LOW-CHROMIUM REDUCED-ACTIVATION CHROMIUM-TUNGSTEN STEELS – R. L. Klueh, D. J. Alexander, and P. J. Maziasz (Oak Ridge National Laboratory)

OBJECTIVE

The goal of this work is the development of reduced-activation ferritic steels.

SUMMARY

Bainitic microstructures formed during continuous cooling can differ from classical upper and lower bainite formed during isothermal transformation. Two types of non-classical bainite were observed depending on the cooling rate: carbide-free acicular bainite at rapid cooling rates and granular bainite at slower cooling rates. The Charpy impact toughness of the acicular ferrite was found to be considerably better than for the granular bainite. It was postulated that alloying to improve the hardenability of the steel would promote the formation of acicular bainite, just as increasing the cooling rate does. To test this, chromium and tungsten were added to the 2 1/4Cr-2W and 2 1/4Cr-2WV steel compositions to increase their hardenability, and the microstructures and mechanical properties were examined.

PROGRESS AND STATUS

Introduction

Most of the work on reduced-activation steels has been concentrated on high-chromium steels [1]. The ORNL alloy development program studied eight steels with chromium contents ranging from 2.25 to 12%[2-4]. An Fe-2.25Cr-2W-0.25V-0.1C (2 1/4Cr-2WV) steel had the highest strength of the eight steels examined [2], but the Charpy impact properties were inferior to an Fe-9Cr-2W-0.25V-0.07Ta-0.1C (9Cr-2WVTa) steel. Despite the excellent behavior of the 9Cr-2WVTa, there are advantages for low-chromium bainitic steels [5]. Because bainitic steels often have excellent strength and toughness in the as-quenched or as-normalized condition, it might be possible to use such steels without a post-weld heat treatment, which is not possible for any of the martensitic 9Cr steels. This could be a very important consideration for the construction of a complicated structure such as a fusion power plant.

Work on an Fe-3Cr-1.5Mo-0.1V-0.1C (3Cr-1.5MoV) steel demonstrated that the Charpy properties depended on the type of bainite microstructure that developed during heat treatment [6]. This information was factored into the earlier work on developing improved low-chromium reduced-activation steels [7], and an extension of that work is discussed in this report.

Bainite forms when a steel transforms from austenite in the critical temperature range between the temperature where ferrite and pearlite form (high temperatures) and the temperature where martensite forms (low temperatures). Bainite was originally described as consisting of only two distinguishable microstructures: upper and lower bainite, which are defined according to their temperature of formation [8,9]. Habraken [10] demonstrated that there are microstructural variations of the classical bainite that formed in the bainite transformation temperature regime. Such "nonclassical" bainite formed more readily during continuous cooling than during isothermal transformation, where upper and lower bainite formed. Habraken and Economopoulos [10] contrasted classical and nonclassical bainite using the isothermal transformation (IT) and continuous-cooling transformation (CCT) diagrams. The bainite transformation region of an IT diagram can be divided into two temperature regimes by a horizontal line. Transformation above the temperature represented by this line produces upper bainite, and transformation below it produces lower bainite. Upper bainite consists of laths with carbides at the lath boundaries. Lower bainite consists of plates or laths containing parallel arrays of carbides that form at $\approx 60°$ to the plate axis [8,9]. For nonclassical bainite, Habraken and Economopoulos [11] found that a CCT diagram could be divided into three vertical regimes. Different microstructures form for cooling rates that pass through these different zones. For the fastest cooling rate (Zone I), a "carbide-free acicular" structure was formed, which consisted of side-by-side plates or laths of ferrite containing a high dislocation density [10]. At an intermediate cooling rate (Zone II), a carbide-free "massive" or "granular" structure resulted, which was designated granular bainite and was described as consisting of equiaxed subgrains of low-carbon ferrite with a high dislocation density coexisting with dark "islands" [11], which were enriched in carbon during the bainite transformation. The islands were shown to be retained austenite with a high carbon concentration, part of which often transformed to martensite when cooled below the M_s temperature. These high-carbon regions are referred to as "martensite-austenite (M-A) islands" [11]. Microstructures developed by still slower cooling rates (Zone III) were not observed in this study and will not be discussed.

