SUMMARY OF IEA WORKSHOP/WORKING GROUP MEETING ON FERRITIC/MARTENSITIC STEELS FOR FUSION—R. L. Klueh (Oak Ridge National Laboratory)

OBJECTIVE

The objective of this report is to describe the working group meeting and workshop held to review planned and completed work that is being undertaken to prove the feasibility of using ferritic/martensitic steels for fusion applications.

SUMMARY

The International Energy Agency (IEA) Working Group on Ferritic/Martensitic Steels for Fusion held a workshop in Tokyo, Japan, 2-3 November 2000. Participants came from Europe, Russia, the United States, and Japan to review the progress of the collaboration on reduced-activation ferritic/martensitic steels and the development of plans for future collaboration. At this workshop, data that have been obtained during the collaboration were reviewed, and it was generally agreed that the testing phase for the IEA heats of steel obtained for this collaboration is near completion. A database has been established on the completed work, and that database is available to the international community. Based partially on the work performed in this collaboration, the European Union has developed specifications for a new reduced-activation steel, EUROFER 97, which has been produced and is now being evaluated. The other material of interest at this workshop was oxide dispersion-strengthened (ODS) steel, which was the subject of presentations from Europe, Japan, and the United States. The consensus is that selective utilization of these steels offers the possibility of a ferritic martensitic steel that will allow higher operating temperatures for a fusion device, although it is recognized that ODS steels are still in the early stage of development.

PROGRESS AND STATUS

Introduction

The IEA Working Group on Ferritic/Martensitic Steels for Fusion under the auspices of the IEA Executive Committee for the Implementing Agreement on Fusion Materials conducted a workshop at Tokyo, Japan, 2-3 November 2000. Researchers from the European Union (6) the United States (8), Switzerland (2), Russia (2), and Japan (23) participated. The purpose of the Working Group is the establishment and coordination of an international collaborative test program to determine the feasibility of using ferritic/martensitic steels for fusion.

This workshop was the eleventh meeting of the Working Group, which was formed as a result of a workshop on ferritic/martensitic steels in Tokyo in October 1992. At the first meeting following the Tokyo workshop, the Working Group developed specifications for large heats of reduced-activation steels and outlined a collaborative research program. Two 5-ton heats of the IEA-modified F82H steel and two 1-ton heats of JLF-1 steel were subsequently produced, fabricated into plates, and distributed to the participants of the collaboration. Weldments were also produced and distributed. Subsequent meetings have been used to plan a test program and to coordinate the acquisition of the data needed to prove feasibility for the steels for fusion applications.

Research and Development Activities

The following is a brief description of the information presented at the Tokyo workshop. Copies of viewgraphs and other information presented at the workshop are available.

RAF/M Development Programs

This session reviewed the programs of the European Union, Japan, Russia, and the United States.

B. van der Schaaf presented the materials development program of the European Union, which is presently in the second year of a four-year program. The program is focused on building a breeding blanket, which means design data, licensing, codes, database, etc., are important. The majority of the work is on the reduced-activation EUROFER 97, on which a range of studies is underway; these studies include: metallurgical characterization, mechanical properties of base metal and welds, irradiation effects, aging effects, dissimilar metal welds, and compatibility. Irradiations up to 30 dpa and 450ºC are to be carried out. Compatibility studies in both water and Pb17Li are planned. In parallel with the studies on the conventional steels, work will also be pursued on ODS steels using the EUROFER 97 alloy to produce the metal powder from which the ODS alloy will be produced.

V. Chernov presented the Russian materials program. The objective of the program is an understanding of the irradiation behavior of ferritic/martensitic steels. To that end, a 5-year irradiation program is planned for the BN-600 reactor. Work will concentrate on 12Cr conventional and reduced-activation steels. Irradiations are planned at 400-600ºC and 35-85 dpa. The 12Cr steels were chosen because of their better heat resistance.

The U. S. program, which was presented by R. L. Klueh, has as its objective the widening of the temperature operating window for the ferritic/martensitic steels. At the low-temperature side, emphasis is on understanding the phenomena and mechanisms of fracture with studies of microstructure-property relationships, specimen size effects, crack geometry effects, etc. Understanding helium effects is extremely important. At the high-temperature side, alloy development, including the development of dispersion-strengthened steels will be pursued.

