Effects of Alloying Elements on Fracture Toughness in the Transition Temperature Region of Base Metals and Simulated Heat-Affected Zones of Mn-Mo-Ni Low-Alloy Steels

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This study is concerned with the effects of alloying elements on fracture toughness in the transition temperature region of base metals and heat-affected zones (HAZs) of Mn-Mo-Ni low-alloy steels. Three kinds of steels whose compositions were varied from the composition specification of SA 508 steel (grade 3) were fabricated by vacuum-induction melting and heat treatment, and their fracture toughness was examined using an ASTM E1921 standard test method. In the steels that have decreased C and increased Mo and Ni content, the number of fine M$_7$C carbides was greatly increased and the number of coarse M$_7$C carbides was decreased, thereby leading to the simultaneous improvement of tensile properties and fracture toughness. Brittle martensite-austenite (M-A) constituents were also formed in these steels during cooling, but did not deteriorate fracture toughness because they were decomposed to ferrite and fine carbides after tempering. Their simulated HAZs also had sufficient impact toughness after postweld heat treatment. These findings indicated that the reduction in C content to inhibit the formation of coarse cementite and to improve toughness and the increase in Mo and Ni to prevent the reduction in hardenability and to precipitate fine M$_7$C carbides were useful ways to improve simultaneously the tensile and fracture properties of the HAZs as well as the base metals.

I. INTRODUCTION

THE Mn-Mo-Ni low-alloy steels such as SA 533 and SA 508 steels are key materials used in nuclear reactor facilities such as pressure vessels, compressors, and steam generators. The most crucial mechanical properties for these steels are sufficient strength, to withstand the internal pressure, and high fracture toughness, to assure safety against unexpected accidents. Because of the continuous neutron irradiation that occurs during the operation of a nuclear reactor, fracture toughness deteriorates and the ductile-brittle transition temperature (DBTT) moves toward high temperatures.

Thus, in order to guarantee the safe operation of a nuclear reactor, steels that have a high fracture toughness should be used. Since large-scale nuclear reactor structures are usually fabricated by welding, it is also important to use steels with excellent welding properties.

The Mn-Mo-Ni low-alloy steels used for nuclear reactor pressure vessels have been continuously developed to establish safe operation and to extend service life. The primary methods used to improve their mechanical properties are grain refinement and the control of alloying elements. Grain refinement can be achieved by grain-boundary pinning with aluminum nitrides or by controlling the austenitization temperature and quenching rate. The control of alloying elements such as C, Mn, Mo, and Ni can improve the performance of these steels. However, studies of the effect of the alloying element on the mechanical properties have yet to be completed. Since the variation of grain size and alloying elements can affect the mechanical properties of materials at the same time, it is crucial to separate the effects of the alloying elements and the grain size by fixing the grain size of the materials in order to isolate the effect of the alloying elements. Even when low-alloy steels with excellent mechanical properties are developed, their mechanical properties may deteriorate after welding, which is unavoidable in actual use. Therefore, the effect of the alloying elements should be interpreted in relation to the mechanical properties of heat-affected zones (HAZs). Sufficient fracture toughness in the HAZs and the quantitative evaluation of that toughness are both important to the safe operation of nuclear reactor structures; thus, the mechanical properties should be investigated.

The fracture toughness of steels in the lower shelf region can be evaluated by measuring plane strain fracture toughness ($K_{IC}$) in accordance with the ASTM E399 standard test method. The $J_{IC}$ can be used in measuring the resistance to ductile-crack propagation in the upper shelf or upper transition region, in accordance with the ASTM E1737 standard test method. However, these two methods have some limitations in measuring fracture toughness in the transition region. Since the plastic zone size at a crack tip should be
II. EXPERIMENTAL

In order to understand the effects of alloying elements on fracture toughness in the transition region of Mn-Mo-Ni low-alloy steels, three steels with the same grain sizes, viz., A, B, and C steels with different alloy contents, were fabricated. The A steel had the composition of the SA 508 steel (grade 3) given in its specification. The B steel was fabricated with decreased C and Mn content, to reduce the formation of cementite, and with increased Ni and Mo content, to make up for insufficient hardenability and strength. In the C steel, the carbon content was further decreased from that of the other two steels to prevent completely the precipitation of coarse cementite. The chemical compositions of these steels are shown in Table I.

