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Tensile and impact behavior of the reduced-activation steels OPTIFER and F82H mod

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Abstract

Tensile and charpy impact tests were carried out on some OPTIFER steel grades and F82H mod. The steels show little difference in tensile properties, but pronounced differences in charpy impact properties. Combinations of low ductile–brittle transition temperature (DBTT) and high yield strength are favored for OPTIFER-IV. After aging at 600°C and higher, F82H mod steel embrittles due to precipitation of Laves phase (Cr, Fe)$_2$W, whereas OPTIFER-IV is resistant to aging. © 2000 Elsevier Science B.V. All rights reserved.

1. Introduction

In the blanket project conducted within the framework of the European fusion technology program, reduced activation structural materials are developed on the basis of martensitic chromium steel grades for the first wall and for blanket structures of ITER test modules. These steel grades are characterized, in particular, by the absence of alloying elements that may be strongly activated, such as Mo, Nb, and Ni, and by the replacement of some of them by alloying elements less prone to activation, such as W and Ta. At the same time, this improves the notch impact properties, thus resistance to brittle fracture of the material after neutron exposure. The success of this alloy development, as far as can be described by the tensile and impact properties of a number of OPTIFER steel grades, will be outlined and explained in this paper.

Martensitic chromium steel grades exhibit their desired mechanical properties only in the quenched and tempered conditions, most of which are not entirely thermodynamically stable. At temperatures above 550°C, the microstructure undergoes a marked change, causing some mechanical properties to deteriorate. As these structural changes often become manifest only after relatively long aging times, but may be accelerated under neutron exposure, aging was investigated at temperatures above 550°C, the highest temperature of use. Effects of aging on change in the ductile–brittle transition temperature (DBTT) were measured.

2. Test material

The chemical compositions of the OPTIFER steel grades studied so far and F82H mod are shown in Table 1. The OPTIFER-II, -III and -VI steel grades contain no tungsten. The OPTIFER-Ia, -Ib, and -V steel grades contain slightly more chromium and slightly less tungsten than the precursor variety, OPTIFER-IV. Aging tests were conducted mostly on F82H mod steel, which was developed within a Japanese JAERI program and produced by NKK as a 5 ton heat (No. 9741). The steel was austenitized at $T_{AU} = 1040$°C for 38 min and tempered at $T_{AN} = 750$°C for 1 h. Several samples were austenitized at $T_{AU} = 950$°C for 0.5 h and tempered at $T_{AN} = 750$°C for 1 h prior to thermal aging (stabilization) to add a higher notch impact toughness to the initial state [1]. Standard ISO V-specimens with the external dimensions of $10 \times 10 \times 55$ mm^3 and with a 45° notch 2 mm deep were used.

3. Test results

The tensile properties of the OPTIFER-Ia, -Ib, -II, -IV, -V and F82H mod. steels show no major difference between the steels, except for the relatively high strength

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Table 1
Chemical composition of the OPTIFER steel grades and F82H mod. in wt % (and ppm, respectively)

OPTIFER	Ia	Ib	II	III	IV	V	VI	VII	F82H mod.
Heat	664	667	668	666	986489	735	734	736	9741
Cr	9.3	9.5	9.5	9.4	8.5	9.48	9.35	8.38	7.7
W	0.96	0.97	–	–	1.16	0.985	–	1.03	2.0
Mn	0.50	0.49	0.49	0.49	0.6	0.39	0.61	0.37	0.16
V	0.26	0.23	0.28	0.25	0.23	0.245	0.275	0.205	0.16
Ta	0.066	0.16	0.018	1.6	0.1	0.061	0.083	0.069	0.02
C	0.11	0.12	0.125	0.13	0.10	0.115	0.125	0.09	0.09
N	0.016	0.006	0.016	0.01	0.06	0.023	0.025	0.026	0.008
Ge (Si)	(0.06)	(0.05)	1.2	(0.07)	(0.01)	(0.04)	0.38	(0.06)	(0.11)
Deoxid.	Ce	Y	Ce	Ce	Al	Ce	Ce	Ce	–
B (ppm)	61	70	59	70	40	2	2	2	–
P (ppm)	46		43		40	35	43	36	20
S (ppm)	50		20		40	25	30	25	–
O (ppm)	47		90		35	60	160	170	–
Al (ppm)	80	150	80	100	80				30

