CHANGE OF CRITICAL EVENT FOR CLEAVAGE FRACTURE OF HSLA STEEL

J. H. Chen and G. Z. Wang
College of Materials Science and Engineering and State Key Laboratory for New Materials of Non-Ferrous Metal, Lanzhou University of Technology, Lanzhou, 730050, China, zchen@lut.cn

ABSTRACT

The greatest difficult step in the cleavage process presents in term of 'critical event'. In this paper results of series investigations on the critical event for cleavage of HSLA steel are presented. It reveals that basically the critical event for cleavage of notched specimens of HSLA steels at low temperature (lower than –130^{o}C) is the 'propagation of a ferrite grain-sized crack'. The criterion for crack propagation can be presented by following formula $\sigma_{yy} = Q\,\sigma_{flow} = Q(\sigma_y + \Delta\sigma_y) \geq \sigma_f$. Any variation, which makes above formula to be satisfied easier, may induce the change of critical event from propagation of a grain-sized crack to propagation of a second phase particle-sized crack and further to the crack nucleation. A precrack is more acute than a notch, thus it increases the stress intensification factor Q and $\sigma_{yy,}$ which can propagate a second phase particle-sized crack even though it is much shorter than a grain-sized crack. Decreasing the test temperature and increasing the loading rate, both increase σ_y and make the term in the left side of above formula easier to reach the σ_f. The prestrain produces a increment of $\Delta\sigma_y$ by work hardening, which put the same effect as increasing σ_y. Increasing grain sizes acts from other hand to decrease σ_f, which also makes the formula to be satisfied easier. In essence, critical event can be transformed to the 'propagation of a second phase particle-sized crack' and further to the 'crack nucleation' by increasing the acuity of defects (in precracked specimen), coarsening the grain size, decreasing the test temperature, raising the loading rate, and subjecting specimens to pre-strain.

1 INTRODUCTION

In past five decades, many works (Stroh [1], Knott[2], McMahon[3] and Smith[4]) have been done to find the critical event for the cleavage process. Based on the Stroh [1] model, which suggested the crack could be nucleated by dislocations piling up at an energy balance higher than that needed for crack propagation, the crack nucleation was considered to be the most difficult step-the critical event for the cleavage process in early 50s'. Based on the Griffiths model and [3] which showed a decisive role played by the hydrostatic tension and the tensile stress on the cleavage fracture, the grain-sized crack propagation was identified as the critical event in 60s'.Supporting this idea, definite relationships were observed between the values of toughness and the grain sizes. Based on the observation of McMahon and Cohen, which showed the majority of the ferrite micro-cracks were originated at carbide cracks and from the viewpoint of a necessary energy barrier for a crack nucleus, the carbide crack propagation into matrix grain was concluded as the critical event in 70-80s'.

In recent years, Wang [5,6] have found that in some cases the crack nucleation can still be a critical step for the cleavage and suggested a dual criteria.

In early work of Oates and Griffiths [7], it was observed that the critical event could be changed from a grain-sized crack propagation in a smooth tensile specimen to a carbide crack propagation in a notched specimen made of same material. Lin [8] proposed a transform of the critical event from crack nucleation to carbide crack propagation and further to grain-sized crack propagation with increasing the test temperature.

In this paper the present authors summarize the results of their work in past decade related to the critical event, especially the transform of critical event induced by the variations of loading environment and the microstructures of steels. An explanation based on a new framework of the cleavage mechanism (Chen [9]) is given as well.

2 MATERIALS AND SPECIMENS

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

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

Three point bending (3PB) precracked specimens (standard COD specimens), Charpy V specimens and four point bending (4PB) specimens with single notch and double notches were used to measure fracture toughness, they are shown in Figure 1 (Chen [11]). The single notch specimens have the same dimensions with the Griffiths and Owen specimens (Griffiths [10]). The double notch specimens were used specially for observing cracks remaining in fracture specimens. The cracks nucleated but failed to propagate in the vicinity of the survived notch tip where the mechanical condition was critical when another notch was fractured. Specimens for metallographic observations are shown in Figure 2 (Chen [11]). Sections perpendicular to the precrack tips (Figure 2(a)) were prepared for observations of cracks remaining in fractured specimens. Sections cut just through the sites of cleavage initiation (Figure 2(b)) were prepared for observations of the microstructure at the initiation sites of cleavage.

