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Post-irradiation mechanical tests on F82H EB and TIG welds

J. Rensman *, E.V. van Osch, M.G. Horsten, D.S. d'Hulst

Nuclear Research & Consultancy Group, P.O. Box 25, 1755 ZG Petten, The Netherlands

Abstract

The irradiation behaviour of electron beam (EB) and tungsten inert gas (TIG) welded joints of the reduced-activation martensitic steel IEA heat F82H-mod. was investigated by neutron irradiation experiments in the high flux reactor (HFR) in Petten. Mechanical test specimens, such as tensile specimens and KLST-type Charpy impact specimens, were neutron irradiated up to a dose level of 2–3 dpa at a temperature of 300°C in the HFR reactor in Petten. The tensile results for TIG and EB welds are as expected with practically no strain hardening capacity left. Considering impact properties, there is a large variation in impact properties for the TIG weld. The irradiation tends to shift the DBTT of particularly the EB welds to very high values, some cases even above +250°C. PWHT of EB-welded material gives a significant improvement of the DBTT and USE compared to the as-welded condition.

1. Introduction

RAFM steel is the EU prime candidate structural material for tritium-breeding blankets of fusion power plants. In the construction of a blanket, many components will be welded. Post-irradiation properties of welds are therefore of much interest to designers. Welded structures contain nucleation sites for defects and it is essential that data on the mechanical properties of the weld zone after irradiation be gathered. Irradiation hardening and embrittlement of the weld zones is expected, as the base material of very similar steels shows this behaviour [1–3]. To quantify the radiation effects, tensile and impact tests on unirradiated and irradiated EB and TIG welds in F82H-mod. have been conducted.

2. Materials and experimental

JAERI supplied to the IEA programme the 15 and 25 mm F82H-mod. plates from heat 9753 with TIG welds and two EB-welded plates of 15 mm from heat 9741 and of 25 mm from heat 9753 F82H-mod. The chemical compositions of heats 9753 and 9741 are given in [4].

On arrival, the TIG welds had received a post-weld heat treated at 720°C for 1 h. The EB welds did not receive any heat treatment before irradiation. We will refer to the TIG welds as TIG15 and TIG25 throughout this paper, and to the two EB variants as EB15 and EB25. All EB and TIG welds had been made parallel to the rolling direction of the plates [4,5].

Small size cylindrical tensile specimens were used with a diameter of 4 mm and a gauge length of 20 mm [4]. We performed the tests at a constant strain rate of 5×10^{-4} s^{-1}. The miniaturised Charpy specimens, KLST-type, for impact testing measured $27 \times 4 \times 3$ mm^3 and contained a notch 1 mm deep [5]. All specimen types were taken perpendicular to the weld in the plane of the plate, L-T, with the weld centred in the gauge length. The KLST's notch was centred with respect to the weld width.

The irradiation dose was targeted at 2.5 dpa at 300°C. The tensile specimens were irradiated in two ILAS-type capsules [6,7], in a He/Ne gas environment. The KLST-type specimens were irradiated in CHARIOT-type capsule [8], also in He/Ne. Fast (>1 MeV) fluences were of the order 2×10^{25} m^{-2}.

In some cases, three weld layers were sampled: top (T), centre (C), and root (R). Not all positions were sampled in every case because of limitations in available material.

* Corresponding author. Tel.: +31-224 56 4857; fax: +31-224 56 1883.

E-mail address: rensman@nrg-nl.com (J. Rensman).

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3. Results

3.1. Tensile tests

The tensile results are summarised in Table 1. For TIG15, a significant amount of irradiation hardening is observed, see Fig. 1, even when tested at 300°C. After irradiation, the strain hardening capacity (SHC = UTS − 0.2% YS) is reduced by 73 MPa to only 2.5 MPa. Uniform elongation (UE) is then practically nil, although considerable fracture elongation (FE) and reduction of area (RoA) are still present. Of TIG25, the specimens were taken from three layers, top (T), centre (C) and root (R), to investigate the influence of differences in microstructure on the post-irradiation properties. In the unirradiated condition, the T specimens have significantly different tensile properties from C and R; e.g., 40–50 MPa higher tensile strength at 27°C, and 2–3% lower fracture elongation. The C and R layers have practically identical properties. Compared to TIG15, the unirradiated TIG25 T specimens have 25 MPa higher 0.2% yield stress (0.2 YS) and the C, R specimens have 25 MPa lower 0.2 YS, both at 27°C and 300°C. In the irradiated state, this difference becomes even 45 MPa for the C, R case at 300°C testing temperature, and the SHC for the C, R specimens is still 14 MPa, as compared to 2.5 MPa only for the TIG15. Elongation data is comparable in both unirradiated and irradiated state for all TIG materials, although ΔRoA is rather large for TIG15. Combined C, R data are in Fig. 1.

