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The effect of neutron irradiation on mechanical properties of Cu/SS joints for ITER applications

S.A. Fabritsiev [a,*], A.S. Pokrovsky [b], D.J. Edwards [c], S.J. Zinkle [d], A.F. Rowcliffe [d]

[a] *D.V. Efremov Scientific Research Institute, 189631 St. Petersburg, Russian Federation*
[b] *Scientific Research Institute of Atomic Reactors, 433510 Dimitrovgrad, Russian Federation*
[c] *Pacific Northwest Laboratory, P.O. Box 999, Richland, WA 99352, USA*
[d] *Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, TN 37831-6376, USA*

Abstract

The paper presents the first results on the properties of Cu//SS-type joints irradiated in the SM-2 reactor up to a dose of 0.2 dpa at $T_{\mathrm{irr}} = 150°\mathrm{C}$ and 300°C. The investigations performed demonstrated that the proposed HIP (RF) and (US) technology, as well as Explosive Bonding (US) holds promises and can be recommended for preparation of samples for subsequent irradiation. On the other hand, the investigation undertaken revealed the problem of 150°C embrittlement of joints observed for Lap Shear specimens GlidCop A125//316LN (US) manufactured by the HIP method.

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1. Introduction

The ITER project now under development assumes that copper alloys will be used for the heat sink system of the most energy stressed components (divertor, first wall, etc.) [1]. As the cooling system is presumed to be made of steel 316 LN [2], the reactor design suggests that bimetallic structures of Cu//SS type will be used in the most energy stressed components. Various methods were proposed to be used to join copper alloys to steel: high-temperature brazing, HIP, friction welding, explosive bonding, etc. The first studies on estimating the mechanical properties of Cu//SS-type joints [3–6] demonstrated that the above joining technology should provide, in principle, a sufficiently high level of strength properties of the joints. But the data on neutron irradiation effect on the mechanical properties of joints are virtually lacking in the literature. This paper presents the results of investigation of the Cu//SS-type joints, when unirradiated and after irradiation to a dose of 0.2 dpa at $T_{\mathrm{irr}} = 150°\mathrm{C}$ and 300°C.

2. Experimental procedure

Table 1 presents the regimes for manufacturing of blanks, i.e. the joints of DS copper alloys MAGT 0.2–316 SS (MAGT 0.2//316SS) made by the HIP method, PH alloy Cu–Cr–Zr to steel 316 (Cu–Cr–Zr//316SS) made by the HIP method in RF. The joint GlidCop A125//316LN was made in EU by the HIP method. The joint GlidCop A115//316SS was made in US by two methods, i.e. HIP and Explosive bonding. Fig. 1 shows the schemes for cutting of tensile specimen from RF and EU blanks. Various specimens were used in the work to investigate tensile properties: 1-mm-thick STS-type sheet tensile specimens with the working part 10 mm in length and CTS-type cylindrical specimens with the working part 10 mm in length and 3 mm in diameter. The specimens were irradiated in Channel N5 of the SM-2 reactor to a dose of Ft$\sim 3.5 \times 10^{20}$ n/cm^2 ($E > 0.1$ MeV), this being consistent with a radiation damage of $\sim$0.2 dpa (in conformity with the NRT standard). According to thermocouple readings the irradiation temperatures were as follows: for ampoules 1.2–175 ± 5°C and for ampoules 3.4–300 ± 10°C. Reference and irradiated specimens were tensile tested in the temperature range of 20–300°C at a deformation rate of 1.6×10^{-3} s^{-1} in

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[*] Corresponding author. Tel.: +7 812 464 4463; fax: +7 812 464 4623; e-mail: fabr@niiefa.spb.su.

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Table 1
Heat treatment of base materials and joining conditions

Materials	Heat treatment	Joints	Joining technique	Joining condition
MAGT 0.2 (RF)	Extruded	MAGT 0.2/316 LN	HIP	1000°C 1.5 h
316 LN (RF)	Annealed 1050°C, 30 min			130 MPa
Cu–Cr–Zr (RF)	SA 980°C, quenching + 480°C aged, 4 h	Cu–Cr–Zr/316 LN	HIP	1000°C 1.5 h
316 LN (RF)	Annealed 1050°C, 30 min			120 MPa
GlidCop A125 (EU)	HIPped	GlidCop A125/316 LN	HIP	980°C 2 h
316 LN (EU)	Forged			100 MPa
GlidCop A115 (US)	–	GlidCop A115/316 SS	HIP	
316 SS (US)	–			
GlidCop A115 (US)	–	GlidCop A115/316 SS	Explosive bonding	
316 SS (US)	–			

