MECHANISM OF CLEAVAGE FRACTURE OF HSLA STEEL

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ABSTRACT

Combined with the observations of configuration changes of pre-crack tips, fracture surfaces and finite element method (FEM) simulation and calculation, this paper suggests a new framework for cleavage mechanism of precracked specimens of HSLA steel at –110^{o}C. This model includes three criteria i.e. $\varepsilon_p \geq \varepsilon_{pc}$, for initiating a crack nucleus; $\sigma m/\sigma e \geq T_c$, for preventing the crack nucleus from blunting; $\sigma_{yy} \geq \sigma_f$, for propagating the crack nucleus into matrix grain and a supplementing requirement that a short crack initiates, extends and is blunted at the precrack tip. As long as the fatigue pre-crack is only blunted, in its vicinity a region, where the accumulated strain is sufficient to nucleate a crack and a region, where the stress (triaxiality) is sufficient to propagate, a crack nucleus is separated by a distance. The nucleated crack cannot be propagated and the cleavage fracture cannot be triggered. A short crack produced at the fully blunted fatigue pre-crack will change the distributions of strain, stress and triaxiality and specially their relative locations ahead of the pre-crack. While the strain retains, the stress (triaxiality) is rebuilt. The initiated, extended and then blunted short crack makes a tip configuration, which is much sharper than that of the fully blunted original pre-crack tip. The sharpened crack tip configuration re-builds a 'sharper' distribution of stress (triaxiality) and make above two regions closer. Finally the two regions overlap each other and a cleavage crack can be initiated and propagated at a distance ahead of the blunted fatigue pre-crack.

1 INTRODUCTION

Since early 1960s, Mahon [1], Knott [2] and Smith [3] have established a crack-propagation controlled model for cleavage fracture with the following tensile stress criterion:

$$\sigma_{yy} \geq \sigma_f \qquad (1)$$

Because with increasing applied load, the maximum principal tensile stress $(\sigma_{yy})_{max}$ ahead of a crack tip, remains constant and only the area covered by the high stress increases (McMeeking [4]). This means that sufficient stress for fracture by cleavage is always present near the tip of a sharp crack or it is never present regardless of the load on the crack if only the criteria (1) is necessary to be satisfied. That is, a cleavage crack will be initiated and propagated in front of a precrack at a vanishingly small applied load, then the minimum possible toughness would be zero or the specimen will never be fractured. For dealing with this inference, which is absurd with practice, Ritchie, Knott and Rice suggested to supplement such a criterion by the additional requirement that critical stress be achieved over some micro-structurally significant distance (the characteristic distance) ahead of the tip. This is the RKR model (Ritchie [5]). However, the argument of a distance criterion deliberately suggested has long been suspected. The present authors have been working for this topic for more than a decade and obtained a series of results (Chen [6-11]), which are summarized in following sections.

2 EXPERIMENTAL

Two HSLA steels and weld metals were used, the compositions of which are shown in Table 1. By various heat treatments, various microstructures with different ferrite grain sizes and different sizes of second phase particles were obtained. In this paper the grain sizes of steels are in the range of 10 to 40μm.

Table 1 Composition of HSLA steel and C-Mn weld metal (in weight %)

	C	Mn	Si	Mo	Cr	V	S	P	B	Ti	O	N
WCF-62	0.048	1.36	0.23	0.21	0.19	0.03	0.01	0.02	0.002		*	*
C-Mn base	0.18	1.49	0.36	-	-	-	0.03	0.01	-	-	*	*
C-Mn weld	0.07	1.24	0.28	-	-	-	0.02	0.01	-	0.03	0.03	0.02

