Risø-R-1007(EN)

Influence of Composition, Heat Treatment and Neutron Irradiation on the Electrical Conductivity of Copper Alloys

M. Eldrup and B.N. Singh

Risø National Laboratory, Roskilde, Denmark
January 1998

Risø-R-1007(EN)

Abstract The electrical conductivities are reported for pure copper as well as for four different types of copper alloys, viz. CuNi, CuNiBe, CuCrZr and $Cu-Al_2O_3$, the latter three of which are under consideration for their applications in the structural components of ITER (International Thermonuclear Experimental Reactor). The alloys have undergone different pre-irradiation heat treatments which simulate the possible thermal histories of the material in ITER, and have been irradiated with fission-neutrons in the DR-3 reactor at Risø at temperatures in the range 100 - 350°C up to doses of 0.3 dpa. In some cases post-irradiation annealing at 300°C for 50 hours has been carried out. The CuNi and CuNiBe have the lowest conductivities ($\leq$ 40% and $\leq$ 55% of that of pure Cu), and $Cu-Al_2O_3$ the highest (75-90% of pure Cu). The results are discussed with reference to equivalent Transmission Electron Microscopy results on the microstructure of the materials and to data from mechanical testing.

ISBN 87-550-2350-9
ISSN 0106-2840

Information Service Department, Risø, 1998

Contents

1 Introduction

Because of the high thermal conductivity of copper, three different copper alloys, i.e. CuNiBe, CuCrZr and the prime candidate Cu-Al_2O_3, are under consideration for their applications in the structural components of ITER (International Thermonuclear Experimental Reactor) [1,2]. The heat sink materials will have to be joined to the first wall and divertor materials at relatively high temperatures (900 - 1000°C). During the joining process at these high temperatures, the microstructure of the alloys may change, the degree of change depending upon the actual composition and structure [3]. The two alloys, CuNiBe and CuCrZr, have been chosen as potential back-up materials to the prime candidate Cu-Al_2O_3, and for that reason it was decided to carry out a series of experiments to simulate the effect of bonding and bakeout thermal treatments on pre- and post-irradiation microstructures, mechanical properties and electrical conductivity of CuNiBe and CuCrZr alloys. In this report we present results of electrical conductivity measurements, in particular the effects of alloy composition, heat treatment, temperature of irradiation by fission-neutrons as well as post-irradiation annealing treatment. The results will be compared to those for Cu-Al_2O_3 alloys and for oxygen-free high conductivity copper (OFHC-Cu). Data for two CuNi alloys are also included.

The conductivity measurements have two purposes. One is to characterize the defect properties of the alloys. This can be done because the conductivity depends on the defect configuration and concentration in the material, i.e. the distribution and concentration of impurities (alloying elements) as well as radiation created defects. The other purpose is to obtain direct information about the electrical conductivity as an approximate measure of thermal conductivity. The conductivity results will be discussed and compared with data from mechanical testing and TEM.

2 Materials and Experimental Procedure

The materials used for the investigations were oxygen-free high conductivity copper (OFHC-Cu), CuNi, CuNiBe, CuCrZr and Cu-Al_2O_3 alloys. The OFHC-Cu, CuNiBe and CuCrZr alloys were supplied by Tréfimétaux (France) as 20 mm thick plates. In addition, specimens of a commercial CuNiBe (Hycon 3HP®) manufactured by Brush Wellman Inc. (USA) and of a CuCrZr alloy from Outokumpu (Finland) were included in the study. Oxide dispersion strengthened copper (Cu-Al_2O_3) was supplied by SCM Metals (USA) (trade mark GlidCop CuAl-25 or CuAl-60) in the form of rods in the as-extruded condition. Another Cu-Al_2O_3 alloy, of the same composition as CuAl-25, was cross rolled to remove texture before the specimens were cut. This material is referred to as CuAl-25 IG0 (ITER Grade 0). The chemical compositions of the alloys are listed in Table 1.

The specimens used for electrical conductivity measurements were the same as those used for tensile testing. They were cut from cold rolled (~80%) sheets (~0.3 mm) to a gauge length of 7 mm and a nominal width of 3 mm. The detailed geometry of the specimens is shown in [4]. Prior to irradiation, the OFHC-Cu specimens were annealed at 550°C for 2 hours, while the CuCrZr and CuNiBe specimens were given the following four different heat treatments: (A) Solution annealing, (E) Prime ageing, (B) Bonding thermal treatment and (C and C') Bakeout thermal treatment. The CuCrZr alloy from Outokumpu was also given a Prime ageing (F), but for somewhat longer time than in the case of E. The only heat treatment given to the CuAl alloys was the bonding thermal treatment (referred to as D). The two CuNi alloys were annealed at 800°C for 4 hours. All heat treatments were carried out in vacuum (~1 mPa). Details of the heat treatments are summarized in Table 2.

To study the effects of irradiation and irradiation temperature, the OFHC-Cu specimens were neutron irradiated in the dose range 0.01 - 0.3 dpa (NRT) at 100 °C and the various alloys to a dose of 0.3 dpa (NRT) (and a few specimens also to lower doses) at temperatures of 100, 200, 250 and 350 °C . Details of the irradiation procedures are given in [4 - 6]. Furthermore, in order to find out to what extent the conductivity (and mechanical properties) may be improved by post-irradiation annealing, a number of the specimens were annealed at 300°C for 50 hours after irradiation.

