1.2 NEW BAINITIC STEEL FOR FUSION STRUCTURAL APPLICATIONS — Y. Yamamoto (Oak Ridge National Laboratory)

OBJECTIVE

This work aims to develop new bainitic steel, based on 3Cr-3WV(Ta) steels originally developed at ORNL, with mechanical properties of both base metal and weldments superior to those of existing commercial bainitic steels or ferritic-martensitic (F-M) steels. The target applications are high temperature structural components in fusion reactors such as vacuum vessel, structural ring which supports the blanket modules, and magnet shields, to be used at or above 400-500ºC range. Improvement of long-term creep properties by introducing additional fine, stable second-phase dispersions, as well as maintaining a good weldability, is targeted via optimization of alloy composition and thermo-mechanical heat treatment.

SUMMARY

Four heats of 3Cr-3WV base bainitic steels were delivered to ORNL. Minor alloying additions of Mn, Si, and N did not affect the as-normalized and tempered microstructure, viewed in an optical microscope, but increased the micro-Vickers hardness. The bainitic transformation kinetics during continuous cooling were measured using a Gleeble™ thermal mechanical simulator, which indicated that the transformation temperature was significantly lowered by the minor alloying additions. This indicates a wider window for the carbide-free acicular bainite ferrite formation in the modified steels compared to the base steels, which would play an important role in improving the creep properties. Creep-rupture property evaluation of these heats was initiated, and the tests of two base steels were completed.

PROGRESS AND STATUS

Introduction

With the alloy design strategy of improving creep performance, two new bainitic steels based on 3Cr-3WV and 3Cr-3WVTa [1,2] with minor alloying additions of Mn, Si, and N were proposed with guidance from computational thermodynamics. The calculation predicted that the minor alloying additions result in formation of stable MN (M: mainly V) in a wide temperature range below ~1100ºC and increase the stability of $M_{23}C_6$ (M: mainly Cr) relative to M_7C_3 (M: mainly Cr). Since both MN and $M_{23}C_6$ are the key strengthening phases of the bainitic steels at elevated temperatures, the proposed alloys would have a potential of improved creep properties compared to the base steels. The calculated continuous-cooling-transformation (CCT) diagram predicted wider austenite stable regions (retarding the transformation to ferrite or pearlite) with lower the bainitic transformation start temperature compared the base steels, indicating that the stable “carbide-free acicular bainite ferrite formation” would be expected which plays an important role to improve the creep properties of the bainitic steels. In this report, the experimental efforts to verify the calculated predictions have been presented.

Experimental Procedure

The 55 kg forged plates of two base bainitic steels and two modified steels have been prepared by Carpenter Technology Corporation. Table 1 summarizes the target and analyzed compositions of the steels in the present study. The heats with nominal 88 kg were vacuum induction melted and cast into a mold with a size of 10 cm x 10 cm x 20 cm (+ hot-top). The ingots were homogenized and forged at 1100ºC to make plates with a size of 25 mm thickness x 15 cm width x ~40 cm length, followed by normalized at 1100°C. A part of each plate was sectioned, and applied tempering at 700ºC for 1h, followed by air cooling.

Microstructure of the as-normalized and tempered materials was characterized by using light optical microscopes, and the same metallographic specimens were used for micro-Vickers hardness analysis with 1kg load. Dilatometry analysis was conducted by using Gleeble™ thermal mechanical simulator. The round bar shape specimens were heated in a backfilled Ar gas atmosphere up to 1100ºC, held for 5min, and then cooled to room temperature with cooling rates at 10 and 1ºC/s. The specimen diameter was

measured by using an extensometer with a ceramic tip during heating and cooling process. Tensile creep-rupture test was conducted at 600ºC and 250MPa in a laboratory air by using dog-bone shape sheet specimens with a size of 0.7 x 3.2 x 12.7 mm at gage portion.

Table 1. Target and analyzed compositions of the steels in the present study.

Heat	Status	Composition, wt%								Remarks
		C	Mn	Si	Cr	N	V	W	Ta	
2750	Target	0.10	0.40	0.16	3.00	-	0.20	3.00	-	3Cr-3WV
	Analyzed	0.10	0.40	0.15	2.95	0.00	0.20	3.01	<0.01	
2751	Target	0.10	0.40	0.16	3.00	-	0.20	3.00	0.10	3Cr-3WVTa
	Analyzed	0.10	0.40	0.14	2.95	0.00	0.20	3.03	0.10	
2752	Target	0.10	1.00	0.50	3.00	0.05*	0.20	3.00	-	3Cr-3WV + MSN
	Analyzed	0.10	0.98	0.49	2.98	0.017	0.20	3.02	<0.01	
2753	Target	0.10	1.00	0.50	3.00	0.05*	0.20	3.00	0.10	3Cr-3WVTa + MSN
	Analyzed	0.11	1.00	0.48	2.95	0.014	0.20	3.03	0.09	

* Assumed that the nitrogen yield would ~30% after melting

Results

Cross-sectional microstructure of both as-normalized and tempered samples exhibited 100% bainitic microstructure for all four steels, with no indication of the delta-ferrite or the retained austenite in the matrix from the optical micrographs. Figure 1 shows typical microstructures of as-normalized and tempered bainitic steels obtained from heat #2753 (the modified 3Cr-3WVTa steel). No significant difference in the OM microstructure was observed among the four different heats.

