1.1 STATUS AND IMPROVEMENT OF REDUCED ACTIVATION FERRITIC-MARTENSITIC STEELS FOR HIGH TEMPERATURE SERVICE — L. Tan and Y. Katoh (Oak Ridge National Laboratory), A.-A.F. Tavassoli and J. Henry (CEA), M. Rieth (KIT), H. Sakasegawa and H. Tanigawa (JAEA), Q. Huang (INEST)

Summary of the content of two presentations at ICFRM 17 now in preparation for submission in two open literature publications.

Reduced activation ferritic-martensitic (RAFM) steels are candidate structural materials for fusion reactors. After about three decades of research and development, RAFM steels have achieved technological maturity with representative RAFM steels including 9Cr–2WVTa (United States), F82H (Japan), Eurofer97 (European Union), and CLAM (China), as well as similar steels being developed in South Korea and India, which evolved from small lab heats to large industrial scale heats of steel larger than 20 tons. A comprehensive set of properties of the RAFM steels have been investigated, including the recent stringent code qualification activity of Eurofer97 to the RCC-MRx edition 2015, and the ongoing materials qualification of F82H and CLAM. Long-term thermal aging resulted in reductions in strength and ductility and degradation of Charpy impact toughness for aging temperatures above about 500°C for F82H and CLAM. An increase of plate thickness from ~10 to 110 mm resulted in some reductions in Charpy impact energy but little influence on tensile properties of F82H and CLAM. Recent addition of fracture toughness data of Eurofer97-1 in the transition regime increased the scatter in the database, which yielded modification of Master curve but retained the same T_0 of –90°C. Comparable fatigue resistance was observed for F82H, Eurofer97, and CLAM at room temperature. However, CLAM with ~9Cr seems to possess somewhat superior fatigue resistance in air at 550°C compared to F82H with ~8Cr.

The current RAFM steels primarily contain $M_{23}C_6$ (M=Cr-rich) and small amounts of MX (M=Ta/V, X=C/N) precipitates, which are not adequate to maintain strength and creep resistance above 500°C. Thermomechanical treatments, including non-standard heat treatments, and alloy chemistry refinement or modification have been employed to development next generation RAFM steels for superior performance. Non-standard heat treatments using lower temperatures of normalization and tempering (e.g., 980 and 700°C) were found to produce similar balanced strength and Charpy impact toughness compared to Eurofer97 normalized and tempered at higher temperatures (e.g., 1150 and 760°C).

Cast nanostructured alloys (CNAs) were recently developed at ORNL with the aid of computational alloy thermodynamics coupled with strength modeling. The new alloys are designed to significantly increase the amount of MX nanoprecipitates, which are manufacturable through standard and scalable industrial steelmaking methods. Either MN or MC nanoprecipitates are favored in the CNAs with designed amounts in the range of ~0.4–0.6 vol%, which is lower than the oxide nanocluster content (>~0.7 vol%) in 9–20Cr oxide dispersion-strengthened (ODS) alloys, but significantly higher than the MX (<0.2 vol%) in the current RAFM steels. The experimental heats of CNAs demonstrated significantly refined MX nanoprecipitates (<~7 nm) with a high density (on the order of 10^{22} m^{-3}), as well as a refined sub grain structures and a high density of free dislocations (~3×10^{14} m^{-2}), leading to improvements in strength, creep resistance, and Charpy impact toughness.

The CNAs exhibited ~100–300 MPa higher yield strength than the RAFM/FM steels at test temperatures up to 800°C, and comparable or slightly superior strength to PM2000 at temperatures above ~500°C. The enhanced strength was achieved at the cost of a modest reduction in ductility. Preliminary creep tests indicated superior creep resistance compared to RAFM steels, which approached the lower bound of the scatter data of ODS-Eurofer. The CNAs showed Charpy impact toughness comparable to or significantly greater than Grade 91, in terms of higher USE and lower DBTT. The improvement levels were even greater when compared to 9–20Cr ODS alloys.

The CNAs with noticeably increased amount of MX nanoprecipitates are expected to have radiation resistance and helium management performance superior to the current RAFM steels because of the

increased defect sinks at the nanoparticle-matrix interface. Preliminary neutron irradiation results on one of the CNAs showed radiation hardening comparable to the large database for Eurofer97 and F82H irradiated in a variety of fission reactors to ~70 displacements per atom at ~300–325°C. Small radiation hardening (<80 MPa) did not impair the ductility of the CNA at low radiation damage. More post irradiation examination and HFIR neutron irradiation experiments on CNAs are in progress or are planned, to provide a more complete picture of radiation resistance. Ongoing research and development activities on RAFM steels and CNAs will provide a solid foundation for their deployment in DEMO and later fusion reactors.

The content of this topic was presented in two presentations at 17th International Conference on Fusion Reactor Materials (ICFRM-17), October 11-16, 2015. Detailed information is reported in Refs. [1,2].

References

[1] L. Tan, Y. Katoh, A.-A.F. Tavassoli, J. Henry, M.Rieth, H. Sakasegawa, H. Tanigawa, Q. Huang, Status and improvement of reduced activation ferritic-martensitic steels for high temperature service, Journal of Nuclear Materials (2016), to be submitted.

[2] L. Tan, L.L. Snead, Y. Katoh, Development of new generation reduced activation ferritic-martensitic steels for advanced fusion reactors, Journal of Nuclear Materials (2016), submitted.