of F82H mod. Strengths meet the criteria so far applied to this steel grade. On the other hand, uniform elongations A_g in the temperature range between 500°C and 600°C are on the low side when judged against the requirements of 2%. Due to the special importance of a low transition temperature of impact energy (DBTT), the tensile and impact properties are measured here for the quenched and tempered condition $T_{AU} = 900°C$ 0.5 h + $T_{AN} = 730°C$ 2 h, which promotes the toughness of the material. Fig. 1 shows the impact energy in the notched bar impact bending test as a function of the test temperature. OPTIFER-Ia, -Ib, -IV, and -V exhibit a transition temperature of the impact energy, DBTT less than −90°C.

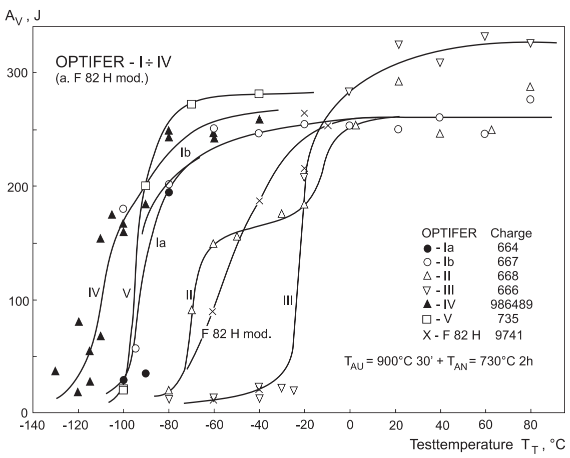

Fig. 1. Variation of impact energy A_V of OPTIFER steel grades and F82H mod. with the test temperature. OPTIFER-Ia, -Ib, -IV and -V steel grades have a lower DBTT.

It is known from earlier studies [1–3] that mechanical properties can be varied within wide limits by variations of the austenitizing (quenching) temperature, T_{AU}, and the tempering temperature, T_{AN}. Fig. 2 shows the influence of T_{AU} and T_{AN} on DBTT for the steel OPTIFER-IV. Their influence on strength and ductility always works in opposite directions. There is no quenching and tempering of this steel grade, which would produce optimum properties in all tests. Consequently, to assess the 'mechanical potential' of a steel grade, which is independent of quenching and tempering, one must always look at strength and ductility at the same time. It is advisable to select one strength level and one ductility level as close as possible to practical applications. Consequently, one measure of strength is the 0.2% yield point at elevated temperature, $R_{p0.2}$ (500°C). Ductility can be described by toughness, which in turn, can be represented by the DBTT.

Fig. 3 shows the relation between 0.2% yield strength at 500°C, $R_{p0.2}$, and DBTT, as a function of austenitizing and tempering conditions for some OPTIFER steel grades and F82H mod. All points with identical austenitizing and tempering conditions can be compared directly. It is much more interesting to see, however, within which ranges of strength and DBTT the different steel grades can be varied. The more these points lie in the range of high strengths and/or low DBTTs, the greater is the 'mechanical potential' of the steel. In light of these criteria, OPTIFER-Ia, -IV, and -V are better than the other steel grades (there is only one point available from OPTIFER-Ia with $R_{p0.2}$ (500°C) = 435 MPa and DBTT = −91°C. It is not represented in the figure).

