts as a lubricant and helps to reduce wear by cushioning the contact between tool and work-piece. The cadmium must be removed before heat treatment.

The choice of materials for punches and dies in forming or cutting processes depends mainly on the length of run required. Carbide tools are long-lasting, whereas, in normal production, air-hardened steel can be used for moderately long runs or oil-hardened steel for shorter runs. Chromium plated tools tend to reduce friction, and chromium plating can be used to build up worn parts or to reinforce positions at which wear is particularly severe. With proper attention to cleanliness and lubrication, tool life for beryllium copper is about the same as for phosphor bronze, but distinctly shorter than for brass.

For blanking and piercing, the cold-worked grades of beryllium copper give sharper edges with less burr than material in the solution annealed condition. For the cold worked grades a clearance between punch and die from 5 per cent. to 10 per cent. of the metal thickness is permissible, but for solution annealed material the clearance should be held to a maximum of about 6 per cent. of the metal thickness in order to minimise burr. When blanking, the face of the punch is usually flat, while the die may be ground at a slight angle to reduce the pressure required. On the other hand, when piercing, a small shear angle may with advantage be given to the punch. A cut edge should not approach the edge of the strip more closely than a distance equal to the thickness of the metal.

The practical limits for the deep drawing of cups from the four commercial tempers of beryllium copper are very approximately as follows:

Temper	Ratio of Blank diameter to Cup diameter	Ratio of Cup depth to Cup diameter
Solution-annealed	1.5	0.3
Quarter hard	1.3	0.2
Half hard	1.2	0.1
Hard	1	nil

These figures should be regarded as no more than a rough guide and, with this reservation, are applicable to both normal and low beryllium copper. They refer to conditions in which there is no ironing, that is to say, in which the thickness of the cup wall remains the same as that of the blank. Moreover, to achieve them it is essential to ensure minimum friction by using smooth, well lubricated tools and no greater blankholder pressure than is necessary to prevent wrinkling. Such factors as metal thickness and radii on the punch and die may considerably modify the stated ratios.

If more severe drawing is required, it may be necessary to introduce one or more solution anneals into the schedule, so spaced that the total reductions between anneals do not exceed the stated figures. The metal should be cleaned both before and after annealing to avoid the possible formation of charred lubricant and to remove oxide scale. It is hardly necessary to add that the material so treated will be in the solution annealed condition, and must subsequently be handled as such, whatever its original temper. Instructions for solution annealing are given in the next topic (Solution Heat Treatment and Annealing), but the process needs careful control and is best, if possible, left in the experienced hands of the manufacturer.

It is claimed that solution-annealed and quarter hard beryllium copper strip up to 0.040-in in thickness can be bent through 90° around a sharp radius without cracking. Nevertheless it is always desirable to use as generous a radius on the tool as design requirements permit. In the case of the half hard and hard grades the direction of the bend relative to that of rolling becomes an important factor, and the following figures can be taken as a guide to the minimum radii required:-

	Minimum radius in inches for stated thickness of strip			
Thickness of strip, ins.	0.01	0.02	0.03	0.04
Half hard -				
Axis of bend parallel to direction of rolling	0.03	0.09	0.12	0.15
Axis of bend perpendicular to direction of rolling	0.03	0.06	0.10	0.13
Hard -				
Axis of bend parallel to direction of rolling	0.08	0.15	0.20	0.25
Axis of bend perpendicular to direction of rolling	0.05	0.09	0.13	0.15

Appreciable spring-back must be expected after bending beryllium copper, and must be allowed for in designing tools. The degree of spring-back depends on a number of factors, including the severity of the bend and its direction relative to that of rolling, as well as the hardness and thickness of the strip. It can best be found by trial in any particular circumstances, but under normal conditions may amount to from 5° to 10°. Spring-back can often be reduced by applying a moderate degree of coining either in the original forming process or in a subsequent operation. Close tolerances can, however, always be held by the expedient of jigging during the final heat treatment. This is particularly valuable in the manufacture of spiral or helical springs from either wire or strip, and in all cases where the preservation of dimensional accuracy and reproducibility of performance of springs is of importance.

Cold hobbing is quite practicable with beryllium copper in the solution heat-treated condition. Tools must be robust and considerable power is necessary.

Coining can be regarded as a comparatively mild form of hobbing, and the same remarks apply. It can be used in conjunction with other cold forming processes and is, with some reservation, applicable to the work hardened grades as well as to the solution-annealed material.

While the foregoing discussion refers more especially to the normal grade of beryllium copper the same principles are, in general, applicable to low beryllium copper. This alloy is less hard and strong than the normal material and is consequently less exacting in the press shop. In the solution annealed or partially cold-worked condition its behaviour is comparable with that of phosphor bronze.

Even in the precipitation hardened condition low beryllium copper retains sufficient ductility to enable light forming operations to be carried out, as already mentioned.

Solution Heat Treatment and Annealing

(See also Foreword)

As explained in Section 3, the object of solution heat treatment is to form the single phase a solid solution, which is comparatively soft and ductile. It is sometimes called "homogenizing", while the term "solution annealing" is appropriate when the process is applied to material which has previously been hardened by cold work.

Reference to Figure 1 shows that the temperature required for the purpose is relatively high, and that its range becomes progressively narrower as the beryllium content of the alloy is increased. At such temperatures there is a tendency to cause grain growth if the time of exposure is unduly prolonged, while the access of oxygen may lead to embrittlement of the surface layers, or even of the whole section in the case of thin stock. It follows that considerable care is necessary in the practical control of the process.

For normal beryllium copper containing about 2 per cent beryllium, the temperature of solution heat treatment ranges from about 790°C to 820°C. Control can, however, be facilitated by reducing the beryllium content to about 1.7 per cent, in which case the lower limit for the temperature of solution heat treatment is brought down to about 760°C, with correspondingly less tendency to grain growth. The solution heat treatment temperature for low beryllium copper is, however, somewhat higher, ranging from about 850°C to 920°C. This is less paradoxical than it might appear, being attributable to the greater cobalt content of the alloy. In all cases the time of heat treatment should be kept rather brief, in order to restrict grain growth, but must be sufficient to ensure that the whole of the furnace charge reaches the desired temperature. It will depend to some extent on the thickness of the stock and on its arrangement in the furnace, but from 10 to 30 minutes may be taken as a practical guide for light material such as strip and wire, extending up to several hours for bulky castings and forgings. In all cases the heat treatment must be completed by a rapid and efficient quench in cold water. "Slack" quenching must be rigorously avoided.

