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Radiation resistance of weld joints of type 316 stainless steel containing about 10 appm He

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Abstract

Welding is supposed to be an important method for making joints in the pipes conducting the heat agent when replacing divertor and first wall elements. Embrittlement through helium accumulation within the ITER components repaired by welding during maintenance is one of the factors limiting the materials lifetime. To investigate this problem, a set of the 316 RF type steel specimens was saturated by He up to 50 appm at 80°C. Another part was irradiated in the SM-2 reactor up to 0.1 dpa at 80°C. Afterwards, they were subjected to e-beam welding and arc welding, respectively. A part of each specimen underwent LCF bending; another part was tested to tension. These tensile and LCF tests of the specimens showed that neutron irradiation of the weld joints leads to their embrittlement and rapidly reduces the number of cycles to failure.

1. Introduction

When replacing units of the divertor and International Thermonuclear Experimental Reactor (ITER) first wall, welding will be used to connect piping in the cooling system. The material for pipes will be a 316-type stainless steel (SS). During irradiation up to 0.5 dpa, He accumulation to 5 appm will occur due to (n,α) reactions in the steel. Investigations [1–5] of irradiated specimens of 316 SS show that welding specimens containing helium results in significant embrittlement of the material, with the appearance of intergranular cracks and reduction in fatigue life.

The analysis of properties of rewelded specimens is a complicated task. This is because there are several zones in specimens with substantially different properties (base material, heat-affected zone, weldments) and fracture localizes in different zones of rewelded specimens during tensile and low cycle fatigue (LCF) testing.

In this work the results of an investigation of the influence of rewelding on the mechanical properties and microstructure of a 316 Russian Federation (RF) type SS specimens are presented.

2. Experimental

In our work we made use of 1 mm thick samples of 316 (RF) SS, which had a composition of 16.1% Cr–11.5% Ni–2% Mo–1.2% Mn. The samples were irradiated in the SM-2 reactor up to a dose of 1.5×10^{20} n/cm^2 ($E > 0.1$ MeV) (0.1 dpa) at $T_{irr} = 80°C$. The measured helium concentration in the irradiated samples was 2 appm He. Unirradiated, irradiated and irradiated and annealed specimens were tested in tension in the temperature range of 20–1050°C at a deformation rate of 5.5×10^{-4} s^{-1}.

Some control samples were irradiated with helium ions in a cyclotron at particle energies of 40 MeV at $T_{irr\text{-}} \leqslant 100°C$. The method of irradiation ensured equal distribution of helium within the near surface layers of 200 μm thick samples. The accuracy of helium beam focusing and localization of the irradiated area were radio-graphically controlled.

Part of the neutron irradiated and control samples were exposed to arc welding in a hot cell using the welding device above.

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Then helium saturated samples (50 appm He) were subjected to e-beam welding. When welded, the samples with and without helium were tested under low cycle fatigue conditions by reverse bending at 20°C. The technique of sample welding and LCF testing is discussed elsewhere [6–8].

3. Results

3.1. Tensile test

Figs. 1(a) and (b) show the tensile test results of the 316 (RF) SS in the initial state, after irradiation up to 0.1 dpa and after irradiation followed by annealing at 1050°C for 1 h. As shown in Fig. 1(a), the irradiation results in strengthening of the steel by 200 MPa at test temperatures in the range of 20–300°C. When tested at

