ELSEVIER
Journal of Nuclear Materials 258–263 (1998) 2030–2035
journal of nuclear materials

Section 10. Technology and knowledge sharing

Irradiation resistance of DS copper/stainless steel joints fabricated by friction welding methods

S.A. Fabritsiev [a,*], A.S. Pokrovsky [b], M. Nakamichi [c], H. Kawamura [c]

[a] *D.V. Efremov Scientific Research Institute, 189631 St. Petersburg, Russia*
[b] *Scientific Research Institute of Atomic Reactors, 433510 Dimitrovgrad, Russia*
[c] *Japan Atomic Energy Research Institute, Higashi Ibaraki-gun, Ibaraki-ken 313-13, Japan*

Abstract

Copper alloys tubes are assumed to be used for the heat sink system of the ITER first wall and divertor. To join copper tubes with type 316LN stainless steel tubes (for the collector system) various methods are provided, the most promising being the friction welding. Specimens of joints and the base materials were irradiated in the SM-2 mixed spectrum reactor to a dose of 0.2 dpa at $T_{irr} = 150°C$ and 300°C. Specimens of GlidCop Al25/316LN friction welded joints have a relatively high level of strength properties and a rather low plasticity after irradiation.

1. Introduction

As is known, different methods for joining various materials are assumed to be used for the construction of ITER first wall, blanket and divertor. Thus, to join copper alloys to steel can be made through brazing [1], HIP [2] and other technologies. The friction welding technology appears to be the most promising for joining water cooling tubes [3]. This technology provides joining of copper alloy tubes to steel tubes eliminating undesirable high-temperature heating of an entire product. With the brazing and HIP used, products should be put through high-temperature heating up to 800–1000°C during 1.5–2 h affecting adversely the strength properties of copper alloys [4]. While employing the friction welding method heating is localized in a sufficiently narrow material layer immediately adjacent to the joint line. As a consequence, the copper alloy destruction is not large thus making it possible to obtain appropriate strength properties of joints [3,5,6]. At the same time, data on radiation resistance of joints are practically unavailable. The real working temperature of copper alloys, including pipelines, is well below 150–300°C [7]. In copper alloys the effects, observed under irradiation, vary significantly within this temperature range. Thus, the low-temperature radiation embrittlement is observed at a temperature of 150°C [8]. At irradiation temperatures of 300–400°C prevailing are softening effects [9,10]. This work reports the first results of investigations into radiation resistance of copper/steel joints produced by the friction welding method and then irradiated to a dose of 0.2 dpa at temperatures of 150°C and 300°C.

2. Experimental procedure

The joints from GlidCop Al25 copper alloy, made by the company SCM (US), with 316IG JIS steel (Japan) were investigated in this work. The compositions of the investigated materials are presented in Table 1. The manufacturing technology consisted in preparation of welded surfaces, compression of blanks to each other and then welding by high-speed rotation of one blank relative to the other under pressure. The friction welding technology is described in detail in Ref. [3].

Specimens were cut from blanks according to the scheme shown in Fig. 1. Specimens were made from base materials blanks (not subjected to the friction welding procedure) both from GlidCop Al25 and 316IG

* Corresponding author. Tel.: +7-812 4644463; fax: +7-812 4644623; e-mail: fabr@niiefa.spb.su.

0022-3115/98/$19.00
PII: S0022-3115(98)00126-3

Table 1
Chemical composition of investigated materials

SS316 JIS (wt%)											
C	Mn	Si	P	S	Cr	Ni	Mo	Cu	Co	N	B (ppm)
0.019	1.35	0.56	0.022	0.001	17.10	12.51	2.52	0.10	0.05	0.11	<3
GlidCop A125 (wt%)											
Fe	Ni	Cu	Co	Pb	Al	B					
0.0018	<0.0025	99.5	<0.0025	0.0006	0.26	0.016					

JIS steel. Specimens were manufactured as well from the GlidCop Al25/316IG JIS joint produced by the friction welding method. These specimens contain, in the working area, the joint line (Fig. 1). Besides, GlidCop Al25 specimens, cut from the joint at a distance of ~40 mm from the joint line, were manufactured to assess the effect of the friction welding cycle on the GlidCop Al25 properties. Two types of specimens were used in the work for investigation of 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$\sim 3.5 \times 10^{24}$ n/m^2 ($E > 0.1$ MeV), this being consistent with a radiation damage of ~0.2 dpa (in conformity with the NRT standard). Irradiation was performed in a loop device making it possible to control temperature on the specimens under irradiation. According to thermocouple readings the irradiation temperatures: for ampoules 1,2 and 3,4 were 175 ± 5°C and 300 ± 10°C, respectively. Irradiated and reference specimens were tested for tension in the temperature range of 20–300°C at a deformation rate of 1.6×10^{-3} s^{-1} in vacuum. SEM investigations of the fractured surface of tested specimens were performed as well.