Though the type of furnace for the purpose is not particularly important, provided that the control of temperature is adequate, it is highly desirable if not essential to use an inert or slightly reducing atmosphere, free from sulphur compounds which would cause discoloration. Electric furnaces with atmospheres consisting of the dried products of cracked and burnt ammonia are suitable, but neither steam atmospheres nor salt baths are recommended. Oxide, charred lubricant or other abrasive films may lead to serious tool wear in subsequent fabricating operations, and for this reason, as well as for surface appearance, it is important thoroughly to clean the stock before solution heat treatment or annealing. If it is impracticable to use an inert atmosphere, the time of heat treatment should be kept to a minimum, and the oxide film which will inevitably form should be removed by pickling, instructions for which are given in - Pickling and Finishing.

An essentially different type of heat treatment, known as sub-critical annealing, is also in use. Heating for 8 hours at about 550°C causes the a phase to recrystallise with little grain growth. At the same time a considerable proportion of the beryllium is precipitated as ?, which spheroidises. Material in this condition has good cold-working properties and can be hardened by drawing or rolling, though its response to precipitation hardening is negligible. In the work-hardened state it can be formed directly into springs and similar articles, and requires no subsequent heat treatment other than stress relief at 150°C for from 15 to 30 minutes. Tensile strengths ranging from 60 to 75 tons per square inch can be achieved.

Precipitation Hardening

(See also Foreword)

The basic principles of the precipitation hardening heat treatment have already been outlined in Section 3. In practice careful control is necessary if the best results are to be obtained, and the process can be modified to meet particular requirements in respect of mechanical and physical properties in the finished product. For example, conditions which lead to maximum hardness and strength differ from those which afford maximum conductivity or freedom from elastic drift. Moreover, not only the exact composition of the material but also the degree of cold work to which it has been subjected affects the response to precipitation hardening. In general, however, normal beryllium copper needs from 2 hours at 310°C to ½ hour at 350°C, while for low beryllium copper, with similar periods of time, the temperatures range from 420°C to 470°C.

Even within these ranges there is considerable scope for variation, and, in the absence of adequate instructions from the supplier, it is undoubtedly desirable to carry out a few pilot trials on any new consignment of beryllium copper before commencing full-scale production. Nevertheless, Figures 3 to 8 inclusive give a guide to the results which may be expected in the case of normal beryllium copper, though individual proprietary alloys may behave somewhat differently from each other. This can be seen by comparing Figure 7 and Figure 8, which show the effects of heat treatment on the diamond pyramid hardness of normal beryllium copper from two different sources.

In general, all the diagrams show the same features. At temperatures less than 300°C response to heat treatment is relatively slow, and the full degree of precipitation hardening is not attained within an economical period of time. The optimum temperature is about 315°C. This gives full hardening in about 2 hours for solution annealed or lightly cold-worked material, or in about 1 hour for the harder grades. At higher temperatures there is a tendency for the alloys to over-age, particularly when they are in the cold-worked condition.

A moderate degree of over-ageing is not, as a rule, harmful, and Figures 3 to 6 inclusive show that it is accompanied by an appreciable improvement in conductivity, as well as slightly increased elongation values. A further advantage of over-ageing is that it tends to improve the performance of calibrated springs by reducing drift of the zero setting in service, and by slightly increasing the modulus of elasticity. This is due mainly to the more complete removal of internal stresses created in the metal by the cold forming processes. The elimination of internal stresses is, moreover, conducive to improved performance under fatigue conditions. With such aims in view, some users advocate temperatures in the neighbourhood of 350°C for from ½ to 1 hour with solution-annealed material and from ¼ to ½ hour with the cold-worked grades. These short times are, however difficult to control in practice because the heating-up period is an appreciable and variable proportion of the whole. Similar results can be obtained with greater reproducibility by adopting somewhat longer times at temperatures in the region of 330°C.

In deciding upon an appropriate heat treatment, it must be remembered that the fabricating processes applied by the user himself will work-harden the alloy to a degree depending on their severity. For example, if solution annealed material is subjected to severe deep drawing, it must be regarded as half hard or even hard stock for purposes of heat treatment. Further in the case of deep drawing, bending, and similar processes, the degree of cold work is rarely uniform throughout the article, and some compromise in the time and temperature of heat treatment may become necessary to allow for this fact. It is clearly impossible to give recommendations covering all such contingencies, the best course being, as already mentioned, to carry out a few trials before proceeding to commercial production.

Reduction of the beryllium content to about 1.7 per cent gives a form of normal beryllium copper which, though not quite so hard as the 2 per cent alloy, tends to behave more consistently under precipitation heat treatment. This is probably due mainly to the fact, already referred to, that the conditions for solution heat treatment are distinctly less critical and consequently easier to reproduce under ordinary industrial conditions.

Procedure for the precipitation hardening of low beryllium copper is basically similar to that for the normal alloy, but the temperature is higher (see first paragraph of this topic) and the conditions, on the whole, less critical, mainly because low beryllium copper is rarely used for calibrated springs and other components calling for high precision and reproducibility of performance. As in the case of the normal alloy, the optimum conditions for any particular product can best be found by trial. Low beryllium copper shows a greater tendency to oxidise superficially during heat treatment than the normal alloy, not only because of the higher temperatures required but also because the alloy lacks sufficient beryllium to form the protective film of beryllia which is a feature of the normal alloy.

Muffle furnaces, air circulating furnaces or salt baths may be used for the precipitation heat treatment. Preferably they should be equipped with thermostats, but in any case the control of temperature must be responsive and its measurement accurate. Muffles are comparatively inexpensive but tend to be slow in operation, and air circulating furnaces represent an important improvement in this respect, combined with greater uniformity of temperature throughout the heated zone.

