Physical Meaning of K_{1C} at Cleavage Fracture

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ABSTRACT

The physical meaning of the stress intensity factor, K_1, and the fracture toughness , K_{1c}, of a cracked specimen at cleavage fracture is expounded in present paper in combining the cleavage micromechanism of the heat-simulated microstructure of the welded 15MnVN steel with the characteristic of the stress field ahead of a blunted crack. K_1 represents the volume of the region of high stress ahead of a crack. K_{1c} at cleavage fracture represents the critical volume at which the region of high stress ahead of the crack should arrive in order to initiate cleavage fracture. An expression relating this volume to K_{1c} is given in present paper.

Based on the concept of the critical volume of the region of high stress the statistic criterion of cleavage fracture of a cracked specimen can be written as

$$(\sigma_{f.cr})^m \cdot V_{e.cr} = \sigma_u^m \cdot V_u \cdot \ln(1/(1-P))$$

which represents that the cleavage fracture of a cracked specimen can be initiated only when the combination of the stress value ahead of the crack and the volume of the region the stress acts on satisfies the determined condition.

Some phenomena observed in experiments are interpreted based on the physical meaning of K_{1c}, as well.

KEYWORDS

Cleavage, fracture toughness; stress intensity factor; physical meaning; 15MnVN steel.

INTRODUCTION

Many of metal structures may fracture by cleavage at lower temperature. Generally, the criterion of brittle fracture, $K_1 \geq K_{1c}$, is valid for such kind micro-crack formed by a cracked *M-A* constituent was referred to as a link of the whole chain. The chain will fracture, that is the cleavage fracture will occur, when at least one microcrack satisfies the condition of crack propagation. Thus, the statistic criterion of cleavage fracture of this microstructure was derived (Hou, *et al.*, 1984), which is as follows,

$$B_{cr} \cdot \sigma_y^m \cdot (K_{1c}/\sigma_y)^4 \cdot F(m,n) = \sigma_u^m \cdot V_u \cdot \ln(1/(1-P)) \tag{1}$$

where B_{cr} is the thickness of a cracked specimen, σ_y the yield stress, K_{1c} the fracture toughness, n the hardening exponent, P the cumulative fracture probability, m, σ_y and V_u parameters of the material, and F(m,n) the value which depends on the stress field at the crack tip.

CHARACTERISTIC OF THE STRESS FIELD AT A BLUNTED CRACK TIP

Using FEM McMeeking computed the stress field at a blunted crack tip of a power hardening material in Mode I loading (plane strain and small-scale yielding). The characteristics of the stress field are as follows, (1).The stress value in the vicinity of a crack tip is limited. The magnitude of the maximum value of the principal stress, $\sigma_{1.max}$, is unchanged on increasing the load (that is, increasing K_1) at a given temperature, that is, the stress intensification value R ($R = \sigma_{1.max}/\sigma_y$), but its position moves further from the crack tip,and the volume of the region of high stress increases with K_1. For example, for the material of $n = 0.1$ in small-scale yielding R is equal to 3.8 even if K_1 changes. The distance of the point at which the maximum principal stress appears from the crack tip, X_m, is equal to $0.003 \times (K_1/\sigma_y)^2$. The size of the scale at which the principal stress, σ_1, is greater than the ninety per cent of $\sigma_{1.max}$ (that is $\sigma_1 > 90\% \ \sigma_{1.max}$), X_1, is equal to $0.006 \times (K_1/\sigma_y)^2$. Consequently, X_m and X_1 increase on increasing K_1. (2).The value of R changes with n, e.g. R=3 for n=0, R=3.8 for n=0.1, and R=5.1 for n=0.2, and the position of the maximum principal stress moves further close to the crack tip on increasing n. It can be known from Table 2 that the values of n change with temperature. Therefore, the value of $\sigma_{1.max}$ changes with temperature, as well.

