1.3 ADVANCED BAINITIC STEEL DEVELOPMENT FOR FUSION STRUCTURAL APPLICATIONS —

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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 the vacuum vessel, the structural ring which supports the blanket modules, and magnet shields, to be used at or above the 400-500ºC range. Improvement of long-term creep properties by introducing additional fine, stable second-phase dispersions, as well as maintaining good weldability, is targeted via optimization of alloy composition and thermo-mechanical heat treatment.

SUMMARY

Four heats of 3Cr-3WV base bainitic steels with or without minor alloying additions of Mn, Si, and N were prepared. Continuous cooling transformation (CCT) diagrams of the bainitic steels were produced by using a Quenching Dilatometer (Material Measuring Corp.). The results indicated successful control of the bainitic transformation kinetics with lower bainitic transformation temperatures in a wide range of continuous cooling rates, compared to those of the base steels. It promoted the formation of “carbide-free acicular bainite ferrite” which improved relatively short-term creep-rupture properties tested at 600°C. Improved oxidation resistance during creep testing was also observed in the modified steels with the Si addition. Weldability screening of the steels has been initiated by using bead-on-plate weld together with cross-sectional hardness measurements.

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 steels would have a potential of improved creep properties compared to the base steels. An improved oxidation resistance would also be expected due to the Si addition [3]. In addition, the calculated continuous-cooling-transformation (CCT) diagram predicted wider austenite stable regions (retarding the transformation to ferrite or pearlite) with lower bainitic transformation start temperature compared to the base steels, indicating that the transformation would occur at relatively lower temperature range even with air cooling which is equivalent to the lower bainite formation during isothermal annealing in TTT diagram (Figure 1).

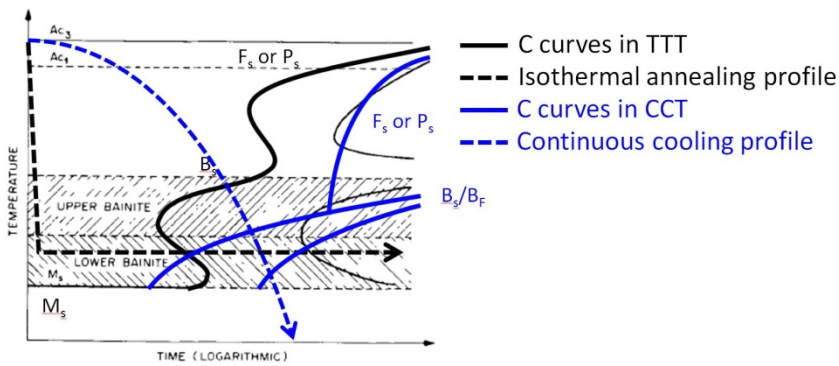

Figure 1. Schematic illustration of TTT and CCT curves for a bainitic steel

This new design of bainite transformation kinetics through alloying additions would result in enhancing the formation of "carbide-free acicular bainite ferrite formation" which also plays an important role of improving the creep properties as well as toughness of the bainitic steels [2]. In this report, the experimental efforts to verify the predicted transformation kinetics, microstructure, and the creep-rupture performance have been summarized by comparing the base and the modified steels. The first trial of weldment by using bead-on-plate gas tungsten arc weld is also discussed.

Experimental Procedure

The 55 kg forged plates of two base bainitic steels and two modified steels have been prepared using a vacuum induction melting by Carpenter Technology Corporation. The heat identifications and the base compositions are listed in Table 1. 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. The forged plates were austenitized at 1100°C, followed by air cooling (normalization). A part of each plate was sectioned, and applied annealing at 700ºC for 1h, followed by air cooling (tempering).