In order to determine the susceptibility of F82H mod steel to aging, the test temperature in the notched bar

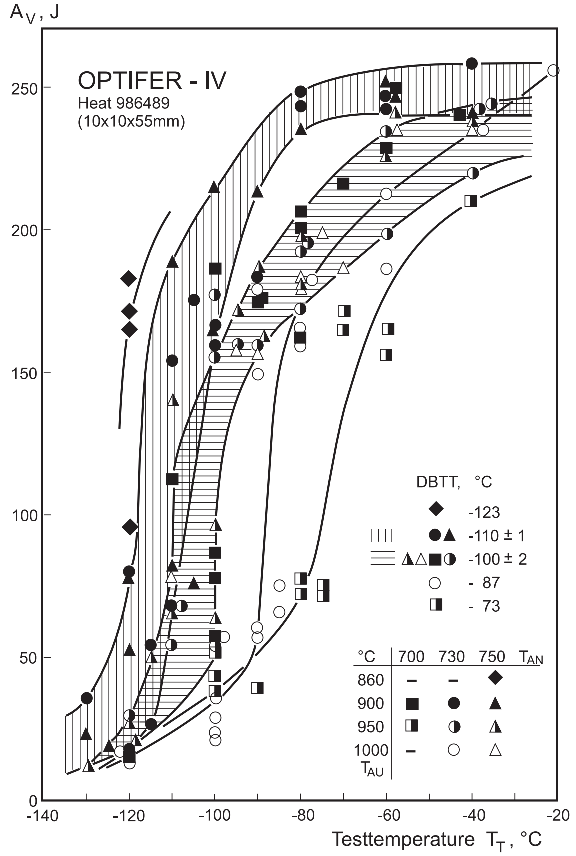

Fig. 2. Variation of impact energy A_V of OPTIFER-IV with test temperature. The influence of austenitization (T_{AU}) and tempering (T_{AN}) temperatures on DBTT are shown. Most of the DBTTs are at or below −100°C.

impact tests was varied so that a DBTT could be determined for each aging condition. From the difference in transition temperatures of the initial state and the aged state, the age-induced increase in the transition temperature of the impact energy, ΔDBTT, is obtained. These values are shown in Fig. 4 as a function of the aging temperature, T_A, and the aging time, t_A, as the aging conditions. The shape of the curves suggests that, above 10,000 h, saturation of ΔDBTT might be expected at approximately 70–75°C. Comparing these values with those of OPTIFER-IV grade steel [5,6], which are at ΔDBTT = 10°C under the same conditions, clearly indicates the difference in susceptibility to aging at 600°C and 650°C. The difference between the two steel grades is exclusively attributable to the tungsten content of the alloys. This is 2% in F82H mod, which is too high, and 1.16% in OPTIFER-IV, which seems just right. The high tungsten content produces the intermetallic Laves phase, $(Cr, Fe)_2W$, at the grain boundaries [4], which initiates cracks in the notched bar impact test. The aging time for

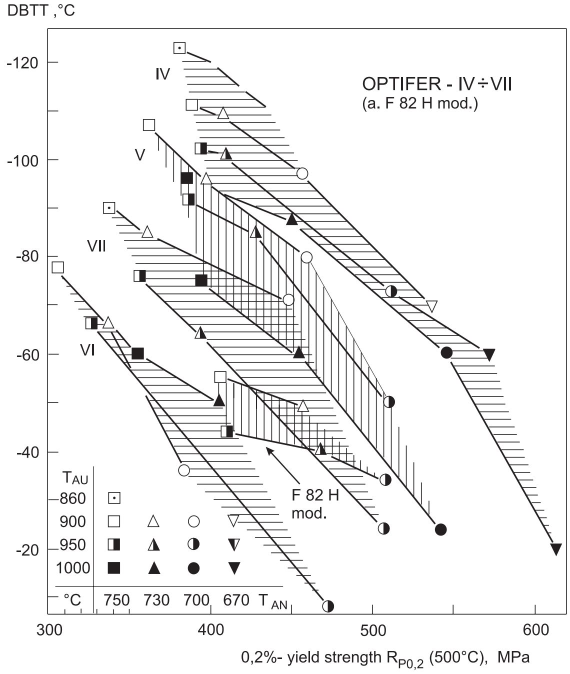

Fig. 3. Transition temperature DBTT and 0.2% – yield strength at 500°C show the mechanical potential of OPTIFER steel grades and F82H mod. OPTIFER-IV has the best combination of strength and DBTT.