- trace, * not determined

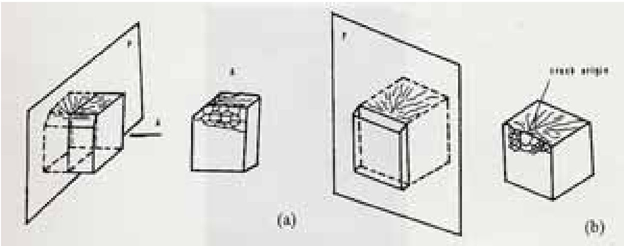


Figure1 Metallographic specimens

Three point bending and four point bending tests were carried out by a universal tester at –110^{o}C. Parameters characterizing toughness were measured. The fracture surfaces were observed in detail for locating cleavage initiation sites. The distances from the sites to the precrack tips were measured. The sections perpendicular to the precracks and those cut through the cleavage initiation sites (shown in Figure 1) were observed. Attentions focus on the microstructural domains, which confine the maximum remaining cracks and the fracture behavior around the precrack tip in specimens fractured or unloaded prior to the fracture.

The 'Rezoning function' of ABAQUS code was used to calculate the stress, strain and stress triaxiality distribution ahead of the precrack tip from an original radius of 0.2μm. The 'Debonding function' was used to simulate a short crack initiated at and extended from the precrack tip.

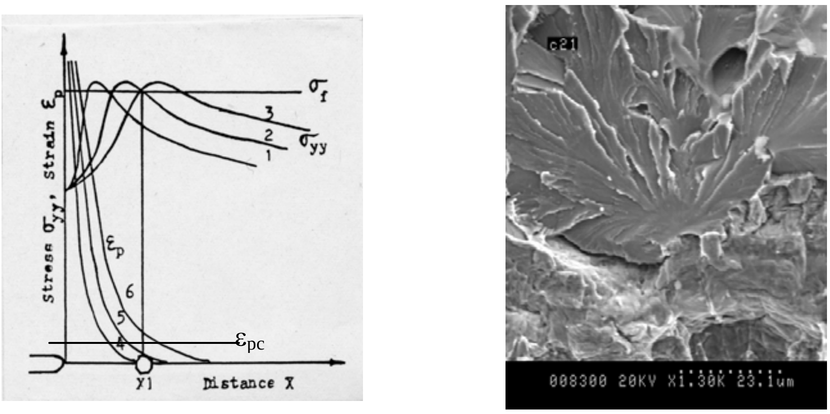
3 RESULTS AND DISCUSSION

3.1 Three criteria for cleavage fracture

Based on a series of investigations the present authors put forward three criteria for cleavage as follows:

1) Criterion 1, $\varepsilon_p \geq \varepsilon_{pc}$ for initiating a crack nucleus (1)

Chen [7-10] found that cracks were nucleated at distances X shorter than those of the maximum normal stress DMS. These facts means that even though the local fracture stress σ_f is reached by the normal stress (Figure2 (a) line 2) the cleavage can not be triggered unless a critical plastic strain is reached ahead of the precrack tip (Line 6). This idea is supported by Figure 2(b) that a cleavage crack was initiated just at the precrack tip where the plastic strain is of maximum and the normal stress is much lower than the maximum value.

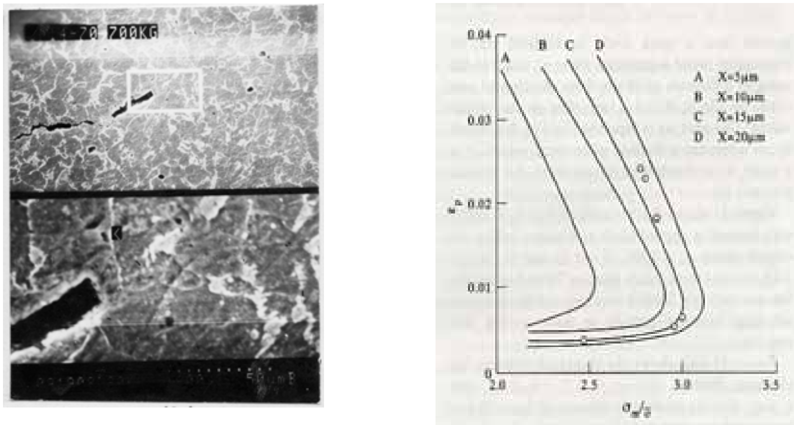


(a) (b)