Before irradiation, for both EB15 and EB25 only about 95 MPa of SHC was recorded. EB25 was only sampled with T specimens. The number of available specimens was very limited, so no duplicate tests were done in unirradiated condition. For EB15, high irradiation hardening was measured of 334 MPa at 27°C and 261 MPa at 300°C testing temperature, whereas we found lower irradiation hardening for EB25, see Fig. 2. After irradiation, there was and very little, if any at all, strain hardening capacity left, see Fig. 2. The elongation data for EB15 and EB25 are not very different in all unirradiated conditions and are almost the same as that for TIG15. When compared to irradiated EB15, the irradiated samples of EB25 show lower reductions of elongation, which corresponds to the lower hardening.

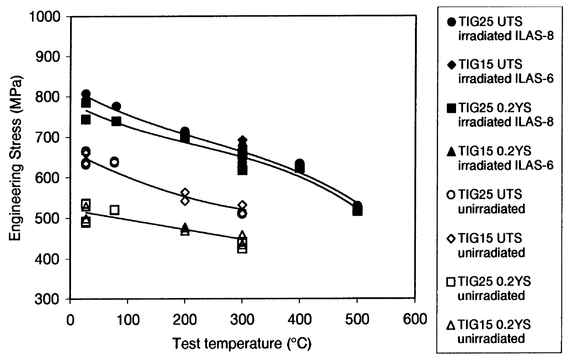

Fig. 1. Tensile engineering stresses for TIG15 and TIG25.

3.2. KLST impact tests

Results for the impact testing are summarised in Table 1. TIG15 was sampled in T, C, and R. The unirradiated tests show no significant difference between the R and C layer; DBTT and upper-shelf energy (USE) are similar, see Fig. 3. The samples from the T layer do show a higher DBTT and possibly a slightly lower USE. After irradiation, still fully ductile behaviour was found for T layer specimens at temperatures well below the transition temperatures of the R and C specimens. The USE of the top specimens seems to be higher than before irradiation. It is also higher than the USE of the R and C layer specimens. The ranking was exactly reversed in the unirradiated conditions.

No TIG25 specimens were available for KLST impact testing.

EB15 in unirradiated, non-heat treated condition shows a DBTT of +25°C with an USE of 10.7 J. After

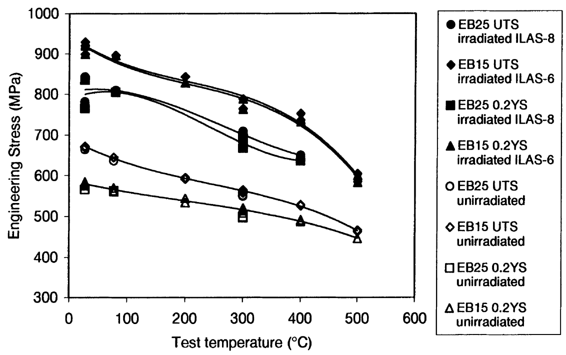

Fig. 2. Tensile engineering stresses for EB15 and EB25.

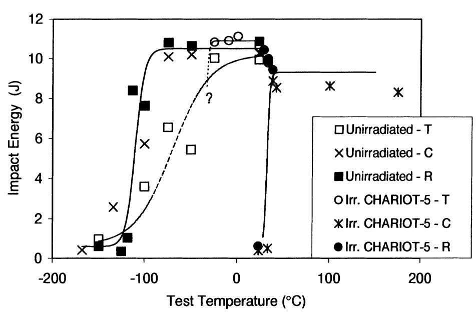

Fig. 3. Transition curves for TIG15 miniature charpy impact tests.

