T. C. Tschanz,¹ D. K. Matlock,² and G. Krauss²

Applicability of the Short Rod Fracture Toughness Test to New Microalloyed Bar Steels


ABSTRACT: The applicability of the short rod fracture toughness test to fracture analyses of new microalloyed bar steels, under consideration as substitutes for quenched and tempered steels, is evaluated. Data on two bainitic steels processed with microstructures of ferrite and austenite in which the austenite transforms to martensite with strain are compared to data on 4140 steel and 1045V steel. The applicability of the short rod fracture toughness test is discussed in conjunction with an analysis of the unique deformation behaviors of the four steels. Alterations to the test criteria for materials with microstructures which change with strain are suggested.

KEY WORDS: microalloyed bar steels, stress assisted martensite formation, strain assisted martensite formation, stress strain analysis, transition temperature, validity requirements

The use of new microalloyed steel grades offers significant potential cost savings in applications which require yield strength levels in the range of 560 to 700 MPa [1–3]. Some of the microalloyed steels exhibit deformation behavior, as summarized in the following sections, which differs significantly from conventional steels. Universal acceptance of the new microalloyed steels has been limited by a lack of a complete understanding of their fracture behavior. Many of the forged bar products under consideration have dimensions (e.g., <30 mm) that make use of standard plane strain fracture toughness tests inapplicable [4]. As a result, the Charpy impact test has been used to evaluate fracture properties. If full acceptance of these new steel grades is to be obtained, then design-oriented fracture toughness data obtained over the complete design temperature range are required. Therefore, the short rod test, which offers many advantages including adaptability to dimensional requirements and inexpensive specimen preparation, was evaluated.

Experimental Materials

Four bar steels were chosen for this study. The steels include two medium-carbon microalloyed bar steels processed with bainite microstructures (designated 0.24%C-Mn-Mo-V and 0.35%C-Mn-Mo-V), a microalloyed ferrite-pearlite steel (1045V), and a conventional quenched and tempered bar steel (4140). The steel processing histories and compositions are summarized in Tables 1 and 2 respectively. All steels were heat treated to produce hardnesses in the range of 25 to 30 HRC.