The temperature required for precipitation hardening is insufficiently high to cause serious oxidation, though protective atmospheres, mildly reducing in character and free from sulphur compounds which cause staining, can be used if desired to diminish the need for subsequent finishing. Also to minimise discoloration, it is important to remove all trace of dirt or lubricant before heat treatment. This is especially true in the case of lubricants containing sulphur compounds. In the case of salt baths, care must be taken thoroughly to wash the products, for residual salt may lead to subsequent corrosion. Salt baths give quick heating with good uniformity of temperature, and appropriate mixtures of alkali nitrates melting at less than 300°C. are available commercially. It is unnecessary to quench from the precipitation temperature, but the rate of cooling should not be so slow that the time of heat treatment becomes, in effect, longer than that intended.

Instrument springs and other products which must be held to close dimensional tolerances can, with advantage, be heat treated in jigs or clamps. Precipitation hardening, especially in the range of over-ageing, tends to eliminate internal stresses from the metal, and articles heat-treated in fixtures will retain the dimensional accuracy of the fixtures themselves. Fixtures can be made from cold rolled steel, which is cheaper and easier to machine than die steel. They should be carefully cleaned after use and preserved with a film of oil, which must be removed before they are again put into service. Because of the greater mass of metal, the total period of heating is longer with fixtures than without them, and experienced operators tend to adopt slightly higher temperatures, a practice which encourages stress relief.

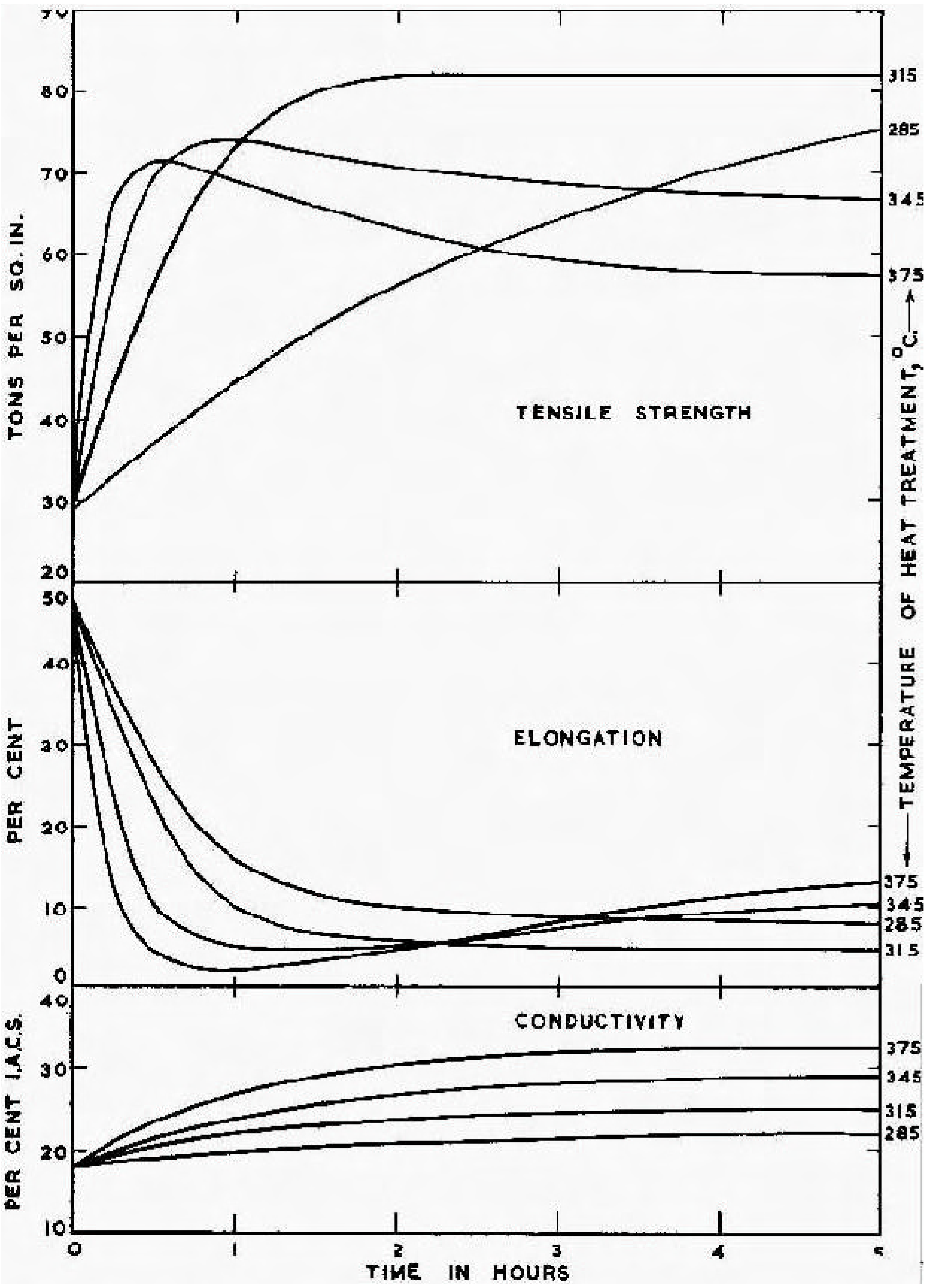


Figure 3 - Effect of precipitation heat treatment on solution-annealed beryllium copper (Beryllium Corporation)