All conductivity measurements were carried out at 23°C, using one of the modules in the A1931a Temperature Controller developed by the Engineering and Computer Department at Risø. The module is designed to measure low resistances, in the present version up to 50 mΩ with a precision of a μΩ or less, by passing a 100mA current through the specimen and measuring the voltage across it. The module applies a four point technique. It switches the current direction during the measurement and averages the two voltages obtained to eliminate the influence of thermo-voltages on the resulting resistance. A PC controls the module and stores the data. Two identical modules are available in the system. All measurements were carried out with both of them to assure reproducibility.

Table 1. Chemical composition of the copper and copper alloys.

OFHC-Cu	Cu - 10, 3, <1 and <1 ppm of Ag, Si, Fe and Mg, respectively
CuCrZr	Cu - 0.8% Cr, 0.07% Zr, 0.01% Si
Outokumpu	Cu - 0.78%Cr, 0.13%Zr, 0.003%Si, 0.008%Fe
CuNiBe	Cu - 1.75% Ni, 0.45% Be
Hycon	Unknown, but similar to CuNiBe
CuAl-25, CuAl-25IG0	Cu - 0.25% Al as oxide particles (0.46% Al_2O_3)
CuAl-60	Cu - 0.60% Al as oxide particles (1.10% Al_2O_3)

Table 2. Summary of bonding and bakeout heat treatments for CuCrZr, CuNiBe and CuAl alloys.

	Heat Treatment
A	Solution annealing at 950°C for 1 hour followed by water quench
E	Prime ageing: Heat treatment A + ageing at 475°C for 30 min. followed by water quench
B	Bonding thermal cycle: Heat treatment E + annealing at 950°C for 30 min. followed by furnace cooling + re-ageing at 475°C for 30 min. followed by furnace cooling
C	Bakeout thermal cycle: Heat treatment B + annealing at 350°C for 100 h followed by furnace cooling
C'	Bakeout thermal cycle: Heat treatment E + annealing at 350°C for 100 h followed by furnace cooling
D	Annealing at 950°C for 30 min. followed by furnace cooling
D'	CuAl in the as-wrought condition, i.e. without any heat treatment
F	Prime ageing: Annealing at 960°C for 1 h followed by water quench + ageing at 460°C for 2 h followed by water quench

Specimens were etched prior to the resistivity measurements to secure good electrical contacts.

For each measurement, the specimen was fixed in a plexiglass holder in a well-defined position and screwed tightly to the current connectors at each end. The voltage connectors were two gold covered, spring loaded and sharply pointed pins which were pressed against the specimen while mounted in the plexiglass holder to secure identical positions for all the measurements. The distance between the pins (~5 mm) was measured in a microscope (with an uncertainty of about ±7μm). The width and thickness of each specimen were measured with a micrometer with estimated uncertainties of ±0.1% and ±1-2%, respectively. The estimated uncertainty on the measured electrical conductances is about ±0.5% (based on many measurements on the same specimen). The electrical conductivity, σ, of a specimen is given by

$$\sigma = G \times l/(t \times w) \qquad (1)$$

where G is the conductance, l the length (i.e. pin distance), t the thickness and w the width of the specimen. With the uncertainties on these quantities mentioned above, we estimate an uncertainty on σ of ±2%.

For each set of measurements, the conductivity, σ_{Cu}, of one or two OFHC-Cu reference samples (annealed at 550°C for 2 hours) was also determined. The results always agreed with the nominal value of 0.589 $(\mu\Omega\text{cm})^{-1}$ within the uncertainty stated above. In the following, the results are presented relative to the measured reference, i.e. as "Relative Conductivity", given by σ/σ_{Cu}.

3 Results

Figure 1 shows the results for OFHC-Cu, neutron irradiated at 100°C to different doses, both in the as-irradiated state and after annealing at 300°C for 50 hours. The conductivity decreases by about 12% at the highest doses, but regains about 5% on annealing.

All the obtained results for the alloys are given in Tables 3 - 6. The conductivities for the un-irradiated CuCrZr and CuNiBe alloys after the different heat treatments are also summarised in Fig. 2. As seen in Tables 3 and 4 certain variations in conductivities were observed between different batches of samples with the same nominal heat treatment, while no such variation was seen between different samples from the same batch. The variations are shown by the "error bars" in Fig. 2. The variation is small for the solution annealed specimens (A), but quite large for most of the other treatments. In the case of CuCrZr alloys, the conductivity increases from slightly less than 50% of the conductivity of pure Cu in the prime aged condition to ~60 - 70% after bonding treatment and finally reaches a value of ~70 - 80% after bakeout treatment. The conductivities of the CuNiBe alloys, on the other hand, do not increase much beyond ~50% (except for the Hycon).

The effects of neutron irradition on the CuCrZr and CuNiBe alloys given in Tables 3 and 4 are also shown in Figs. 3 and 4. Here the results are presented as the *changes* in relative conductivity resulting from irradiation to 0.3 dpa at different temperatures, i.e. $(\sigma_{irr} - \sigma_{un\text{-}irr})/\sigma_{Cu}$, where σ_{irr} and $\sigma_{un\text{-}irr}$ are the relative conductivity for the irradiated and the un-irradiated sample with the same heat treatment, respectively. As mentioned above, variations in conductivity were observed for the un-irradiated samples between batches with the same nominal heat treatment. Therefore, to make a comparison of σ_{irr} and $\sigma_{un\text{-}irr}$ meaningful, the changes plotted in Figs. 3 and 4 are all for samples belonging to the same batches. The figures also display data for post-irradiation annealing of samples. For CuCrZr (Fig. 3), the A, E and B samples show conductivity increases by about 10% on irradiation which is only moderately dependent on irradiation temperature, while the Outokumpu alloy shows only little sensitivity to irradiation. Only the C sample shows a strong decrease on irradiation. Post-irradiation annealing (300°C/ 50 hours) leads in all cases to an increase of conductivity, although by different amounts.

