The Development of Low Activation Ferritic Steels for Fusion Application

著者	Kohyama A., Hishinuma A., Kohno Y., Shiba K., Sagara A.
journal or publication title	Science reports of the Research Institutes, Tohoku University. Ser. A, Physics, chemistry and metallurgy
volume	45
number	1
page range	137-141
year	1997-03-28
URL	http://hdl.handle.net/10097/28716

Sci. Rep. RITU A45 (1997) pp. 137-141
No. 1, March 1997

The Development of Low Activation Ferritic Steels for Fusion Application

A. Kohyama[a], A. Hishinuma[b], Y. Kohno[c], K. Shiba[c] and A. Sagara[d]

[a] Institute of Advanced Energy, Kyoto University, Gokasho, Uji, Kyoto 611, Japan
[b] Tokai Establishment, JAERI, Tokai, Ibaraki, Japan
[c] Department of Materials Science, University of Tokyo, Hongo, Tokyo 113, Japan
[d] National Institute for Fusion Science, Toki, Gifu, Japan

(Received March 28, 1997)

The development of low-activation ferritic/martensitic steels is a key to the achievement of nuclear fusion as a safe, environmentally attractive and economically competitive energy source. The Japanese and the European Fusion Materials programs have put low-activation ferritic and martensitic steels R & D at the highest priority for a demonstration reactor (DEMO) and the beyond. An international collaborative test program on low-activation ferritic/martensitic steels for fusion is in progress as an activity of the International Energy Agency (IEA) fusion materials working group to verify the feasibility of using ferritic/martensitic steels for fusion by an extensive test program covering the most relevant technical issues for the qualification of a material for a nuclear application. The development of a comprehensive data base on the representative industrially processed reduced-activation steels of type 8-9Cr-2WVTa is underway for providing designers a preliminary set of material data for the mechanical design of components, e.g. for DEMO relevant blanket modules. The current design status of FFHR and SSTR utilizing low-activation ferritic steels is reviewed and future prospects are defined.

KEYWORDS: low activation ferritic steel, F82H, nuclear fusion

1. Introduction

Research and development (R & D) of low-activation materials is one of the most important challenges in fusion technology for making fusion energy systems acceptable and feasible energy options for the 21st century. Presently, low activation ferritic steels (LAFs), vanadium alloys and SiC/SiC composite materials are considered promising candidates[1,2]. Among them, the LAFs R&D is placed at the highest priority in the Japanese and the European programs. [3,4]

To accelerate the development of LAFs, a working group under the Annex-II of the International Energy Agency (IEA) implementing agreement on a program of research and development on fusion materials has been formed to coordinate a collaborative program between the European Union (EU), USA and Japan. The steels for the IEA test program have been provided from the two Japanese research sectors: the Monbusho universities program and the STA JAERI program. Two large heats (1 and 1.5metric tons) of JLF-1 steel (a 9Cr-2W steel) and two 5metric ton heats of F82H steel (an 8Cr-2W steel) were produced. Plates with thicknesses from 7 to 25 mm and plates of these thicknesses with EB or narrow gap TIG welded joints have been distributed to the participants of IEA working group and those of Japan/US collaboration program of fusion materials, JUPITER Program.

Together with the materials R & D activities, many conceptual design studies using LAEs are in progress. As the representing design studies, Steady State Tokamak Reactor (SSTR) [5] and Forced Free Helical Reactor (FFHR) [6] are introduced with the emphasis on "how LAFs are applied in the reactor systems, especially for blankets". It is also the objective of this paper to describe in some details the status and future perspectives of the LAFs development program.

Although the chemical composition of the JLF-1 used for the IEA round-robin test is the same from the pre-IEA heats, that of the F82H has been slightly modified. However, the physical and mechanical properties of the IEA heat alloys are almost the same as those of the pre-IEA heat alloys [7] Thus, in this paper, the baseline properties of F82H [8] and the irradiation data of JLF-1 are mainly introduced [9].

2. Baseline properties of LAFs

Physical properties[8]:

The temperature dependence of specific heat, thermal expansion and thermal conductivity are shown in Figs. 1 and 2.

