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Accumulation of engineering data for practical use of reduced activation ferritic steel: 8%Cr–2%W–0.2%V–0.04%Ta–Fe

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A reduced activation ferritic steel, 8Cr–2W–0.2V–0.04Ta–Fe, is one of the candidates for the first wall material of SSTR (Steady State Tokamak Reactor). There is a growing demand for extensive properties data for designing the structure of the first wall. In a program of expanding of the data base, tensile tests at room, and elevated temperatures, creep rupture tests, Charpy impact tests and measurements of the physical properties were performed on the mill production plates as well as some laboratory heats. Some of the tests were conducted on specimens that were thermally aged up to 36Ms. Recent data were summarized and compared with those for the well known ferritic steels, HT9 and modified 9Cr.

1. Introduction

As a material for the first wall of a Tokamak reactor, we have developed a 0.1C–8Cr–2W–0.2V–0.04Ta steel (hereafter referred to as F-82H) [1,2], which excludes elements which are activated by high energy neutron irradiation. Recently, reduced-activation ferritic steels of an Fe–Cr–W system have also been studied in several institutions [3–6]. These studies have shown that the strength and the toughness of the Cr–W steels are comparable to and/or better than those of conventional Cr-Mo steel, for example, 12Cr–1Mo–VW steel, and that some of these Cr–W steels have potential applications as the first wall of the fusion reactor. However, these studies were made on laboratory samples. Accumulation of engineering data on the mill product of a reduced activation steel is one of the critical issues in consideration of the application of these steels to the construction of a fusion reactor. The main differences in performance between the laboratory sample and the mill product are caused by impurity levels and the degree of segregation. This is especially critical for a reduced activation steel, which, when made from commercial raw materials, must be essentially free from high activation impurity elements.

In this study, F-82H plate was manufactured on a mill production scale and the engineering properties were compared with those from laboratory samples Well known ferritic/martensitic steels, e.g. 12Cr–1Mo–VW steel (hereafter referred to as HT9) [7] and the modified 9Cr steel (ASTM A213 T-91) [8], were also tested for comparison.

2. Experimental procedure

In order to reduce contents of the activation elements below the guidelines of reduced activation [9], high purity commercial raw materials were prepared, and a 5000 kg ingot was made using a vacuum induction furnace. The ingot was heated at 1523K and rolled into a slab. The slab was cut into two parts and they were then rolled to 15 mm and 25 mm thickness plates each. Both of the 15 mm and 25 mm thickness plates were heat-treated as follows: normalized for 1.8 ks at 1313 K followed by tempering for 3.6 ks at 1013 K. Chemical analyses were done on the plates using samples from three positions corresponding to the top, middle and bottom of the ingot. The activation elements were analyzed by an ICP-MAS (inductively coupled plasma mass spectrometry).

Specimens for the tensile and the creep rupture tests were machined from plates to 6 mm diameter and 30 mm gauge length. The axis of the specimens was in the direction of the rolling. The plates were aged in the temperature range of 673–973 K up to 36 Ms. After aging, Charpy impact tests were done using the full size 2 mm V-notch specimen.

Weight loss was measured at 523 K, 2.5 MPa for 0.9 Ms in a recirculating high temperature water environment containing 0.2 ppm dissolved oxygen. Physical properties were measured using the laser flash method for specific heat and thermal conductivity, the four-terminal method for electric resistivity, the differential thermomechanical analysis for thermal expansion, and the Archimedes method for density.

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Table 1
Chemical analysis of raw materials [a]

Element	Raw materials	Nb [ppm]	Mass of melting [kg]	Nominal content [wt.%]	Calculated Nb content in F-82H [ppm]
C	carbonet	–	5	0.1	–
Si	metallic silicon	< 1.0	5	0.1	< 0.001
Mn	metallic manganse	< 1.0	5	0.1	< 0.001
Cr	high purity metallic chromium	2.0	385	7.7	0.15
W	metallic tungsten	2.0	100	2.0	0.04
V	metallic vanadium	10.0	10	0.2	0.02
Ta	metallic tantalum	85.0	2	0.04	0.034
Ti	sponge titanium	1.1	1	0.02	< 0.0004
Fe	converter steel	< 0.5	4487	bal.	< 0.45
	total		5000	100	< 0.7

[a] The dash means: not analyzed.