Figure2 Schematics for criterion 2 (Chen [6]) (a) Cleavage crack of nucleation-controlled (b)

2) Criterion 2, $\sigma m/\sigma e \geq T_c$ for preventing crack nucleus from blunting (2)

It is found in observations that the radius of an original fatigue precrack tip is very acute but has definite sizes of around 0.2μm. Thus the stress triaxiality at the very close vicinity of the crack tip cannot reach the theoretical value of 2.39 calculated from an infinitesimal tip radius. Correspondingly in experiments only blunted crack nuclei (cavities) were observed in close vicinity ahead of the precrack tip as shown in Figure 3 (a) (Chen [7]). This fact indicates the stress triaxiality is insufficient to prevent the crack nuclei from blunting. FEM calculation indicated that cleavage fractures (shown by solid dots in Figure 3 (b)) (Chen [8]) could only be triggered beyond a minimum distances around 15μm, which is consistent with the experimental results of 17 μm. Therefore the minimum distance for cleavage fracture has definite physical meaning that within this minimum distance the stress triaxiality is insufficient for preventing the crack nuclei from blunting.



(a) (b)

Figure 3 Blunted cavities in close vicinity of a precrack tip (a) and calculation results (b)

3) Criterion 3, $\sigma_{yy} \geq \sigma_f$ for propagating a crack nucleus (3)

Chen [11] shows that the local fracture stress σ_f are very stable. In Figure 4, second phase particle-sized cracks remaining in fractured COD specimens were observed, which means the cracks were nucleated but failed to be propagate due to insufficient normal stress. Both phenomena support the well- known stress criterion (3)

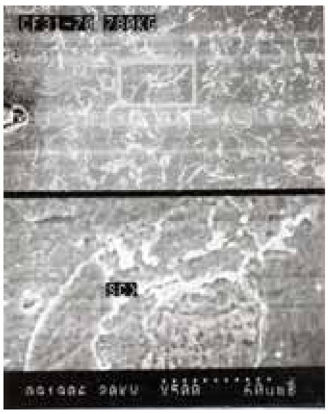


Figure 4 Second phase particle-sized crack remaining in fractured COD specimen

Three criteria for cleavage fracture could be summarized as:

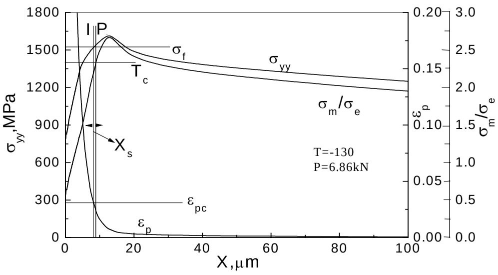
$\varepsilon_p \geq \varepsilon_{pc}$, for initiating a crack nucleus;

$\sigma m/\sigma e \geq T_c$, for preventing the crack nucleus from blunting;

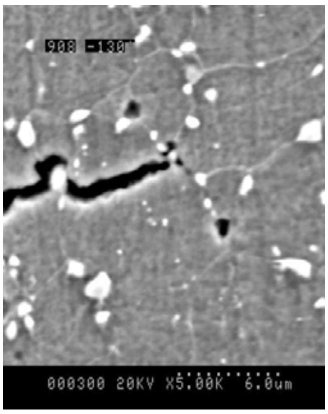
$\sigma_{yy} \geq \sigma_f$, for propagating the crack nucleus into matrix grain