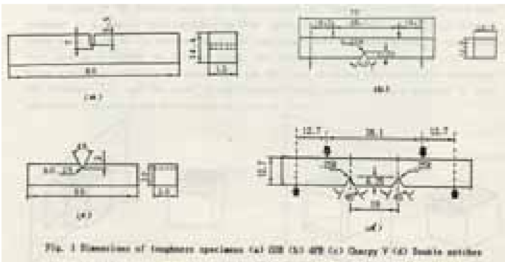


Figure 1 Specimens for toughness measurement

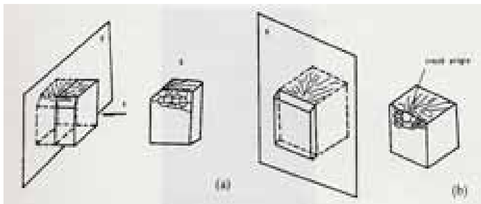


Figure 2 Metallographic specimens

3 EXPERIMRNTAL PROCEDURE

3.1 Determination of critical events

Observation of cracks remaining in fractured or unloaded specimens on the section shown in Figure 2(a) is the main method to determine the critical event. The microstructural domain (ferrite grain or carbide particle), which confines the maximum remaining crack, is defined as the domain of the critical event.

Observation of microstructure around the cleavage initiation site by the section shown in Figure 2(b) is often used to support obtained results. The distances from the sites to the precrack tips were measured.

Toughness parameters are plotted against parameters characterizing microstructural domains. The microstructural constituent, which puts regular effect on the toughness, is referred as the critical event domain.

The location of cleavage initiation relative to that of the maximum normal stress is determined. The crack initiated at a distance shorter than that of the maximum normal stress means the crack-nucleation controlled.

Observation of the vicinity around the blunted precrack tip of unloaded specimen can find the difficult step during the cleavage process.

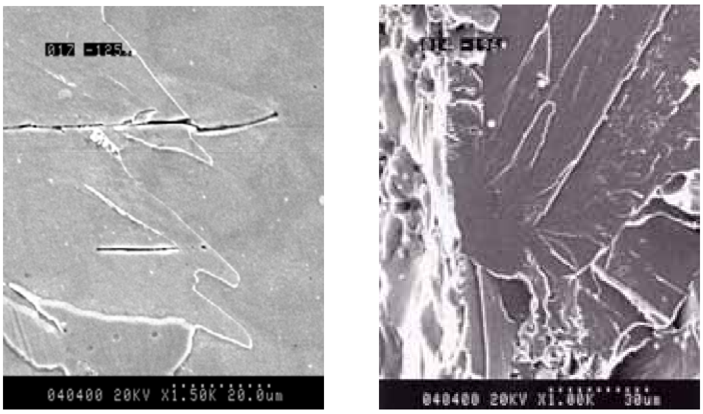
3.2 FEM calculations and simulations were carried out by the ABAQUS code.

4 RESULTS AND DISCUSSION

Chen [11] have concluded that Grain-sized crack propagation is the critical event for the cleavage fracture of notched specimen of steel with normal grain sizes around 30-40μm tested at low temperature, and the critical event for cleavage is changeable.
Recently more evidences for the change of critical event were revealed.

4.1 Critical event changed from crack-propagation to crack-nucleation with decreasing temperature

Figure 3(a) (Chen [12]) shows ferrite grain sized-cracks remaining ahead of the survived notch root in a doubly notched specimen tested at –125°C, which fail to be propagated due to insufficient normal stress and show the crack-propagation controlled model. In Figure 3(b) a very large fracture facet is directly initiated and propagated at the notch root, showing a typical crack-nucleation controlled cleavage at –196°C. This change of critical events in the same WCF62 steel specimens is caused by decreasing temperature from –125°C to –196°C, by which the yield strength increases from 469MPa to 793MPa. While at –125°C the normal stress is insufficient to propagate the crack, at –196°C the normal stress just at the notch root, which even though is much lower than the peak stress, is sufficient to propagated a crack of a grain size. As soon as a crack nucleated at the notch root, where the plastic strain is highest, the crack is propagated.