The CuNiBe alloys show a different behaviour (Fig. 4). On irradiation at 100, 200 and 250°C the conductivity decreases (or is unchanged in one case), while it increases on irradiation at 350°C, the amount of change depending upon the heat treatment. Annealing increases the conductivity also for this alloy.

The results for CuNi (Table 5) show a strong decrease of conductivity with Ni content. Irradiation and post-irradiation annealing have a very small or no effect on the conductivity.

Results for the Cu-Al_2O_3 alloys, both in the heat treated and the as-irradiated state and after annealing, are given in Table 6. In all cases, irradiation leads to a decrease in conductivity, while annealing has only a minor, if any, influence on the conductivity.

Table 3. Electrical conductivities for Cu-Cr-Zr alloys. Results are for as-heat treated and for subsequently annealed specimens as well as for neutron irradiated and for subsequently annealed specimens. Heat treatments with different numbers refer to different batches. Conductivities for different batches may differ, while the conductivities of different specimens from the same batch agree closely.

Un-irradiated		**Irradiated**			**Annealed ($300^oC/50h$)**
Heat Treatment	Relative Conductivity (%)	Irradiation Temp. (^oC)	Irradiation dose (dpa)	Relative Conductivity (%)	Relative Conductivity (%)
Solution Anneal (A1)	46.4	-	-	-	-
Solution Anneal (A4)	47.9	100	0.3	55.1	67.8
Prime Ageing (E2)	64.9	-	-	-	67.6
Prime Ageing (E4)	52.3	-	-	-	55.9
Prime Ageing (E4)	52.3	100	0.2	53.8	66.0
Prime Ageing (E4)	52.3	100	0.3	61.2	69.1
Prime Ageing (E4)	52.3	200	0.25	63.2	69.9
Prime Ageing (E1)	56.2	250	0.3	66.0	-
Prime Ageing (E3)	61.5	350	0.3	77.3	-
Bonding (B4)	59.5	100	0.3	72.4	76.3
Bonding (B1)	57.7	250	0.3	67.4	-
Bonding (B3)	71.3	350	0.3	84.5	-
Bakeout (C3)	80.6	-	-	-	-
Bakeout (C4)	78.8	100	0.3	66.3	72.8
Bakeout (C'1)	63.9	-	-	-	-
Bakeout (C'4)	72.9	-	-	-	-
Outokumpu (F12)	76.6	-	-	-	76.9
Outokumpu (F12)	76.6	200	0.3	74.5	76.4
Outokumpu (F12)	76.6	350	0.3	77.4	79.1

Table 4. Electrical conductivities for Cu-Ni-Be alloys. Results are for as-heat treated and for subsequently annealed specimens as well as for neutron irradiated and for subsequently annealed specimens. Heat treatments with different numbers refer to different batches. Conductivities for different batches may differ, while the conductivities of different specimens from the same batch agree closely.

Un-irradiated		**Irradiated**			**Annealed (300^{o}C/50h)**
Heat Treatment	Relative Conductivity (%)	Irradiation Temp. (^{o}C)	Irradiation dose (dpa)	Relative Conductivity (%)	Relative Conductivity (%)
Solution Anneal (A4)	33.7	100	0.3	31.3	42.5
Solution Anneal (A1)	31.0	250	0.3	31.1	-
Solution Anneal (A3)	32.0	350	0.3	48.5	-
Prime Ageing (E4)	48.8	-	-	-	51.6
Prime Ageing (E9)	46.2	-	-	-	49.4
Prime Ageing (E4)	48.8	100	0.3	41.4	49.5
Prime Ageing (E6)	-	200	0.25	43.5	47.7
Prime Ageing (E1)	-	250	0.3	43.0	-
Prime Ageing (E3)	42.6	350	0.3	50.1	-
Bonding (B19)	51.0	-	-	-	51.2
Bonding (B4)	49.3	100	0.3	37.7	43.8
Bonding (B1)	49.7	250	0.3	45.0	-
Bonding (B3)	42.1	350	0.3	52.8	-
Bonding (B10)	-	350	0.3	57.5	-
Bakeout (C1)	49.0	-	-	-	-
Bakeout (C4)	54.6	-		-	-
Bakeout (C'1)	46.6	-	-	-	-
Bakeout (C'4)	52.5	-	-	-	-
Hycon	64.6	100	0.3	54.6	59.7
Hycon	64.6	250	0.1	59.5	62.2
Hycon	64.6	250	0.3	53.5	55.5
Hycon	64.6	350	0.3	65.7	-

Table 5. Electrical conductivities for Cu-Ni alloys. Results are for as-heat treated and for subsequently annealed specimens as well as for neutron irradiated and for subsequently annealed specimens.