Table 1. Heat identifications and base alloy compositions of the steels

Heat	Base composition, wt.%	Remarks
2750	Fe-3Cr-3W-0.2V	Base 3WV
2751	Fe-3Cr-3W-0.2V-0.1Ta	Base 3WVTa
2752	Fe-3Cr-3W-0.2V + Mn, Si, and N	Modified 3WV
2753	Fe-3Cr-3W-0.2V-0.1Ta + Mn, Si, and N	Modified 3WVTa

Continuous cooling transformation diagrams were produced by using Quenching Dilatometer (Material Measuring Corp., MMC) refurbished at ORNL. Columnar specimens with a size of 3 mm diameter x 10 mm length were machined from the steels for the dilatometry analysis. The specimens were kept at 1100°C for 30 s in a vacuum chamber, and then cooled down to room temperature by using a controlled He gas blow in order to achieve various cooling rates in a range of from 1°C/s to 180°C/s. The bainitic transformation start and finish temperatures were determined from the obtained dilatometry curves. Microstructure of the specimens cooled at a cooling rate of 1°C/s were characterized by using light optical microscope (OM), and the same metallographic specimens were used for micro-Vickers hardness analysis with 1kg load. A series of creep-rupture tests of the base and the modified steels after tempering was conducted at 600°C and various constant loads in a range of 170 to 250MPa in a laboratory air. The test was conducted with sub-sized sheet dog-bone shape specimens with the gage dimension of 0.7 mm thickness x 3.2 mm width x 13 mm length. The extensometer was not attached to the specimens but the pull-rod to measure the creep-deformation, so that the creep-test was semi-quantitative. Bead-on-plate welding (gas tungsten arc weld, GTAW) was performed on the selected steel plates with the conditions of both as-normalized and tempered. Cross-sectional microstructure characterization was conducted by

using OM, and the Vickers hardness of the as-welded materials was measured with 300g load across the base metal – heat affected zone – weld metal, in order to produce a hardness distribution map.

Results

Continuous cooling transformation (CCT) diagrams of the base and the modified bainitic steels are shown in Figure 2. The bainitic transformation start (B_s) and finish (B_f) temperatures before and after alloy modification were compared in Ta-free (Figure 2a) and Ta-containing (Figure 2b) steels. Alloy modification resulted in lowering both B_s and B_f with ~20-100°C in the cooling rates studied, as expected from the alloy design strategy described above. There was no significant difference in the transformation temperatures between Ta-free and Ta-containing steels, indicating that the addition of Ta would have little effect on controlling bainitic microstructure (i.e. formation of carbide-free acicular bainite ferrite) but be more effective on the second-phase precipitation (MX/MC) which would contribute to improving creep properties significantly [2]. Optical micrographs of the steels cooled at 1°C/s (shown in Figure 3) indicates that there was no ferrite or pearlite formation at the cooling rate which was quite slower than a typical cooling rate of air-cooling (~10°C/s). This result suggests that the formation of locally weakened microstructure (= ferrite or pearlite) would not be expected during cooling after a typical welding, either at the heat affected zone or in the weld metal. The Vickers hardness increased with the alloy modification in both Ta-free and Ta-containing steels, which supported that the hardenability was successfully improved by controlling the microstructure with the stable carbide-free acicular bainite ferrite as expected.

