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Effect of hydrogen on tensile properties of martenistic steels for fusion application

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Abstract

The present work is aimed at giving a contribution to the characterisation of hydrogen embrittlement (HE) resistance of two martensitic steels, i.e. the modified F 82 H and the MANET. The study is based on tensile low strain rate tests, conducted on notched cylindrical specimens which were previously charged with hydrogen. In the case of modified F 82 H steel, two different heat treatments were considered, i.e. the as-received (AR) and the aged condition. The results of the tests indicated that the analysed steels show a noticeable reduction of the area reduction coefficient (Z%), even for rather low global hydrogen content. As an example, 1–2 wppm are sufficient to lower the Z% of mod. F 82 H to 14–18%, from the 35–40% value typical of the virgin material. In the paper, these results are discussed with the aid of microstructural investigations and SEM analysis which allowed to characterise the microstructural properties of the materials.

1. Introduction

The development of the next generation of fusion reactor prototypes requires, among many other investigations, a relevant activity aimed at characterising the behaviour of materials under the special anticipated operating conditions. The effects of the susceptibility of the first wall and blanket components to the embrittling effects of hydrogen appears to be one of the most relevant point to be clarified, particularly as this susceptibility is known to be potentially high for many of the proposed candidate materials (i.e. martensitic steels, vanadium alloys) [1–3].

In particular, it is known that ferritic and martensitic steels may exhibit hydrogen embrittlement (HE) phenomena, such as lowering of ductility and delayed fracture under static load, for hydrogen concentrations quite lower than those required to produce similar effects on the austenitic steels usually employed in nuclear application [4]. Such a susceptibility appears particularly worrying if one considers the presence, in a fusion reactor, of several hydrogen sources (e.g. generation by (n,p) reactions, adsorption from plasma) which may potentially affect the first wall and blanket materials [5–7].

Therefore, in order to select the most appropriate steels to be proposed as candidate materials for fusion application, it is important to achieve meaningful information about their HE susceptibility. The present investigation is aimed at contributing to achieve such a characterisation for two martensitic steels, i.e. the modified F 82 H and the MANET II. In the case of modified F 82 H steel, two different heat treatments were considered, i.e. the as-received (AR) and the aged condition.

Several tensile low strain rate tests were conducted on notched cylindrical specimens which were previously charged with hydrogen. The results of these tests were analysed with the aid of micrographic and SEM analyses aimed to characterise material microstructure, which is known to be a key parameter in determining material response to the presence of hydrogen.

2. Materials

The chemical composition of the materials investigated in this study is reported in Table 1. Both steels

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Table 1
Chemical composition of the materials

	C (%)	Cr (%)	Ni (%)	Mo (%)	V (%)	Si (%)	Mn (%)	S (%)
MANET	0.11	10.3	0.62	0.57	0.2	0.27	0.94	0.005
F82H	0.09	7.68	0.02	0.003	0.16	0.11	0.11	0.002
	P (ppm)	B (ppm)	N (%)	Co (%)	W (%)	Ta (%)	Ti (%)	Fe
MANET	0.005	0.007	0.03	0.01	–	–	–	Bal.
F82H	20	2	0.007	–	1.96	0.02	0.01	Bal.

were available as 15 mm thick wrought plates. The heat treatment applied for MANET during manufacturing was as follows: 965°C 2 h, 1075°C 0.5 h, 750°C 2 h; related prior austenitic grain size (GS) was found to be ASTM 8-9 (15–20 μm). In the case of F 82 H, which can be classified as a lower chromium content steel, the heat treatment for the AR material was as follows: 1040°C 0.5 h, 750°C 1 h; corresponding GS was ASTM 5–6 (about 55 μm). The additional heat treatment for the aged (AG) included 2000 h in a vacuum furnace at 500°C. The yield ($\sigma_{y0.2}$) and ultimate (σ_u) strength of the analysed materials were as follows: F82H AR: $\sigma_{y0.2} = 515$ MPa, $\sigma_u = 625$ MPa; F82H AG: $\sigma_{y0.2} = 518$ MPa, $\sigma_u = 634$ MPa; MANET: $\sigma_{y0.2} = 654$ MPa, $\sigma_u = 803$ MPa;

3. Experimental activity

Several low strain rate tensile tests were conducted on specimens either virgin or previously charged with hydrogen. Specimens were machined according to the shape reported in Fig. 1, with an orientation parallel to the lamination direction.

