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Influence of Tempering on Mechanical Properties of Ferritic-Martensitic Steels

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1. Introduction

In the mid-1980s research programs for development of low activation materials began. This is based on the US Nuclear Regulatory Commission Guidelines (10CFR part 61) that were developed to reduce long-lived radioactive isotopes, which allows nuclear reactor waste to be disposed of by shallow land burial when removed from service. Development of low activation materials is also key issue in nuclear fusion systems, as the structural components can became radioactive due to nuclear transmutation caused by exposure to high-dose neutron irradiation. Reduced-activation ferritic-martensitic (RAFM) steels have been developed in the leading countries in nuclear fusion technology [1-3], and are now being considered as primary candidate material for the test blanket module (TBM) in the international thermonuclear experiment reactor (ITER). RAFM steels developed so far (e.g., EUROFER 97 and F82H) meet the requirement for structural application in the ITER. However, if such alloys are used in the DEMO or commercial fusion reactor is still unclear, as the reactors are designed to operate under much severe conditions (i.e., higher outlet coolant temperature and neutron fluences). Such harsh operating conditions lead to development of RAFM steels with better creep and irradiation resistances.

Mechanical properties of RAFM steels are strongly affected by microstructural features including the distribution, size and type of precipitates, dislocation density and grain size [4, 5]. For a given composition, such microstructural characteristics are determined mainly by thermo-mechanical process employed to fabricate the final product, and accordingly a final heat treatment, i.e., tempering is the key step to control the microstructure and mechanical properties. In the present work, we investigated mechanical properties of the RAFM steels with a particular attention being paid to effects of tempering on impact and creep properties.

2. Methods and Results

2.1 Experimental procedures

The materials investigated in the present work include two reference alloys (i.e., F82H and EUROFER97) developed in Japan and the Europe Union, respectively, and two experimental alloys (i.e., F164 and F168) currently being developed by the present authors. Rectangular shaped ingots were produced by vacuum induction melting (VIM) in the POSCO. The ingots were hot rolled to 15mm-thick plates, following a pre-heat treatment at 1200°C for 2 h. The hot-rolled plates were heat treated to produce a fully martensite structure and then tempered at three different conditions according to the schedules given in Table I: one is a normal tempering condition which has been optimized for each alloy by its developer [6, 7], and the others are those with a shorter or longer annealing time, which leads to the under- or over-tempered microstructure, respectively.

Plate-type sub-size tensile specimens with a gage dimension of 2.5 mm in thickness, 6.25 mm in width and 25 mm in length (ASTM E8) were machined from the tempered plates, and an uniaxial tensile test was performed at temperatures between 25~600 °C at an initial strain rate of 10^{-3} s^{-1}. Creep rupture test was conducted at 550 °C under an applied stress of 240 MPa, using a rod-type specimen with a gage dimension of 6 mm in diameter and 28 mm in length. A ductile-brittle transition temperature (DBTT) of the tempered plates was determined by the Charpy impact test, for which a full-size notched bar was used according to the ASTM E23.

Table I: Normalizing and tempering schedules employed for the RAFM steels studied in the present work. All the samples were air-cooled following each heat treatment.

	Normalizing	Tempering		
		Under	Normal	Over
F82H	1040°C/38m	750°C/30m	750°C/60m	750°C/180m
EUROFER97	980°C/30m	760°C/30m	760°C/90m	760°C/180m
F164 F168	1050°C/30m	760°C/30m	760°C/90m	760°C/180m

2.2 Results and Discussion

The increase in tempering time lowers the yield strength but enhances the total elongation of the alloys examined. The yield strengths of the tempered plates are shown in Fig. 1. In the under-tempered condition, the yield strength of F82H and EUROFER97 is ~680 MPa at room temperature, while experimental alloys show slightly lower values, i.e., 654 and 615 MPa for F164 and F168, respectively. Increase in tempering time to 60 or 90 min. results in a significant reduction in yield strength and the extent of which is much greater for EUROFER97. In the over-tempered condition, yield strengths of the alloys are quite similar each other, showing values ~430 MPa. The increase in tempering time, on the other hand, enhances ductility of the alloys: the under-tempered samples show 16~20% in total elongation and it is ~25% when over-tempered.

