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Tensile properties and transition behaviour of RAFM steel plate and welds irradiated up to 10 dpa at 300 °C

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Abstract

Reduced activation ferritic/martensitic (RAFM) steels have been irradiated in a large irradiation campaign in the high flux reactor at a target temperature of 300 °C up to target dose levels of 2.5, 5, and 10 dpa. Tensile and impact properties have been determined of RAFM plate, tungsten inert gas (TIG) welds and Electron beam (EB) welds. The dose level dependence of both properties is evaluated. In addition, impact properties of F82H powder hot isostatic pressing after 2.5 dpa and transition fracture toughness of F82H-mod. plate after 5 dpa have been measured. The tensile properties at irradiation temperature of F82H-mod. plate and welds show an increase in yield and ultimate strength up to about 5 dpa, after which saturation seems to set in. The elongation data show evidence of increasing localisation of deformation at higher doses. Impact properties of untempered EB welds and not sufficiently tempered NF616 show the need for good tempering treatment. Impact properties of various zones of irradiated TIG welds further illustrate the influence of the microstructural state of 8–9Cr steels on the irradiation response.

1. Introduction

F82H-mod., a modified heat of F82H that was supplied by the Japanese to the IEA [1], was the reference steel in the fourth framework programme's (FP) European Blanket Project. The steel represents an intermediate step in the development of structural reduced activation ferritic/martensitic (RAFM) steel for the first wall of a DEMO-type power plant. The irradiation performance of F82H-mod. at the irradiation temperature of 300 °C has been investigated by NRG up to a dose level of 10 dpa, which is a continuation of the 2.5 dpa programme [2,3].

During the last FP, F82H-mod. has been extensively characterised in the US, Europe and Japan [4–7]. Electron beam (EB) welds and tungsten inert gas (TIG) welds were also supplied and investigated in Europe and Japan [8–11]. While the larger part of the effort was directed to F82H-mod. plate and welds, other advanced processing forms like powderised F82H-mod. consolidated by hot isostatic pressing (HIP) – so-called powder HIP – and other materials like modified 9Cr steels have been investigated by NRG [10].

2. Experimental

2.1. Materials

The steels in this study are martensitic steels which are used in the normalised and tempered condition. The nominal composition of F82H-mod., the reference steel, is 7.7Cr–2W–0.2V–0.1C (Fe balance) composition (all wt%). The F82H-mod. materials have been characterised by Fontes and Castilan [8,9] and Schuring [10]. The EB-welds have not received any post-weld heat treatment (PWHT). Consequently, they are untempered martensitic and have high hardness (400–425 HV). The TIG welds did receive a PWHT of 1 h 720 °C/AC. The

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powder HIP shows ferritic phase morphology in some grains in a predominantly martensitic matrix [10].

A 9Cr–2W–0.2V–Ta heat VS2160 was ordered by NRG at British Steel – and hence named BS-9Cr2WVTa – and included in the irradiation programme in 1997. The normalisation and tempering treatment is 1050 °C/2 h 750 °C. Around the same time, NF616 [12], a 9Cr–0.5Mo–1.8W–V–Nb steel, has been included in this study. The normal treatment of this material is 1 h l050 °C/1 h 780 °C, obtaining a hardness of ≈220 HV. The hardness of the as-received material studied by NRG is 300 HV, which indicates insufficient tempering has been performed.

2.2. Irradiations

A comprehensive irradiation programme targeted at 300 °C irradiation temperature has been performed in the high flux reactor (HFR) in Petten, The Netherlands. The F82H-mod. irradiation programme was performed with He-filled and gas-gap temperature-controlled capsules. Tensile and impact data from more than six 2.5 dpa irradiations have been reported in [2,3].

The new tensile data come from two medium dose irradiations code-named SINEXT-06 and ILAS-07, targeted at 5 and 10 dpa, respectively. F82H-mod. plate material was incorporated in both the SINEXT and ILAS, although the latter mostly contained EB and TIG welds. Miniaturised impact specimens were irradiated in 2.5 and 10 dpa target irradiations code-named SINEXT-05 and CHARIOT-07, respectively. The SINEXT contained F82H powder HIP and weld specimens from 25 mm thick TIG weld, while the CHARIOT harboured F82H-mod. EB weld, F82H-mod. TIG weld (15 mm) and NF616 plate specimens. Fracture toughness experiments were performed on compact tension (CT) specimens from F82H-mod. plate material from the SINEXT-06 capsule.

2.3. Mechanical testing

All mechanical tests have been performed in the Hot Cell Laboratory (HCL) of NRG in Petten, The Netherlands. The tensile tests are performed in air at a strain rate of 5×10^{-4} s^{-1}. Tensile specimens are sub-size, with 4 mm diameter and 20 mm gauge length. All weld specimens have been taken in T orientation with respect to the weld.

