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COPPER-ZIRCONIUM ALLOYS
(A Literature Survey)

by

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ABSTRACT

A review of work on high-conductivity copper-zirconium alloys is presented, covering such topics as the phase diagram, melting procedures, fabrication, heat treatment, properties and applications. Comparative reference is made to other high-conductivity alloys. The further development of copper-zirconium alloys includes the addition of third elements such as chromium, arsenic and hafnium.

RÉSUMÉ

Les auteurs passent en revue les recherches effectuées sur les cupro-zirconiums à haute conductibilité électrique, touchant aux sujets suivants: diagramme d'éguilibre, procédés de fusion, fabrication, traitment thermique, propriétés et usages. Ils comparent le cupro-zirconium à d'autres alliages à haute conductibilité électrique. D'autres essais sur les cupro-zirconiums comportent l'addition de tiers éléments comme le chrome, l'arsenic et le hafnium.

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CONTENTS

Page

Abstract i

Résumé i

Introduction 1

Phase Diagram. 2

Melting and Fabrication. 2

Heat Treatment 4

Room-Temperature Properties. 5

Elevated Temperature Properties. 6

Corrosion Resistance 7

Joining and Machinability. 8

Applications 8

Further Development. 8

References 10

Figures 1-11 12-17

Tables 1-14. 18-24

FIGURES

No. Page

1. Solid solubility of zirconium in copper 12
2. Comparison of creep properties of air-melted and vacuum-melted copper-zirconium alloys with different zirconium contents. 12
3. Effects of ageing, in combination with cold work, on the tensile strength. 13
4. Electrical conductivity as a function of ageing temperature and zirconium content 13
5. Effects of zirconium content. 14
6. Effect of temperature and time on grain size. 14
7. Average grain size as a function of zirconium content 15
8. High-temperature strength of Cu-0.15% Zr and Cu-0.70% Cr alloys. 15
9. High-temperature ductility of Cu-0.15% Zr and Cu-0.70% Cr alloys. 16
10. Comparison of creep properties. 16
11. Electrical conductivity and resistivity as functions of temperature. 17

TABLES

1. Room-Temperature Properties of Copper-Zirconium Alloys Prepared by Different Methods. 18
2. Comparison of Room and Elevated Temperature Tensile Properties of Copper-Zirconium Alloys Prepared by Different Methods 18
3. Recommended Solution-Annealing and Ageing Cycles. . . 18

(Tables, cont'd) -

No. Page

4. Properties of the Alloys Containing Different Amounts of Zirconium 19

5. Mechanical and Physical Properties Data for 0.13% Zirconium-Copper Given a 980°C (1795°F) Solution Anneal and Various Cold-Working Treatments 20

6. Mechanical and Physical Properties Data for 0.13% Zirconium-Copper Given a 980°C (1795°F) Solution Anneal and Various Cold-Working Treatments and Then Aged. 20

7. Mechanical and Physical Property Data for 0.13% Zirconium-Copper Given a 980°C (1795°F) Solution Anneal, Various Cold-Working Treatments, and Aged. . 21

8. Comparative Property Data Showing Effect of Cold-Working after Ageing. 21

9. Rupture Strength of Three High-Conductivity Alloys at 260°C (500°F) 21

10. High-Temperature Impact Strength of Cu-0.15% Zr and Cu-0.70% Cr Alloys 22

11. Coefficient of Linear Expansion of Cu-0.15% Zr and Cu-0.70% Cr Alloys 22

12. Properties of Various Zirconium and Chromium Alloys at Room Temperature and 600°C (1110°F) 23

13. Tensile Properties at 400°C (750°F) of Copper-Hafnium and Copper-Hafnium-Zirconium Alloys. 24

14. Properties of Copper-Zirconium and Copper-Arsenic Alloys 24

INTRODUCTION

Copper-zirconium alloys are being increasingly utilized in applications requiring material which combines high electrical conductivity with good resistance to softening at elevated temperatures. As operating temperatures in the electrical field have increased, designers have turned from pure copper to copper-silver alloys and then to copper-chromium alloys. Now, copper-zirconium has further increased the temperature at which high-electrical-conductivity copper alloys can be used. With proper cold-working and heat-treating procedures, tensile strengths of 70,000 psi and electrical conductivities up to 96% I.A.C.S. can be developed, and this alloy will retain most of its tensile and yield strength at temperatures up to 450°C (840°F) and its hardness at temperatures up to 500-550°C (930-1020°F). It has a softening temperature in excess of 550°C (1020°F), as compared with approximate softening temperatures of 200°C (390°F) for copper, 325°C (615°F) for phosphorus-deoxidized copper, and 350°C (660°F) for silver-bearing copper and cadmium copper. Although copper-chromium can develop superior mechanical properties at room temperature, and can resist softening very well both under long-time exposure up to 400°C (750°F) and during properly controlled brazing cycles as high as 700°C (1300°F), copper-zirconium still has the advantage of better electrical conductivity and better ductility, both at room and elevated temperature. Furthermore, copper-chromium is notch-sensitive, whereas copper-zirconium is not. Copper-zirconium also shows its superiority in one of the ever-present problems in the brazing of copper, copper-silver, copper-chromium and copper-beryllium alloys, where softening at the joint and in the adjacent heat-affected area occurs. In zirconium-copper, there is a marked decrease in this tendency to soften compared to tough-pitch copper and silver-bearing copper, its electrical counterparts. When copper-zirconium is compared with copper-chromium and copper-beryllium, the difference is not so marked, but it is still in favour of the copper-zirconium alloy.

So, considering the potential importance of this new alloy, and the interest in developing high-electrical-conductivity, high-strength materials where resistance to softening on heating is important, it seems appropriate to summarize the published work about this new material.

American Metal Climax, Inc., refers to its alloy as Amzirc. Following its own development program, Nippert Electric Company designated the alloy N-4.

