Journal of Nuclear Materials 386–388 (2009) 824–829

Contents lists available at ScienceDirect

Journal of Nuclear Materials

journal homepage: www.elsevier.com/locate/jnucmat

Effect of irradiation temperature and dose on mechanical properties and fracture characteristics of Cu//SS joints for ITER

S.A. Fabritsiev [a,*], A.S. Pokrovsky [b], A. Peacock [c], M. Roedig [d], J. Linke [d], A.A. Gervash [a], V.R. Barabash [e]

[a] D.V. Efremov Scientific Research Institute, 196641 St. Petersburg, Russia
[b] Scientific Research Institute of Atomic Reactors, 433510 Dimitrovgrad, Russia
[c] EFDA Close Support Unit – Garching, Boltzmannstrasse 2, Germany
[d] Forschungszentrum Juelich, 52425 Juelich, Germany
[e] ITER International Team, F-13108 St. Paul lez Durance, France

A B S T R A C T

In this paper, the authors present the results of investigations into the mechanical characteristics after irradiation of GlidCopAl25/316L(N) and CuCrZr/316L(N)-type joints produced by two joining technologies. Specimens of the joints were irradiated in the RBT-6 reactor in the dose range of 10^{-3}–10^{-1} dpa at T_{irr} = 200 °C and 300 °C. Irradiation at T_{irr} = 200 °C causes strengthening of the joints specimens (by about 100 MPa at the maximum dose). The uniform elongation drops from 8% in the initial state to 2–3%. But the total elongation remains at a relatively high level of ~7%. Irradiation at 300 °C does not practically change the ultimate strength of CuCrZr/316L(N) joints, but the total and uniform elongation of the joints decreases monotonously with a dose. But in this case, the level of elongation remains considerably higher than that when irradiated at 200 °C.

1. Introduction

Joints of Cu//SS type will be widely used in ITER high-heat flux components like the divertor and first wall [1–3]. At present, two joining technologies, i.e. hot isostatic pressure (HIP) and cast-copper-to-steel (CC), are considered as the most promising for joints production.

The first investigations into the radiation resistance of the first generation of HIP joints of CuCrZr//316L(N) and GlidCopAl25//316L(N) type revealed that even at a dose of 0.2 dpa ($T_{irr} \sim 150$ °C and 300 °C) the joints suffer marked embrittlement [4,5]. Considerable efforts were made to improve the quality of the HIP procedures of Cu alloy and SS joints and to produce new high-strength joints [6,7].

The first investigations of the effect of neutron irradiation at T_{irr} = 150 °C [8] have demonstrated that these new joints are more resistant to radiation embrittlement.

The report presents the results of the last investigations into the effect of neutron irradiation at $T_{irr} \sim 200$°C and 300 °C on the mechanical properties of CuCrZr//316L(N) and GlidCopAl25//316L(N) joints produced by the HIP and CC methods.

2. Experimental procedure

Three grades of Cu//SS joints were investigated in this work: CuCrZr//316L(N) and GlidCopAl25//316L(N) joints manufactured in the EU by HIP and CuCrZr//316L(N) joints manufactured in the RF, by cast-copper-to-steel technique (CC).

Blanks of CuCrZr alloy (Cu-bal, 0.84 wt% Cr, 0.14 wt% Zr) and GlidCopAl25 alloy (Cu-bal, 0.25 wt% Al as Al_2O_3) were hipped to 316 L(N) blanks. HIP condition was 1040 °C – 2 h, at 140 MPa. The solutioning for CuCrZr//316L(N) joints was done at 1040 °C, cooling rate ~70 °C/min, aged at 580 °C, 2 h [9]. Grain size in CuCrZr alloy was ~150 μm in GlidCopAl25 ~2–5 μm.

Bi-material specimens of Cu//SS joints were irradiated at T_{irr} = 200 °C in the RBT-6 reactor in irradiation facilities SMM01-10; SMM01-11; SMM01-12. Other batch of specimens of Cu//SS joints were irradiated at T_{irr} = 300 °C in the RBT-6 reactor in irradiation facilities SMM01-7; SMM01-8; SMM01-9.

Flat specimens for tensile testing (1 mm in thickness, with a gauge length of 10 mm) STS type were irradiated in tight helium-filled subcapsules.