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<table>
<thead>
<tr>
<th>Alloy</th>
<th>Bar Diameter, mm (in.)</th>
<th>Heat Treatment</th>
<th>Microstructure</th>
<th>Hardness (HRC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1045V</td>
<td>31.8 (1.25)</td>
<td>As-Received</td>
<td>Ferrite/Pearlite</td>
<td>27.8–28.4</td>
</tr>
<tr>
<td>4140</td>
<td>31.8 (1.25)</td>
<td>Austenitized 1 h @ 845°C Oil Quenched Temper 1 h @ 670°C Air Cool</td>
<td>Tempered Martensite</td>
<td>28.2–28.6</td>
</tr>
<tr>
<td>0.24C-Mn-Mo-V</td>
<td>30.2 (1.19)</td>
<td>Austenitized 1 h @ 1100°C Air Cooled</td>
<td>Bainite</td>
<td>25.3–28.4</td>
</tr>
<tr>
<td>0.35C-Mn-Mo-V</td>
<td>31.8 (1.25)</td>
<td>Austenitized 1 h @ 1100°C Air Cooled</td>
<td>Bainite</td>
<td>26.9–30.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Fe</th>
<th>Al</th>
<th>C</th>
<th>Cr</th>
<th>Cu</th>
<th>Mn</th>
<th>Mo</th>
<th>Ni</th>
<th>P</th>
<th>S</th>
<th>Si</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>1045V</td>
<td>bal.</td>
<td>0.019</td>
<td>0.45</td>
<td>0.21</td>
<td>0.14</td>
<td>0.79</td>
<td>0.03</td>
<td>0.18</td>
<td>0.022</td>
<td>0.022</td>
<td>0.26</td>
<td>0.22</td>
</tr>
<tr>
<td>4140</td>
<td>bal.</td>
<td>0.001</td>
<td>0.35</td>
<td>0.84</td>
<td>0.24</td>
<td>0.89</td>
<td>0.22</td>
<td>0.10</td>
<td>0.013</td>
<td>0.021</td>
<td>0.29</td>
<td>0.13</td>
</tr>
<tr>
<td>0.24C-Mn-Mo-V</td>
<td>bal.</td>
<td>0.001</td>
<td>0.24</td>
<td>0.13</td>
<td>0.44</td>
<td>1.78</td>
<td>0.22</td>
<td>0.17</td>
<td>0.016</td>
<td>0.028</td>
<td>0.41</td>
<td>0.13</td>
</tr>
<tr>
<td>0.35C-Mn-Mo-V</td>
<td>bal.</td>
<td>0.040</td>
<td>0.35</td>
<td>0.07</td>
<td>0.06</td>
<td>1.46</td>
<td>0.19</td>
<td>0.06</td>
<td>0.012</td>
<td>0.019</td>
<td>0.79</td>
<td>0.16</td>
</tr>
</tbody>
</table>
The 0.24% C-Mn-Mo-V and 0.35% C-Mn-Mo-V steels were processed by controlled cooling to produce steels with fine bainitic microstructures. In contrast to Bainites which consist of ferrite and cementite, the microstructures of the bainite steels of this investigation consisted of ferrite and retained sustenite [5,6]. The 0.35% C-Mn-Mo-V steel had a higher volume fraction of retained austenite than the 0.24% C-Mn-Mo-V steel [5]. The ferrite-pearlite of the 1045V steel was composed of grain boundary allotriomorphs of proeutectoid ferrite and a high volume fraction of pearlite. The vanadium contributed to precipitation strengthening of the ferrite. The 4140 steel had a standard quenched and tempered martensitic structure. Complete summaries of the microstructures of the steels are presented elsewhere [4,5].

The mechanical properties as measured by standard Charpy V-notch testing, instrumented impact testing, and crack tip opening displacement (CTOD) testing were evaluated previously as a function of temperature [5]. The temperature-dependent tensile properties of the two bainitic steels differed significantly from both the ferrite-pearlite (1045V) and martensitic steel (4140). Figures 1a and 1b show the effect of test temperature on the 0.2% offset yield (σ₀₅) and ultimate strengths (σₚₚ₆₅₅), respectively. The temperature dependence of the yield strength for both the 1045V and 4140 steel decrease with an increase in temperature, a behavior which is common to most steels. In contrast, the yield strengths of the two bainitic steels decreased with decreasing test temperatures. All four steels exhibit similar effects of temperature on the ultimate tensile strength, an increase with a decrease in temperature.

Figure 2 shows two sets of schematic stress-strain curves based on complete experimental stress-strain curves [5] and illustrates the effects of temperature on the overall deformation behavior of the four steels. Figure 2a illustrates the behavior observed for the bainitic steels, while Fig. 2b illustrates the behavior for the 1045V and 4140 steel. The schematic stress-strain curves in Fig. 2 clearly show that the temperature dependences of both the yield and ultimate tensile strengths shown in Fig. 1 translate into two distinctively different sets of flow curves. The stress-strain behavior shown in Fig. 2b illustrates the anticipated response of most alloy systems with stable microstructures. In contrast, the behavior illustrated in Fig. 2a, where the stress-strain curves at various temperature cross at an intermediate strain level, reflects the effects of an unstable microstructure in which the microstructure changes with strain. The retained austenite in the bainitic steels transforms to martensite with strain. Austenite transformation with deformation occurs by either stress-assisted or strain-assisted mechanisms and is enhanced with a decrease in test temperature [7]. Therefore, the decrease in yield strength with decreasing temperature for the bainitic steels reflects contributions of low-strain stress-assisted transformation of austenite to martensite. Transformation of austenite to martensite produces an extra increment in strain at stress levels less than the conventional macroscopic 0.2% offset yield stress. Thus the initial shape of the curve is altered to produce the behavior shown in Fig. 2a in which the proportional limit decreases with a decrease in temperature. Therefore conventional yield strength definitions (i.e., the 0.2% offset) lead to a decrease in yield strength with a decrease in temperature as shown in Fig. 1a. Note also for the bainitic steels that immediately after yielding, high strain hardening rates are observed, leading to low ratios of yield strength to ultimate tensile strength.

