Microstructural Basis for the Effect of Chromium on the Strength and Toughness of AF1410-Based High Performance Steels

RAGHAVAN AYER and P.M. MACHMEIER

The variation in strength and Charpy impact toughness as a function of tempering temperature in the range of 200 °C to 650 °C was investigated in AF 1410 and AF 1410 + 1 pct Cr steels produced in a laboratory-scale, and a commercially produced AerMet 100 steel. The tensile test results showed that AF 1410 + 1 pct Cr had lower strength compared to AF 1410, while AerMet 100 had the highest strength of the three steels examined. Transmission electron microscopy (TEM) studies demonstrated that the strength variations among the steels can be attributed to differences in the matrix/carbide coherency strain and the volume fraction of the strengthening M2C carbides. The toughness values of the three steels were comparable when tempered up to 424 °C. Tempering at and above 454 °C resulted in a relative enhancement of toughness in AF 1410 + 1 pct Cr steel compared to AF 1410. This toughening was attributed to the destabilization of cementite at lath and prior austenite boundaries and the formation of reverted austenite.

I. INTRODUCTION

OVER the past several decades, there has been extensive interest in the structure and mechanical properties of secondary hardening ultrahigh strength steels. These studies have resulted in the successful development of several commercial steels, notably, HY-180, AF 1410, and, more recently, AerMet 100. The modern steels have achieved a unique combination of strength and toughness by embodying all the concepts developed to date, such as (1) retardation of recovery, (2) hardening through the precipitation of a fine dispersion of coherent carbides, (3) enhancing cleavage resistance, and (4) inclusion-free matrix. Although these high performance steels have been successfully developed and commercialized, the microstructural basis for their superior properties is not yet completely understood. In particular, during the development of AF 1410, Machmeier observed that chromium had a noticeable effect on both strength and toughness. Using laboratory heats of steels containing 0.16 pct C, 10 pct Ni, and 14 pct Co (base composition for AF 1410), it was determined that a chromium addition of 2 pct provided the best combination of strength and toughness. It was also observed that when the chromium level was increased to 3 pct, the steel showed a modest drop in strength and a significant increase in the steel toughness. These studies provided the basis for identifying the optimum level of chromium for commercial AF 1410 steel to be 2 pct. However, the microstructural basis for the lower strength and higher toughness of the AF 1410 type steel with 3 pct Cr was not determined. AerMet 100 was prepared by vacuum induction melting and casting 20-kg ingots which were subsequently rolled into bars. AerMet 100 was prepared by vacuum induction melting/vacuum arc remelting and rolled to 67- and 21-mm rounds, respectively. Blanks of steels AF 1410E and AF 1410E + 1Cr were double austenitized at 850 °C for one hour and 801 °C for one hour and then water-quenched to room temperature.*

II. EXPERIMENTAL PROCEDURE

One commercial and two experimental steels were investigated in this study. The compositions of these steels are listed in Table I. The experimental steels, marked AF 1410E (suffix “E” refers to experimental) and AF 1410E + 1Cr, had compositions identical to that of commercial AF 1410, except that the steel marked AF 1410E + 1Cr had an additional 1 pct Cr compared to AF 1410E. The third steel, AerMet 100, was commercially purchased from CarTech, Reading, PA.

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**Samples were water-quenched after the first austenizing treatment.

AerMet 100 was austenitized at 871 °C, oil-quenched, and immediately transferred to a cryogenic bath at −73.3 °C for two hours. One blank was saved in the as-quenched condition and the other blanks were tempered at 427 °C, 454 °C, 482 °C, 510 °C, 538 °C, 566 °C, or 593 °C for times ranging from one to 100 hours.** One tensile and one Charpy V-notch specimen were machined from the heat-treated blanks for each tempering condition and tested at room temperature. Tensile tests were performed as per ASTM E8-91 at a strain rate of 10^-4 s^-1 using an MTS 810 universal testing machine and Masscomp data acquisition...
Table I. Composition of Steels

