TENSILE PROPERTIES OF HIGH-STRENGTH, HIGH-CONDUCTIVITY COPPER ALLOYS AT HIGH TEMPERATURES — S. J. Zinkle (Oak Ridge National Laboratory)

OBJECTIVE

The objective of this report is to summarize recent tensile measurements on several different unirradiated commercial high-strength, high-conductivity copper alloys that are being considered for fusion energy applications.

SUMMARY

The unirradiated tensile properties of wrought GlidCop AL25 (ITER grade zero, IG0), solutionized and aged CuCrZr, and wrought and aged CuCrNb have been measured at temperatures up to 700°C at strain rates between $4x10^{-4}$ s^{-1} and 0.02 s^{-1}. GlidCop Al25 exhibited rapid softening with increasing test temperature ≥300°C, whereas the CuCrZr and CuCrNb precipitation hardened alloys decreased more slowly with increasing temperature. The difference in tensile behavior of the GlidCop and precipitation-hardened alloys is attributed to the small grain size in GlidCop, which allows grain boundary sliding (Coble creep) to become the dominant deformation mode at temperatures above ~400°C.

PROGRESS AND STATUS

Introduction

High-strength, high-conductivity copper alloys are being considered for first wall heat sink and divertor structural applications in the proposed International Thermonuclear Experimental Reactor (ITER), and are also under consideration for the center post magnet of spherical tokamaks [1-3]. Copper alloys under consideration for fusion energy high heat flux applications include dispersion strengthened copper ($Cu-Al_2O_3$), CuCrZr and CuNiBe. We have recently examined the tensile and electrical properties of a CuCrNb alloy developed by NASA [4]. Although Nb poses problems for waste disposal in fusion systems, the strategy was to determine whether any high strength, high conductivity copper ally exhibits a superior combination of conductivity and elevated temperature (200-400°C) strength. A reduced activation version of the CuCrNb alloy could presumably be developed by substituting V or other elements for Nb if favorable tensile and conductivity results were obtained.

The purpose of the present report is to summarize the completion of a series of tensile measurements performed on unirradiated specimens of copper alloys at various temperatures and strain rates. The tests were performed on as-wrought dispersion-strengthened copper, solutionized and aged CuCrZr, and extruded and annealed CuCrNb. The results of previous tensile and electrical resistivity tests on these alloys and CuNiBe are summarized elsewhere .[4-7].

Experimental Procedure

The dispersion strengthened (DS) copper specimens were cut from a 2.5 cm thick plate of GlidCop Al25 DS copper produced by SCM Metal Products (now known as OMG Americas), which was fabricated according to "ITER grade 0" [8] specifications (heat #C-8064). This alloy contains 0.25 wt.% Al in the form of finely dispersed aluminum oxide particles. The copper cladding on the plate surface was machined off prior to specimen fabrication. The tensile axis of the specimens were oriented along the longitudinal direction of the wrought plate. The Cu-0.65%Cr-0.10%Zr specimens were obtained from a 2 cm thick plate that was originally fabricated under the trade name of Elbrodur G by KM-Kabelmetal, Osnabrück, Germany as an F37 (cold-worked and aged) temper, heat #AN4946. A 2x3x5 cm piece from this plate was solution annealed in flowing argon for 1 hour at 980°C, water quenched, then aged in flowing helium at 475°C for 2 hours (furnace

cool) at ORNL, in accordance with ITER heat treatment specifications for CuCrZr. The nominal Cu-8at.%Cr-4at.%Nb alloy was extruded at NASA-Lewis (heat NHB920396) and then exposed to a simulated brazing cycle of 925°C for 1 h. A chemical analysis of this heat indicated the composition was 6.3wt.%Cr, 5.75wt.%Nb with 267 wt. ppm oxygen. Type SS3 sheet tensile specimens in both longitudinal and transverse orientations were machined from the 0.71 x 2.8 x 10.7 cm strip. Miniature SS-3 sheet tensile specimens with nominal gage dimensions 0.76 mm x 1.5 mm x 7.6 mm were electro-discharge machined from the bulk heat treated sheets and tested without any subsequent heat treatment.