Most fracture criteria consider the yield strength a critical parameter as it can be used to assist in descriptions of crack tip constraint. However, conventional fracture toughness tests inherently assume that the stress-strain behavior is as illustrated in Fig. 2b; thus potential effects of the yield behavior illustrated in Fig. 2a must be incorporated in fracture criteria. In this study the effects of the different yielding and deformation behavior of the four steels on fracture behavior are considered.
FIG. 1—Effects of test temperature on the tensile properties of the four experimental steels. (a) 0.2% yield stress. (b) Ultimate tensile strength [5].
Experimental Procedure

Cylindrical short rod fracture toughness test specimens were machined and tested in accordance with ASTM Test for Plane-Strain (Chevron-Notch) Fracture Toughness of Metallic Materials (E 1304-89). Full sized (25.4 mm) and sub-sized (12.7 mm) diameter specimens were machined with the dimensions summarized in Table 3. According to the nomenclature for the test orientations summarized in ASTM Terminology Relating to Fracture Testing (E 616-89), full sized samples were machined in the R-L orientation while sub-sized samples were machined in both the R-L and L-R orientations. Fifteen full sized (25.4 mm) specimens were machined in the R-L orientation for each of the four steels and tested as a function of temperature. Eight sub-sized (12.7 mm) short rod specimens were also machined for each orientation (L-R and R-L). All the short rod specimens were removed from center of the heat treated bar stock.

Chevron notches were machined with either a diamond slitting saw or by electrical discharge machining (EDM). Slitting of the chevron notch with the diamond saw proved to be difficult and time consuming. Achieving proper slot alignment on both sides of the specimen was very difficult because the diamond blade warped due to overheating or misalignment.

As an alternative to slitting, the slots in the samples were machined by electrical discharge machining (EDM). After EDM, the depths of the chevron tip ($a$) were found to be slightly out-of-tolerance because of inconsistent grip groove depths ($S$ in Table 3) which were used as a reference for $a_n$. The as-machined $a_n$ measurements for the 25.4 mm diameter samples were out-of-tolerance with an average $a_n$ of 11.58 mm. Even though the samples were slightly out-of-tolerance, the results, corrected with the method summarized below in the Discussion,
TABLE 3—ASTM E 1304 dimensional requirements for short rod specimens (dimensions in mm).

<table>
<thead>
<tr>
<th>Symbol</th>
<th>25.4 mm Specimen</th>
<th>12.7 mm Specimen</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dimension</td>
<td>Tolerance</td>
</tr>
<tr>
<td>B</td>
<td>25.4</td>
<td>. . .</td>
</tr>
<tr>
<td>W</td>
<td>36.830</td>
<td>± 0.254</td>
</tr>
<tr>
<td>a₀</td>
<td>12.217</td>
<td>± 0.127</td>
</tr>
<tr>
<td>S</td>
<td>3.302</td>
<td>± 0.254</td>
</tr>
<tr>
<td>X</td>
<td>1.270</td>
<td>± 0.076</td>
</tr>
<tr>
<td>T</td>
<td>7.950</td>
<td>± 0.127</td>
</tr>
<tr>
<td>τ</td>
<td>≤ 0.762</td>
<td>. . .</td>
</tr>
<tr>
<td>φ</td>
<td>54.6°</td>
<td>± 0.5°</td>
</tr>
</tbody>
</table>

*B = Specimen Diameter
W = Length
a₀ = Distance to Chevron Tip
S = Grip Groove Depth
X = Distance to Load Line
T = Grip Groove Width
τ = Slot Thickness
φ = Slot Angle

were included in this study and found to correlate directly with those on samples with acceptable dimensions.