To demonstrate that the microstructure of the 2 1/4Cr-2W and 2 1/4Cr-2WV was determined by cooling rate, 10-mm- and a 3-mm-square bars of the steels were austenitized in a helium atmosphere in a tube furnace and then cooled in static or flowing helium, respectively. Granular bainite formed in the slowly cooled 10-mm bar, and acicular bainite formed in the 3-mm bar rapidly cooled in the flowing helium [6].

It was proposed previously that formation of carbide-free acicular bainite could be promoted by improving the hardenability [6]. Hardenability is defined as the relative ability of a steel to avoid forming ferrite when cooled from the austenitizing temperature. Increasing hardenability should have the same relative effect as increasing cooling rate: the transformation of austenite to ferrite is delayed so the steel can be cooled more slowly and still obtain a martensitic or bainitic microstructure (depending on the cooling rate). It was reasoned that increased hardenability should also widen the zone for acicular-bainite formation to longer times and allow it to form at a slower cooling rate [6]. Hardenability can be altered by changing composition. As a first attempt to vary hardenability, more chromium and small amounts of boron were added to the 2 1/4Cr-2WV composition [6]. Boron was chosen because small amounts are known to increase hardenability [12,13]. The chromium concentration was increased to 2.6%, and ≈0.005 B was used. Tantalum additions were also made, because tantalum in 9Cr-2WVTa appeared to improve the properties of that steel compared to a steel without tantalum [6]. The addition of the Cr and B resulted in a marked improvement in the Charpy properties. However, there were still indications of granular bainite in the microstructure of an Fe-2.6Cr-0.25V-0.004B-0.1C (2.6Cr-2WVB) steel. Therefore, it was decided to add still more chromium (to a total of 3%) and also to add additional tungsten (up to 3%). These 3Cr-W and 3Cr-WV steels are the subject of the work presented here.

Experimental Procedure

Small 450-g vacuum arc-melted button heats of nominal composition Fe-2Cr-2W-0.1C (3Cr-2W), and Fe-3Cr-3W-0.1C (3Cr-3W), Fe-3Cr-2W-0.25V-0.1C (3Cr-2W), and Fe-3Cr-3W-0.25V-0.1C (3Cr-3WV) steels were made using the 2 1/4Cr-2W and 2 1/4Cr-2WV from the original eight heats of reduced-activation steel [3] as starting material. Data on these latter two heats and the 9Cr-2WVTa from the original heats were used for comparison [2-4]. Half of each 12.7 x 25.4 x 127 mm ingot was hot rolled to 6.4 mm and half to 0.76 mm. Tests were made on normalized-and-tempered SS-1 tensile specimens taken from the 0.76-mm sheet. In the normalization treatment, the steels without vanadium were austenitized at 900°C and those with vanadium were austenitized at 1050°C. Steels were tested after tempering at 700 and 750°C. The steels were examined by transmission electron microscopy (TEM) after normalization to determine the type of bainite formed.

Results and Discussion

Microstructure

The addition of ≈0.75% Cr to the 2 1/4Cr-2W composition to produce 3Cr-2W resulted in an acicular bainite microstructure after normalization, as expected for a steel with increased hardenability [Fig. 1(a)]. However, the microstructure of 3Cr-3W produced by the addition of 0.75% Cr and 1% W contained a significant amount of coarse precipitate, and the laths were not well defined [Fig 1(b)]. It is not known whether the additional tungsten induces the formation of this precipitate or whether the 900°C austenitization temperature was too low to dissolve all the carbides for a steel with this much tungsten. When vanadium was added to produce 3Cr-2WV and 3Cr-3WV steels, this coarse precipitate did not form during austenitization at 1050°C.