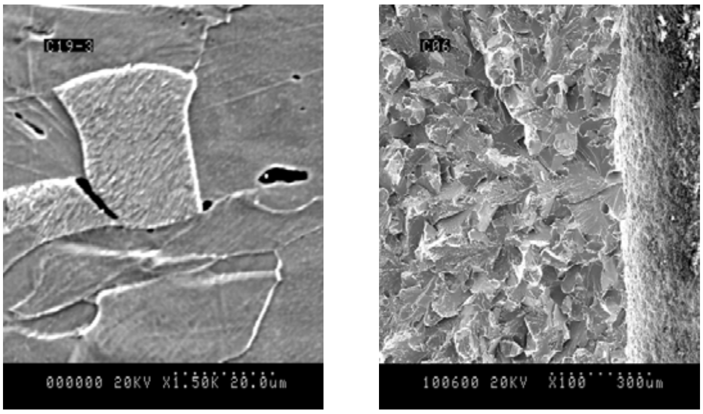


(a) (b)

Figure 3 Remaining grain-sized cracks (a), crack initiated and propagated just at notch root (b)

4.2 Critical event changed from crack-propagation to crack-nucleation with increasing loading rate

Similar to Figure 3, Figure 4(a) (Wang [13]) shows grain-sized crack remaining in fractured specimen tested at lower loading rate, which means the critical event of crack-propagation controlled. At high loading rate as shown in Figure 4(b) a typical crack-nucleation-controlled mode, as described in last section, is presented by a crack facet directly initiated at the notch root. This change is induced also by an increase in yield strength from 415MPa at loading rate of 60mm/min to 479MPa at loading rate of 500mm/min.

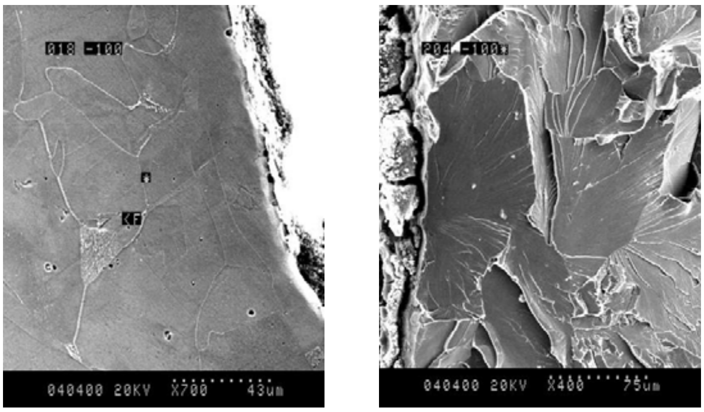


(a) (b)

Figure 4 Grain and pearlite crack remaining in notched specimen loaded at 60mm/min (a), crack directly initiated and propagated at notch root of specimen loaded at 500mm/min (b)

4.3 Critical event changed from crack-propagation to crack-nucleation by pre-strain

Figure 5 (Chen [12]) shows grain-sized crack remaining in fractured notch specimen without prestrain, which means the critical event of crack-propagation controlled. In specimen subjected to 9.97% prestrain as shown in Figure 4(b), a crack facet directly initiated at the notch root, as described in section 4.1, presents a typical crack-nucleation-controlled mode. This change is caused by an increase from 402MPa of the yield strength in free-prestrain specimen to 577MPa of the flow strength in specimen with 10% prestrain.

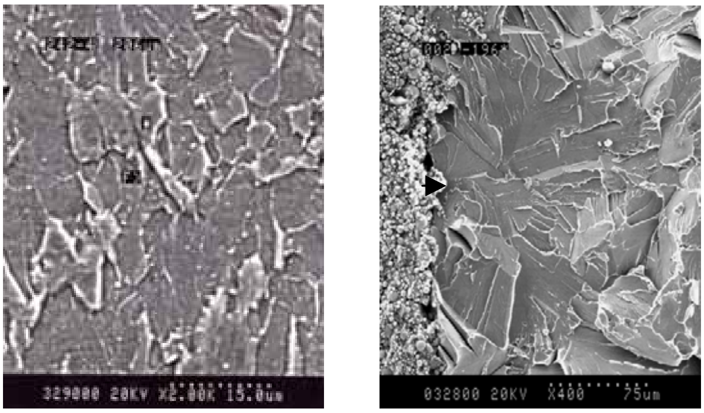


(a) (b)

Figure 5 Grain-sized crack remaining in notched specimen without prestrain (a), crack directly initiated and propagated at notch root of specimen with 10% prestrain (b)