PHYSICAL MEANING OF K_{1c} AT CLEAVAGE FRACTURE

From the description above it can be seen that the process of initiating cleavage fracture at a crack tip is as follows. When a cracked specimen is loaded at a given temperature K_1 at the crack tip in small-scale yielding raises, and the volume of the region of high stress increases, but the value of $\sigma_{1.max}$ is unchanged. Only when the volume increases to an extent that at least one microcrack which satisfies the Griffith condition is involved in it the cleavage fracture of the specimen can be initiated. Therefore, one of the mechanical conditions to initiate the cleavage fracture of a cracked specimen is that the volume of the region of high stress at the crack tip reaches a certain critical value. Thus, it is necessary to understand the relation between K_1 and the volume of the region of high stress.

Define the maximum principal stress, $\sigma_{1.max}$, ahead of a crack tip at cleavage fracture as the cleavage stress of a cracked specimen, $\sigma_{f.cr}$, that is, $\sigma_{f.cr} == \sigma_{1.max} = R \cdot \sigma_y$. Eqn.(1) can be written as

$$(\sigma_{f.cr})^m \cdot V_{e.cr} = \sigma_u^m \cdot V_u \cdot \ln(1/(1-P)) \tag{2}$$

where

$$V_{e.cr} = B_{cr}/R^m \cdot (K_{1c}/\sigma_y)^4 \cdot F(m,n) \tag{3}$$

of which the dimension is a volume dimension.

In terms of expected average behaviour, if the load on a specimen is less than a certain critical value (relatively, K_1 is less than its critical value K_{1c}), the cleavage fracture of the specimen does not occur, that is, the cleavage condition expressed by Eqn.(2) is not satisfied. Thus,

$$(\sigma_{f.cr})^m \cdot B_{cr}/R^m \cdot (K_1/\sigma_y)^4 \cdot F(m,n) < \sigma_u^m \cdot V_u \cdot \ln(1/(1-P))$$

or

$$(\sigma_{f.cr})^m \cdot V_e < \sigma_u^m \cdot V_u \cdot \ln(1/(1-P)) \tag{4}$$

where

$$V_e = B_{cr}/R^m \cdot (K_1/\sigma_y)^4 \cdot F(m,n) \tag{5}$$

of which the dimension is a volume dimension, too.

When P and test temperature are given, $\sigma_u^m V_u \cdot \mathrm{Ln}(1/(1-P))$ is of a given value for a given material, $\sigma_{f.cr}$ ahead of the crack in small-scale yielding is unchanged, and B, R, σ_u, m and F(m,n) are also constant. Comparing Eqn.(2) with Eqn.(4) it can be known that the reason of not initiating the cleavage fracture of the specimen is

$$V_e < V_{e.cr} \tag{6}$$

Because V_e changes only with K_1 at a given temperature, V_e is raised to $V_{e,cr}$ when K_1 is raised to K_{1c} so as to initiate the cleavage fracture. Of course, when an over-load is put on a specimen suddenly, which makes $K_1 > K_{1c}$, the cleavage fracture can also be initiated. Thus, the cleavage condition of a cracked specimen under small-scale yielding condition can be described as

$$V_e \geq V_{e.cr} \tag{7}$$

which is equivalent to the brittle fracture criterion $K_1 \geq K_{1c}$, and is consistent with the mechanical condition to initiate the cleavage fracture of a cracked specimen mentioned above. In addition, it can be known that the criterion expressed by Eqn.(7) is equivalent with the criterion of $K_1 \geq K_{1c}$ from comparing the calculated values of V_e from Eqn.(5) with the estimated volume of the region of high stress ahead of a crack, V_h. If $X_1^2 \cdot B_{cr}$ is taken as V_h, it can be calculated out

$$V_h = 3.6 \cdot 10^{-5} \cdot B_{cr} \cdot (K_1/\sigma_y)^4 \tag{8}$$

If the volume of the sector of $\pm(7/18) \cdot \pi$ ahead of a crack is taken as V_h, then

$$V_h = 4.4 \cdot 10^{-5} \cdot B_{cr} \cdot (K_1/\sigma_y)^4 \tag{9}$$

Meanwhile, from Eqn(5) it can be found that

$$V_e = (8.56 \rightarrow 3.18) \cdot 10^{-5} \cdot B_{cr} \cdot (K_1/\sigma_y)^4 \tag{10}$$

for n=0.1, and

$$V_e = (5.54 \rightarrow 2.15) \cdot 10^{-5} \cdot B_{cr} \cdot (K_1/\sigma_y)^4 \tag{11}$$

for n=0.14 and with m values from 10 to 20. Therefore, V_h is approximately equal to V_e.

