A MECHANICS-METALLURGY APPROACH TO CLEAVAGE BEHAVIOR IN MILD STEEL

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ABSTRACT

Four groups of specimens of mild steels were tested in plain-tension and four-point notch bending over a range of temperatures from -196 °C to 200 °C. Finite element method (FEM) was used to calculate the stress field of notched bar. Experimental results were analysed with a combined viewpoint of mechanics-metallurgy. Probabilistic demand is emphasised in notch bend tests and a concept of "effective yield zone" is proposed. Based on this concept, expression for cleavage criterion and that for brittle-to-ductile transition condition in notch bending were derived and verified by test results. It is indicated that for mild steels there exists an important parameter — cleavage characteristic stress $S_c$, which controls the cleavage behavior in both plain-tension and notch bend tests.

KEYWORDS

Cleavage, mild steel, finite element analysis, probabilistic aspect, effective yield zone, brittle-to-ductile transition.

INTRODUCTION

On cleavage fracture, it is one of the most important problems to establish a criterion for fracture. Based on notch bend tests, Knott (1966, 1971, 1973), Tetelman (1967), Ritchie (1973), and Wilshaw (1973) proposed that cleavage will occur when the maximum of principal stress near notch-tip reaches a characteristic parameter — critical cleavage stress $S_c$. But experimental data of $S_c$ were always larger than that of tension tests. Beremin (1980) tried to explain this fact using the aspect of Weibull distribution of cleavage stress. Krafsur (1980) extrapolated the fracture stresses in tension at different temperatures to 0 K and assumed this value to be the critical cleavage stress.

The aim of our study is to establish a characteristic parameter
which is responsible for cleavage behavior in both plain-tension and notch bend tests and to discuss its role in brittle-to-ductile transition behavior in notched bar.

EXPERIMENTAL PROCEDURES AND RESULTS

The carbon content, heat-treatment and grain size of four rimming steels studied are shown in Table 1. Tension and four-point bend tests were carried out over a range of temperatures from -196°C to 200°C. Specimens used are shown in Fig. 1. The fracture surfaces were analysed with SEM.

**Table 1: Characterization of Steels Used**

<table>
<thead>
<tr>
<th>Steel</th>
<th>C (wt%)</th>
<th>Heat-treatment</th>
<th>Grain Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>A3-1</td>
<td>0.14</td>
<td>670°C, 4h, W3; 100°C, 1h</td>
<td>0.100 mm</td>
</tr>
<tr>
<td>A3-2</td>
<td>0.14</td>
<td>500°C, 4h, W3; 660°C, 1h, Annealing</td>
<td>0.075 mm</td>
</tr>
<tr>
<td>A3-3</td>
<td>0.19</td>
<td>660°C, 2h, W3; 660°C, 4h, Annealing</td>
<td>0.094 mm</td>
</tr>
<tr>
<td>A3-4</td>
<td>0.19</td>
<td>660°C, 2h, W3; 200°C, 1h, Annealing</td>
<td>0.094 mm</td>
</tr>
</tbody>
</table>

**Fig. 1. Plain-tension (a) and V-notched bend (b) specimens.**

The mechanical behavior of steel A3-1 at different temperatures are shown in Fig. 2, as an example. Here, σ is nominal fracture stress. The other three groups of specimens behaved similarly. General yield stress σ_y was calculated with the model of slip-line field (Green and Hundy, 1956). The fracture behavior is characterized by dividing the whole temperature range into four similar to the tension case: A, ductile fracture (omitted); B, mixed fracture after total yielding; C, cleavage after general yielding of notch-section; D, cleavage before general yielding. The temperatures at which D to C transition and C to B transition occur are symbolized as T_D and T_C respectively. Our discussion will be concentrated on fracture behavior in C and D.

**Fig. 2. The mechanical behavior of steel A3-1 in tension.**

**Fig. 3. The fracture behavior of steel A3-1 in bending.**

The fracture behavior of steel A3-1 in four-point notch bending is shown in Fig. 3 as an example. Here, σ is nominal fracture stress. The other three groups of specimens behaved similarly. General yield stress σ_y was calculated with the model of slip-line field (Green and Hundy, 1956). The fracture behavior is characterized by dividing the whole temperature range into four similar to the tension case: A, ductile fracture (omitted); B, mixed fracture after total yielding; C, cleavage after general yielding of notch-section; D, cleavage before general yielding. The temperatures at which D to C transition and C to B transition occur are symbolized as T_D and T_C respectively. Our discussion will be concentrated on fracture behavior in C and D.