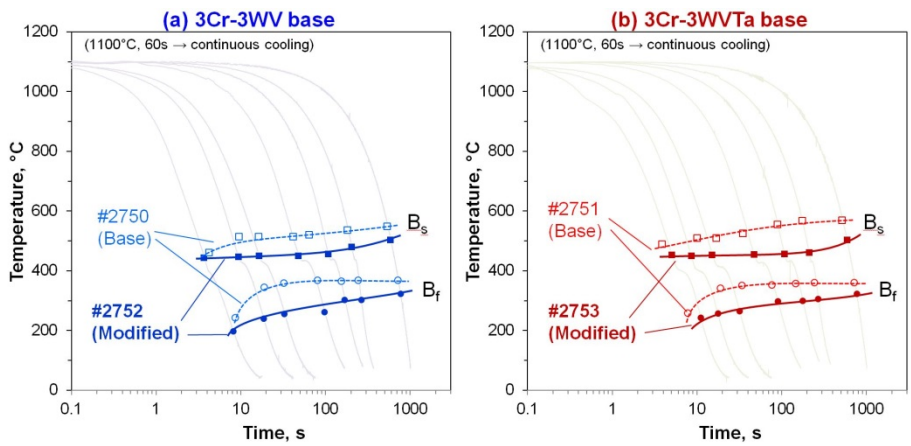

Figure 2. Continuous cooling transformation diagrams of (a) Ta-free, and (b) Ta-containing steels.

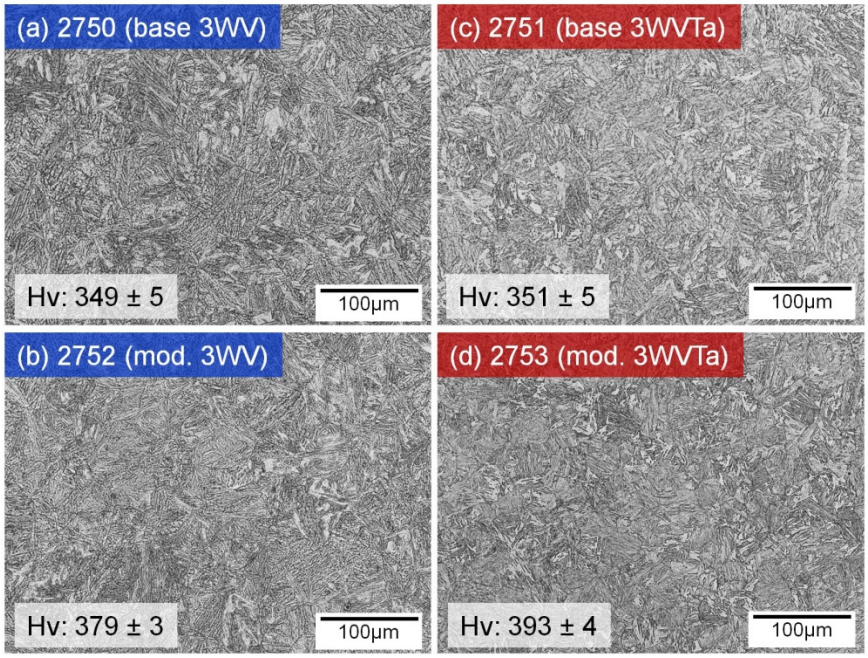

Figure 3. Optical micrographs of the bainitic steels after cooling at 1°C/s; (a) #2750, (b) #2752, (c) #2751, and (d) #2753.

Comparison of creep-rupture properties of the base and the modified bainitic steels were summarized in Figure 4. The creep-rupture life of the 3Cr bainitic steels at 600°C/200MPa were quite longer than that of P92 (9Cr-2W-0.5Mo base) ferritic-martensitic steel (Figure 4a), and the Ta-containing steels showed almost doubled creep-life compared to the Ta-free steels. However, no apparent or consistent effect of alloying additions on the creep-rupture properties was observed at the test condition. At 600°C/170MPa (Figure 4b), on the other hand, only the Ta-containing steels exhibited longer creep-life compared to that of P92, although the alloy modification resulted in ~10-20% improvement of creep-rupture life in the bainitic steels. These results suggested that the effect of alloy modification on creep-properties would be more apparent in the milder creep test conditions. Since 600°C test temperature is quite aggressive and the creep-rupture life is in a range of “short-term” compared to the target applications of the developing steels, further evaluation of creep properties in a range of more than “mid-term (= several thousand hours)” would be required. The creep tests of the steels at slightly lower temperature (550°C) have been initiated and are currently in progress.