PHASE DIAGRAM

Although the copper-zirconium phase diagram is reasonably well established(1), there are different opinions about the copper-rich portion. Recently Saarivirta(2), Zwicker(3) and Showak(4) have reported the maximum limit of solubility of zirconium in copper as 0.15, 0.11 and 0.24% by weight respectively, with room-temperature solubility between 0.01 and 0.02%. Figure 1 shows the copper-rich portion of the copper-zirconium phase diagram, after Saarivirta(2), based on microstructural examination. The dashed line is the result obtained by Showak, using metallographic and electrical resistivity measurements. The first intermediate phase has been reported as Cu_3Zr(1-3); however, few data are available to substantiate this conclusion. Hansen(1) has suggested that Cu_4Zr might be more appropriate. More recent work by Donachie(5), using microprobe analysis supplemented by metallographic and thermal analyses, indicated that the first intermediate phase was Cu_4Zr and reported the maximum limit of solubility as 0.17% by weight. The latter corresponds closely to Saarivirta's value of 0.15% of zirconium but it is substantially lower than that reported by Showak (0.23%). Donachie fixed the eutectic temperature at ~970°C, which is close to the values of 965°C (1764°F) chosen by Hansen and 980°C (1796°F) reported by Saarivirta and Showak. The eutectic composition was reported by Allibone et al.(6), Pogodin et al.(7) and Raub et al.(8) as 12.5, 12.9 and 13.7% by weight of zirconium, respectively; while a microprobe trace of the eutectic perpendicular to the lamellae, by Donachie, suggests an average composition of ~13.5 weight per cent of zirconium.

MELTING AND FABRICATION

The successful production of alloys containing a reactive element is often made difficult by the affinity of the added element for impurities and for oxygen and nitrogen, since the formation of stable compounds, particularly oxides, reduces the proportion of the element which is effective in improving properties. This is especially true of copper alloys containing a small proportion of zirconium. Thus, the commercial product containing a nominal 0.13% Zr is made up from OFHC copper and high-purity zirconium which have been melted and cast under a protective reducing atmosphere. The techniques of vacuum melting and air melting may also be used, and a comparison of the effects of these melting methods on the properties of the alloy, compared with the commercial materials, has been reported by Dooley et al.(9). Cathode copper and a higher zirconium content were used, giving the results shown in Tables 1 and 2. Apart from the difference in the main characteristics of the material, i.e. method of manufacture of the alloy and zirconium content, the vacuum-melted alloys contained higher amounts of the impurities iron and silicon than the other two alloys. The presence of these impurities doubtless accounts for the lower conductivity of the vacuum-melted alloys as seen in Table 1. It may also explain the higher strength of the vacuum-melted alloy containing 0.23% Zr in comparison with the corresponding air-melted alloy, the small difference being significant statistically. This higher strength may also be attributed to the availability of a greater proportion of zirconium, since the strength of alloys prepared out of contact with the atmosphere increases with zirconium content even when this exceeds the solubility limit determined by Saarivirta(2)(10)(11). Table 2, which compares room and elevated temperature properties, shows small differences in the properties of copper-zirconium made in the three different ways. It also shows that all the alloys are notch-insensitive up to 300°C (570°F). However, creep properties are affected by the method of preparation of the alloy, as is shown by a comparison of an OFHC copper-0.61% Zr alloy with an air-melted alloy of similar zirconium content. Although the tensile strength of these two alloys differed by only 0.9 kpsi at room temperature in favour of the OFHC copper brand, the latter gave a plastic creep strain of 0.19% after 400 hours at 230°C (445°F), by which time the air-melted alloy had fractured(9). As can be seen from Figure 2, creep resistance increases with zirconium content, and vacuum-melted alloys are slightly superior to air-melted alloys.

In general, manufacturing processes that take into account the reactivity of zirconium make possible the achievement of good properties with zirconium contents lower than those required to achieve similar properties with an air-melted and cast alloy.

The cast structure of billets, irrespective of melting techniques, may be broken down by hot-rolling, extrusion or forging at about 900°C (1650°F). If more convenient, they can be worked at lower or higher temperatures. Although the alloy is not nearly as susceptible to oxygen penetration along the grain boundaries as pure copper, it is nevertheless recommended that preheating be done under either a reducing or a neutral atmosphere. Exposure to an oxidizing atmosphere will result in subscale formation, which, in return, will retard further diffusion of oxygen(10)(11). The subsurface layers affected will not respond to precipitation hardening, but the mechanical and electrical properties of the internally oxidized layers are almost identical with those of pure copper(11).

Once the cast structure has been refined, the alloy is amenable to all hot and cold working operations. The cold drawing characteristics of this alloy are very similar to those of tough-pitch copper(11).

HEAT TREATMENT

Although zirconium additions to copper produce an age-hardening type of alloy, in that the zirconium solubility decreases with decreasing temperature (Figure 1), response to precipitation hardening is slight and the mechanical properties are developed primarily by cold working, as can be seen in Figure 3, which shows the effects of ageing in combination with cold work on the tensile strength of Amzirc (0.13% Zr)*. Solution annealing imparts to the copper-zirconium alloys their excellent resistance to softening, up to 550°C (1020°F). However, this process results in low electrical conductivity (55-72% I.A.C.S.) because of zirconium being taken into solid solution, and a low-temperature ageing treatment is required to precipitate the zirconium and thus bring the electrical conductivity up to 85-95% I.A.C.S.(2)(11)(12). The effect of ageing temperature on electrical conductivity is illustrated in Figure 4 for a range of zirconium contents(2).

The normal processing with the copper-zirconium alloys consists of solution-annealing, quenching, cold-working, and ageing. Table 3 shows the recommended solution-annealing and ageing cycles for a zirconium content from 0.13% to 0.20% after Lynch(11). Normally, as the solution-annealing temperature is increased, the ageing temperature should also be increased in order to maintain a high electrical conductivity. If the material is cold-worked after annealing and quenching, the ageing treatment can be carried out at lower temperature, since precipitation will occur more rapidly. For example, with a 900°C (1650°F) solution anneal (approximately 0.07% Zr taken into solution), 500°C (950°F) for 3 hours would be a typical ageing treatment for material given no cold work before ageing, while 3 hours at 400°C (750°F) will be preferred for a material that has been cold-worked before ageing. For a material given no cold work before ageing and solution-annealed at 980°C (1795°F) (approximately 0.15% Zr taken into solid solution), 3 hours at 550°C (1020°F) would be a typical ageing treatment, while 3 hours at 450°C (840°F) would be the typical ageing treatment if the material has been cold-worked before ageing(11).

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*Materials used were OFHC copper and zirconium.