Un-irradiated Heat Treatment: 800°C/4h		**Irradiated**			**Annealed (300°C/50h)**
Alloy	Relative Conductivity (%)	Irradiation Temp. (°C)	Irradiation dose (dpa)	Relative Conductivity (%)	Relative Conductivity (%)
Cu-2%Ni	37.8	-	-	-	37.8
Cu-2%Ni	37.8	200	0.3	35.5	35.4
Cu-5%Ni	20.6	-	-	-	20.2
Cu-5%Ni	20.6	200	0.3	20.1	19.7

Table 6. Relative electrical conductivity for Cu-Al_2O_3 alloys (0.25% and 0.6% Al). Results are for as-heat treated and for subsequently annealed specimens as well as for neutron irradiated and for subsequently annealed specimens.

	Heat Treatment		**Irradiated**			**Annealed (300°C/50h)**
Sample	Heat Treatment	Relative Conductivity (%)	Irradiation Temp. (°C)	Irradiation dose (dpa)	Relative Conductivity (%)	Relative Conductivity (%)
CuAl-25	D'	86.9	–	–	–	–
CuAl-25	D	89.2	100	0.2	80.3	82.2
CuAl-25IG0	D	88.2	–	–	–	88.8
CuAl-25IG0	D	88.2	200	0.25	81.7	82.5
CuAl-25IG0	D	88.2	350	0.3	79.6	78.9
CuAl-60	D'	78.7	–	–	–	81.6
CuAl-60	D'	78.7	100	0.3	69.6	75.0
CuAl-60	D'	78.7	250	0.1	74.4	72.7
CuAl-60	D'	78.7	350	0.3	76.7	76.4

4 Discussion

Measurements of electrical conductivity result in only one number which provides information about the average scattering of conduction electrons in the sample by thermal fluctuations and by impurities and defects of different densities and configurations. Hence, on one hand such measurements can detect changes on the atomistic scale. On the other hand they are not able to provide detailed information about densities and configurations in any way comparable to those obtained from TEM, except in special cases. However, changes in conductivities maybe still give useful complementary information. For example, generally the scattering cross section per impurity (alloying) atom or defect is largest when the atoms/defects are in solid solution and decreases when the atoms/defects agglomerate. Thus, the conductivity will normally increase when agglomeration or precipitation takes place.

The irradiation of pure copper (Fig. 1) clearly reduces the conductivity as a result of the creation of defects and their clusters. For irradiation at 250°C the cluster density increases with dose, tending towards saturation in the dose range 0.1 - 0.3 dpa [7], while for irradiation at room temperature saturation occurs at about 0.01 dpa [8]. The results in Fig. 1 (T_{irr} = 100°C) for the as-irradiated specimens seem to reflect a behaviour with dose more similar to the one for T_{irr} = 250°C than the behaviour for T_{irr} = RT. Annealing for 50 hours at 300°C evidently does not lead to a complete, but only a partial recovery of the irradiated Cu, since the conductivity only increases by about one third of its initial decrease on annealing. This agrees with results from a positron annihilation study of the isochronal annealing of Cu, neutron irradiated at 50°C and at 250°C. For an annealing rate of 1°C/min., recovery started at ~250°C, but was not completed until ~500°C [9].

To illustrate a comparison between results of conductivity measurements and mechanical testing, Fig. 5 shows the results of the latter for OFHC-Cu after irradiation at 100°C in the as-irradiated state and after post-irradiation annealing (i.e. the same specimens as in Fig. 1) [10]. Like the conductivity decrease (Fig. 1), the strong increase in strength and loss in ductility on irradiation (Fig. 5) saturate in the range 0.1 - 0.3 dpa. After annealing (lower part of Fig. 5) some recovery is observed (but the saturation behaviour is maintained). However, like for the conductivity the tensile curves deviate appreciably from the curve for the un-irradiated material.

The data for the un-irradiated alloys (Table 3, 4 and Fig. 2) show that the conductivities for CuNiBe are clearly smaller than for CuCrZr. One reason for this probably is that the concentration of alloying elements is higher in the former than in the latter alloy (Table 1). The heat treatments E, B, C and C' following the solution anneal (A) lead to the formation and growth of precipitates [3 - 6]. Therefore, as expected, the solution annealed samples have the lowest conductivities. The density of precipitates in the Tréfimétaux CuNiBe is appreciably higher and the size larger than those in CuCrZr (13 -18$\times10^{23}$m^{-3} and 4 - 7nm compared to 0.4 - 0.6$\times10^{23}$m^{-3} and 2.3 - 2.9nm [3, 4]). This may be an additional reason for the conductivity of CuNiBe generally being lower than that of CuCrZr.

Some changes in the microstructure of CuNiBe take place during the bonding heat treatment (B), but less in the bakeout (C and C') [3, 4]. However, the conductivity stays almost independent of heat treatment after prime ageing, probably reflecting the fact that there is only a minor variation in the precipitate density. This is in qualitative agreement with the relatively high conductivity for the Hycon specimen, since the precipitate density in this material is about 5 - 6 times lower than that in the Tréfimétaux CuNiBe [5]. For the CuCrZr specimens, TEM shows only modest differences in precipitate densities among heat treatments E, B and C' which is in agreement with the conductivities for these samples. In contrast to this, the C bakeout treatment results in a rather high conductivity (~80%) which suggests that a larger fraction of the alloying elements are found in the form of precipitates. Also the Outokumpu CuCrZr alloy shows a high conductivity. This may reasonably be associated with the fact that the prime ageing of this material took place over 2 hours which would lead to a higher degree of precipitation than during the E heat treatment of Tréfimétaux CuCrZr for only 30 minutes.