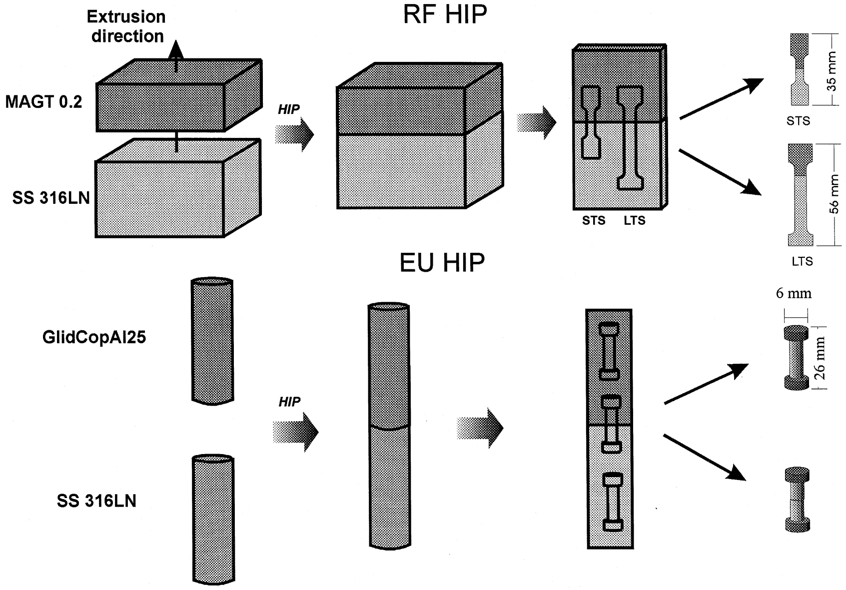

Fig. 1. Scheme of specimen cutting from the joints MAGT0.2//316SS made by HIP (RF) and GlidCopA125/316SS made by HIP (EU).

vacuum. The tested specimens were investigated for fracture by optical and SEM methods.

3. Results

3.1. Effect of irradiation on tensile properties of joints

(*a*) *DS copper alloys*: Fig. 2 shows the ultimate strength dependencies of DS copper alloys//SS316 type joints produced by the HIP method in RF and EU. As follows from Fig. 2, the level of ultimate strength for base materials and the joints practically coincides. Both MAGT 0.2 alloy and the joints MAGT 0.2//316SS (HIP) on its basis have close σ_u at $T_{test} = 150$°C after irradiation at $T_{irr} = 150$°C and in the unirradiated state. Irradiation at 300°C results in a slight reduction (by 50–100 MPa) in σ_u of the joints. It is different with the alloy GlidCop A125 (HIP) EU. At $T_{test} = 20$°C both the base metal and the joint GlidCop A125//316 (HIP) have high σ_u ($\sim$400 MPa) after irradiation. But at increased testing temperatures both the DS alloy and the joint have a low level of strength $\sigma_u \sim 150$–100 MPa in the irradiated state.

All investigated DS copper alloys and their joints demonstrate similar temperature dependence of the uniform elongation. At $T_{test} = 20$°C both the base DS alloys and their joints have a satisfactory level of ductile properties $\delta_{uniform}$ 4–12%. But, at increased testing temperatures the DS alloys and their joints embrittle considerably. In this case both the DS alloy MAGT0.2 and the joints MAGT0.2//316SS (HIP) at $T_{test} = T_{irr} = 150$°C