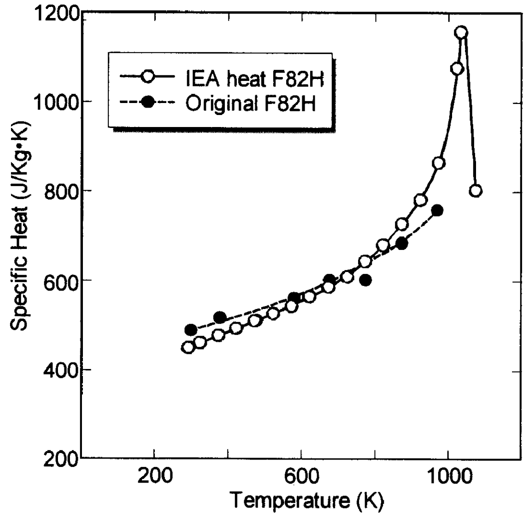

Figure 1. Specific heat of F82H

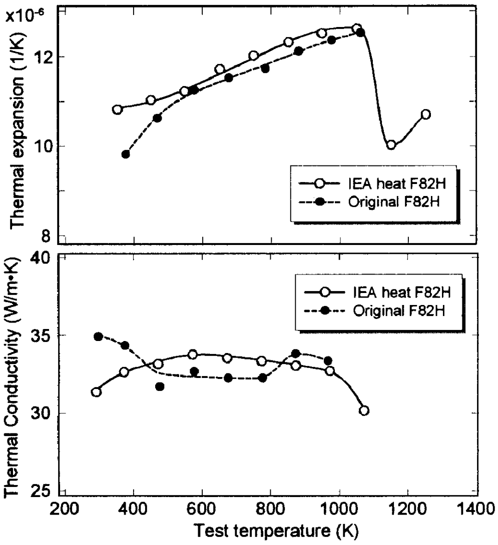

Figure 2. Thermal expansion and conductivity of F82H

The immersion density measured at 20°C (7.87 g/cm^3) was used to calculate the thermal conductivity. These properties of the IEA heat material are almost the same as those of the original F82H with slight difference above 800°C. These phenomenon were due to the re-austenization (A_{C1}). Both Young's modulus and modulus of rigidity decreased linearly with the test temperature from room temperature to 450°C, then decreased linearly with steeper slope at higher temperatures, in quantitatively similar manner with 9Cr type heat resistant ferritic/martensitic steels. Poisson ratio was constant to 500°C, then increased with temperature over the temperature corresponding the change in Young's modulus and modulus of rigidity. The same temperature dependence was obtained by the hardness measurement at high temperature. Magnetic properties are key properties for magnetic fusion application. As shown in Fig.3, the temperature dependence of the saturation and residual magnetization were measured. Saturation and residual magnetization were about 19500 and 200 Gauss at room temperature and both of them decreased with temperature increase.

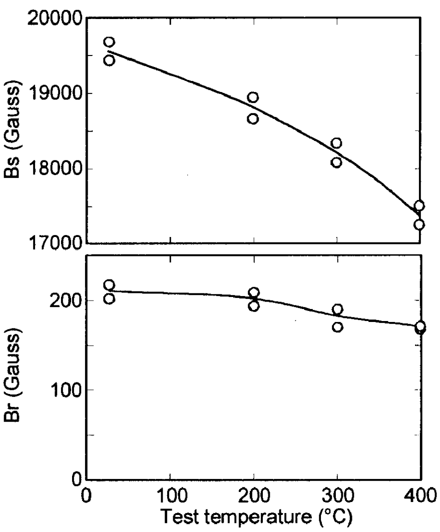

Figure 3. Saturation and residual magnetization of F82H

Mechanical properties

The results of the IEA round robin test have been published which showed improvement of basic mechanical properties wit better homogeneity[1,2,8,9]. The main origin of these improvements is due to the higher purity and improved quality and process controlls by Nippon Steel Corporation and Nippon Kohkan Co.

3. Properties under Neutron Irradiation[9]

The temperature dependence of yield stress and elongations of the FFTF/MOTA irradiated LAFs are shown in Figs. 4 and 5. Basically the same irradiation effects on tensile properties were observed in HFIR irradiated F82H[10]. The similar temperature and dose dependence was observed in FFTF irradiation on 3 points bending test[11].

Below about 400 C, radiation introduced increase in yield stress and loss of elongation at low dose level with larger effects for lower temperature, but this hardening and loss of ductility were recovered with the increase of the damage level. At temperature higher than 400 C, thermal effects dominated the mechanical property change under neutron irradiation.