In contrast to the machining of the 25.4 mm samples, in which the grip groove and chevron notch were machined in two steps, all machining was done in a single EDM step on the sub-sized samples. As a result, the dimensional tolerances of the sub-sized samples were acceptable according to ASTM E 1304 [4].

Machining of specimens within the dimensional tolerances specified by ASTM E 1304 for the sample geometries used in these steels (W/B = 1.45 and a₀/W = 0.332 configuration) may result in specimens which do not meet the tolerance for the chevron slot angle, φ. This point is demonstrated in Fig. 3, where φ is determined geometrically by assuming the maximum and minimum dimensions within the tolerance bands. For example, as summarized in Table 4, if W is at the high end of the tolerance band while a₀ is at the low end of the band (i.e., W = 37.084 mm and a₀ = 12.090 mm respectively), then the calculated φ is 53.9°. If the reverse conditions are chosen for W and a₀ (i.e., W = 36.576 mm and a₀ = 12.34 mm), then φ is 55.3°. Thus even though the dimensions are within the allowable specification, the calculated value of φ is outside the allowable range of 54.6° ± 0.5°. In practice direct measurement of φ is not made during machining, and the acceptability of a sample is based primarily on dimensions. Careful consideration of all the dimensions must be given to ensure that all specifications are satisfied.

Short rod testing was performed on a commercial short rod fracture toughness test unit equipped with computer control. The test unit meets the requirements of ASTM E 1304. Copper heating and cooling jackets were used for temperature control in the temperature range of −100°C to +125°C. For cooling, liquid nitrogen was sprayed though four nozzles into each corner of the copper jackets; for heating four resistance heaters were used. The jackets heat or cool the specimens through conduction. Two thermocouples were used: (1) a control thermocouple in the copper jackets near the heating/cooling elements, and (2) a monitoring thermocouple placed in the machined notch and held in place against the inside surface of the notch on the short rod specimen.
FIG. 3—Schematic drawing of chevron notch in the short rod test sample identifying the parameters used in the calculations summarized in Table 4.

TABLE 4—Calculated chevron notch angles based on tolerance extremes in ASTM E 1304.

<table>
<thead>
<tr>
<th>Tolerance Case</th>
<th>Assumed Values</th>
<th>Resulting φ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>W</td>
</tr>
<tr>
<td>Ideal</td>
<td>25.400</td>
<td>36.830</td>
</tr>
<tr>
<td>Worst (+, −)</td>
<td>25.400</td>
<td>37.084</td>
</tr>
<tr>
<td>Worst (−, +)</td>
<td>25.400</td>
<td>36.576</td>
</tr>
<tr>
<td>Worst (+, +)</td>
<td>25.400</td>
<td>37.084</td>
</tr>
<tr>
<td>Worst (−, −)</td>
<td>25.400</td>
<td>36.576</td>
</tr>
</tbody>
</table>

Results

Load-displacement data as a function of test temperature were obtained for the samples, and the results were used to calculate the critical stress intensity factors. In this paper selected data are discussed to illustrate the relationship between stress-strain behavior (as shown in Fig. 2) and calculated short rod fracture toughness data. A complete discussion of all the data is included elsewhere [4]. The resulting calculated stress intensity data for the 1045V steel and the two bainitic steels are shown in Figs. 4, 5, and 6. All three materials exhibit a decrease in toughness with a decrease in temperature. In contrast, the 4140 steel exhibited a slight increase in toughness with a decrease in temperature. As the load-displacement data
for the 4140 steel differ significantly from the other steels, and the UTS data are higher, further analysis of the fracture toughness data are omitted from the discussion below.