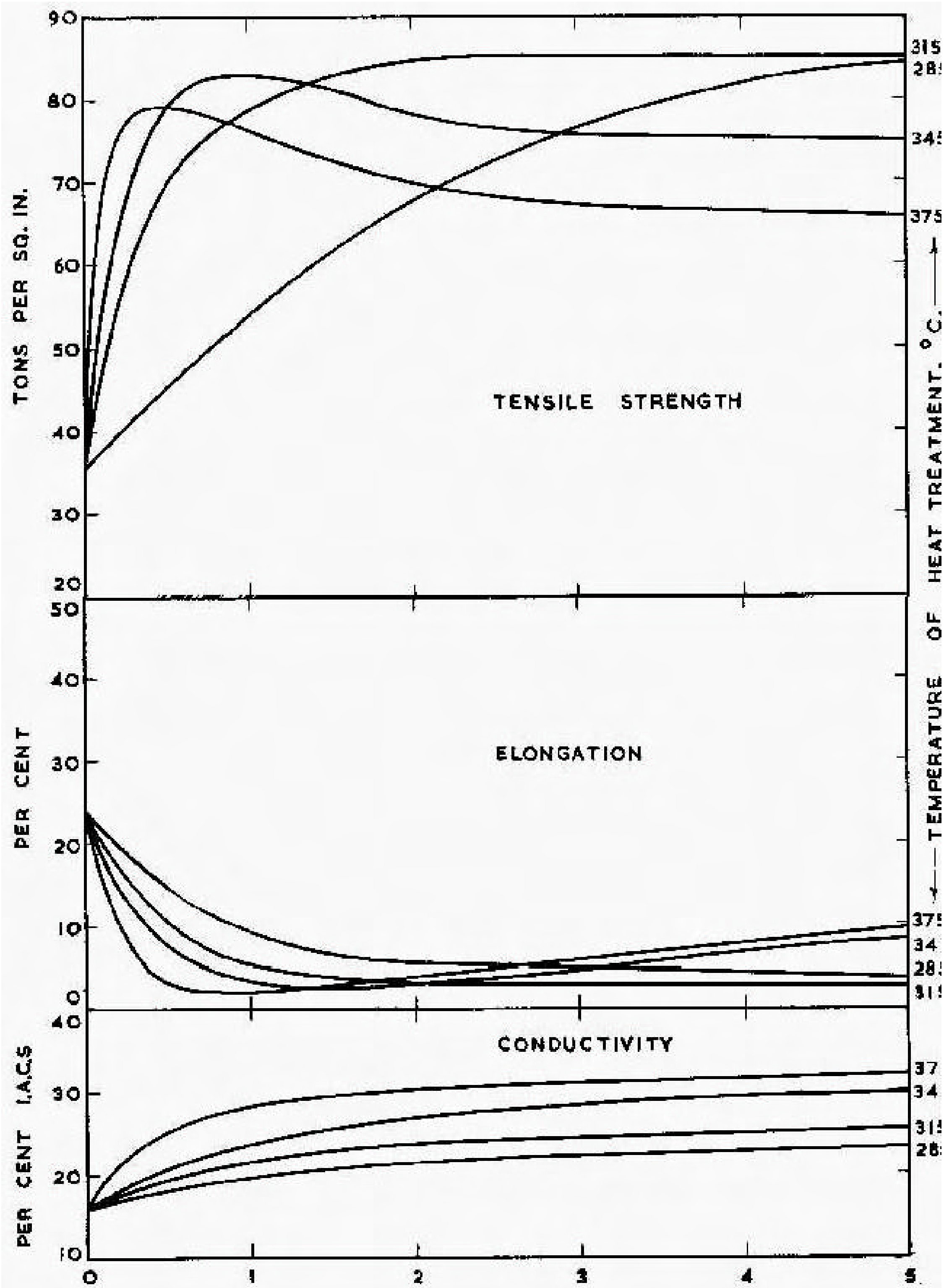


Figure 4 - Effect of precipitation heat treatment on quarter hard beryllium copper (Beryllium Corporation)