For the Japanese program discussed by S. Jitsukawa, the primary target of the program is the development of ferritic/martensitic steels with improved properties at elevated temperature. These studies, which involve Japanese national institutes, universities, and industry, are of importance because reduced-activation ferritic/martensitic steel has been selected as the candidate material for a blanket structure of a prototype reactor. Development of ODS steels is also a part of the program. The Japanese program is carried out in conjunction with a blanket design concept and the service conditions projected for an operating machine. Design studies of prototype reactors with ferritic/martensitic steels have been and are being conducted. In the future, blanket test modules using these materials are planned.

The final paper of this session was by T. Hatano, who discussed the conceptual design of a DEMO blanket that has been developed by JAERI. Any such fusion plant must be competitive with other power-generation systems and must predict the technological requirements for a commercial reactor. To meet such objectives, a system with high thermal efficiency is required, and the result was a blanket designed to be cooled with supercritical water with a first wall temperature above 600ºC. This would probably mean that conventional ferritic/martensitic steels could not be used, and ODS steels would have to be developed if a ferritic steel is to operate at such a temperature.

Baseline Properties

K. Shiba discussed the status of the database (unirradiated) on mechanical properties of the IEA heats of F82H and JLF-1 steels developed primarily by the IEA collaboration. Large amounts of tensile, creep, and impact data have been obtained. Fracture toughness, fatigue, and thermal fatigue data have also been determined, and the mechanical properties of welds and welded joints have been measured. The round robin test results indicated reasonable agreement between the IEA parties participating in the testing. A recommendation from the testing program is the use of a rolling temperature <1050ºC, which will produce a smaller and more favorable prior austenite grain size.

Aging studies of F82H at 500-650ºC have demonstrated the propensity of the steel to form Laves phase, which lowers the impact toughness.

A. Möslang presented data generated at Karlsruhe on the isothermal strain-controlled low-cycle fatigue and thermal fatigue properties on several steels, including F82H, OPTIFER, MANET, and EUROFER 97. A large number of results for these steels was presented. Among those results, it was observed that MANET II displayed an order of magnitude better thermal fatigue strength (200-600ºC) than OPTIFER and F82H. The reason for this is probably the higher strength of the MANET. For the thermal creep, the effect of hold time and the temperature window (upper and lower temperatures) has a large effect on the properties. Because of the large effect of the test conditions, care needs to be exercised in the selection of conditions to arrive at a manageable testing schedule.

N. Baluc discussed the constitutive behavior of ferritic/martensitic steels and, in particular, F82H. This behavior is determined up to the uniform strain with tensile tests over a broad range of temperatures (-196 to 450ºC) and strain rates supplemented with strain-rate jump, relaxation, and Cottrell-Stokes (reversibility of the flow stress with temperature) experiments. The constitutive relations were then based on a dislocation mechanics model that is based on the decomposition of thermal and athermal components of the yield stress and strain-hardening components.

Irradiation Effects on Mechanical Properties and Microstructure

The radiation effects studies in the Japanese program were presented by K. Shiba, Y. Kohno, A. Kohyama, and T. Sawai. Shiba reviewed the irradiation studies of F82H. A wide-range of tensile and Charpy results have been generated, including studies to determine a helium effect. Kohno detailed the irradiation studies of the impact behavior of JLF-1 and F82H to 60 dpa at 365-425ºC in EBR-II and FFTF. Kohyama discussed the university results, primarily fatigue and tensile behavior. Sawai discussed recent microstructure studies on irradiated F82H.

F. Tavassoli, using the European properties database developed for ITER as an example, discussed the development of a design database for reduced-activation ferritic/martensitic steels. This database was started by collecting and analyzing the data on modified 9Cr-1Mo steel, after which it was extended to F82H steel and the data that have been generated in the IEA collaboration. In the future, collection of data on F82H will continue, and data collection on EUROFER will begin. The importance of fully traceable material (i.e., fabrication history, thermomechanical treatments, test conditions and procedures, irradiation conditions, etc.) was emphasized.