The irradiation doses in the RBT-6 reactor amounted to ~10^{-3}; 10^{-2}; 10^{-1} dpa. Irradiation temperature for irradiation facilities SMM01-10; SMM01-11; SMM01-12, as recorded by thermocouples, was 190 ± 10 °C. Irradiation temperature for irradiation facilities SMM01-7; SMM01-8; SMM01-9, as recorded by thermocouples, was 290 ± 13 °C. Different doses were attained by varying the irradiation time, i.e. 24 h; 240 h; 1500 h. Average ratio between

* Corresponding author. Tel.: +7 812 464 44 63; fax: +7 812 464 46 23.
E-mail address: fabrsa@sintez.niiefa.spb.su (S.A. Fabritsiev).

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doi:10.1016/j.jnucmat.2008.12.241

thermal and fast neutrons in the RBT reactor was $\Phi t_{therm}/\Phi t_{fast} \sim 1.04$. The irradiated and control specimens were tested in tension at strain rate $\sim 1.66 \times 10^{-3}\,s^{-1}$ at $T_{test} = T_{irr}$. The character of joint fracture was investigated by optical microscopy and SEM.

3. Results

3.1. Unirradiated condition

The CuCrZr/316L(N) and GlidCop Al25//316 L(N) bi-material samples (samples from joints) have demonstrated sufficiently high-strength properties $\sigma_u > 200$ MPa and satisfactory plastic properties $\delta_{tot} > 7\%$ (Figs. 1 and 3). Study of the fracture character of unirradiated and irradiated bi-material samples from joints revealed that all specimens fail only in the copper part of a specimen at a distance of 2–3 mm from the joint line (Fig. 2(a)). The fracture is of ductile transcrystalline character (Fig. 2).

3.2. Irradiated condition

Fig. 1(a) shows the typical engineering stress-strain curves (σ_{eng} versus δ) for CuCrZr//316L(N) HIP bi-material samples in unirradiated condition and after neutron irradiation at $T_{irr} = T_{test} = 200$ °C. Obviously, an increase in the irradiation dose results both in hardening (increase in the yield strength) and embrittlement (decrease in the uniform elongation).

Fig. 1(b) presents the typical engineering stress-strain curves for CuCrZr//316L(N) HIP bi-material samples in unirradiated condition and after neutron irradiation at $T_{irr} = T_{test} = 300$ °C. Irradiation at $T_{irr} = 300$ °C causes a slight strengthening of the joints specimens ($\sim 30 \pm 12$ MPa). The uniform elongation remains at relatively high level ~6%. The total elongation also maintains a relatively high level of ~8–13%.

3.3. Dose effect

The CuCrZr/316L(N) bi-material samples have demonstrated an increase in the yield strength and a decrease in the elongation with dose at $T_{irr} = 200$ °C (Fig. 4). An increase in the irradiation damage does not practically affects the ultimate strength of the bi-material samples. The total elongation is decreased with dose.

Irradiation at $T_{irr} = 200$ °C leads to hardening and a decrease in both total and uniform elongation of GlidCopAl25//316L(N) bi-material samples (see Figs. 3(a) and 4(a)). At the maximum irradiation doses the ultimate strength of the GlidCopAl25//316L(N) bi-material samples is appreciably higher (by 30 MPa) than in CuCrZr//316L(N) bi-material samples.