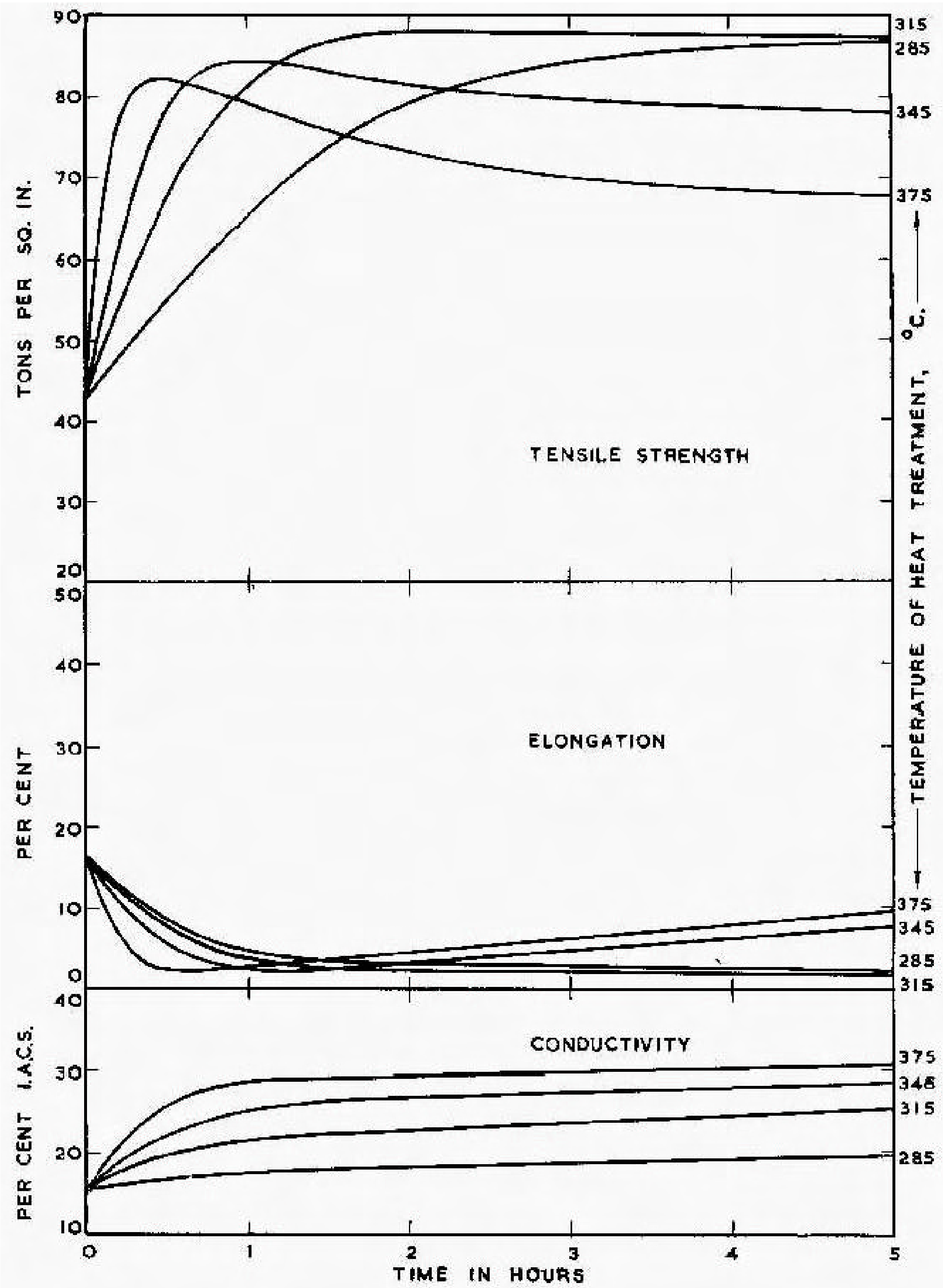


Figure 5 - Effect of precipitation heat treatment on half hard beryllium copper (Beryllium Corporation)

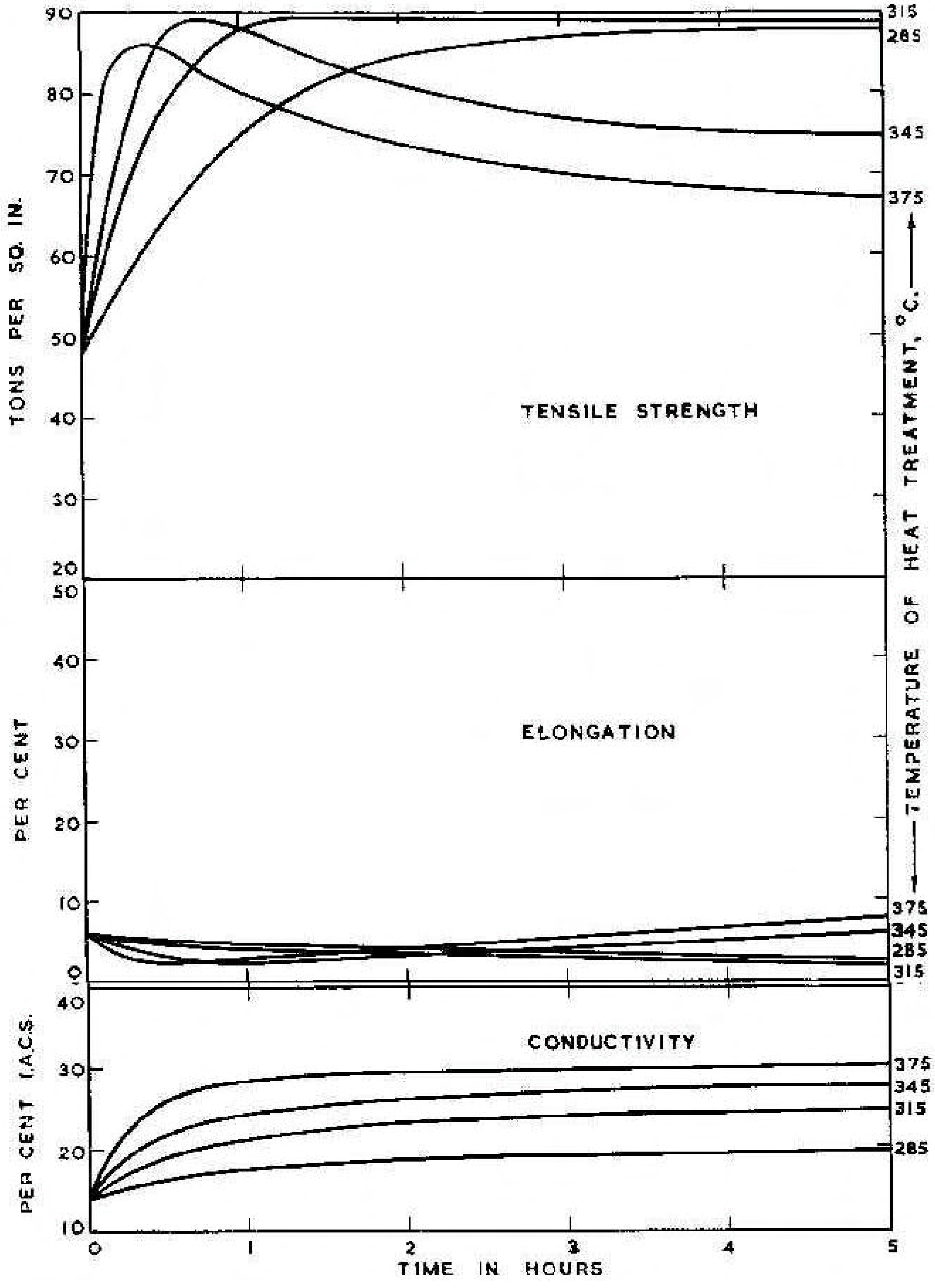


Figure 6 - Effect of precipitation heat treatment on hard-worked beryllium copper (Beryllium Corporation)