B. van der Schaaf discussed an irradiation program on electron beam and TIG weldments being carried out at Petten. KLST impact specimens taken from various positions of the welds were irradiated at a nominal 300ºC to about 2.5 dpa. Differences in properties with position in the weld were demonstrated, with the bottom material having the lowest DBTT, the top the highest. Similar effects were observed before and after neutron irradiation. Certain of the weldments had DBTT values over 200ºC after irradiation.

R. L. Klueh described preliminary fracture toughness results for F82H steel before and after irradiation to about 3.8 dpa at 220-280ºC and 310-405ºC. Embrittlement occurred for the lower temperature irradiation, with only small changes occurring at the higher temperatures. In the second part of Klueh's presentation, microstructural observations and tensile and creep properties of two Fe-12Cr ODS steels were described. An Fe-Cr-W-Ti-Y_2O_3 steel showed excellent creep and tensile properties. Dual-beam ion irradiations of the ODS steels indicated the effect of particle size and particle number density on the distribution of the helium in the microstructure.

Advanced Alloys

In fracture toughness studies of the commercial ODS ferritic steel MA 957 discussed by G. R. Odette, it was found that the properties were very anisotropic, as determined by the fabrication process

(extrusion), the inclusion content, and geometry. Remarkably high fracture toughness was found in the L-R (longitudinal-radial direction of the extruded rod) direction where a transition temperature of -40ºC was measured. This compared to very poor properties in the other two perpendicular directions. The properties in these directions were hindered by elongated Al_2O_3 inclusions.

M. Toloczko reported on the irradiation creep of pressurized tubes drilled from extruded rods of the commercial ODS ferritic steel MA 957 irradiated to 110 dpa in FFTF at 400-600ºC and compared the results to those on HT9 irradiated similarly. MA 957 steel had equal or slightly better irradiation creep resistance than HT9, with the difference improving with increasing temperature, indicating the effectiveness of the Y_2O_3 dispersion on the creep strength.

Initial results of the European Union program to produce an ODS steel based on a matrix of the EUROFER 97 composition with about 0.25% Y_2O_3 were reviewed by F. Tavassolli. Billets of 400 g and 5 kg were produced by a combination of mechanical alloying and the hot isostatic pressing (HIP) process at 1020ºC and 1000 bars for 2 h. Results indicated a higher strength at 600ºC than the EUROFER 97 produced by conventional techniques.

S. Ukai presented results on a ferritic and martensitic ODS steel developed at JNC, on a martensitic ODS steel based on JLF-1 developed by MONBUSHO, and on a series of martensitic steels based on F82H being developed by JAERI. He remarked on the positive effect of Ti in the JNC steels. The JNC ferritic and martensitic steels had similar internal creep strength, although the martensitic alloy had a slightly higher ultimate tensile strength at 700ºC in tensile tests on rings in the hoop direction. The MONBUSHO and JAERI ODS steel programs are in the early stages of development. Researchers in the MONBUSHO program at Kyoto university produced a steel using JLF-1 powder and 0.3% Y_2O_3, and they are in the process of determining the optimum heat treatment and mechanical properties. The JAERI program with F82H powder and a Y_2O_3 oxide dispersion is in the process of determining the optimum composition.

Activities on RAF Development

K. Ehrlich reported on the European effort to develop EUROFER 97. He explained the rationale for the higher chromium and tantalum and lower tungsten and boron contents in the EUROFER 97 compared to previous steels, particularly the F82H steel. A large-scale (3.5 ton) heat of EUROFER 97 has been produced, and preliminary results show good behavior (physical metallurgy, transformation behavior, hardenability, and mechanical properties—tensile, impact, and creep) relative to previous grades of reduced-activation steel. Preliminary results were also presented on ODS steels with 0.3 and 0.5 % Y_2O_3 produced by the HIP process using EUROFER 97 powder. The tensile strength of the ODS steels was higher than for the EUROFER 97 produced by the conventional process with no apparent sacrifice in tensile ductility.

