ELSEVIER

Journal of Nuclear Materials 258–263 (1998) 1991–1996

journal of nuclear materials

The effect of helium accumulation and radiation damage on the weldability of 316-type steel

S.A. Fabritsiev [a,*], A.S. Pokrovsky [b]

[a] D.V. Efremov Scientific Research Institute, 189631 St. Petersburg, Russian Federation
[b] Scientific Research Institute of Atomic Reactors, 433510 Dimitrovgrad, Russian Federation

Abstract

The embrittlement simulated by helium accumulation, with the ITER components repaired by welding during maintenance, is one of the factors limiting the materials lifetime. This work presents the results of the investigations into the effect of neutron produced helium, 0.1 dpa T_{irr} – 80°C, (at a low He/dpa and cyclotron introduced helium, 5–430 appm He (at high He/dpa) on the quality and mechanical properties of the type 316 steel welds. The samples, both irradiated and controls, were welded by e-beam welding (cyclotron injection) or on the automatic argon-arc welding device in the hot cell SRIIAr (neutron irradiation). Low-cycle fatigue (LCF) testing in bending was used to assess impact of helium on the degradation of welded joint properties.

1. Introduction

Of special importance at the present ITER stage are those materials properties that determine their life time. For the main structural reactor material, i.e. steel 316LN, resistance to embrittlement after rewelding is sure to be one of such properties.

Preliminary evaluations show that even in one–two months of operation more than 1 appm of helium will be accumulated in the materials of the first wall, pipelines and vacuum vessel of the ITER due to (n,α) reactions [1].

The overheating of a similar material, caused by plasma disruption, coolant loss, rewelding or brazing will inevitably result in its damage. The degree of material damage will be controlled simultaneously by several factors: helium concentration, heating temperature, time of heating, stresses appearing in the material during the overheating. This problem has been studied up to the present almost exclusively applied to the problem of the irradiated steel welding [2–4].

Investigations of the rewelding problem were first based on the study of 316 steel containing helium introduced by a tritium trick [2.3]. Some studies were made into weldability of neutron-irradiated steels [4–6]. The results are ambiguous: in some cases cracks were observed in irradiated steels, but in other cases they were not.

Currently the possibilities for welding of neutron-irradiated samples exist in Pettern (EC) [7], where conditions are created for laser welding of irradiated samples, as well as in SRIAR (RF).

The paper presents the results of the investigation of neutron irradiation effects on austenitic steel weldability. The choice of low-cycle fatigue (LCF) testing in reverse bending for the assessment of the mechanical properties was determined because in bending the deformation was localized in the surface layers of a plane sample. It is in this area that the cracks oriented transverse to the sample cross-section start emerging and developing, resulting in the long run in fracture. Thus, all the main fracture factors are realized with neutron irradiation technique and the LCF in reverse bending for the assessment of the mechanical properties of welded samples. When welding, high temperatures in this welded joint and Heat Affected Zone (HAZ) region determine the generation of helium pores and microcracks. With the LCF testing in this region the maximum deformations are realized and microcracks emerge and develop.

---

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

0022-3115/98/$19.00
PII: S0022-3115(98)00417-6

2. Experimental procedure

In our work we made use of 1-mm-thick samples of Cr16NillMo3Ti and 316LN steels. A hot cell device for automatic arc welding was developed for neutron-irradiated samples. The samples were irradiated in capsules of the RBT-10 reactor up to two doses 1×10^{20} n/cm^2 and 3×10^{20} n/cm^2 ($E > 0.1$ MeV)(0.05 and 0.15 dpa, respectively) at T_{irr} 80°C. Calculated helium concentration in irradiated samples were 1 and 2.5 appm He, respectively.

Then the irradiated and control samples were exposed to hot cell arc welding using the above welding device. When welded, the samples with and without helium were tested for LCF in reverse bending at 20°C and 350°C.

Some samples were irradiated with helium ions on the cyclotron at particles energies of 40 MeV at $T_{irr} < 100$°C. The method of irradiation ensured equilibrium saturation of near-to-surface layers of 200 μm thick samples with helium. The accuracy of helium beam focusing and localization of the irradiated area were radio graphically controlled.