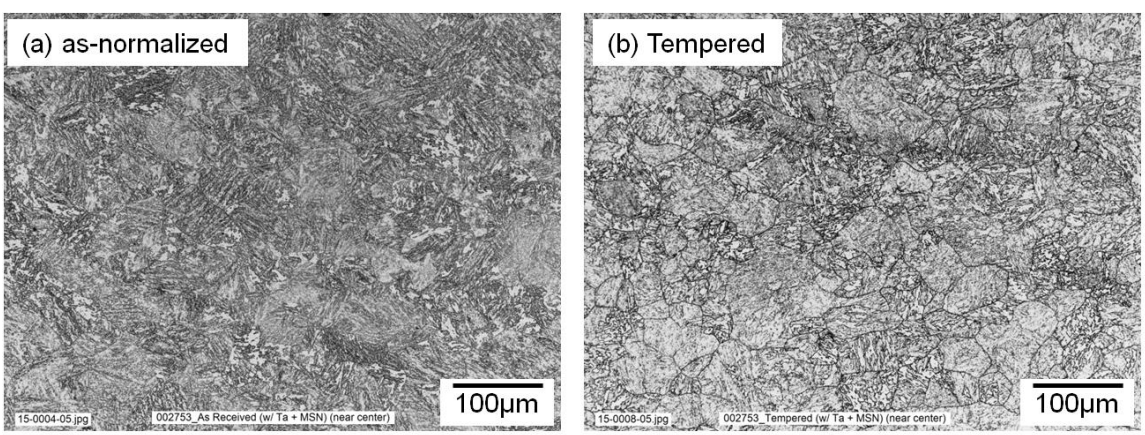

Figure 1. Optical micrographs of the heat #2753; (a) as-normalized, and (b) tempered.

Micro-Vickers hardness measurements of the four different heats at as-normalized and tempered conditions were completed, as summarized in Figure 2. The base steels (heats #2750 and #2751) at as-normalized condition showed ~340-350HV with almost no difference between with and without Ta addition, although #2751 exhibited significantly higher hardness than #2750 after tempering (280HV and 220HV, respectively). This result is consistent with the alloy design strategy that the Ta addition promotes the formation of strengthening carbides (TaC) [1,2] which appear not at as-normalized state but after tempering. The hardness increased to ~370HV by the additions of Mn, Si, and N (#2752 and #2753) at as-normalized conditions, but no significant improvement in the hardness at the tempered conditions compared to the Ta addition in #2751. This result indicates that the minor alloying additions potentially

have an impact on transformation kinetics lowering the bainite transformation temperature which promotes the formation of carbide-free acicular bainite ferrite to strengthen the materials, rather than the formation of strengthening carbides or carbonitrides.

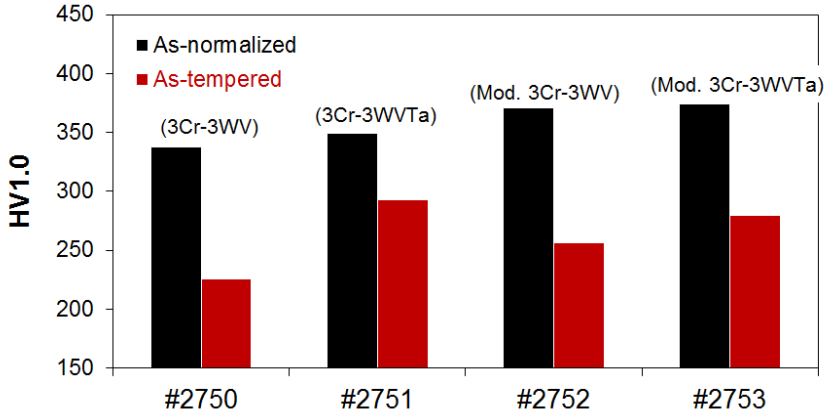

Figure 2. Micro Vickers hardness test results (load: 1kg) of the four different heats.