3. Results

3.1. Chemical analysis of raw materials and ingot

The mass of each of the raw materials, and its Nb content, are shown in table 1. Only Nb among the harmful activation elements was analyzed because the upper limit of Nb was remarkably low in order to satisfy the reduced activation guidelines [9], i.e. 1.7 ppm. The Nb content of the ingot was expected to be less than 0.7 ppm by calculation from the result of chemical analyses of the raw materials. Nb contents of the hot rolled plate were in the range of 0.5–0.7 ppm (shown in table 2).

The chemical compositions of the ladle and the plates corresponding to the top, middle, and bottom of the ingot are shown in table 2. Fluctuation of the chemical compositions between the three sampling po-

Table 2
Chemical composition of alloys tested (wt.%) [a]

	Mill product of F-82H				Laboratory sample		
	Ladle	Plates			F-82H	HT9	Mod.9CR
		top	middle	bottom			
C	0.096	0.097	0.110	0.094	0.093	0.19	0.11
Si	0.10	0.09	0.09	0.09	0.09	0.22	0.45
Mn	0.15	0.07	0.07	0.07	0.49	0.48	0.43
P	0.003	0.002	0.003	0.003	0.005	0.018	0.006
S	0.003	0.0032	0.0029	0.0027	0.001	0.001	0.002
Cu	0.01	< 0.01	< 0.01	< 0.01	–	–	–
Ni	< 0.1	0.03	0.03	0.03	0.01	0.59	0.10
Cr	7.71	7.46	7.46	7.46	7.65	12.0	8.57
Mo	< 0.01	< 0.001	< 0.001	< 0.001	< 0.01	1.00	1.00
V	0.18	0.18	0.18	0.18	0.18	0.29	0.22
Ti	0.008	0.007	0.007	0.007	–	–	–
Nb	< 0.0005	0.00007	0.00005	0.00007	< 0.0005	< 0.0005	0.08
Sol Al	0.005	0.007	0.007	0.008	0.01	0.02	0.03
W	2.1	2.1	2.1	2.1	2.0	0.51	< 0.01
Ta	0.04	0.03	0.03	0.03	0.04	–	–
B	–	0.0004	0.0003	0.0004	0.0034	–	–
T.N	0.0043	0.0043	0.0044	0.0047	0.002	0.002	0.032
T.O	0.0028	0.0033	0.0049	0.0037	–	–	–
Ag	–	–	< 0.005	–	–	–	–
Co	–	–	0.005	–	–	–	–

[a] A dash means: not analyzed.

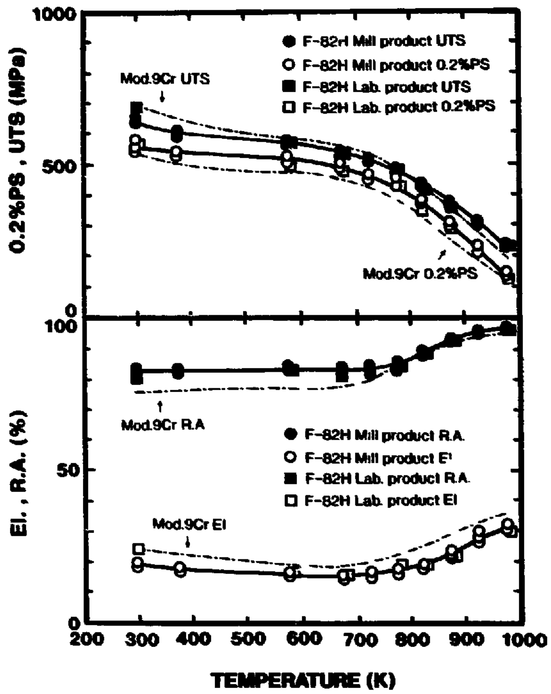

Fig. 1. Tensile strength and ductility of F-82H and the modified 9Cr–1Mo steel [8].

sitions is negligibly small. Therefore, the fluctuation of the engineering properties caused by the segregation should be minimal.