The tensile properties of the SS-3 sheet tensile specimens were determined at temperatures between 150 and 700°C at crosshead speeds ranging from 0.0016 to 0.17 mm/s, which corresponds to initial strain rates of 2.1×10^{-4} to 0.022 s^{-1} in the gage region. The tensile tests were performed in vacuum (10^{-6} to 10^{-5} torr). The specimens were held at the test temperature for 0.25 h prior to the start of each tensile test. A single specimen was tested in an Instron servohydraulic machine for each experimental condition. The tensile properties were determined from graphical analysis of the load versus crosshead displacement curves, which were recorded as both digital data and as chart recorder graphs. A plastic deformation offset of 0.2% was used for measuring the yield strength.

Results and Discussion

Table 1 summarizes the results of the room temperature electrical resistivity and ultimate strength measurements performed at ORNL on GlidCop Al25, CuCrZr, CuNiBe and CuCrNb, which have been previously reported [4-7]. Recent resistivity results obtained on 48 pure copper (Johnson-Matthey Puratronic) SS-3 tensile specimens are also included in this table. The relation 17.241 nΩ-m=100% IACS (international annealed copper standard) was used to convert the resistivity measurements to normalized conductivity values. GlidCop Al25 exhibited the highest conductivity, followed by CuCrZr, CuCrNb and CuNiBe. The room temperature ultimate tensile strength was highest for CuNiBe (700-800 MPa), with values of ~400MPa obtained for the remaining three types of alloys.

The tensile properties obtained in the present study are summarized in Table 2. Figure 1 compares the ultimate tensile strength of the 4 different copper alloys as a function of test temperature, and Figure 2 shows the corresponding uniform elongation results. All of the data in these two plots were obtained at an initial strain rate of 1.1 to 2.2×10^{-3} s^{-1}. The CuCrZr, CuCrNb and GlidCop Al25 alloys exhibited similar temperature dependence in their strengths over the temperature range of 20-700°C, whereas both the AT and HT1 CuNiBe heats had much higher strengths (by about a factor of two). The strengths of CuCrZr and CuCrNb determined from these short-term tensile tests were higher than that of GlidCop Al25 at temperatures >300°C. The strength of GlidCop dropped off more rapidly with increasing test temperature than any of the other alloys. Similar temperature-dependent tensile behavior has been reported by other investigators [9,10]. The tensile strength of GlidCop also exhibited a strong strain rate sensitivity at elevated temperatures compared to CuCrZr and CuCrNb. For example, the yield strength of GlidCop at 600°C decreased by a factor of two as the strain rate was decreased from 0.022 s^{-1} to 2.1×10^{-4} s^{-1}. In contrast, the yield strength of CuCrNb decreased by less than 50% over the same range of test conditions.

All of the materials tested exhibited good ductility at temperatures up to 200°C. However, the behavior at temperatures above 200°C was significantly different for each of the different alloys. The uniform elongation at a strain rate of 1 to 2×10^{-3} s^{-1} of CuCrZr varied from 10 to 15% over the entire investigated temperature range (20-700°C). The uniform elongation of CuCrNb decreased gradually with increasing temperature, falling below 5% at a test temperature of 700°C. In contrast, the uniform elongations of GlidCop and both CuNiBe heats decreased strongly with increasing test temperature above 200°C. The uniform elongation of GlidCop Al25 decreased from ~13% at room temperature to ~2% at 400°C, and then increased with increasing test temperature. The GlidCop Al25 total elongation remained high at all temperatures, with values between 25 and

Table 1. Summary of Cu alloy room temperature ultimate tensile strength (UTS) and electrical conductivities measured at ORNL [4-7]. The tensile data were obtained at 1-2x10^{-3} s^{-1}.