Table 1
Summary of tensile results at 27°C and 300°C before and after irradiaton and impact results before and after irradiation and heat treatment

Material	Unirradiated						Irradiated					
	T_{test} (°C)	0.2 YS (MPa)	SHC (MPa)	UE (%)	FE (%)	RoA (%)	Irradiation capsule	ΔYS (MPa)	SHC (MPa)	ΔUE (%)	ΔFE (%)	ΔRoA (%)
Tensile results												
F82H-TIG15	27	513	134	2.8	12	76	–	n.a.[a]	n.a.	n.a.	n.a.	n.a.
F82H-TIG25 (T)	27	536	129	3.4	14	77	–	n.a.	n.a.	n.a.	n.a.	n.a.
F82H-TIG25 (C, R)	27	490	143	4.1	12	77	ILAS-8	274	34	3.4	4.3	6.5
F82H-EB15	27	580	92	2.7	15	79	ILAS-6	334	2.7	2.5	5.4	2.4
F82H-EB25	27	566[b]	98	2.3	14	78	ILAS-8	234	12	1.6	3.5	3.3
F82H-TIG15	300	447	75	1.7	9.7	78	ILAS-6	233	2.5	1.5	3.0	16.9
F82H-TIG25 (T)	300	n.a.	n.a.	n.a.	n.a.	n.a.	–	n.a.	n.a.	n.a.	n.a.	n.a.
F82H-TIG25 (C, R)	300	433	78	1.8	10	79	ILAS-8	203	14	1.4	1.7	7.0
F82H-EB15	300	515	46	1.7	13	80	ILAS-6	261	0.5	1.5	4.4	13.7
F82H-EB25	300	498	53	1.6	12	80	ILAS-8	182	22	1.0	2.8	8.7

Material	Unirradiated		Irradiated				
	USE (J)	DBTT (°C)	USE (J)	DBTT (°C)	ΔUSE (J)	ΔDBTT (°C)	Irradiation capsule
Impact test results							
TIG15 (R)	10.5	−110	10.0	n.a.	−0.5	n.a.	CHARIOT-5
TIG15 (C)	10.5	−110	9.3	32	−1.2	142	CHARIOT-5
TIG15 (T)	10.2	−70	10.9	−35	0.7	35	CHARIOT-5
EB15 (C, R)	10.7	25	11.0	185	0.3	160	CHARIOT-5
EB25 (R)	7.0	25	8.2	260	1.2	235	CHARIOT-5
	Unirradiated		Heat treated				
	USE (J)	DBTT (°C)	USE (J)	DBTT (°C)	ΔUSE (J)	ΔDBTT (°C)	Heat treatment
EB25 (R)	7.0	25	11.8	−5	4.8	−30	PWHT 720°C/1 h
EB25 (T)	n.a.	n.a.	11.0	−15	n.a.	n.a.	PWHT 720°C/1 h

[a] Not available or not analysed.
[b] One data point only.

2.5 dpa 300°C irradiation, the DBTT has shifted by 160°C to +185°C, see Fig. 4. The USE seems to be at the same level as before irradiation. However, all upper-shelf tests showed cracking outside the notch in the heat affected zone (HAZ) region, and give therefore an overestimation of USE and are thus invalid.

The EB25 specimens were taken from the R and the T layer. To investigate the impact toughness and DBTT change after a post-weld heat treatment (PWHT), the specimens from the R layer were used for three experiments: (a) unirradiated as-welded without PWHT, (b) irradiated as-welded without PWHT, (c) unirradiated with PWHT. The T specimens were only tested in the (c) condition.

The specimens taken from the root in the (a) condition show again a fairly high DBTT: +25°C, see Fig. 5. The USE is low: 7 J. In the (b) condition, the DBTT has shifted by 235°C to +260°C, the highest value observed in this study. The USE increases to 8.2 J. Many upper-shelf tests showed cracking outside and alongside the notch, and were ignored as invalid.

The DBTT of the R layer in (c) condition is, with −5°C, significantly lower than the as-welded R layer. The USE is much higher; 11.8 J. Similar observations go for the T layer in the (c) condition: DBTT is −15°C, USE is 11.0 J. The scatter of impact energies in the transition region is large.