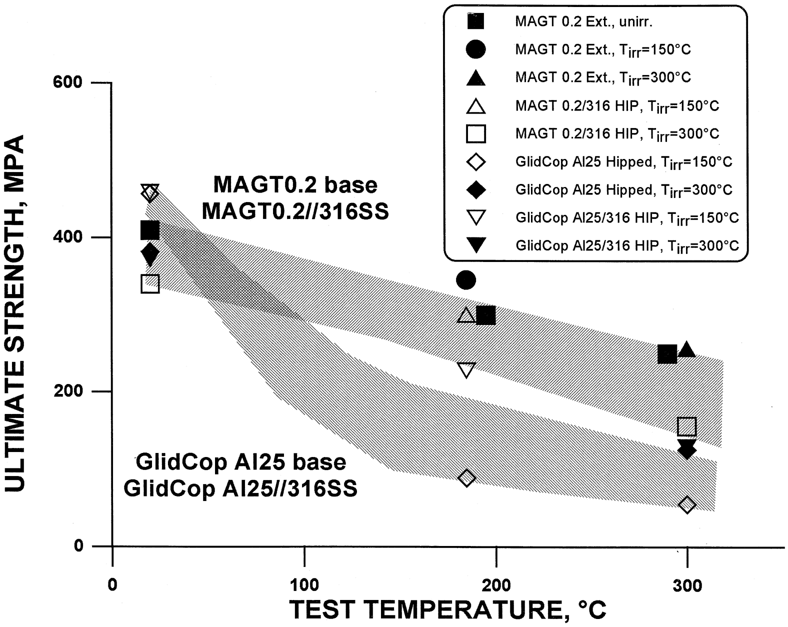

Fig. 2. Ultimate strength versus testing temperature of the DS copper alloys MAGT 0.2 (as Extruded) and GlidCopA125 (HIP) and of the joints MAGT 0.2//316SS (HIP) and GlidCop A125//316SS (HIP), when unirradiated and after irradiation to 0.2 dpa at $T_{\mathrm{irr}} = 150$°C and $T_{\mathrm{irr}} = 300$°C.

and 300°C demonstrate, when irradiated, a low but not zero level of uniform elongation, i.e. ~1–2%. Yet, the GlidCop A125 (EU) alloy and the joint GlidCop A125//316 (EU) at $T_{\mathrm{test}} = T_{\mathrm{irr}} = 150$°C and 300°C embrittle $\delta_{\mathrm{tot}} = \delta_{\mathrm{uniform}} = 0$.

(*b*) *PH copper alloys*: The joint PH copper alloy Cu–Cr–Zr//316SS HIP is characterized by a rather low level of strength characteristics, when unirradiated, i.e. $\sigma_u = 150$ MPa (Fig. 3). After irradiation at $T_{\mathrm{irr}} = 150$°C there is observed a slight (~50 MPa) hardening of the joint. Irradiation at $T_{\mathrm{irr}} = 300$°C does not practically affect σ_u. The uniform elongation of the joint Cu–Cr–Zr//316SS (HIP) is at a high level $\delta_{\mathrm{uniform}} > 17\%$ both in the irradiated and unirradiated state. The exception is

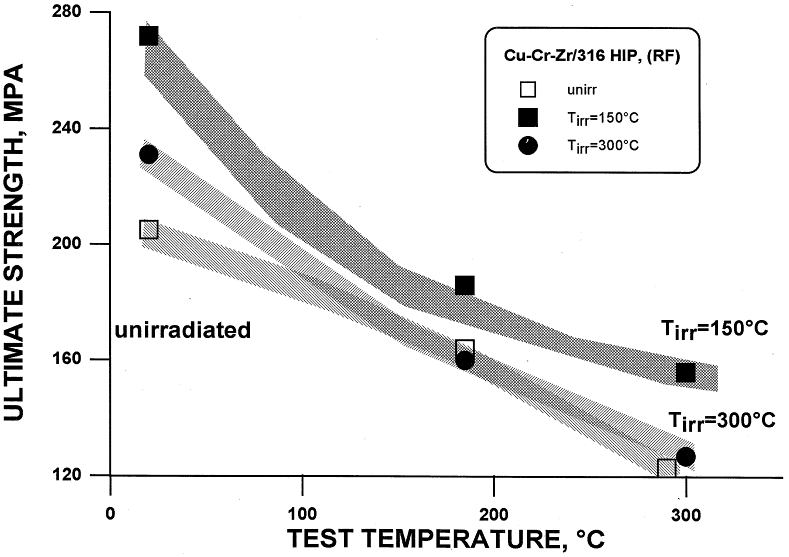

Fig. 3. Ultimate strength versus testing temperature for specimens of the Cu–Cr–Zr/316SS joint (HIP), when unirradiated and after irradiation to 0.2 dpa at $T_{\mathrm{irr}} = 150$°C and $T_{\mathrm{irr}} = 300$°C.

the specimens irradiated at 150°C and tested at 20°C, for which the level of δ_{uniform} is less (~7%). But the same specimens tested at 150°C and 300°C have δ_{uniform} ~15–22%.