On irradiation at 250°C and 350°C small precipitates are formed in the A specimens and the precipitates in the E and B specimens generally tend to grow in size. In CuCrZr the density increases with increasing irradiation temperature (except for B which shows a decrease at 350°C) while in CuNiBe the density decreases with increasing irradiation temperature [5]. The precipitate formation in A and the general coarsening in this and the E and B specimens may explain the increase in conductivity in CuCrZr on irradiation (Table 3 and Fig. 3). The post-irradiation annealing results in further segregation and thereby increases the conductivity to close to the high value observed for the pre-irradiated C sample (Fig. 2). The data for the C and Outokumpu (F) CuCrZr specimens show a decrease of conductivity due to irradiation. Both had high conductivities in the pre-irradition state, probably resulting from the development of large precipitates. It is expected that irradition will lead to some resolution of the alloying elements from the precipitates and thereby to a decrease in conductivity, as observed.

The conductivity decrease in the irradiated CuNiBe found at the lower irradiation temperatures (Table 4 and Fig. 4) may be ascribed to dissolution of precipitates. Because of the high density of precipitates there is a high probability that a displacement cascade created by a neutron may impinge directly on a precipitate, causing its dissolution. Above 250°C coarsening of precipitates takes place, as mentioned above, which results in the increases in conductivities observed for the irradition temperature of 350°C.

For both CuCrZr and CuNiBe the post-irradiation annnealing (300°C/50h) lead to increases in conductivity, irrespective of the initial heat treatments. This effect is ascribed to the annealing of radiation created defects and, for the solution annealed (A) specimens for which the effect is largest, to the formation and/or growth of precipitates.

The Cu-Al_2O_3 alloys show the highest conductivities of all the alloys (Table 6). On irradiation moderate decreases (<10%) are observed which depend only to a small degree on irradiation temperature. This is in accord with the rather small changes in microstructure found by TEM [3 - 6]. In contrast to the other two alloys, the 300°C/50h anneal leads to only a small or no increase in conductivity, and no difference can be detected between the results for the two CuAl-25 alloys. Thus, based on the present rather low dose experiments one may confirm that, in terms of electrical conductivity, the CuAl-25 alloys are to be preferred as prime candidate material for ITER with the Outokumpu alloy coming rather close.

5 Conclusion

In spite of the fact that results of electrical conductivity measurements reflect average bulk properties of the specimens, the present work shows that at least a qualitative characterization of the precipitate microstructure in differently heat treated and irradiated Cu alloys may be obtained by such measurements.

The electrical conductivities of the four investigated Cu alloys are clearly different, since the conductivities for un-irradiated and irradiated (0.3 dpa) CuNi, CuNiBe, CuCrZr and Cu-Al_2O_3 roughly speaking fall within four ranges, viz. below 40%, below 55%, 50-80% and 75-90%, respectively, of the conductivity of pure Cu (with the values for the Hycon CuNiBe material close to 65% though). Within these ranges, variations in conductivities reflect heat treatment, irradiation temperature and post-irradiation annealing. The results underline the problem of cascade-induced dissolution of precipitates by cascade impingement, segregation of alloying elements and reprecipitation, and they show that even in the case of pure OFHC-Cu not all defects recover by post-irradiation annealing at 300^{o}C for 50 hours.

The fact that the conductivities of the CuNiBe alloys are so low raises a serious question regarding the application of this alloy in the environment of a fusion reactor, while on the other hand the high values for the Cu-Al_2O_3 alloys confirm their position as prime candidate.

Acknowledgements

We are grateful to N. J. Pedersen and B. F. Olsen for their strong involvement in the electrical conductivity measurements and thank S. J. Zinkle for supplying specimens of CuNiBe (Hycon). This work was partly funded by the European Fusion Technology Programme.

References

[1] ITER Joint Central Team, J. Nucl. Mater. 212-215 (1994) 3.

[2] J.W. Davies, D.E. Driemeyer, J.R. Haines and R.T. McGrath, J. Nucl. Mater. 212-215 (1994) 1353.

[3] B.N. Singh, D.J. Edwards, M. Eldrup and P. Toft, J. Nucl. Mater. 249 (1997) 1.

[4] B.N. Singh, D.J. Edwards, M. Eldrup and P. Toft, *Pre- and Post-Irradiation Properties of Copper Alloys at 250°C Following Bonding and Bakeout Thermal Cycles*, Risø Report R-937(EN), Risø National Laboratory, Roskilde, Denmark, January (1997) 55pp.

[5] B.N. Singh, D.J. Edwards, M. Eldrup and P. Toft, *Effect of Bonding and Bakeout Thermal Cycles on the Properties of Copper Alloys Irradiated at 350°C*, Risø Report R-971(EN), Risø National Laboratory, Roskilde, Denmark, February (1997) 44 pp.

[6] D.J. Edwards, B.N. Singh, P. Toft and M. Eldrup. In: Proceedings of 8th International Conference on Fusion Reactor Materials, Oct. 1997, Sendai, Japan.(to be published)

[7] B.N. Singh, A. Horsewell, P. Toft and D.J. Edwards, J. Nucl. Mater. 224 (1995) 131.

