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 ℃ to 200 ℃. 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 emphasized 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_0} 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 σ_F. But experimental data of σ_F were always larger than that of tension tests. Beremin (1980) tried to explain this fact using the aspect of Weibull distribution of cleavage stress. Krafka (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 ℃ to 200 ℃. Specimens used are shown in Fig. 1. The fracture surfaces were analysed with SEM.

TABLE 1 Characterization of Steels Used

Steel	C, wt%	Heat-treatment	Grain Size
A3-1	0.14	670 ℃, 4h. WQ; 100 ℃, 1h.+	0.100 mm
A3-2	0.14	150 ℃, 4h. Aging.	0.075 mm
A3-3	0.19	660 ℃, 2h. WQ; 660 ℃, 1h. Annealing.	0.094 mm
A3-4	0.19	660 ℃, 2h. WQ; 200 ℃, 1h. Aging.	0.094 mm

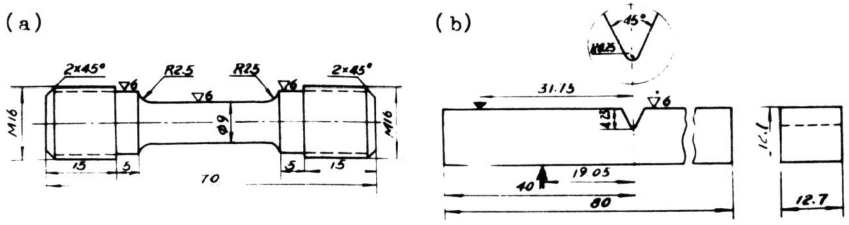

Fig. 1. Plain-tension (a) and V-notched bend (b) specimens.

The mechanical behavior of steel A3-1 at different temperatures are shown in Fig. 2, as an example. Here, σ_Y is yield strength; S_f, fracture stress; and φ_f, reduction of area. The other three groups of specimens behaved in a similar way. It is characterized by dividing the whole temperature range into four: A. ductile fracture with fibred surface; B. ductile fracture with mixed (fibred and cleavage) surface; C. ductile cleavage; D. brittle cleavage. At the brittle-to-ductile temperature T_{C_0}, cleavage stress gets to a minimum value S_{C_0}. The data of T_{C_0} and S_{C_0} for steels investigated are shown in TABLE 2.

TABLE 2 Some Experimental Results

Steel	T_{C_0} (℃)	S_{C_0} (MPa)	T_W (℃)	Q_W
A3-1	-150	588	40	2.35
A3-2	-160	618	16	2.37
A3-3	-179	574	-60	2.34
A3-4	-171	691	-10	2.40

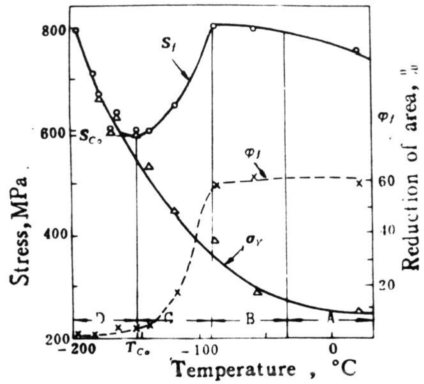

Fig. 2. The mechanical behavior of steel A3-1 in tension.

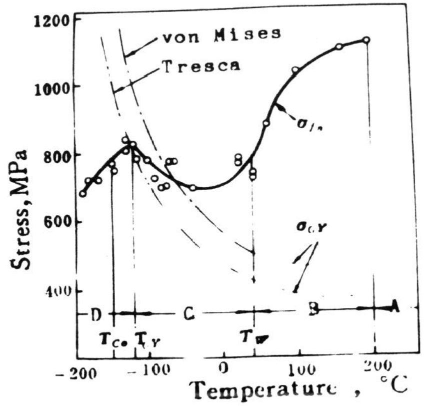

Fig. 3. The fracture behavior of steel A3-1 in bending.