**Table 2: Some Experimental Results**

<table>
<thead>
<tr>
<th>Steel</th>
<th>T_c (°C)</th>
<th>S_f (MPa)</th>
<th>T_w (°C)</th>
<th>ω</th>
</tr>
</thead>
<tbody>
<tr>
<td>A3-1</td>
<td>-150</td>
<td>538</td>
<td>40</td>
<td>2.35</td>
</tr>
<tr>
<td>A3-2</td>
<td>-160</td>
<td>618</td>
<td>16</td>
<td>2.37</td>
</tr>
<tr>
<td>A3-3</td>
<td>-179</td>
<td>574</td>
<td>-60</td>
<td>2.34</td>
</tr>
<tr>
<td>A3-4</td>
<td>-171</td>
<td>641</td>
<td>-10</td>
<td>2.40</td>
</tr>
</tbody>
</table>

**Fig. 4.**

**Fig. 5.**

The relation between the ratio of the maximum principal stress to yield strength, S_f/σ_y, and non-dimensional distance from notch-tip, x = X/ρ, where x is the distance from notch-tip, ρ is the radius of curvature of notch-tip, is shown in Fig. 4a, and can be expressed in an approximate formula:

\[
S_f/\sigma_y = 2.1 - 0.1222(3-x)^2
\]

The relation between the non-dimensional width of plastic zone,
Fig. 4. Results of FEM with Fresca criterion. (a) Stress distribution at different level of \( \sigma_{y}/\sigma_{y} \) (indicated by numbers nearby). (b) Plastic zone size at various loads.

\[ x_{p} = x_{p}/\sigma_{y}, \] and the ratio of nominal bend stress to yield strength \( \sigma_{y} \), is shown in Fig. 4b, and can be also expressed approximately:

\[ x_{p} = 1.83(\sigma_{y}/\sigma_{y} - 0.2). \] (2)

### Discussion

**Cleavage Process in Plain-tension Tests**

The cleavage process in mild steel in plain-tension has been studied in our previous work (Yao, 1981). It was concluded that the initiation and propagation of cleavage crack are both stochastic processes and probabilistic demand must be considered. The whole process consists of three stages: (i) yielding to cause plastic deformation within the mass of grains; (ii) crack initiation in a number of grains in which internal stress-concentration condition is favorable; (iii) propagation of one of primary cracks across grain boundaries under the condition of rather small angles between the propagating crack and the cleavage planes in neighbouring grains.

Fig. 2 shows that at \( T_{C} \), cleavage stress sets to a minimum value \( \sigma_{c} \), which is equal to yield strength at this temperature. This indicates that \( T_{C} \) is the highest of the temperatures at which initiation and propagation of cleavage cracks occur immediately once yielding has begun.

In plain-tension tests, the principal stress at any section is even, so probabilistic demand can be satisfied easily as soon as a critical stress is reached. Thus \( \sigma_{c} \) is regarded as the critical stress for the propagation of primary crack (not yet blunted) in advantageous conditions. As temperatures lower than \( T_{C} \), fracture occurs when principal stress reaches yield strength \( \sigma_{y} \), so the cleavage is "Yield-controlled". At temperatures higher than \( T_{C} \), \( \sigma_{c} \) is larger than \( \sigma_{c} \) due to the blunting effect of primary cracks during plastic deformation prior to crack propagation. Then the brittle-to-ductile transition of cleavage occurs at \( T_{C} \) and its critical condition is:

\[ \sigma_{c} = \sigma_{c}. \] (3)

It can be concluded that \( \sigma_{c} \) is an important parameter related to cleavage resistance of mild steel in plain-tension.

**Cleavage Behavior of Notched Bar in Temperature Range B**

It was shown in our previous work (He, 1982) that in notched bending, cleavage in notch is not uniform, this non-uniformity makes the probabilistic demand probabilistic in studying cleavage. In order to satisfy the probabilistic demand for cleavage, enough ferrite grains should be under the action of stress equal to or larger than \( \sigma_{c} \). Therefore, the maximum of principal stress reaches \( \sigma_{c} \). In another word, an "effective yield zone" should be formed prior to cracking. Then the criterion for cleavage in B is:

\[ \sigma_{c} = Q_{d} \sigma_{y} = \sigma_{c}. \] (4)

where \( Q_{d} \) is the principal stress intensification factor (\( \sigma_{y}/\sigma_{y} \)) at \( x_{p}(\sigma_{y}/\sigma_{y}) \), where \( x_{p} \) is the edge of effective yield zone.

