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First results on the characterisation of the reduced-activation-ferritic-martensitic steel EUROFER

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Abstract

Reduced activation ferritic/martensitic (RAFM) steels are being considered for structural application in potential fusion energy systems. Based on the substantial experience with RAFM developmental steels of OPTIFER type, an industrial 3.5 tons batch of a 9CrWVTa-RAFM steel, called EUROFER 97 had been specified and ordered. A characterisation programme has now been launched to determine the relevant mechanical and physical-metallurgical properties in order to qualify it for fusion application. The hardening, tempering and transformation behaviour of EUROFER is in good agreement with that of other RAFM-steels like OPTIFER and the Japanese industrial scale heat F82H mod. Tensile tests, performed between RT and 750 °C, show comparable strength and ductility values that are not strongly affected by ageing at 580 and 600 °C up to 3300 h. Impact bending tests indicate a superior ductile to brittle transition temperature (DBTT) of EUROFER in the as-received condition compared to that of F82H mod. First results of creep tests between 450 and 650 °C up to test times of 4000 h reveal a creep strength similar to OPTIFER and F82H mod. The first results of the investigations show that it is possible to transfer the good mechanical and structural properties of precursor laboratory melts to an industrial scale melt. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Reduced activation ferritic martenstic (RAFM); OPTIFER; EUROFER; Tensile; Charpy; Creep tests

1. Introduction

Reduced activation ferritic/martensitic (RAFM) steels are being considered for structural application in potential fusion energy systems. Based on the substantial experience with RAFM developmental steels of OPTIFER type, produced as laboratory melts of 25 kg, a RAFM steel of the 9CrWVTa type, called EUROFER 97 had been specified under the leadership of FZK in close co-operation with CEA. BÖHLER EDELSTAHL GmbH in Austria was finally selected as manufacturer for about 3.5 tons of semi-finished products (plates, forgings, filler wire material and tubes). Apart from different technological goals the question of transferability of properties from laboratory to industrial scale melts is of major interest.

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Table 1
Content of main alloying elements of examined steels in mass%

Alloy	Heat	C	Si	Mn	Cr	V	W (Mo)	Ni	Ta (Nb)
EUROFER	E83699	0.12	0.06	0.42	8.87	0.19	1.10	–	0.14
EUROFER	E83698	0.11	0.04	0.42	8.82	0.20	1.09	–	0.13
OPTIFER V	735	0.12	0.06	0.39	9.48	0.245	0.985	–	0.061
F82H mod.	9741	0.09	0.11	0.16	7.7	0.16	1.94	–	0.02
MANET II	50761	0.11	0.27	0.94	10.3	0.19	(0.56)	0.62	(0.15)

2. Experimental

A characterisation programme has been launched to determine the relevant mechanical and physical-metallurgical properties in order to qualify EUROFER for fusion application. The results are being compared to the previous conventional reference steel MANET II and the Japanese RAFM steel F82H mod. All examinations have been undertaken on specimens prepared from a forged bar with a diameter of 100 mm (Heat E 83699), or rolled plate material (Heat E 84698) of 14 mm thickness. The main alloying element content of EUROFER 97 and other relevant alloys is given in Table 1. On the basis of far-reaching experience with precursor RAFM-alloys of OPTIFER type, for EUROFER the contents of Cr, Ta, W were specified carefully. Since the ductile-brittle transition temperature (DBTT) in impact tests reaches a minimum at 9% Cr and in order to achieve a better corrosion resistance, 9% Cr was regarded to be appropriate. Ta stabilises the grain size by carbide formation and improves DBTT and strength. A higher content than chosen has no advantage [1]. About 1% W represents a good compromise regarding low activation, DBTT, tensile strength, ductility and creep strength. The tritium breeding ratio is higher for lower W-content. To achieve reduced activation behaviour the radiological undesired elements, such as Nb, Mo, Ni, Cu, Al and others, have to be limited to contents in the wppm-range. Except for Ni, all contents were lower than the specified values. The reasons for the deviation have been identified and can be avoided in future [2].

3. Results and discussion

3.1. Hardening-, tempering- and transformation-behaviour

For practical applications the transformation-, hardening- and tempering behaviour of ferritic/martensitic steels are of great importance. A continuous-cooling-transformation-diagram (CCT-diagram) has been created Fig. 1, which gives relevant parameters such as transformation temperatures and critical cooling rates, i.e. the minimum cooling rate to achieve a full martensitic transformation. Using air-cooling, a value of 5 K/min corresponds to a cross-section of approximately 220 mm in diameter, where an overall martensitic transformation is achieved. Raising the austenitising-temperature and/or -time to

