TENSILE AND ELECTRICAL PROPERTIES OF HIGH-STRENGTH HIGH-CONDUCTIVITY COPPER ALLOYS — S.J. Zinkle and W.S. Eatherly (Oak Ridge National Laboratory)

OBJECTIVE

The objective of this report is to summarize recent data on the electrical conductivity and tensile properties of CuCrNb and low-temperature diffusion bonded CuCrZr alloys

SUMMARY

Electrical conductivity and tensile properties have been measured on an extruded and annealed CuCrNb dispersion strengthened copper alloy which has been developed for demanding aerospace high heat flux applications. The properties of this alloy are somewhat inferior to GlidCop dispersion strengthened copper and prime-aged CuCrZr over the temperature range of 20-500°C. However, if the property degradation in CuCrZr due to joining operations and the anisotropic properties of GlidCop in the short transverse direction are taken into consideration, CuCrNb may be a suitable alternative material for high heat flux structural applications in fusion energy devices. The electrical conductivity and tensile properties of CuCrZr that was solution annealed and then simultaneously aged and diffusion bonded are also summarized. A severe reduction in tensile elongation is observed in the diffusion bonded joint, particularly if a thin copper shim is not placed in the diffusion bondline.

PROGRESS AND STATUS

Introduction

High-strength copper alloys are being considered for the divertor structure and first wall heat sink of the proposed International Thermonuclear Experimental Reactor, as well as the centerpost magnet in low aspect ratio tokamaks. The unirradiated electrical conductivity and mechanical properties of several candidate high-strength, high-conductivity copper alloys have been recently measured, including GlidCop Al25 (IG0) dispersion strengthened copper produced by OMG Americas, Hycon 3HP CuNiBe produced by Brush-Wellman, and CuCrZr produced by Kabelmetal and Zollern [1-4]. The effect of various heat treatment cycles including simulation hot isostatic pressure (HIP) and diffusion bonding treatments with fast or slow cooling have been investigated to a limited degree [3,4].

In order to provide additional data on high strength, high conductivity copper alloys, electrical conductivity and tensile measurements were initiated on an alternative dispersion strengthened copper alloy that is being considered for aerospace applications (Cu-8at.%Cr -4at.%Nb). The CuCrNb alloy contains a moderate density of refractory Cr_2Nb precipitates which are resistant to particle coarsening for heat treatment temperatures approaching the melting point of copper [5-7]. This alloy has been reported to exhibit superior tensile strengths compared to conventional copper alloys such as precipitation hardened NARloy Z, Cu-3%Ag-0.5%Zr [6]. However, there is very little published information on the electrical or thermal conductivity of CuCrNb, and also there is no known published information on the effect of specimen orientation (longitudinal vs. transverse).

The results of tensile tests on CuCrZr which had been solution quenched and simultaneously aged and HIP diffusion bonded are also reported in this contribution.

Experimental Procedure

The CuCrNb was extruded at NASA-Lewis and then exposed to a simulated brazing cycle of 925°C for 1 h. Type SS3 sheet tensile specimens and miniature disk compact tension specimens in both longitudinal and transverse orientations were machined from the 0.71 × 2.8 × 10.7 cm strip. The 2 cm thick plate of Cu-0.65%Cr-0.10%Zr (Elbrodur G) obtained by Boeing was fabricated by KM-Kabelmetal, Osnabrück, Germany as an F37 (solution quenched, cold-worked and aged) temper, heat #AN4946. According to the vendor's specifications, the F37 temper produced a room temperature yield strength of 363 MPa and an electrical conductivity of 90% IACS. The CuCrZr plate was subsequently solution annealed for 1 h at 980°C and water quenched at Boeing, machined, and then HIP diffusion bonded at 500°C for 3 h at a pressure of 207 MPa. The diffusion bonded components were then shipped to ORNL, and miniature type SS-3 sheet tensile specimens (gage dimensions 7.6 x 1.5 × 0.76 mm) were machined such that the diffusion bondline was contained in the central portion of the gage region. Since the height of the diffusion bonded component was approximately 2 cm, the 2.54 cm long SS-3 specimens were machined at an inclined angle of ~35 degrees.

Four-point probe electrical resistivity measurements were performed at room temperature on a total of 4 to 6 different SS-3 sheet tensile specimens for each of the thermomechanical conditions, using procedures summarized elsewhere [1]. The temperature was recorded for each measurement and the resistivity data were corrected to a reference temperature of 20°C using the copper resistivity temperature coefficient of $d\rho/dT = 6.7 \times 10^{-11}$ Ω-m/K. Nonuniformities in the width and thickness in the specimen gage region caused the typical experimental uncertainty of individual resistivity measurements to be ±0.5%. The relation 17.241 nΩ-m=100% IACS (international annealed copper standard) was used to convert the resistivity measurements to electrical conductivity values.

The tensile properties of the SS-3 sheet tensile specimens were measured at crosshead speeds of 0.0016 to 0.42 mm/s, which corresponds to initial strain rates of 2.1×10^{-4} to 0.056 s^{-1} in the gage region, respectively. The room temperature tests were performed in air, and the elevated temperature tests were performed in vacuum (10^{-6} to 10^{-5} torr). One specimen was tested in an Instron servohydraulic machine for each experimental condition. The tensile properties were determined from graphical analysis of the chart recorder curves. A plastic deformation offset of 0.2% was used for measuring the yield strength.