From probabilistic aspect, the "effective yield zone" is the one in which enough grains are included so that the probability of crack initiation and propagation across grain boundary is "One". If the probability of crack initiation within a grain is \( P_{i} \), then the general probability \( P_{p} \) should be:

\[ P_{p} = \int_{\sigma_{p}}^{\infty} d\sigma_{p} = e^{-1} \] (5)

where \( \sigma_{p} \) is the volume of "effective yield zone", \( V_{p} \) is the volume of a grain. Approximately, the shape of grain is a cube, thus \( P_{p} \) is regarded as a constant. \( P_{p} \) is related to the angle \( \theta \) between propagating crack and the cleavage planes of neighbouring grains. If the stress required to separate a cleavage plane is \( S_{p} \), and the stress concentration factor at crack-tip is \( k_{s} \), the critical condition for crack propagation is given by:

\[ k_{s}S_{p}\cos^{2} \theta = S_{p}. \] (6)

while in plain-tension case, we have:

\[ k_{s}S_{p}\cos^{2} \theta = S_{p}. \] (7)

where \( \theta \) is the angle for crack propagating at \( S_{p} \). Considering the fact that a number of primary cracks ended at grain boundary could be observed in a broken specimen (Yao, 1981), it is believed that \( \theta \) is a rather small value, then \( \cos^{2} \theta = 1 \). Let (6)/(7), the critical \( \theta \) for crack propagation at a principal stress \( S_{p} \) is:
\[
\cos \theta > \sqrt{\frac{S_c}{S_b}}, \quad (10)
\]

\(p_f = \frac{1 - (1 - \cos \theta)}{(1 - \cos \theta)(1 - \frac{S_c}{S_b})} \left( \frac{S_c}{S_b} \right) \quad (11)
\]

From equations (6), (7) and (11), equation (5) changes to
\[
\left[ (1 - \frac{S_c}{S_b}) \right] \cdot dx = C
\]

where
\(C = 0.5 \sigma_y \beta_{p_f} \)

Substituting equation (1) for equation (12) and integrating gives
\[
\frac{S_c}{S_b} = \frac{1}{2} \left( \frac{3 - \sqrt{1 - K^2}}{K} \right)
\]

where
\(K = \sqrt{S_c/\sigma_y} \quad (15)\)

With some simplifications, the non-dimensional width of plastic zone needed for crack initiation and propagation is
\[
S_c = 0.285x + 0.223K \quad (16)
\]

At temperatures below \(T_c\), \(x = 0\), while at temperatures above \(T_c\), \(x\) can be derived from equation (16):
\[
x = 3 - 2.86(2.1 - K) \quad (17)
\]

At temperature \(T_c\), \(x = 1\), \(x = 0\), then equation (16) becomes
\[
C = 0.31x \sqrt{\sigma_y} \quad (18)
\]

Using the experimental data of \(\sigma_y\) and \(\sigma_y\) at \(T_c\) \(x\) at \(T_c\) can be found from Fig. 4b or equation (2), and constant \(C\) can be determined. Then, using experimental data of yield strength at various temperatures, \(x\) can be calculated from equation (16); finally, the nominal fracture stress \(\sigma_f\) at corresponding temperatures can be evaluated from Fig. 4b or equation (2).

**TABLE 3. Tested and Calculated \(\sigma_f\) (MPa) in A3-1**

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Test Data</th>
<th>Calculated Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>-160 °C</td>
<td>717</td>
<td>740</td>
</tr>
<tr>
<td>-160 °C</td>
<td>732</td>
<td>736</td>
</tr>
<tr>
<td>-140 °C</td>
<td>753</td>
<td>763</td>
</tr>
<tr>
<td>-120 °C</td>
<td>794</td>
<td>784</td>
</tr>
</tbody>
</table>

The tested and calculated data of \(\sigma_f\) (A3-1, as an example) are given in TABLE 3. It is obvious that a good agreement has been found. Since the above mathematical modelling is based on the assumption that \(S_c\) is the parameter characterising cleavage resistance of mild steels, it is clear that the cleavage behavior in \(S\) is also controlled by \(S_c\), as in p-n ual tensile.

**Cleavage Behavior of Notched Bar in Temperature Range C**

In \(\sigma_f\) is higher than general yield stress \(\sigma_y\) which is equal to 1.06 \(\sigma_f\) for Tranca criterion (Green and Hundy, 1956). In this case fracture occurs after general yielding, so the effects of work-hardening and crack blunting must be considered. Then the cleavage criterion in \(\sigma_f\) can be expressed as
\[
Q(\sigma_f + \Delta \sigma) = S_c + \Delta S \quad (19)
\]

It may be supposed that the model of slip-line field is still valid after general yielding if \(\sigma_f\) is substituted by \((\sigma_f + \Delta \sigma)\).