Work was reported by R. L. Klueh on the effect of Cr, W, Ta, and B on the properties of 5-9Cr-WV steels containing 0.25% V and 0.1% C. Tungsten had little effect on strength but had a positive effect on DBTT. Tantalum improved the strength and the DBTT, but doubling Ta from 0.1 to 0.2 had no effect. Boron had little effect on strength and a negative effect on DBTT of 5 and 7% Cr steels, but it had a positive effect on 9% Cr steel. For 5, 7, and 9Cr-2WVTa steels, the 5 and 9Cr steels had the best strength, and the 5Cr steel had the best Charpy properties.

V. Chernov presented work on the 12 Cr reduced-activation steels developed in Russia. Two industrial-size heats have been manufactured, and their initial microstructures and mechanical properties have been determined. These steels contained about 20% delta-ferrite, but it was concluded that this amount should not adversely affect the properties. In the future, they will seek to make steels without delta-ferrite. The new steels will be included in the future irradiation experiments that were discussed in an earlier presentation.

A. Kimura described work on JLF-1 reduced-activation steels without and with 1.5% Ni and showed that irradiation of the steels in ATR and JMTR produced a larger hardening in the nickel-containing steel. He also presented work for TEM specimens of helium-injected steel tested in a small-punch test. No effect of hardening due to helium could be detected, and no change in fracture mode of the helium-containing specimens tested at low temperatures was observed. TEM studies on JLF-1 after irradiation (425-600ºC) and thermal aging (375-600ºC) were presented that demonstrated the formation of Laves phase under the test conditions. A (Ti,Ta)-rich precipitate also formed during irradiation.

M. Victoria showed results from pure iron and F82H irradiated with neutrons in an experimental reactor and with 600 keV protons in the PIRX facility at PSI. The displacement damage in the neutron-irradiated iron produced a cavity structure. When helium was generated in the proton irradiation for irradiation doses similar to the neutron irradiation, a similar cavity structure was produced. Therefore, the fact that helium does not produce hardening, as observed in numerous experiments, is explained, because the helium is distributed in the pre-existing cavities (those produced by displacement damage). Cavity structures similar to those observed in the iron were also observed in F82H after irradiation, indicating a similar explanation applies to the more complicated alloy. This observation of a lack of hardening caused by helium in the steels complicates any explanation of the increase in DBTT of these steels that has been attributed to helium.

G. R. Odette reported on progress in master curve development for BCC alloys. The use of the master curve is part of a larger effort that has the objective to eventually use small test specimens to obtain data that can be used in the structural analysis of a design and to set operating limits for the structure. To reach this goal, a science- and engineering-based process is proposed that involves the use of constitutive models developed from microstructure-property relationships to produce micromechanical-based local fracture models that can be applied to small specimens used to measure mechanical properties. Examples of the use of the procedure for unirradiated and irradiated materials were presented.

N. Yamamoto reported on load-controlled in-situ fatigue tests of F82H irradiated by 17 MeV protons at 60ºC and 1×10^{-7} dpa/s. Fatigue life was enhanced under irradiation that was explained by the radiation-induced point defects that are continuously produced during the fatigue process. F82H was also implanted by alpha-particles with 1000 appm helium at 550ºC, after which creep-rupture tests were made at 550ºC. No indication of helium embrittlement was observed in terms of the rupture time and ductility, and there was no indication of a change in fracture mode.

V. Chernov discussed corrosion of Armco iron by lead that contained oxygen. An oxygen effect was established in terms of the oxide phases that form. A model was developed to explain the observations. The model involves the cyclical formation and dissolution of the various oxides on the iron surface.

Other Presentations

Three presentations not on the agenda were made during one of the discussion sessions.

A Kohyama presented work by H. Sakasegawa et al. on the microstructure-mechanical properties correlations for high-temperature properties of JLF-1 with 2% W and the JLF-1 composition but with higher tungsten concentrations (2.5, 3.0, and 3.5% W were examined). Increasing tungsten to above 2% is considered a possible way to produce a steel for use at higher temperatures than is possible for a steel with 2% W. Increasing the tungsten to 3.5% increased the tensile and creep strength and lowered the impact toughness. For long-time creep-rupture tests, TEM indicated that the increased tungsten increased the amount of Laves phase that formed and caused the elimination of M_6C from the microstructure compared to the JLF-1 with 2% W. Although the amount of tungsten in solution was greater in a 3% W steel than a 2% W steel before test, there was little difference after a 650 or 700ºC creep-rupture test.