3.2. *Effect of irradiation on shear strength of joints*

Testing of specimens for Shear Strength showed (Fig. 4), that the specimens of the joints GlidCop A115//316ST (US) made by the HIP method have, when unirradiated, a sufficiently high level of Shear Strength σ_{sh} ~ 150 MPa. After irradiation the level of σ_{sh} is somewhat decreased (~20 MPa) at $T_{\text{test}} = T_{\text{irr}} = 300$°C and drops by a factor of 3–4 at $T_{\text{irr}} = T_{\text{test}} = 150$°C. The GlidCop Al15/316 (US)-type joints produced by the Explosive bonding method are characterised by a rather high level of σ_{sh} throughout the temperature range of 150–300°C after irradiation.

3.3. *Effect of irradiation on joint fracture character*

The study of fractured specimens by optical microscopy and SEM allows the conclusion that practically in all cases the joints of DS Cu alloy//316SS type, both irradiated and unirradiated, fracture in base copper alloy in the zone adjacent to the joint line (at a distance of ~500–2000 µm from the joint line). The joints of Cu–Cr–Zr//316SS type fracture in the Cu–Cr–Zr alloy, but there is no clearly localised fracture site. Fracture sometimes occurs nearby the joint and sometimes well off it. The study of the fracture character of specimens by SEM showed that the joints Cu–Cr–Zr//316SS fracture exceptionally in a ductile way.

4. Discussion

4.1. *Radiation resistance of DS copper alloy joints to steel*

As of now, a certain body of data on properties of unirradiated joints produced by the HIP method [4,5] and Friction Welding [3,7,8] is accumulated. This information, when combined with the results presented in Ref. [9] and the results of this study, where the first data on radiation resistance of such joints were obtained, makes it possible to assess the role of technology and radiation damage in embrittlement of the joints. Fig. 5 constructed on the basis of the data obtained in the present study, as well as in studies [4,5,7,9,10] show that both the HIP and Friction Welding methods affect only slightly the level of the strength properties of GlidCop A125, when unirradiated. Irradiated specimens harden somewhat at T_{irr} ~ 150°C and $T_{\text{test}} = 20$°C and have a lower σ_{u} than unirradiated joints at $T_{\text{irr}} = T_{\text{test}} = 300$°C.

Much more stronger is the effect of the joining procedure on the total elongation. The joining procedure involves a twofold decrease in the total elongation, and

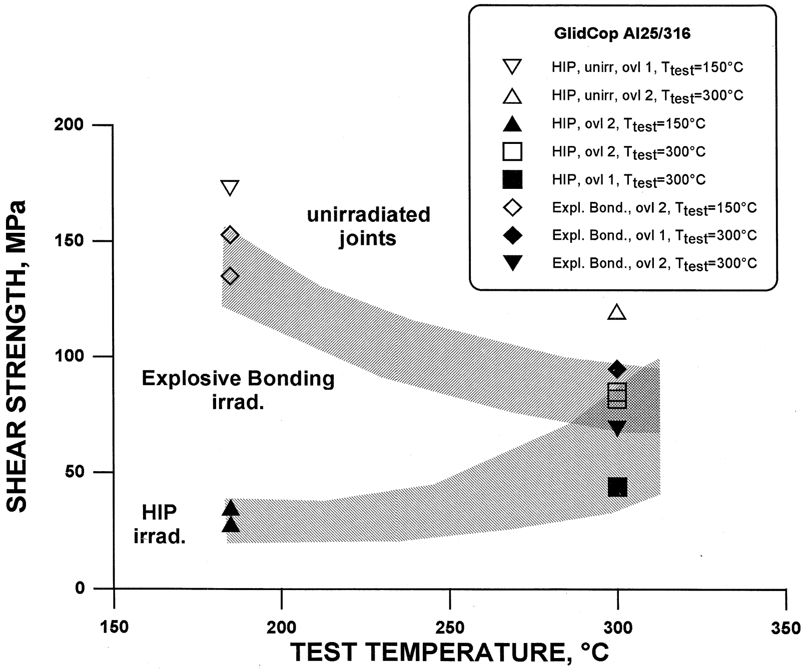

Fig. 4. Shear strength versus irradiation temperature, $T_{\text{test}} = T_{\text{irr}}$, for specimens of the GlidCopA115/316 SS joint (HIP) and GlidCopA115/316 SS joint (Explosively Bonded), when unirradiated and after irradiation to 0.2 dpa at $T_{\text{irr}} = 150$°C and $T_{\text{irr}} = 300$°C.