The tests were conducted on a standard electro-hydraulic MTS test frame under displacement control. The average strain rate employed for the hydrogen charged specimen tests was 2.5×10^{-6} s^{-1} for the F82H steel and ranged between 4.25×10^{-5} and 2.5×10^{-6} s^{-1} for MANET. These strain rates were fixed after some preliminary tests, which indicated that they were sufficiently low to prevent any significant influence on results.

After test completion, fracture section diameter was carefully measured by means of macro photographs (the average of six angularly equi-spaced diameter estimates was employed), in order to evaluate the area reduction coefficient, $Z\%$.

The specimens for HE tests were hydrogen charged by an electrochemical technique. The average (bulk) hydrogen content of the samples was accurately measured by an electrochemical system and by a thermal desorption apparatus [6], which gave results with an

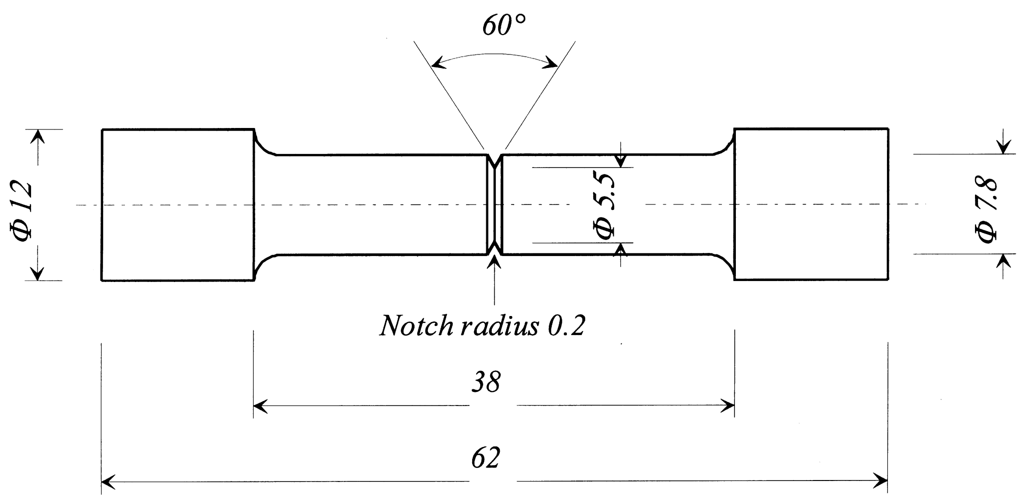

Fig. 1. Notched specimens employed for the test.

agreement better than 5%. Seven and five tests were conducted on AR and AG F82H, respectively, with bulk hydrogen content ranging from 0 to 3 wppm. As regards MANET, eight tests were conducted, four of which on specimens with a 5 wppm hydrogen content and the remaining on virgin (0 wppm) specimens.

4. Results

An example of the effects produced by hydrogen on the tensile behaviour of the specimens employed in the present research is depicted in Fig. 2, where applied load is plotted vs. average strain measured over a 25.4 mm gauge length including the notch. The typical marked reduction of fracture elongation is observed, while yield and maximum loads do not appear to be significantly affected.

In Fig. 3 a SEM image of the fracture area obtained in a mod.F82H AR specimen having a 3 wppm hydrogen content is reported as an example. It is possible to see the typical brittle fracture consequence of the hydrogen embrittlement. In the case of mod. F 82 H the microstructural analysis shows the presence of globular