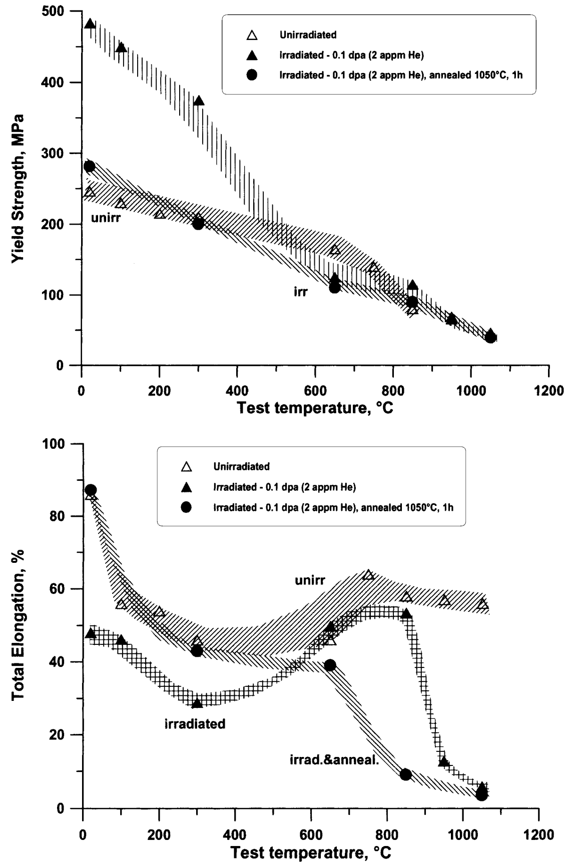

Fig. 1. Yield strength (a) and total elongation (b) versus testing temperature of 316 (RF) type steel tensile specimens, when unirradiated and after irradiation to 0.1 dpa (2 appm He) at $T_{irr} = 80°C$ and irradiated and annealed at $T_{ann} = 1050°C$ for 1 h after irradiation.

650–1050°C, the yield strength of irradiated specimens is about that of unirradiated specimens.

Total elongation of the specimens at low test temperature after irradiation is about half of that of the specimens in the initial state (Fig. 1(b)). After annealing at 1050°C for 1 h, the total elongation of the specimens at 20–300°C recovers to the initial level. The situation differs for tests at elevated temperature, 850–1050°C, where the total elongation is 5–10 times lower for irradiated specimens as compared with unirradiated specimens, and after annealing and does not recover even decreases further.

3.1.1. Character of material fracture

Unirradiated, irradiated, irradiated and annealed specimens tested in the range of 20–650°C were found to fracture in a ductile, transcrystalline mode. At test temperatures in the range of 750–1050°C the unirradiated specimens fractured in a mixed mode with predominant transcrystalline fracture. The irradiated, irradiated and annealed specimens tested at temperatures in the range of 750–850°C show predominant, and at 950–1050°C exclusively, intercrystalline fracture.

3.2. Low-cycle fatigue tests

Fig. 2 shows the results of room temperature LCF tests of specimens after rewelding (irradiated by neutrons and saturated by helium up to 50 appm in the cyclotron).

It is obvious that when compared with unirradiated welded specimens, the rewelded specimens show a significant reduction in the number of cycles to failure, especially at high amplitude loads.

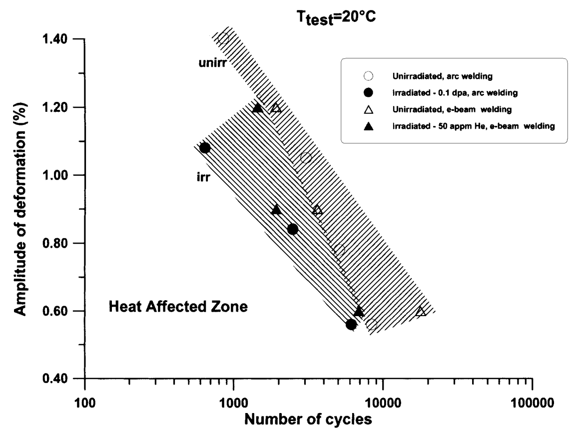

Fig. 2. Effect of neutron irradiation and automatic arc welding and cyclotron injection and e-beam welding on LCF life of 316 (RF) type steel welded joints for $T_{test} = 20°C$.

3.2.1. Character of material fracture

3.2.1.1. Neutron irradiation. Fig. 3 shows the optical microstructure of 316 (RF) rewelded specimens tested in LCF experiments. As follows from Fig. 3, multiple microcracks are developing in the direction normal to the surface. The longest cracks are observed in the HAZ