Then helium saturated samples (5–430 appm He) were subjected to e-beam welding. The technique of sample welding and LCF testing was discussed in detail earlier [8,9].

3. Results

3.1. Effect of neutron irradiation on LCF of welded joints

Fig. 1 shows the number of cycles to fracture as a function of deformation amplitude for steels of Cr16Nill and 316 types, when nonirradiated. As follows from Fig. 1, both steel samples (base metal) and welded joint samples have, when nonirradiated, a sufficiently high fatigue life. Whatever the type of applied welding (automatic arc welding or e-beam welding), the welded joints fracture at $\Delta\varepsilon \sim 1.4\%$ after ~1000 cycles and at $\Delta\varepsilon \sim 0.6\%$ after ~10 000 cycles. Thus, the available welding technologies provide, in principle, the required high level of fatigue resistance of a welded joint.

Neutron irradiation to comparatively small doses of $\sim 10^{20}$ n/cm^2 causes, as seen from Fig. 2, the fatigue life of the base metal to drop. At $T_{test} = 20$°C and $T_{test} = 350$°C irradiated Cr15NillMo3Ti steel samples fracture at a factor of the two fewer cycles than nonirradiated samples.

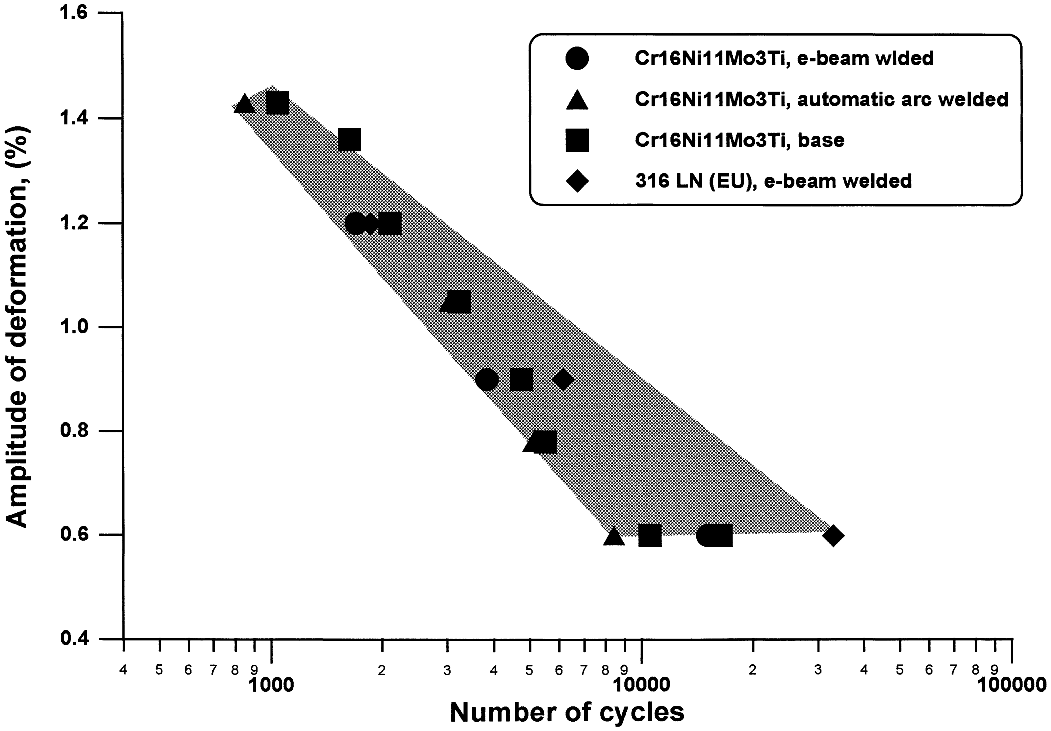

Fig. 1. Effect of automatic arc welding and e-beam welding on LCF of nonirradiated Cr16NillMo3Ti steel and 316LN steel for $T_{test} = 20$°C.