Dilatometer analysis of the heats confirmed that the minor alloying additions successfully lowered the bainite transformation temperatures. Figure 3 showed the bainitic transformation percentage during continuous cooling calculated from the obtained dilatometry curves, plotted as a function of temperature. The base steels (heats #2750 and #2751) showed relatively rapid transformation kinetics since the bainitic transformation was mostly completed within very narrow temperature range from 520 to 480ºC during cooling at 10ºC/s. The additions of Ta seemed not to impact the transformation kinetics. On the other hand, the modified steels (#2752 and #2753) started the bainitic transformation a little higher temperature than the base steels, but the transformation kinetics was significantly slow and the 90% bainitic transformation occurred around 65-70°C lower than that of the base metals. Similar result was obtained in the case of the cooling rate at 1ºC/s. These results indicate that the transformed bainite ferrite would contain larger amounts of supersaturated carbon and nitrogen than the base steels because the transformation temperature is low enough to expect limited transportation of such elements in the matrix. This would result in wider window of the carbide-free acicular bainite ferrite formation in the modified steels compared to the base steels. Detailed microstructure characterization is required to verify the mechanism, and is currently in progress.

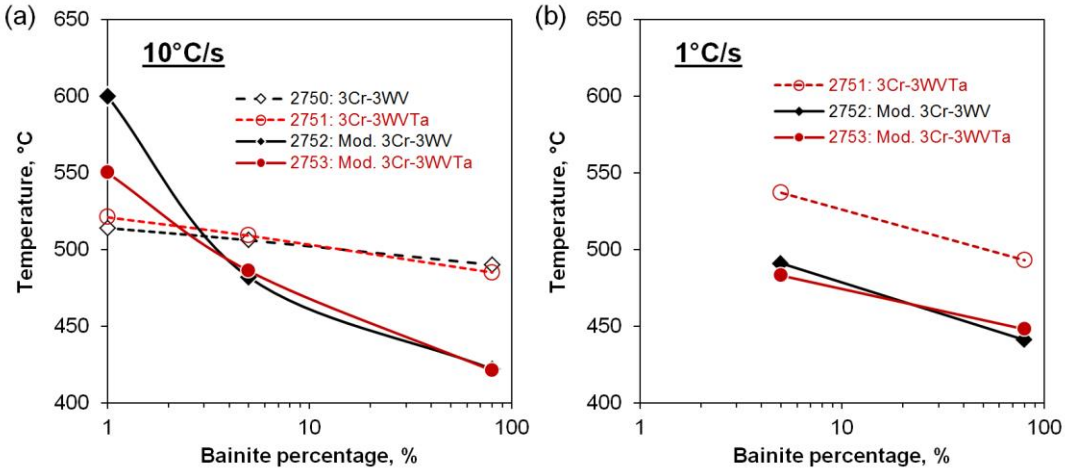

Figure 3. Bainitic transformation temperatures of four different bainitic steels plotted as a function of the transformation percentage; (a) cooled at 10ºC/s and (b) at 1ºC/s.

Creep-rupture test of the bainitic steels was initiated. The creep-rupture life of the base steels (heats #2750 and #2751) tested at 600ºC and 250MPa are shown in Figure 4. The rupture life of Grade 92 (9Cr-2W base) F-M steel reported in NIMS Creep Data Sheet is also shown for comparison. The results indicate the advantage of the base steels to the existing F-M steel at the test condition, which is consistent with the report by Klueh et al [1,2]. The tests of the modified steels (#2752 and #2753) are currently in progress.

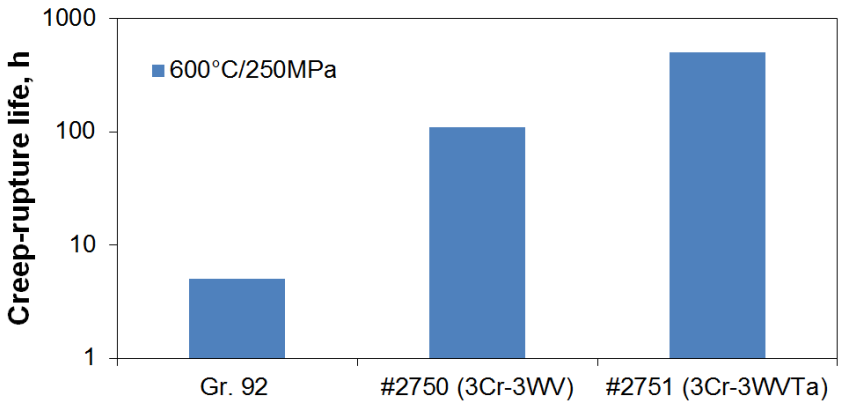

Figure 4. Creep-rupture life of the heats #2750 and #2751 tested at 600ºC and 250MPa compared with that of Grade 92 (reported in NIMS Creep Data Sheet, http://smds.nims.go.jp/creep/index_en.html).

References

[1] R.L. Klueh, Elevated-Temperature Ferritic and Martensitic Steels and Their Application to Future Nuclear Reactors, ORNL/TM-2004/176, November 2004.

[2] R.L. Klueh, N.D. Evans, P.J. Maziasz, V.K. Sikka, Creep-rupture behavior of 3Cr-3W-V bainitic steels, International Journal of Pressure Vessels and Piping, 84 (2007) 29-36.