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Mechanical properties of hot isostatic pressed type 316LN steel after irradiation

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Abstract

Hot isostatic pressing (HIPing) of powder is considered as a tentative manufacturing method for primary wall components of thermonuclear reactors. In the present work some mechanical properties of specimens from HIPed powder as well as from wrought, reference type 316 LN international thermonuclear experimental reactor (ITER) grade steel have been compared. Tensile, low cycle fatigue and fracture toughness tests were performed after neutron irradiation to a dose of 0.7 dpa at 290°C. The tensile properties in the unirradiated condition were found to be almost identical for the two materials. After irradiation the HIPed material showed a slightly increased hardening. No significant difference in fatigue endurance was observed. However, the fracture toughness tests showed a greatly reduced toughness of the particular HIPed material used in this investigation as compared to the wrought steel. Valid J_{1c} data could not be obtained owing to specimen size limitations. Micrographs are provided of the fracture surfaces. © 2000 Elsevier Science B.V. All rights reserved.

1. Introduction

Powder metallurgy hot isostatic pressing (HIPing) is under consideration as one possible method for the manufacture of primary wall modules for the International Thermonuclear Experimental Reactor (ITER). Powder HIPing involves the compression of metal powder under high isostatic pressure and high temperature.

Several ITER-related demonstration blocks have been successfully produced by HIPing of steel powder, up to a size of 1940 × 960 × 465 mm^3. In the production process, welded cooling tube galleries have been included and show excellent bonding to the matrix material. In the unirradiated condition the mechanical properties of the HIPed steel were well within the ITER specification [1].

While likely effects of neutron irradiation have been discussed by Harries et al. [2], experimental data are lacking. In the following we report some results of mechanical testing of unirradiated and irradiated specimens of HIPed and wrought type 316LN steel. This investigation used type 316LN ITER grade (IG) powder with specified nitrogen content similar to the 316LN reference material. Tensile, low cycle fatigue and fracture mechanical tests were performed after irradiation to a damage level of 0.7 dpa [3].

2. Specimens

A block of type 316LN steel prepared by HIPing at 140 MPa, 1160°C for 2 h was available. The steel powder was delivered by ANVAL (charge 84043) with the composition given in Table 1.

The oxygen content of the powder, 195 ppm, is close to the preliminary upper limit of the 316LN ITER powder grade specification (200 ppm).

Miniature specimens were prepared from the HIPed block as well as from the European type 316LN IG wrought reference steel as follows:

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PII: S 0 0 2 2 - 3 1 1 5 (0 0) 0 0 0 8 4 - 2

Table 1
Powder composition

Element	wt%
C	0.028
Si	0.24
Mn	1.70
P	0.018
S	0.008
Cr	17.2
Ni	12.2
Mo	2.50
Cu	0.12
Co	0.07
N	0.078
B	0.001
	ppm
O	195

- Tensile specimens with gage length 20 mm and diameter 3 mm
- Low cycle fatigue specimens of hour-glass shape with a minimum diameter of 3.2 mm
- Compact tension (CT) fracture mechanics specimens with thickness $B = 6.25$ mm and width $W = 12.5$ mm. The reference material specimens were taken out in L–T orientation. Materials HIPed from powder are isotropic.

2–5 specimens of each kind were irradiated to a displacement dose of 0.7 dpa in a pressurized water loop in the Studsvik R2 reactor. The specimen temperature during the irradiation was 290°C.

3. Testing procedures and results

3.1. Tensile tests

Two specimens of each variant were tested at 290°C. Almost identical results were obtained for each pair of specimens and also for all the four unirradiated specimens. The results are shown in Table 2 and in Fig. 1, as stress vs crosshead displacement traces. As can be seen from the results, the irradiated HIPed specimens show a slightly larger increase of yield stress and a reduction of elongation compared to the specimens of the wrought reference material.

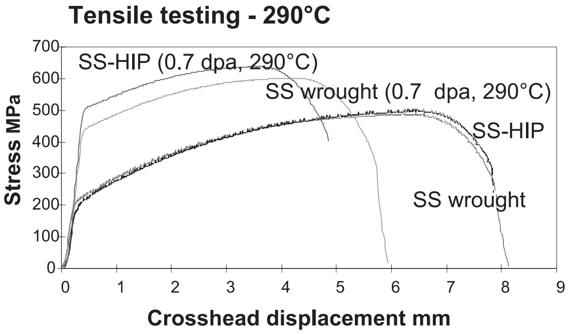

Fig. 1. Tensile behaviour at 290°C of wrought and HIPed 316LN steel before and after irradiation (0.7 dpa).