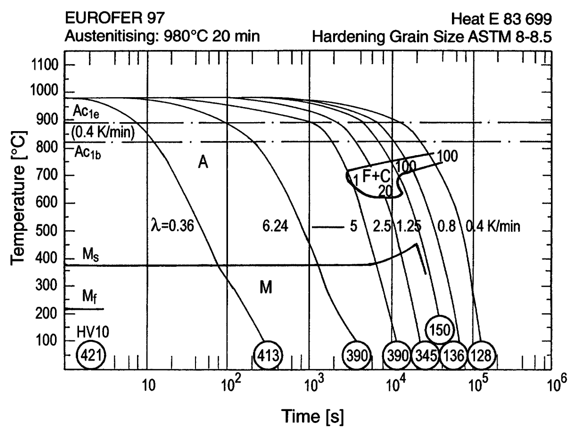

Fig. 1. Continuous Cooling Transformation (CCT) diagram for EUROFER 97, Heat E83699 after austenisation at 980 °C.

higher values would lead to a shift of ferrite/carbide-region to longer times and thus to higher full hardening diameters. The transformation behaviour of EUROFER is in good agreement with that of other RAFM-alloys like OPTIFER and F82H mod. [3]. The hardening and tempering behaviour of EUROFER corresponds to that of the 25 kg laboratory melts of OPTIFER-type. The higher Ta-content leads to more stable and smaller grain size (11–21 μm $\approx$ ASTM 10.5–8) in the relevant temperature region between 900 and 1050 °C compared to F82Hmod. (27–51 μm $\approx$ ASTM 7.5–5.5) [4]. First results of ageing experiments in the temperature region from 550 to 750 °C up to 3300 h indicate the good structural stability of EUROFER and an equal or even better ageing resistance compared to OPTIFER and the Japanese RAFM steel F82H mod, respectively.

3.2. Tensile tests

Cylindrical tensile specimens of EUROFER 97 with 5 mm in diameter and 25 mm gauge length were machined from the ∅100 mm forged bar and the 14 mm plate material and subjected to tensile tests in the temperature range between RT and 750 °C. Fig. 2 gives the ultimate tensile strength R_m and total elongation A_5 of EUROFER 97 compared to an developmental alloy OPTIFER V with a similar composition, the Japanese RAFM-steel F82H mod. and MANET II, the previous reference steel.

In the temperature range between RT and 500 °C EUROFER 97 reaches higher, at 600 and 700 °C slightly lower strength values than F82H mod. The strength values coincide very well with those of the precursor alloys of OPTIFER-type, represented by OPTIFER V. Increasing the austenitising temperature to 1075 °C leads to lower strength values, most pronounced at lower test temperatures, whereas the ductility is less affected. This loss in strength is accompanied by higher ductile–brittle transition temperatures (DBTT) in the impact test. Ageing at 580 and 600 °C up to 3300 h causes only a marginal decrease in tensile strength. It is worthwhile to mention that the strength of the 14 mm plate

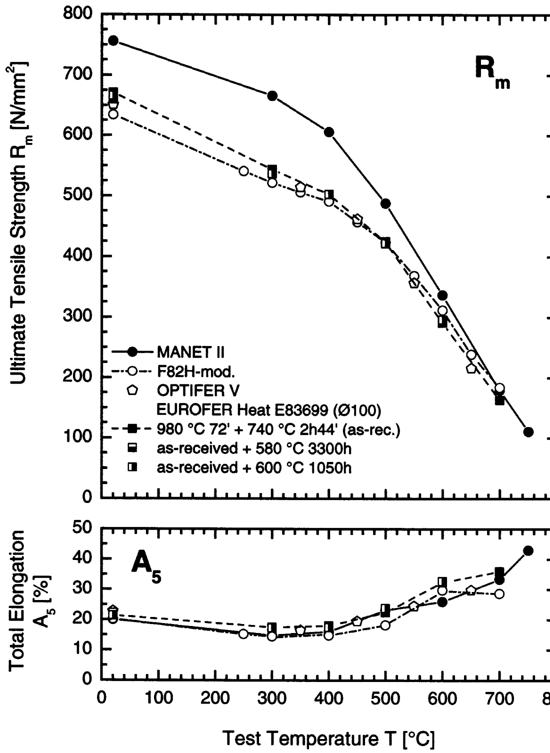

Fig. 2. Ultimate tensile strength and total elongation of different RAFM-steels as a function of the test temperature.

material, not plotted here for clarity reasons, matches very well the values of the bar material. The total elongation A_5, representing the ductility, is similar in appearance for all alloys. This applies also for the uniform elongation A_u and Reduction of Area Z, which are not indicated here (nomenclature according to European standard EN 10 002). A complementary and expanded description of tensile results can be found in [1] and [4].