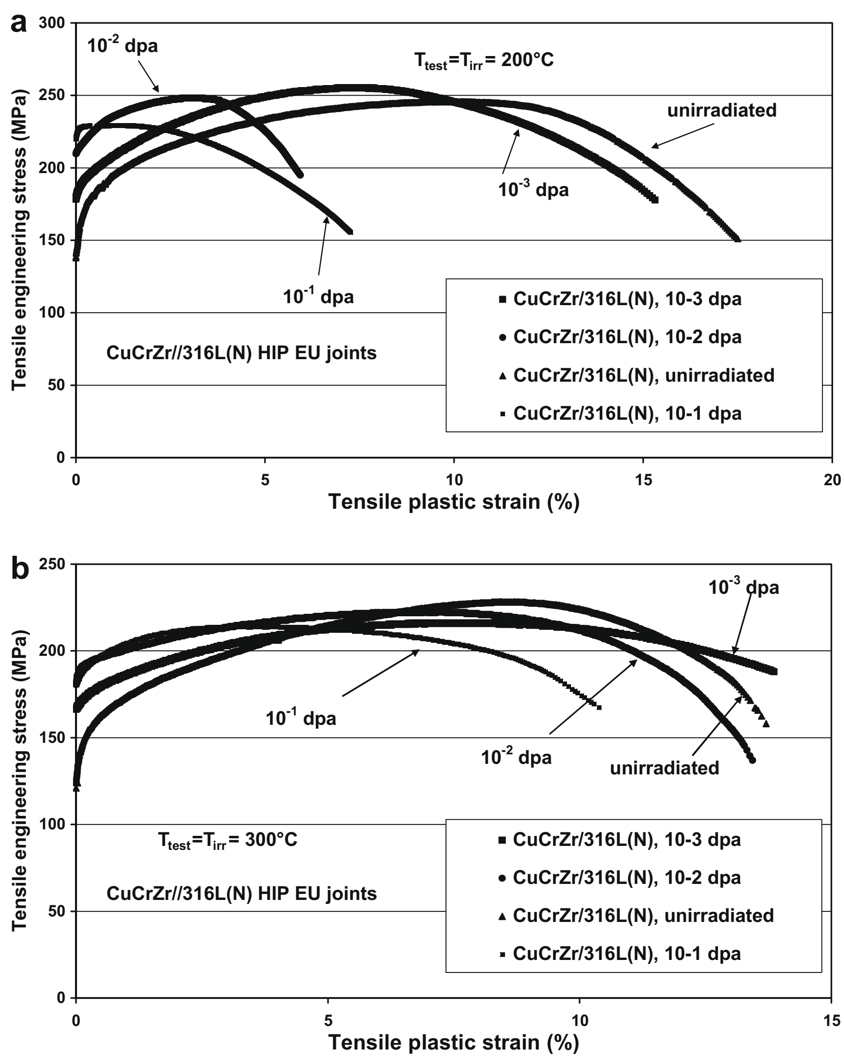

Fig. 1. Effect of neutron irradiation on engineering stress–strain curves of CuCrZr//316L(N) HIP EU joints, $T_{test} = T_{irr} = 200$ °C (a); $T_{test} = T_{irr} = 300$ °C (b).

3.4. Irradiation temperature effect

Fig. 3(a) and (b) show the dose dependence of the ultimate strength, as well as the total elongation for all joints investigated in our work after irradiation at T_{irr} = 200 °C and 300 °C (for comparison on this figures are presented data at T_{irr} = 150 °C [8]).

The ultimate stress of the bi-material samples from CuCrZr// 316L(N) HIP joints (Fig. 3(a)) rises monotonically with the dose at T_{irr} = 200 °C, and radiation hardening reaches ∼60 MPa at a dose of 0.07 dpa. This value coincides with that of hardening for CuCrZr base alloy observed under the same conditions [10]. The uniform and total elongation of all bi-material samples is monotonically decreased at T_{irr} = 200 °C with increasing the dose to the values $\delta_{unif} > 0.5\%$, $\delta_{tot} > 4\%$.

Irradiation at 300 °C does not practically change the ultimate strength of the bi-material samples (Fig. 3(a)), but the total and uniform elongation bi-material samples decreases monotonously with a dose. But in this case, the level of δ_{un} and δ_{tot} remains considerably higher than that when irradiated at 150 °C and 200 °C.

3.5. Fracture character

The fracture character of irradiated bi-material samples is, on the whole, similar to that for unirradiated bi-material samples. The irradiated bi-material samples (from joints) fail, as a rule, in copper alloy well apart (1–3 mm) from the joint line (Fig. 2(a) and (c)). But in irradiated CuCrZr//316L(N) CC, the bi-material samples fracture was sometimes observed on the joint plane at $T_{test} = T_{irr}$ = 200 °C.

Study of the fracture surface of the tested irradiated bi-material samples from joints of CuCrZr//316L(N) and GlidCopAl25//316L(N) type revealed that they fracture, on the whole, in a ductile transcrystalline way (Fig. 2(b) and (d)).