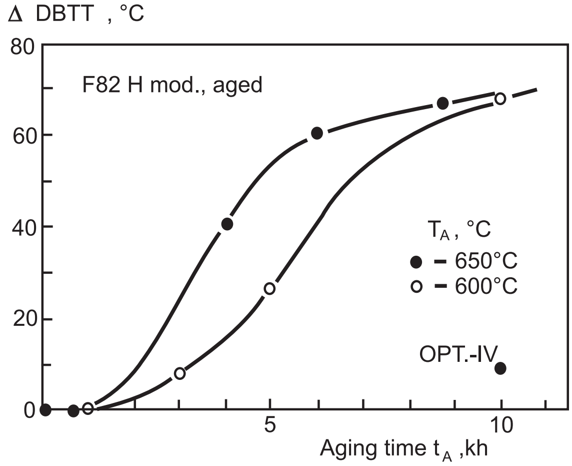

Fig. 4. Shift of the transition temperature ΔDBTT of the steel F82H mod. (and OPTIFER-IV) as a function of aging time at 600°C and 650°C showing a saturation after about 10 kh (in comparison with the aging resistant steel OPTIFER-IV).

the occurrence of the Laves phase passes through a minimum at 650°C. At increasingly higher and lower temperatures, it becomes increasingly longer. Annealing at 550°C does not produce any major changes in transition temperature. The OPTIFER-Ia steel grade is similar resistant to aging as OPTIFER-IV [5,6]. The results of tensile tests are reported in [6].

4. Discussion

The main causes known so far for the different qualities of OPTIFER steel grades are the following: the OPTIFER-VI and -VII steel grades have oxygen contents of 160 and 170 ppm, respectively, which are too high. Consequently, they contain agglomerated deoxidation products which act as crack initiators in the notched bar impact test [7]. The OPTIFER-II grade of steel has not only an oxygen content which is too high (90 ppm), but also an austenite grain size which is too coarse, due to insufficient tantalum content. The OPTIFER-III steel grade contains 1.6% tantalum, which is too high. The primary carbides of tantalum favor brittle fracture and extract the carbon from the steel needed for martensite formation. The absence of tungsten in OPTIFER-II, -III and -VI steel contributes to their low high-temperature strength (in this case, $R_{p0.2}$ (500°C)). Despite the limitations mentioned above, OPTIFER-Ib, -II, and -III are not inferior to the comparable F82H mod steel grade [1] or to MANET-II steel [3]. A particularly good mechanical potential is exhibited by OPTIFER-Ia, -IV, and -V. This requires a number of important conditions to be met: a tantalum content of 0.06–0.12%; an oxygen content $\leqslant 60$ ppm; a smaller austenite grain size of $\leqslant 15$ μm (at $T_{AU} \leqslant 950$°C), a low ratio of Al to N. The OPTIFER steel grades (except for OPTIFER-III) exhibit similar hardening and tempering behavior, similar α–γ transition temperatures and M_s temperatures; they are free of δ-ferrite, and they are largely resistant to aging (stabilization). The creep-rupture properties are comparable [8]. In dynamic tests, the irradiation response of this steel grades depends mainly on the boron content of the grain boundaries [9].

5. Summary

The OPTIFER and F82H mod steel grades examined show little difference and consistently good tensile properties, but exhibit pronounced differences in their impact properties. This is especially true after aging at 600°C and 650°C, where the F82H mod steel grade embrittles as a consequence of precipitation of Laves phase (Cr, Fe)$_2$W. The potential of the mechanical properties of these steel grades can be estimated and compared using a combination of strength and DBTT. OPTIFER-IV is favored.

Acknowledgements

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