3.2 A supplementing requirement

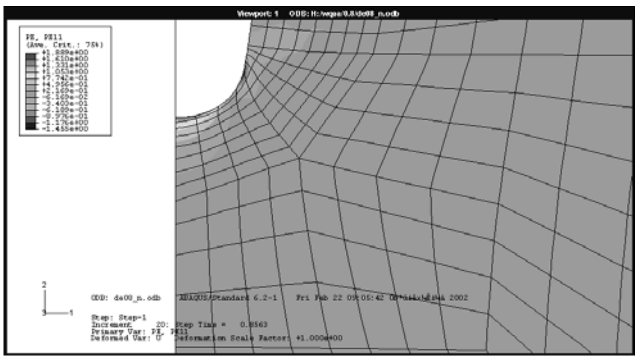
Recent investigation revealed that at small applied load the precrack tip was only blunted, in this case the three criteria were satisfied in different regions separated by a distance as schematically shown in Figure 5 (Chen [9]). In the region left to the Line I, the plastic strain is higher than the critical strain for initiating a crack nucleus($\varepsilon_p \geq \varepsilon_{pc}$). In the region right to the Line P the stress triaxiality reaches the critical value for preventing the crack nucleus from blunting ($\sigma m/\sigma e \geq T_c$ also $\sigma_{yy} \geq \sigma_f$). But The ‘Two Regions’ are separated by a distance X (Figure 5(a)). While in the first region cracks are nucleated but are soon blunted (Figure 5(b)), in the second region no available crack nucleus could be propagated. With increasing the applied load the distance separating the ‘Two Regions’ increases. Therefore the cleavage fracture could not triggered even though a sufficient high normal stress has been produced ahead of the precrack tip.



(a)



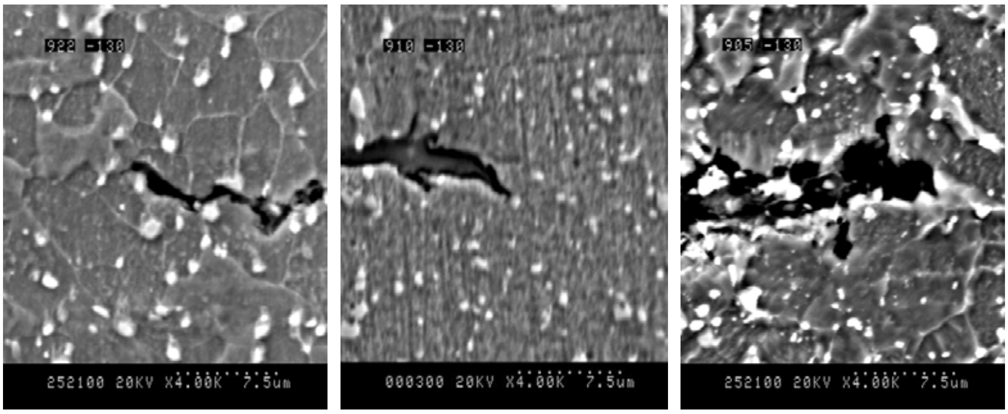
(b)



(c)

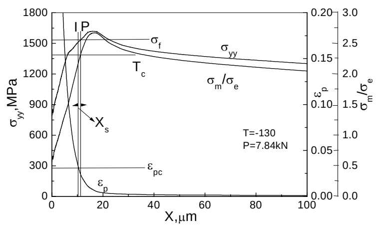
Figure 5 Criteria are satisfied in different regions (a) blunted crack nucleus (cavities) (b) precrack tip is simulated to be only blunted (c)

This process continued until a short crack initiated and extended at the precrack tip and was blunted as shown in Figure 6(a-c) (Chen [9]). While this process repeated several times, the distance separating the ‘Two Regions’ decreases (Figure 7(a-b)) (Chen [9]). Finally at a critical applied load the distance decreased to zero and the ‘Two Regions’ overlap each other (Figure 7(c-d)) (Chen [9]). In the overlapped region a crack nucleus can be initiated and then be propagated. The cleavage fracture can be triggered. Figure 8 (Chen [9]) shows the FEM simulations to build a short crack configuration for calculation.