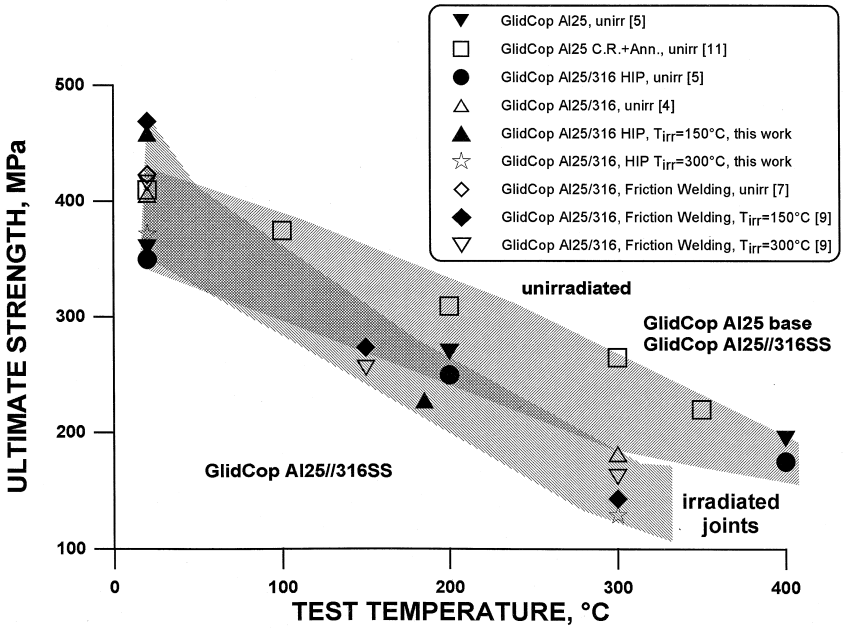

Fig. 5. Ultimate strength versus testing temperature of the DS copper alloy GlidCopA125 and of the joints GlidCopA125//316SS produced by HIP (this work and [4,5]) and Friction Welding [7], when unirradiated and after irradiation to 0.2 dpa at $T_{irr} = 150°C$ and $T_{irr} = 300°C$.

at $T_{test} \sim 300$–400°C the joint ductility can be lower than that of the GlidCop A125 base alloy by factor of 8–10. Irradiation shifts the temperature range, at which embrittlement shows up, into the region of lower temperatures. At $T_{test} = 20°C$ ductility of produced joints after irradiation remains still at an acceptable level of 3–10%. But at increased testing temperatues $T_{test} > 150°C$ irradiated GlidCop A125//316SS joints have practically zero elongation. Thus, joint embrittlement at $T_{test} = T_{irr} = 150°C$ is likely to be related to the combination of degeneration of GlidCop A125 alloy capability for local deformation, while being joined, on the one hand, and a drop in the uniform elongation of specimens as results of low-temperature radiation embrittlement, on the other hand [11,12]. As for embrittlement of the joints at $T_{irr} = T_{test} = 300°C$, it is usually associated with brittleness of GlidCop A125 alloy at 300°C after the joining cycle even in unirradiated state. Irradiation only adds to embrittlement. The assumption that the zone adjacent to joint line is susceptible to LTE is confirmed by testing of the joints for shear. Specimens of GildCop A115//316SS HIP demonstrated a very low level of properties at $T_{test} = T_{irr} = 150°C$. Since the configuration of shear specimens is such that loaded (and deformed) is the zone immediately adjacent to HAZ, the observed brittleness is obviously the result of embrittlement of precisely this zone. SEM investigations substantiate that fracture of initial Shear Strength specimens occurs in the DS alloy immediately nearby the HAZ zone.