A comparison between the fracture character of the bi-material samples based on CuCrZr and GlidCopAl25 shows that CuCrZr// 316L(N) bi-material samples is characterized by a considerable neck developing in the copper part of a specimen. Considerable plastic deformation is observed on the fracture surface. The irradiated GlidCopAl25//316 L(N) bi-material samples are characterized

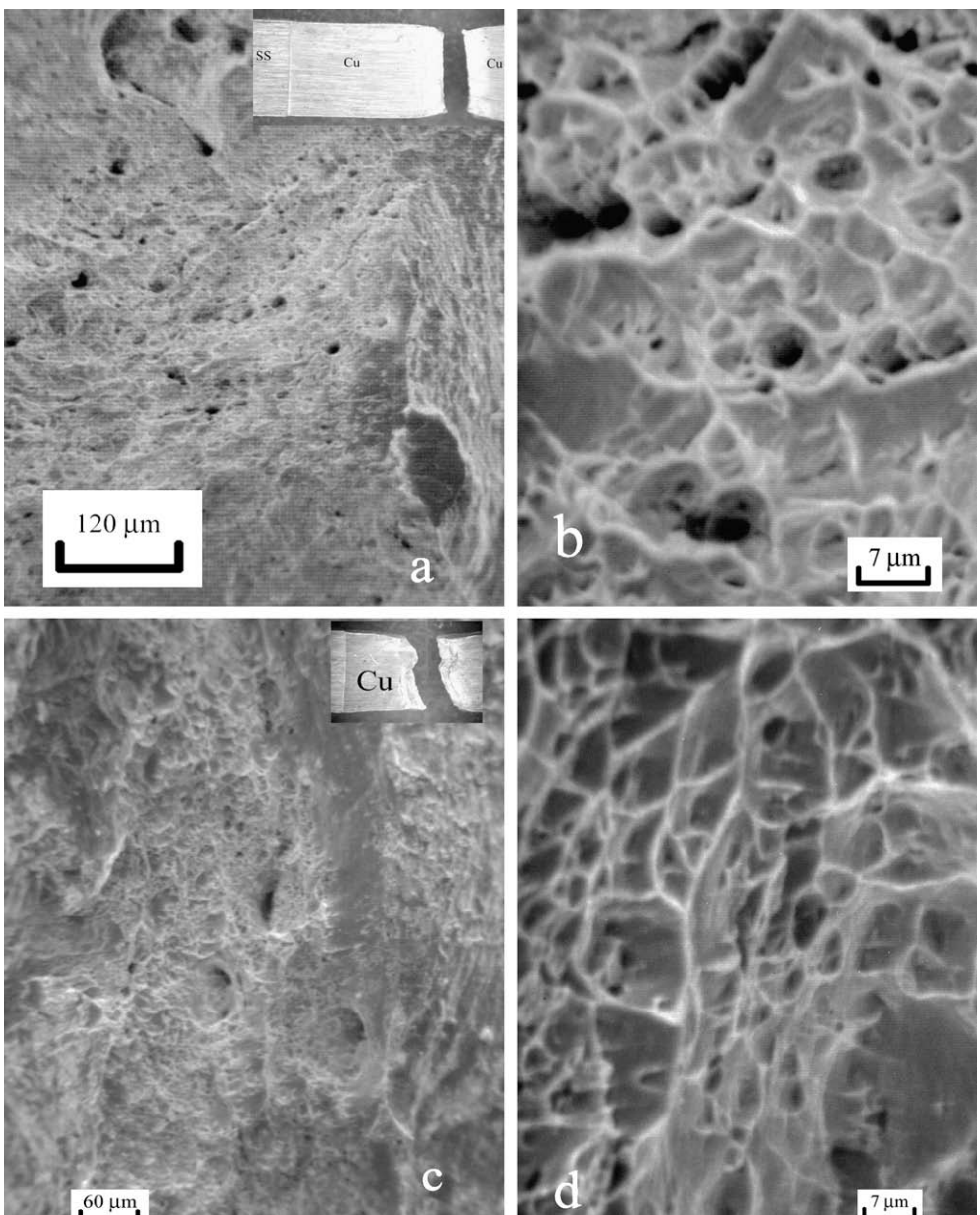

Fig. 2. The character of CuCrZr//316L(N) HIP EU joints fracture at tensile tests: 0.07 dpa, $T_{test} = T_{irr}$ = 300 °C – (a, b); 0.09 dpa, $T_{test} = T_{irr}$ = 200 °C – (c, d).

by fracture with little necking. Plastic deformation of the fracture surface is less. By and large, the bi-material samples from CuCrZr//316L(N) joints fail in a more ductile manner than those based on GlidCopAl25.

4. Discussion

The data obtained make it possible to compare the radiation resistance of the CuCrZr//316L(N) and GlidCopAl25//316L(N) joints at different irradiation temperatures.