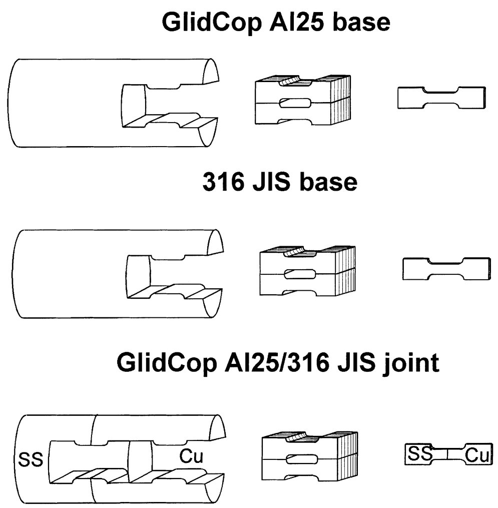

Fig. 1. Scheme of specimen cutting from blanks of the base alloys DS copper (GlidCopAl25) and type 316 (JIS) stainless steel and from the joint GlidCopAl25/316 JIS made by friction welding method.

3. Results

3.1. Effect of irradiation on the mechanical properties of GlidCop Al25 alloy

Measurement of yield strength and uniform elongation of reference and irradiated specimens of GlidCop Al25 alloy revealed (Figs. 2 and 3), that after irradiation to 0.2 dpa this DS copper alloy demonstrates typical behavior. In the initial state the GlidCop Al25 alloy has a sufficiently high yield strength $\sigma_y \sim 420$ MPa at $T_{test} = 20°C$. With the testing temperature is increased, the alloy yield strength drops and at 300°C amounts to ~220 MPa. Uniform elongation of the material is not large and amounts to ~3–4% throughout the testing temperature range of 20–300°C. Note that the total elongation of the alloy is essentially higher and is as high as ~9–15%. Irradiation at 150°C results in hardening of the GlidCop Al25 alloy. At $T_{test} = 20°C$ the gain in $\Delta\sigma_y$ is 50 MPa. With the testing temperature is increased, hardening practically disappears. Uniform elongation of specimens irradiated at 150°C decreases by nearly twice at $T_{test} = 20°C$, but at the higher testing temperatures embrittlement is practically lacking. Irradiation at 300°C results in a slight softening ($\Delta\sigma_y = -50$ MPa) of the GlidCop Al25 alloy, hence increased is its uniform elongation, amounting to 6–10% in the testing temperature range of 20–300°C.

3.2. Effect of irradiation on the mechanical properties of GlidCop Al25/316IG JIS joint

Testing for tension of unirradiated specimens cut from the joints so that the welding line is in the centre of the specimen working part normally to the tension axis,