4.2. Radiation resistance of PH copper alloy joints to steel

PH alloy Cu–Cr–Zr (IG) in the state SA + quenching + aged have a somewhat lower σ_u at $T_{test} = 20°C$, but at $T_{test} = 300$–400°C its σ_u is even slightly higher than that of GlidCop A125. After the HIP procedure the Cu–Cr–Zr//316SS joint specimens demonstrate a decrease in σ_u by about 100 MPa (Fig. 6). But as shown in Ref. [4], it is possible to increase the strength characteristics of the alloy to a level of Cu–Cr–Zr (IG) by Post Treatment Procedure (PTP): heating to $T \sim 980°C$, quenching and subsequent ageing at 480°C, during 4 h. Irradiation at $T_{irr} \sim 150°C$ and 300°C affects but slightly the strength of Cu–Cr–Zr//316SS joints. Total elongation of the base alloy Cu–Cr–Zr (IG) is at a high level $\delta_{tot} > 25\%$ throughout the testing temperature range. The total elongation of the joint Cu–Cr–Zr//316SS (HIP) remains at a high level, i.e. $\delta_{tot} > 20\%$, while under irradiation to 0.2 dpa at $T_{irr} = 150°C$ and $T_{irr} = 300°C$.

4.3. Comparison of radiation resistance of joints made by different methods

When analysing the data presented in Figs. 5 and 6, some general regularities true for all joints made by different technologies and specific problems inherent in individual technologies can be pointed out. All investigated joints made by both the HIP method and Friction Welding had high properties at $T_{test} = 20°C$ both in the

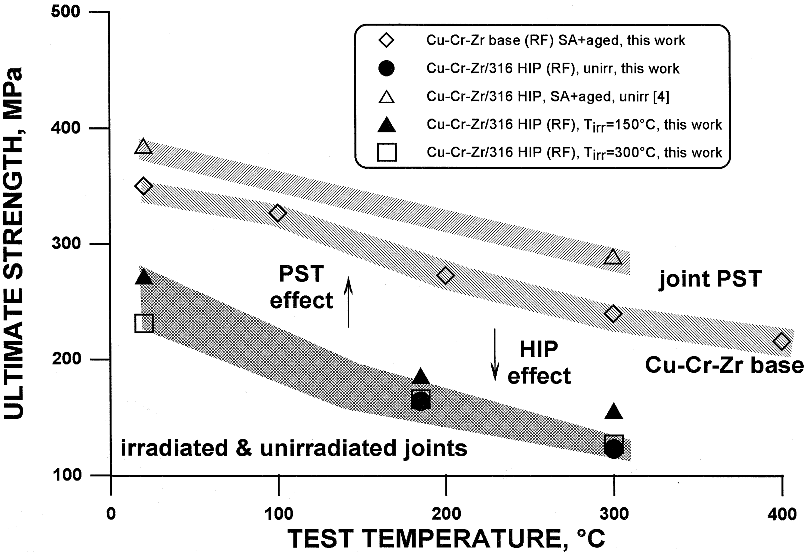

Fig. 6. Ultimate strength versus testing temperature of the PH copper alloy Cu–Cr–Zr after different heat treatment: (a) SA + quenching + ageing, (b) SA + quenching + ageing + HIP, (c) SA + quenching + ageing, + HIP + SA + quenching + ageing [4], and of the joints Cu–Cr–Zr//316SS produced by HIP when unirradiated and after irradiation to 0.2 dpa at $T_{irr} = 150°C$ and $T_{irr} = 300°C$.

initial and irradiated state. In this case all joints had a sufficiently high strength $\sigma_u = 200–400$ MPa and a satisfactory ductility $\delta_{tot} = 5–30\%$. At increased testing temperatures the joints of DS copper alloys to steel made both by the HIP method and Friction Welding had a satisfactory strength and ductility in unirradiated state. Irradiation of the DS Cu//316SS joints to 0.2 dpa at 150°C and 300°C resulted in a drop in the strength properties at increased testing temperatures and to embrittlement. For DS copper alloy joints to steel characteristic was the fracture localisation at $T_{test} > 150°C$ nearby the joint line in DS copper. The PH copper alloy joints of Cu–Cr–Zr//316SS (HIP) type had very high ductile characteristics throughout the testing temperature range both in the initial and irradiated states. This type of joints was distinguished by a comparatively moderate strength ($\sigma_u \sim 150$ MPa).

5. Conclusion

The investigations described in the paper made it possible to estimate, as a first approximation, the radiation resistance of Cu alloy//SS-type joints made by different technologies. It is shown that all irradiated joints have a high level of properties at $T_{test} = 20°C$. It was found that the GlidCop A125/316-type joints produced by the HIP method are characterised by a low level of ductile properties at $T_{irr} = T_{test} = 150°C$ and 300°C. It is demonstrated that the Cu–Cr–Zr//316SS-type joints have a high ductility and the ability for the local deformation both in the irradiated and unirradiated state.

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