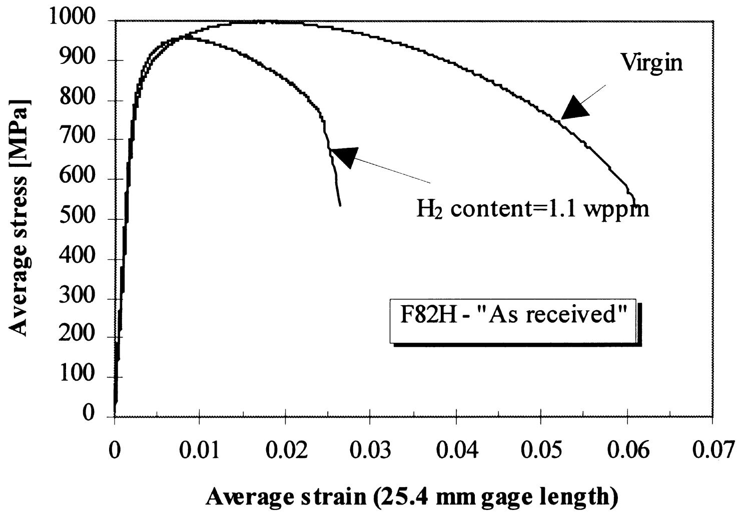

Fig. 2. Typical stress strain pattern as observed in HE tests.

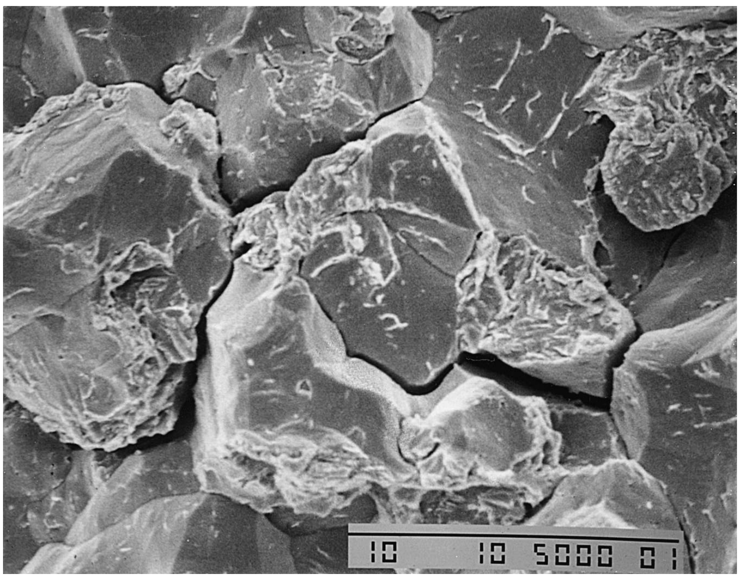

Fig. 3. Typical SEM image of the fracture surface (F82H AR; hydrogen content: 3.1 wppm).

Table 2
Results of HE tests

MANET		F82H AR		F82H AG	
H_2 cont. (wppm)	Z%	H_2 cont. (wppm)	Z%	H_2 cont. (wppm)	Z%
0.0	40.0	0.0	43.4	0.0	34.7
0.0	33.1	1.1	16.2	1.2	21.5
0.0	37.0	1.4	17.4	1.7	21.4
0.0	33.6	1.7	17.7	1.8	15.5
5.0	11.5	2.1	13.9	2.7	6.5
5.0	14.6	2.7	7.0		
5.0	11.2	3.1	7.2		
5.0	9.7				

inclusion identified as aluminium-oxide compounds. These inclusions seem to be points of nucleation for the hydrogen fracture.

As the actual strain occurring at the notch root cannot be measured, it was decided to employ the area reduction coefficient (Z%) to represent the effects produced by hydrogen on material ductility. The results obtained in the all the tests for the three materials are reported in Table 2 and compared in Fig. 4, where the experimental Z% is plotted versus initial average hydrogen content. For the mod. F 82 H steel with both heat treatments a relevant reduction in ductility (about 40–60%, leading to area reduction coefficient values ranging between 15% and 20%) is observed even for rather low (1–2 wppm) hydrogen content, while for 3 wppm the Z% is lowered to 15%.

As regards the MANET steel, available data did not allow to analyse in detail the dependence of Z% from hydrogen content. However, it was still possible to observe a rather strong (about 60%) reduction of ductility for a 5 wppm initial hydrogen content.

5. Discussion

The results obtained in the present work can be considered to be in general qualitative agreement with other studies carried out on the same steels by the authors [8,9] making use of a different experimental technique, i.e. the Disk Pressure Test (DPT). Indeed, in DPT tests, the lower limit for hydrogen content in order to achieve a significant ductility reduction was 8–9 wppm for MANET and 3–4 wppm and for AR F82H.

