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Effect of ITER components manufacturing cycle on the irradiation behaviour of 316L(N)-IG steel

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Abstract

The main options for the manufacturing of high heat flux (HHF) components is hot isostatic pressing (HIP) using either solid pieces or powder. There was no database on the radiation behaviour of these materials, and in particular stainless steel (SS) 316L(N)-IG with ITER components manufacturing thermal cycle. Irradiation of wrought steel, powder-HIP, solid-HIP and HIPed joints has been performed within the framework of an ITER task. Specimens cut from 316L(N)-IG plate, HIP products, and solid-HIP joints were irradiated in the SM-3 reactor in Dimitrovgrad up to 4 and 10 dpa at 175°C and 265°C. The paper describes the results of post-irradiation tensile and fracture toughness tests. © 2000 Elsevier Science B.V. All rights reserved.

1. Introduction

The austenitic stainless steel (SS) 316L(N)-IG type is one of the main structural materials considered for the in-vessel components of ITER [1]. The material shall operate in the temperature range ~100–300°C, the dose of irradiation is up to 2.1 dpa during the basic performance phase and up to 13 dpa during the extended performance phase [2]. It is known that a high irradiation dose results in hardening, loss of ductility, loss of strain hardening capacity and significant changes of the fracture toughness of wrought 316 type SS [3–8].

Both traditional (rolling, forging, hot pressing, casting, etc.) and advanced manufacturing technologies (powder- and solid-HIP) are proposed for the ITER components manufacturing. However, the different thermal cycles and deformation processes produce a different steel microstructure and result in different irradiation behaviour. The irradiation resistance of austenitic SS 316L(N)-IG after different manufacturing cycles has been studied.

Specimens cut from 316L(N)-IG plate (wrought material, reference heat), powder-HIP and solid-HIP products and solid-HIP steel to steel joints (SS/SS) were irradiated in the SM-3 reactor up to a dose of ~4 and 10 dpa at 175°C and 265°C. Tensile properties, fracture toughness and changes in resistance to intergranular stress corrosion cracking (IGSCC) have been investigated after irradiation.

2. Experimental procedure

The compositions of the different 316L(N)-IG steels used in this investigation are given in Table 1.

The solution annealed plate (thickness 30 mm) manufactured by Creusot Loire (heat T 1103) for the fusion program is designated as the European reference heat. A solid-HIP billet with a 214 mm diameter and

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Table 1
Chemical composition of 316L(N)-IG steel specimens (wt%)

Material	Fe	Ni	Cr	Mo	Mn	Si	C	N	P	S	B
Plate	Bal.	12.3	17.5	2.3	1.8	0.45	0.022	0.06	0.027	0.001	0.0008
Solid-HIP	Bal.	12.1	17.5	2.4	1.73	0.41	0.02	0.068	0.025	0.001	Un-known
Powder-HIP	Bal.	12.2	17.2	2.5	1.7	0.24	0.028	0.078	0.018	0.0008	0.001

~100 mm height (heat *T* 5091) was supplied by Tecphy for Cerem. Hot isostatic pressing (HIP) was carried out at 1100°C for ~2 h under a pressure of 100 MPa. A powder-HIP billet with a ~108 mm diameter was supplied by Powdermet. HIP was carried out at 1150C for ~2 h at ~140 MPa (heat #84043).

Cylindrical specimens with a diameter of 1.5 mm and gauge length of 7.5 mm were used for the tensile tests.

Miniature 3-point bend specimens $4 \times 4 \times 32$ mm^3 were used for the fracture toughness tests. Pre-cracking of the specimens was performed by fatigue loading. The specimen orientation (the length) was perpendicular to the rolling direction.

Specimens were manufactured from the solid-HIP base metal and from the SS/SS joint, with the bonding area in the centre of the specimen.

The specimens were irradiated in the core of the SM-3 reactor. The irradiation was performed in special capsules at 175 ± 15°C and 265 ± 15°C, to doses of approximately 4 and 10 dpa.

Tensile and bend tests of unirradiated and irradiated specimens were carried out on a type 1794U-5 test machine at a cross-head speed of ~1 mm/min. All specimens were tested in air at a temperature corresponding to the irradiation temperature. The 0.2% yield strength (YS), ultimate tensile strength (UTS), total elongation (TEL) and uniform elongation (UEL) and reduction of area (RA) were determined as described in the standard GOST 1497 [9]. Crack-opening displacement (COD) was determined at the maximum load according to the requirements of the GOST 25.506 standard [10]. After testing, the tensile specimens were used to measure the resistance to IGSCC by the electrochemical potential reactivation method (EPR, double loop), which was carried out according to the GOST 9.914 standard [11].