4.1. Radiation hardening

Fig. 4(a) presents the dose dependence of the yield strength of the bi-material samples from joints at three irradiation temperatures. It is evident that a rise in the irradiation temperature causes a decrease in the radiation hardening of the bi-material samples. The difference in hardening of the CuCrZr//316L(N) joints at T_{irr} = 150 and 300 °C at a dose of 0.1 dpa is about 100 MPa. Note that the same irradiation temperature effect on hardening is observed for CuCrZr base alloy [11,12].

Irradiation at T_{irr} = 200 °C causes a comparatively slight hardening of the joints amounting to about 40 MPa. As follows from Fig. 4(a), hardening values of the joints at 200 °C and 300 °C are rather close and are considerably lower at T_{irr} = 150 °C. The irradiation temperature effect on hardening of the bi-material samples from GlidCopAl25//316L(N) joints is, by and large, similar to that on hardening of the samples from CuCrZr//316L(N) joints.

The dose dependence of the ultimate strength of the bi-material samples from joints repeats practically that of the yield strength (Fig. 3(a)) differing only in that the level of the ultimate strength gain under irradiation is somewhat less (by about 30 MPa) than the yield strength gain.

The purpose of the work was just to preliminary estimate the properties of new generation of joints. The investigations verified a sufficiently high quality of the joints. No fracture over the joint line was observed for HIP joints. Note, that the first generation of joints made for ITER in 1998–1999 fractured very often in a brittle way even, when unirradiated [4,5,13].

4.2. Radiation embrittlement

Uniform elongation of the bi-material samples from joints increases with the irradiation temperature (Fig. 4(b)). At T_{irr} = 150 °C at irradiation doses of $\sim 10^{-2}$–10^{-1} dpa, uniform elongation of all joints is at a level of ∼1–2%. Note that CuCrZr and GlidCopAl25