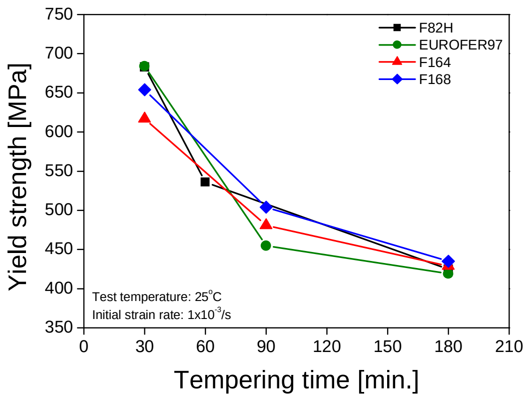

Fig. 1. Effects of tempering time on yield strength of the RAFM steels studied in the present work.

The influence of tempering time on the DBTT of the RAFM steels is shown in Fig. 2. For the under-tempered samples, the F164 alloy shows the lowest DBTT (–43 °C) while the DBTT of the reference alloys are much higher, ~10 °C. The DBTT of the samples examined decreases as the tempering time increases up to 90 min. However, further increase in tempering time (up to 180 min.) has little influence on DBTT.

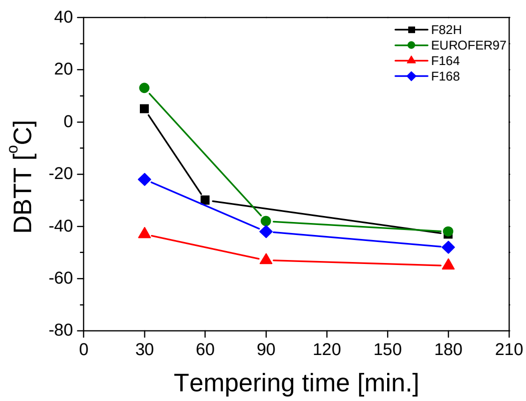

Fig. 2. Effects of tempering time on the DBTT of RAFM steels studied in the present work.

The short-term creep rupture test suggests that the creep rupture time at constant temperature and stress is significantly affected by the extent of tempering: the rupture time of the under-tempered samples are at least three times longer than that of the normally tempered counterparts.

Transmission electron microscopy reveals a high density of dislocations in the under-tempered samples, which is significantly reduced in the normally-tempered one. The over-tempered samples show a well-defined sub-grain structure and a huge number of precipitates. Most of precipitates formed are found to be carbides which are much larger than those formed in the under- and normally-tempered counterparts. It is surmised that a higher dislocation density in the as-tempered state enhances the creep resistance but impairs impact resistance. This in turn suggests that a proper choice of tempering condition is the key to optimizing mechanical properties of the RAFM steels.

3. Conclusions

The present work has demonstrated that the tensile properties, impact resistance and creep properties are significantly affected by the degree of tempering. An attempt was made to correlate the mechanical properties with microstructural characteristics and it is concluded that dislocation density and distribution of precipitates have great influence on mechanical properties. This in turn emphasizes an importance of optimizing tempering condition of the RAFM steels.

REFERENCES

[1] H. Tanigawa, K. Shiba, A. Möslang, R.E. Stoller, R. Lindau, M.A. Sokolov, G.R. Odette, R.J. Kurtz, S. Jitsukawa, Status and key issues of reduced activation ferritic/martensitic steels as the structural material for a DEMO blanket, Journal of Nuclear Materials, Vol. 417, p. 9, 2011.
[2] R.L. Klueh, Reduced-activation steels: Future development for improved creep strength, Journal of Nuclear Materials, Vol. 378, p. 159, 2008.
[3] E. Lucon, W. Vandermeulen, Overview of the tensile properties of EUROFER in the unirradiated and irradiated conditions, Journal of Nuclear Materials, Vol. 386-388, p. 245, 2009.
[4] J. Vanaja, K. Laha, R. Mythili, K.S. Chandravathi, S. Saroja, M.D. Mathew, Creep deformation and rupture behavior of 9Cr-1W-0.2V-0.06Ta Reduced Activation Ferritic-Martensitic Steel, Materials Science and Engineering A, Vol. 533, p. 17, 2012.
[5] R. Lindau, A. Möslang, M. Schirra, Thermal and mechanical behavior of the reduced-activation ferritic-martensitic steel EUROFER, Fusion Engineering and Design, Vol. 61-62, p. 659, 2002.
[6] N. Okubo, E. Wakai, T. Tomita, S. Jitsukawa, Mechanical properties and microstructures in F82H steel irradiated under alternating temperature, Journal of Nuclear Materials, Vol. 367-370, p. 112, 2007.
[7] M. Kytka, M. Brumovsky, M. Falcnik, Irradiation embrittlement characterization of the EUROFER 97 material, Journal of Nuclear Materials, Vol. 409, p. 147, 2011.