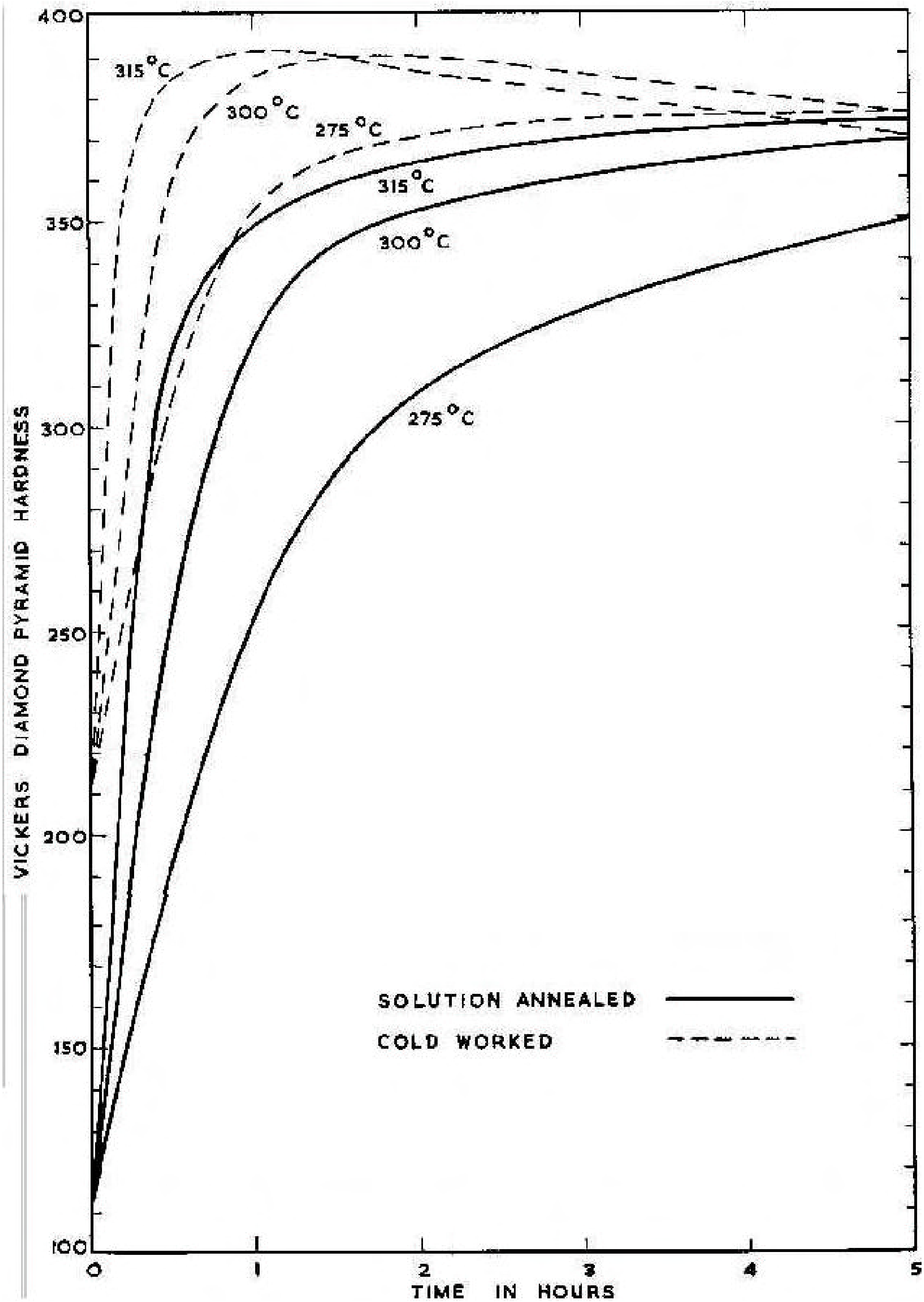


Figure 7 - Effect of precipitation heat treatment on the hardness of beryllium copper (Johnson, Matthey & Co Ltd)

