Journal of Nuclear Materials 465 (2015) 20–27

Contents lists available at ScienceDirect

Journal of Nuclear Materials

journal homepage: www.elsevier.com/locate/jnucmat

Effect of the bainitic and martensitic microstructures on the hardening and embrittlement under neutron irradiation of a reactor pressure vessel steel

B. Marini [a, *], X. Averty [b], P. Wident [a], P. Forget [a], F. Barcelo [a]

[a] *Commissariat à l'Energie Atomique et aux Energies Alternatives, DEN/DANS/DMN/SRMA, F-91191 Gif-sur Yvette, France*

[b] *Commissariat à l'Energie Atomique et aux Energies Alternatives, DEN/DANS/DMN/SEMI (now DEN/DANS/DM2S/SEMT), F-91191 Gif-sur Yvette, France*

ARTICLE INFO

Article history:
Received 20 February 2015
Received in revised form
18 May 2015
Accepted 27 May 2015
Available online 31 May 2015

Keywords:
RPV steel
Irradiation induced embrittlement
Microstructure
Bainite
Martensite

ABSTRACT

The hardening and the embrittlement under neutron irradiation of an A508 type RPV steel considering three different microstructures (bainite, bainite-martensite and martensite)have been investigated These microstructures were obtained by quenching after autenitization at 1100 °C. The irradiation induced hardening appears to depend on microstructure and is correlated to the yield stress before irradiation. The irradiation induced embrittlement shows a more complex dependence. Martensite bearing microstructures are more sensitive to non hardening embrittlement than pure bainite. This enhanced sensitivity is associated with the development of intergranular brittle facture after irradiation; the pure martensite being more affected than the bainite-martensite. It is of interest to note that this mixed microstructure appears to be more embrittled than the pure bainitic or martensitic phases in terms of temperature transition shift. This behaviour which could emerge from the synergy of the embrittlement mechanisms of the two phases needs further investigations. However, the role of microstructure on brittle intergranular fracture development appears to be qualitatively similar under neutron irradiation and thermal ageing.

1. Introduction

The reactor pressure vessel (RPV) of nuclear power plant is a heavy component built by welding thick parts like rings, nozzles and domes and which is submitted to neutron irradiation and thermal ageing. During the fabrication process, low alloy RPV steels are quenched to obtain a bainitic microstructure. Because of the thickness of the wall of the vessel, the cooling rate during the quench varies from few tens of degrees per minutes in the centre to few degrees per second at the vicinity of the surface of the shell [1]. In addition, macro and micro segregation inherited of the solidification of the ingot modify locally the chemical composition of the steel [2]. Welding of the different parts of the vessel and the cladding deposit in the inner face introduce different heat affected zones (HAZ) with coarse and refined grains. Consequently, the microstructure and the initial mechanical properties are not uniform through the wall thickness and along the axis of the vessel. As an example, the transition temperature can vary by several tens of degrees through the thickness [3,4].

It has been identified since many years that simulated coarse grained heat affected zones present a larger susceptibility to thermal ageing than other microstructuctures. However, this tendency to embrittlement appears to be smaller for real HAZ [5–7].

In a previous study, the response of different coarse grained microstructures of a A533 type steel submitted to step cooling heat treatment have shown a larger susceptibility of martensite to temper embrittlement associated with the enhancement of intergranular fractureand P segregation on the prior austenite grain boundaries [8]. It was also observed for a DIN 22NiMoCr37 RPV steel thermally aged at 520 °C, that coarse grained martensite presents mixed transgranular and intergranular fracture for notch specimens as the fracture for the bainite remains, transgranular cleavage [9]. Recently, the sensitivity of martensite bearing microstructures to thermal ageing of A508 type steels without prior coarsening of the austenite grain has been demonstrated [7,10].

Neutron irradiation, in general, increases only slightly the P segregation at prior austenitic grain boundaries of RPV steels and non-hardening embrittlement is low [11–13]. However, some cases of irradiation enhancement of brittle intergranular fracture (BIF)

---

[*] Corresponding author.
E-mail address: bernard.marini@cea.fr (B. Marini).

http://dx.doi.org/10.1016/j.jnucmat.2015.05.023
0022-3115/© 2015 Elsevier B.V. All rights reserved.

are reported in the literature for the formerly called "western" RPV base metals (A302, A508 and A533):

- Increase in BIF and of the phosphorus coverage of the grain boundaries is reported for a A533-B with a content of 0.017 wt% of phosphorus and heat treated to simulate heat affected zone with coarse grains (>220 μm) [11].
- Onset of BIF (10% of the total surface) was observed after irradiation on a A533 B base metal with a content of 0.017wt% of phosphorus [14].
- Onset of BIF after irradiation on a low phosphorus A302B type steel heat treated to simulate a heat affected zone [15].
- Increase in BIF surface and of the phosphorus coverage of the grain boundaries is reported for a P doped A533-B (570 ppm) [16].

For these cases, it appears that the factors triggering the irradiation enhanced BIF is a high level of P content and/or a coarse grained microstructure produced by austenitization at high temperature.