To obtain optimum mechanical and physical properties of copper-zirconium alloys, as determined by Saarivirta(2) (Figure 5), it is necessary to put 0.13% to 0.15% Zr into solid solution. This requires solution-annealing at 950°C to 980°C (1740 to 1795°F) and then quenching. However, when the material must be reannealed prior to final cold-working, the alloy tends to form excessively large or non-uniform grains during high-temperature solution annealing, as shown in Figure 6. This condition may weaken the structure and cause early failure under prolonged stresses. It may also cause rough surfaces in the cold-drawn rod. To avoid these adverse effects, Saarivirta(13) selected 900°C (1650°F) as a practical solution-annealing temperature since annealing at this temperature puts most of the zirconium into solid solution and does not create a serious grain growth problem. Based on the fact that solution and diffusion of the zirconium occur very rapidly at the normal solution-annealing temperature of 900-980°C (1650-1795°F), Lynch(11) states that it is only necessary to insure complete heating of the furnace load prior to quenching. This will limit grain growth by minimizing the exposure time at solution-annealing temperature. Further work by Saarivirta(10) suggests the use of a higher zirconium content, i.e., more than 0.15%. The average grain size of various copper-zirconium alloys, compiled from the last reference, is shown as a function of zirconium content in Figure 7. The grain size decreases rapidly with increasing zirconium content. Despite undissolved particles of the first intermediate phase throughout the grain and grain boundaries, the alloy does not become anisotropic -- the mechanical properties remain nearly the same either longitudinally or transversely to the rolling direction regardless of zirconium content (Table 4). However, the alloys containing 1.11% Zr have poorer cold-workability than the others(10). It appears from these observations that the zirconium content should be at least 0.35%, to obtain the desirable combination of small and uniform grain size along with optimum mechanical and physical properties.

ROOM-TEMPERATURE PROPERTIES

Tables 5, 6 and 7, after Lynch(11), show mechanical and physical properties of a copper-zirconium alloy. Since the composition range for this alloy is 0.13% to 0.20% Zr, these data indicate the approximate minimum mechanical properties obtainable for material solution-annealed at 980°C (1795°F) and given various combinations of cold-working and ageing. Table 5 shows data on material that has been solution-annealed and cold-worked only. Comparison with Table 6 and 7, where the material has been aged after annealing and cold-working, further reveals the effects of ageing. The electrical conductivity is brought up from 64%

I.A.C.S. to 85-95% I.A.C.S., while the mechanical properties are only slightly improved by ageing treatment. Comparison of the tensile data for material cold-worked and aged (Table 6 and 7) indicates higher mechanical properties for material cold-worked 40% or more with the 400°C (750°F) 3-hour ageing treatment than for material cold-worked less than 40% with the 450°C (842°F) 3-hour ageing treatment. It should be noted that higher electrical conductivities are obtained with the 450°C (842°F) 3-hour ageing treatment. Other combinations of mechanical and electrical properties are possible with different ageing time-temperature cycles, and still higher tensile and yield strength may be developed if the material is cold-worked after the ageing treatment. However, elongation and electrical conductivity would be decreased by such a practice, as is seen from Table 8. Thus, it is important to avoid heavy reduction after the ageing treatment if high electrical conductivity is necessary. Material with a higher zirconium content than that used for the data in Tables 5, 6 and 7 will yield slightly superior mechanical properties, both as drawn from solution-annealed material and after ageing, due to greater precipitation hardening effects, but a higher ageing temperature or a longer ageing time will be required to develop the same electrical conductivity(11).

Endurance strength tests reported by American Metal Climax, Inc., show that copper-zirconium (0.13%) is superior to unalloyed copper. An endurance strength of 28,800 psi was found after over 30,000,000 test cycles. When extrapolated to 100,000,000 cycles the endurance strength is approximately 28,000 psi, which contrasts with 17,000 psi for hard-drawn copper under the same test conditions.

ELEVATED TEMPERATURE PROPERTIES

The short-time, high-temperature tensile properties of Cu-0.15% Zr and Cu-0.70% Cr alloys were determined by Saarivirta and Taubenblat(13) at temperatures up to 600°C (1110°F). The results of these tests are shown in Figures 8 and 9. Figure 8 shows that at temperatures up to 500°C (930°F), the strength of 84% cold-worked copper-chromium alloy is lower than similarly cold-worked copper-zirconium alloy and about equal to that of the 54% cold-worked copper-zirconium alloy. Above this temperature, the strength of the copper-chromium alloy is lower than that of the copper-zirconium alloy, regardless of the amount of cold work. In addition to higher strength, copper-zirconium in the cold-worked and aged condition is also more ductile than copper-chromium, as seen in Figure 9. However, in the solution-annealed and aged condition, the copper-chromium alloy is stronger than copper-zirconium at all temperatures, but its ductility is low at elevated temperatures. Tests at 260°C (500°F) by Peckner(14) show that copper-zirconium has tensile properties that are somewhat better in the transverse direction than in the longitudinal direction (Table 9). This is important for commutator bar applications where stresses are transverse to the drawing operations(15). Thus, copper-zirconium compares very well for this application with copper-chromium in which the strength is better in the longitudinal direction. These stress-rupture data also show that the copper-zirconium alloy is essentially insensitive to the presence of a notch, whereas copper-chromium is not. Comparison of high-temperature impact strength of Cu-0.15% Zr and Cu-0.70% Cr (Table 10) shows that the impact strength of copper-zirconium is about 30% higher than that of copper-chromium at room temperature and this difference is maintained throughout the temperature range, although the strengths of both alloys decrease slightly up to 400°C (750°F) and more noticeably at 500°C (930°F)(13). Comparative data on the creep properties by Shapton(16) again show the superiority of copper-zirconium over copper-chromium (Figure 10). Saarivirta(13) determined the coefficient of linear expansion on material solution-annealed and aged as well as on cold-worked and aged material. According to these results (Table 11), there is a tendency for cold-worked and aged material to expand slightly more than the solution-annealed and aged material, particularly at the temperature above 100°C (210°F), both for copper-zirconium (0.15% Zr) and copper-chromium alloys.

Figure 11 shows the electrical conductivity and the resistivity as functions of temperature. For comparison purposes, the value for OFHC copper was also determined. As can be seen, the conductivity decreases rapidly with increasing temperature. OFHC copper has the highest conductivity at all temperatures, followed by the copper-zirconium alloy, whereas the copper-chromium alloy has the lowest conductivity(13). Thermal conductivity is reported by American Metal Climax, Inc., as constant up to 500°C at 187-211 BTU/M/sq ft/ft/°F, depending on the degree of cold-working done on the material.