Results and Discussion

The room temperature electrical conductivities of the Cu-8Cr-4Nb and diffusion bonded CuCrZr specimens are listed in Table 1. The CuCrZr specimens exhibited high conductivity values. The CuCrNb specimens had conductivities comparable to that measured in the higher conductivity heats of Hycon 3HP CuNiBe [1].

Table 1. Room temperature electrical properties measured in the present study.

Alloy and heat treatment	Meas. resistivity at 20°C	Electrical conductivity
Cu-8Cr-4Nb, extruded & annealed		
longitudinal	23.50 nΩ-m	73.4±0.8% IACS
transverse	23.61 nΩ-m	73.0±1.0% IACS
Kabelmetal CuCrZr, diffusion bonded		
with 0.13 mm Cu shim	19.12 nΩ-m	90.1±0.7% IACS
without Cu shim	19.50 nΩ-m	88.4±0.3% IACS

The tensile properties of the Cu-8Cr-4Nb specimens tested at different strain rates are listed in Table 2. The ultimate strength decreases by about a factor of two between room temperature and 500°C , with no significant difference between longitudinal and transverse orientations. The uniform and total elongations were high at all test temperatures up to 500°C. The strength and elongation generally increased with increasing strain rate, in agreement with previous studies on copper alloys [2,4]. The measured tensile strengths are rather impressive, considering that the material was annealed at 925°C for 1 h prior to testing. Such a high temperature annealing would produce dramatic softening in CuCrZr or CuNiBe precipitation hardened alloys. The yield and ultimate strengths of the annealed CuCrNb at test temperatures of 20-500°C are about 10 to 20% lower than that of CuCrZr in the ITER solutionized and aged condition. The yield and ultimate strength of the annealed CuCrNb is about 10% larger than for CuCrZr that was given a simulated diffusion bond heat treatment at ~950°C with a moderate gas quench (~2°C/s) followed by thermal aging at 475 for 2 h [3].

Table 2. Summary of extruded and high temperature annealed Cu-8Cr-4Nb tensile test results.

Orientation, ID number	Temperature (°C)	strain rate (s^{-1})	Yield Strength (MPa)	Ultimate Strength (MPa)	Uniform Elongation (%)	Total Elongation (%)
longitudinal						
CN02	20	1.1×10^{-3}	219	397	16.4	22.6
CN03	200	1.1×10^{-3}	201	308	12.8	22.0
CN01	300	2.1×10^{-4}	170	238	10.7	18.6
CN04	300	1.1×10^{-3}	155	253	12.9	23.0
CN06	300	0.056	247	280	10.7	22.3
CN05	500	1.1×10^{-3}	147	203	9.5	17.6
transverse						
CN07	20	2.1×10^{-4}	213	370	16.1	21.7
CN08	20	1.1×10^{-3}	274	387	16.1	21.9
CN09	200	1.1×10^{-3}	189	306	14.9	25.0
CN10	300	1.1×10^{-3}	159	248	12.4	21.4
CN12	300	0.056	199	279	14.3	21.0
CN11	500	1.1×10^{-3}	146	196	10.4	17.5

The fracture toughness measurements on CuCrNb [8] indicated values of about 55 MPa-$m^{1/2}$ for the T-L orientation and ~65 MPa-$m^{1/2}$ for the L-T orientation over the temperature range of 20-250°C. These values are much lower than the fracture toughness measured for CuCrZr in both the ITER heat treatment condition (210 MPa-$m^{1/2}$ at 20°C and ~145 MPa-$m^{1/2}$ at 250 C for both orientations) and for a simulated gas quench (~2°C/s) and aged condition that is representative of a divertor module diffusion bond thermal cycle (219 MPa-$m^{1/2}$ at 20°C and 152 MPa-$m^{1/2}$ at 250°C) [8]. Therefore, the extruded and annealed CuCrNb base metal does not appear to offer any clear advantages over the CuCrZr alloy for ITER applications since the tensile properties and the electrical conductivity are comparable whereas the fracture toughness is much lower than CuCrZr. The effects of irradiation on the mechanical properties of CuCrNb are not known.

Table 3 summarizes the tensile property measurements performed on the diffusion bonded CuCrZr specimens. The tensile strength was considerably lower than that of CuCrZr base metal in the optimized solution quenched and aged condition [2,3]. This may be due to precipitate overaging associated with the long aging time and high aging temperature compared to the strength- and conductivity-optimized condition of 460-480°C for 2 h. Of greater significance is the low tensile ductility observed at all test conditions. From the near equivalence of the uniform and total elongations, it can be concluded that the reduction in area is very low (reduction in area measurements have not yet been performed on these specimens). The specimens which contained a 0.13 mm pure copper shim in the diffusion bondline exhibited higher ductility compared to specimens which did not contain a copper shim.

Table 3. Summary of diffusion bonded Cu-Cr-Zr tensile test results.

Orientation, ID number	Temperature (°C)	strain rate (s^{-1})	Yield Strength (MPa)	Ultimate Strength (MPa)	Uniform Elongation (%)	Total Elongation (%)
with Cu shim 67-1	20	1.1×10^{-3}	213	298	5.5	5.7
67-3	20	1.1×10^{-3}	225	311	6.9	7.0
67-2	200	1.1×10^{-3}	196	257	4.2	4.5
67-4	200	1.1×10^{-3}	198	255	4.2	4.4
w/o Cu shim 77-3	20	1.1×10^{-3}	209	209	~0.1	~0.1
77-1	200	1.1×10^{-3}	229	235	0.3	0.3
77-2	200	1.1×10^{-3}	210	210	0.2	0.2
77-4	200	1.1×10^{-3}	199	199	~0.1	~0.1

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