Two different types of load-displacement data were observed: (1) incremental instabilities associated with "crack jump" and (2) smooth data associated with stable or ductile crack growth. Crack jump behavior is characterized by "pop-ins" associated with unstable growth.

Unstable crack growth can occur several times within a single test, and at each point of instability the stress intensity reaches a critical value \( (K_{\text{tvj}}) \) which is equivalent to the plane-strain fracture toughness. At lower test temperatures only incremental load drops were observed, while at higher temperatures only smooth crack behavior occurred.

The plane-strain fracture toughness was determined using different loads for different types of behavior:

\[
K_{\text{tv}} = \frac{Y^*mP_c}{B\sqrt{W}}
\]

\[
K_{\text{tvj}} = \frac{Y^*P_{c'}}{B\sqrt{W}}
\]

where \( K_{\text{tv}} \) is the toughness based on smooth crack growth behavior, \( K_{\text{tvj}} \) is the toughness based on crack jump behavior, and \( P_c \) and \( P_{c'} \) are the critical loads for smooth crack and
FIG. 5—Effect of test temperature on the critical stress intensity factor for the 0.24% C-Mn-Mo-V bainitic steel as measured with the short rod fracture toughness test. Data for two specimen diameters (25.4 and 12.7 mm) and two orientations (R-L and L-R) are shown. The dashed line marks the transition from crack jump to smooth crack growth behavior.

crack jump behavior, respectively. During a test both types of behavior require unloading and reloading, which measure the compliance through the unloading slope ratios, r.

The equation for the stress intensity coefficient (\(Y^*\)) as a function of the slope ratio is given in ASTM E 1304 by

\[
Y^* = \exp(5.052 - 9.488r + 19.78r^2 - 18.48r^3 + 6.92r^4)
\]  

Furthermore, the minimum value of the stress intensity coefficient (\(Y_m^*\)) can be found by inserting the critical slope ratio (\(r_c\)) for a given specimen into Eq 3. For the short rod specimen in this study (i.e., \(a/B\) of 1.45 and \(a_p/W\) of 0.332) the critical slope ratio is 0.52, resulting in a \(Y_m^*\) value of 29.21. The accuracy of Eq 3 is estimated to be \(\pm 0.5\%\) for slope ratios between 0.2 and 0.85. Generally, crack jump behavior indicates lower fracture toughness because the crack tends to grow in an unstable manner, whereas smooth crack behavior is associated with stable crack growth.

The transition from crack-jump to smooth crack growth with test temperature is indicated by the dashed line in Figs. 4, 5, and 6. All the load-displacement curves for the 4140 steel exhibited smooth crack behavior over the test temperature range \((>-70^\circ C)\).

The critical stress intensity data for the 25.4 mm diameter samples in Figs. 4 to 6 indicate similar behavior, a gradual increase with temperature followed by a transition region to an upper plateau. The observed transition in toughness is mirrored by a change in fracture surface appearance. For example, the fracture surfaces for the four 1045V steel samples,
FIG. 6—Effect of test temperature on the critical stress intensity factor for the 0.35%C-Mn-Mo-V bainitic steel as measured with the short rod fracture toughness test. Data for two specimen diameters (25.4 and 12.7 mm) and two orientations (R-L and L-R) are shown. The dashed line marks the transition from crack jump to smooth crack growth behavior.

indicated by the letters A, B, C, and D in Fig. 4, are shown in Fig. 7. The scanning electron microscope fractographs in Fig. 7 were taken at the crack position which corresponded to the crack lengths used in the toughness calculations.