The rather low Z% values which were obtained in the present research for hydrogen contents well below the above limits appear justifiable, if two main aspects are considered. First of all, the stress state produced in the notched tensile specimen exhibits an higher degree of triaxiality as compared with the DPT specimen, which is essentially equi-biaxial; this difference, lowering the basic material ductility, may also have enhanced the embrittling effects of hydrogen. Moreover, in DPT specimen the hydrostatic stress is essentially constant over a rather wide (some square centimetres) region, enclosing the final rupture zone; as a consequence, a low tendency toward a large scale stress driven migration is to be expected, leaving the hydrogen concentration essentially to the initial uniform value. On the contrary, high hydrostatic stress gradients are present in notched specimens, which is likely to produce, during the test

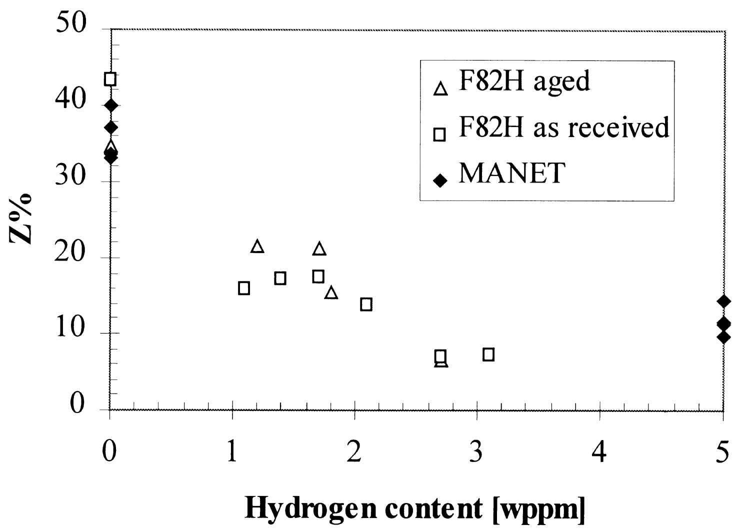

Fig. 4. Area reduction coefficient vs. hydrogen content.

duration, a significant increase of hydrogen concentration in the critical zone.

As regards the influence of heat treatment on the behaviour of the F82H steel, this appeared to be rather small (Fig. 3), with the two materials showing essentially the same properties. As a general conclusion, it can be observed that the hydrogen contents capable of giving a large reduction in ductility for the steel appear to be very low for this class of materials. This is particularly true for the F82H, which exhibits appreciable HE effects for hydrogen concentration equal to 1–2 wppm, while some more investigation should be required for the MANET, in order to characterise its behaviour for concentrations under 5 wppm.

This results seems to indicate that caution should be employed when applying this steels for the first wall or the blanket of a fusion reactor, as some studies have shown [5,7] that hydrogen concentration in these components, for the DEMO reactor, is likely to reach values very close to such limits. However, it has also to be observed that, as indicated by other papers, the HE sensitivity is likely to be significantly affected by the degree of stress triaxiality, by the presence of stress gradients and by temperature, which are likely to be more favourable in operating conditions than in the tensile notched specimen.

A prediction of the behaviour of actual reactor components would therefore require the development of reliable analysis tools, capable of properly account for such effects. In addition, future work should carefully analyse, among other aspects, the interaction between HE and radiation damage and the susceptibility of weld and heat affected zones.

6. Conclusion

Low strain rate tests conducted on notched specimens showed that the mod. F82H steels exhibit hydrogen embrittlement susceptibility even for rather low hydrogen concentrations (1–2 wppm). This susceptibility does not appear to be significantly affected by heat treatment, as the material was tested both in the AR and in the aged conditions, giving almost equal results. Tests conducted on the MANET steel showed a marked effect in the presence of a 5 wppm hydrogen content, while it was not possible, at the moment, to analyse the effect of lower concentrations. The results suggests that some cautions and further studies are required in order to employ these steel in first wall or blanket applications. To this end, an analysis tool capable of predicting the influence of stress state appears to be quite useful, as it would allow a better and reliable transfer of data between laboratory and operating conditions.

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