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Effect of high-dose neutron irradiation on the mechanical properties and structure of copper alloys and Cu/SS joints for ITER applications

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Abstract

The base copper alloys Cu–Cs–Zr IG and GlidCopAl25 IG and Cu/SS joints manufactured in Russian Federation (RF), United States (US), Europe (EU) and Japan (JA) with the HIP method were irradiated up to 2 dpa at 200°C in SM-2 reactor. Tensile tests, shear tests, metallography and SEM investigations were performed. Mechanical test results on the base alloys and joints irradiated up to 2 dpa at 200°C indicate that the trends established at lower dose (0.3–0.4 dpa) tests are still valid at higher doses. The main effect of the irradiation dose increase can be considered as a shift of the low temperature embrittlement towards higher temperatures.

1. Introduction

Unirradiated precipitation hardened (PH) and oxide-dispersion-strengthened (ODS) copper alloys are considered as the main candidate materials for the ITER high-heat flux components; these materials have high levels of strength and ductility in the unirradiated condition [1,2]. The question of how such alloys will behave at large damage doses of ~2–5 dpa, i.e., close to the lifetime operation conditions, is of special interest. Without this knowledge, the lifetime of ITER components cannot be substantiated. At the same time, the effect of rather high doses of radiation damage (>1 dpa) on copper alloy properties in the operation temperature range typical of ITER operation conditions (100–350°C) has not been adequately investigated. For example, data on the properties of CuCrZr(Mg) alloy after irradiation to 3–9 dpa are found only in three studies [3–5]. These studies refer to the alloys in a solution annealed (SA) + cold worked + aged state, while for ITER the SA + aged state is recommended. Similarly, very few data exist for ODS GlidCopAl25 alloy irradiated at ITER-relevant conditions of 100–350°C and >1 dpa. Thus, the data necessary for an assessment of the radiation lifetime of candidate copper alloys for ITER application is lacking.

This study presents the first results of an investigation into the properties of the base copper alloys Cu–Cr–Zr IG and GlidCopAl25 IG, as well as Cu–Cr–Zr/316 and GlidCopAl25/316 joints irradiated to 2 dpa at 200°C.

2. Experimental

GlidCopAl25 IG (IGO modification) specimens were fabricated from a 25-mm thick plate in longitudinal and transverse directions. GlidCopAl25/316SS specimens were fabricated of GlidCopAl25IGO/316 joints made in Japan (JA) and Europe (EU) [6].

Cu–Cr–Zr specimens were fabricated from two Cu–Cr–Zr heats. Heat No. H822 supplied by Zollern was

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solutionized at 970°C for 2 min followed by water quenching and aging at 457°C for 2 h. Heat AN4946 was supplied by Kabelmetall in the F37 temper and was heat-treated by solutionizing at 980°C for 1 h followed by water quenching, and aging at 475°C for 2 h. Specimens were also prepared directly from Cu–Cr–Zr/316SS HIPped joints.

Therefore, in the present study the influence of fabrication procedures: (CR + ann), (CR + ann + HIP solid) on the GlidCopAl25 IGO alloy and (SA + aged), (SA + aged + HIP solid) on the Cu–Cr–Zr alloy properties were investigated. Specimen fabrication procedures are detailed in [6]. One-mm thick STS-type (sheet tensile specimens) with the gauge length of 10 mm was used in the study for the investigation of tensile properties of copper alloys and Cu/SS joints.

The specimens were irradiated in Channel N5 of the SM-2 reactor to a fluence of $\sim 3.5 \times 10^{21}$ n cm^{-2} ($E > 0.1$ MeV) that corresponds to the radiation damage of ~2 dpa (NRT). Irradiation was performed in a special ampoule with boiling water making it possible to control the temperature of the specimens while under irradiation. According to thermocouple readings, the irradiation temperatures were in the range 190–200°C for STS samples.

Irradiated and reference specimens were tensile tested at a strain rate of 1.6×10^{-3} s^{-1}. SEM investigations of the fracture surface of tested specimens were also performed. The irradiation and testing techniques are detailed in [6].