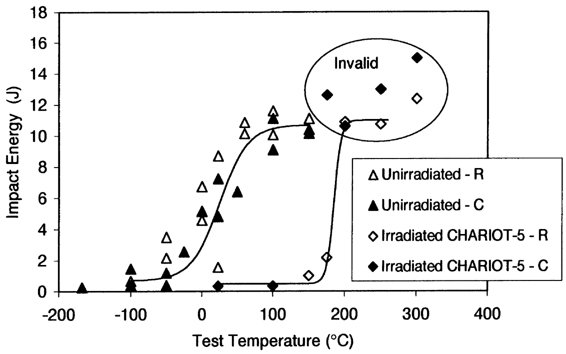

Fig. 4. Transition curves for EB15 miniature charpy impact tests.

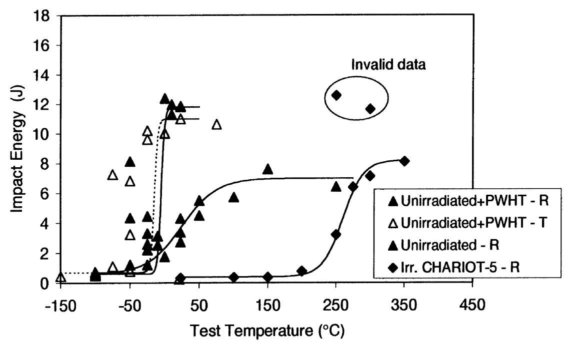

Fig. 5. Transition curves for EB25 miniature charpy impact tests.

4. Results summary

4.1. Discussion

The temperature trends of the tensile properties of welded joints are as expected. Irradiation hardening is largest at the lowest test temperature, which is room temperature. The strain hardening capacity SHC (= UTS − 0.2% YS) is also reduced considerably; in some cases the remaining SHC is practically zero. This is reflected by the loss of uniform elongation; in many cases the UE is practically zero after irradiation. The fracture elongation reduction is largest at room temperature, as is the uniform elongation reduction, and both tend to diminish with rising temperature. ILAS-6 and ILAS-8 show an overall significant difference in hardening, although irradiation circumstances have not been very different. It is not clear where this difference originates. Because of the difference between these capsules, it has not been possible to analyse the influence of thickness of the welds on hardening, since the particular thicknesses have all been irradiated in different capsules.

The tensile results of the welded materials like EB-welded F82H are not entirely representative of the actual weld properties. As the gauge length consists of weld metal with a very high hardness and strength and of softer base metal with a much lower strength, plastic deformation and failure will occur almost entirely in the HAZ/base metal. For the TIG welds, this was true as well.

A difference was observed in behaviour of TIG and EB welded joints for the impact tests. The smallest DBTT shift was found for the top layer of the TIG-welded joint. The irradiation induced shift was only 35°C. Compared to the centre layer from the same joint that shows a shift of more than 140°C, this is surprisingly low. Further study could point to critical microstructural factors for the development of low-embrittlement RAFM steels.

The EB joints have a brittle martensitic structure in the as-welded, non-tempered condition since the material is a martensitic material in the first place. The effect of this can easily be seen; all EB welds have a DBTT of around room temperature in the unirradiated state. PWHT improves the toughness properties of these welds. After irradiation the shift ranges from 160°C to 235°C, with the DBTT ending up close to or even above 250°C. The largest DBTT shift due to irradiation has occurred for the EB25 root layer specimens.

4.2. Conclusions

The EB welds are a little stronger than TIG welds but they have similar elongation properties before and after irradiation. The UE is in most cases negligible after 2.5 dpa at 300°C. Differences in hardening between various irradiation capsules prevent rigorous analysis of pre-irradiation microstructural effects on hardening.

There is a large variation in impact properties for the TIG weld. The DBTT is in the same range as that of the irradiated plate material according to [5], but the poor statistics due to the limited number of specimens has to be borne in mind. The impact properties are worst for the top layer specimens, whereas after irradiation the top layer performs better than the centre layer.

The fusion zone of EB welded joints without PWHT in the unirradiated condition has a DBTT around room temperature. Irradiation tends to shift the DBTT to very high values, some cases even above +250°C. PWHT of EB-welded material gives a significant improvement of the DBTT and USE compared to the as-welded condition. It is expected that properties can be improved further by optimising the PWHT. There does not seem to be a systematic effect of the sampling location on the impact properties for EB-welded material.

Acknowledgements

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