1.1 DEVELOPMENT OF ADVANCED REDUCED ACTIVATION FERRITIC/MARTENSITIC STEELS —

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OBJECTIVE

Traditional reduced activation ferritic/martensitic (RAFM) steels suffer noticeable strength reduction at temperatures above 500°C, which limits their high temperature applications for DEMO and beyond DEMO fusion reactors. This project is to develop cast nanostructured alloys (CNAs) that are manufacturable and affordable advanced RAFM steels having optimized alloy composition and thermomechanical treatment (TMT) to produce a high density of stable nanoprecipitates to retain superior high temperature performance.

SUMMARY

New heats of CNAs have been fabricated, which showed superior yield and tensile strength at test temperatures up to 750°C. The superior strength is explained by their refined microstructure with significantly increased amount of MX-type nanoprecipitates. Charpy impact toughness of the CNAs was assessed in this work, which showed excellent upper shelf energies that are more than double that of Grade 91 steel and about 8–10 times that of oxide dispersion strengthened (ODS) steels. The ductile-brittle transition temperature (DBTT) of the CNAs is comparable or lower than Grade 91 steel. Characterization of the high-dose Fe^{2+} ion-irradiated samples containing VN nanoprecipitates exhibited evolution with irradiation depth, that is, with increasing irradiation dose. The growth of VN particles was found to be dependent on the irradiation direction.

PROGRESS AND STATUS

Introduction

Two heats of CNAs were fabricated using arc melting followed by drop casting into 1” × 1” × 6” bars. The bars were hot-rolled into 0.3”-thick plates. The plates were subjected to standard heat treatments using normalization at ~1100°C/0.5 h followed by tempering at 750°C/0.5 h and air-cooling. Samples of the heats have shown excellent yield and tensile strength at testing temperatures up to 750°C as compared to F82H and Eurofer97. The effect of increased number density of MX in CNA on helium management is being conducted by one of colleagues using ion irradiation. This report describes the Charpy impact toughness of the CNAs. Additionally, the characterization of high-dose Fe^{2+} ion-irradiated samples bearing TaC, TaN and VN nanoprecipitates, respectively, has been continued using TEM, with new findings briefly reported here.

Experimental Procedure

Charpy impact tests were conducted on a Tinius Olsen Charpy 300 ft-lb machine according to the ASTM Standard E23-12c, “Standard test methods for notched bar impact testing of metallic materials.” Sub-size V-notch (1 mm deep) Charpy specimens with a dimension of 5 × 5 × 25 mm were extracted from the plates along the T-L orientation.

A FEI CM200 field-emission-gun transmission electron microscope (TEM) equipped with an EDAX energy dispersive X-ray spectroscopy (EDS) detector was primarily used to characterize the Fe^{2+}-irradiated samples. TEM specimens, perpendicular to the surfaces (i.e., parallel to the ion irradiation direction), were lifted out and thinned to electron-transparent using focused ion beam (FIB) on a Hitachi NB5000. Specimen thickness of the characterized regions was estimated using convergent beam electron diffraction (CBED) technique.

Results

The Charpy impact resistance of the specimens in the transition region was tested at temperatures from –100°C to above room temperature. Oxide-dispersion strengthened (ODS) ferritic steel 14YWT was also tested using the same type of specimens, which yielded Charpy impact toughness comparable to other 12-14Cr ODS ferritic steels. The measured absorbed Charpy energy of each specimen of CNAs was normalized to that of ODS ferritic steel 14YWT and plotted as a function of testing temperature as shown in Figure 1. Literature data of Grade 91 steel are included for comparison [1]. The Charpy data are fitted with a function of $y = \frac{a_1+a_0}{2} + \frac{a_1-a_0}{2} tanh\left(\frac{T-T_0}{k}\right)$, where T is testing temperature, a_1, a_0, T_0, and k are fitting parameters for upper shelf energy, lower bound energy, transition temperature and slope of the fitting curve changing from upper shelf to lower bound, respectively. The results indicate that CNAs have noticeably increased upper shelf energies about 8 to 12 times of ODS ferritic steels, which are also more than double of Grade 91 steel. The ductile-brittle transition temperature (DBTT) of the CNAs is comparable or lower than that of Grade 91 steel. As compared to conventional RAFM and FM steels, the CNAs were found to have refined microstructure with significantly increased amount of MX-type precipitates, which may have benefited the improved Charpy impact toughness.