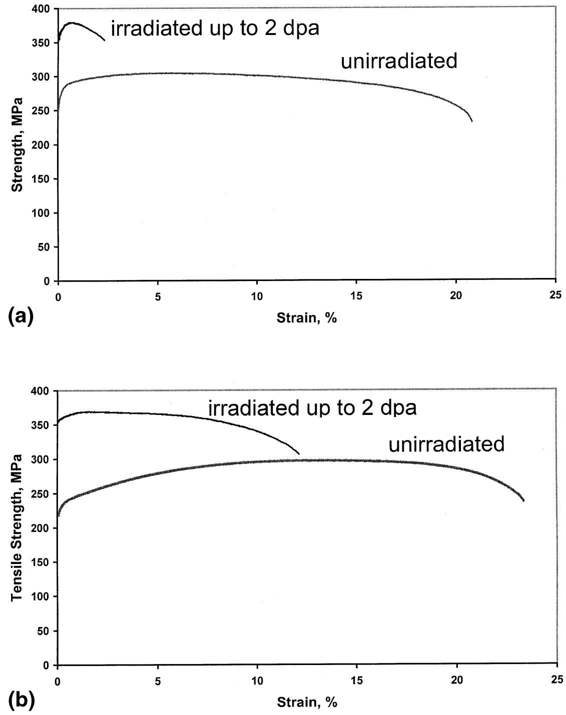

Fig. 1. Engineering stress–strain curves of GlidCopAl25 IG (CR + ann) alloy (a); and CuCrZr (SA + aged) alloy (b), tested at 200°C, before and after irradiation up to 2 dpa at $T_{irr} = 200$°C.

3. Results

3.1. Mechanical properties

3.1.1. Base materials

Fig. 1 shows typical engineering stress–strain curves of Cu–Cr–Zr IG and GlidCopAl25 IG alloys at $T_{test} = 200$°C prior to and after irradiation to 2 dpa ($T_{irr} \sim 200$°C). It is apparent that irradiation involves hardening of both alloys, and a reduction of their uniform elongation (by a factor of 4 to 5). The total elongation of samples is also decreased nearly four times for GlidCopAl25 and by a factor of two for Cu–Cr–Zr. Examination of stress–strain curves shows that soon after yielding, the materials demonstrate plastic flow instability. Note, that such an effect is not observed in the same materials when irradiated up to 0.4 dpa at 150°C [7,10].

Fig. 2 presents the temperature dependence of the yield strength and uniform elongation of Cu–Cr–Zr IG and GlidCopAl25 IG alloys, when unirradiated, and the same properties of alloys after irradiation to 2 dpa at $T_{test} = T_{irr} = 200$°C. The behavior of the alloys is similar; both alloys demonstrate after irradiation a strong hardening increase of ~100 MPa, and their uniform elongation decreases from ~6–10%, to values in the range 1–2%.

3.1.2. Cu Alloy/316 SS HIP Joints

The ultimate tensile strength, σ_u, is the most useful property with which the effects of irradiation on the performance of joints are assessed. Fig. 3 presents σ_u values for samples of GlidCopAl25/316LN type joints made in Russian Federation (RF), EU, JA and Cu–Cr–Zr/316 LN type joints made in RF, prior to and after irradiation to 2 dpa at $T_{test} = T_{irr} = 200$°C. For the joints of GlidCopAl25/316, σ_u after irradiation is higher by about 80 MPa than in the unirradiated state. For all three types of joints (RF, EU, JA), the level of σ_u after irradiation is nearly the same, i.e., ~360 MPa. The ductility characteristics of different irradiated joints vary over a wider range. Thus, EU joint fractures at zero deformation; RF joints have an elongation of about 0.2%; JA joints, when irradiated, have a rather high level of total elongation of ~2.3%. The Cu–Cr–Zr/316 joint has, when irradiated, a somewhat lower strength level σ_u (~230 MPa), but demonstrates a high (~16%) ductility.