All fracture surfaces for samples tested below the transition region had a shiny faceted appearance when viewed without magnification. Figure 7a, for a specimen at the lowest test temperature (−25°C), exhibits primarily brittle cleavage fracture. The 90°C sample shown in Fig. 7b exhibits a mixed-mode cleavage fracture with increased microvoid coalescence. Between 90 and 95°C, the fracture toughness increased abruptly to a upper plateau. Above 95°C, the fracture surface consists of microvoid coalescence due to ductile rupture as shown by fractographs in Figs. 7c (95°C) and 7d (141°C). Thus the transition in toughness shown in Fig. 4 directly reflects a transition in fracture surface morphology and correspondingly a true transition temperature between 90 and 95°C. Below the transition region, the load versus displacement plots were characterized by crack jump or unstable behavior (between −25 to 90°C) and high strain rates. Within this 5°C range the load displacement curves were found to change from crack jump to smooth crack growth behavior. In other words, the upper plateau is characterized by smooth (stable) crack growth behavior (≥95°C) and low strain rates. Therefore the test record directly reflects the change in the fracture mode that accompanies the transition zone.

Similar correlations between the fracture surface and the load versus displacement records are demonstrated by the bainitic steels with 25.4 mm short rod specimens shown in Figs. 5
FIG. 7—Scanning electron microscope fractographs of the 1045V steel at the temperatures indicated in Fig. 4. (a) -25°C. (b) 90°C. (c) 95°C. (d) 140°C.

and 6. Both steels demonstrated three different types of load versus displacement behavior as a function of temperature: 100% crack jump, mixed mode, and smooth crack growth behavior. At low temperatures, crack jump behavior was observed where the specimens displayed multiple small crack jumps in the valid slope ratio region. At intermediate temperatures the specimens displayed mixed mode behavior, where the initial portions of the load versus displacement plot showed smooth crack growth behavior (i.e., woody fracture texture) followed by crack jump behavior (i.e., shiny faceted texture) in the final portions of the test record. This smooth crack growth behavior occurred in the initial part of the load versus displacement data and accounted for a larger fraction of the test record as the temperature increased. An example of a specimen with both types of behavior and the corresponding fracture surface is shown in Fig. 8 for a sample of the 0.24%C-Mn-Mo-V steel tested at 70°C. The increasing load is associated with ductile tearing, while the abrupt load drop is associated with crack growth which leads to the observed brittle fracture (shiny regions).

The effect of sample diameter and orientation was evaluated with sub-sized samples (12.7
mm diameter) for the four steels. The results for the bainitic steels are included in Figs. 5 and 6. All sub-sized samples of the 1045V steel exhibited bulk yielding except for the two L-R samples tested below −77°C. Calculated toughness values for these samples were significantly higher than the data shown in Fig. 4. For the bainitic steels there was no observable effect of orientation for either steel. However, the effect of sample size differed between the two steels. Data for the sub-sized samples of the 0.24%C-Mn-Mo-V steel in
Fig. 5 exhibited the same behavior as for the 1045V steel (i.e., higher toughnesses for subsized specimens). In contrast, there was no apparent sample size effect for the 0.35%C-Mn-Mo-V steel as shown in Fig. 6 where the data for the two sample diameters are superimposed. The significance of the sample size effects are discussed below in conjunction with a discussion of validity requirements.

Discussion

To interpret the fracture data shown in Figs. 4 to 6, it is necessary to evaluate the validity requirements described in ASTM E 1304 along with a consideration of the various stress-strain behaviors exhibited by the steels in this study. Two criteria, the specimen size requirement and the allowable compliance plasticity factor, may be influenced by the extent of stress-induced martensite formation in the plastic zone on loading. As indicated previously, the decrease in yield strength with a decrease in temperature (Fig. 1) was a result of increasing amounts of martensite formation with decreasing test temperatures. Furthermore, the retained austenite volume fraction was higher in the 0.35%C-Mn-Mo-V steel and as a result the extent of transformation was greater.