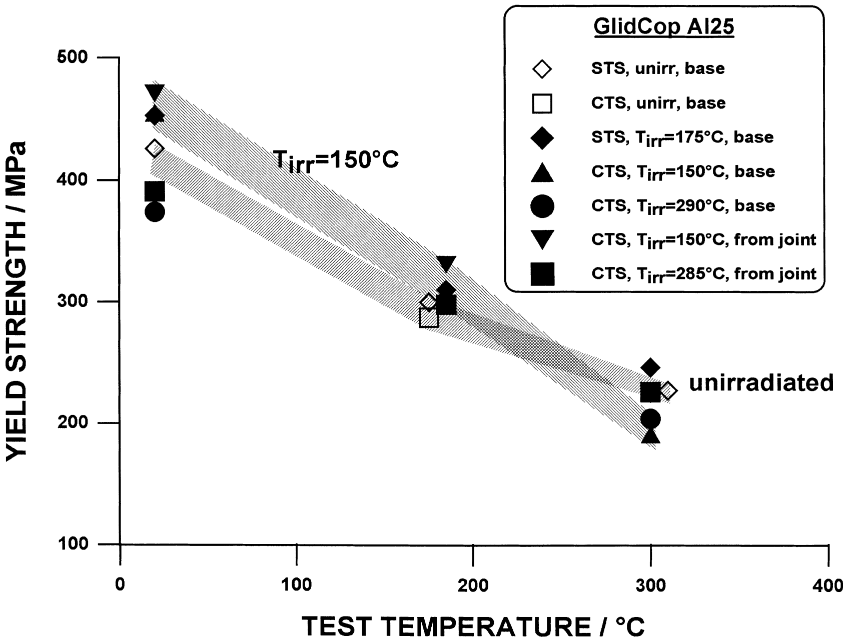

Fig. 2. Yield strength versus testing temperature of the DS copper alloy GlidCopAl25, unirradiated and after irradiation to 0.2 dpa at $T_{irr} = 150°C$ and $T_{irr} = 300°C$.

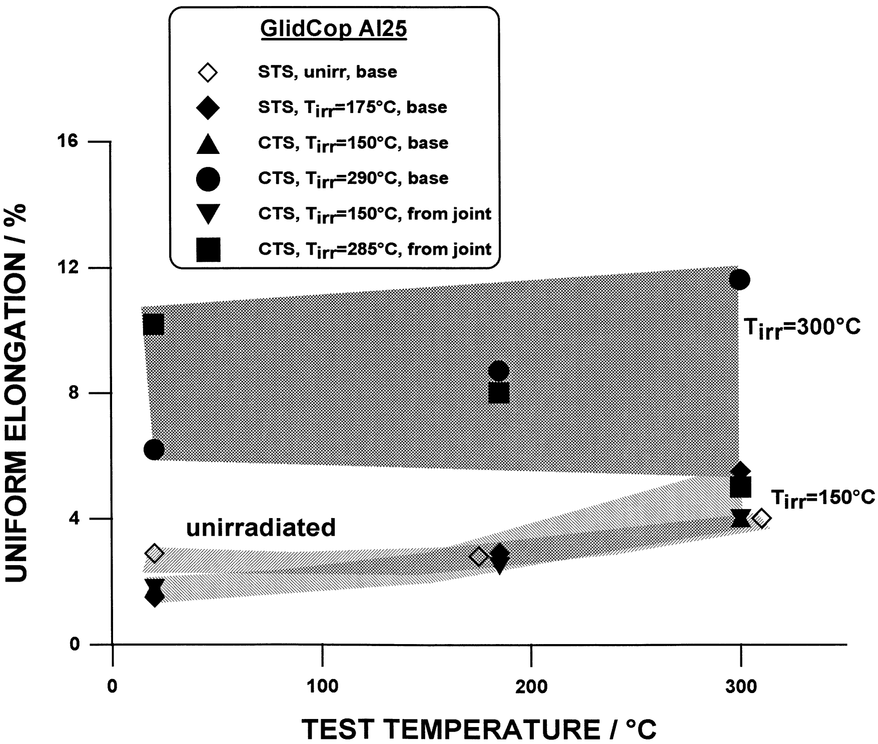

Fig. 3. Uniform elongation versus testing temperature of the DS copper alloy, GlidCopAl25, unirradiated and after irradiation to 0.2 dpa at $T_{irr} = 150°C$ and $T_{irr} = 300°C$.