Thus it can be seen that V_e represents the volume of the region of high stress ahead of a crack, and Eqn.(5) represents the relation between this volume and K_1. While, $V_{e,cr}$ is equivalent with the critical value of the region of high stress at cleavage fracture,and Eqn.(3) represents the relation between the critical value with K_{1c}.

For a given specimen V_e and $V_{e,cr}$ are determined by K_1 and K_{1c}, respectively. Therefore, the physical meaning of K_1 is that it represents the value of the volume of the region of high stress which may initiate a cleavage fracture ahead of a crack, and K_{1c} represents the critical value of the volume of the region of high stress needed to initiate a cleavage fracture. In this sense, the physical meaning of the brittle fracture criterion, $K_1 \geq K_{1c}$, is that the volume of the region of high stress ahead of a crack should be equal to or greater than its critical value to initiate a cleavage fracture.

Now, the physical meaning of the criterion of cleavage fracture expressed by Eqn.(2) is more obvious, which represents that the cleavage fracture of a cracked specimen can initiated only when the combination of the stress value ahead of the crack (its maximum value is $\sigma_{f,cr}$) with the region the stress acts on (its volume is $V_{c,cr}$) satisfies the determined condition.

The fracture criterion expressed by Eqns.(1) and (2) was derived from the micromechanism of cleavage fracture initiated by cracked *M–A* constitutes, but it can also be applied to the case in which the cleavage fracture is initiated by other cracked particles. The discussion on the region of high stress in present paper is not yet limited to the microstructure including *M–A* constituent. Therefore, the physical meanings of K_1 and K_{1c} expounded may also be applicable for other microstructures which have similar cleavage micromechanism with the microstructure in present experiment.

INTERPRETATION OF SOME EXPERIMENTAL RESULTS

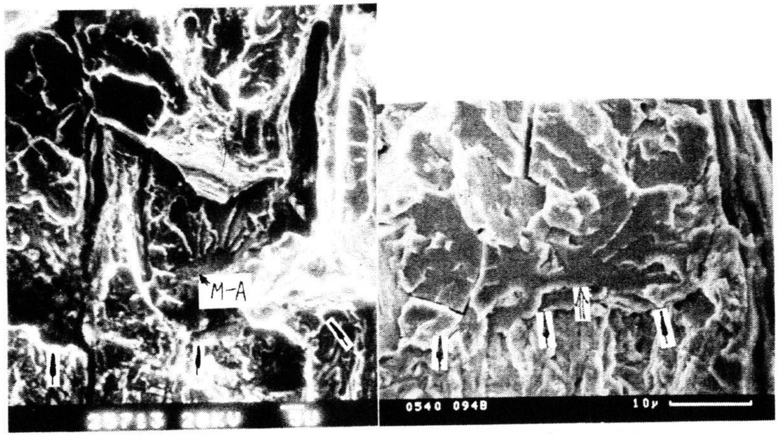
It can be seen in Fig.1 that for values of J_{1c} (or K_{1c}) of the specimens of the same kind of microstructure at different low temperatures the values of J_{1c} at a higher temperature are, generally, greater than those at a lower temperature. For example, the mean value of K_{1c} of seven specimens at 193K is 50.7MPam$^{1/2}$, and that of nine specimens at 170K is 45.2 MPam$^{1/2}$. The reason is as follows. σ_y increases on decreasing temperature, and the maximum principal stress ahead of a crack,$\sigma_{1,max}$(that is, $\sigma_{f,cr}$), increases, too. From the Griffith condition it is known that the minimum crack size (the length is $2a_{cr}$) which can initiate cleavage fracture is smaller when $\sigma_{1,max}$ is greater (see Table 3). Consequently, the critical size of *M–A* constituent can decrease which can form the microcrack whose size is $2a_{cr}$. Because the size distribution of *M–A* constituents is definite, the percent of microcracks increases, which are formed by cracked *M–A* constituents and whose sizes are equal to or greater than $2a_{cr}$. Thus, when the volume of the region of high stress ahead of a crack is smaller, the microcracks which satisfy Griffith condition can be involved in it, and a cleavage fracture can be initiated. That is, its critical volume to initiate cleavage fracture is smaller, therefore, the relative K_{1c} is smaller.