The fracture behavior of steel A3-1 in four-point notch bending is shown in Fig. 3 as an example. Here, σ_{f_n} is nominal fracture stress. The other three groups of specimens behaved similarly. General yield stress σ_{GY} 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_{GY} and T_W respectively. Our discussions will be concentrated on fracture behavior in C and D.

RESULTS OF STRESS FIELD CALCULATIONS

In order to analyse the experimental results, FEM was used to calculate the stress distribution near notch-tip of bending bar in plain-strain state. The calculations are based on the theory of plastic increment and flowing law (Wang, 1981). The mesh division is similar to that adopted by Griffiths and Owen(1971). The detail of procedure was described in special works (Li,1979; He, 1982). Both von Mises and Tresca yield criteria were adopted. Only the results on Tresca criterion are shown here (Fig. 4), considering the fact that this criterion is in better concordance with the results in this work.
The relation between the ratio of the maximum principal stress to yield strength, S_1/σ_Y, and non-dimensional distance from notch-tip, $x\,(=X/\rho$, 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:

$$S_1/\sigma_Y = 2.1 - 0.1222(3-x)^2 \qquad (1)$$

The relation between the non-dimensional width of plastic zone,

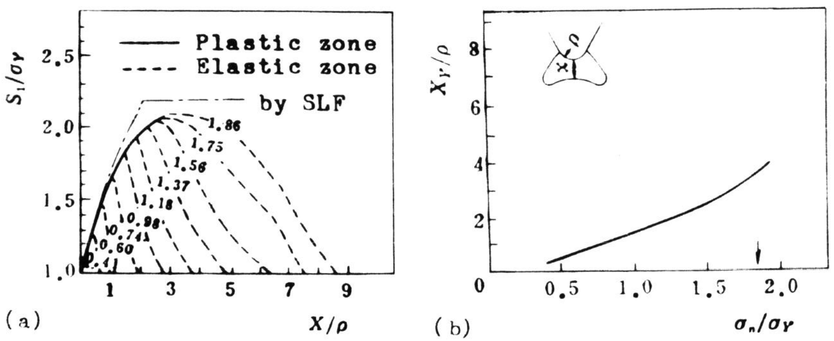

Fig. 4. Results of FEM with Tresca criterion. (a) Stress distribution at different level of σ_n/σ_Y (indicated by numbers nearby). (b) Plastic zone size at various loads.

x_Y ($= X_Y/\rho$), and the ratio of nominal bend stress to yield strength σ_n/σ_Y, is shown in Fig. 4b, and can be also expressed approximately:

$$x_Y = 1.83(\sigma_n/\sigma_Y - 0.2) \quad (2)$$

DISCUSSIONS

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_{Co} cleavage stress gets to a minimum value S_{Co} which is equal to yield strength at this temperature. This indicates that T_{Co} 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 S_{Co} is regarded as the critical stress for the propagation of primary crack (not yet blunted) in advantageous conditions. At temperatures lower than T_{Co}, fracture occurs when principal stress reaches yield strength σ_Y, so the cleavage is "yield-controlled". At temperatures higher than T_{Co}, σ_Y is lower than S_{Co}, the cleavage is "propagation-controlled". But the real fracture stress S_C is larger than S_{Co} 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_{Co} and its critical condition is:

$$\sigma_Y = S_{Co} \quad (3)$$

It can be concluded that S_{Co} (termed "cleavage characteristic stress") is an important parameter related to cleavage resistance of mild steel in plain-tension.