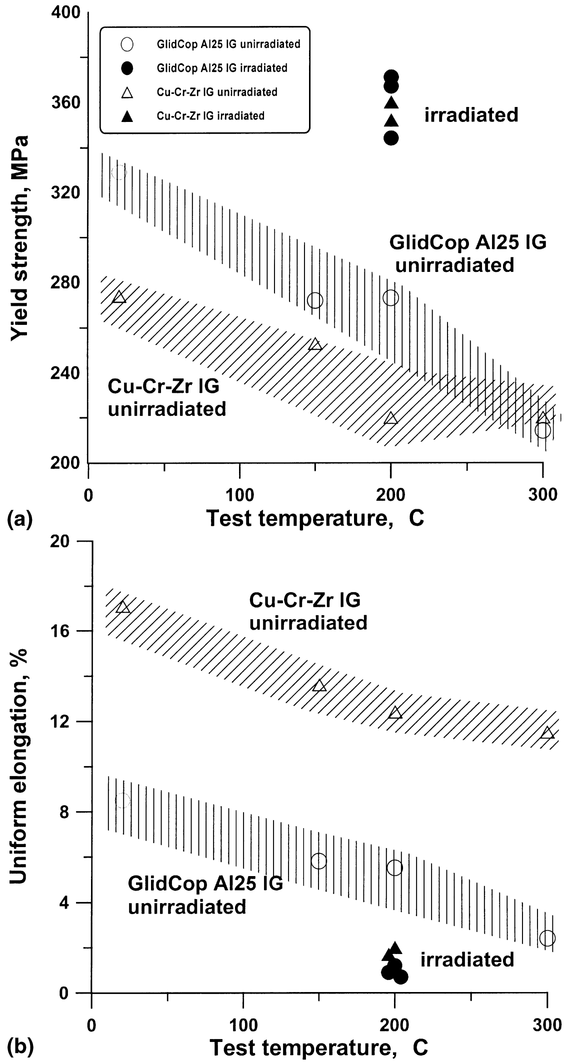

Fig. 2. Yield strength (a) and uniform elongation (b) versus testing temperature of the CuCrZr (SA + aged) alloy and GlidCopAl25 IG (CR + ann) when unirradiated and after irradiation to 2 dpa at $T_{irr} = 200°C$.

3.2. Character of materials fracture

Optical metallography shows that the base alloys at $T_{test} = 200°C$, both prior to and after irradiation, undergo ductile fracture. The Cu–Cr–Zr IG alloy fractures after formation of a marked neck. In GlidCopAl25 IG alloy, the amount of necking is substantially less, especially after irradiation.

GlidCopAl25/316 joint samples suffer relatively brittle fracture near the joint line (for EU joints fracture is localized immediately along the joint line). Samples of Cu–Cr–Zr/316 joint undergo ductile fracture in the Cu alloy at a distance of ~1–2 mm from the joint interface.

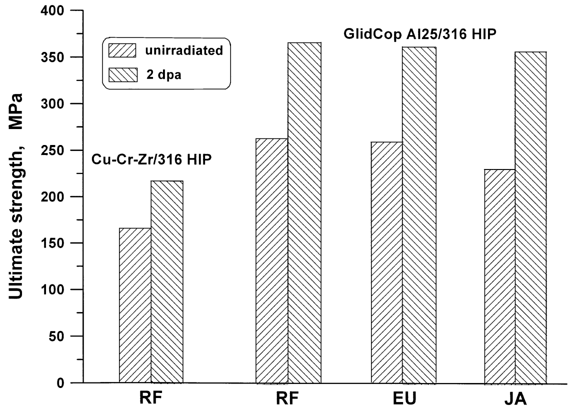

Fig. 3. Effect of neutron irradiation on the ultimate strength of ClidCopAl25/SS316 HIP joints and CuCrZr/SS316 HIP joint, irradiated to 2 dpa at $T_{irr} = 200°C$, $T_{test} = 200°C$.

4. Discussion

In summary, increasing the irradiation dose from 0.4 to 2 dpa at 200°C results in the localization of deformation at an earlier stage and in the emergence of a plateau in yield strength. Note that the ductility as measured by total elongation in the irradiated alloys is still fairly high. For example, despite the low uniform elongation of ~1–2%, the total elongation in the irradiated Cu–Cr–Zr IG alloy is $\delta_{tot} = 15\%$.

Fig. 4 combines the data on high-dose irradiation obtained at 200°C and previous results [6–9] on irradiation of identical samples to 0.2–0.4 dpa at 150°C and 300°C. Since, in our study, hardening at 200°C was measured at only one irradiation dose, we supplement the graphs with the data from the study of Tahtinen et al. [7], where GlidCopAl25 IGO was irradiated at 200°C. Analysis of Fig. 4 shows that the hardening curve during irradiation at 200°C lies between the hardening curves during irradiation at T_{irr} 150°C and 300°C.

The same situation is realized for uniform elongation. As it follows from Fig. 4, the degree of embrittlement ($S = \delta_{unif\ irr}/\delta_{unif\ unirr}$) is practically the same for temperatures of 150°C and 200°C. At $T_{irr} = 300°C$, embrittlement is not observed and $S = 1 \ldots 3$, i.e., uniform elongation is even increased by irradiation. The similarity of irradiated behavior in copper alloys of ODS and PH type is obvious. Independent of the type of hardening particles, alloys are hardened in the temperature range 150–300°C essentially by the same amount. It seems likely that the accumulation of defects and the formation of point defect clusters are the main factors controlling the hardening and the loss of uniform strain of these alloys in this dose–temperature range. The effect of phases is likely to be of minor importance.