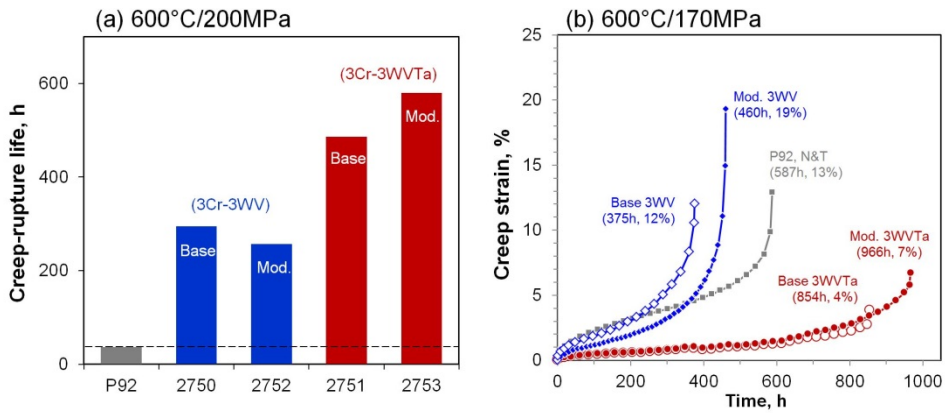

Figure 4. Creep-rupture test results of the 3Cr bainitic steels compared with the result of P92; tested at (a) 600°C/200MPa (creep-life), and (b) 600°C/170MPa (creep-rupture curves)

The Si addition improved the surface protection during creep-rupture testing, as shown in Figure 5. The base 3Cr-3WV with 0.16 wt.% Si showed rusty specimen surface, especially at the gage portion, and the cross-sectional near the surface exhibited the formation of thick oxide layers. The oxidation resulted in not only consuming the material volume but also a formation of a wedge-shape oxide penetration along the grain boundary which would also affect to the mechanical properties such as crack initiation site. On the other hand, the modified steel with 0.5 wt.% Si addition do not show such thick oxide layers after the same creep-rupture test condition as the base metal. This Si effect was reported by Ishitsuka et al. [3] in case of Grade 92 steel in a steam exposure. However, as far as the PI is aware of, no such effect of Si addition was reported in the heat-resistant bainitic steels. Further systematic study would be required to understand the oxidation characteristics after long-time exposure at elevated temperatures as well as the potential benefits or limitations in the new bainitic steels, and the test planning is currently in progress.

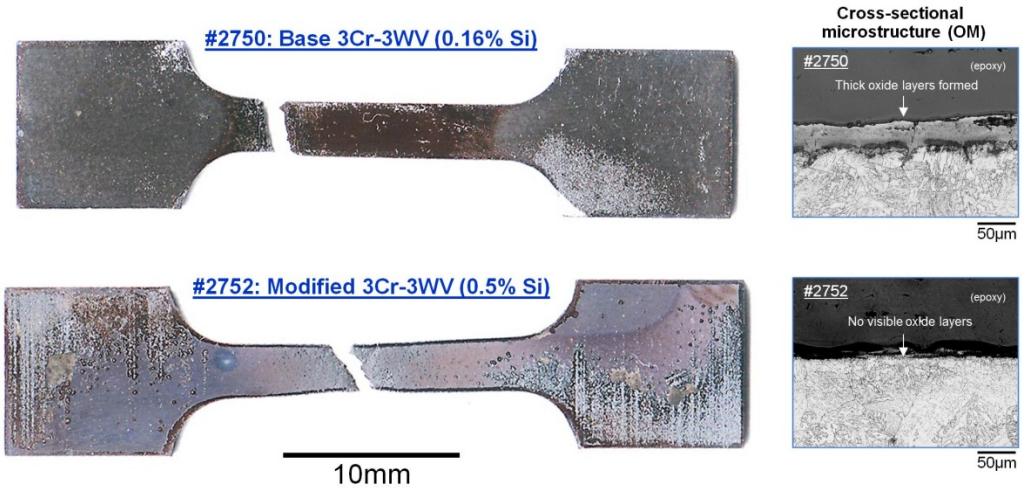

Figure 5. Creep-ruptured specimens of the steels #2750 and #2752 tested at 600°C and 200MPa, together with cross-sectional microstructure near the specimen surface showing the surface oxide layers.

