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S.J. Zinkle, R.A. Dodd and G.L. Kulcinski

Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706

http://fti.neep.wisc.edu

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Fusion Engineering Program
Nuclear Engineering Department
University of Wisconsin-Madison
Madison, WI 53706

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S.J. Zinkle, R.A. Dodd and G.L. Kulcinski

Fusion Engineering Program, Nuclear Engineering Department
University of Wisconsin, 1500 Johnson Drive
Madison, Wisconsin 53706

Abstract

The microstructures of two candidate high-strength, high-electrical conductivity copper alloys (AMZIRC and AMAX-MZC) have been studied after heavy ion irradiation and after thermal annealing. An investigation of the behavior of these alloys following thermal treatment has shown that much of their strength is due to cold-working (high dislocation density). Microhardness measurements revealed that the MZC and AMZIRC copper alloys have a recrystallization temperature of about 475°C. Both alloys have been irradiated with 14-MeV Cu ions in the temperature range of 400-550°C (0.5 - 0.6 T_m). Samples were irradiated to maximum fluences of 3 x 10^{20} ions/m^2, which corresponds to a calculated peak displacement damage of 15 dpa based on a damage efficiency of K = 0.3. The irradiated foils have been examined in cross-section with an electron microscope. No void formation was observed in either alloy for this temperature range. Irradiation was found to enhance dislocation recovery and grain recrystallization processes in both alloys at the lower temperatures. The observed results imply that the MZC and AMZIRC copper alloys may undergo a significant degradation in their mechanical properties when exposed to irradiation at temperatures around 400°C.

Key Words: copper alloy, Cu-Cr-Zr, Cu-Zr, ion irradiation, dislocation recovery, radiation-enhanced, recrystallization, TEM, Vickers microhardness

Introduction

There has recently been a renewed interest in the irradiated properties of copper alloys as a result of design studies which call for incorporation of high-strength, high-conductivity materials in fusion reactors. A recent workshop sponsored by the Department of Energy serves to highlight the relative importance of copper alloys for fusion reactor applications [1]. Requirements of high axial magnetic fields have led to a hybrid magnet design where a normal-conducting coil is inserted inside of a shielded superconducting coil. High-strength copper alloys have been considered for use as high magnetic field insert coils in both tandem mirror and tokamak fusion reactors [2]. Several copper alloys are also being considered for use as unshielded magnet coils and as the first wall in compact fusion devices [3,4]. Other proposed areas of use for copper alloys in high irradiation zones include divertors, limiters and rf antennas.

The properties of irradiated pure copper have been investigated in great detail, and a large data base has been established (see, e.g. Ref. 5 for a review). However, there is relatively little information available on the response of copper alloys to irradiation. Several copper alloys which are commercially available have unirradiated mechanical and electrical properties which are suitable for the above-mentioned fusion reactor applications, and extensive alloy development work is continuing. Unfortunately, there is no known irradiation data available at the present time for these high-strength, high-conductivity alloys [5]. There is therefore an urgent need for irradiation data at conditions which will be typical of the environment experienced by these alloys in the reactor. The temperature range of interest varies from

25°C to greater than 450°C. Expected lifetime damage levels for these alloys range from less than 1 dpa to greater than 40 dpa [1], based on a 14-MeV neutron damage efficiency of K = 0.3.

Two candidate high-strength, high-conductivity copper alloys have been selected for the present investigation of the microstructural alterations which occur during heavy ion irradiation. AMZIRC and AMAX-MZC are heat-treatable copper alloys which have unirradiated yield strengths of 400-500 MPa and electrical conductivities which may approach the range of 80-90% IACS (International Annealed Copper Standard) [6]. An additional advantage of these copper alloys is that they have a relatively high recrystallization temperature of about 450°C. They are therefore potentially suitable for use at temperatures up to 400°C. Table 1 lists the composition of these alloys, along with some typical physical properties quoted by the manufacturer.

The present study concentrates on the microstructural evolution of the AMZIRC and MZC copper alloys following Cu ion irradiation to moderate damage levels at temperatures near the upper range of interest for fusion reactor applications. The damage microstructure is compared to the microstructure observed following thermal annealing in order to estimate the magnitude of the change in physical properties due to irradiation.

Experimental Procedure

Samples of the AMZIRC and AMAX-MZC copper alloys were obtained from AMAX Copper, Inc. in the form of 250 μm thick foils. Specifications given to the manufacturer for the alloy heat treatment called for obtaining the highest electrical conductivity achievable which was consistent with a yield strength of 415 MPa (60 ksi). The alloy preparation consisted of a solution heat treatment at 900°C for 1 hr, followed by 90% cold-rolling and then aging for

30 minutes at 375°C for the AMZIRC alloy and 400°C for the MZC alloy. Tensile tests performed by the manufacturer on these two lots of materials indicated that both alloys had yield strengths in excess of 480 MPa (70 ksi). No electrical conductivity tests were made by the manufacturer.

Electrical resistivity measurements were performed on the as-received alloys using standard 4-point probe techniques [7]. Measurements were made at room temperature (23°C) and 4.2 K. The gage length over which the voltage drop was measured was about 5 cm and the current density was maintained at about 200 A/cm^2. At least four specimens from each alloy were measured. Readings were taken with the current going both ways through the specimen and the results averaged in order to cancel the effect of thermal emfs.

As-received specimens from both copper alloys were mechanically polished using 0.3 μm alumina powder prior to their thermal annealing treatment. Specimens were annealed for 1 hour in a high vacuum furnace and cooled using a combination of furnace and air cooling. The specimen temperature decreased by 100°C within 1 minute following the anneal. Temperature control during the anneal was maintained to within ± 5°C. The pressure in the vacuum chamber ranged from 1×10^{-6} to 1×10^{-8} torr during the anneal. All specimens were electropolished immediately prior to making microhardness measurements in order to remove the oxide layer present from the anneal.

Vickers microhardness measurements were obtained from as-received and annealed specimens of each alloy at an indenter load of 200 g. A minimum of nine different indentations in three widely separated areas were measured for each alloy at the different annealing conditions. The measurements were obtained using a Buehler Micromet® microhardness tester and an antivibration test stand. Details of the specimen preparation and measurement procedure have been previously described [8].

Specimens of the as-received AMZIRC and AMAX-MZC alloys were mechanically polished and then electropolished at an applied potential of 5 V in a solution of 33% HNO_3/67% CH_3OH cooled to -40°C prior to their irradiation. Irradiations were performed on the as-received alloys at the Heavy Ion Irradiation Facility of the University of Wisconsin tandem Van de Graaf accelerator [9] with 14-MeV Cu^{3+} ions. The incident ion flux was approximately 5×10^{16} ions/m^2-s for all of the irradiations. The resultant irradiation time for the high fluence samples was $\lesssim$ 2 hours.

The depth-dependent damage energy ($S_D(x)$) for 14-MeV Cu ions incident on copper was calculated using the BRICE code [10]. This damage energy was then converted into displacements per atom (dpa) using the modified Kinchin-Pease model [11]:

$$N_d(x)\ (\text{dpa/s}) = (\phi/N)\,\frac{K\ S_D(x)}{2\ E_d} \qquad (1)$$

where ϕ is the incident particle flux, N is the atomic density of the target, E_d is the spatially-averaged displacement energy and K is the displacement efficiency. A value of E_d = 29 eV has been used in the dpa calculations [12]. The displacement efficiency (K) has generally been assumed to be equal to 0.8, independent of energy. Recent work indicates that K varies strongly with energy (see Ref. 13 for a review). At high energies (such as in the present case of 14-MeV Cu ions), K becomes roughly constant with a value $\lesssim$ 0.3 for copper. Therefore, we have used <u>K = 0.3</u> for all of our dpa calculations in this paper. Figure 1 shows the calculated damage and injected ion distributions for 14-MeV copper ions incident on copper.