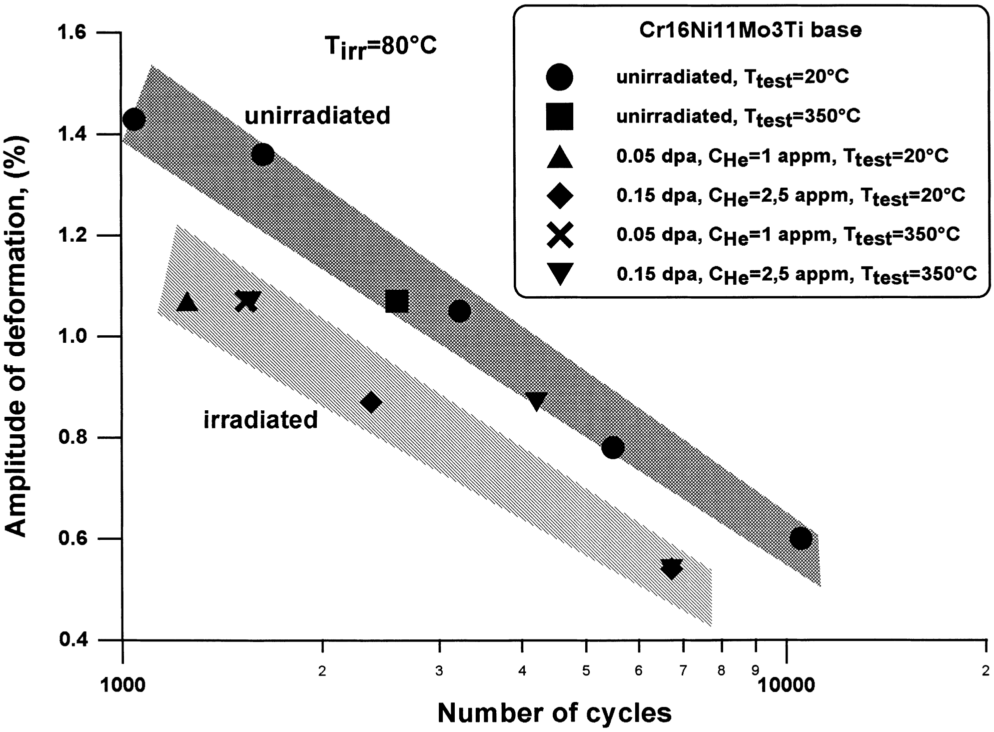

Fig. 2. Effect of neutron irradiation at dose up to 0.15 dpa ($T_{\mathrm{irr}} = 80$°C) on the LCF life of base metal of Cr16NillMo3Ti steel, $T_{\mathrm{test}} = 20$°C and 350°C.

An even larger drop in the number of cylces to fracture is observed for welded joints from steel Cr16NillMo3Ti (Fig. 3). A particularly strong drop, 5–10 fold is realized at maximum deformation amplitudes of 1.1–0.9%. At small deformations (0.6%) the number of cylces to fracture of irradiated joint samples drops only by 20–30%. The fact that large irradiation doses result regularly in severe embrittlement deserves attention. Samples of joints tested at 350°C behave practically in the same way as those tested at 20°C but with a somewhat higher number of cylcles to fracture, when tested under the same conditions.

3.2. *Effect of helium injection on structure and fracture character of welded joints*

The investigation of the sample surface after welding found out the following mechanisms of the helium effect on the structure of the welded joint Cr16NillMo3Ti steel. In nonirradiated samples microcracks in the HAZ and weld after welding are not observed. In Cr16NillMo3Ti steel samples irradiated up to 0.15 dpa (2.5 appm He) when welded, there appear microcracks in the HAZ. No cracks are observed in the fusion zone of weld at this helium concentration.

The investigations of the character of fracture in neutron-irradiated Cr16NillMo3Ti steel samples, when welded and tested for LCF, revealed transgranular fracture in samples irradiated up to 0.05 dpa (1 appm He).

The character of fracture in high dose neutron-irradiated Cr16NillMo3Ti steel samples, when welded and tested for LCF, revealed that in samples with 2.5 appm He the fracture had a mixed transgranular–intergranular nature. The fracture is localized in the HAZ.

4. Discussions

The investigations undertaken allow for the conclusion that the automatic welding technology (both automatic arc welding and e-beam welding) provides fatigue properties of a welded joint at a level of the base metal.