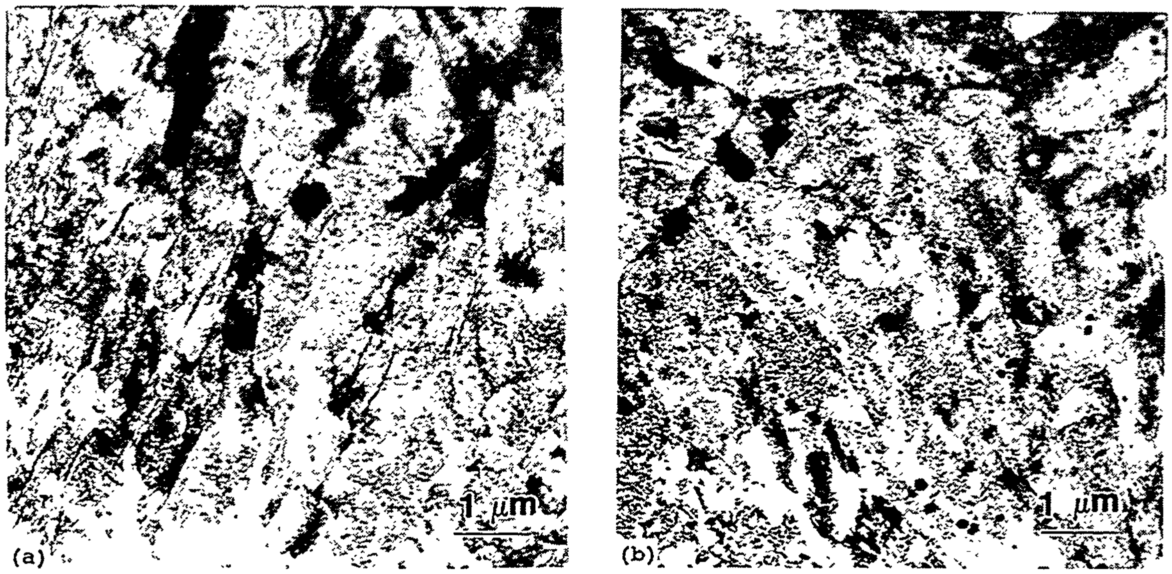

Figure 1. Transmission electron micrographs of normalized (a) 3Cr-2W and (b) 3Cr-3W steels.

TEM indicated that both the normalized 3Cr-2WV [Fig. 2(a)] and 3Cr-3WV [Fig. 2 (b)] steels contained carbide-free acicular microstructures, with the lath size decreasing with increasing tungsten. Thus, the combination of additional chromium and tungsten produces the preferred acicular bainite structure when normalized.

The microstructures of the the 3Cr-2WV and 3Cr-3WV contrasted with those of the 2 1/4Cr-2WV, which had a granular bainite structure when heat treated in the 3-mm-bar geometry used for the Charpy specimens [6]. Thus, the additional chromium and tungsten improved the hardenability and promoted the desired microstructure.

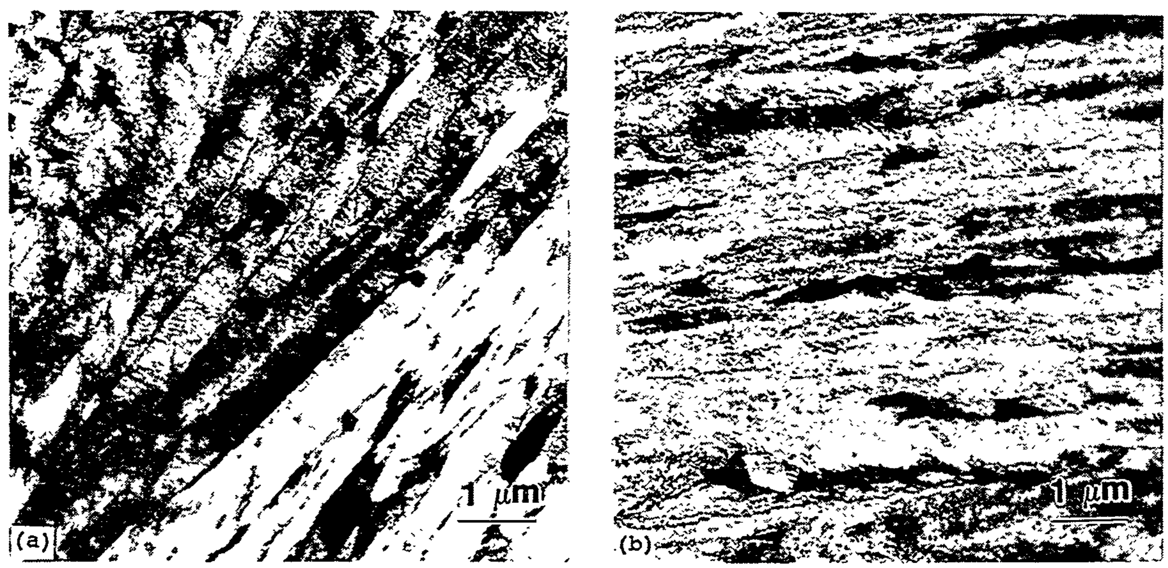

Figure 2. Transmission electron micrographs of normalized (a) 3Cr-2WV and (b) 3Cr-3WV steels.