Following the irradiation, the samples were electroplated with copper and cut into foils suitable for cross-sectional analysis using techniques developed by Knoll et al. [14]. Transmission electron microscope (TEM) specimens were jet-electropolished using a solution of 33% HNO_3/67% CH_3OH cooled to -20°C at an applied voltage of 15-20 V. Specimens were examined in a JEOL TEMSCAN-200CX electron microscope equipped with a Tracor-Northern TN2000 energy dispersive x-ray spectroscopy (EDS) system.

Results

A. Investigation of As-Received and Thermal-Annealed Specimens

The microstructure of the as-received AMZIRC and AMAX-MZC copper alloys is shown in Fig. 2. The dominant feature evident from these micrographs is the very high dislocation density present in the matrix. A relatively low density ($\sim 10^{18}/m^3$) of medium-sized precipitates (diameter $\lesssim$ 0.5 μm) was found to exist in both alloys. Examples of these precipitates are highlighted in Fig. 2. The MZC precipitates have been identified as pure chromium by using a combination of EDS and microdiffraction techniques. The exact composition of the AMZIRC precipitates is currently uncertain. Qualitative EDS analysis indicates that these precipitates are zirconium-rich. In addition, a very low density ($\lesssim 10^{17}/m^3$) of precipitates ranging in size from 1 μm to 10 μm was also observed in the AMZIRC alloy. Microdiffraction and EDS analysis has shown that these large precipitates are pure zirconium. The occurrence of these fairly large Cr and Zr precipitates is an indication that excessive amounts of these solutes were added to the MZC and AMZIRC alloy, respectively. However, the precipitates should not have any deleterious effects on the physical properties of the alloys due to their low density and small volume fraction.

The resistivity and Vickers microhardness (VHN) results obtained from the as-received alloys are shown in Table 2. The AMZIRC alloy has the higher conductivity and residual resistivity ratio (RRR), while the MZC alloy exhibits a larger microhardness number. The microhardness measurements were obtained using a 100 g load. A comparison between Table 1 and Table 2 reveals that both measured values of the alloy electrical conductivity are significantly lower (by ~ 35%) than the manufacturer's quoted optimum values.

Using appropriate hardness-yield strength correlations found in the literature, it is possible to estimate the yield strength of the two alloys [15]:

$$\sigma_y(\mathrm{kg/mm^2}) = (\mathrm{VHN}/3)(0.1)^n \qquad (2)$$

where n is the strain hardening coefficient. Typical values for copper are n = 0.1 and n = 0.45 for cold-worked and annealed conditions, respectively [16]. Using n = 0.1, the results of this correlation may be plotted along with the observed electrical conductivity to give a "figure of merit" for high-strength, high conductivity materials. The results are shown in Fig. 3. For purposes of comparison, the quoted materials parameters of a high-strength, high-conductivity copper alloy being developed by INESCO, Inc. [3] are shown in this figure along with the properties of annealed and lightly cold-worked copper. The estimated yield strengths of AMZIRC and AMAX-MZC are both in good agreement with the manufacturer's specifications, but the electrical conductivities are substantially lower than expected.

The microhardness results obtained from the two alloys following a 1 hour anneal at various temperatures are shown in Fig. 4. Both AMZIRC and AMAX-MZC exhibit a recrystallization temperature of about 475°C. Upon recrystallization, their microhardness numbers approach values typically found for annealed copper.

B. Ion Irradiation Results

As-received samples of AMZIRC and AMAX-MZC were irradiated with 14-MeV Cu ions at temperatures betewen 400°C and 550°C (0.5 - 0.6 Tm) up to calculated peak damage levels of 15 dpa (K = 0.3). No void formation was observed in these alloys for these conditions. As reported elsewhere [17], a 14-MeV Cu irradiation of an annealed AMZIRC sample to 15 dpa at 300°C resulted in the formation of a very low density of large voids (diameter $\lesssim$ 0.5 μm).

The major effect of irradiation of AMZIRC and MZC in this temperature regime was to greatly accelerate recovery and recrystallization processes. Figure 5 shows the effect of irradiation on AMZIRC to a peak damage level of 15 dpa (K = 0.3) as a function of temperature. These cross-sectional micrographs allow both the damage region and the control region of the foil to be simultaneously examined. At 400°C there is evidence of dislocation recovery and subgrain nucleation in the damage region, while the control region microstructure shows no signs of recovery. Both the control and damage regions have completely recrystallized following irradiation at 500°C and 550°. Small Cu-Zr precipitates are visible in the recrystallized regions. No significant difference was observed in the precipitate size or density between the damage and control regions.

The effect of irradiation temperature on the damage microstructure of AMAX-MZC is shown in the cross-section micrographs of Fig. 6. At 400°C, Cu ion irradiation to a peak damage level of 15 dpa (K = 0.3) causes recrystallization to occur while the control microstructure remains essentially unchanged. Irradiation at 500°C results in a fine-grained (grain diameter ~ 0.5 μm) microstructure in the damage region, while the control region has completely recrystallized and has grains which have grown to a size $\lesssim$ 10 μm. Once again, small precipitates are visible in the fully recrystallized regions. No differences in the precipitate size or density of the damage region versus the control region was discernible.

The AMAX-MZC alloy exhibited a more dramatic radiation-enhanced recrystallization behavior than AMZIRC for the same irradiation conditions. This result is conclusively demonstrated in Fig. 7, where cross-section microstructures of AMZIRC and MZC are compared following a 400°C, intermediate-fluence (peak damage level = 4.5 dpa, K = 0.3) irradiation. Subgrain formation is well established in the MZC damage region, while recrystallization is just beginning in the AMZIRC damage region.

In order to investigate the minimum irradiation temperature and damage level required to initiate recrystallization in AMAX-MZC, a low-fluence, low-temperature ion irradiation was performed. Figure 8 compares the cross-section microstructure in MZC following a 300°C, 1.5 peak dpa (K = 0.3) irradiation with the microstructure observed after a 400°C, 4.5 peak dpa (K = 0.3) irradiation. It is seen that some recrystallization has occurred in this alloy even at these relatively modest irradiation conditions.

Discussion

A. As-Received and Thermal Anneal Effects

As can be seen from Fig. 3, the correlated yield strength of the as-received AMZIRC and AMAX-MZC copper alloys as inferred from microhardness measurements is in good agreement with the manufacturer's specifications. On the other hand, the measured electrical conductivities of both alloys were substantially below the manufacturer's quoted optimum values (by ~ 35%). This discrepancy is apparently due to insufficient aging by the manufacturer. When the as-received alloys are aged for an additional 1 hour at 400°C, the measured electrical conductivity and estimated yield strength (from microhardness measurements) are in good agreement with the manufacturer's specifications [18].

The thermal annealing study (Fig. 4) indicates that a substantial portion of the strength of these alloys is due to their cold-worked structure. A supplemental annealing study was performed in order to quantify the relative strength of these alloys due to precipitation hardening versus cold-working. Several AMZIRC and AMAX-MZC specimens were encapsulated in evacuated quartz tubes and annealed at 950°C for 100 hours. Following a water quench, one-half of the specimens were resealed in quartz tubes and aged at 470°C for 1 hour. The results of microhardness measurements made on the solution annealed and solution annealed plus aged alloys are shown in Table 3. It can be seen from this table that the AMZIRC alloy has no observable response to precipitation hardening for these conditions. The MZC alloy shows a significant strength increase due to this precipitation-hardening treatment. This observation is in agreement with other thermal aging studies reported for these alloys [19-21]. Both aged alloys show microhardness numbers which are substantially below their as-received values. It can therefore be concluded that a large portion of the strength of both of these alloys is due to their cold-worked structure.

The recrystallization temperature for both AMZIRC and AMAX-MZC has been found to be about 475°C (see Fig. 4), in agreement with other literature results [6,22]. Upon recrystallization, the microhardness numbers for both alloys are similar to the value for pure copper. Therefore, both AMZIRC and AMAX-MZC will be unsuitable for use as a high strength alloy when conditions are present which might cause recrystallization to occur.