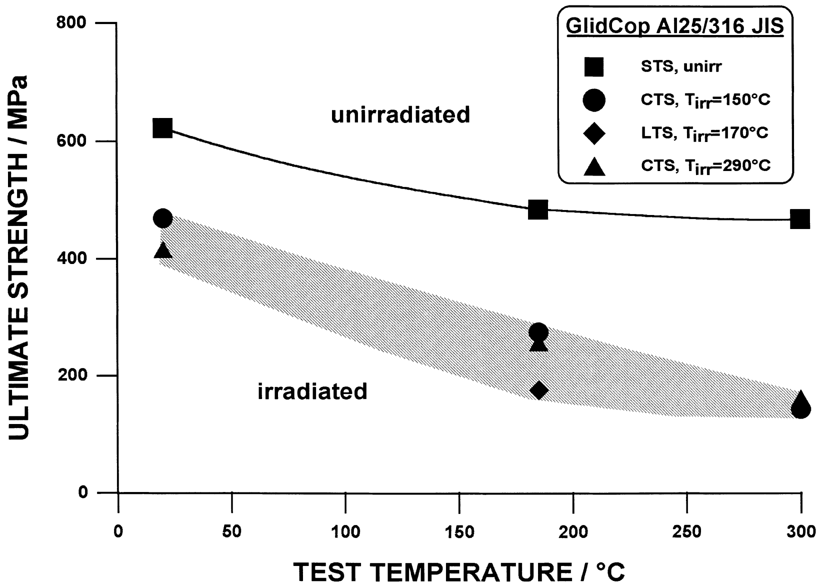

Fig. 4. Ultimate strength versus testing temperature for specimens of the GlidCopAl25/316 JIS joint, when unirradiated and after irradiation to 0.2 dpa at $T_{irr} = 150°C$ and $T_{irr} = 300°C$.

shows that the joints have a rather high level of ultimate strength of 600–500 MPa at $T_{test} = 20–300°C$ (Fig. 4). Irradiation to 0.2 dpa causes the joint ultimate strength to decrease (Fig. 4), the difference $\Delta\sigma_u = \sigma_{u(unirr)} - \sigma_{u(irr)}$ being increased with the testing temperature. At $T_{test} = 20°C$ it amounts to $\sim$200 MPa, while at $T_{test} = 300°C$ $\Delta\sigma_u = 350$ MPa. Unirradiated joint specimens, when tested for tension, demonstrated an extremely high total elongation up to 70%. The joint specimens, when irradiated, had a satisfactory (3–4%) level of total elongation at $T_{test} = 20°C$ (Fig. 5). At increased testing temperatures (150–300°C) total elongation of irradiated specimens was low, i.e. 0–1.5%. It should be noted that specimens irradiated at 300°C had regularly higher total elongation than specimens irradiated at 150°C.

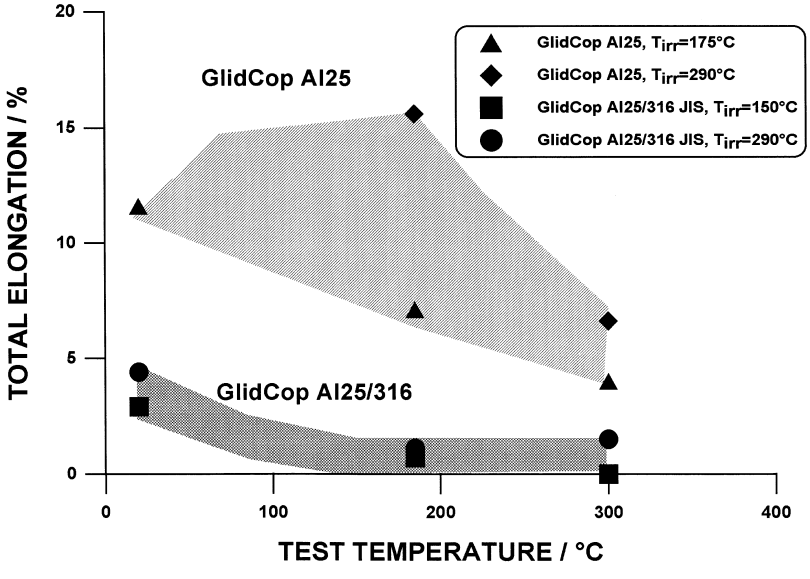

Fig. 5. Comparison of temperature dependence of total elongation of the base material GlidCopAl25, and the joint GlidCopAl25/316 JIS in the irradiated state.

3.3. Effect of irradiation on the fracture character of joint specimens

Optical microscopy and SEM investigations are made on the fracture character of the unirradiated and irradiated specimens of GlidCop Al25/316 JIS joints tested for tension, showing that in the initial specimens the deformation is localized in the specimen portion of 316 steel. It is in 316 steel where fracture with a distinct ductile character occurs. In the irradiated joint specimens the deformation is localized in the specimen portion of GlidCop Al25. Specimens are fractured in GlidCop Al25 in the zone adjacent to the joint line and at 200–1000 μm off from it.