3.2. Tensile test and creep rupture test

The results of the tensile tests are shown in fig. 1. The differences between the mill product and the laboratory samples are negligibly small. The results of the creep rupture tests of the mill product are shown in fig. 2 along with the curves of the experimental alloy of F-82H. The curves are fitted to both of the mill product and the laboratory sample of F-82H, because the difference of rupture data between both of the heats were very small. The creep rupture strength of F-82H steel [8] is comparable to the modified 9Cr-1 Mo steel in the temperature range of 773–923 K except for over 1 Ms at 923 K.

3.3. Charpy impact test

The ductile-brittle transition temperature of the mill product of F-82H was 10–40 K higher than the laboratory sample before aging, e.g. 230 K and 200 K for the as tempered mill product and the laboratory sample, respectively. The absorbed energies at 273 K of thermally aged steels are plotted in fig. 3 as a function of aging time. The absorbed energy tends to decrease with increasing aging temperature and aging time. The absorbed energy at 273 K of the aged laboratory sample were 15, 147, 147, 284 J for 36 Ms at 923, 873, 823, 773 K respectively [2]. These results indicate the absorbed energies of the mill product are comparable to or higher than the laboratory sample. In either case, it is clear that the absorbed energies of F-82H are always higher than those of the modified 9Cr steel and HT9 if the aging temperature is below 873 K.

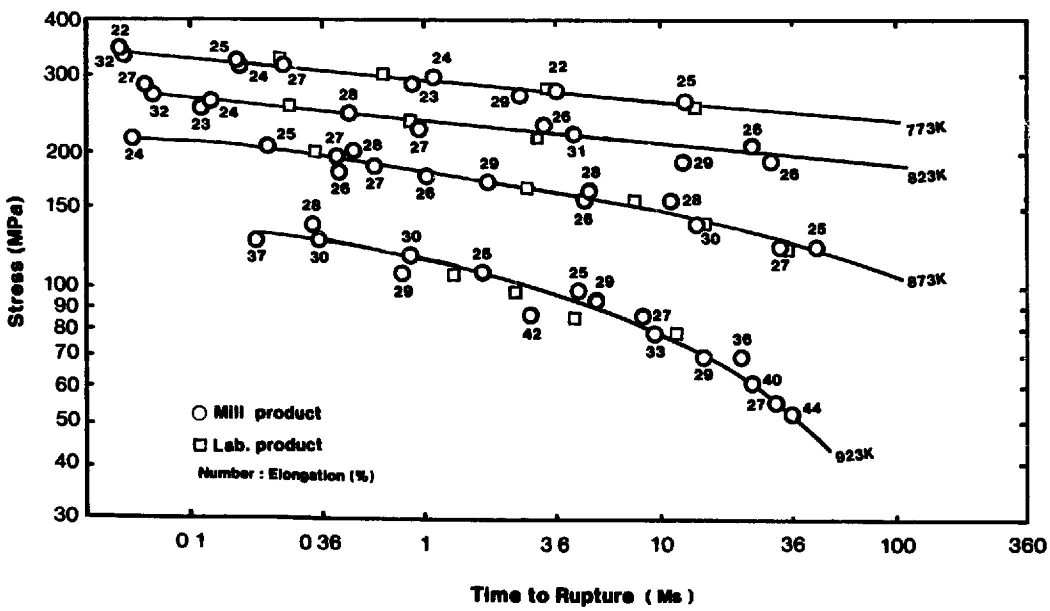

Fig 2 Results of creep rupture tests of F-82H.