B. Ion Irradiation Effects

A review of the published irradiation data on copper shows that void formation occurs readily for neutron irradiation temperatures between 220 and 550°C (0.35 - 0.60 Tm) [5]. The present irradiations did not result in detectable void formation in either the as-received AMZIRC or the AMAX-MZC alloy for temperatures between 400 and 550°C. A limited number of large voids were observed in a companion ion irradiation of an annealed AMZIRC sample at 300°C [17], which indicates that the peak void swelling temperature for ion irradiation of these alloys is below 300°C. The cause of this large apparent shift in the void swelling temperature regime may be due to gas effects. Void nucleation calculations for copper irradiated in the absence of gas nucleating agents indicate that void formation is not expected for temperatures $\gtrsim$ 300°C [17]. Experimental studies on ion-irradiated copper by Glowinski [23] and Knoll [14] have found that de-gassed copper does not form voids for temperatures between 400-500°C. Both AMZIRC and AMAX-MZC are manufactured under carefully controlled (oxygen-free) environments using OFHC copper, so they do not initially contain any gas. It appears that more basic work regarding the effect of gas on void nucleation in copper is needed.

The main effect of ion irradiation on the microstructure of AMZIRC and AMAX-MZC at temperatures between 300 and 550°C was to greatly accelerate dislocation recovery and grain recrystallization processes. There are relatively few published reports which have examined the phenomenon of radiation-enhanced recrystallization. The major reported effect of radiation-enhanced recrystallization is to cause a reduction of the void density in the nucleated grains compared to unrecovered regions of the crystal [24,25]. Perhaps a more important effect to consider in the present case is the dramatic loss of strength in the AMZIRC and MZC alloys upon recrystallization. Since much of the strength of these alloys is due to their cold-worked structure, the irradiation results observed in Figs. 5-8 imply that AMZIRC and MZC will suffer a substantial degradation of strength during irradiation at temperatures $\lesssim$ 400°C. This argument will be quantified to a certain extent later in this paper.

A qualitative comparison of the irradiated microstructures of AMZIRC and AMAX-MZC for temperatures of 400-500°C reveals differences in their behavior (Figs. 4-6). The MZC alloy appears to be much more sensitive to irradiation with regard to recrystallization -- subgrain formation is observed to occur even at relatively modest irradiation conditions (Fig. 8) of 300°C and a peak damage level of 1.5 dpa (K = 0.3). Polygonization of the subgrains is observed in MZC following irradiation at 400°C to a peak damage level as low as 4.5 dpa (K = 0.3). In contrast, irradiation of AMZIRC at 400°C to a peak damage level of 15 dpa does not result in polygonization of the subgrains in the irradiated region. For higher irradiation temperatures (500°C), the

AMZIRC alloy has completely recrystallized and there is no discernible difference between the irradiated and nonirradiated regions (Fig. 4). The MZC alloy has essentially retained the small polygonized subgrain structure in the damage region following a 500°C irradiation, while the unirradiated region of the crystal has completely recrystallized. Microdiffraction analysis of the MZC damage region has revealed the presence of low-angle (~ 5°) sub-boundaries which separate the subgrains along with some high angle boundaries. It appears that some type of solute segregation/precipitation mechanism may be causing the pinning of the subgrain boundaries of MZC in the damage region. This mechanism apparently does not operate in the AMZIRC alloy. There was no readily evident effect of irradiation on precipitate size or density for either AMZIRC or MZC due to inhomogeneities in the alloy precipitate distributions.

Examination of Fig. 8 indicates that radiation-enhanced recrystallization may start to occur in AMZIRC and MZC irradiation conditions as moderate as 300°C, 1.5 peak dpa (K = 0.3). Since recrystallization is indicative of a large loss in strength, this implies that large engineering safety factors will be required when considering these types of alloys for high-strength reactor applications. Unfortunately, the strength of the ion-irradiated damage region cannot be directly measured due to its limited size. This is not due to technological difficulties -- several investigators have successfully developed microhardness indentation techniques which are capable of sampling regions as small as a few hundred nanometers in depth [26,27]. Instead, the problem is that it is presently impossible to directly correlate low-load microhardness results to bulk behavior due to the influence of the surface [8].

An alternative approach which may be used to quantify the loss of strength of the AMZIRC and MZC alloys in the damage region is to directly compare the irradiated microstructure to the microstructure obtained from thermal annealed specimens. Such a comparison is made in Fig. 9. The top two micrographs correspond to the microstructure observed in AMZIRC and AMAX-MZC after annealing for 1 hour at 475°C (i.e the onset of recrystallization). The two inset figures show the microhardness values which were obtained for this annealing condition (Fig. 4). The bottom two micrographs show the typical damage microstructure which is observed in AMZIRC and MZC after irradiation at conditions as indicated. The similarity in the annealed and irradiated microstructures for the two alloys is taken as an indication of equivalent strength. Two related effects are immediately evident: First, irradiation causes an effective shift of the recrystallization temperature to lower values. The magnitude of this shift is on the order of 100°C for AMZIRC irradiated to a peak damage level of 15 dpa ($K = 0.3$) and about 200°C for MZC irradiated to a peak damage level of 1.5 dpa (this comparison once again shows the stronger influence of irradiation on the MZC alloy as compared to the AMZIRC alloy). One of the previously mentioned advantages of these copper alloys is that they offer an unirradiated recrystallization temperature which is substantially above that of pure copper. The above discussion indicates that this advantage may be lost to a large extent upon irradiation, and the recrystallization temperature may approach a value comparable to pure copper.

The second effect (which is caused by the above-mentioned shift in the recrystallization temperature) is that both alloys lose a significant portion of their strength when irradiated at temperatures of 300-400°C. Comparison with the thermal annealed microhardness numbers (VHN) indicates that the irradiated AMZIRC microhardness number has dropped to 80% of its original value (new VHN = 115 HV), while the irradiated MZC microhardness number has fallen to 75% of its original value (new VHN = 130 HV). The corresponding decrease in yield strength will be even greater than the microhardness change because the work-hardening exponent (n) will also change (it will increase compared to the cold-worked case) as the alloys undergo recovery and recrystallization (see discussion of Eq. 2). A simple (pessimistic) estimation of the yield strength of the irradiated regions in AMZIRC and AMAX-MZC may be made by assuming the work-hardening exponent n has a value similar to that for annealed copper (n = 0.45). This gives lower limits for the yield strength of the irradiated alloys of $\sigma_y \sim 130$ MPa and $\sigma_y \sim 150$ MPa, respectively, for AMZIRC and MZC. This may be compared with their estimated unirradiated yield strengths of 375 and 450 MPa, respectively. The inferred dramatic loss of strength upon irradiation would make these alloys unacceptable for their proposed use in fusion reactors.

Still another factor to consider is that the present investigation deals with radiation-enhanced recrystallization effects in the absence of any external stresses. High-strength copper alloys are being proposed for use in fusion reactors in places where they will be exposed to fairly large stress levels while they are being irradiated. Since it is well known that applied stress can accelerate the recrystallization process [28], it appears obvious that the combined effects of stress and irradiation can lead to deleterious strength changes in any alloy which relies on thermomechanical treatment for a large portion of its nonirradiated strength.

In summary, it appears that a significant loss in strength may occur in AMZIRC and AMAX-MZC (or any alloy which relies extensively on thermomechanical treatment for its strength) during irradiation. However, more data is needed at lower irradiation temperatures in order to confirm the trends which have been observed at the higher irradiation temperatures.