CORROSION RESISTANCE

The resistance of copper-zirconium to corrosive agents and oxidation is similar to that of copper. Like copper, copper-zirconium is not resistant to sulphides, nitric acid, ferric chloride, or ammonia. In resistance to attack by mercury, zirconium-copper is superior to copper. In thin sections such as small-size wire, copper-zirconium alloy should be protected against oxidation, since its rate of oxidation at elevated temperature is approximately the same as that of copper(17).

JOINING AND MACHINABILITY

Copper-zirconium may be soft-soldered or silver-alloy-brazed by using the same materials and procedures as are applicable to copper(17). Because of copper-zirconium's high softening point, there is a marked decrease in its tendency to soften during brazing as compared with other high-conductivity alloys. High-temperature brazing (900 to 1000°C) will result in the softest condition possible, and the properties will be the same as for the solution heat-treated condition.

The machinability of copper-zirconium compares favourably with that of copper-silver, whereas copper-chromium is more difficult to machine(16)(18).

APPLICATIONS

The copper-zirconium alloy is used for resistance welding tips and wheels, motor commutators (particularly for aircraft), semiconductor stud bases, coils and windings that must retain strength at elevated temperature, and other applications that require an electrical conductivity closely approaching that of copper and where mechanical properties similar to those of chromium copper are desired. Its high modulus of elasticity (18.7 x 10^6 psi), combined with its high electrical conductivity, enables this alloy to be used for switch jaws, springs, and other structural parts, which must be conductors as well(12)(15)(18). This alloy has also been reported(19) to be an excellent material for rocket nozzle liners. Use of the copper-zirconium alloy is said to double the chamber pressure limit of test rocket engines, boosting it to 1000 psi for the hottest-burning propellants (4690°C) (8500°F).

FURTHER DEVELOPMENT

The use of a third element with zirconium appears to denote the most promising trend in the development of copper-zirconium alloys, since the effects of heat treatment and cold work have already been well investigated. The combinations of zirconium and chromium, zirconium and hafnium, or zirconium and arsenic, are favoured.

Pavlova(20) reports some results on copper-chromium alloys containing zirconium, but the properties of copper-chromium-zirconium alloys have been more comprehensively examined by Mizuno(21) who suggests an optimum composition of 0.5% Cr and 0.2 to 0.6% Zr. This choice is supported by the properties given in Table 12. Zakharov et al.(22) studied the ternary system copper-chromium-zirconium up to 3.5% each of chromium and zirconium and reported that the additions of zirconium markedly increase the solubility of chromium in copper but additions of chromium have little influence on the solubility of zirconium in copper.

The similarity between the characteristics of hafnium and those of zirconium led Saarivirta(10) to investigate the additions of hafnium to copper with and without small amounts of zirconium. Small additions of hafnium affect the properties of copper in a manner similar to that of chromium and zirconium. The properties are similar to those of copper-chromium alloys, except for tensile strength, which is somewhat higher. Additions of zirconium result in ternary alloys precipitation hardenable to a greater degree than are the binary copper-zirconium or copper-hafnium alloys. However, in this respect they are still inferior to the copper-chromium alloys. So, in order to obtain higher hardness and strength, the copper-hafnium and copper-hafnium-zirconium alloys must be cold-worked. As indicated by the fact that maximum precipitation hardening in copper-hafnium and copper-hafnium-zirconium alloys occurs at a higher temperature than in other known high-conductivity copper alloys, the high-temperature properties are superior. Table 13 shows the results of tests at 400°C (750°F) where copper-chromium and copper-zirconium alloys are used for comparison. Binary copper-hafnium alloy has higher strength and elongation than copper-chromium and copper-zirconium. It is interesting to note that zirconium additions to the copper-hafnium alloy further increase the strength and elongation. This makes the copper-hafnium-zirconium alloy superior for use at high temperature. Values of electrical conductivity at room temperature for the lower and higher zirconium content of the ternary alloys shown in Table 13 are 83 and 86% I.A.C.S., respectively, in the solution-annealed and aged condition.

The effect of arsenic on binary copper-zirconium alloys was also investigated by Saarivirta(23)(24). Arsenic is reported to raise the eutectic temperature to 1000-1020°C (1830-1870°F) and to increase the solubility of zirconium at this temperature and decrease it at lower temperature. As a result, electrical conductivity is markedly improved over that of binary copper-zirconium alloys. Arsenic reacts with zirconium in the alloy to form finely dispersed particles which retard grain growth during solution-annealing of the wrought material and also assist in improving castability. As in binary copper-zirconium alloys, the response of the ternary alloy to precipitation hardening is slight, and the properties are developed by a combination of heat treatment and cold work. The optimum ratio of zirconium to arsenic is stated to be 2:1. Table 14 shows that, along with electrical conductivity, hardness and tensile strength are improved by arsenic additions, the most desirable combination of properties being obtained in an alloy containing 0.5% Zr and 0.25% As.

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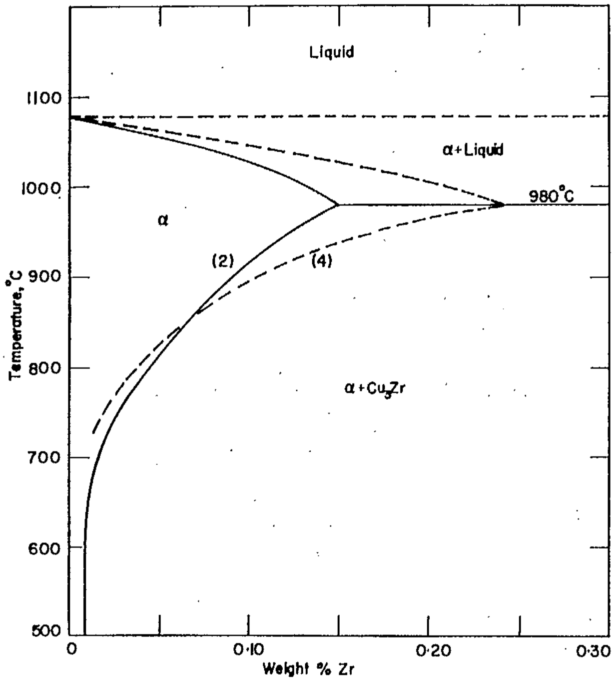

Figure 1.
Solid solubility of zirconium in copper. (Ref. 2, 4).