3.2. Low cycle fatigue tests

Two irradiated specimens of each material were tested at 290°C. The tests were performed at one single axial strain range of 0.8%, at a strain rate of 0.002 s^{-1}. The diametral strain was held constant, causing a slight variation of the axial strain during the test. The fatigue endurances of the four specimens are reported in Table 3. There was no significant difference of fatigue endurance between the two materials. Hysteresis curves at cycles to failure $(N_F)/2$ are shown in Fig. 2.

3.3. Fracture toughness tests

Two HIPed irradiated specimens and one reference wrought specimen were available for testing. The precracking was performed at room temperature after the irradiation whereas the testing was performed at 290°C. The ASTM standard E1737-96 was followed. Crack lengths were determined by means of elastic compliance. The results are plotted as J vs crack extension Δa, Fig. 3. Valid J_{1c} data could not be obtained owing to the small size of the specimens. The intersections with the 0.2 mm offset lines $(2 \times \sigma_y)$ are:

$$\text{Wrought} \quad 316\text{LN IG (0.7 dpa)}, \quad J_Q = 1270\ \text{kJ/m}^2$$

$$\text{HIPed} \quad 316\text{LN (0.7 dpa, average)}, \quad J_Q = 350\ \text{kJ/m}^2$$

As can be seen from Fig. 3, not only the J_Q but also the slopes dJ/da are lower for the HIPed steel compared to the wrought reference.

Table 2
Tensile test results $T_{\text{irr}} = T_{\text{test}} = 290°\text{C}$

Material condition	Yield stress Rp0.2 (MPa)	Ultimate tensile strength Rm (MPa)	Uniform elongation (%)
Ref 316LN IG unirr	219	486	28
HIPed 316LN unirr	213	494	28
Ref 316LN IG 0.7 dpa	426	595	18
HIPed 316LN 0.7 dpa	494	632	16

Table 3
Results of low cycle fatigue tests

Material condition	Cycles to failure N_F		
	Test 1	Test 2	Average
Wrought 316LN IG 0.7 dpa	9009	18 403	13 700
HIPed 316LN 0.7 dpa	12 358	16 425	14 400

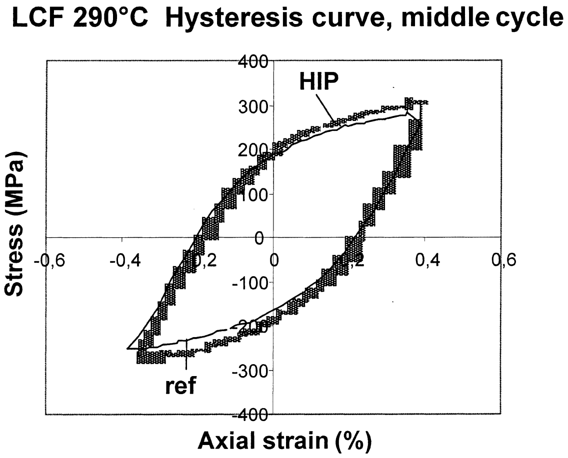

Fig. 2. Hysteresis curves from one wrought (3u13) and one HIPed (4u13) steel specimen at $N_F/2$ show larger elastic amplitude of the HIPed material.

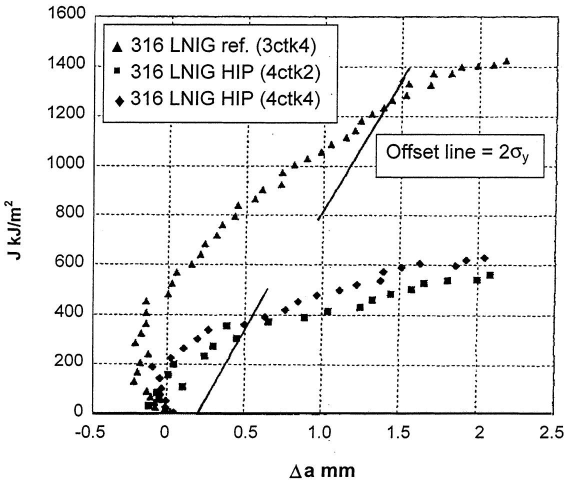

Fig. 3. J integral vs crack extension Δa.