C. Application of Results to Current and Proposed Fusion Devices

Table 4 lists the various fusion applications for which high strength copper alloys are being considered. For devices where dpa values were not available, the damage level was calculated from the neutron wall loading by assuming that 1 MW/m^2 = 3 dpa/FPY (K = 0.3), where FPY stands for full power year of operation. It can be seen that several devices approach or exceed the irradiation conditions investigated in this paper. In particular, the extreme demands of the RIGGATRON [3] may require a very advanced high-strength, high conductivity alloy yet to be developed. The insert magnets for MARS [2] and the limiters for STARFIRE [30] are two other applications which may require further alloy development before a satisfactory material is found. The AMZIRC alloy is currently being used in RTNS-II as the 50-cm diameter rotating neutron source target [22]. Accumulated damage levels are too low to be of concern in this device.

Conclusions

No voids were observed in the cold-worked plus aged AMZIRC and AMAX-MZC copper alloys following ion irradiation to calculated peak damage levels of 15 dpa (K = 0.3) at temperatures of 300-550°C (0.42 - 0.61 Tm).

The main effect of ion irradiation of AMZIRC and AMAX-MZC in the temperature region of 300-550°C is to cause an acceleration of the recovery and recrystallization processes. Since a significant amount of the strength of these alloys is due to their cold-worked structure, large safety margins must be used when considering these types of alloys for fusion reactor applications, at least for the above temperature range.

The effect of applied stress in conjunction with irradiation was not investigated in this study. However, since this type of environment will be present in reactor applications, basic work needs to be done to determine what additional enhancement at recrystallization kinetics, if any, will occur.

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Table 1. Composition and Optimum Physical Properties of AMZIRC and MZC (from Ref. 6)

Alloy	Zr (at %)	Cr (at %)	Mg (at %)	Electrical Conductivity @ 20°C	Yield Strength (0.2% Offset)
AMZIRC	0.13-0.20	-	-	93% IACS	410 MPa
MZC	0.15	0.80	0.04	80% IACS	517 MPa

Table 2. Measured Resistivity and Vickers Microhardness Values for As-Received AMZIRC and AMAX-MZC

Alloy	Resistivity (nΩ-m) 296 K	4.2 K	RRR = ρ 296 K/ρ 4.2 K	Conductivity (23°C)	Microhardness (HV_{100})
AMZIRC	23.0 ± 1.0	3.9 ± 0.3	6.0	73% IACS	144 ± 5
MZC	29.5 ± 1.6	13.5 ± 0.8	2.2	58% IACS	174 ± 7

Table 3. Vickers Microhardness of Solution-Treated Copper Alloys (200 g load)

Alloy	Microhardness (HV_{200}) As-Received	Solution Annealed (SA)	SA + Aged at 470°C
AMZIRC	146 ± 1	50 ± 2	48 ± 2
AMAX-MZC	168 ± 2	46 ± 5	84 + 4

Table 4. Current or Proposed Applications of High-Strength Copper Alloys in the Fusion Energy Community

Device	Use	Peak Temperature	Max. Damage Level*	Design Yield Stress
RTNS-II [22]	14-MeV Neutron Source Targets	100-200°C	$< 10^{-5}$ dpa	345 MPa
RIGGATRON [3]	First Wall	$\gtrsim$ 250°C	40 dpa	> 1000 MPa
	Toroidal Coils	150°C	40 dpa	760 MPa
	OH Coils	130°C	<< 1 dpa	410 MPa
CRFPR [29]	First Wall	300-350°C	~ 65 dpa/FPY	70-80 MPa
MARS [2]	Insert Magnet	150°C	~ 10 dpa/FPY	360 MPa
STARFIRE [30]	Limiter	200°C	~ 15 dpa/FPY	330 MPa
TFCX [31]	Magnet	150°C	$\lesssim 10^{-2}$ dpa	?

*assuming damage efficiency K = 0.3

Figure Captions

Fig. 1. Calculated ion displacement damage and implanted ion distribution for 14-MeV Cu incident on a copper target using the BRICE code [10]. DPA calculation assumes a displacement efficiency of K = 0.3, as opposed to the "standard" value of 0.8 (see text).

Fig. 2. TEM micrographs showing the as-received microstructure of AMZIRC and AMAX-MZC at a magnification of 50,000.

Fig. 3. Measured electrical conductivity and correlated yield strength of as-received AMZIRC and AMAX-MZC as compared to other high-strength copper alloys and the manufacturers specifications. AMAX copper data is from Ref. 6. INESCO data is from Ref. 3.

Fig. 4. Vickers microhardness number of as-received AMZIRC and AMAX-MZC as a function of annealing temperature following a 1 hour anneal.

Fig. 5. Depth dependent microstructure of AMZIRC as a function of temperature following ion irradiation to a calculated peak damage level of 15 dpa (K = 0.3). The top through bottom figures correspond to irradiations at 400, 500 and 550°C, respectively.

Fig. 6. Depth dependent microstructure of AMAX-MZC as a function of temperature following ion irradiation to a calculated peak damage level of 15 dpa (K = 0.3). Top figure: 400°C. Bottom figure: 500°C.

Fig. 7. Comparison of the depth-dependent microstructures of ion-irradiated AMZIRC and AMAX-MZC following irradiation at 400°C to a calculated peak damage level of 4.5 dpa (K = 0.3). Top figure: AMZIRC. Bottom figure: AMAX-MZC.

Fig. 8. Evolution of the depth-dependent recrystallization region in ion-irradiated AMAX-MZC. The top figure corresponds to a 300°C, 1.5 peak dpa (K = 0.3) irradiation and the bottom figure corresponds to a 400°C, 4.5 peak dpa (K = 0.3) irradiation.

Fig. 9. Microstructural comparison of thermal annealing vs. radiation damage effects in AMZIRC and AMAX-MZC. The AMZIRC specimen was irradiated to at 400°C to a calculated peak damage level of 15 dpa (K = 0.3). The MZC specimen was irradiated at 300°C to a calculated peak damage level of 1.5 dpa (K = 0.3).

FIGURE 1

DPA and ION DISTRIBUTIONS (BRICE)