Table 3 σ_y, $\sigma_{f,cr}$ and a_{cr} of two kinds of specimens

Specimen Type	T(K)	σ_y MPa	*n*	*R*	$\sigma_{f,cr}$ MPa	$2a_{cr}$
H	193	728.3	0.13	4.08	2971.3	0.458
L	170	753.9	0.14	4.18	3149.2	0.408

The other phenomenon observed in the experiment is shown in Fig.3 on which it is seen that the cleavage origin on Specimen A029 of higher value of K_{1c} (at 193K) is further from the precrack tip compared with that of specimen S178 of lower value of K_{1c} (at 77K). This phenomenon can be also explained with the physical meaning of K_{1c}. From the calculated results it is known that maximum principal stress ahead of the crack of Specimen A029 locates at X_m=0.017 mm, but one of Specimen S178 locates at X_m=0.0013 mm. In Fig.3 it is seen that the distance of the cleavage origin of Specimen A029 from the precrack tip is 0.014 mm, and the cleavage origin of Specimen S179 is almost by the precrack tip, which expresses that the cleavage origins locate principally in the regions of high stress ahead of the cracks. In each of specimens of the same microstructure microcracks of various sizes are randomly distributed relative to the precrack tip, and the cleavage fracture can be initiated only when the volume of the region of high stress ahead of the crack is greater for the specimen in which the microcrack whose size satisfies the Griffith condition locates further from the precrack tip. Thus, it is seen from Eqn.(3) that the relative K_{1c} of such specimen is higher.

Rosenfield *et al.*(1983) also observed a similar phenomenon on the fracture surface of the specimens of a reactor pressure vessel steel. They said, "more interesting observation was that in specimens tested at the lower temperature and which showed no stable-crack growth, fracture toughness appeared to correlate with the location of the cleavage origin relative to the fatigue-crack front; i.e., K_{qj} increased with increasing *X*." This phenomenon is easily explained based on the physical meaning of K_{1c} expounded in present paper.



a. Specimen A029 b. Specimen S178

Fig.3 The cleavage origins (pointed out by ↓) at precrack tip (pointed out by ↑).

From the physical meaning of K_{1c} it can also be noted that many factors will affect the cleavage fracture toughness K_{1c} (or J_{1c}) of materials, which can change the number of the microcracks which satisfy the Griffith condition ahead of a precrack, and, thus, can change the critical volume of the region of high stress needed to initiate cleavage fracture. For example, the cleavage fracture of a material can be increased by means of decreasing the size and number of the particles or constituents in a material which are easy to crack and to form microcracks (e.g., decreasing the size and number of *M–A* constituents for the microstructure used in present experiment, decreasing the size and number of carbides for the microstructure of ferrite and carbide, and decreasing the size of perlite colonies for the microstructure of ferrite and perlite), and thus decreasing the size and number of the microcracks formed, which increases the volume of the region of high stress needed to initiate cleavage fracture.

CONCLUSIONS

1. The stress intensity factor, K_I, represents the value of the volume of the region of high stress which may initiate a cleavage fracture ahead of a crack, and the fracture toughness, K_{Ic}, represents the critical value of the volume of the region of high stress needed to initiate a cleavage fracture. The relation between K_{Ic} and the critical volume of the region of high stress, $V_{e,cr}$, is as follows,

$$V_{e.cr} = B_{cr}/R^{m} \cdot (K_{Ic}/\sigma_y)^4 \cdot F(m,n)$$

2. The cleavage criterion of a cracked specimen can be rewritten as

$$(\sigma_{f.cr})^m \cdot V_{e.cr} = \sigma_u^m \cdot V_u \ln(1/(1-P))$$

which represents that, on average, the cleavage fracture of a cracked specimen can be initiated only when the combination of the stress value ahead of the crack with the volume of the region the stress acts on satisfies the determined condition.

3. The location at which the maximum principal stress appears is further from the crack tip in the specimen of higher K_{Ic} than in that of lower K_{Ic}, therefore, the cleavage origin observed on the fracture surface is, generally, further from the crack tip in the former than in the later.

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