Specimen Size Requirement

The specimen size requirement given by ASTM E 1304 states that allowable diameters must be larger than the quantity, $1.25 \left( K_{OV}/\sigma_y \right)^2$. Calculations based on the yield data shown in Fig. 1 indicate that valid toughness measurements on the 0.35%C-Mn-Mo-V steel require diameters of 61 to 70 mm, dimensions which are significantly greater than those used in this study. However, the coincidence of the fracture data for the two sample diameters shown in Fig. 6 suggests that both sets of data are valid; otherwise a measurable size effect would have been observed. The possible difference between the observed behavior and the prediction of the allowable diameter may reflect the value of the yield strength used in the dimension validity calculation. Most steels exhibit yield strengths of approximately $0.7\sigma_{UTS}$. However, the bainitic steels exhibit low yield strengths, as low as $0.3\sigma_{UTS}$, and high initial strain hardening rates. Thus, use of abnormally low yield strengths in the constraint requirement would predict larger than required diameters. Therefore it is concluded that the data shown in Fig. 6 are valid. This leads to the further conclusion that the size validity requirement is not applicable to the 0.35%C-Mn-Mo-V steel and needs to be modified. One possible modification is to use $\sigma_F$, an average flow stress defined by

$$\sigma_F = \frac{1}{2} (\sigma_y + \sigma_{UTS}) \quad \text{or} \quad \sigma_F = \frac{\sigma_y + \sigma_{UTS}}{2} \quad (4)$$

The average flow stress in Eq 4 would more realistically describe the constraint requirements.

In contrast to the behavior of the 0.35%C-Mn-Mo-V bainitic steel, the other three low steels exhibited fracture data which depended on specimen diameter, and the smaller diameter samples did not produce valid fracture toughness measurements. The 0.24%C-Mn-Mo-V steel, with its lower volume fraction of retained austenite, did not produce significant austenite transformation to offset the size effect.

Compliance Plasticity Factor

The austenite transformation may also influence analysis of the compliance plasticity factor. The compliance plasticity factor, $p$, is illustrated in Fig. 9 for materials that exhibit two different deformation behaviors. Idealized behavior in Fig. 9a obeys the basic principles
FIG. 9—Schematic drawings of the load versus crack mouth opening displacement data used to evaluate the compliance plasticity factor as defined in ASTM E 1304-89. (a) Linear elastic behavior. (b) Elastic-plastic behavior.

of linear elastic fracture mechanics (LEFM), which is displayed by linear unloading/reloading paths. If the material behaves in an elastic manner, the specimen would completely close when unloaded. In the case of elastic/plastic behavior, the formation of a plastic zone at the crack tip (and the resulting residual stresses) prevent the specimen from completely closing. This causes the slopes of the unloading/reloading cycles to deviate from the origin of the load versus crack mouth as shown in Fig. 9b. Since LEFM requires negligible plasticity, an elastic-plastic validity check has been developed for short rod specimens to account for plasticity effects. The plasticity is measured by a sequence of unloading and reloading cycles,
which allows graphical determination of the "plasticity" from load versus crack mouth opening displacements ratio, $\Delta x_o/\Delta x$, and must be between $-0.05$ and $0.1$ for a valid short rod test. Values outside this range indicate excessive residual stresses ($\rho < -0.05$) or excessive plasticity ($\rho > 0.1$), which may indicate specimen failure by plastic tearing instead of crack extension. Thus the mouth opening or plasticity can be taken as a measure of the degree to which LEFM assumptions are violated.

The compliance plasticity factor ($\rho$) exceeded the maximum value of 0.1 by a large margin (0.33 to 0.41) for the 0.35%C-Mn-Mo-V bainitic steel and to a lesser extent (approximately 0.17) for the 0.24%C-Mn-Mo-V bainitic steel. However, the maximum load plasticity validity requirement was met (i.e., the $1.1P_o > P_m$ requirement). This indicates that the compliance plasticity factor ($\rho$) may be affected by austenite transformation in the plastic zone. The plasticity factor may be affected if the slopes of the compliance measurements are altered by crack closure effects due to martensite formation on loading. In other words, martensite formation may alter closure mechanisms as follows: (1) as stress and resulting induced strain is applied to the crack tip, the retained austenite transforms to martensite; (2) a volume expansion is associated with the transformation from austenite to martensite [5]; (3) the expansion produces compressive residual stress at the crack or notch tip; and (4) the compressive residual stress tends to increase the stress needed to propagate the crack (similar to crack closure effects in fatigue). This mechanism would be expected to decrease the CMOD and reduce the compliance or slope of the unloading/reloading, indicating a smaller crack length than actually exists. Therefore the formation of martensite may alter the appearance of the load displacement curve.