14.0 MeV Cu IONS ON Cu TARGET

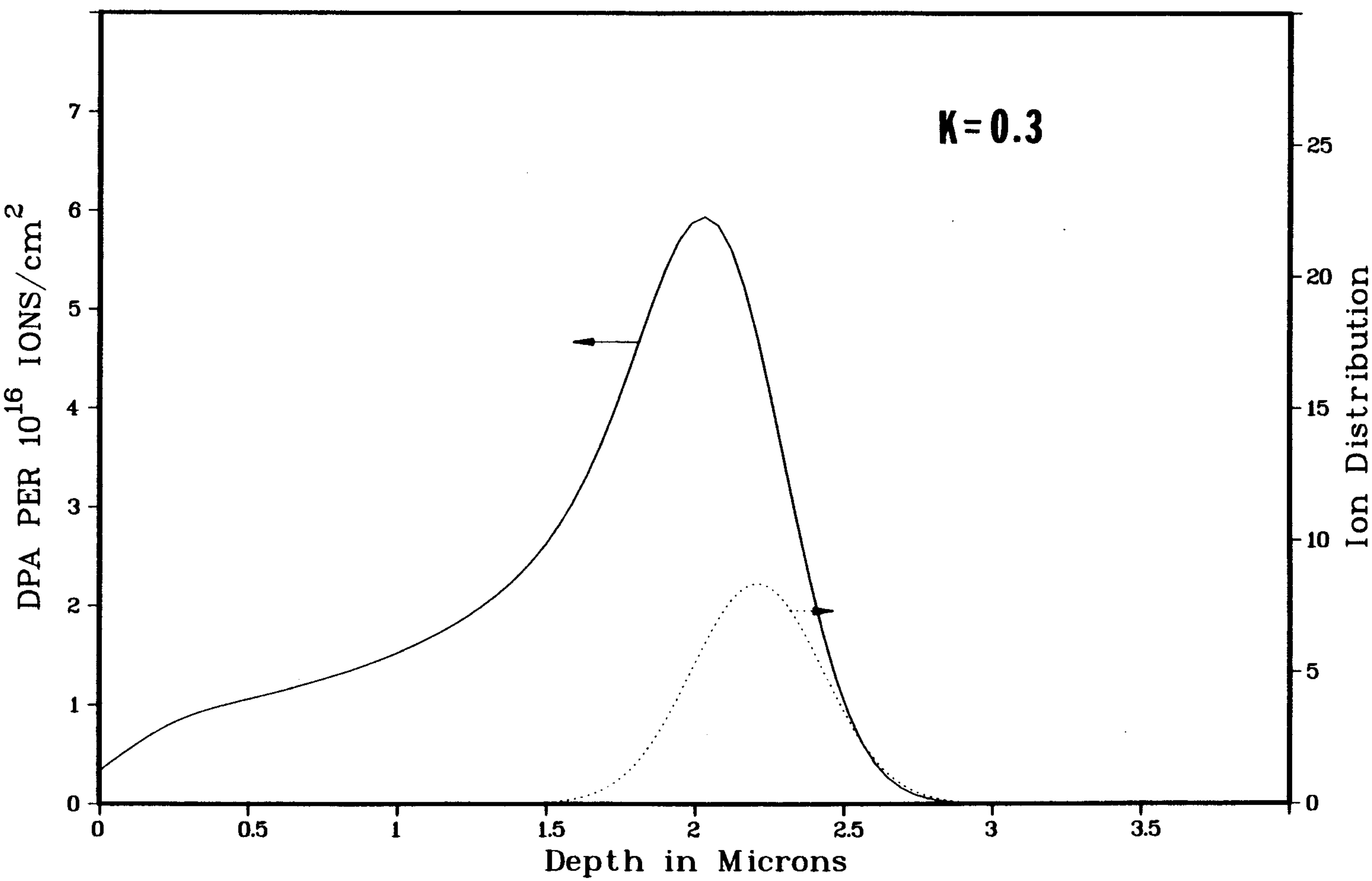


FIGURE 2

CONDUCTIVITY AND CORRELATED YIELD STRENGTH OF COPPER ALLOYS

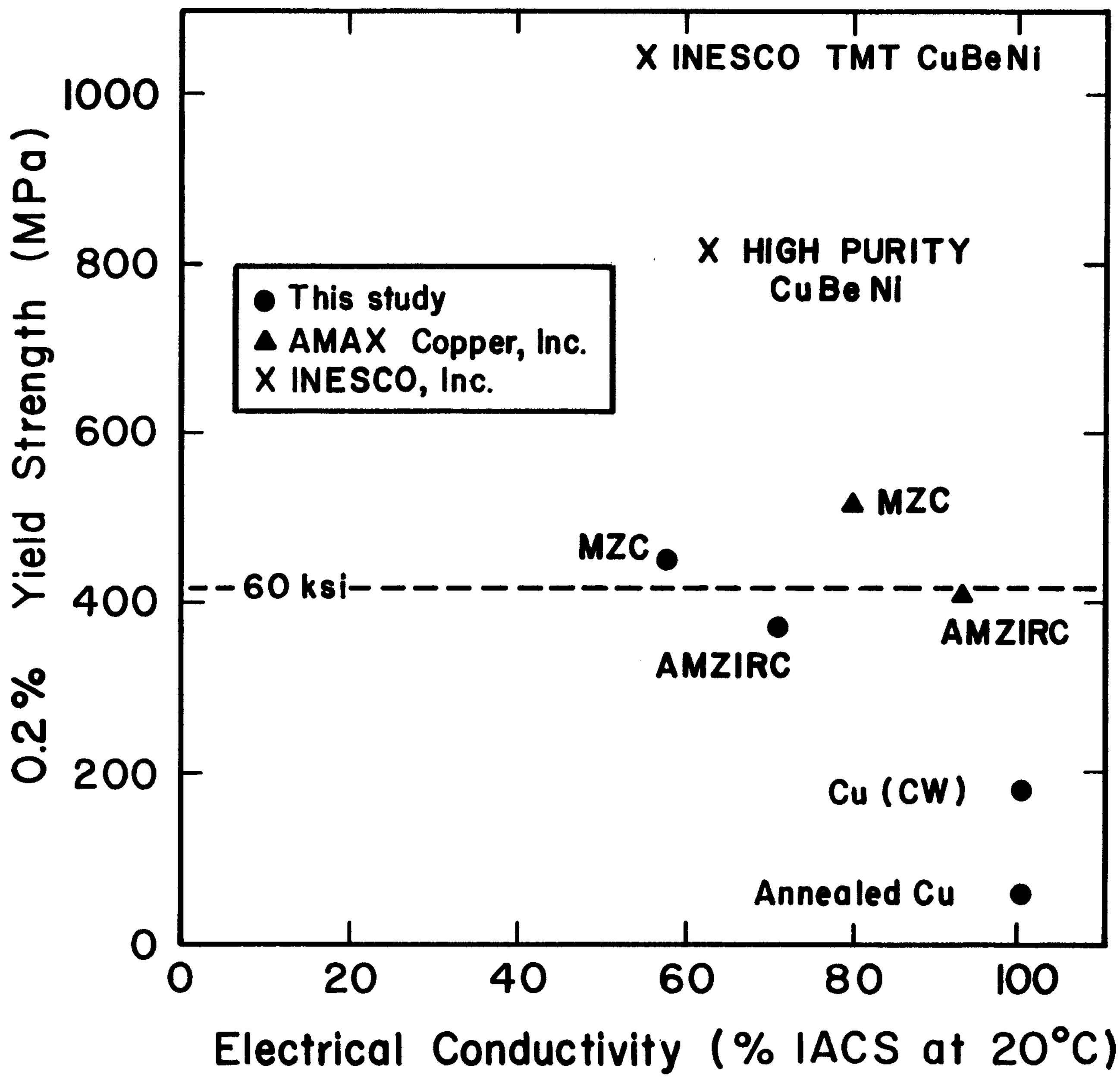
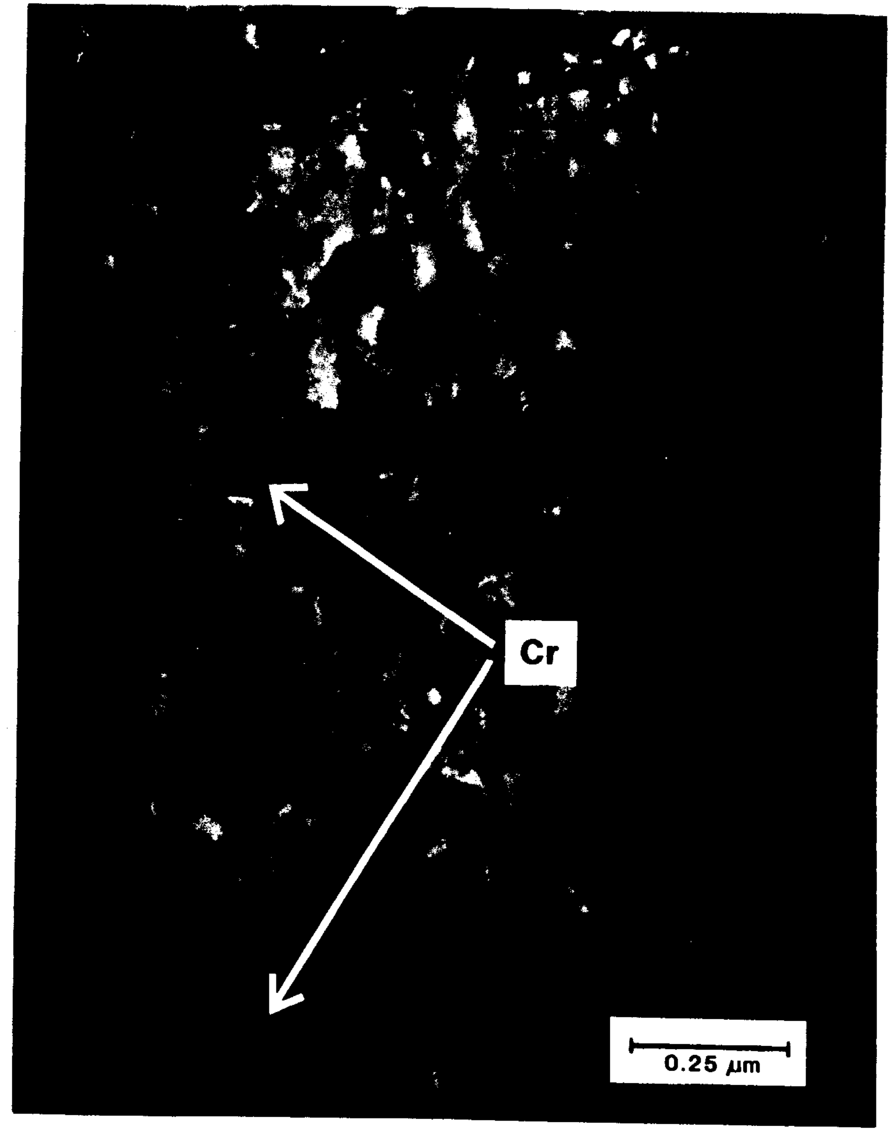