Irradiation at $T = 80$°C to doses of 0.05…0.15 dpa involves nearly a twofold drop in the metal fatigue life (both at $T_{\mathrm{test}} = 20$°C and at $T_{\mathrm{test}} = 350$°C). As demonstrated by tensile testing of irradiated base metal samples, low-temperature irradiation to 0.15 dpa results in a considerable hardening ($\approx$200 MPa) and a drop in the uniform elongation at $T_{\mathrm{test}} = 20$°C. At $T_{\mathrm{test}} = 350$°C hardening is appreciably lower; embrittlement is also lower. This is associated with annealing of radiation defect complexes during prolonged testing. That is why,

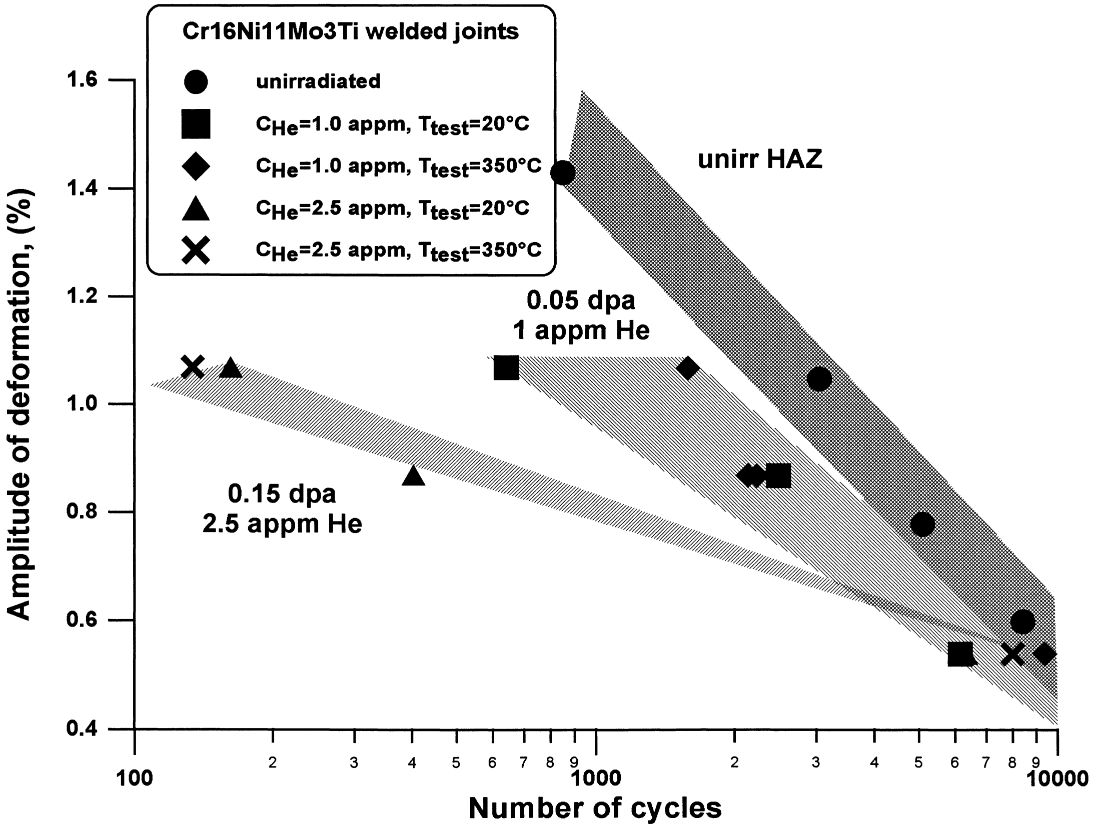

Fig. 3. Effect of neutron irradiation and automatic arc welding on LCF life of Cr16NillMo3Ti steel welded joints for $T_{\text{test}} = 20°\text{C}$ and 350°C.

the number of cylces to fracture of irradiated samples is regularly higher at $T_{\text{test}} = 350°\text{C}$ than at $T_{\text{test}} = 20°\text{C}$ with the same deformation amplitude (Fig. 3).