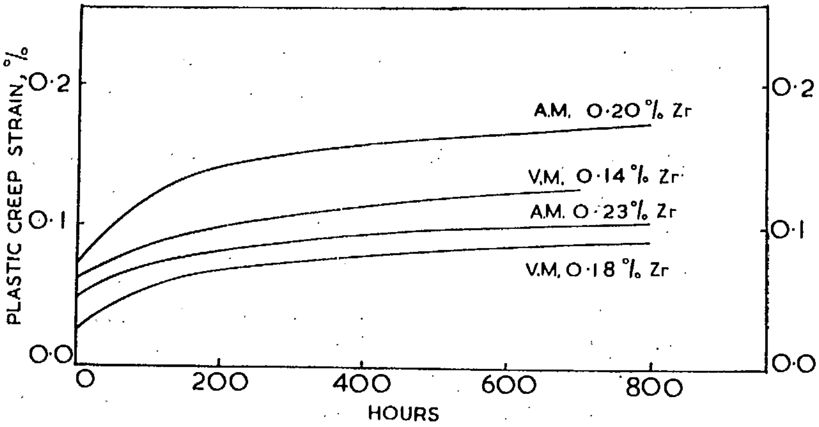

Figure 2. Comparison of creep properties of air-melted and vacuum-melted copper-zirconium alloys with different zirconium contents. Material solution-annealed 20 min at 850°C (1560°F), aged 2 hr at 400°C (750°F), cold-rolled 50%, and aged 2 hr at 400°C (750°F). Tested at 230°C (445°F) and 44.8 kpsi.

AM - air-melted
VM - vacuum melted (Ref. 9).

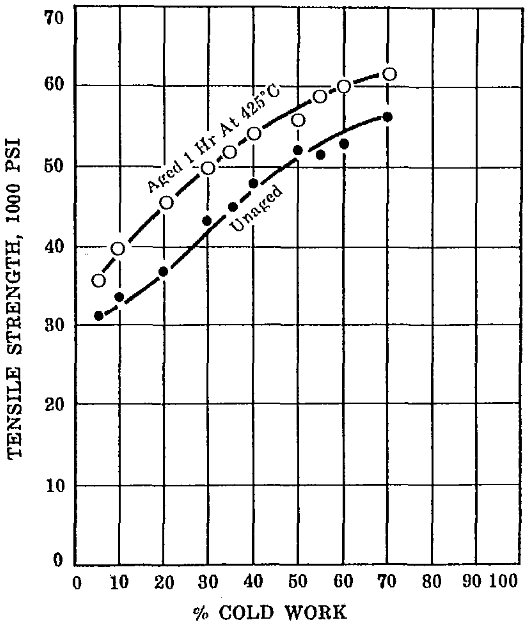

Figure 3. Effects of ageing, in combination with cold work, on the tensile strength. Material solution-annealed at 900°C (1650°F). Source: American Metal Climax, Inc., New York.

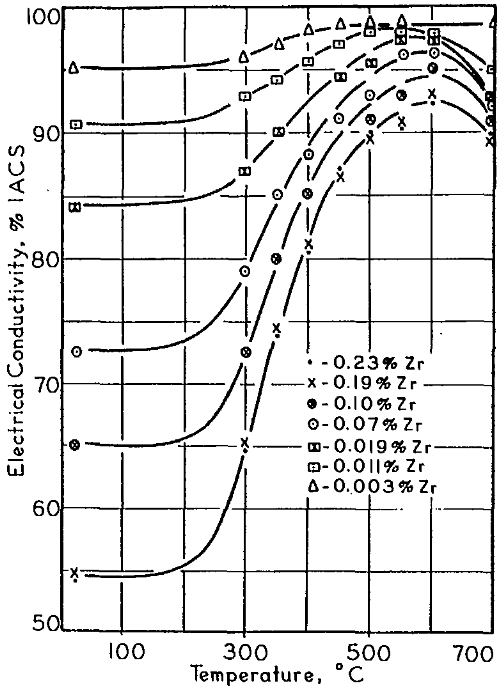

Figure 4. Electrical conductivity as a function of ageing temperature and zirconium content. Material cold-drawn 90% and aged 1 hr. (Ref. 2).

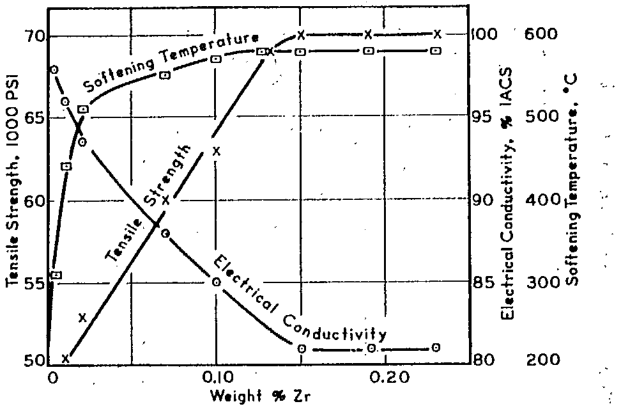

Figure 5. Effects of zirconium content. Material solution-annealed at 980°C, quenched, cold-drawn (90%), and aged at 400°C (750°F) for 1 hr. (Ref. 2).

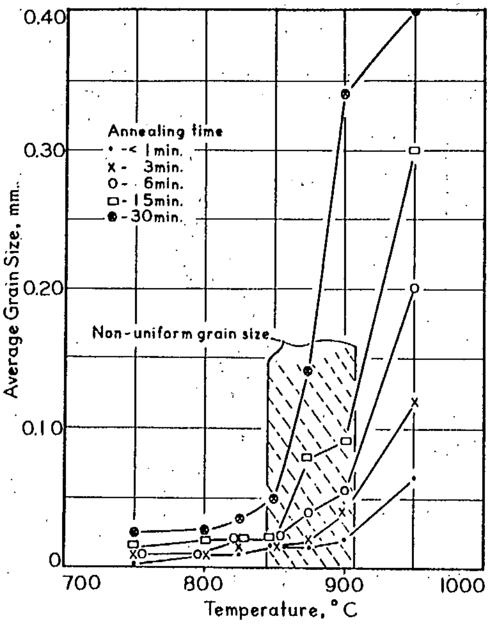

Figure 6. Effect of temperature and time on grain size. Material solution-annealed for 1 hr at 980°C (1795°F), cold-drawn (72%) prior to reannealing. (Ref. 2).