3.3. Impact bending tests

Standard ISO-V Charpy-specimens have been machined from the 14 mm plate material. The specimen orientation was transverse (closed symbols in Fig. 3), additionally in one case longitudinal (open square) with respect to the final roll of the plates. BÖHLER BLECHE applies the so-called cross rolling technology to achieve isotropic mechanical and physical properties, which has been verified here in an excellent way. Fig. 3 shows the impact energy in dependence of the test temperature for EUROFER 97 compared with F82H mod. The upper shelf energy of both alloys with different heat treatments is roughly between 240 and 300 J. The Ductile to Brittle Transition Temperature (DBTT), which is an important measure for the suitability of RAFM alloys for structural applications in a fusion reactor, is for all EUROFER-variants remarkably better than for the Japanese steel F82H mod. (solid line) in the as-received condition (1040 °C 30 min + 750 °C 1 h). One reason for the higher DBTT (−20 °C) of F82H mod. is the larger grain size (55 μm), which depends on the austenitisation temperature. Another reason could be the higher oxygen content (124 ppm) [1] compared to 10 ppm for EUROFER which for the as-received condition (980 °C 27 min + 760 °C 90 min) exhibits a DBTT of −70 °C. Increasing the austenitising temperature to 1050 °C does not alter the DBTT (−73 °C) significantly although the grain size increases to 26 μm. A further increase to 1075 °C however increases the DBTT to −56 and −57 °C for the transverse (closed squares) and longitudinal specimens (open squares) respectively. The shift in DBTT can be related to a further increase of the grain size (45 μm), the shape of the energy

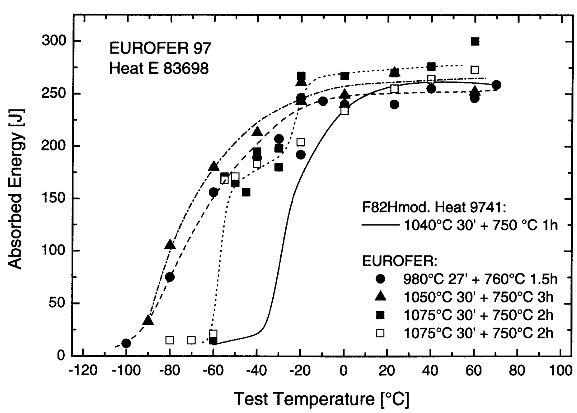

Fig. 3. Absorbed energy vs. test temperature of EUROFER 97 14 mm plate material compared with F82H mod., sampling transverse (closed symbols) or longitudinal (open square) to final rolling direction.

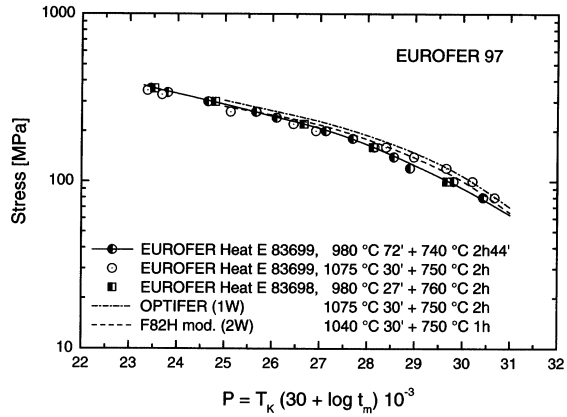

Fig. 4. Larson–Miller-Plot for EUROFER 97 bar and plate material with different heat treatments in comparison with OPTIFER developmental alloy and F82H mod.

curve not. The energy–temperature-curve (dotted line) shows in the transition region between upper and lower shelf energy a step-like behaviour which can be observed to varying degree for this type of alloy. This behaviour in the transition region will be subject of further investigations.

3.4. Creep behaviour

Creep tests at temperatures between 450 and 650 °C and test times up to 4000 h, using the same specimen type as for the tensile tests, have been conducted on EUROFER bar and plate material in different heat treatment conditions. The results are presented in Fig. 4 in the form of a so-called Larson–Miller-Plot which allows a good comparison and extrapolation of creep strength to different temperatures and times. The creep strength of EUROFER (solid line) in the as-received condition with an austenitising temperature of 980 °C is identical for both, bar (circles) and plates (squares). If the austenitisation temperature is raised to the same value as for OPTIFER (1075 °C) the creep strength at lower stress levels is improved and reaches the curve for OPTIFER and surpasses F82H mod. which is austenitised at 1040 °C. At high stress levels, the creep strength is decreased as compared to OPTIFER and F82H mod.

4. Conclusions

The first results of these investigations show that it is possible to transfer the good mechanical and structural properties of precursor laboratory melts to an industrial scale melt. Although progress has been made in order to achieve low contents of undesirable elements, a further reduction into the sub-ppm-range is necessary on the way from reduced to real low activation alloys.

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