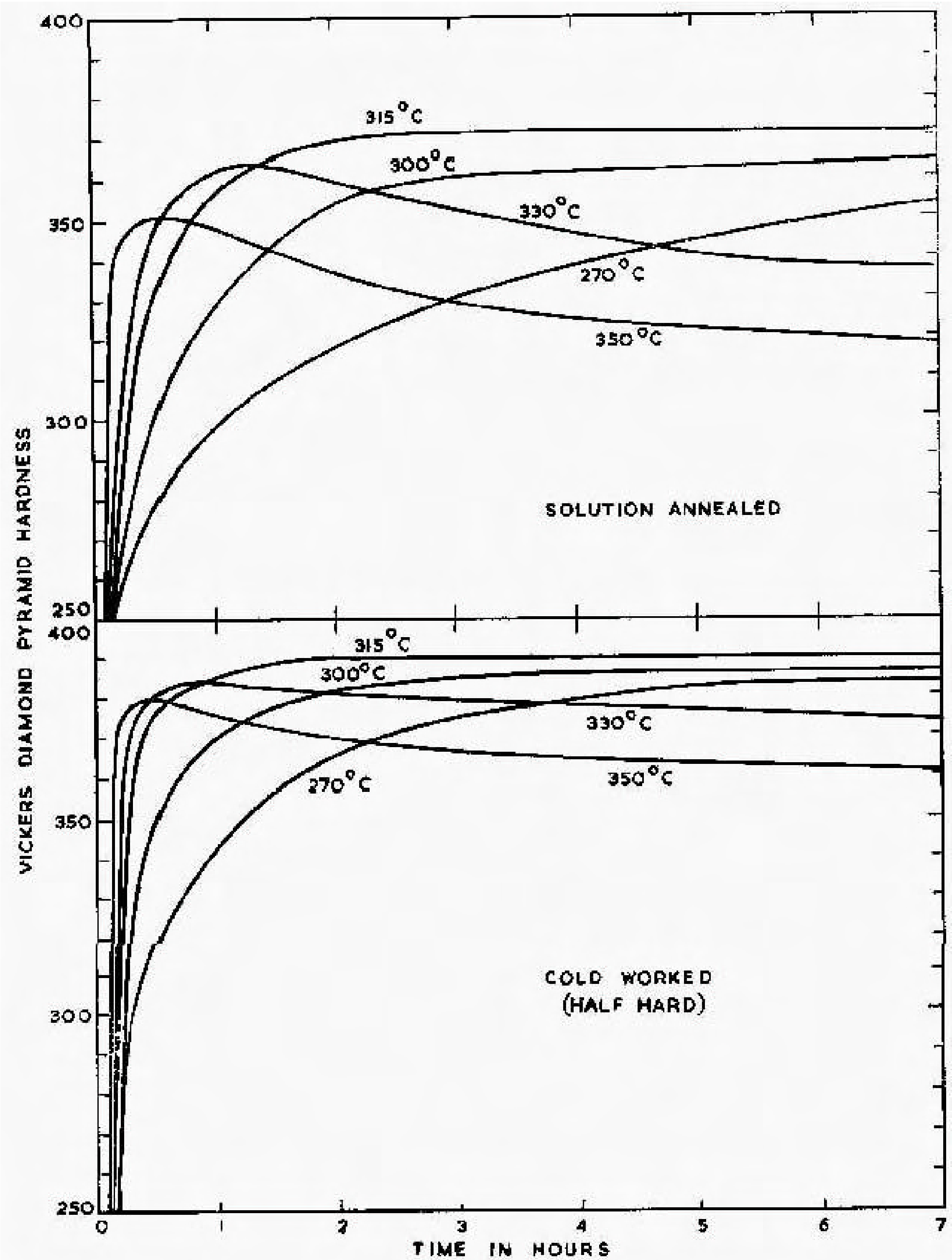


Figure 8 - Effect of precipitation heat treatment on the hardness of beryllium copper (Beryllium and Copper Alloys Ltd)

Pickling and Finishing

Oxide scale formed during the heat treatment of beryllium copper can be removed by pickling in a solution of 1 volume of concentrated sulphuric acid in about 4 volumes of water, preferably used hot. The surface may subsequently be brightened either in cold 30 per cent nitric acid, or by a quick dip in the following bath:-

Concentrated sulphuric acid	2 pints
Sodium dichromate	5 lb
Water	5 gallons

It need hardly be added that the articles must be thoroughly washed to remove all trace of acid, before being dried. Over-pickling may lead to a roughened surface detrimental to the mechanical properties, especially under conditions involving fatigue.

Beryllium copper products can be finished by any of the normal techniques but for obvious reasons it is desirable to carry out preliminary polishing and to remove surface imperfections before the final hardening treatment. The alloy can be electroplated with all the usual metals, but it is important to remove any surface film of beryllium oxide, which, though often invisible tends to impair adherence of the deposit. A dip in cold 30 per cent nitric acid, with or without the addition of a little sulphuric acid, can be used for the purpose; an alternative recommendation consists of two short dips, first in a mixture of 3 volumes of strong nitric acid and 1 volume of strong sulphuric acid, these proportions being reversed for the second dip. According to Haas[4], a dip for from 5 to 10 seconds in 25 per cent hydrochloric acid serves the same purpose. Chromate films, resulting from the bright dip mentioned in the preceding paragraph, are said by some authorities to be detrimental to the adherence of the deposit. Like the films of beryllium oxide, they can be removed by either of the acid treatments.

Thorough rinsing is necessary before transferring to the appropriate plating vat. A flash coating of copper is a useful preliminary to plating with other metals, and, as an exception to the foregoing statement, it is understood that good adhesion can be achieved by flashing with copper from an acid sulphate bath after using the dichromate pickling solution.

Heat tinting is hardly practicable with beryllium copper, not only because of the protective film of beryllia which forms so readily, but also because the temperature required might well upset the final heat treatment. It is claimed, however, that chemical colouring can be applied if desired, the following procedures being mentioned in the literature: aqueous potassium sulphide at 40°C for black, arsenious oxide in hydrochloric acid at 80°C for steel grey, and liver of sulphur in aqueous caustic soda for reddish brown to blue-black. The most satisfactory concentrations of these chemicals can best be found by trial; alternatively various proprietary preparations are obtainable for the purpose. Articles must be quite clean before any attempt is made to colour them, and must be well washed afterwards. Lacquering is advisable to preserve the colour.

As sulphur compounds tend to stain beryllium copper, oils or other substances containing this element should be carefully removed. Either vapour degreasing or alkaline cleaning solutions may be used for the purpose, with or without electrolysis.

Tarnish resulting from moist or sulphurous atmospheres can be removed by a short immersion either in a 10 per cent solution of sodium cyanide or in 5 to 10 per cent sulphuric acid at room

[4] *Metal Finishing*, 1956, Vol. 54, pp 48-50

temperature. Parts to be so treated should be free from grease, and should be well washed afterwards.

Machining

In the solution-annealed or partially cold worked condition beryllium copper is comparable in machinability with other non-leaded copper-base alloys, detailed recommendations concerning which will be found in CDA. Publication No. 34, "The Machining of Copper and Its Alloys" (now superseded by TN44, Machining Brass, Copper and its Alloys). The partially cold-worked grades are, on the whole, easier to machine than the solution heat-treated material, which tends to be "sticky" and to drag under the tool. Tools of high-speed steel give satisfactory performance at moderate rates of cutting, but carbide-tipped tools can be used with advantage where rapidity of production is essential.

In the precipitation hardened condition the normal alloy is usually too hard for ordinary cutting operations, but adjustments of size can be achieved by grinding. Precipitation hardened low beryllium copper can, however, be cut with carbide or diamond tools if necessary, though it is preferably machined before the final heat treatment.

Solution heat-treated stock is generally free from internal stress, and is unlikely to distort during machining. The same remark applies to material in the precipitation hardened condition. Distortion due to internal stress is, in fact, only likely to arise in the case of the partially cold-worked grades. While no clear recommendations concerning stress-relief heat treatment appear to have been published, it is probable that this could be accomplished at a temperature below that at which precipitation hardening becomes appreciable. From half to one hour at about 250°C is suggested for purposes of trial.

Beryllium copper is often covered with a thin film of hard oxide, and it is consequently desirable that preliminary cuts should be deep enough to reach well beneath the original surface. Alternatively the film may be removed by pickling, as described in Pickling and Finishing. Moreover, light cuts tend to work-harden the surface layers of beryllium copper, with consequent wear of the tools. A depth of cut of at least 0.007 inch should be maintained wherever practicable.

