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TITLE:
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MASTER

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PROMISING COPPER ALLOY FOR HIGH HEAT LOAD APPLICATIONS IN NEUTRON ENVIRONMENTS

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Abstract

Four candidate copper alloys and two elemental coppers were irradiated in the Experimental Breeder Reactor to damage levels of about 3 and 15 dpa at 385°C. The irradiated and control samples were evaluated to determine swelling, room temperature tensile properties, transmutation product levels, and electrical resistivity. Transmission electron microscopy was used to characterize the damaged microstructures. Among the six materials studied, the alumina-dispersed copper alloys (Glidcop Al-20 and Al-60 sheet material) exhibited the best, overall resistance to fast neutron damage as they had minimal swelling and retained their original values of yield strength and electrical resistivity (corrected for transmuted elements) after irradiation. The two cold worked and age-hardened alloys (AMZIRC and MZC) suffered loss of yield strength after irradiation at 385°C. The two elemental coppers and the AMZIRC alloy showed large swelling (3.6-6.8 vol%) due to void formation after the high neutron fluence. Further study is needed to understand microstructural alterations caused by neutron damage of the alumina-dispersed copper alloy.

Introduction

High-strength, high-conductivity copper alloys are being considered for several magnetic fusion energy (MFE) applications such as the first wall in high power-density devices, resistive magnetic coils, and high heat flux components. The high thermal conductivity of copper-base alloys, relative to other candidate structural materials such as stainless steel and refractory alloys, offers the design potential of higher thermal fluxes at the first wall which is especially important for compact, high power-density reactors [1,2]. The purpose of this investigation is to determine the effects of fast neutron irradiation on the microstructure and relevant properties of four commercial copper alloys having high thermal conductivity and good elevated temperature properties.

Procedure

Two elemental coppers and four dilute copper alloys were irradiated in the Experimental Breeder Reactor (EBR-II) at 385°C to two fluences ($E_n > 0.1$ MeV) of 0.4 and 2.0 x 10^{26} n/m^2 corresponding to about 3 and 15 displacements per atom (dpa). The nominal compositions of the six copper test materials (in wt.%) are MARZ-grade copper - 99.999% purity, oxygen-free (OF) copper - 99.95% purity, Al-20 - 0.20% alumina, Al-60 - 0.60% alumina, AMZIRC - 0.17% Zr, and MZC - 0.5% Cr + 0.18% Zr + 0.04% Mg. Control samples were annealed at the same time and temperature (245 days at 385°C) as the full-power days exposure of the irradiated samples. The irradiation temperature used is a realistic near-maximum temperature for high power-density first wall designs based on copper alloys.

The MARZ-grade copper was irradiated in the cold rolled condition, and the oxygen-free copper had been annealed 5 minutes at 500°C in argon after cold rolling. The two precipitation-hardened alloys (AMZIRC and MZC) supplied by AMAX Base Metals were irradiated in the 90% cold rolled and aged condition (one hour at 425°C). The two alumina-dispersed copper alloys (Al-20 and Al-60) were supplied by SCM Metal Products that had produced them by the hot extrusion and subsequent fabrication of internally oxidized powders. These two alloys had been cold rolled 83% reduction in thickness followed by an intermediate anneal at 850°C in argon and then given a final cold reduction of 70% with a stress relief anneal at 850°C in argon.

Density changes for the control and irradiated samples were measured using the immersion method with bromobenzene. Room temperature tensile properties were determined for triplicate specimens measuring 35 mm long x 2 mm wide x 0.5 or 0.25 mm thick. Fractographic examination of the broken tensile specimens was conducted using a scanning electron microscope.

Results and discussion

The increases in volume (or swelling) after irradiation of these copper alloys are given in Figure 1. The results are based on density measurements made of triplicate specimens with a typical standard deviation of about 0.3% for each condition. [3] The two elemental coppers (MARZ and OF) exhibited the same swelling response after irradiation within the accuracy of the density measurements. For the two alumina-dispersed copper alloys, the thin copper clad produced by the manufacturing process was chemically removed from the specimens before measuring the densities. The variability of the data for these two samples indicates relatively little swelling at the high fluence compared to the other tested samples. The two precipitation-hardened copper alloys did not swell at the low fluence, whereas at the high fluence the AMZIRC alloy exhibited a large change in volume. Previous dual-ion irradiation experiments with this

AMZIRC sample [4] found non-uniform void formation occurring in the temperature range 300-400°C. An encouraging observation is that the MZC alloy did not swell at the high fluence corresponding to about 15 dpa.