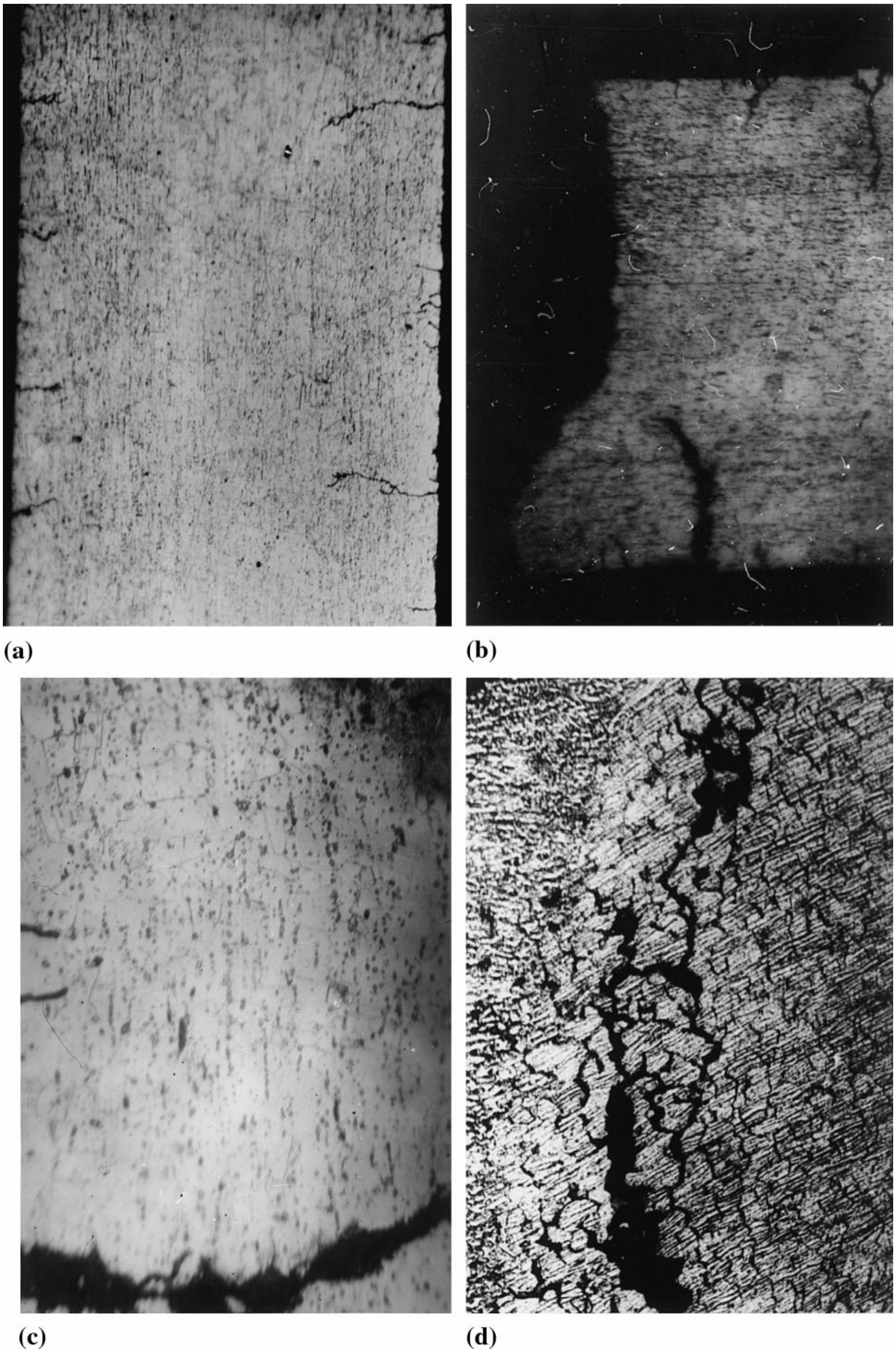

Fig. 3. Optical microstructure of neutron irradiated and automatic arc welded specimens of 316 (RF) type steel after LCF tests at $T_{test} = 20°C$. (a) ×60; (b) ×60; (c) ×300; (d) ×300.

immediately adjacent to the weld (Fig. 3(d)). From Fig. 3(d) it is clearly seen that the cracks develop only on grain boundaries.

3.2.1.2. Cyclotron injection. Fig. 4 shows the results of SEM investigations of the fracture mode of rewelded specimens containing 50 appm He and tested in LCF experiments. The development of intergranular cracks in the HAZ is clear. The cracks develop in a manner typical for the LCF tests (Fig. 4(d)). In general, fracture is controlled by the coalescence of intergranular cracks.

4. Discussion

The results obtained allow the analysis of the reasons of fatigue property degradation of rewelded specimens