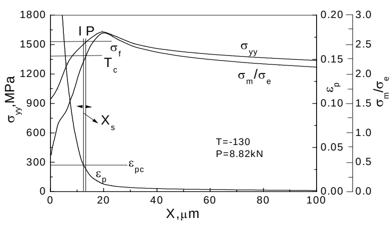


(a) 7.84kN (b) 9.80kN (c) 12.74kN

Figure 6 Process of initiation, extension and blunting of a short crack at precrack tip



(a)



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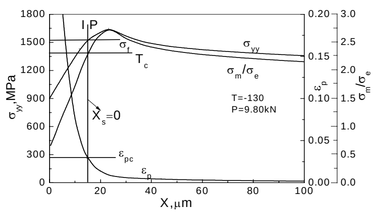
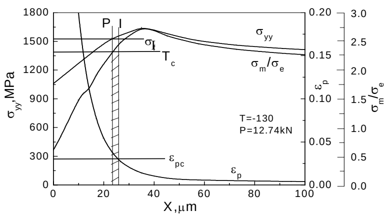
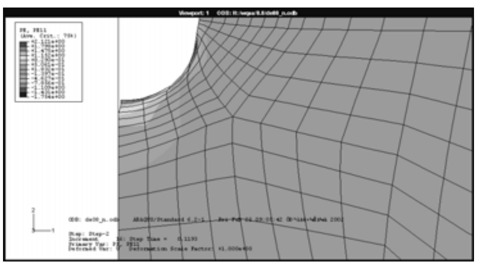


(c)

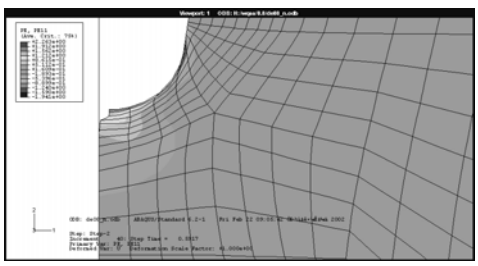


(d)

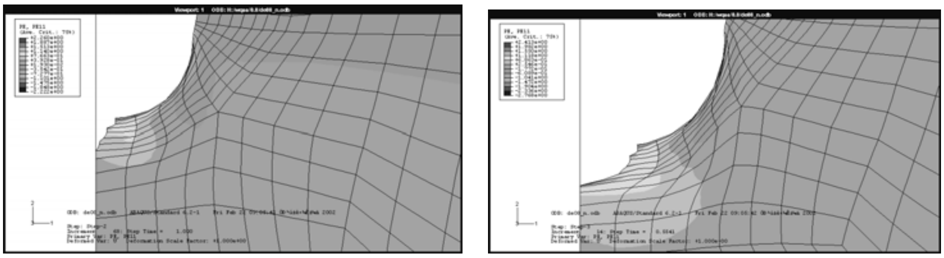
Figure 7 The 'Two regions' move closer (a-b) and finally overlap each other (c-d)



(a)



(b)



(c) (d)

Figure 8 FEM simulation of a short crack initiated, extended and blunted at the precrack tip

Because in the case the precrack tip was only blunted, the regions satisfying the three criteria for cleavage cannot overlap each other, even though the applied load increases, a supplementing requirement is necessary for triggering the cleavage fracture that a short crack initiated, extended and blunted at the precrack tip. This process re-sharpens the precrack tip while a widely developed plastic strain field remains, the stress field is rebuilt and moves closer to the precrack tip, finally makes the ‘Two Regions’ overlap and trigger the cleavage. The physical figure of the supplementing requirement is essential, which describes the controversial relative movements of the ‘Two Regions’, that is, moving to separate further in case the precrack is only blunted, against moving closer after an initiated short crack is repeatedly extended and blunted.

4 EXPECTED APPLICATIONS OF THIS MODEL

On the base of this model, following work can be done:

1) Investigation on fracture behaviors of various materials with different microstructures and properties, which affect the critical values of ε_{pc}, T_c and σ_f.

2) Investigation on the fracture behaviors of various specimens with different acuities of defects (notch radius and crack tip), which affect the distribution of stress and strain ahead of the precrack.

3) Investigation on the effects of loading condition such as the strain rate, test temperature and prestrain which affect the yield strength.

4) A local approach for fracture probability estimation can be based on a comprehensive physical model including three criteria instead of the only stress criterion.

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