Trial GTAW was conducted by using bead-on-plate weld on the 3Cr-3WVTa steels after tempering. Cross-sectional microstructures of the welded samples are shown in Figure 6. There are two weld beads on the samples, and the weld metals locate inside the yellow lines in the pictures. The boundary between the heat affected zone and the base material can easily be identified because of abrupt change in the contrast. There was no delta-ferrite or martensitic microstructure was observed in the weld metal or the

heat affected zone. The hardness distributions across the weld metal are also shown by using contour color maps which were obtained from the area with the white rectangle in the picture. The tempered base metals exhibited ~320-350Hv, and the hardness of the modified 3Cr-3WVTa showed slightly higher hardness compared the base steels. The weld metal and the heat affected zone, on the other hand, showed the hardness of ~370-400 Hv and ~390-440Hv for the base and the modified steels, respectively, which were much higher than the base materials. Such high hardness could possibly be beneficial for the high temperature creep properties similar to as-normalized materials [2], but may have a significant impact on the ductility, toughness, or potential residual stresses. Further characterization efforts is planned.

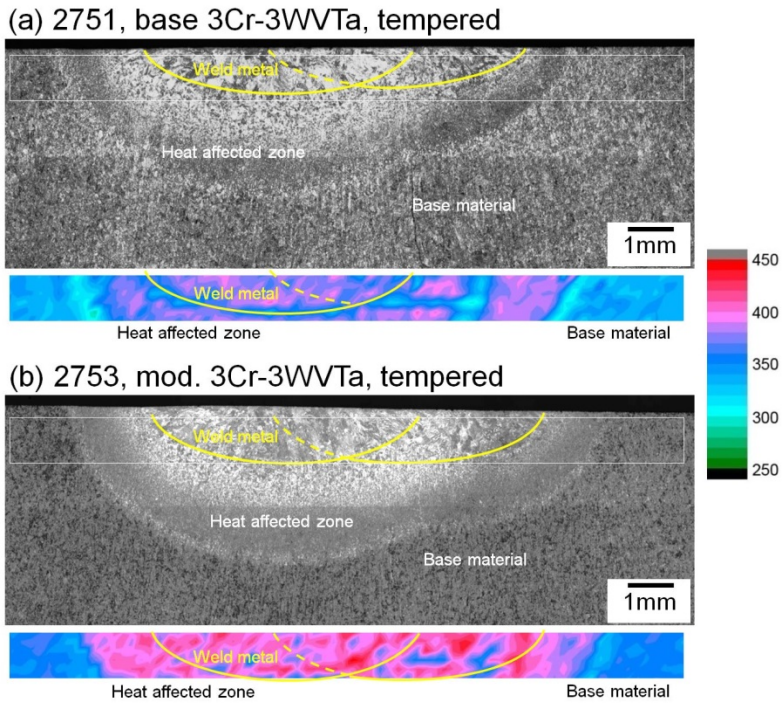

Figure 6. Cross-sectional microstructure of the 3Cr-3WVTa base bainitic steels with bead-on-plate weld (GTAW), together with the contour color map of the hardness distribution across the weld metal; (a) #2751, tempered, and (b) #2753, tempered.

This material was presented at ICFRM 17 with the title “Development of Advanced 3Cr-3WV(Ta) Bainitic Steels for Fusion Structural Applications”.

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.
[3] T. Ishitsuka et al., Effect of Silicon on the Steam Oxidation Resistance of a 9%Cr Heat Resistant Steel, Oxidation of Metals v.61(1-2) p125 (2004).