4. Examination of fracture surfaces

The fracture surfaces of the tensile specimens had a different appearance for the reference and the HIPed steel, but there was no significant effect of the irradiation on the fracture appearance of the materials. SEM micrographs of the fracture surfaces of two of the irradiated specimens are shown in Figs. 4 and 5. The reference specimens fractured perpendicular to the axial direction of the specimen after extensive necking almost without any shear lips. The HIPed specimens showed less necking, had large shear lips close to the outer surface, and fractured finally in a plane perpendicular to the axial direction leaving an undulating surface. Dimples were visible at all the fracture surfaces. The dimples on the fracture surface of the HIPed material were generally smaller compared to those of the reference material. An estimation of the reduction in area before rupture was made (from the SEM photos 75×). The area reduction was about the same for the wrought material in both unirradiated and irradiated conditions. Compared to the wrought reference material the area reduction of the

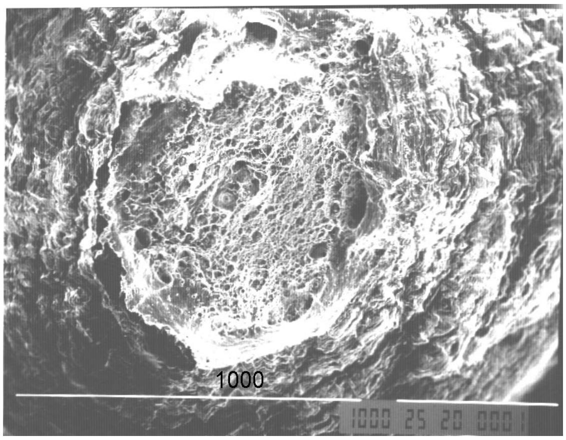

Fig. 4. Fracture surface of the irradiated reference steel, tensile specimen 3D6. SEM.

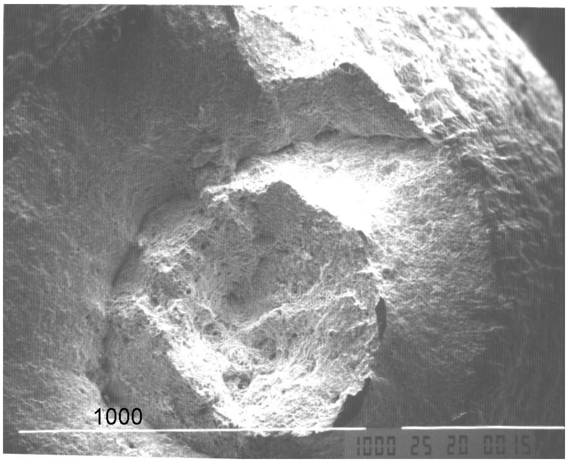

Fig. 5. Fracture surface of the irradiated powder HIPed steel, tensile specimen 4D6. SEM.

HIPed steel specimens was about 10% smaller in the unirradiated condition and 15% smaller after irradiation.

The fracture of the CT specimens of the powder HIPed material differs from the fracture in the reference material. The differences were similar to the differences shown by tensile tests: smaller amount of necking and 45 shear lips on the fracture surfaces of the HIPed material.

5. Conclusions and comments

The tensile properties of unirradiated HIPed type 316LN steel were very similar to those of the wrought 316LN IG reference material at 290°C.

Irradiation to a moderate displacement dose of 0.7 dpa had a somewhat larger effect on the tensile properties of the HIPed steel, resulting in a larger increase of yield stress and larger reduction of uniform elongation compared to the wrought steel.

The low cycle fatigue tests did not show any significant difference of endurance between the two materials. A possible reduction of inelastic strain of the HIPed material may be compensated by the increased elastic strain.

The fracture test results indicated a considerable toughness difference. Both materials were ductile after irradiation but the two HIPed steel specimens show a mean J_Q value of 350 kJ/m^2 compared to 1270 kJ/m^2 for the wrought steel. A determination of fracture toughness of unirradiated HIPed 316LN steel was performed in a prior study resulting in a J_Q-value of 680 kJ/m^2 at room temperature [1] which was judged to be within the scatter band of wrought 316LN IG steel [4].

The reduced ductility of the HIPed steel may be related to the oxygen content of the metal powder. Finely dispersed precipitates are expected to form. The neutron irradiation causes not only formation of interstitial and vacancy clusters but can also induce redistribution and further dispersion of the precipitates.

Acknowledgements

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