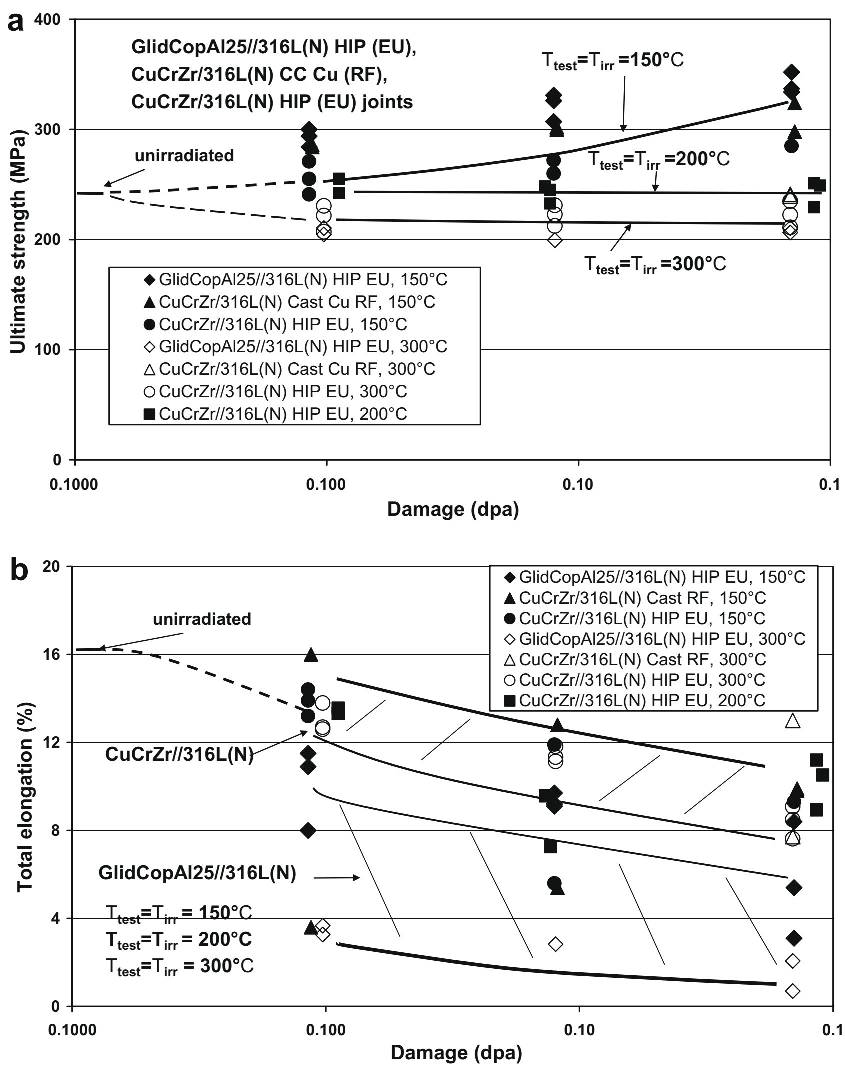

Fig. 3. Ultimate strength (a) and total elongation (b) versus damage dose for CuCrZr//316L(N) HIP EU, CuCrZr//316L(N) CC RF and GlidCopAl25//316L(N) HIP EU joints, $T_{test} = T_{irr}$ = 200 °C and $T_{test} = T_{irr}$ = 300 °C.

base copper alloys demonstrate nearly the same level of uniform elongation at low irradiation temperatures [10,11]. At T_{irr} = 200 °C, uniform elongation of the bi-material samples from CuCrZr//316L(N) joints is considerably increased. At T_{irr} = 300 °C, the CuCrZr//316L(N) bi-material samples have even higher uniform elongation (Fig. 4(b)). For the GlidCopAl25//316L(N) bi-material samples an increase in the irradiation temperature from 150 to 300 °C in the low dose range of $\sim 10^{-3}$ dpa causes the uniform elongation to increase by about a factor of two. But, at higher irradiation doses of $\sim 10^{-2}$–10^{-1} dpa bi-material samples from the GlidCopAl25//316L(N) joints have practically the same elongation at T_{irr} = 150 and 300 °C.

The dose dependence of the total elongation demonstrates most clearly the difference in the behavior of the CuCrZr//316L(N) and GlidCopAl25//316L(N) bi-material samples from joints (Fig. 3(b)). The CuCrZr//316L(N) bi-material samples have a higher total elongation in the dose range of 10^{-3}–10^{-1} dpa. In fact, the irradiation temperature does not affect the value of the total elongation of these types of joints.

The bi-material samples from GlidCopAl25//316L(N) joints have a marked dependence of embrittlement on the irradiation temperature. At T_{irr} = 150 °C, the GlidCopAl25//316L(N) bi-material samples have a sufficiently high total elongation in dose range 10^{-3}–10^{-1} dpa. But, at T_{irr} = 300 °C the total elongation of bi-material samples from GlidCop base joints decreases by more than a factor of two and at a dose of 10^{-1} dpa is as low as ~1%. Low ductility under irradiation at T_{irr} = 300 °C was observed also for the GlidCopAl25 base alloy, for samples cut in *Z*-direction, i.e. precisely in the orientation the joint samples are made [13]. Hence, the observed brittleness of the bi-material samples from GlidCopAl25//316L(N) joints at T_{irr} = 300 °C can be attributed to embrittlement of the base copper alloy.

The optical microscopy and SEM investigations of the irradiated samples showed that the bi-material samples from CuCrZr//316L(N) joints fracture in a more ductile way than the bi-material samples from GlidCopAl25//316L(N) joints. With a rise in the irradiation temperature the fracture character of the CuCrZr//316L(N) bi-material samples does not practically change and remains ductile and transcrystalline. At $T_{irr} = T_{test}$ = 300 °C, the GlidCopAl25//316L(N) bi-material samples fracture with an appreciably lower plastic deformation of the fracture surface than at $T_{irr} = T_{test}$ = 150 °C.

Thus, at $T_{irr} \sim$ 150–300 °C the CuCrZr//316L(N) joints have a higher radiation embrittlement resistance than the GlidCopAl25//316L(N) joints. It is obvious that the radiation resistance of the CuCrZr//316L(N) joints is determined not by the properties of the