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>Co</th>
<th>Mn</th>
<th>Si</th>
<th>Ti</th>
<th>Al</th>
<th>S</th>
<th>P</th>
<th>O (ppm)</th>
<th>N (ppm)</th>
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<tbody>
<tr>
<td>AF 1410E</td>
<td>0.16</td>
<td>10.05</td>
<td>1.99</td>
<td>1.01</td>
<td>13.80</td>
<td>0.16</td>
<td>0.051</td>
<td>0.01</td>
<td>0.01</td>
<td>0.003</td>
<td>0.001</td>
<td>22</td>
<td>20</td>
</tr>
<tr>
<td>AF 1410 + 1Cr</td>
<td>0.16</td>
<td>10.02</td>
<td>2.97</td>
<td>1.21</td>
<td>13.74</td>
<td>0.16</td>
<td>0.048</td>
<td>0.01</td>
<td>0.01</td>
<td>0.003</td>
<td>0.001</td>
<td>18</td>
<td>20</td>
</tr>
<tr>
<td>AerMet 100</td>
<td>0.24</td>
<td>11.08</td>
<td>3.04</td>
<td>1.20</td>
<td>13.40</td>
<td>0.01</td>
<td>0.001</td>
<td>0.012</td>
<td>0.009</td>
<td>0.001</td>
<td>0.003</td>
<td>10</td>
<td>10</td>
</tr>
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<td>2000</td>
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</tbody>
</table>

Fig. 1—Variation of yield and ultimate strength as a function of tempering temperature. Box: AF 1410 E + 1Cr; diamond: AF 1410E; and triangle: AerMet 100. ±3σ values for Aermet 100 are indicated.

Fig. 2—Effect of tempering on Charpy V-notch toughness of AF 1410E and AF 1410E + 1Cr steels.

system. Although only one tensile and one Charpy test were performed for each tempering condition, the relative differences in the properties among the steels were similar at all the tempering times examined. Therefore, only the results of the samples tempered for five hours are described in this article to represent the trends in the properties of the steels.

The microstructural characterization of heat-treated specimens of these three steels was performed by transmission electron microscopy (TEM). Thin specimens for TEM were cut from the heat-treated blanks, ground to about 75 μm, and electropolished in a perchloric acid-methanol solution at −40 °C. The second-phase particles present in the samples were too small to be analyzed in thin specimens without matrix interference. Therefore, the chemical composition and crystal structures of these particles were determined after extracting them in carbon replicas. These replicas were prepared by evaporating a thin film of carbon on polished and etched specimens. The film was floated in the electropolishing electrolyte and supported on a copper grid. Spectra from individual precipitates were collected and analyzed by thin film analysis using independent k values. Only the TEM results of samples tempered in the peak hardening range, viz. 482 °C, 510 °C, and 538 °C, are reported in this article. Volume fraction of reverted austenite was measured by X-ray diffraction using the method described previously.[16]

III. RESULTS

A. Mechanical Properties

Figure 1 shows the yield and ultimate strength values for AF 1410E, AF 1410E + 1Cr, and AerMet 100 steels. The plot shows that the strength varied as AerMet 100 > AF 1410E > AF 1410E + 1Cr over the tempering range of 300 °C to 550 °C. Both AF 1410E and AF 1410E + 1Cr steels peak hardened at the same tempering temperature, viz. 482 °C, while AerMet 100 hardened at a slightly lower temperature, 464 °C. Figure 2 shows Charpy V-notch toughness values for the steels. The plots indicate that the toughness values of the steels were comparable when tempered up to 454 °C. At higher tempering temperatures, AF 1410E + 1Cr showed higher toughness. The values for the commercial AerMet 100 cannot be quantitatively compared with those for AF 1410E and AF 1410E + 1Cr steels which were produced in the laboratory. Steels produced by modern commercial melting and refining methods have fewer inclusions due to lower impurity levels and, for the same steel chemistry, have been shown to exhibit superior toughness performance.[14,17]

B. Transmission Electron Microscopy

Since it is well known that the M₂C carbides are the major strengthening source in these steels, thin foil and replica TEM analyses were performed to determine the size, precipitate/matrix coherence, and chemistry of these carbides. Similarly, it is accepted that the formation of coarse cementite and other alloy carbides could impair the toughness of the steels, while reverted austenite has a toughening contribution in these steels[9] therefore, the formation of these phases was also investigated to better understand the toughness variations in the steels. Samples from AF 1410E and the AF 1410 + 1Cr steels tempered in the range of 482 °C to 538 °C were examined by TEM. The results were compared with similar studies on AerMet 100 conducted recently by the authors.[15,16]