A welded joint is characterized by a dramatic drop in the fatigue life at maximum deformation amplitude (1.1%) and a weal embrittlement at a small deformation amplitude of 0.6%.

A drastic increase in embrittlement with a rise in irradiation dose attracts attention. While at a dose of 0.05 dpa and accumulation of 1.0 appm He, the number of cycles to fracture for irradiated joints drops by not more than a factor of 2–3, at a dose of 0.15 dpa and at 2.5 appm Ge a decrease in the number of cycles to fracture is as high as tenfold.

The observed effect is obviously associated with two reasons. On the one hand, with a rise in the damage dose, the difference in strength between joint components is increased. When tested, the base metal, well apart from a welded joint, is strengthened under irradiation, with the strengthening degree increased with dose. In the HAZ the material is softened, since irradiation defect complexes therein were annealed during the thermal cycle in HAZ. The microhardness tests demonstrate that the fusion zone of weld itself has a high strength. Under LCF loading, maximum stresses are localized in the weakest cross-section of a sample (i.e. in HAZ), hence it is here where deformation and fracture occur.

An increase in He concentration with the rise in the irradiation dose involves a rise in the number of microcracks on the grain boundaries in the HAZ during welding. Therefore, a strong embrittlement is observed in samples with maximum helium concentration. It is essential for designers that a “critical” irradiation dose, at which fatigue characteristics of a joint vary only slightly, is 0.05 dpa and the corresponding He concentration is about 1 appm. At higher irradiation doses a joint has a low fatigue life at a high loading level.

In the ITER construction only a limited number of components intended for rewelding will be significantly loaded in the standard regime.

The usual situation is a low level of fatigue loading of elements. Therefore, of prime interest for designers is the behavior of joints at low loading levels. Fig. 4 shows the change in the number of cycles to fracture as a function of helium concentration in samples. In this case along-