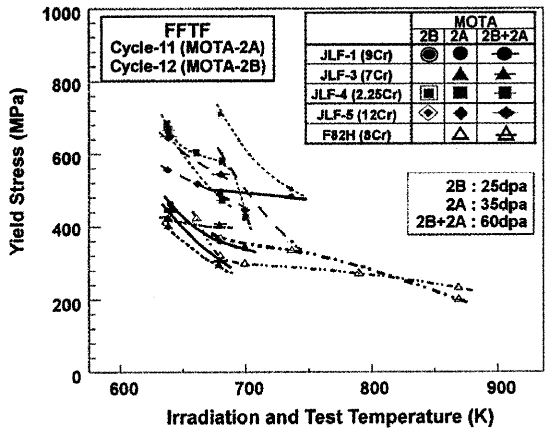

Figure 4. Temp. dependence of Yield Stress

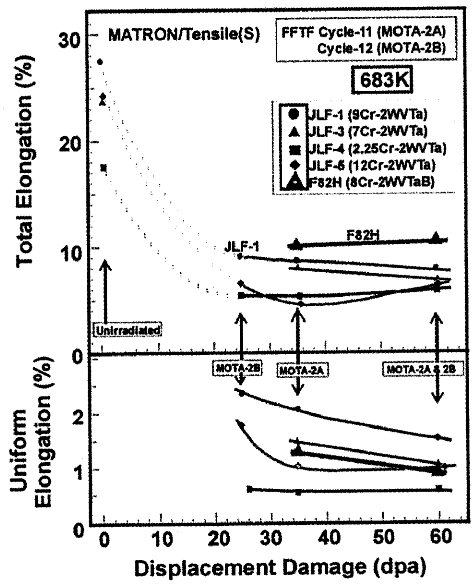

Figure 5. Temp. dependence of Elongations

In spite of the low dose level, heavy increase in yield stress with loss of elongation was observed after the irradiation at 520 K and 570 K in HFIR. However, with this low uniform elongation, the fracture toughness of the specimen irradiated in the same condition retained relatively high. The new HFIR irradiation experiment including tensile, Charpy and fracture toughness specimens of F82H and JLF-1 IEA heat has started since last January. This may provide important insights about this issue.

Heavy neutron irradiation in FFTF/MOTA was performed as high as 62 dpa for JLF-1 and 36 dpa for F82H. The results are shown in Fig.6 together with other low temperature irradiation data. Although the PIE has not been completed, the highest DBTT for JLF-1 was 215 K for 36 dpa and at higher dose of 62 dpa the DBTT recovered to 180 K. This is consistent with the dose dependence of tensile properties. Because the data was obtained by 1.5mm size small Charpy V-notched specimens, the absolute temperature has to be adjusted, it may be reasonable to define that DBTT of JLF-1 and F82H will be kept below room temperature even after heavy irradiation. Another concern is the effects of helium and ^{10}B-doping method has been utilized to study this. One of the recent results by JAERI group is on tensile properties of F82H with or without ^{10}B after irradiation in JMTR and JRR-2. There was almost no differences in yield strength over the all irradiation conditions. Although a slight difference in elongation was observed above 840 K, room temperature tensile test performed on the same irradiated specimens did not showed any differences in elongation. The new HFIR irradiation experiment including tensile, Charpy and fracture toughness tests of F82H and JLF-1 IEA heats has been started since the last January. It will provide insights about the correlation between tensile and fracture properties.

Irradiation creep is one of the most important mechanical properties at elevated temperature. Figure 7 is the results from FFTF/MOTA irradiated pressurized tubes of pre-IEA heats of JLF-1 and F82. Creep rate measured was not enhanced by neutron irradiation at the temperature higher than 500C. Although there is a indication of swelling enhanced creep deformation at 430C, the average creep coefficients for both JLF-1 and F82H are smaller than 10-12 Cr steels and 5-7 Cr steels.