Cleavage Behavior of Notched Bar in Temperature Range D

It was shown in our previous work (He, 1982) that cleavage in notch bending consists of the same three steps as those in plain-tension. The main difference here is that step (i) is local yielding around notch-tip near which stress distribution is not uniform. This non-uniformity makes the probabilistic demand protuberant 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 S_{Co} other than only the maximum of principal stress reaches S_{Co}. In another word, an "effective yield zone" should be formed prior to cracking. Then the criterion for cleavage in D is:

$$S_{1e} = Q_e\sigma_Y = S_{Co} \quad (4)$$

where Q_e is the principal stress intensification factor (S_1/σ_Y) at x_e ($= X_e/\rho$, where X_e 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, and that of crack propagation is p_j, then the general probability P_g should be:

$$P_g = \int_o^{V_e} p_i p_j dv/v = 1 \quad (5)$$

where V_e is the volume of "effective yield zone", v is the volume of a grain. Approximately, the shape of grain is a cube, thus $v = a^3$ (a is grain size). Considering stress concentration near notch-tip, it is reasonably regarded that only the grain stratum at notch-section is effective for fracture, therefore

$$dv = B \cdot a \cdot dX \quad (6)$$

$$V_e = B \cdot a \cdot (X_Y - X_e) \quad (7)$$

where B is the width of specimen. In equation (5), p_i reflects the effect of internal stress concentration and is related to the structural features of the steels investigated. For a given steel p_i is regarded as a constant. p_j is related to the angle θ between propagating crack and the cleavage planes of neighbouring grains. If the stress required to separate a cleavage plane is S_T, and the stress concentration factor at crack-tip is k, the critical condition for crack propagation is given by

$$k \cdot S_1 \cos^2\theta = S_T \quad (8)$$

while in plain-tension case, we have

$$k \cdot S_{Co} \cos^2\theta_0 = S_T \quad (9)$$

where θ_0 is the angle for crack propagating at S_{Co}. 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 θ_0 is a rather small value, then $\cos^2\theta_0 = 1$. Let (8)/(9), the critical θ for crack propagation at a principal stress S_1 is:

$$\cos\theta \geqslant \sqrt{S_{Co}/S_1} \qquad (10)$$

p_i has to satisfy formula (10), then

$$p_i = (1-\cos\theta)\Big/\left(1-\cos\frac{\pi}{4}\right) \doteq 3.4(1-\sqrt{S_{Co}/S_1}) \qquad (11)$$

From equations(6), (7) and (11), equation (5) changes to

$$\int_{x_e}^{x_Y}(1-\sqrt{S_{Co}/S_1})dx = C \qquad (12)$$

where $C = 0.3a^2/B\cdot\rho\cdot p_i$ (13)

Substituting equation (1) for equation (12) and integrating gives

$$(x_Y - x_e) - 2.86K\left[\arcsin\left(\frac{3-x_e}{4.1455}\right) - \arcsin\left(\frac{3-x_Y}{4.1455}\right)\right] = C \qquad (14)$$

where $K = \sqrt{S_{Co}/\sigma_Y}$ (15)

With some simplifications, the non-dimensional width of plastic zone needed for crack initiation and propagation is

$$x_Y = \frac{C - 0.25x_e + 0.223K}{1 - 0.69K} + x_e \qquad (16)$$

At temperatures below T_{Co}, $x_e = 0$, while at temperatures above T_{Co}, x_e can be derived from equation (1):

$$x_e = 3 - 2.86\sqrt{2.1 - K^2} \qquad (17)$$

At temperature T_{Co}, K=1, $x_e = 0$, then equation (16) becomes

$$C = 0.31x_Y - 0.223 \qquad (18)$$

Using the experimental data of σ_{fn} and σ_Y at T_{Co}, x_Y at T_{Co} 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_Y can be calculated from equation (16); finally, the nominal fracture stress σ_{fn} at corresponding temperatures can be evaluated from Fig. 4b or equation (2).

TABLE 3 Tested and Calculated σ_{fn} (MPa) in A3-1

Temperature	Tested Data	Calculated Data
-180 ℃	717	740
-160 ℃	732	736
-140 ℃	753	763
-130 ℃	794	788

The tested and calculated data of σ_{fn} (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_{Co} is the parameter characterising cleavage resistance of mild steels, it is clear that the cleavage behavior in D is also controlled by S_{Co}, as in plain-tension.