Tensile Properties

After tempering at 700°C, the yield stress [Fig. 3(a)] between room temperature and 600°C of the new steels and those used for comparison fell into two regimes, depending on whether or not the steels contained vanadium. There was little difference in the yield stress of the 2 1/4Cr-2W, 3Cr-2W, and 3Cr-3W steels—steels without vanadium. For the steels containing vanadium, the 3Cr-3WV was slightly weaker than 2 1/4Cr-2WV at all temperatures but 600°C, but it was stronger than 9Cr-2WVTa, which was stronger than the 3Cr-2WV, indicating that the tungsten content had an effect on the 3Cr-WV steels that was not apparent in the 3Cr-W steels without vanadium. Note, however, that the strength of the 3Cr-2WV approached that of the 9Cr-2WVTa at 500 and 600°C. The relative behavior of the ultimate tensile strength was similar to the yield stress.

The ductility (uniform and total elongations) after tempering at 700°C also fell into two regimes and, with one exception, the steels could again be separated on the basis of vanadium content. The three steels without vanadium, which were the weakest, had the highest total elongation [Fig. 3(b)], with the 2 1/4Cr-2W having the highest elongation at the highest temperatures. The 2 1/4Cr-2WV, 3Cr-2WV, and 3Cr-3WV steels all had similar total elongations, slightly above those for 9Cr-2WVTa. The uniform elongation showed a similar behavior, except that the 2 1/4Cr-2WV steel had a uniform elongation that approached those of the steels without vanadium below 600°C, and then became less than those steels at 600°C.

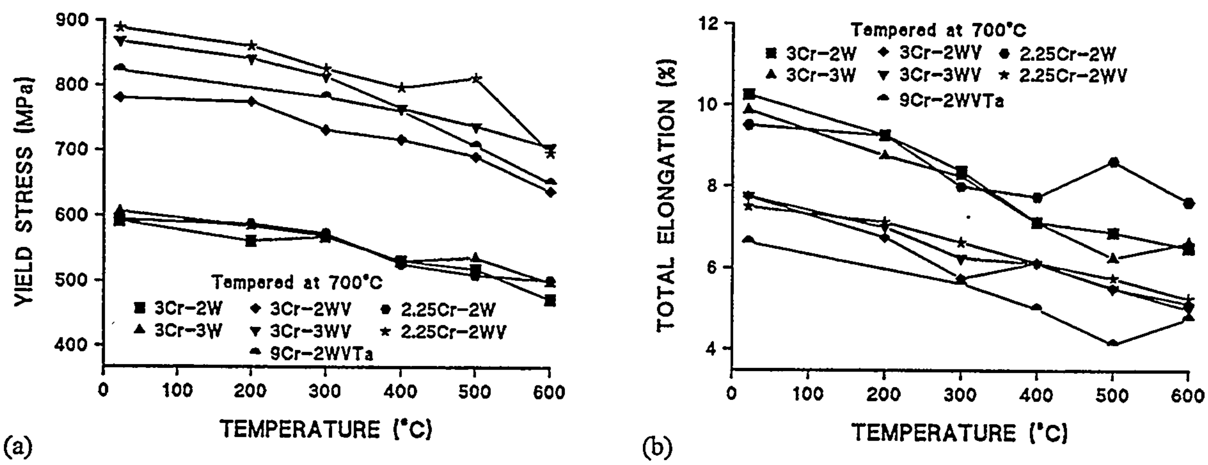

Figure 3. (a) Yield stress and (b) total elongation vs. test temperature for the 3Cr-2W, 3Cr-3W, 3Cr-2WV, 3Cr-3WV, 2 1/4Cr-2W, 2 1/4Cr-2WV, and 9Cr-2WVTa steels after normalizing and tempering 1 h at 700°C.