Tensile yield strengths and reductions of area measured at room temperature for the irradiated and control samples are given in Figures 2 and 3. Tabulated values of the measured tensile properties are given in Ref. 3. The cold worked, MARZ-grade copper did not show any pronounced changes in 0.2% offset yield strength due to neutron irradiation, although it did have a lower reduction of area at the high neutron dose. The yield strength of the annealed OF copper doubled after the neutron irradiation. The two alumina-dispersed alloys exhibited relatively stable tensile properties after irradiation.

The two precipitation-hardened alloys exhibited pronounced softening after irradiation as reflected by the lower yield strength levels with the AMZIRC alloy showing larger changes than the MZC alloy. These two alloys were irradiated at a temperature somewhat below their aging temperature range so that radiation-enhanced overaging effects at long times would be anticipated. A previous investigation [5] of the thermal and ion irradiated behavior of these two alloys found that Cu-ion irradiation accelerated dislocation recovery and grain recrystallization processes in the temperature range 300-550°C resulting in significant softening.

Fractographs of the broken tensile specimens are given in Ref. 6. The OF copper control sample exhibited a very ductile failure as evidenced by the knife-edge fracture and wavy slip appearance. After irradiation to 15 dpa, the OF copper showed less reduction of area at the failure and large dimples on the fracture surface that may be associated with voids. The MARZ-grade copper had similar fractographic features as the OF copper.

The fracture appearance of the Al-20 and Al-60 samples did not change with irradiation. Small dimples observed on the fracture surface are characteristic of a microvoid coalescence failure mechanism. These observations confirm the measured ductility values given in Figure 3 which did not change very much with irradiation for the alumina-dispersed alloys.

Irradiation produced large changes in the fracture appearance of the AMZIRC samples. The control specimen showed wavy slip or serpentine glide which characterizes ductile failure. After irradiation, large dimples were observed on the fracture which may be associated with voids formed during neutron irradiation.

The electrical resistivity of the irradiated and control samples were measured at room temperature using the four-point, dc probe method. [7] For metallic conductors, the electrical and thermal conductivities are directly proportional as given by the Wiedeman-Franz relationship. A relative figure of merit for resistance to thermal stress is the product of the material's tensile yield strength and electrical (or thermal) conductivity. The bar chart given in Figure 4 clearly indicates that, based on this figure of merit, the alumina-dispersed copper alloys have the best resistance to thermal stresses after neutron irradiation of the six copper-base materials tested.

Transmission electron microscopy was used to characterize microstructural changes resulting from the neutron irradiation. [8] The two elemental coppers exposed to 15 dpa damage contained large, faceted voids with typical dimensions of ≈200 nm as expected from earlier irradiation studies done on copper. [9,10] The AMZIRC alloy had recrystallized after the high dose, neutron exposure at 385°C, whereas the MZC alloy had retained the dislocated, subgrain structure imparted by the prior mechanical cold working. The dislocation substructure and particle morphology of the alumina-dispersed copper alloys were not visibly altered by the neutron irradiation.

Chemical analyses for three of the copper test materials are given in Ref. 5 for both irradiated and unirradiated samples. Transmutation of copper by neutron irradiation increased the nickel and zinc contents of all three materials by measurable amounts. The major effect of these chemical changes for MFE applications will be to decrease the thermal conductivity of the materials during irradiation with subsequent impact on the design and operating parameters of a fusion energy device.

Summary

Among the six copper-base materials studied, the alumina-dispersed copper alloys (Al-20 and Al-60) exhibited the best resistance to neutron damage. Fast neutron irradiation at 385°C to a damage level of 15 dpa produced large swelling of elemental copper and the Cu-Zr (AMZIRC) alloy. The other three commercial alloys tested (MZC, Al-20, and Al-60) did not exhibit pronounced swelling under these irradiation conditions. The two precipitation-hardened alloys softened significantly after irradiation, whereas the two alumina-dispersed alloys showed relatively stable tensile properties after irradiation. Additional evaluation and development of oxide-dispersed copper alloys are needed to establish the viability of using these materials for high heat flux components in MFE applications.