To illustrate the effects of martensite formation on load displacement data, Fig. 10 shows how the increased volume fraction of retained austenite affects load versus displacement records displaying smooth crack growth behavior and may affect the compliance for the various steels studied. These test records were taken just above the transition from crack jump to smooth crack growth behavior, so they can be directly compared without concern for additional plasticity due to elevated test temperatures. In the 4140 steel the load versus displacement record displays linear elastic behavior as shown in Fig. 10a. This steel has little or no retained austenite. For the 0.24%C-Mn-Mo-V steel in Fig. 10b, the test record demonstrates increased elastic/plastic behavior where the slopes of the unloading/reloading cycles deviate from the origin (i.e., as previously shown in Fig. 9b). The final test record for the 0.35%C-Mn-Mo-V steel, shown in Fig. 10c, demonstrates elastic/plastic behavior to even a greater extent than the 0.24%C-Mn-Mo-V steel in Fig. 10b. As previously mentioned, the 0.35%C-Mn-Mo-V steel has considerably larger volume fraction of retained austenite than the 0.24%C-Mn-Mo-V steel, which resulted in more martensite formation with strain. These results indicate two major changes in the load/displacement plots as the degree of martensite formation with strain increases: (1) the $\Delta x_o$ term in Fig. 10 increases while the $\Delta x$ term remains relatively constant for all the test records, and (2) the degree of elastic/plastic behavior increases. The increase of the $\Delta x_o$ term relative to the $\Delta x$ term would result in larger $\rho$ values, which may be associated with the larger volume fraction of retained austenite which transforms to martensite on deformation.

This mechanism may also affect the toughness results in crack jump behavior, since the toughness is determined by evaluating the slope ratios of the critical load (i.e., $0.8r_e \leq r \leq 1.2r_e$). If the slope ratios or compliances are altered by austenite transformation to martensite, the critical loads ($P_o$) used to evaluate $K_{tv}$ may also be altered.

**Evaluation of Out-of-Tolerance Specimens**

The short rod fracture toughness values were reported as apparent fracture toughness values, $K_{Ov}$, instead of true plane-strain values primarily due to specimens out-of-tolerance
FIG. 10—Direct traces of the load versus displacement test records for the 4140 steel in (a) and the two bainitic steels in (b) and (c).
with respect to the machined notch depth, $a_n$. An analysis, presented elsewhere [4], showed that correction of the calculations based on the modified stress intensity coefficients determined by Bubsey et al. [8] indicated that the out-of-tolerance crack lengths contributed a maximum error of 4% to the toughness values. Errors of this magnitude are within the experimental measuring capability of most equipment. Thus it is concluded that coefficients in ASTM E 1304 result in conservative limitations to crack geometries, and that proper correction factors can be used to expand the dimension range for short rod samples which produce valid results.

Summary and Conclusions

The results of this study have shown that the short rod test is a viable test for the evaluation of the fracture behavior of several new bar steel grades if the steel microstructures are considered in the analysis. The specification, as written, is appropriate for steels with stable microstructures that exhibit conventional behavior (i.e., both yield and ultimate tensile strengths increase with a decrease in test temperature and the yield to tensile strength ratio is approximately 0.7). However, for steels with microstructures and properties as were exhibited for the bainitic steels, modifications to the validity requirements may be required in order to properly evaluate the fracture toughness.

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