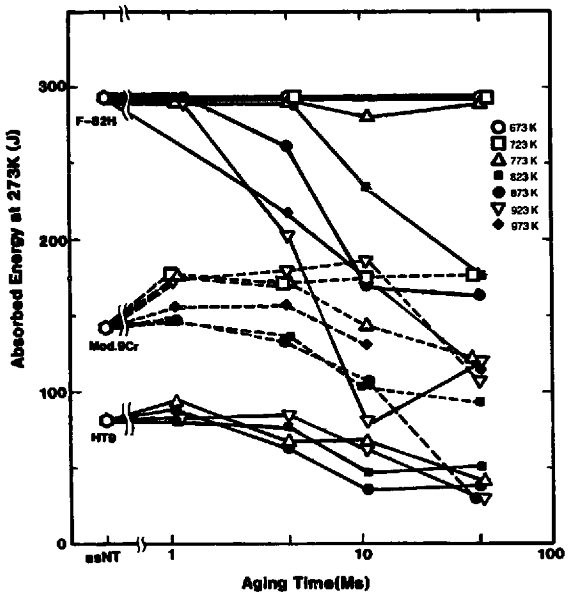

Fig 3 Change in toughness due to aging.

3.4. Corrosion test

Weight losses of F-82H, HT9 and 18Cr–4W steel after descaling are shown in fig. 4. A steel named 18Cr–4W steel was designed as a reduced activation material with high corrosion resistance in high temperature pure water, and was developed as a cladding material for F-82H [10]. The corrosion rate of 18Cr–4W steel is lower than 3 $\mu g/m^2s$, which shows 18Cr–4W steel is an excellent corrosion resistant material. The corrosion rate of F-82H was rather high and comparable to HT9.

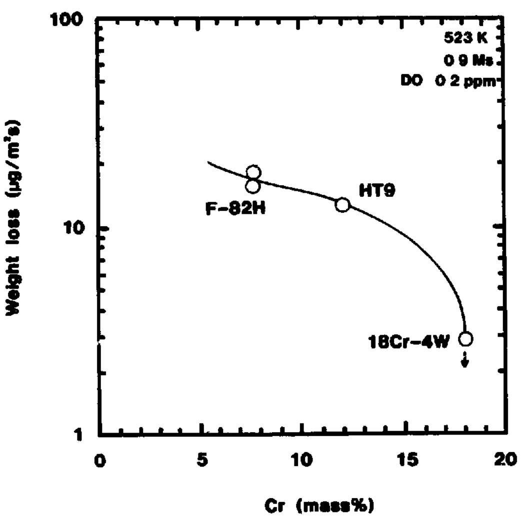

Fig. 4. Corrosion rate in high temperature water.

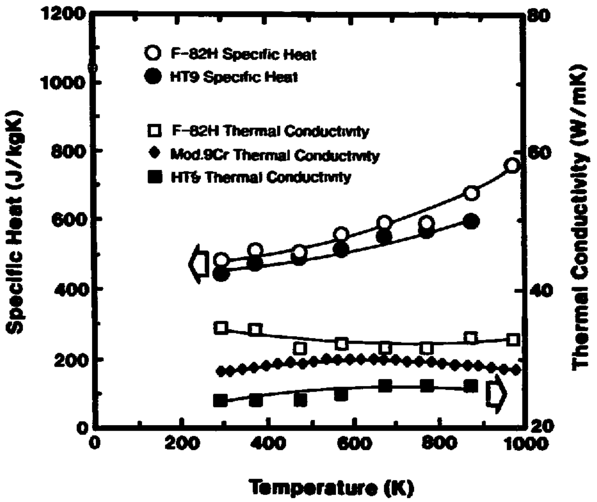

Fig 5. Specific heat and thermal conductivity of F-82H, HT-9 [11] and the modified 9Cr–1Mo steel [8].

3.5. Physical properties

The specific heat, thermal conductivity, electric resistance, and thermal expansion coefficient of F-82H steel are shown in Figs. 5 and 6. The room temperature density of F-82H was 7.89 Mg/m^3.