The testing of some other properties, such as fracture

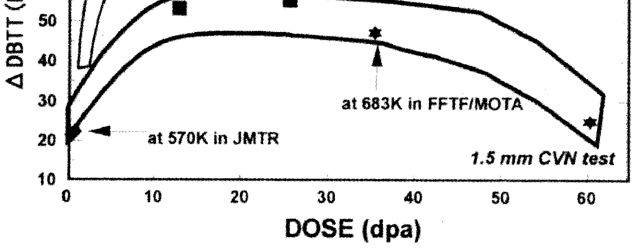

Figure 6. Dose dependence of DBTT shift

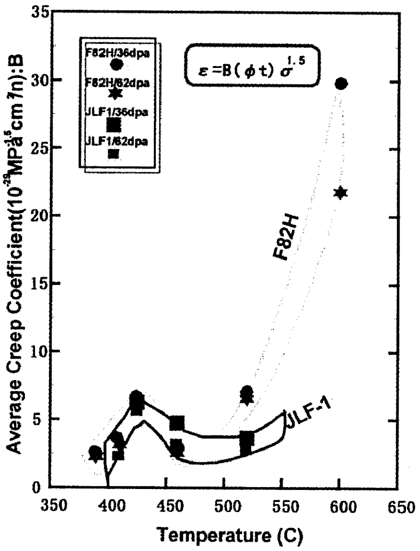

Figure 7. Temp. dependence of irradiation creep

toughness, fatigue and thermal cycling properties are in progress. Also the properties of welded joints by TIG, EBW and Laser welding are under investigation to optimize materials and processes. The recent results by JAERI group indicated that both TIG and laser welded joints did not exhibit the degradation than base metal after the HFIR RB* irradiation to 9 dpa at 670 K.

4.Preliminary design window for JLF-1

It has been requested to provide a temperature vs. total wall loading window over which the steels can be used for fusion applications. As was mentioned in the above, the current materials database is still insufficient to define the design window. Still, it may be worth providing a design window under the current knowledge even if it is a preliminary one. Figure 8 is a preliminary design window mostly based on the data of JLF-1 steel with fast neutron irradiation. The upper temperature is determined by either coolant compatibility (i.e., FLiBe, Li, Pb-Li, etc.) and/or creep and should approach 550 - 600C. The lower temperature is expected to be determined by radiation embrittlement effects that cause a decrease in toughness. The important thing is that we don't have the data on the effects of nuclear transmutation, such as the formation of helium, hydrogen, manganese and Re + Os, on irradiated properties[2].

5.Current design activities

Based on the first all-superconducting-coils device, LHD(Large Helical Device), the blanket design for Force-Free Helical Reactor, FFHR, has been developed.

The neutron wall loading was reduced to 1.5MW/m^2 for the 3GW fusion output. At any rate this wall loading in the reactor lifetime of 30 years leads to the total neutron dose of about 450 dpa. At present, within the available databases, no structural materials for the main in-vessel components has been demonstrated. However, by allowing of maintenance in every 10 years, materials reliable up to 120 dpa are reasonably used. With considering engineering

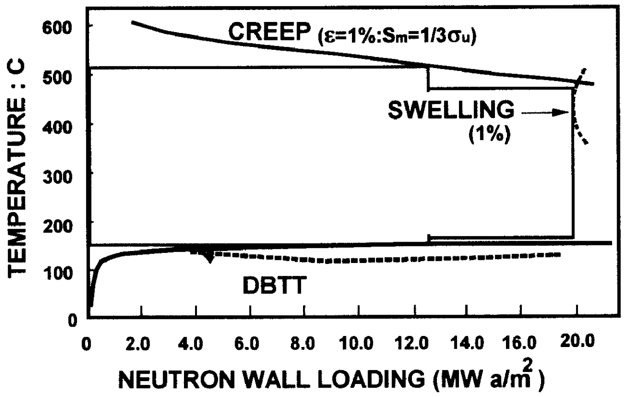

Figure 8. A Preliminary design window for JLF-1

databases and radioactivity, a ferritic steel JLF-1 (Fe9Cr2W) was selected as the first candidate. This bottom line would be improved greatly by the potential ODS (Oxide Dispersion Strengthened) steels. The advantage of FFHR is a low pressure operation with FLiBe due to low MHD resistance and fairly low vapor pressure around 800K. The coolant inlet temperature 723 K, determined from the melting temperature and viscosity of FLiBe limits the lower limit and the upper limit, i.e., the outlet temperature is determined from creep strength of JLF-1. As shown in Fig 8, under conditions of creep strain less than 0.5% at 100 MPa for the lifetime of 120 dpa, JLF-1 is hopefully used at temperatures around 823K. There is even a possibility to operate FFHR with much lower FLiBe pressure which allows much higher temperature operation. FLiBe is quite stable and less hazardous than other liquid metal or molten salt coolant, but the compatibility between FLiBe and JLF-1 is still an open question. The details of the materials-coolant interaction is discussed in reference 6.