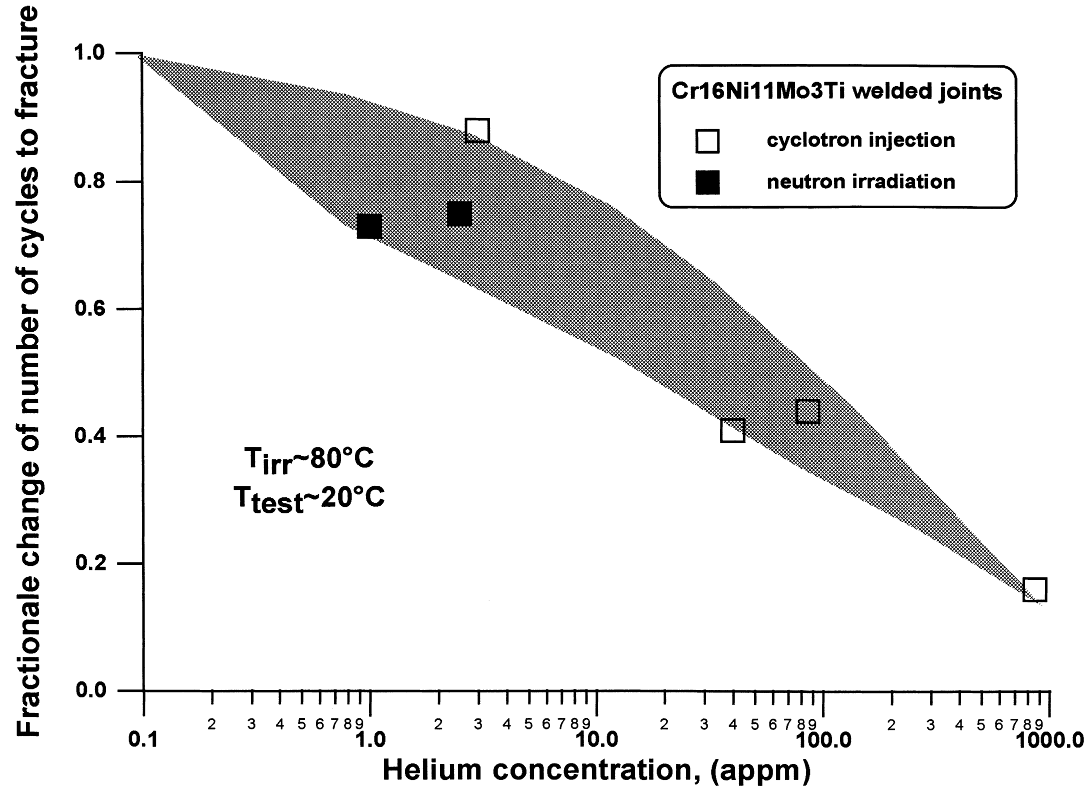

Fig. 4. Effect of helium concentration on fractional change of number to fracture $N_{f\,irr}/N_{unirr}$ of Cr16NillMo3Ti steel welded joints (neutron-irradiated and helium-injected).

side with the data from this study, use is made of the data from Ref. [9] on the effect of helium cyclotron injection at minimum deformation amplitude of 0.6%. As follows from Fig. 4, at small helium concentrations and small deformation amplitudes the fatigue life welded Cr16NillMo3Ti steel joint drops only slightly, i.e. $N_{f\,irr}/N_{f\,unirr} = 0.8$. A considerable drop in the number of cycles to fracture is observed only at a helium concentration of 100 appm.

As for a fusion reactor, helium accumulation rate in steel is 10 appm/dpa [1]. This means that at low loading levels the vacuum vessel components will retain a satisfactory level of fatigue properties after rewelding to doses of ~0.5 dpa ($C_{He} = 5$ appm). Needless to say that this conclusion is tentative and requires further investigation so as to construct the dependence the change in the number of cycles to fracture (N_{irr}/N_{unirr}) as a function of He and dpa at a He accumulation rate close to that postulated for ITER.

5. Conclusions

The present investigations allow for the conclusion that the automatic arc welding and e-beam welding technology assures the welded joint properties close to those of the base metal.

After rewelding, a welded joint from Cr16NillMo3Ti steel fractures in the HAZ at a high loading level, and in this case the number of cycles to fracture drops tenfold at a dose of ~0.15 dpa and $C_{He} = 2.5$ appm.

The critical dose, at which after rewelding a welded joint has a satisfactory level of properties under maximum loading, is a dose of ~0.05 dpa and $C_{He} = 1$ appm. At low loading levels welded joints have a satisfactory level of fatigue life at $0 < C_{He} < 10$ appm.

References

[1] A.V. Karasev, S.A. Fabritsiev, Voprosy Atomnoi Nauki i Tehniki (in Russian), Termojadernyi sintez 12 (3) (1992) 54.
[2] H.T. Lin, S.H. Goods, M.L. Grossbeck, B.A. Chin, in: N.H. Packan, R.E. Stoller, A.S. Kumar (Eds.), ASTM-STP 1004, Philadelphia, 1989, p. 301.
[3] S.H. Goods, N.Y.C. Yang, Metall. Trans. A 23 (1992) 1021.
[4] S.D. Atkin, ADIP Seminannual Progress Report, September 1981, p. 110.
[5] M.M. Hall, Jr., A.G. Hins, I.R. Summers, D.E. Wakker, Proceedings of the Fifth Botton Landing Conference on

Weldment: Physical Mettalurgy and Failure Phenomena, General Electric Co, Schenectady, New York, 1978, p. 365.

[6] W.R. Kanne, C.L. Angermann, B.J. Eberhard, DP-1470, E.I. du Pont de Nemours and Co., Inc., Savannah River Laboratory, Aiken, SC, 1987.

[7] E.V. van Osch, D.S.d'Hulst, J.G. van der Laan, Proceedings of the 18th Symposium on Fusion Technology 1994, Karlsruhe, Germany, vol. 1, 22–26 August 1994, pp. 399–402.

[8] S.A. Fabritsiev, A.S. Pokrovsky, V.A. Brovko, J. Nucl. Mat. 233–237 (1996) 173–176.

[9] S.A. Fabritsiev, J.G. van der Laan, in: D.S. Gelles, R.K. Nanstad, A.S. Kumar, E.A. Little (Eds.), ASTM-STP 1270, Philadelphia, 1996, pp. 980–994.