Impact tests are performed on an instrumented miniaturised impact machine with an impact speed of 3.85 m s^{-1} with a 50 J ISO striker. The impact specimens are so-called KLST specimens of size $3 \times 4 \times 27$ mm^3 with a 1.0 mm deep notch. The quasi-static fracture toughness experiments have been done on plane sided, sub-size CT specimens of nominal $10 \times 27 \times 29$ mm^3 and $5 \times 27 \times 29$ mm^3 dimensions with a W-size of 22.5 mm. The specimens are pre-cracked up to an a/W of 0.5. The toughness values are calculated in accordance with ASTM 1921. They are not corrected for loss of constraint.

3. Results

3.1. Tensile tests

The yield stress and tensile strength vs. dose level at 300 °C testing temperature are shown in Fig. 1(a). A remarkably homogeneous trend for all investigated materials is observed. There seems to be a linear increase in both strength parameters up to about 5 dpa, after which a hardening saturation seems to set in, although at 10–12 dpa strength values seem to be lower than at intermediate doses. Total elongation remains around 7%, uniform elongation drops below 0.5% above ≈7 dpa.

The reduction of diameter on the non-necked parts of the gauge length is practically 0 above 5 dpa within the optical measurement accuracy. The reduction of area

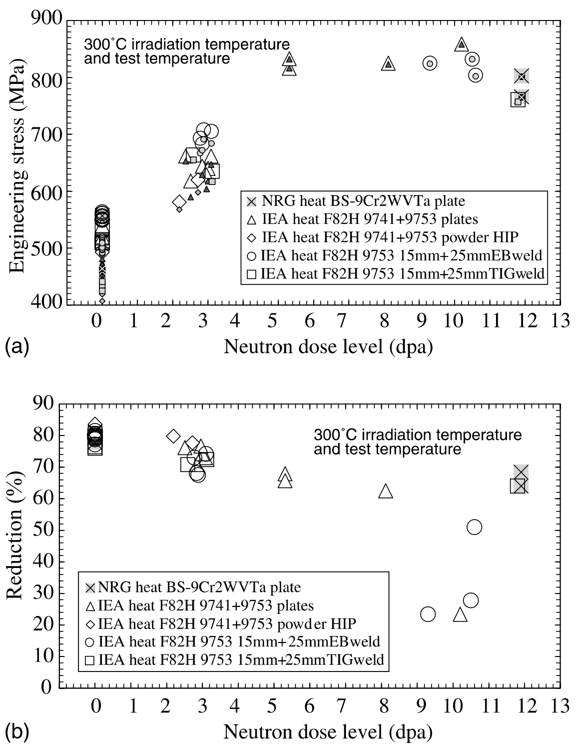

Fig. 1. (a) Tensile engineering data of several RAFM steels: $R_{p0.2}$ (small/dark symbols) respectively R_m (large/light symbols) vs. dose level at 300 °C. (b) RA of several RAFM steels vs. dose level at 300 °C.

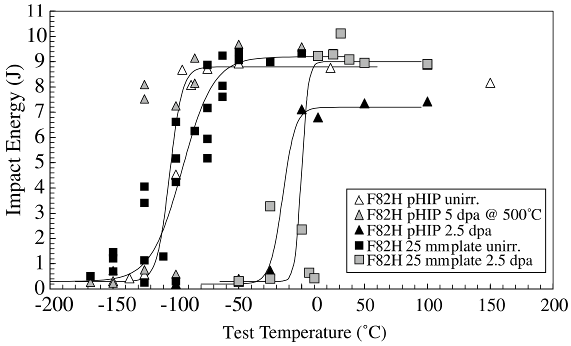

Fig. 2. KLST impact energies for 300 °C irradiated F82H powder HIP compared with F82H-mod. 25 mm plate.

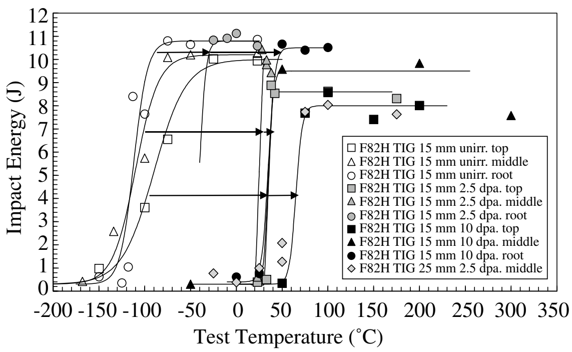

Fig. 3. KLST impact energies for 300 °C irradiated F82H-mod. TIG weld specimens.