[8] B.N. Singh and S.J. Zinkle, J. Nucl. Mater. 206 (1993) 212.

[9] M. Eldrup, J.H. Evans, O.E. Mogensen and B.N. Singh, Rad. Effects 54 (1981) 65.

[10] B.N. Singh, D.J. Edwards, M. Eldrup, P. Toft, Risø Report R-10xx (to be published).

Figures

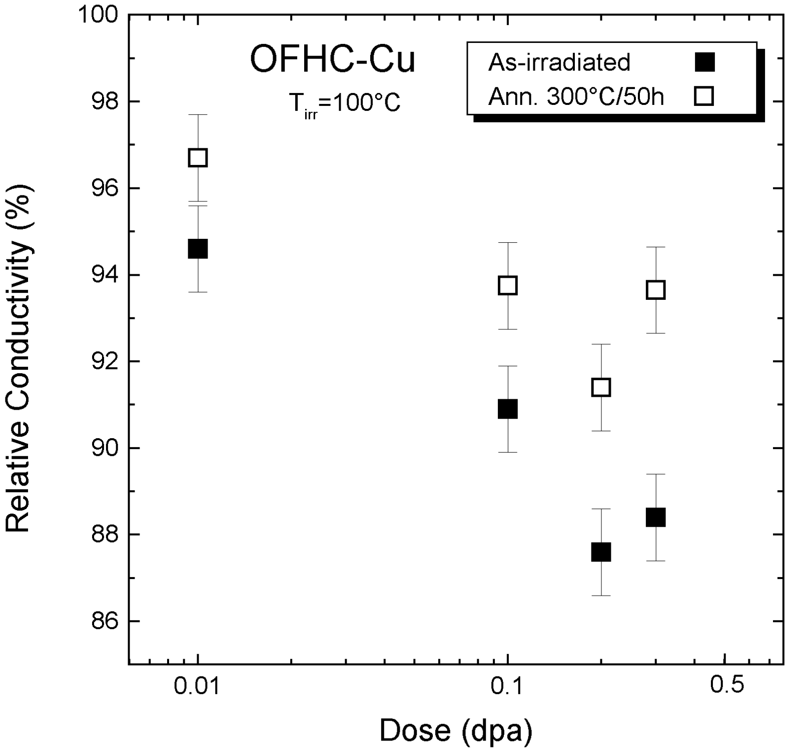

Figure 1. Relative electrical conductivity of OFHC copper, neutron irradiated at 100°C to different doses (dpaNRT), in the as-irradiated state and after annealing at 300°C for 50 hours. The error bars represent estimated uncertainties on the conductivity measurements.

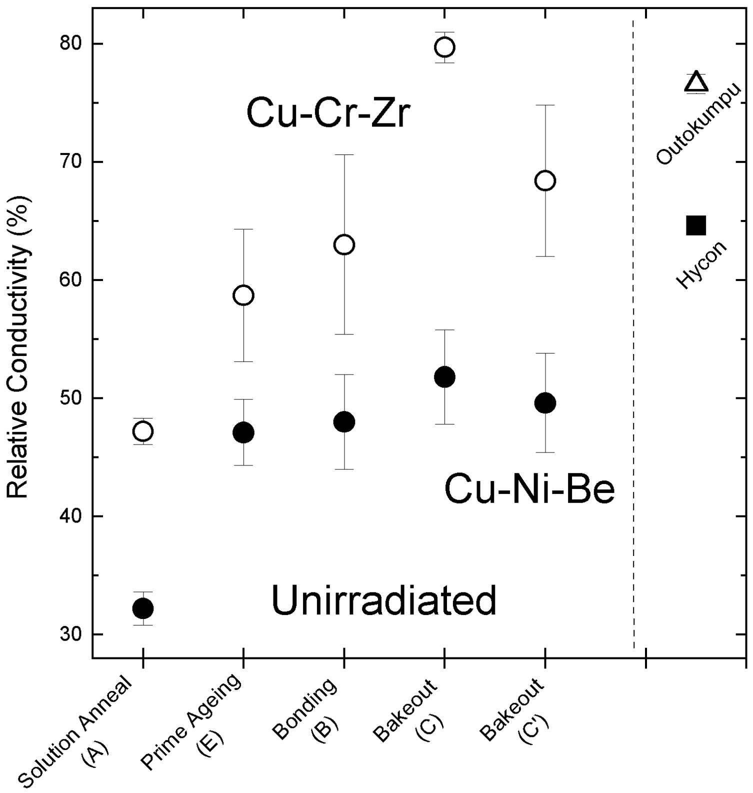

Figure 2. Relative electrical conductivity of CuCrZr (O, Δ) *and CuNiBe* (●,■) *alloys after different heat treatments in the un-irradiated state. The "error bars" represent variations in conductivities observed between different batches of samples with the same nominal heat treatment. Hycon is a commercial CuNiBe alloy and Outokumpu the CuCrZr alloy from this company after heat treatment F.*