On the other hand JAERI has been developing conceptual design of Steady State Tokamak Reactor (SSTR) for many years, utilizing F82H[5] and other low activation materials. An improved SSTR concept, A-SSTR[12], indicates very attractive features within the reasonable material performance of low activation ferritic steels. The ODS version of JLF-1 and F82H and their claddings with corrosion resistant alloys may broaden the designers flexibility with satisfying the reactor acceptability in future.

6. Limitation and future prospects

As described the above, the available data are insufficient to quantitatively draw a design window for fusion application. Also, compatibility with coolant and other blanket materials is recognized to be an important issue for fusion and is considered one of the high priority tasks in the IEA collaborative program. Another important issue concerns the use of a ferromagnetic LAFs in the high magnetic fields of a Tokamak reactor. R & D strategy for JLF-1 and F82H to be used in ITER, DEMO and power reactors is still unfixed, but the JFT-2M experiment to test the ferromagnetic effects in a Tokamak reactor is an important issue. The ferromagnetic effects of JLF-1 in a helical reactor will be also studied in the NIFS-universities program. A potential use for testing LAFs in the ITER are the DEMO-relevant blanket test modules under considerations by the different parties for the ITER Extended Performance Phase(EPP).

Testing of DEMO-relevant blankets in ITER with a new low-activation ferritic material may be possible if

(i) the general qualification tests are performed and,

(ii) a reference material specification including weld metal can be defined within the next 3-4 years,

(iii) the preliminary data and design methods can be verified in the next phase up to about 2005.

As usual for development projects that are carried out in parallel to design and fabrication, there is still further work for qualification and validation of data and processes.

For a qualification of new materials such as LAFs for nuclear application about 10 years are needed to develop the data, assuming adequate resources and tools are available for the test program.

7. Conclusions

1) The Japanese domestic and the IEA low-activation ferritic steel working group activities has been and is effective in planning and coordinating the international and domestic R & D programs on LAFs.
2) Preliminary data on LAFs and the current individual efforts are quite promising, but further coordination efforts and support are required to accomplish the R & D programs of LAFs.
3) To qualify and finally validate the application of 8-9CrWVTa steel, a sufficient design data base must be accumulated, including code approval aspects. A continuous use of mixed neutron spectra irradiation facilities(HFR, Phenix,..) is needed; however, for final validation of alloy performance under irradiation more relevant to fusion, the high-energy neutron source IFMIF should be available soon.
4) As an important milestone for the development of a blanket test module in ITER, a preliminary set of material design data is required by about 1999. For further verification and qualification, significant efforts are needed for a next milestone about 2005.

References

[1] Proceedings of International Conference on Fusion Reactor Materials, J. Nucl. Mater., Tokyo(1984), Chicago(1985), Kurlsrhue(1987), Kyoto(1989), Clearwater(1991), Streza(1993), Obninsk(1995).
[2] A. Kohyama,, H. Matsui and A. Hishinuma: Proceedings of 10th Pacific Basin Nuclear Conference (1996)883.
[3] Proceedings of the IEA Working Group Meeting on Ferritic/Martensitic Steels, Tokyo(1992), Oak Ridge(1993), Sun-Valley(1994), Oak Ridge(1995), Baden(1995), Culhum(1996).
[4] A. Kohyama, A. Hishinuma, D.S.Gelles, R.L.Klueh, W.Dietz and K.Ehrlich: J. Nucl. Mater. 233-237(1996)138.
[5] Y. Seki et al: IAEA-CN-G-1-2(1990),
[6]. A. Sagara et al.: in this proceedings
[7] K. Shiba, N. Yamanouchi and A. Tohyama: Fusion Materials, DOE/ER-0313/20(1996)190.

[8] N. Yamanouchi, M. Tamura, H. Hayakawa, A. Hishinuma and T. Kondo: J. Nucl. Mater. 191-194 (1992) 822.

[9] Y. Kohno and A. Kohyama: "Materials for Advanced Energy Systems & Fission and Fusion Engineering '94"(1994)325.

[10] K. Shiba, I. Ioka, J.E. Robertson, M. Suzuki and A. Hishinuma: Proc. of EUROMAT 96 (1996)

[11] Kohyama A, Kohno Y, Asakura K, Kayano H: J. Nucl. Mater. 212-215 (1994) 684-689.

[12] M. Kikuchi: JAEI-Research 97-004(1997)