(RA) is still more than 60% for all product forms up to 12 dpa, although around 10 dpa three F82H-mod. EB welds and one F82H-mod. plate specimen show a severe drop to 25% in RA, see Fig. 1(b). The specimens are still under investigation, but this could indicate a transition to an even more localised fracture process after yielding interfering with regular necking. In general, the BS-9Cr2WVTa heat shows the lowest hardening and highest ductility after 12 dpa.

3.2. Impact tests

The impact results of 2.5 dpa irradiated powder HIP F82H-mod. are shown in Fig. 2. In unirradiated condition, the impact curve is not significantly different from F82H-mod. 25 mm plate. After 2.5 dpa irradiation, the DBTT is also the same as for 25 mm plate, but there is a significant drop in the upper shelf energy (USE).

The impact test results in Fig. 3 concern specimens from the root, middle, and top sections of a multi-pass 15 mm thick TIG weld and a 25 mm thick TIG weld. There are three main trends visible in these data. Firstly, there is a continuous trend for specimens from all sections of the 15 mm TIG weld to show a shift in DBTT to higher temperatures with increasing dose level (0, 2.5, 10 dpa), as well as a systematic decrease in USE. Secondly, the root specimens show in all cases the highest USE and the lowest DBTT, followed by the specimens from the mid-section of the weld, which also show lower USE. The specimens from the top of the weld were taken from the weld beads that have been laid last and they show the highest DBTT and lowest USE. There are different absolute shifts for the three regions. Thirdly, the DBTT for the 25 mm TIG weld after 2.5 dpa is almost high as for 15 mm TIG weld after 10 dpa with similar USE.

The latter trend is also visible in Fig. 4, where impact properties of the as-welded F82H-mod. EB welds are shown. The 15 mm EB weld has much higher USE than the 25 mm EB weld. When a PWHT is applied to the unirradiated 25 mm EB weld, it regains the USE level of around 11 J of plate material. However, the DBTT of

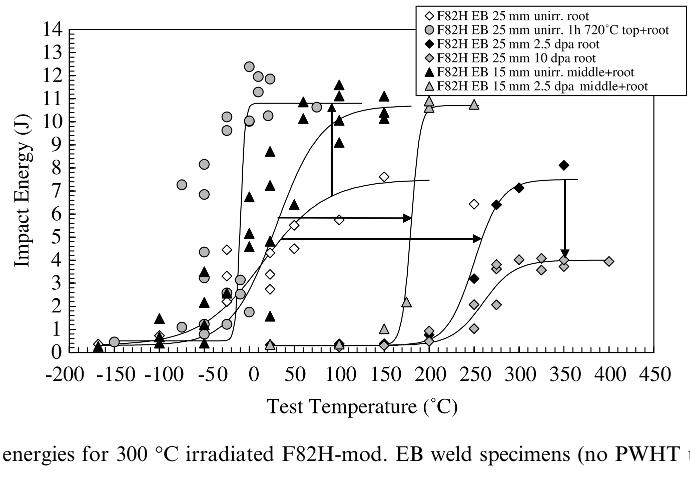

Fig. 4. KLST impact energies for 300 °C irradiated F82H-mod. EB weld specimens (no PWHT unless noted otherwise).

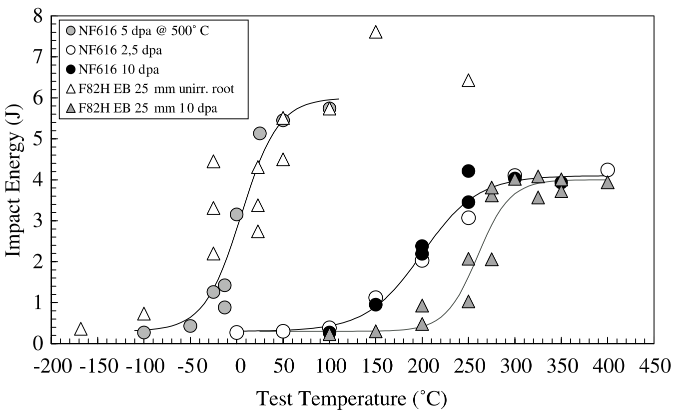

Fig. 5. KLST impact energies for 300 °C irradiated F82H-mod. EB weld specimens (no PWHT) compared to NF616 plate specimens.

plate material (around −100 °C) is not reached by far by this heat treatment.