Cleavage Behavior of Notched Bar in Temperature Range C

In C, σ_{fn} is higher than general yield stress σ_{GY} which is equal to 1.86σ_Y for Tresca 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 C can be expressed as

$$Q_e(\sigma_Y + \Delta\sigma_Y) = S_{Co} + \Delta S_C \qquad (19)$$

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

Thus the nominal cleavage stress in C is

$$\sigma_{fn} = 1.86(\sigma_Y + \Delta\sigma_Y) = \sigma_{GY} + 1.86\Delta\sigma_Y \qquad (20)$$

Our calculations indicated that Q_e at T_{GY} is about 1.8 and is lower than its maximum Q_{max} (=2.1). So in C, Q_e increases (approaching Q_{max}), while σ_Y decreases with temperature. Then, to satisfy equation (19), $\Delta\sigma_Y$ (and ΔS_C) must be rather small at temperatures near T_{GY}, and, acoording to equation (20), σ_{fn} is only a little larger than σ_{GY}; 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 engineering viewpoint, cleavage in C should be regarded as macro-brittle fracture.

The Brittle-to-Ductile Transition in Notch Bending

As temperature increases, Q_e approaches Q_{max}, then equation (19) becomes

$$Q_{max}(\sigma_Y + \Delta\sigma_Y) = S_{Co} + \Delta S_C \qquad (21)$$

Because Q_e will not change after getting to Q_{max}, while σ_Y still decreases with temperature, so $\Delta\sigma_Y$ must increase obviously to satisfy equation (21). This increases the difference between σ_{fn} and σ_{GY}. When the temperature gets to a critical point T_W (termed "engineering brittleness transition temperature"), the total yielding and macro-plastic deformation occur prior to fracture. The criterion for this transition at T_W is

$$M_f = M_{Yw} \qquad (22)$$

where M_f and M_{Yw} are moments for fracture and total yielding respectively:

$$M_f = B(W-a_n)^2\sigma_{fn}/6 = [1.86B(W-a_n)^2](\sigma_Y + \Delta\sigma_Y)/6 \qquad (23)$$

$$M_{Yw} = BW^2\sigma_Y \qquad (24)$$

where W is the thickness of specimen, a_n is the depth of notch. Substituting equations (23) and (24) into (22), the relation of σ_Y and $\Delta\sigma_Y$ at T_W is

$$\Delta\sigma_{Yw} = m\sigma_{Yw} \qquad (25)$$

where $m = [W^2/1.86(W-a_n)^2] - 1$ (26)

From experimental data in plain-tension, ΔS_C owing to blunting effect is approximately proportional to $\Delta\sigma_Y$:

$$\Delta S_C = n\Delta\sigma_Y \qquad (27)$$

with a proportional coefficient n. Substituting equations (23) to (27) for equation (22) and relating to equation (21) give:

$$S_{Co}/\sigma_{Yw} = Q_w = Q_{max}\cdot(1+m) - mn \qquad (28)$$

In our experimental case, $a_n = W/3$, $m = 0.21$, $Q_{max} = 2.1$, $n = 1/2\sim1/3$, evaluated value of Q_W is $2.4\sim2.46$. As a comparison, experimental data of T_W and Q_W is also shown in TABLE 2. It can be seen that experimental data of Q_W are near to but a little lower than evaluated ones ($2.4\sim2.46$). We deem that in actual case, Q_{max} can not get to its calculated value (=2.1) at T_W, due to the blunting of notch-tip during plastic deformation. From T_W, fracture stress rises steeply with temperature (Fig. 3) and so does the macro-plastic deformation prior to cracking, so T_W 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 S_{c_0} .

CONCLUSIONS

1. Both cleavage crack initiation and its propagation across grain boundary are random processes. Probabilistic demand must be considered besides the critical stress condition. In plain-tension, the condition of stress and probability can be satisfied simutaneously,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" S_{c_0} 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_{ϖ} is more clear than that of traditional parameters such as FATT and NDT. Then the brittle-to-ductile transition behavior of mild steel in notch bending is also controlled by S_{c_0} .

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