4. Discussion

4.1. Effect of irradiation on the strength properties of joints

Now let us analyze the strength properties of the alloys composing the joint and the joint itself. As follows from Fig. 6, the yield strength of the GlidCop Al25 base alloy (as well as from joints, as shown above), when unirradiated, is considerably higher than that of the specimens of GlidCop Al25/316 JIS joints. At $T_{test} = 20°C$ this difference is as high as ~120 MPa, whereas at $T_{test} = 300°C$, ~50 MPa. At the same time, the yield strength of 316 JIS steel is considerably lower than that of the GlidCop Al25 alloy and practically coincides with the yield strength of specimens of the GlidCop Al25/316 JIS joints. Thus, it is evident that during loading of unirradiated specimens the deformation will start in softer steel and after a considerable uniform deformation of ~40–60% it will give rises to the neck and ductile fracture. This conclusion is completely confirmed by the results of the optical and SEM investigations of fractured specimens. As follows from Fig. 6, irradiation results in a drastic hardening of 316 steel and an extremely weak hardening of GlidCop Al25 alloy. Irradiation to 0.2 dpa at temperatures of 150°C and 300°C results in the formation of fine complexes of radiation defects in steel [11], whose density is high. Consequently, the yield strength of steel is drastically increased (by 300–200 MPa), as the density of traps for dislocations is high. A different situation arises with the DS copper alloy GlidCop Al25. Even in the initial state this alloy has an extremely high density ($\rho \sim 10^{21}$ m^{-3}) of fine Al_2O_3 particles (2 nm) [9]. Under irradiation to a small dose the density of produced radiation defects is comparable to that of hardening particles Al_2O_3 [12], consequently, no gain in the yield strength is observed, as the density of stoppers for dislocations, after irradiation, increases but slightly.

Thus, a change in the deformation localization in the GlidCop Al25/316 JIS joint specimens in the initial state and after irradiation, is related to the difference in the

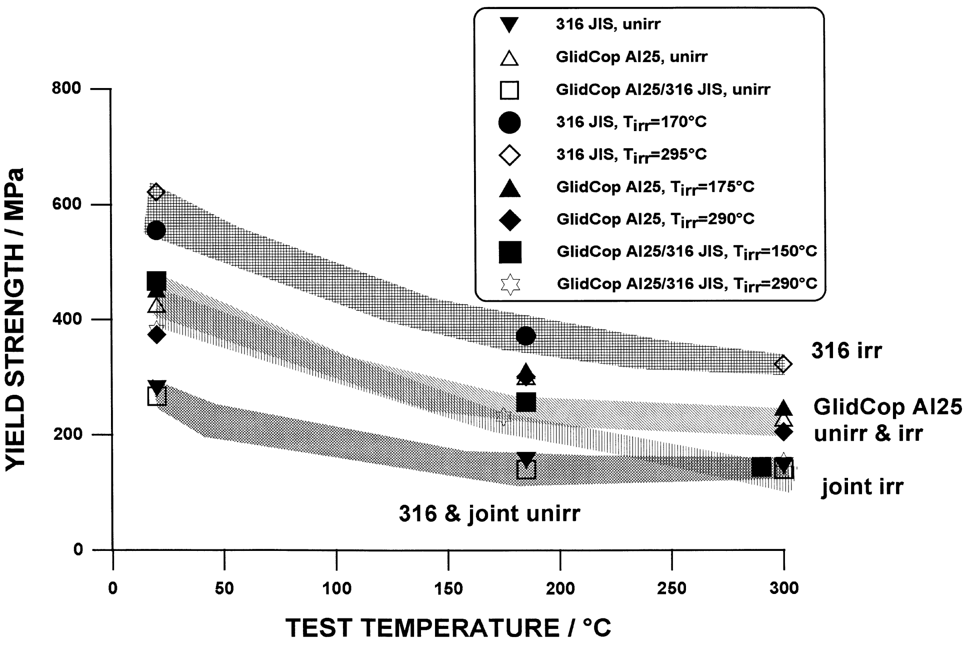

Fig. 6. Comparison of temperature dependence of yield strength of the base materials GlidCopAl25, 316 JIS and joint GlidCopAl25/316 JIS in the initial and irradiated state.

dose dependence of radiation hardening of the base materials GlidCop Al25 and 316 JIS steel.

Note, that Zinkle was the first who suggested the possibility of this situation while analyzing the dose dependencies of hardening of GlidCop and steel 316 [13]. He suggested as well that designers, when calculating, should take into account that in the Cu/steel joint the yield strength would be lower in steel during initial work of ITER materials and then precisely in steel the deformation would be localized. Even at doses of 0.1–0.2 dpa the yield strength of steel type 316 becomes higher due to a higher rate of radiation hardening, hence the deformation will be localized in DS copper alloy.