A vacuum-induction melting furnace with a 30-kgf capacity was used for fabricating the steels. Cast ingots were hot rolled to a thickness of 35 mm, and then homogenized at 1200 °C for 12 hours. They were then austenitized at 900 °C for 1 hour, water quenched, austempered at 900 °C for 1 hour again, and cooled at a rate of 20 °C/min to obtain a bainitic microstructure. Tempering was then conducted at 660 °C for 10 hours.

Microstructures were analyzed using an optical microscope, a scanning electron microscope (SEM), and a transmission electron microscope (TEM). Bulk specimens were polished and then etched in either a 2 pct nital solution or a mixed solution of 1 pct nital and 1 pct picral. They were separated by applying a voltage of 5 V in an electrolyte of 10 ~ 15 pct perchloric acid and methanol. For the TEM observation of thin foils, specimens were cut into 10 × 10 × 5-mm pieces whose surfaces were polished and etched in a mixed solution of 1 pct nital and 1 pct picral. On the etched surface, carbon thin films were deposited. They were separated by applying a voltage of 5 V in an electrolyte of 10 ~ 15 pct perchloric acid and methanol. For the TEM observation of thin foils, specimens were mechanically polished to a thickness of 100 μm, punched to prepare 3-mm-diameter discs using a disc cutter, and then electropolished in a solution of 95 pct methanol and 5 pct perchloric acid. The thin foils and replicas were observed by TEM at an acceleration voltage of 200 kV.

The volume fraction of retained austenite was measured using an X-ray diffractometer. The Mo Kβ characteristic rays were used, and the volume fraction of retained austenite, \( V_r \), was calculated from the integrated intensity of ferrite and austenite peaks using the following equation:\(^{(25,26)}\)

\[
V_r = \frac{1.4I_y}{1.4I_y + I_a}
\]

where \( I_y \) and \( I_a \) are the average integrated intensity obtained at \{220\}₀ and \{311\}₀ peaks and that obtained at a \{211\}₀ peak, respectively.

Tensile bars parallel to the transverse direction with a gage diameter of 4 mm and a gage length of 12.5 mm were tested at room temperature at a strain rate of 4 × 10⁻⁶/s using a 10-t Instron machine (Instron, Canton, MA). Low-temperature tensile tests were conducted after the tensile bars were kept for 15 minutes inside a chamber in which the testing temperature was controlled by supplying the cold nitrogen vapors from liquid nitrogen into the chamber. Charpy impact tests were performed on Charpy V-notch specimens (transverse-longitudinal (T-L) orientation) over the temperature range −150 °C to 100 °C. In order to reduce errors in data interpretation, a regression analysis of absorbed impact energy \( V \) vs test temperature was made using a hyperbolic-tangent

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Mn</th>
<th>Mo</th>
<th>Ni</th>
<th>Cr</th>
<th>Si</th>
<th>Al</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.193</td>
<td>1.350</td>
<td>0.482</td>
<td>0.922</td>
<td>0.128</td>
<td>0.190</td>
<td>0.009</td>
<td>bal</td>
</tr>
<tr>
<td>B</td>
<td>0.099</td>
<td>0.701</td>
<td>0.962</td>
<td>2.500</td>
<td>0.143</td>
<td>0.196</td>
<td>0.023</td>
<td>bal</td>
</tr>
<tr>
<td>C</td>
<td>0.060</td>
<td>1.550</td>
<td>1.000</td>
<td>1.460</td>
<td>0.150</td>
<td>0.220</td>
<td>0.023</td>
<td>bal</td>
</tr>
</tbody>
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