FIGURE 3

TRANSMISSION ELECTRON MICROGRAPHS OF AS-RECEIVED COPPER ALLOYS

AMZIRC



AMAX-MZC

FIGURE 4

VICKERS MICROHARDNESS VERSUS ANNEALING TEMPERATURE

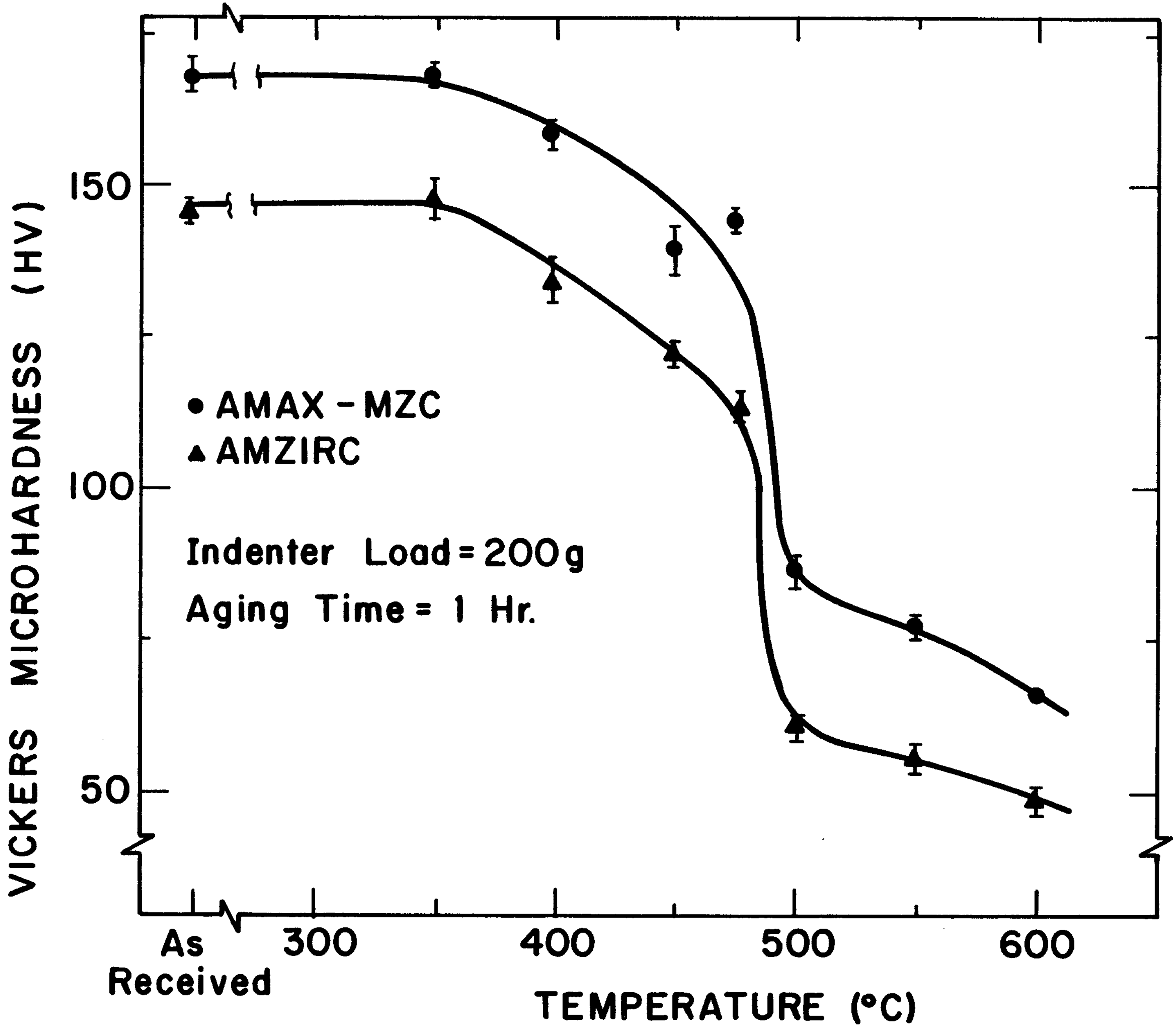