3. Result of tests and discussion

3.1. Tensile behaviour

The typical shapes of the tensile stress–strain curves for the investigated materials are given in Fig. 1.

After irradiation the tensile tests show hardening, reduction of ductility and a change of the shape of tensile strain–stress curve. The smooth yielding behaviour of the unirradiated materials is replaced by the appearance of a yield drop and the capacity to strain hardening is decreased or eliminated. However, the extent of these changes was different for steels manufactured using different methods.

The dose dependence of the tensile properties for the rolled plate of the reference steel 316L(N)-IG, irradiated at 265°C, is shown in Fig. 2(a). The data for the solid-HIPed steel is shown in Fig. 2(b) and the powder-HIPed material in Fig. 2(c).

The YS of the rolled steel plate increases about 200% relative to the YS of the unirradiatied material, and actually coincides with the UTS after irradiation to a dose of ~4 dpa at 265°C. The strain hardening capability essentially disappears; however, the value of UEL remains at a high level, ~3.5–6.5%. After irradiation at a dose of about 10 dpa at 265°C, the strain hardening capability is negligible and the UEL is reduced to 0.5–0.8%. However, the change of the reduction in area (ΔRA) is very small, less than 7–10% (see Fig. 2(a)).

Irradiation of the rolled steel to a dose of ~10 dpa at the lower irradiation temperature, 175°C, results in less hardening (by a factor of two) and reduction of ductility compared with the 265°C irradiation. The yielding behaviour is evident by the yield drop. The UEL is diminished to ~5% and TEL ~20%.

Radiation hardening of the solid-HIP material was more significant than that of the rolled material after irradiation at 265°C. However, values of the UTS and YS after irradiation were less by almost 50–100 MPa compared to the rolled plate. After the 4 dpa irradiation, the shape of the strain–stress curves was similar to that of the unirradiated solid-HIPed steel. The UEL was 9–16%. After the 10 dpa irradiation, a yield drop is observed and the strain hardening capability decreases significantly. The UEL is reduced to 5–10% and the TEL remains at ~20%, higher than for the rolled material by a factor of approximately two (see Fig. 2(b)). At 175°C, irradiation hardening is approximately the same as for the rolled steel. However, the loss of ductility is a little bigger (see Fig. 1).

After irradiation to 4 and 10 dpa at 265°C, powder-HIP material exhibits radiation hardening identical to the solid-HIP material. The yield drop is observed in the stress–strain curves. The strain hardening capability of the powder-HIPed material remains the same for rolled steel after irradiation to 4 dpa. The UEL is ~6%. After the 10 dpa irradiation the strain hardening capability