Zr content - 0.15%

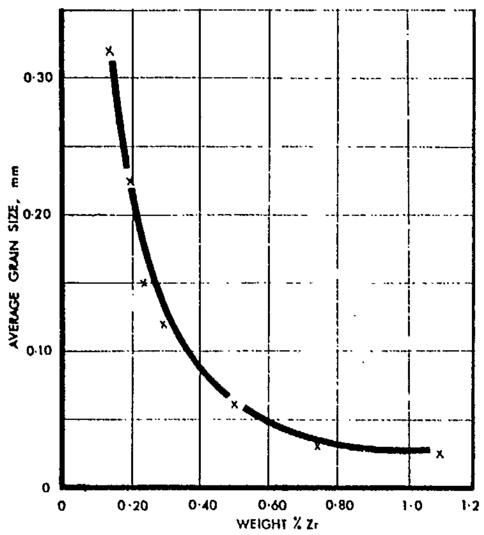

Figure 7. Average grain size as a function of zirconium content. Material cold-rolled (25%), solution-annealed at 950°C (1740°F) for 30 min, and quenched. (Ref. 10).

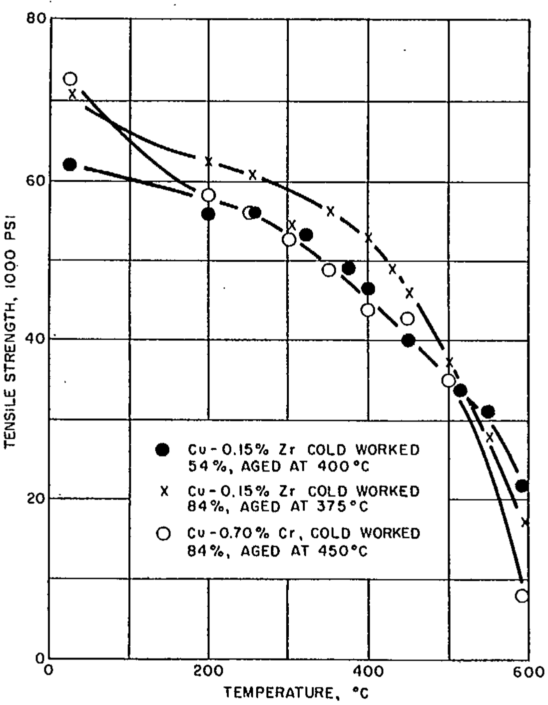

Figure 8. High-temperature strength of Cu-0.15% Zr and Cu-0.70% Cr alloys. (Ref. 13).

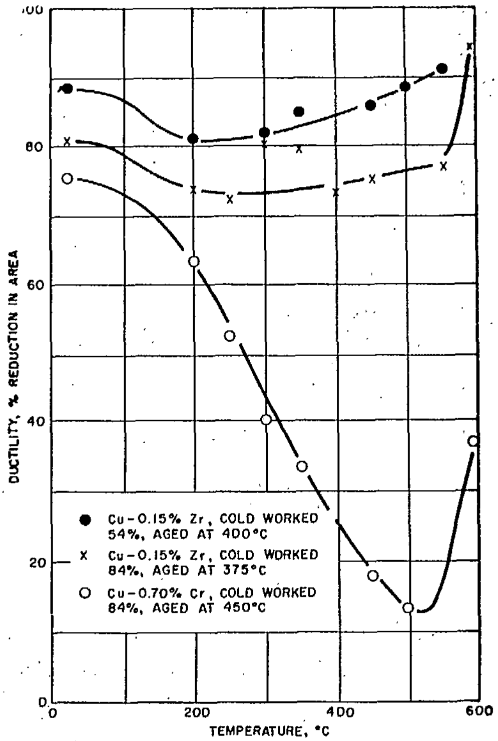

Figure 9. High-temperature ductility of Cu-0.15% Zr and Cu-0.70% Cr alloys. (Ref. 13).

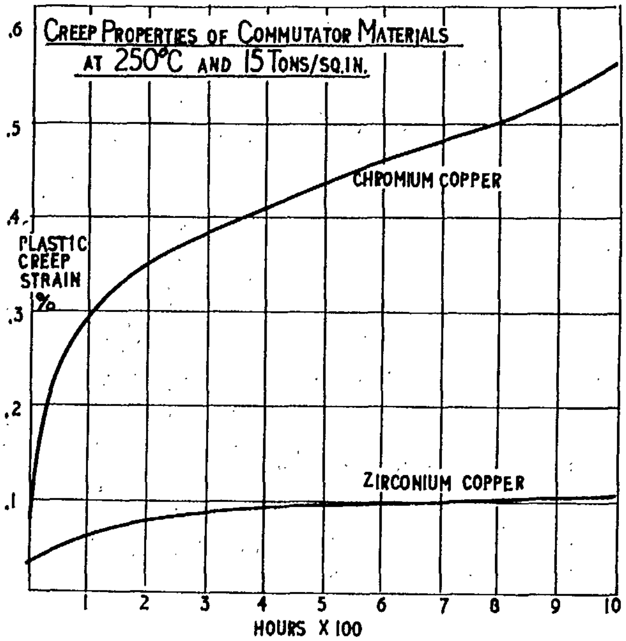

Figure 10. Comparison of creep properties. (Ref. 16).

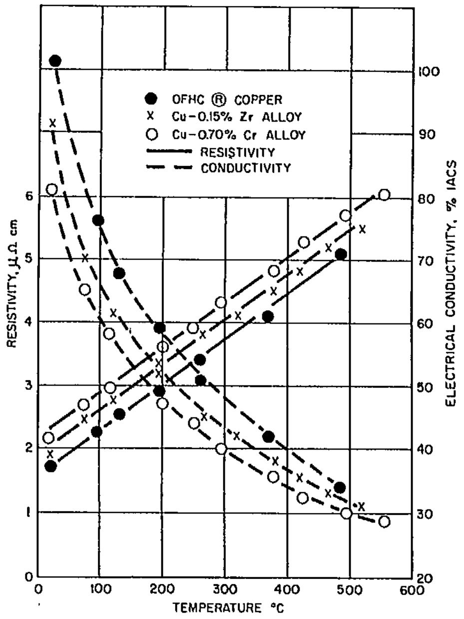

Figure 11. Electrical conductivity and resistivity as functions of temperature. Materials cold-drawn 84% and aged prior to testing. OFHC copper tested in annealed condition. (Ref. 13).