FIGURE 5

EFFECT OF IRRADIATION TEMPERATURE ON THE MICROSTRUCTURE OF AMZIRC

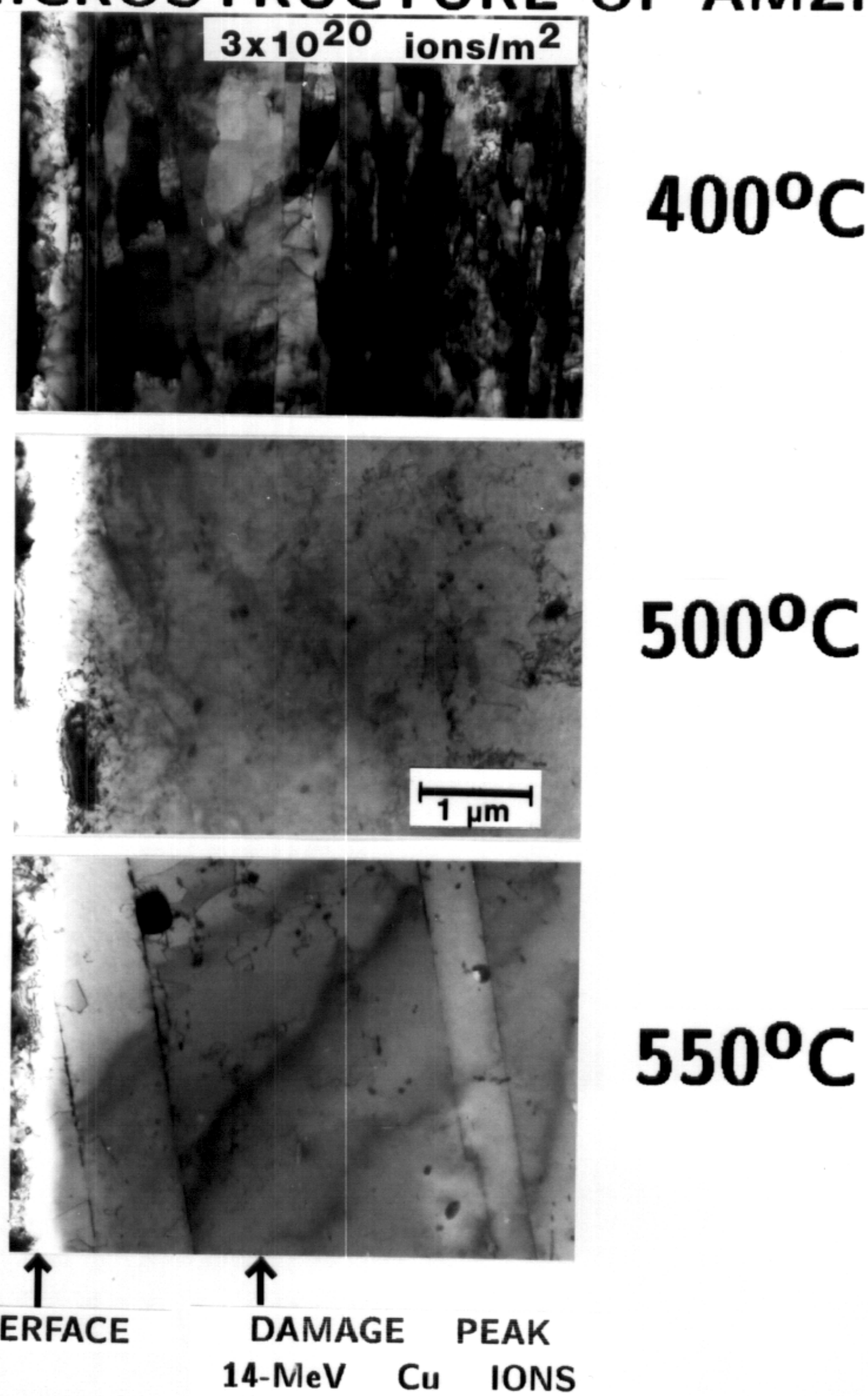
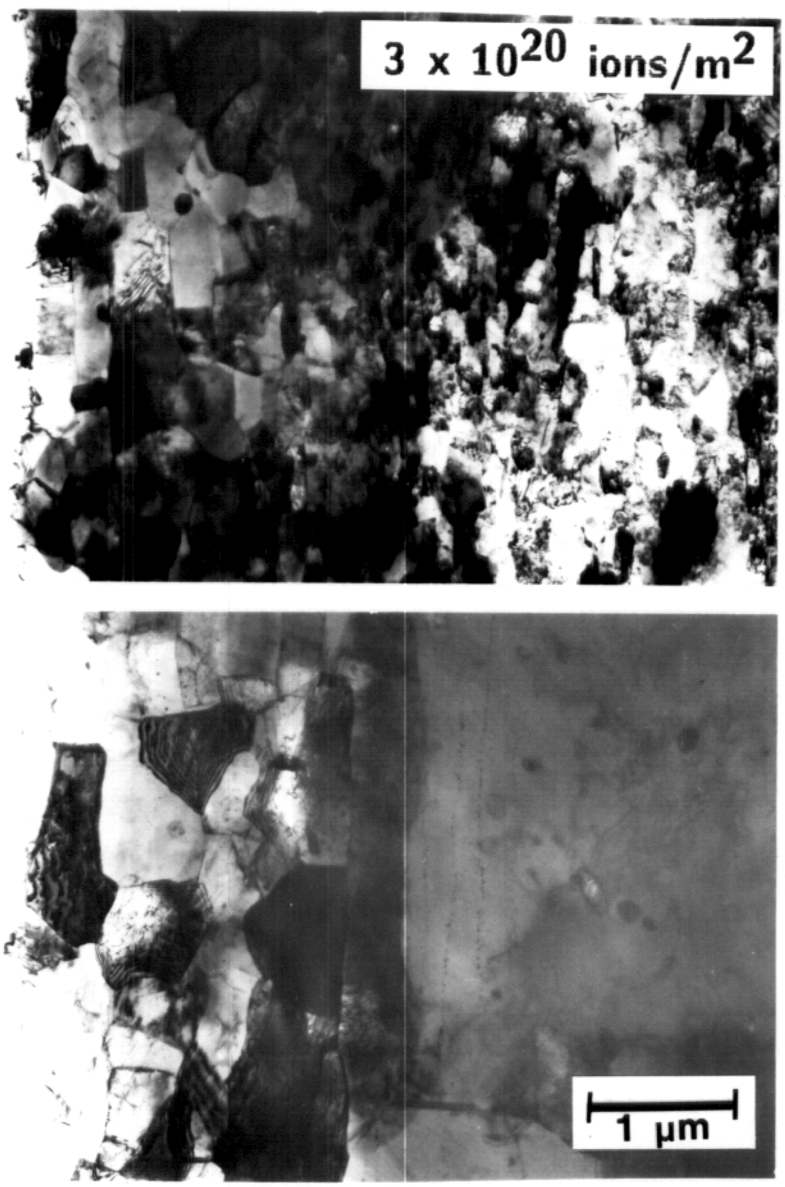