After 2.5 dpa the impact curves of both 15 and 25 mm EB welds shift, but the latter by a factor 1.5 of the former, up to 250 °C. With further irradiation of EB 25 mm up to 10 dpa, a small additional shift in DBTT is accompanied by a marked drop in USE from 7.5 J to about 4 J. Similar behaviour is also observed in Fig. 5, where the impact curves of NF616 are compared to that of the 25 mm EB weld of F82H-mod. In the absence of a curve for unirradiated NF616, the 500 °C irradiated NF616 serves as a reference. It is shown in Fig. 2 that a 5 dpa, 500 °C irradiation does not alter the impact behaviour of, for instance, F82H powder HIP material. Although NF616 is plate material, the high ab initio hardness apparently correlates to a large shift in DBTT accompanied by a drop in USE to about 4 J.

3.3. Fracture toughness

The quasi-static fracture toughness of F82H-mod. 25 mm plate material is shown in Fig. 6. The shift in T_0 is from about −110 to 125 °C, or 235 °C. This makes very clear that the DBTT shift as measured in dynamic testing with KLST-size specimens underestimates the shift in T_0 by more than 75 °C, if the impact properties of plate material are comparable to that of TIG material, which is a conservative assumption.

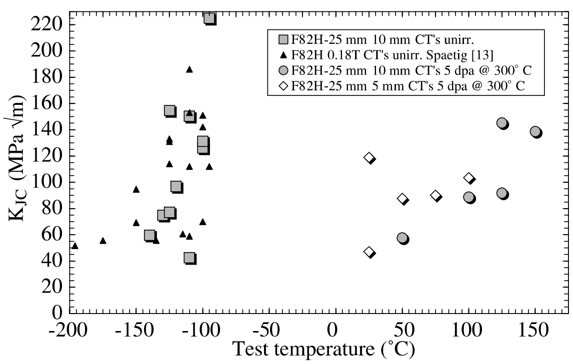

Fig. 6. Transition fracture toughness values for unirradiated and 300 °C irradiated F82H-mod. 25 mm plate, also data from [13] included.

4. Discussion

The very low uniform elongation in the tensile tests indicates that strain softening occurs directly after yielding. The corresponding non-existent uniform deformation is confirmed by measurements on the specimens. Because the deformation process clears irradiation-induced damage by dislocation movement which softens the material locally, plasticity will confine itself to a necking region only.

The impact properties on all welds show that there is dependence of the irradiation response on the microstructure of the material before irradiation. The root specimens from the 15 mm TIG welds have seen many passes and are austenitised several times. They have the finest PAG and are well tempered. There is a consistent increase in DBTT and decrease in USE when going to the top part of the weld. There are also compositional and hardness differences over the height of the weld [4]. The bottom and middle specimens seem to saturate in DBTT at ≈40 °C, whereas the specimens of the top of the weld show further shift to 70 °C at 10 dpa, as is also seen for the middle specimens from the 25 mm TIG weld. Furthermore, the USE of the top specimens is still dropping at the 10 dpa dose level. This suggests that the PWHT of 1 h 720 °C, which is all tempering that these top specimens have seem, has been insufficient to prevent increasing deterioration of impact properties at medium dose levels.

The difference between the 15 and the 25 mm welds (both EB and TIG) may be explained by the higher plate thickness and the consequently larger heat capacity of the material and associated higher cooling rates for the 25 mm welds. For thicker sections therefore, the PWHT becomes of more importance. The worse impact properties for the 25 mm mid-section TIG specimens support this, and again it is concluded that 1 h 720 °C gives insufficient tempering for welds in F82H-mod. This also follows from the EB specimens that have been given this PWHT: USE is regained, but high pre-irradiation DBTT persists. The sampling location in case of EB welds is of less importance since this is a single pass process.

The post-irradiation DBTT of untempered or insufficiently tempered 8–9%Cr steels shifts to temperatures above 150 °C at doses below 2.5 dpa, and eventually the USE has dropped to 4 J at the 10 dpa dose level. This is illustrated for the untreated EB welds and also for the high hardness NF616.

5. Conclusions

The tensile properties of irradiated RAFM plate and welds stabilise at $\approx$5 dpa at 300 °C. No uniform elongation is left after more than 7 dpa and all remaining total elongation (around 7%) is accounted for by strain softening and subsequent necking. In general the BS-9Cr2WVTa gives the best post-irradiation tensile results.

We have shown with the impact test series that the pre-irradiation state of the microstructure, and more specifically the state of tempering, are of significant influence on the post-irradiation impact properties of RAFM steel. The 1 h 720 °C PWHT is not sufficient for welds to give good irradiation response in all parts of the weld.

F82H-mod. powder HIP has a DBTT equal to that of F82H-mod. plate material, however, the USE after irradiation is lower. The static fracture toughness experiments give much larger shifts in transition temperature for F82H-mod. than the impact tests on miniaturised specimens.

Acknowledgements

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