4.2. Effect of irradiation on embrittlement of joints

The most interesting question following from the results of the present work is related to the reasons for radiation embrittlement of joints from GlidCop Al25/316 JIS made by the friction welding method. Since the deformation of irradiated specimens of joints is realized in the specimen portion comprising DS alloy, it would make sense to tackle this question precisely in the change in the properties of this alloy, after irradiation. As follows from Fig. 5, irradiation of DS alloy GlidCop Al25 to 0.2 dpa at 150 and 300°C affects but rather slightly the total elongation.

For the produced specimens of the GlidCop Al25/316 JIS joint the level of δ_{tot} is satisfactory only at $T_{test} = 20$°C. At higher testing temperatures the joints are fractured after small (0–1%) deformation and, as follows from Fig. 4, at low levels of fracture stress of ~150 MPa. Note that under the same irradiation and testing conditions the GlidCop Al25 alloy has a higher level of maximum stress $\sigma_u \sim 250$–200 MPa, while steel 316 under the same conditions demonstrates $\sigma_u \sim 500$ MPa and the elongation $\delta_{tot} = 40\%$. All these data point to the fact that the observed radiation embrittlement of GlidCop Al25/316 JIS joints is not directly related to embrittlement of base materials composing the joint, as each of them, when irradiated under the same conditions, has a good ductility and higher strength than the joint. The conclusion suggests itself that in the GlidCop Al25/316 JIS joint there is the specimen portion comprising GlidCop Al25, which has a higher sensitivity to radiation embrittlement than the GlidCop Al25 alloy itself.

5. Conclusion

The presented results showed that the joints of GlidCop Al25/316 JIS type manufactured in Japan by the friction welding method hold rather good promises for radiation resistance. After irradiation to 0.2 dpa at $T_{irr} = 150$°C and $T_{irr} = 300$°C these joints demonstrated a high level of the strength properties (~400 MPa) and a satisfactory level of ductile properties (~4%) during tests at $T_{test} = 20$°C. At increased testing temperatures of 150°C and 300°C irradiated specimens of joints had strength properties at a level of ~150 MPa and a rather low ductility (~1%). The analysis of the obtained data allows for the preliminary conclusion, that the observed radiation embrittlement of the joints at increased testing temperatures is related to degradation of the GlidCopAl25 structure during friction welding in the HAZ.

References

[1] B.C. Odegard, B.A. Kalin, J. Nucl. Mater. 233–237 (1996) 44.
[2] G. Le Marois, Ch. Dellis, J.M. Gentzbittel, F. Moret, J. Nucl. Mater. 233–237 (1996) 927.
[3] K. Tshuchia, H. Kawamura, M. Saito, in: K. Herbschbach, W. Maurer, J.E. Vetter (Eds.), Fusion Technol., SOFT-18, 1995, pp. 447–450.
[4] S.A. Fabritsiev, A.S. Pokrovsky, V.R. Barabash, Yu.G. Prokofiev, Neutron spectrum and transmutation effect on properties of copper alloys, Fusion Eng. and Design, in press.
[5] K. Tshuchia, H. Kawamura, J. Nucl. Mater. 233–237 (1996) 913.
[6] T. Kikuchi, H. Kawamura, JAERI-M 88-150, 1988.
[7] G. Kalinin, W. Gauster, R. Matera, A.A.F. Taqvassoli, A. Rowcliffe, S. Fabritsiev, H. Kawamura, J. Nucl. Mater. 233–237 (1996) 9.
[8] S.A. Fabritsiev, A.S. Pokrovsky, S.J. Zinkle, D.J. Edwards, J. Nucl. Mater. 233–237 (1996) 513.
[9] S.A. Fabritsiev, V.R. Barabash, A.S. Pokrovsky, V.P. Chakin, N.I. Grechanjuk, B.A. Movchan, V.A. Osokin, Plasma Devices Operations 4 (1995) 1.
[10] S.J. Zinkle, S.A. Fabritsiev, Copper alloys for high heat flux applications, Atomic and Plasma Materials Interaction Data for Fusion (supplement to Nuclear Fusion) 5 (1994) 163–192.
[11] P. Maziasz, J. Nucl. Mater. 191–194 (1992) 701.
[12] B.N. Singh, D.J. Edwards, P. Toft, J. Nucl. Mater. 238 (1996) 244.
[13] S.J. Zinkle, private communication.