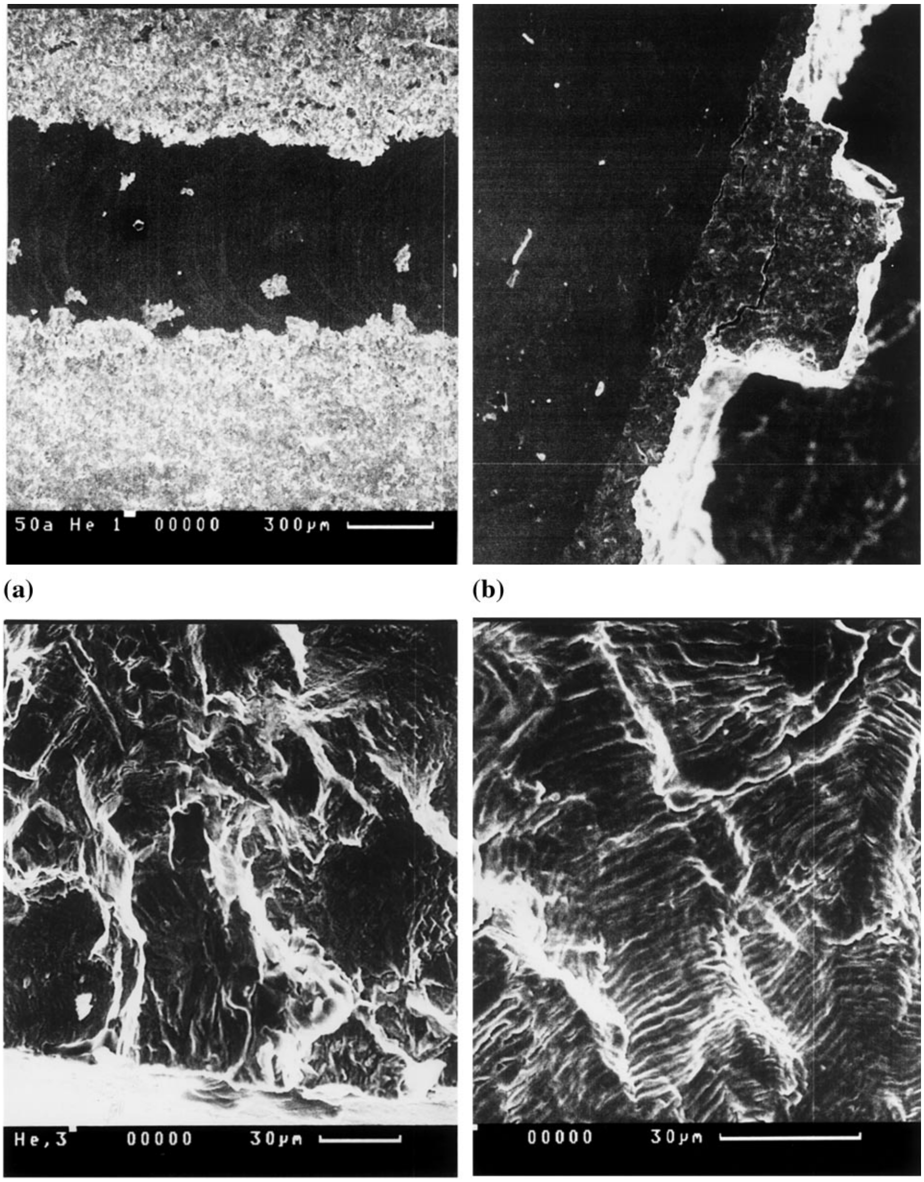

Fig. 4. SEM microstructure of cyclotron injected and e-beam welded specimens of 316 (RF) type steel after LCF tests at $T_{test} = 20°C$. (a) ×50; (b) ×100; (c) ×4000; (d) ×7000.

at low test temperatures. A distinctive feature of helium embrittlement is that it requires sufficiently high (>0.4 T_{melt}) test temperatures. As seen in Figs. 1(a) and (b), the tensile properties of specimens containing about 2 appm He after annealing are at the level of the unirradiated specimens.

At the same time room temperature LCF tests show significant reduction of the number of cycles to failure for the rewelded specimens, and the fracture occurs in the HAZ where the thermal effect of welding is very similar to the influence of annealing.

Two main reasons of this difference can be specified. The main difference is that, during the rewelding process, not only does heating take place in the HAZ but also high-temperature deformation. Welding leads to the high temperature deformation of the HAZ during 2–3 s [9,10], during which the temperature in this zone reaches values in the range 1300–1400°C, i.e., close to the melting point. Special experiments performed in [10] show that deformation of the austenitic alloy containing about 6 appm He at a test temperature of 1250°C leads to drastic embrittlement (total elongation of about 0.5%). Hence, the combination of high temperatures and thermal stresses produces high temperature deformation (1–2%) in the HAZ and will result in the appearance of small microcracks directly on grain boundaries during the welding.

Another very important reason is the heterogeneity of specimen properties after welding. When using the data from Fig. 1(a) and estimating from this figure the yield strength distribution along the rewelded specimen length, it is possible to conclude that when performing LCF tests, deformations are concentrated in the HAZ (and it is confirmed by computer simulation) in the region adjacent to the weld. The combination of these two factors leads to the fast fracture of rewelded specimens in room-temperature LCF tests.

5. Conclusion

The investigation has shown that specimens containing helium after neutron irradiation retain high plasticity in low-temperature tensile tests.

Reduction of the LCF life of the rewelded specimens is explained by the appearance of small intergranular cracks in the HAZ during the welding which grow as a result of the concentration of stresses in the HAZ in the rewelded specimens.

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