TABLE 1

Room-Temperature Properties of Copper-Zirconium Alloys Prepared by Different Methods

No. of Results Averaged	Property	OFHC Brand Copper (0.12% Zr)	Vacuum Melted (0.17% Zr)	Vacuum Melted (0.23% Zr)	Air Melted (0.23% Zr)
48	Tensile Strength, psi	61,600	64,700	65,600	63,400
20	0.1% Permanent Set Stress, psi	56,700	60,000	60,700	58,500
24	Conductivity, % I.A.C.S.	94.1	91.0	90.3	92.7

Tested on full section of 3/8 in. diameter rod. Results averaged from all figures for a range of heat treatment and cold work. (Ref. 9).

TABLE 2

Comparison of Room and Elevated Temperature Tensile Properties of Copper-Zirconium Alloys Prepared by Different Methods

Temperature	Tensile Strength (psi)							
	OFHC Brand Copper (0.12% Zr)		Vacuum Melted (0.17% Zr)		Vacuum Melted (0.23% Zr)		Air Melted (0.23% Zr)	
	P	N	P	N	P	N	P	N
Room	62,300	62,300	65,600	64,700	65,900	64,100	63,200	64,300
200°C(390°F)	53,100	54,200	56,400	55,600	55,300	55,600	54,200	55,100
300°C(570°F)	50,400	49,500	52,900	54,200	53,300	53,500	50,200	51,700

Averages of 4 results from 0.1785 in. diameter test pieces.

P = plain test piece.

N = notched test piece. (Ref. 9).

TABLE 3

Recommended Solution Annealing and Ageing Cycles

Condition	Solution Treating T° - Time	Ageing T° - Time
Solution-annealed and aged	900-980°C; 5-30 min	500-550°C; 1-4 hr
Solution-annealed, cold-worked and aged	900-980°C; 5-30 min	375-475°C; 1-4 hr

(Ref. 11).

TABLE 4

Properties of the Alloys Containing Different Amounts of Zirconium

Property	Copper - 0.19% Zr		Copper - 0.29% Zr		Copper - 0.40% Zr		Copper - 0.50% Zr		Copper - 0.74% Zr	
	Long.	Trans.	Long.	Trans.	Long.	Trans.	Long.	Trans.	Long.	Trans.
Tensile Strength (psi)										
Cold-worked condition	45,500	48,800	48,800	49,800	47,800	49,800	49,800	51,800	49,800	49,800
Cold-worked and aged condition*	-	-	55,800	55,800	-	-	56,900	56,900	-	-
Tested at 400°C (750°F)	39,800	40,800	-	-	39,800	39,800	41,800	42,700	41,800	41,800
Yield Strength (0.2% offset) (psi)										
Cold-worked condition	45,800	47,800	46,900	46,900	46,900	47,800	46,900	49,800	45,800	50,800
Cold-worked and aged condition	-	-	47,800	44,800	-	-	48,600	45,800	-	-
Proportional Strength (psi)										
Cold-worked condition	32,700	29,900	31,900	30,900	35,800	32,700	29,900	33,900	29,900	35,800
Cold-worked and aged condition	-	-	37,000	35,800	-	-	35,800	34,800	-	-
Elongation (% on 2 in.)										
Cold-worked condition	6.0	7.0	6.0	7.0	5.0	7.0	5.0	5.0	5.0	5.0
Cold-worked and aged condition	-	-	-	-	-	-	11.0	11.0	-	-
Tested at 400°C (750°F)	6.0	6.0	-	-	6.0	7.0	6.0	7.0	6.0	6.0

*Materials solution-annealed at 900°C (1650°F) and quenched, cold-rolled 25% and aged at 400°C for 1 hr, when quoted. (Ref. 10).

TABLE 5

Mechanical and Physical Properties Data for 0.13% Zirconium-Copper Given a 980°C (1795°F) Solution Anneal and Various Cold Working Treatments

Solution Treatment	Cold Work, %	Tensile Strength, psi	Yield Strength 0.5% Ext., psi	Elongation in 2 in., %	Hardness, Rockwell B	Elec. Cond., % IACS @ 20°C
980°C - 30 min.; water quenched	0	29,000	6,000	54	--	64
980°C - 30 min.; water quenched	20	39,000	36,000	26	37	64
980°C - 30 min.; water quenched	40	49,000	47,000	20	57	64
980°C - 30 min.; water quenched	60	57,000	51,000	19	65	64
980°C - 30 min.; water quenched	75	63,000	61,000	19	71	64
980°C - 30 min.; water quenched	85	64,000	61,000	19	73	64

(Ref. 11)

TABLE 6

Mechanical and Physical Properties Data for 0.13% Zirconium-Copper Given a 980°C (1795°F) Solution Anneal and Various Cold Working Treatments and Then Aged

Solution Treatment	Cold Work, %	Ageing Treatment	Tensile Strength, psi	Yield Strength, 0.5% Ext., psi	Elongation in 2 in., %	Hardness, Rockwell B	Elec. Cond., % IACS @ 20°C
980°C - 30 min.; water quenched	0	500°C, 3 hr	30,000	13,000	51	-6	87
980°C - 30 min.; water quenched	20	400°C, 3 hr	48,000	38,000	31	50	80
980°C - 30 min.; water quenched	40	400°C, 3 hr	59,000	50,000	25	67	84
980°C - 30 min.; water quenched	60	400°C, 3 hr	64,000	54,000	22	72	85
980°C - 30 min.; water quenched	75	400°C, 3 hr	68,000	61,000	25	77	85
980°C - 30 min.; water quenched	85	400°C, 3 hr	72,000	64,000	24	79	85

(Ref. 11)

TABLE 7

Mechanical and Physical Property Data for 0.13% Zirconium-Copper Given a 980°C (1795°F) Solution Anneal, Various Cold-Working Treatments and Aged

Solution Treatment	Cold Work, %	Ageing Treatment	Tensile Strength, psi	Yield Strength, 0.5% Ext., psi	Elongation in 2 in., %	Hardness, Rockwell B	Elec. Cond., % IACS @ 20°C
980°C - 30 min.; water quenched	0	550°C, 3 hr	30,000	13,000	49	--	95
980°C - 30 min.; water quenched	20	450°C, 3 hr	48,000	40,000	28	57	92
980°C - 30 min.; water quenched	40	450°C, 3 hr	57,000	50,000	24	62	92
980°C - 30 min.; water quenched	60	450°C, 3 hr	60,000	53,000	24	71	91
980°C - 30 min.; water quenched	75	450°C, 3 hr	64,000	59,000	25	75	91
980°C - 30 min.; water quenched	85	450°C, 3 hr	68,000	62,000	23	74	91