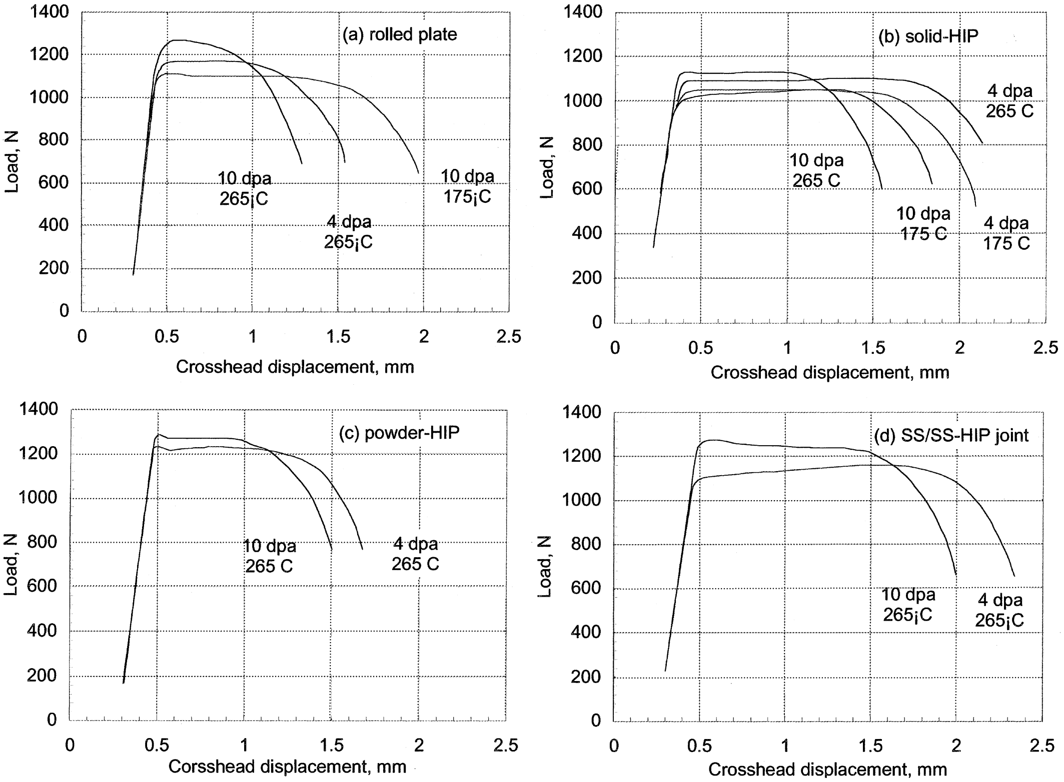

Fig. 1. Typical tensile stress–strain curves of irradiated 316L(N)-IG stainless steel manufactured by different technologies.

has disappeared. However, after the yield drop some softening with a constant rate is observed, the load rapidly decreases until fracture. The UEL is about 3.5–4% and TEL ~15% (see Fig. 2(c)).

The radiation hardening of the solid-HIP joints is slightly less than for the base metal (soled-HIPed) after 4 dpa and similar to the base metal after 10 dpa. However, the shape of the stress–strain curves is the same only after 4 dpa. After 10 dpa, a small yield drop and a 'softening' with a small constant rate is observed up to the reduction the load and fracture of the specimen. UEL and TEL of the solid-HIP joints are similar to the base material (see Fig. 2(d)).

The influence of neutron irradiation on the mechanical properties of wrought 316 type SSs is relatively well studied and the main results are reported in Refs. [3–8, 12–17]. However, the effect of advanced manufacturing technologies, like HIPing, on the radiation behaviour of steel is not well known. The only known data are published in [18,19], where tensile properties of EB welds, TIG deposits and powder-HIPed steel have been presented. Irradiation temperatures were 500 and 600 K. Comparison of data presented in Refs. [18,19] and in this paper indicates a very good agreement with data for rolled plate and for the powder-HIPed steel. All the tensile properties coincide within the scatter band.

3.2. Fracture toughness

The crack-opening displacement, COD, (δ_c) was used as a measure of fracture toughness. Fracture toughness of unirradiated steel for all investigated manufacturing technologies was high, and the value of δ_c was more than 0.4 mm. Irradiation produces a significant decrease in δ_c. Results are presented in Table 2. After 4 dpa, the values of δ_c are diminished to 0.06–0.1 mm, which is approximately 5–6 times less than the δ_c of unirradiated steel. The differences in crack opening between the investigated materials (rolled plate, solid-HIP and powder-HIP) is not significant, no more than 30–40%. The biggest value of $\delta_c = \sim 0.098$–0.093 mm is exhibited by solid-HIPed steel. The minimum value of $\delta_c = \sim 0.06$ mm was exhibited by the powder-HIPed material. After 10 dpa, the values of δ_c are further reduced. However, the rate of fracture toughness decrease is significantly lower than at the initial stages of irradiation. Reduction of δ_c for plate material is less than ~35%, and for the HIPed material the reduction of δ_c is about 60–90%.

It is difficult to compare this data with irradiation effects on fracture toughness published by E. van Osch [19] because, different parameters have been used for estimation of fracture toughness (δ_c and J_c). However,