FIGURE 6

EFFECT OF IRRADIATION TEMPERATURE ON THE AMAX-MZC MICROSTRUCTURE



400°C

500°C

INTERFACE

DAMAGE PEAK
14-MeV Cu IONS

FIGURE 7

COMPARISON OF RADIATION DAMAGE IN AMZIRC vs. AMAX-MZC

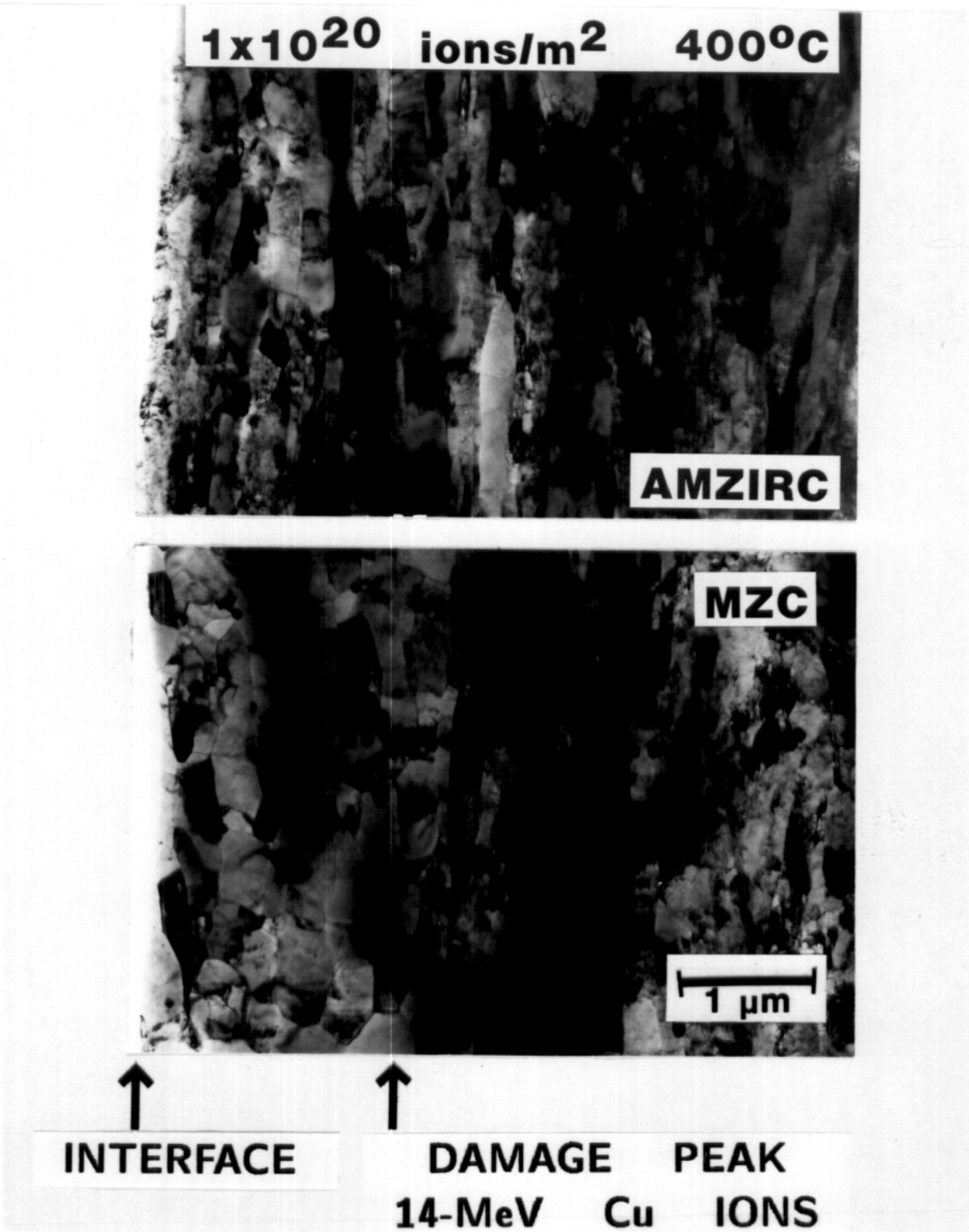


FIGURE 8

EVOLUTION OF THE RECRYSTALLIZATION REGION IN IRRADIATED AMAX-MZC

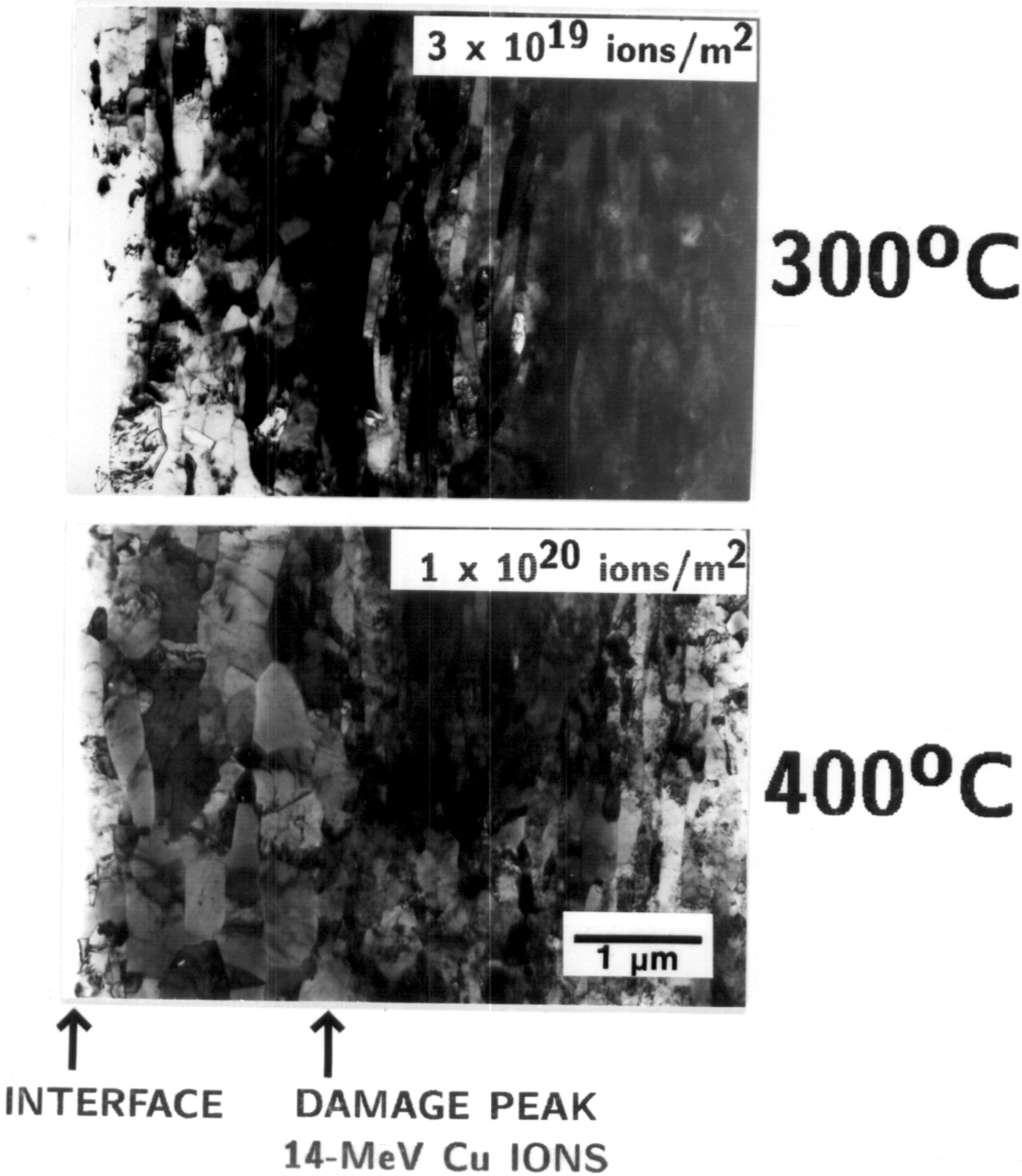
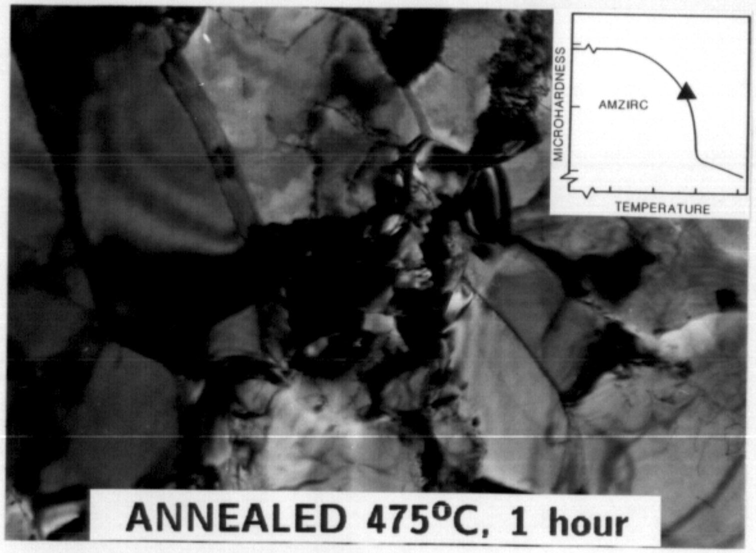
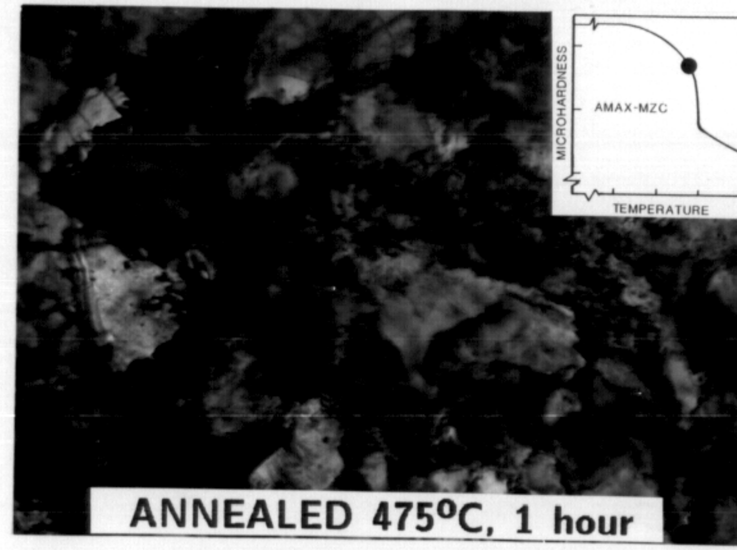


FIGURE 9

MICROSTRUCTURAL COMPARISON OF RADIATION DAMAGE vs. THERMAL ANNEALING EFFECTS





AMZIRC

AMAX–MZC