4. Discussion

4.1. Production in industrial scale

It was shown in a section 3.1 that F-82H, as a reduced activation steel, was able to be produced on an industrial scale by the careful selection of the raw

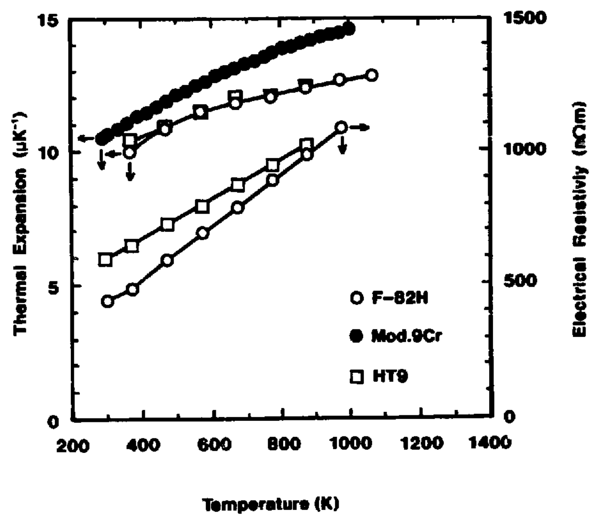

Fig. 6. Thermal expansion and electrical resistivity of F-82H, HT-9 [11] and the modified 9Cr–1Mo steel [8]

materials. Good accordance of the Nb contents calculated from the raw materials with the Nb contents of the mill product shows that picking up additional Nb from the crucible did not occur during the melting process. The process of production of F-82H plates is the same as the conventional Cr–Mo steels except for the selection of the raw materials and the cleaning of the crucible. This means that there should be no difficulty in producing F-82H on a commercial basis.

4.2. Properties

The mill product of F-82H showed almost the same level of tensile strength and creep rupture strength as the laboratory sample, and also showed about the same tensile and creep rupture strength when compared with the modified 9Cr steel up to 873 K. The tensile elongation of F-82H was lower than the modified 9Cr steel and the reduction in area of the tensile tests of F-82H was higher than the modified 9Cr steel as shown in fig. 1. These results are explained by the effect of the ratio of the gauge length and the diameter of a specimen, i.e. 5 for F-82H and 4 for the modified 9Cr–1Mo steel. The elongation of F-82H might become the same as the modified 9Cr–1Mo steel by the compensation of the size effect. The differences in the ductile-brittle transition temperature between the mill product and laboratory sample were explained by the difference of contents of N, i.e. 20 ppm for laboratory sample and 44 ppm for mill product. The higher absorbed energies of the mill product of F-82H than both modified 9Cr steel and HT9 might indicate F-82H will show higher absorbed energy after irradiation.

The corrosion rate in high temperature pure water clearly depends on Cr content of alloys, as shown in fig. 5. The corrosion rate of F-82H, which is higher than that of 18Cr–4W steel, is almost same as HT9. This value of the corrosion rate ($17\ \mu g/m^2 s = 0.07$ mm/yr) may be acceptable as structural component with a water treatment system to exclude dissolved ions. Helium gas, liquid metals, and molten salts are also candidates of the coolants of Tokamak reactor [11]. As a next step, there is need for investigation of the corrosion resistance of F-82H in these media.

The thermal conductivity of F-82H in fig. 5 is higher than the modified 9Cr–1Mo steel [12] and HT9 [13]. The lower thermal expansion compared with the modified 9Cr–1Mo steel is observed in fig. 6 The observed higher thermal conductivity and the lower thermal expansion of F-82H is one of the advantages of this alloy for use in high heat flux environment such as Tokamak reactor.

5. Conclusions

Large size F-82H plates were produced in a factory and measurements of various engineering properties were made. The following conclusions could be made.

(1) Plates of 15 mm and 25 mm thickness were successfully made from a 5000 kg ingot on an industrial scale.

(2) The contents of Nb in the mill product satisfied the guidelines for reduced activation when careful attention was paid to selection of the raw materials and cleaning the crucible.

(3) The mill product of F-82H showed almost the same levels of tensile and creep rupture strengths as the laboratory sample of F-82H.

(4) The corrosion rate of F-82H is marginally acceptable for structual components, cladding of 18Cr–4W steel on F-82H is more suitable to avoid the problems of dissolved ions from the component.

(5) F-82H is expected to allow higher heat flux compared with the modified 9Cr–1Mo steel and HT9 because of the higher thermal conductivity and lower thermal expansion.

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