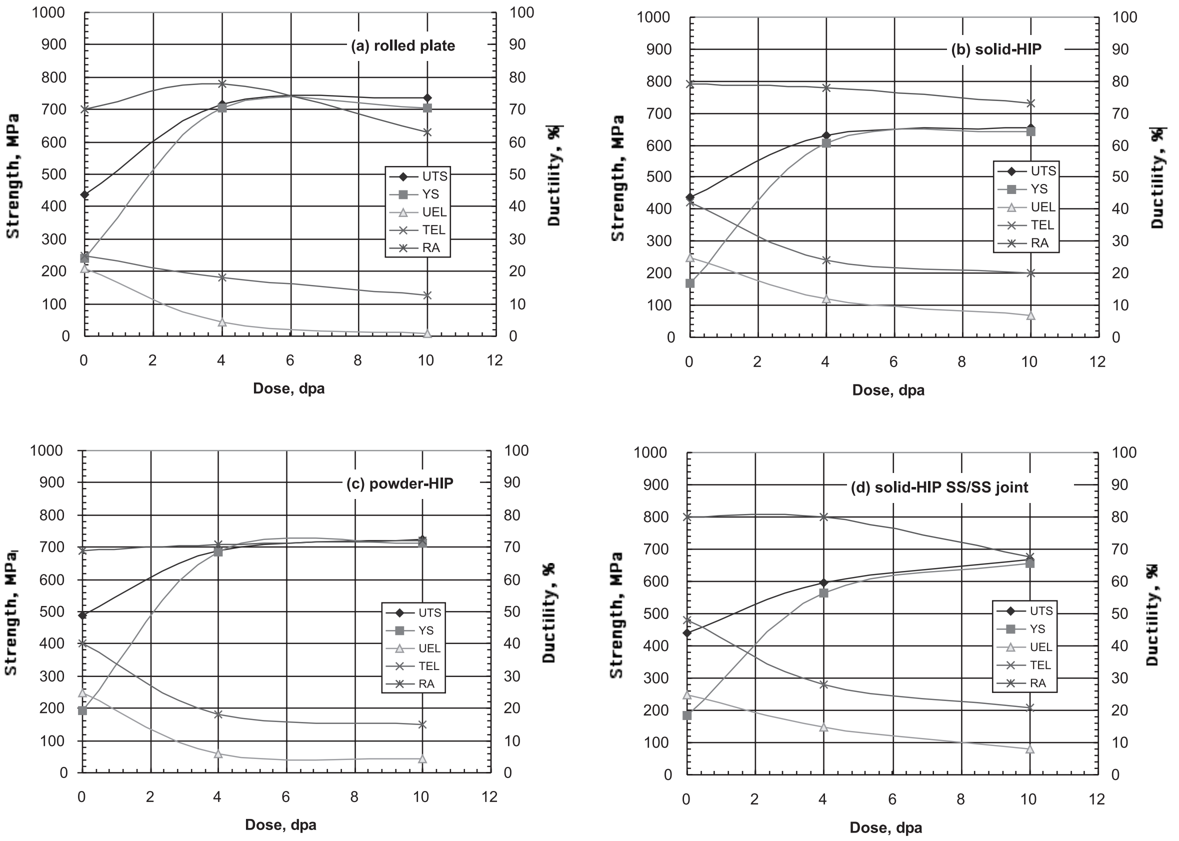

Fig. 2. Irradiation effect on the tensile properties measured at 265°C for 316L(N)-IG stainless steel, manufactured by different technologies.

Table 2
Fracture toughness (crack opening) measurement results

Material	Irradiation and test temperature (°C)	Dose (dpa)	Crack-opening displacement, δ_c (mm)
Rolled plate	265	4	0.076
		10	0.051
	175	10	0.083
Solid-HIP	265	4	0.093
		10	0.007
	175	4	0.1
		10	0.09
Powder-HIP	265	4	0.06
		10	0.006–0.02
Solid-HIP SS/SS joint	265	4	0.098
		10	0.008–0.037

the tendency of the fracture toughness decreasing for the powder-HIPed steel compared with rolled or wrought material is similar.

3.3. Resistance to IGSCC

All unirradiated materials show high resistance to IGSCC estimated using the EPR method. There was no evident susceptibility to SCC of the different 316L(N)-IG steel products (rolled, solid-HIP and powder-HIP) after irradiation to 10 dpa at 265°C.

4. Conclusions

Rolled plate, solid-HIP, solid-HIP joints and powder-HIP steel 316L(N)-IG type have been irradiated in the SM-3 reactor up to about 10 dpa at 175°C and 265°C. The tensile properties, fracture toughness, δ_c, and resistance to IGSCC was measured.

Radiation hardening (more than ~200%) is observed for all materials after irradiation at 265°C. A saturation in hardening was observed after 4 dpa. The most significant hardening (~260–280%) was observed for HIPed material.

After irradiation at 175°C, the hardening of rolled plate increases by about ~100%, and of the HIPed materials by ~200–230%. Rolled material lost the capability to strain hardening after irradiation to ~4 dpa at 265°C. However, uniform plastic deformation capability remained relatively high (UEL = ~3.5–6.5% and TEL = ~18%). After irradiation to ~10 dpa, the UEL was below 0.4–0.8%. A relatively low capability to strain hardening was observed after 10 dpa at 175°C (UEL = ~3–7.5%).

Powder-HIP 316L(N)-IG steel completely lost the ability to strain hardening after 10 dpa at 265°C, however, the UEL was at a level of ~4%.

The strain hardening capability remains for solid-HIP SS after irradiation at 265°C up to 10 dpa. Strain to necking was about 7%. The irradiation behaviour of the solid-HIP joint could not be distinguished from the base material.

Fracture toughness of 316L(N)-IG steel decreased significantly after irradiation at 265°C. The value of the COD, δ_c, was diminished by 5–6 times after 4 dpa. After irradiation to 10 dpa, the degradation of δ_c was less than 35% for the rolled plate steel, and for HIPed materials the degradation was ~60–90%.

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