Thus the nominal cleavage stress in \(C\) is
\[
\sigma_f = 1.06(\sigma_f + \Delta \sigma) = \sigma_f + 1.06 \Delta \sigma \quad (20)
\]

Our calculations indicated that \(Q\) at \(T_f\) is about 1.3 and is lower than its maximum \(Q_{\text{max}}(=2.1)\). So in \(C\), \(Q\) increases (approaching \(Q_{\text{max}}\)), while \(\sigma_f\) decreases with temperature. Then, to satisfy equation (19), \(\Delta \sigma\) and \(\Delta S\) must be larger small at temperatures near \(T_f\) and, according to equation (20), \(Q_{\text{max}}\) is only a little larger than \(\sigma_f\); furthermore, the macro-plastic deformation prior to fracture must be unobvious. As shown in Fig. 3, these points are concordant with the experimental results. From an engineering viewpoint, cleavage in \(C\) should be regarded as macro-brittle fracture.

**The Brittle-to-Ductile Transition in Notch Bending**

As temperature increases, \(Q\) approaches \(Q_{\text{max}}\), then equation (19) becomes
\[
Q_{\text{max}}(\sigma_f + \Delta \sigma) = S_c + \Delta S \quad (21)
\]

Because \(Q\) will not change after getting to \(Q_{\text{max}}\), while \(\sigma_f\) will still decreases with temperature, so \(\Delta \sigma\) must increase obviously to satisfy equation (21). This increases the difference between \(\sigma_f\) and \(\sigma_f\), so the temperature gets to a critical point \(T_f\) termed "engineering brittleness transition temperature"), the total yielding and macro-plastic deformation occur prior to fracture. The criterion for this transition at \(T_f\) is
\[
M_r = M_p \quad (22)
\]

where \(M_p\) and \(M_r\) are moments for fracture and total yieldning, respectively:
\[
M_p = \frac{B(W - a)^2}{6} \left( \frac{1}{8} \right) \left( \frac{W - a}{\sigma_y + \Delta \sigma} \right) \quad (23)
\]

\[
M_r = \frac{BM_0}{\sigma_y} \quad (24)
\]

where \(W\) is the thickness of specimen, \(W\) is the depth of notch. Substituting equations (23) and (24) into (22), the relation of \(\sigma_f\) and \(\Delta \sigma\) at \(T_f\) is
\[
\Delta \sigma = \sigma_f \quad (25)
\]

where
\[
m = \frac{W}{1.06(W - a) - 1} \quad (26)
\]

From experimental data in plain-tension, \(\Delta S\), owing to blunting effect is approximately proportional to \(\Delta \sigma\):
\[
\Delta S = n \Delta \sigma \quad (27)
\]

with a proportional coefficient \(n\). Substituting equations (23) to (27) for equation (22) and relating to equation (21) give:
\[
S_c/\sigma_y = Q_{\text{max}}(1 + m) - mn \quad (28)
\]

In our experimental case, \(a = W/3, m = 0.21, Q_{\text{max}} = 2.1, n = 1/2\), the evaluated value of \(Q_f\) is 2.4-2.46. As a comparison, experimental data of \(T_f\) and \(Q_f\) is also shown in TABLE 2. It can be seen that experimental data of \(Q_f\) are near to but a little lower than evaluated ones (2.4-2.46). We deem that in actual case, \(Q_{\text{max}}\) can not get to its calculated value (=2.1) at \(T_f\); due to the blunting of notch -tip during plastic deformation. From \(T_f\), fracture stress rises steeply with temperature (Fig. 3) and so does the macro-plastic deformation prior to cracking, so \(T_f\) has clear significance in
practice. As seen from equation (28), the brittle-to-ductile transition behavior of mild steels is also controlled by cleavage characteristic stress $\sigma_c$.

CONCLUSIONS

1. Both cleavage crack initiation and its propagation across grain boundary are random processes. Probabilistic approach must be considered besides the critical stress condition. In plain-tension, the condition of stress and probability can be satisfied simultaneously, while in notch bending an "effective yield zone" is needed.

2. Based on the consideration of probability, cleavage criterion in notch bending can be derived as equation (16) and is verified by experimental results.

3. "Cleavage characteristic stress" $\sigma_c$ is an important parameter for mild steels. It controls cleavage behavior in both plain-tension and notch bending.

4. The significance of "engineering brittleness transition temperature" $T_e$ is more clear than that of traditional parameters such as FATT and NOT. Then the brittle-to-ductile transition behavior of mild steel in notch bending is also controlled by $\sigma_c$.

REFERENCES

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