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Figure captions

Figure 1. Increases in volume (or swelling) based on immersion density measurements of control and irradiated copper-base materials.

Figure 2. Tensile yield strengths (0.2% offset) measured at room temperature of control and irradiated copper-base materials.

Figure 3. Reduction of areas measured on broken tensile specimens of control and irradiated copper-base materials.

Figure 4. Figure of merit comparing relative resistances to thermal stresses for control and irradiated copper-base materials.

Figure 1: SWELLING OF IRRADIATED COPPER ALLOYS

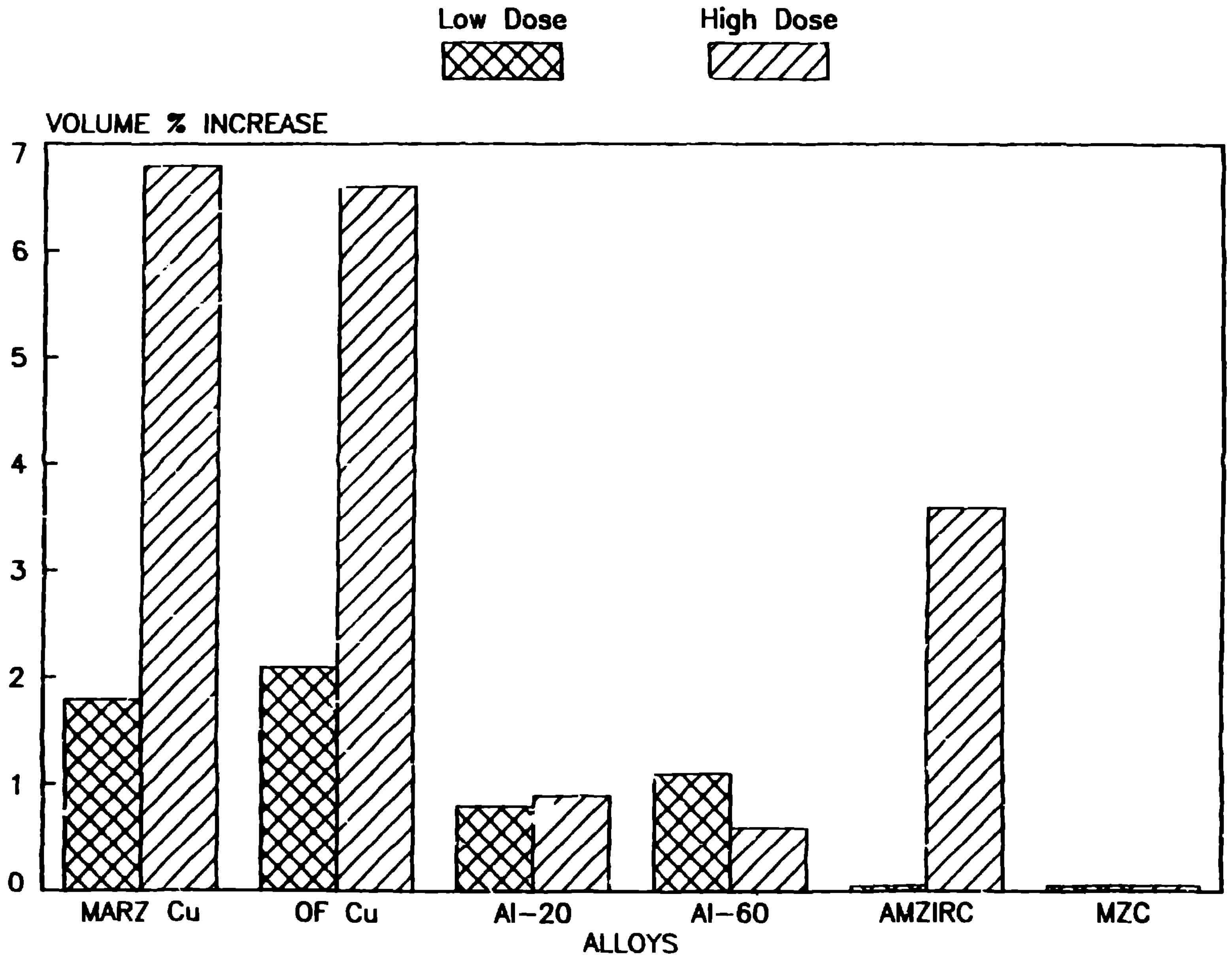

Figure 2: YIELD STRENGTH OF IRRADIATED COPPER ALLOYS

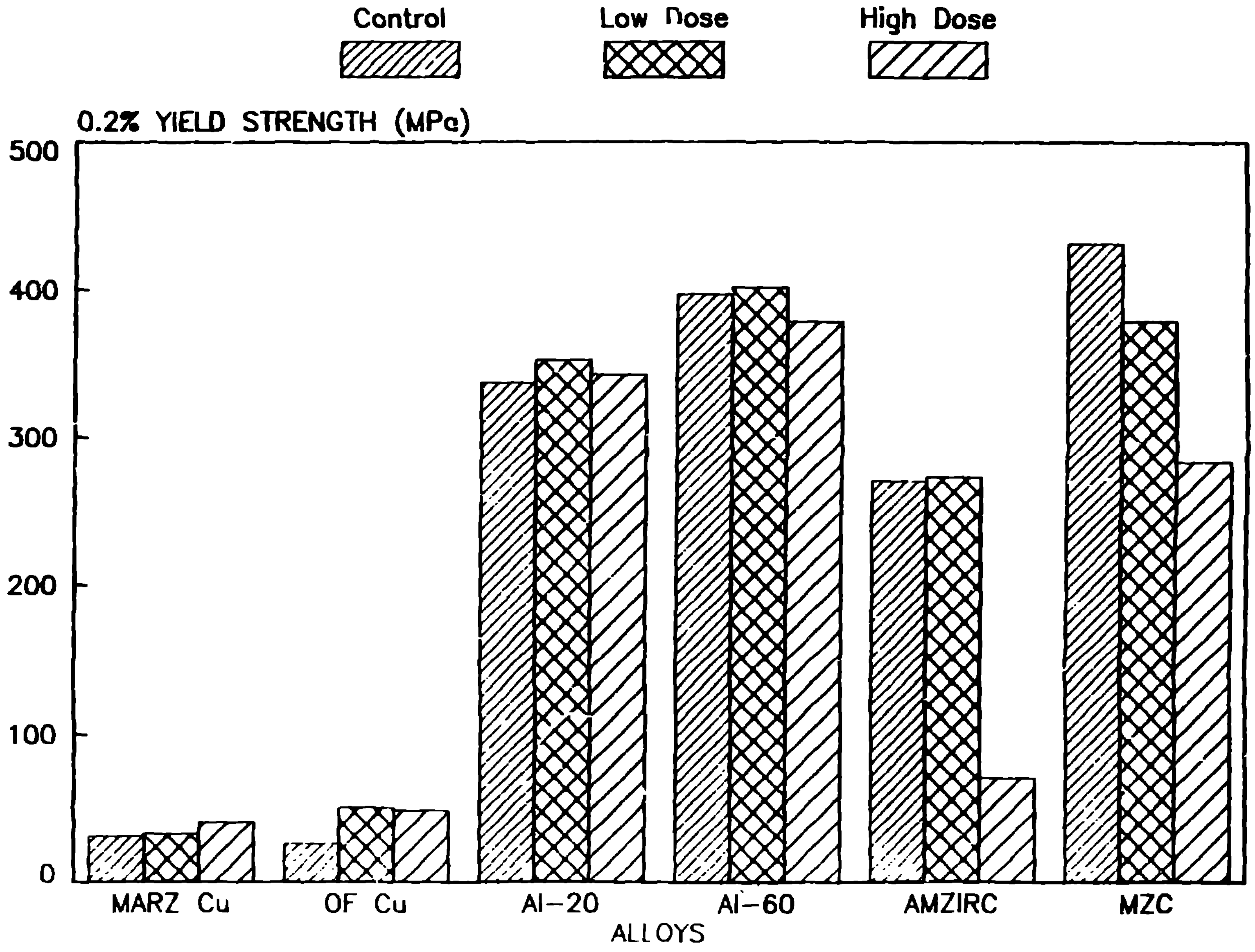

Figure 3: REDUCTION OF AREA FOR IRRADIATED COPPER ALLOYS

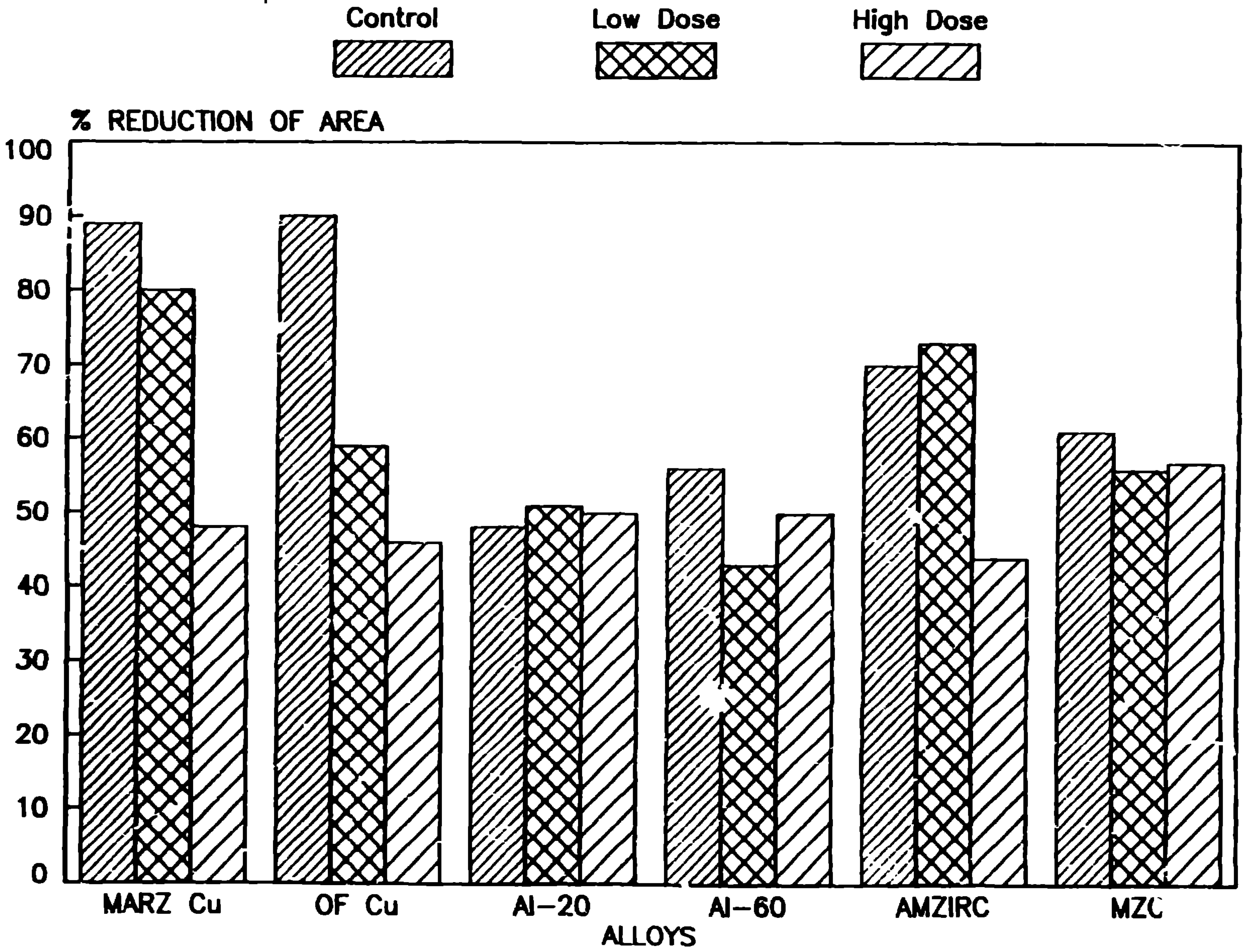

Figure 4: RESISTANCE TO THERMAL STRESSES FOR IRRADIATED COPPER ALLOYS