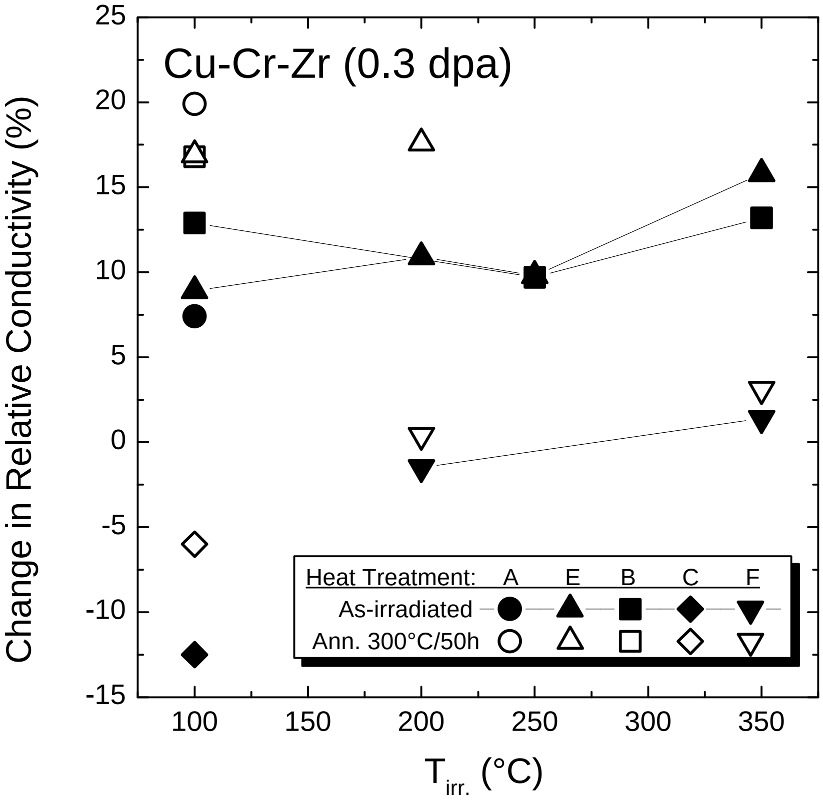

Figure 3. The change in relative conductivity for CuCrZr resulting from neutron irradiation to 0.3 dpa at different temperatures (closed symbols) and from post-irradiation annealing (300^{o}C/50 hours) (open symbols).

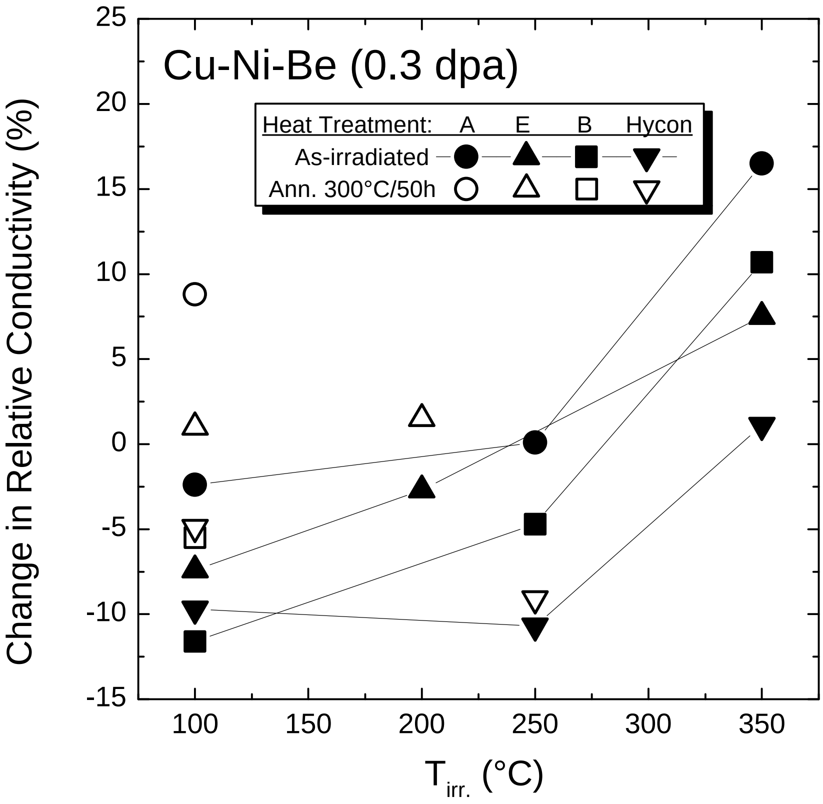

Figure 4. The change in relative conductivity for CuNiBe resulting from neutron irradiation to 0.3 dpa at different temperatures (closed symbols) and from post-irradiation annealing (300^{o}C/ 50 hours) (open symbols).