D. S. Gelles described the use of isotopic tailoring with ^{54}Fe to study hydrogen and helium effects. When ^{54}Fe is irradiated in HFIR, both helium and hydrogen is produced, and this is a possible way to conduct a single-variable irradiation experiment on the effect of these gases on mechanical properties. A small number of TEM disks have been irradiated, and a technique was developed that made it possible to obtain not only microstructural information, but also mechanical property data with a shear punch test from a single specimen. In principle, the use of ^{54}Fe appears to be the ideal technique for studying helium effects, the only problem being the high cost of the isotope (about $20,000/g).

T. Hirose presented data on the fatigue of JLF-1 and F82H at ambient temperature obtained using 25.4-mm-long miniature hourglass specimens and a laser extensometer. No effect of specimen size was observed when compared to full-size (100-mm long) specimens. Cyclic softening occurred up to failure; the failure appeared to start with a crack that initiated at a prior austenite grain boundary. Transmission electron microscopy of specimens from the vicinity of the fracture surface indicated a polygonization-like structure replacing the tempered martensite structure during the test.

A presentation on results of irradiation experiments of ferritic/martensitic steels by V. K. Shamardin indicated that a large amount of data have been generated in Russian irradiation experiments in the BOR-60 reactor over the range 335-390ºC up to a maximum damage dose of about 50 dpa. Irradiations have been made on 9Cr-1WVTa steel with 0.1% C and a 12Cr-2WVTiB steel with 0.15% C. The results are important because the experiments have considered the effect of composition, processing, microstructure, etc., and the results need to be considered as further alloy development proceeds.

Discussion Sessions

Discussion sessions were held on the following topics: (1) Summary of Round-Robin Tests and Future Collaboration, (2) Irradiation Effects, and (3) Improvement of the Alloy.

The testing of the IEA heats of F82H and JLF-1 and the round-robin testing that was part of the overall testing has produced a large amount of data. A database has been established by JAERI, and there was a discussion about the need to document the data. Specimen types and sizes were also discussed. The type of specimen used for fatigue tests was thought to be most important, as there appears to be discrepancies on data obtained on hourglass and parallel-side specimens.

The still unanswered question of helium effects hangs over the ferritic/martensitic steels. Simulation techniques (implantation, ^{54}Fe, Ni, and B doping) with their inherent uncertainties are the only methods presently available for such studies, and there are proposals for future work to try and use these techniques constructively. This uncertainty with helium makes the need for a 14 MeV neutron source urgent for the fusion program.

Alloy development for fusion has now moved beyond the F82H and JLF-1 used in the IEA collaboration, as the Europeans and Japanese have determined compositions and processing schedules for the 7-9 Cr class of steel, and large heats are being procured for characterization and development of an engineering database. The area of interest for future development is the ODS steels. The general approach in Europe is to use the EUROFER 97 composition for the matrix and Y_2O_3 for the dispersion to produce a martensitic ODS steel. Similar approaches are being used in Japan with the F82H and JLF-1. In the United States, both ferritic and martensitic ODS steels will be investigated. There is a need to explore a collaborative approach in this endeavor.

Action Items

The following action items were proposed:

1. Produce a report documenting the data collected in the collaborative work on the IEA heats of steel.
2. A meeting will be organized for around February 2001 to discuss a collaboration on ODS steels.
3. A large heat of the new European reduced-activation steel, EUROFER 2001 will be produced. Any of the IEA participants that wish to obtain material to incorporate in their test program should inform B. van der Schaaf of their needs (how much and what type of geometry).

No time or place for the next workshop was determined. It would be possible to hold a workshop in conjunction with ICFRM-10, but the need for a workshop in addition to the ICFRM-10, where much of the new work on ferritic/martensitic steels would be expected to be discussed, needs to be determined.