Deformation of irradiated joints GlidCopAl25/316LN and Cu–Cr–Zr/316LN, as shown in earlier

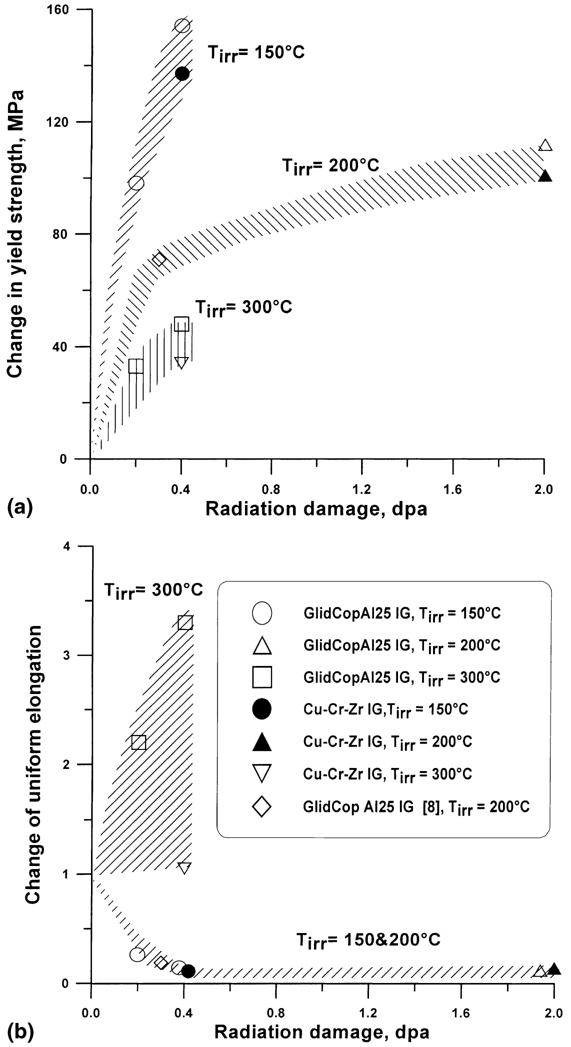

Fig. 4. Radiation damage effect on the yield strength change $\sigma = \sigma_{y\ irr} - \sigma_{y\ unirr}$ of CuCrZr (SA + aged) and GlidCopA125 IG (CR + ann) copper alloys, irradiated in SM-2 reactor up to 0.2–2 dpa and tested at $T_{test} = T_{irr}$ (a). Radiation damage effect on the uniform elongation fractional change $S = \delta_{unif\ irr}/\delta_{unif\ unirr}$ of CuCrZr (SA + aged) and GlidCopAl25 IG (CR + ann) copper alloys, irradiated in SM-2 reactor up to 0.2–2 dpa and tested at $T_{test} = T_{irr}$ (b).

studies [8,9], is determined by a rather complicated process of deformation localization near the joint zone. Therefore, the observed effects can be interpreted in detail only after completion of the SEM and TEM investigation of irradiated samples. Nevertheless, some consistent trends resulting from the observed change in the mechanical properties of joints after irradiation can be pointed out.

The irradiated joints of GlidCopAl25/316 type demonstrated a high level of strength properties ($\sigma_u \sim 350$ MPa). Still, their σ_u is lower by about 100 MPa than for the irradiated base alloy GlidCopAl25 IG. But the geometry of samples cut from the joints is such that the samples are oriented in the Z (short transverse) direction of the plate. To assess the change in the properties of the base alloy in this direction, about 20 samples cut from a 24-mm thick plate in the Z direction were loaded in the same ampoule for irradiation to 2 dpa at 200°C. These samples demonstrated $\sigma_y \sim 380$ MPa and $\sigma_u \sim 395$ MPa, i.e., lower by about 50 MPa than the same alloy in the longitudinal and long transverse directions. Thus, a lower ultimate strength of joints is partly determined by the lower σ_u of GlidCopAl25 alloy in the Z direction.

Cu–Cr–Zr/316 joint demonstrated strength properties at a level of the irradiated Cu–Cr–Zr (HIP) alloy, $\sigma_u \sim 260$ Mpa, and a high ductility $\delta_{tot} \sim 13\%$. It is apparently associated, first of all, with a higher capacity of the base alloy Cu–Cr–Zr for local deformation, when irradiated, than in GlidCopAl25 alloy.

It should be noted that the last generation of joints demonstrated an essentially higher level of strength properties as compared with the first generation despite a 10 times higher irradiation dose. The fact that none of the new joints (EU, JA, RF) demonstrated brittle fracture at low ~150–200 MPa stresses, as happened with the first generation of joints [6], reflects substantial progress in the technology of joint fabrication.

5. Conclusion

The first results of investigations of the base copper alloys GlidCopAl25 IG and Cu–Cr–Zr IG and their joints with 316 steel irradiated to 2 dpa at $T_{irr} = 200$°C revealed that, in general, the trends in radiation hardening and embrittlement observed previously at lower irradiation doses (0.2–0.4 dpa) are continued at higher irradiation doses.

Hardening and embrittlement have been found to be practically the same in copper alloys of different types, i.e., PH – Cu–Cr–Zr and DS – GlidCopAl25.

The joints of GlidCopAl25/316 and Cu–Cr–Zr/316 type had high-strength characteristics and a satisfactory ductility after irradiation.

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