Alloy	UTS at 20°C (MPa)	Resistivity at 20°C	Electrical conductivity
Copper (99.999% J-M Puratronic)	---	17.19 nΩ-m	100.3%IACS
GlidCop Al25 (IG0)	410	19.12 nΩ-m	90% IACS
Kabelmetal CuCrZr, heat AN4946			
ITER solution quenched & aged	414	20.67 nΩ-m	83% IACS
Zollern CuCrZr, heat Z822			
solution quenched & aged	418	22.55 nΩ-m	76% IACS
solution quenched	243	48.29 nΩ-m	36% IACS
HIP furnace cool	---	25.41 nΩ-m	68% IACS
HIP furnace cool & aged	217	24.94 nΩ-m	69% IACS
HIP fast cool	216	39.57 nΩ-m	44% IACS
HIP fast cool & aged	328	25.91 nΩ-m	66% IACS
Hycon 3HP CuNiBe			
heat #46546, sol'n quenched & aged (AT2)*	723	26.78 nΩ-m	64% IACS
heat #33667, cold worked & aged (HT1)	810	26.27 nΩ-m	66% IACS
heat #46546, cold worked & aged (HT2)	695	24.05 nΩ-m	72% IACS
heat 28626, solution quenched & aged (AT3)	---	25.62 nΩ-m	67% IACS
heat 28626, cold-worked & aged (HT3)	---	25.45 nΩ-m	68% IACS
heat 35562, cold-worked & aged (HT4)	---	25.41 nΩ-m	68% IACS
CuCrNb (longitudinal and transverse)	392	23.55 nΩ-m	73% IACS

* the AT2 plate was prepared by subsequent heat treating of the cold-worked and aged HT2 (heat #46546) plate.

Table 2. Summary of tensile data from the present study.

	Temperature	σ_y (MPa)	UTS (MPa)	e_u (%)	e_{tot} (%)
GlidCop Al25 (IGO)					
2.1 x 10^{-4} s^{-1}	400°C	152	172	1.2	34.2
	600°C	48	66	13.6	28.5
1.1 x 10^{-3} s^{-1}	400°C	173	182	1.3	20.3
	600°C	67	74	3.7	19.5
	700°C	53	63	7.6	15.2
0.022 s^{-1}	600°C	102	121	2.1	29.2
CuCrZr (ITER SAA)					
2.1 x 10^{-4} s^{-1}	150°C	291	372	13.9	22.4
2.2 x 10^{-3} s^{-1}	400°C	228	266	9.2	17.9
	600°C	132	155	11.3	33.0
	700°C	77	88	14.0	40.3
CuCrNb (longitudinal)					
2.1 x 10^{-4} s^{-1}	600°C	99	133	4.8	30.9
	700°C	48	72	5.1	38.1
1.1 x 10^{-3} s^{-1}	600°C	122	151	6.0	36.7
	700°C	71	99	3.7	45.2
0.022 s^{-1}	600°C	127	178	11.2	32.3
CuCrNb (transverse)					
2.1 x 10^{-4} s^{-1}	300°C	180	228	9.9	18.0
	600°C	82	114	3.3	33.7
	700°C	52	74	4.2	26.0
1.1 x 10^{-3} s^{-1}	600°C	106	138	6.4	30.0
	700°C	71	96	3.7	30.3

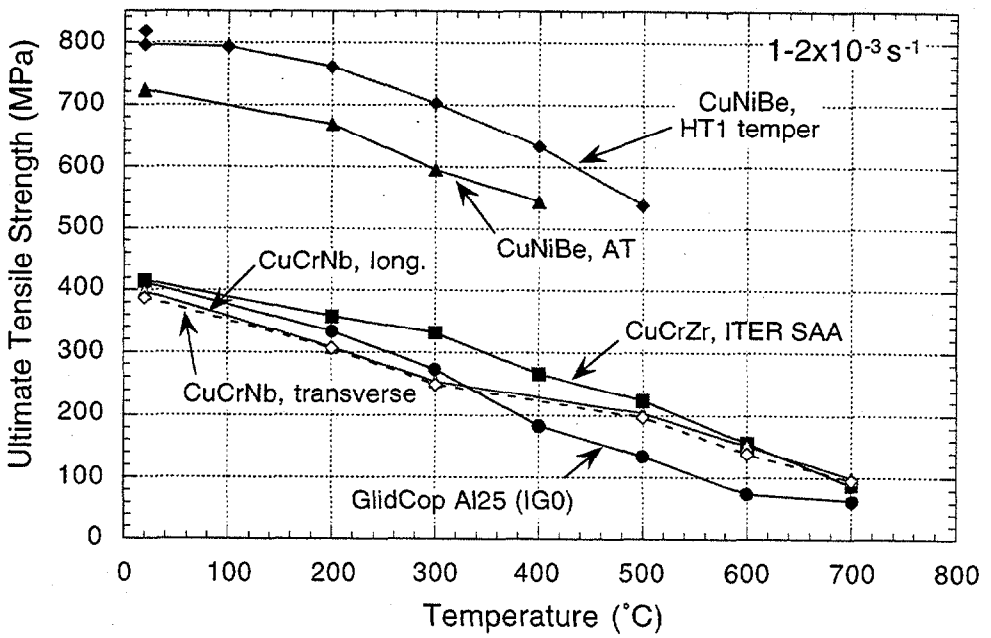

Fig. 1. Comparison of the temperature-dependent ultimate tensile strengths of the four high-strength, high-conductivity copper alloys.