(Ref. 11)

TABLE 8

Comparative Property Data Showing Effect of Cold-Working After Ageing

Condition	Tensile Strength, psi	Yield Strength, 0.5% Ext., psi	Elongation, 4 x Dia. %	Elec. Cond., % IACS @ 20°C
Solution-annealed, cold-worked 75%, aged	62,600	58,000	24	91.8
Solution-annealed, cold-worked 50%, aged, cold-worked 50%	67,800	61,400	20	89.4

(Ref. 11)

TABLE 9

Rupture Strength of Three High-Conductivity Alloys at 260°C (500°F)

Rolling Direction	Alloy[a]	After 100 Hours, psi		After 500 Hours, psi[b]	
		Unnotched	Notched	Unnotched	Notched
Longitudinal	OF copper plus Zr	34,000	37,500	32,000	35,500
	Chromium copper	36,000	28,000	32,500	23,500
	Silver-bearing copper	17,500	15,500	10,500	c
Transverse	OF copper plus Zr	38,000	41,500	36,500	38,500
	Chromium copper	18,500	17,000	13,000	12,000
	Silver-bearing copper	20,000	15,500	14,000	d

[a] Condition of specimens: OF copper + Zr solution-annealed, quenched, cold-rolled, aged R_B64.
Chromium copper solution-annealed, quenched, cold-rolled, aged, R_B82. Silver-bearing copper, cold-rolled, R_B61.

[b] Extrapolated from tests running up to 350 hr.

[c] Approximately 10,000 psi after 210 hr and decreasing rapidly.

[d] Approximately 10,000 psi after 300 hr and decreasing rapidly. (Ref. 14)

TABLE 10

High-Temperature Impact Strength of Cu-0.15% Zr and Cu-0.70% Cr Alloys

Testing Temperature	Cu-0.15% Zr Alloy Solution-annealed at 950°C (1740°F), cold-worked 69% reduction in area, and aged at 400°C (750°F) for 1 hr	Cu-0.70% Cr Alloy Solution-annealed at 1000°C (1830°F), cold-worked 69% reduction in area, and aged at 450°C (840°F) for 1 hr
20°C (68°F)	28.6 ft-lb	22.0 ft-lb
250°C (480°F)	27.2 ft-lb	21.0 ft-lb
400°C (750°F)	27.0 ft-lb	21.0 ft-lb
500°C (930°F)	22.5 ft-lb	16.0 ft-lb

(Ref. 13)

TABLE 11

Coefficient of Linear Expansion of Cu-0.15% Zr and Cu-0.70% Cr Alloy

Cu-0.15% Zr Alloy

Temperature Range	Solution-annealed at 950°C (1740°F), quenched, and aged at 500°C (930°F) for 1 hr, cm/cm/°C x 10^{-6}	Solution-annealed, cold-worked 84%, and aged at 400°C (750°F) for 1 hr, cm/cm/°C x 10^{-6}
20-100°C	16.37	16.27
20-300°C	17.78	18.01
20-600°C	19.46	20.13

Cu-0.70% Cr Alloy

Temperature Range	Solution-annealed at 1000°C (1830°F), quenched, and aged at 500°C (930°F) for 1 hr, cm/cm/°C x 10^{-6}	Solution-annealed, cold-worked, and aged at 450°C (750°F) for 1 hr, cm/cm/°C x 10^{-6}
20-100°C	16.67	16.27
20-300°C	17.97	18.05
20-600°C	19.51	20.71

(Ref. 13)

TABLE 12

Properties of Various Zirconium and Chromium Alloys at Room Temperature and 600°C (1110°F)

Alloy	Condition of Material	UTS psi	El, % in 2 in.	Hardness, Rockwell B	Elect. Cond., % I.A.C.S.
Tested at Room Temperature:					
Cu+0.37% Zr	Solution-treated at 900°C (1652°F), cold-rolled 60%, and aged at 550°C (1020°F) A	55,600	22	72	89
Cu+0.60% Cr	Solution-treated at 1000°C (1830°F), cold-rolled 40%, and aged at 475°C (885°F) B	71,000	16	80	81
Cu+0.52% Cr+0.42% Zr	Solution-treated at 950°C (1740°F), cold-rolled 40%, and aged at 475°C (887°F) C	78,200	21	86	78
Tested at 600°C (1112°F):					
Cu+0.37% Zr	as in A	28,400	18	40	27
Cu+0.60% Cr	as in B	15,900	32	36	27
Cu+0.52% Cr+0.42% Zr	as in C	47,300	20	60	26

(Ref. 21)

TABLE 13

Tensile Properties at 400°C (750°F) of Copper-Hafnium and Copper-Hafnium-Zirconium Alloys

Alloys		UTS, psi	El. % in 10 in.
Cu-0.63% Hf-0.11% Zr		61,200	10
Cu-0.66% Hf-0.04% Zr		61,200	6
Cu-0.65% Hf		56,900	4
Cu-0.15% Zr	For	49,700	3
Cu-0.7% Cr	Comparison	44,100	1

Material solution-annealed at 965°C (1700°F), cold-worked 90%, aged at 400°C (750°F) for 1 hr, and reheated at 400°C (752°F), held for 1 hr, and tested. (Ref. 10)

TABLE 14

Properties of Copper-Zirconium and Copper-Arsenic Alloys

Zirconium, % Arsenic, %	0.15 -	0.13 0.072	0.30 -	0.30 0.15	0.50 -	0.50 0.28	1.0 -	0.94 0.56
UTS, psi	64,730	56,900	65,400	71,000	65,400	72,600	76,200	74,800
0.1% PS, psi	54,700	49,700	58,900	64,700	57,600	67,400	-	66,000
El., % in 2 in.	11.0	11.0	10.0	11.0	10.0	10.0	9.0	10.0
Hardness, VPN	145	152	151	157	150	162	171	171
Elect. Cond., % IACS	89	98	86	91	83	90	80	83

Material solution-annealed at 900°C (1650°F), cold-worked 90%, and aged at 450°C (842°F) for 1 hr. (Ref. 23)

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