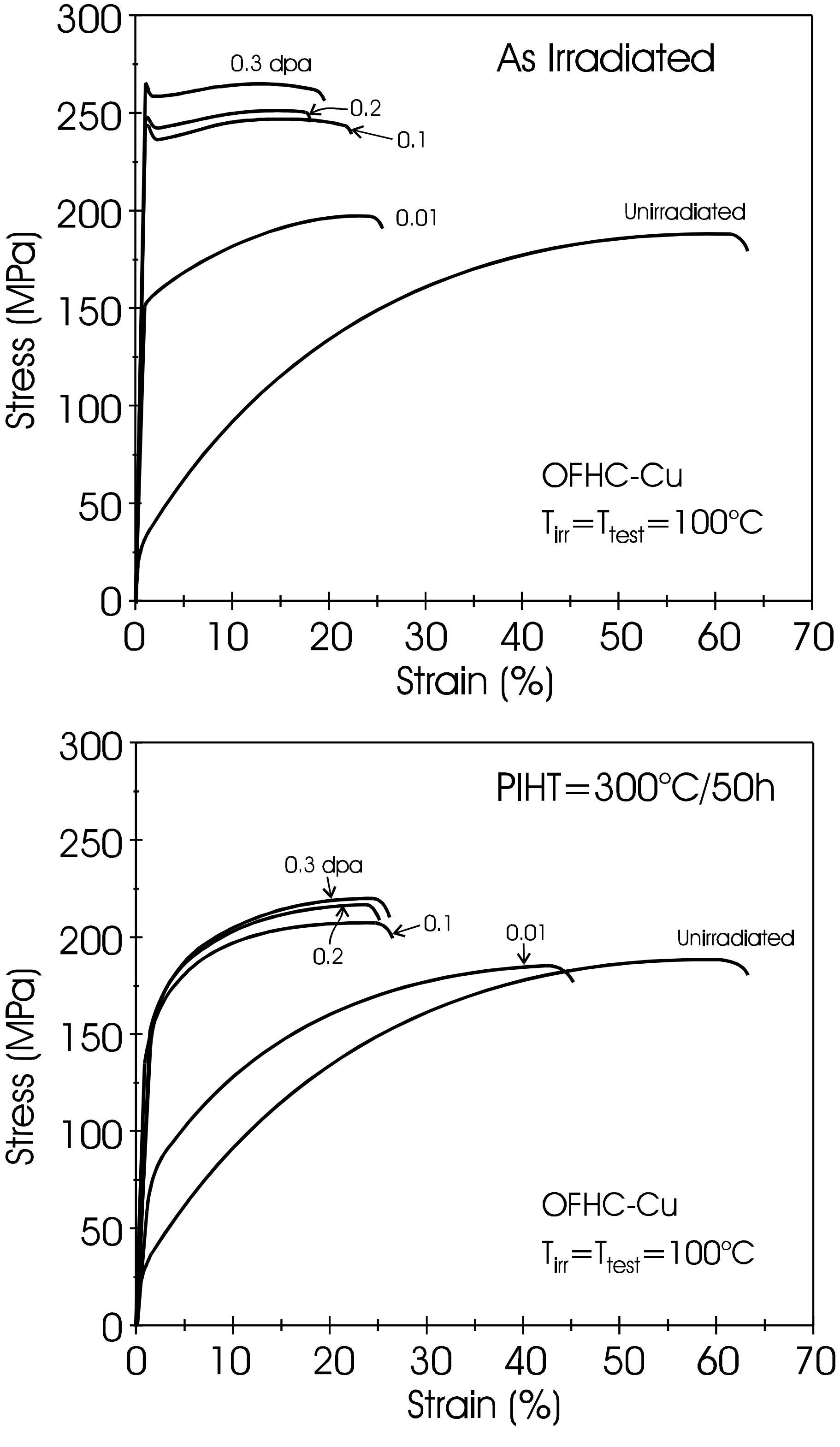

Figure 5. Tensile curves for OFHC-Cu, un-irradiated, after neutron irradiation to different doses at 100°C and after post-irradiation annealing (from [10]). The top part shows curves for as-irradiated specimens, and the lower part after post-irradiation heat treatment (PIHT) at 300°C for 50 hours. The saturation of the strength at the highest doses and the lack of total recovery after the PIHT are in agreement with the conductivity data for the same specimens (Fig. 1).

Bibliographic Data Sheet **Risø-R-1007(EN)**

Title and authors

Influence of Composition, Heat Treatment and Neutron Irradiation on the Electrical Conductivity of Copper Alloys

M. Eldrup and B.N. Singh

ISBN	ISSN
87-550-2350-9	0106-2840

Department or group	Date
Materials Research Department	January 1998

Groups own reg. number(s)	Project/contract No(s)

Pages	Tables	Illustrations	References
22	6	5	10

Abstract (Max. 2000 characters)

The electrical conductivities are reported for pure copper as well as for four different types of copper alloys, viz. CuNi, CuNiBe, CuCrZr and Cu-Al_2O_3, the latter three of which are under consideration for their applications in the structural components of ITER (International Thermonuclear Experimental Reactor). The alloys have undergone different pre-irradiation heat treatments which simulate the possible thermal histories of the material in ITER, and have been irradiated with fission-neutrons in the DR-3 reactor at Risø at temperatures in the range 100 - 350°C up to doses of 0.3 dpa. In some cases post-irradiation annealing at 300°C for 50 hours has been carried out. The CuNi and CuNiBe have the lowest conductivities ($\leq$ 40% and $\leq$ 55% of that of pure Cu), and Cu-Al_2O_3 the highest (75-90% of pure Cu). The results are discussed with reference to equivalent Transmission Electron Microscopy results on the microstructure of the materials and to data from mechanical testing.

Descriptors INIS/EDB

COPPER, COPPER BASE ALLOYS; NEUTRON IRRADIATION; FIRST WALL MATERIAL; ELECTRIC CONDUCTIVITY; HEAT TREATMENTS; THERMONUCLEAR REACTOR MATERIALS; PHYSICAL RADIATION EFFECTS.

Available on request from Information Service Department, Risø National Laboratory,
(Afdelingen for Informationsservice, Forskningscenter Risø), P.O.Box 49, DK-4000 Roskilde, Denmark.
Telephone +45 46 77 40 04, Telefax +45 46 77 40 13