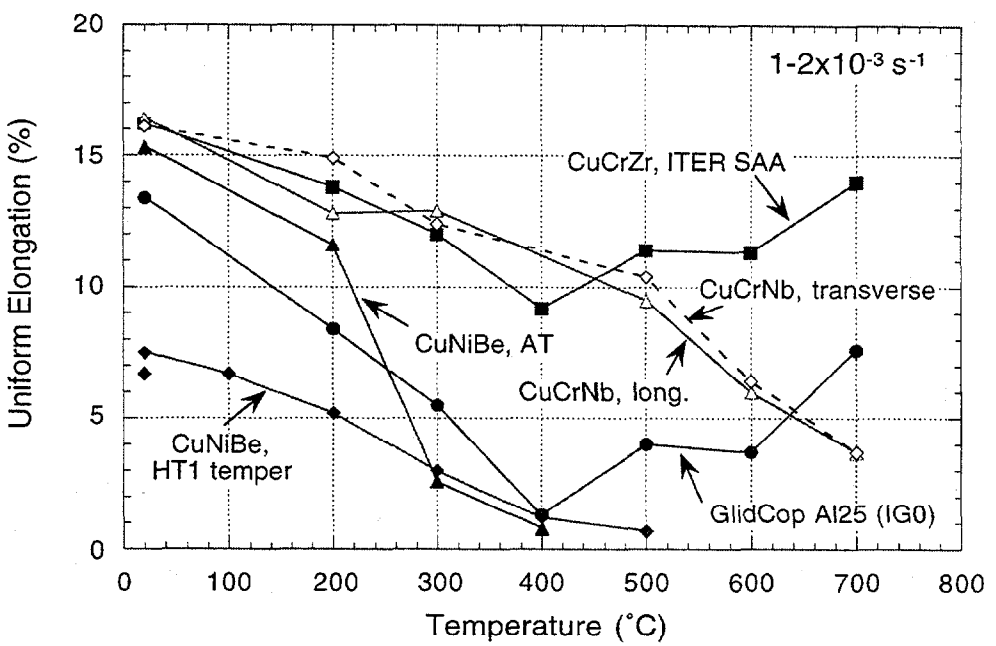

Fig. 2. Comparison of the temperature-dependent uniform elongations of the four high-strength, high-conductivity copper alloys.

45% at temperatures of 300-700°C (Table 2 and refs. [5,6]). The GlidCop elongation data indicate that necking (localized deformation) occurred at lower deformation levels with increasing test temperature, but high ductility was present in the necked region at all temperatures. The most severe elevated temperature embrittlement behavior occurred in the CuNiBe alloys, where the uniform elongation was reduced to <5% at a temperature of ~250°C [5-7]. The decrease in uniform elongation in the CuNiBe alloys at elevated temperatures was accompanied by a pronounced decrease in the total elongation as well. Scanning electron microscopy of the CuNiBe fracture surfaces showed a transition from ductile transgranular failure at room temperature to intergranular failure (with localized ductile deformation) at elevated temperatures [5].

Analysis of the temperature-dependent strengths indicates that a distinct change in slope occurs in all of the Cu alloys at a temperature of ~300°C, which corresponds to a homologous temperature of 0.42 T_M where T_M is the melting temperature. According to an Ashby map analysis of the deformation mechanisms (S. Zinkle and G.E. Lucas, to be published), the decrease is strength at temperatures above 300°C is due to thermal creep occurring during the tensile testing. Several different creep mechanisms were predicted to be dominant in the different copper alloys. The fine grain size in GlidCop enabled grain boundary sliding (Coble creep) to be the dominant deformation mode in this alloy at temperatures above ~400°C. In CuCrZr and CuCrNb, the calculated dominant deformation mechanism was dislocation creep (power law creep).

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