Rigid support of both work-piece and tool is essential, and toolholders should be robust. Owing to its lower modulus of elasticity, an unsupported beryllium copper rod will deflect more under a given tool pressure than a steel rod of the same size.

A cutting fluid or lubricant should always be applied, an important function of which is to keep the metal cool. Without such precautions the surface layers may reach a temperature sufficient to cause partial precipitation hardening, with dire consequences to the life of the tool. Aqueous emulsions of the so-called "soluble" oils have excellent cooling properties, while mineral and vegetable oils provide superior lubrication. In most cases the emulsions are to be preferred for beryllium copper. With either type of cutting fluid it must be remembered that the sulphur compounds which they often contain will stain beryllium copper if allowed to remain on the metal. Emulsions, unless removed with warm water, are apt to contract into droplets as they dry, and, if sulphur is present, will lead to objectionable dark spots.

In general, tool design as well as cutting speeds and feeds should follow the recommendations given in CDA. Publication No 44 for the class of alloys to which beryllium copper belongs, namely those of "Group A" which are strong and tough with homogeneous structures, but which lack specifically free-machining qualities.

Joining

Beryllium copper can be successfully joined by welding, brazing and soldering, but all joining processes which involve the application of heat must be considered in relation to two fundamental properties of beryllium copper, namely its susceptibility to precipitation hardening and the formation of a thin but tenacious film of beryllium oxide on the surface when heated.

Welding should preferably be carried out before the solution heat treatment, so that the whole of the product, including the weld zone, receives the same full heat treatment. Gas welding of beryllium copper appears to be impracticable because of the rapid formation of beryllium oxide which is difficult to remove by fluxing. The carbon arc method, using coated filler rods of beryllium copper, aluminium bronze or silicon bronze, is, however, more satisfactory, provided that melting is rapid and the rate of welding high. No flux is required in view of the blanketing effect of the carbon arc gases. Metal arc welding with coated beryllium copper or coated aluminium bronze electrodes gives good results. Suitable fluxes include ordinary brazing fluxes with admixtures of sodium carbonate and potassium bifluoride, and boric acid containing sodium fluoride. Spot, butt and seam welds in beryllium copper can also be made by the resistance welding process without difficulty. Good welds can be made by the argon arc process, without flux.

Brazing and particularly silver soldering with alloys melting between 600°C and 700°C can be applied to beryllium copper, using the normal fluxes supplied with the solders. If, however, the surface is badly oxidised it is desirable to clean it mechanically before brazing, while solvent degreasing is recommended when specimens are heavily coated with grease. Brazing and silver soldering should be carried out quickly and are necessarily restricted to material in the solution heat-treated condition, since the temperature involved would destroy the effects of previous precipitation hardening. It is, however, an advantage that brazed or silver soldered articles can subsequently be hardened and strengthened by heat treatment at relatively low temperatures, even though response to heat treatment in the vicinity of the joint may be somewhat impaired.

Though it is often claimed that the soft soldering of beryllium copper presents no difficulty, certain precautions are necessary if consistently good joints are to be obtained. It is of primary importance that the surfaces to be soldered should be free from beryllium oxide. Since soft soldering must clearly be carried out after the final heat treatment, the melting point of solder being lower than the precipitation hardening temperature, it is evident that superficial oxide arising from both the high and low temperature heat treatments will be present on the surface unless special precautions are taken to remove it. Though a considerable amount of beryllium oxide may be formed during the solution heat treatment, the precipitation hardening treatment is much less detrimental from this point of view. It is, however, definitely expedient to remove the oxide film between the two heat treatments since the second of these tends to make any beryllium oxide previously present less easy to eliminate. Where possible it is desirable to adopt abrasive or mechanical cleaning, using a file, emery paper or even metal polish, but in many cases, as in the mass production of minute components, this is hardly practicable. Such articles should be pickled between the two heat treatments, in the solution described in Pickling and Finishing. In obstinate cases it may be necessary to repeat the pickling process after the final heat treatment; but it will generally be found that ordinary soft soldering fluxes based on zinc chloride effectively combat any traces of oxide which may be reformed at this stage, as also do certain of the activated resin fluxes.

More specific recommendations concerning the various techniques of joining beryllium copper are included in CDA. Publication No. 47, "The Welding, Brazing and Soldering of Copper and Its Alloys", to the index of which the reader is referred.

9 - Beryllium Copper in Relation to Health

Certain compounds of beryllium, notably the oxide, are known to be toxic and detrimental to health if inhaled or otherwise absorbed into the body. Accidents have occasionally occurred among operatives or others handling fluorescent electric lamps some of which are coated internally with beryllium compounds but, as far as can be ascertained, none has ever been reported in connection with the manufacture or use of beryllium copper.

As a safety precaution, furnaces in which beryllium copper is melted must be hooded and provided with extractor fans, and adequate forced ventilation must be installed in casting shops. The use of respirators is desirable in foundries, and also when welding, especially if fluxes such as fluorides which are likely to carry volatile beryllium compounds into the atmosphere are employed. Once the metal has solidified, however, it can be regarded as perfectly harmless, and beryllium copper can be handled in press shops, machine shops and heat treatment plants with complete safety, except for the possible formation of oxide dust during high temperature heat-treatment. In subsequent use the metal is quite innocuous.

10 – Conclusion

It will be appreciated that the information and data recorded in these notes are intended to serve as a guide to the range of properties obtainable with beryllium copper and low beryllium copper under various conditions. It does not follow that all grades of commercially available material will behave exactly in the manner outlined; on the contrary, considerable variations are to be expected. In planning the use of beryllium copper for any particular application it is, therefore, likely that trials may be necessary before the most satisfactory procedure is established, especially in respect of the degree of cold work to be applied and the optimum duration and temperature of the precipitation hardening treatment.

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The publications included in this short bibliography have been selected from the extensive literature of the subject as being informative and representative. All are relatively modern, and much of the information given in the text is based upon them. An attempt has been made to group them under convenient headings, but many of the publications deal with more than one aspect of the subject.

Copper Development Association regrets that, its own publications excepted, it is unable to make available on loan or otherwise any of the items in the list.

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