In this study, we investigate the microstructural conditions of the non-hardening embrittlement and the enhancement of BIF observed under irradiation at RPV service temperature. In this objective, three different microstructures (bainite, bainite-martensite and martensite) with prior austenitic coarse grains have been generated for the same RPV steel by changing the cooling rate during the quench. Their hardening and embrittlement under neutron irradiation are discussed.

2. Material

The material used in this study is similar to a 16MND5 type steel, equivalent to A508 Cl.3 type steel. It comes from a forged nozzle and its chemical composition is given in Table 1. In this as received condition, the microstructure is a granular bainite. This microstructural state is a monitor and is not considered in the discussion of the effect of the microstructure.

Table 1
Chemical composition (wt %).

C	Mn	Ni	Mo	Si	Cr	Al	S	Cu	P
0.25	1.29	0.72	0.49	0.23	<0.05	0.035	0.080	0.030	0.014

In order to select the cooling rates to obtain the different microstructures, continuous cooling transformation diagram (CCT) of these steel has been determined (Fig. 1). The critical cooling rate of the ferrite is between 0.3 and 1 °C/s and the critical cooling rate of the bainite is between 10 and 20 °C/s. Bainite and martensite coexist between 3 and 10 °C/s. Because of the austenitization at 1100 °C during ½ h, the prior austenite grain size is approximatively of 100 μm. Typical microstructures for different cooling rates are presented in Fig. 2.

Using the CCT diagram (Fig. 1), it has been decided to produce three different microstructures containing respectively 100% of bainite, 100% of martensite and a mixture of bainite and martensite.

Fifteen and 30 mm thick plates were cut from the nozzle to prepare the different microstructures. The material was austenitized at 1100 °C during ½ h then quenched at different cooling rates in order to produce martensite, bainite-martensite and bainite. The aimed cooling rates were respectively equal to 0.5, 5 and 50 °C/s. During the quenches, the actual cooling rates were monitored by thermocouples at mid thickness of the plates. The average of the measured cooling rates at mid thickness between 700 and 300 °C are, respectively for the three cooling conditions, 0.4, 3 and 37 °C/s. After the quench, the plates were tempered at 610 °C during 20 h in order to simulate the post-weld heat treatment (PWHT) then air cooled at room temperature. Some of the martensite and bainite plates were thermally aged thanks to a step cooling heat treatment (Table 2).

Small flat tensile and sub-size Charpy specimens were machined from the heat treated plates at mid thickness. Tensile specimens have a section of 2 × 1 mm and a gage length of 8 mm. The subsize Charpy specimens have a length of 27 mm and a section of 3 × 4 mm. The notch is 1 mm deep.

Part of the specimens were irradiated in OSIRIS reactor at 280 °C up to a fluence of $7.75 \cdot 10^{19}$ n/cm^2 (En > 1 MeV) for tensile specimens and of $8.55 \cdot 10^{19}$ n/cm^2 (En > 1 MeV) for sub-size Charpy specimens. The average neutron flux was 4.10^{12} n cm^{-2} s^{-1}

3. Results

3.1. Tensile results

For the bainitic and martensitic microstructures, respectively

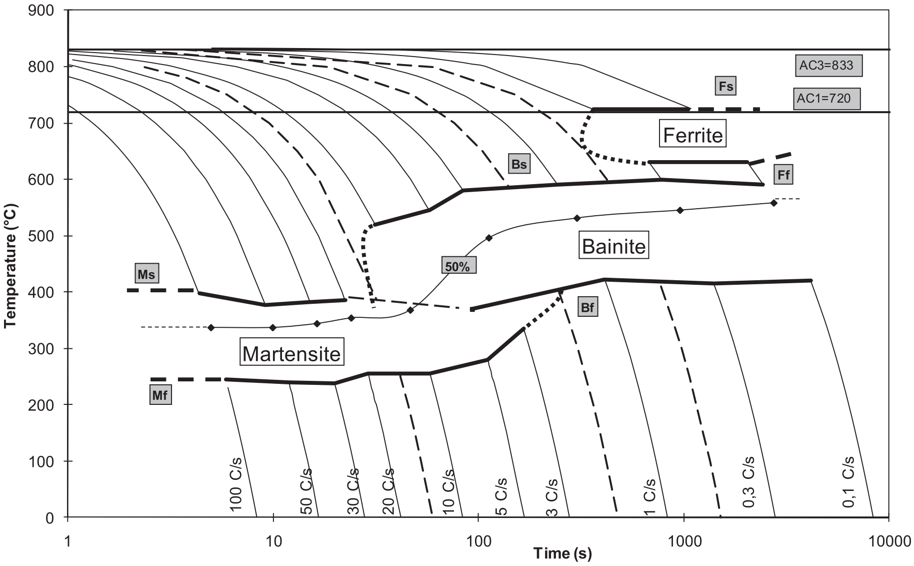

Fig. 1. Continuous cooling transformation diagram (austenitization 1100 °C, ½ h). The dotted lines represent the critical cooling rates of the different phases.