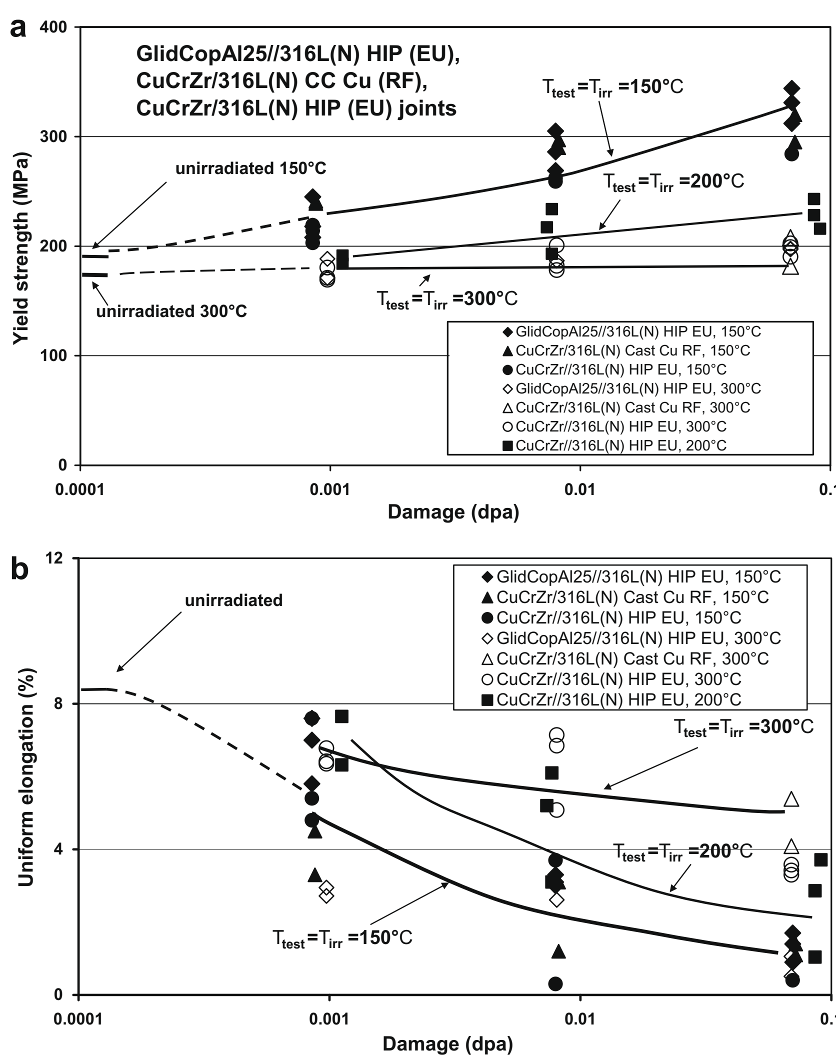

Fig. 4. Yield strength (a) and uniform elongation (b) versus damage dose for CuCrZr//316L(N) HIP EU, CuCrZr//316L(N) CC RF and GlidCopAl25//316L(N) HIP EU joints, $T_{test} = T_{irr}$ = 200 °C and $T_{test} = T_{irr}$ = 300 °C.

fusion line but by those of the base copper alloy. After the HIP treatment CuCrZr alloy has a higher ductility and, as distinct from GlidCopAl25 alloy, is homogeneous and has no texture. It is this that determines higher properties of the irradiated CuCrZr//316L(N) joints.

The first obtained data on irradiation resistance of the CuCrZr//316L(N) joints made by the cast-copper-to-steel technology (CC) testify to good prospects this technology holds. The joints have high strength and ductile properties in the irradiated state. But, the data base on the radiation resistance of these joints needs to be replenished.

5. Conclusion

The investigations carried out have made it possible to estimate the effect of the irradiation temperature (in the temperature range of 150–300 °C) on the radiation resistance of the GlidCopAl25//316L(N) and CuCrZr//316L(N) joints. The bi-material samples from joints demonstrate a noticeable radiation hardening only at $T_{irr} = 150$ °C. This hardening entails an appreciable drop in uniform elongation of the bi-material samples from joints. At increased irradiation temperatures of 200 °C and 300 °C radiation hardening of the bi-material samples from joints is noticeably lower. In this case, i.e. at T_{irr} 200 °C and 300 °C, uniform and total elongation of the bi-material samples from CuCrZr//316L(N) joints remains sufficiently high up to doses of 10^{-1} dpa. On the contrary, the bi-material samples from GlidCopAl25//316L(N) joints are characterized by a sufficiently marked radiation embrittlement at $T_{irr} = 300$ °C.

On the whole, the investigations performed have revealed that the CuCrZr//316L(N) joints made by the HIP and CC methods have a sufficiently high radiation resistance and hold good promises for ITER application in the high-heat flux components.

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