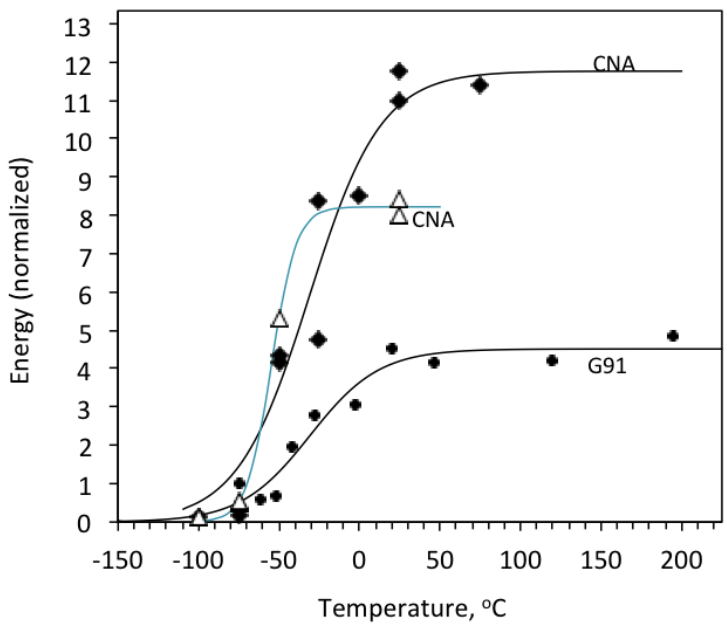

Figure 1. Normalized Charpy absorbed energy (referring to ODS ferritic steels) of CNAs and Grade 91 steels.

The stability of VN nanoprecipitates in a ferritic steel under Fe^{2+} ion irradiation at 500°C for up to ~50 dpa and ~246 dpa was characterized using TEM in both bright-field and dark-field modes. Analysis of the nanoprecipitates exhibited evolution with irradiation depth, namely irradiation dose. The low-dose irradiation results have been reported in Ref. [2,3]. The high-dose irradiation results will be reported in a Journal article. An interesting observation during comparison of the results is that the growth of the nanoprecipitates is dependent upon the irradiation direction. Figure 2 shows an example of the nanoprecipitate in two orientations referring to the irradiation direction. The particle length of the two VN nanoprecipitates in Figure 2 (left) aligns the irradiation direction. The irradiation (~20 dpa) slightly elongated the particle length but did not alter the lattice fringes of the particles. In contrast, the particle length of the VN nanoprecipitate in Figure 2(right) is perpendicular to the irradiation direction. The irradiation (~150 dpa) significantly altered the lattice fringes and increased the thickness of the particle.

Additional FIB-TEM specimens from the high-dose irradiated sample with VN-particle orientation aligning the irradiation direction are being characterized to confirm the phenomenon. Neutron-irradiated VN samples will be characterized to elucidate potential difference from ion irradiation results.

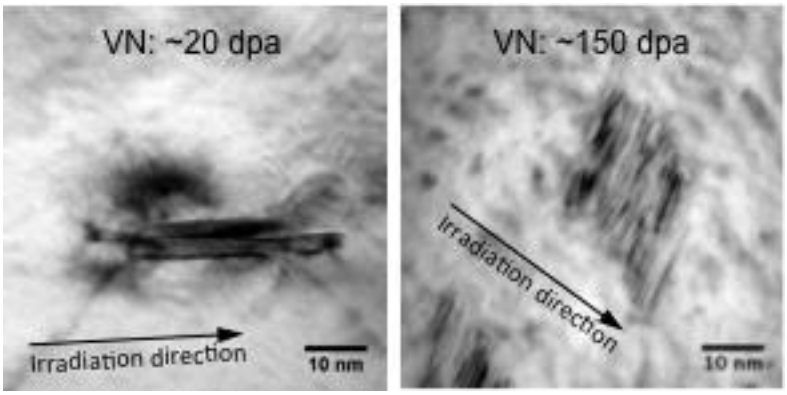

Figure 2. Effect of ion-irradiation direction on the growth of VN nanoprecipitates at 500°C.

References

[1] W.R. Corwin, A.M. Hougland, Effect of specimen size and material condition on the Charpy impact properties of 9Cr-1Mo-V-Nb steel, in: W.R. Corwin, G.E. Lucas (Eds.), The Use of Small-Scale Specimens for Testing Irradiated Material, ASTM STP 888, American Society for Testing and Materials, Philadelphia, 1986, pp. 325-338.

[2] L. Tan, Y. Kotah, L.L. Snead, Stability of the strengthening nanoprecipitates in reduced activation ferritic steels under Fe^{2+} ion irradiation, Journal of Nuclear Materials 445 (2014) 104-110.

[3] L. Tan, T.S. Byun, Y. Katoh, L.L. Snead, Stability of MX-type strengthening nanoprecipitates in ferritic steels under thermal aging, stress and ion irradiation, Acta Materialia 71 (2014) 11-19.