There was more variation in the tensile properties after tempering at 750°C. The steels without vanadium were again the weakest, with little difference between the yield strengths of the 3Cr-2W and 3Cr-3W [Fig. 4(a)]. Although 2 1/4Cr-2W was stronger than these two steels below 400°C, it became weaker at 500 and 600°C. For the vanadium-containing steels, the 2 1/4Cr-2WV was strongest over the entire temperature range; the 9Cr-2WVTa was slightly stronger than the 3Cr-3WV at the lower temperatures, becoming similar at 500 and 600°C. The 3Cr-2WV was the weakest of the vanadium-containing steels except at 600°C, where it approached the strength of the 3Cr-3WV and 9Cr-2WVTa. The ultimate tensile strength behave similar to the yield strength, except there was less difference between the strongest and weakest steels. Also, for the vanadium-containing steels, the 2 1/4Cr-2WV and 9Cr-2WVTa showed less difference than for the yield stress, although at 600°C, the 9Cr-2WVTa had the lowest strength of the vanadium-containing steels, with the value for the 3Cr-2WV and 3Cr-3WV approaching that of the 2 1/4Cr-2WV. Ductility after tempering at 750°C [Fig. 4(b)] again fell into two categories, with the steels without vanadium having the highest ductility (uniform and total elongation). The 9Cr-2WVTa had the lowest ductility.

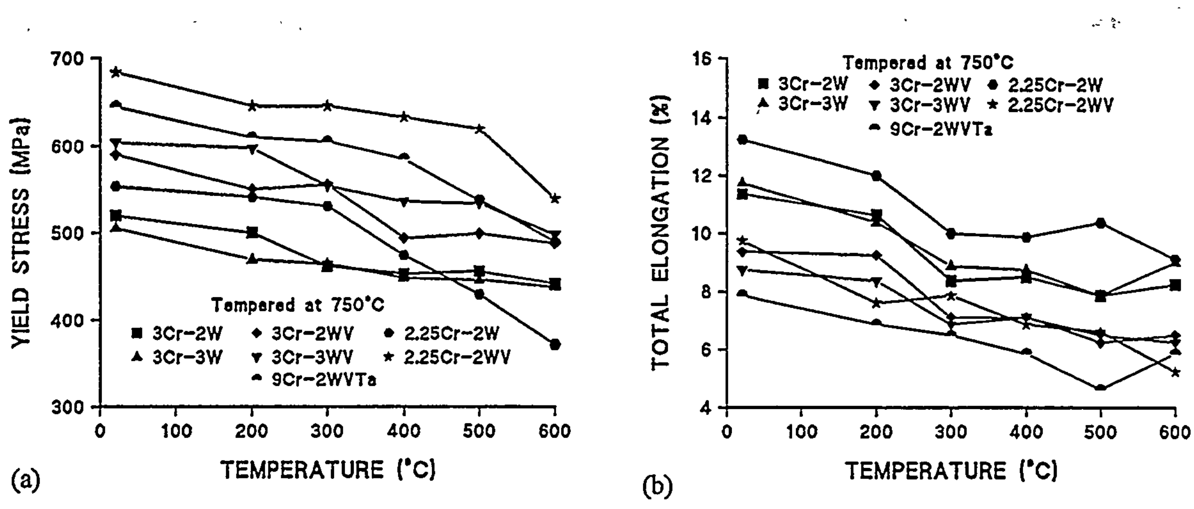

Figure 4. (a) Yield stress and (b) total elongation vs. test temperature for the 3Cr-2W, 3Cr-3W, 3Cr-2WV, 3Cr-3WV, 2 1/4Cr-2W, 2 1/4Cr-2WV, and 9Cr-2WVTa steels after normalizing and tempering 1 h at 750°C.

The results indicated that the 3Cr-3WV steel had strength and ductility generally as good as or better than that of 9Cr-2WVTa and approached the strength of the 2 1/4Cr-2WV, which was the strongest steel of the original eight heats of reduced-activation steel [3].

SUMMARY

It was proposed that increasing the hardenability of a steel that forms granular bainite under a given cooling rate could promote the formation of acicular bainite, just as an increased cooling rate does. Hardenability of a 2 1/4Cr-2WV reduced-activation steel was increased by adding chromium and tungsten to obtain 3Cr-2W, 3Cr-3W, 3Cr-2WV, and 3Cr-3WV. These steel had a 100% acicular bainitic microstructure in the normalized condition. The tensile properties of one of the new steels in the normalized-and-tempered condition was as good or better than those of the 9Cr-2WVTa steel, which was the best of the steels of the original reduced activation steels studied.

FUTURE WORK

The Charpy properties of the new steels will be presented in the next report, and the mechanical properties results for the new steels will be compared with those for the conventional steels and the earlier reduced-activation steels.

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