4.4 Critical event changed from crack-propagation to crack-nucleation with increasing grain sizes

In notched specimens of steels with grain sizes around 30-40μm tested at temperature lower than -130^{o}C the critical event for cleavage fracture is the grain-sized crack propagation as indicated by the grain-sized crack remaining in fractured specimens shown in Figure 2 and figure 6(a) (Chen [14]). However for the steel with much larger grain such as 100-160μm in sizes the critical event is changed to crack-nucleation as indicated by the crack initiated directly at the notch root shown in Figure 6(b) (Chen [14]). This change is considered to be caused by decrease of local fracture stress σ_f from about 1525MPa to 793MPa.



(a) (b)

Figure 6 Grain-sized crack remaining in notched specimen with normal grain sizes (a), crack directly initiated and propagated at notch root of specimen with larger grain of 160μm in sizes (b)

5 SUMMARY

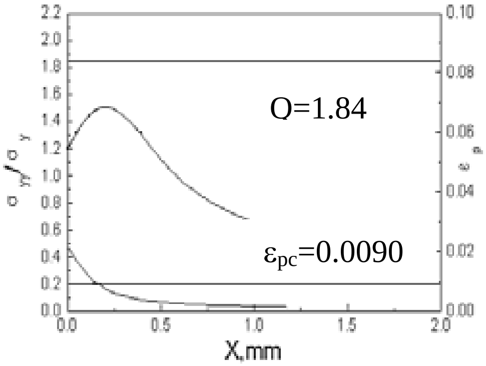
Basically the critical event for cleavage of notched specimens of HSLA steels with normal grain sizes of 30-40μm tested at low temperature (lower than -130^{o}C) is the propagation of a ferrite grain-sized crack. The criterion for crack propagation can be presented by following formula

$\sigma_{yy} = Q\ \sigma_{flow} = Q(\sigma_y + \Delta\ \sigma_y)\ \ \geq \sigma_f$

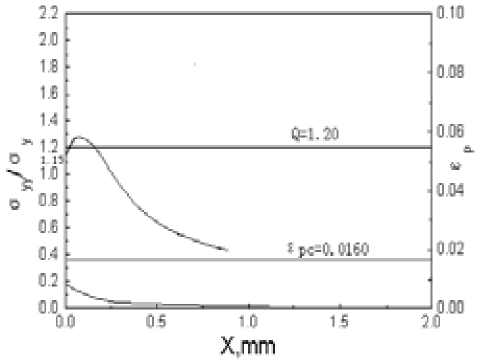
Here σ_{yy} is the normal stress ahead of a defect tip (notch root or the precrack tip), Q is the stress intensification factor which is caused by the stress triaxiality ahead of a defect tip, σ_{flow} is the flow strength of steel, σ_y is the yield strength of steel, $\Delta\ \sigma_y$ is the increment of yield strength of steel due to work hardening, σ_f is the local fracture stress

Because the critical event means the difficult step during the cleavage process, any variation, which makes above formula to be satisfied easier, may induce the change of critical event from propagation of a grain-sized crack to propagation of a second phase particle-sized crack and further to the crack nucleation.

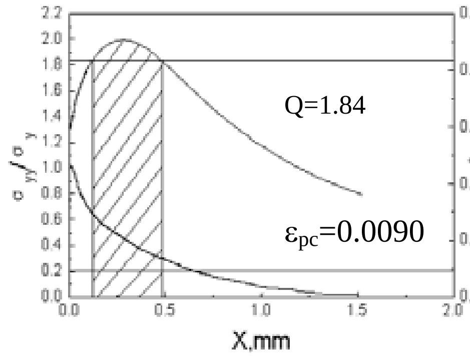
A precrack is more acute than a notch, thus it increases the stress intensification factor Q and $\sigma_{yy,}$ which can propagate a second phase particle-sized crack even though it is much shorter than a grain-sized crack. Decreasing the test temperature and increasing the loading rate, both increase σ_y and make the term in the left side of above formula easier to reach the σ_f. The prestrain produces a increment of $\Delta\ \sigma_y$ by work hardening, which put the same effect as increasing σ_y. Increasing grain sizes acts from other hand to decrease σ_f, which also makes the formula to be satisfied easier. All of these factors act in direction to transform the critical event from the crack-propagation to the crack nucleation and make the toughness lower. Figure 7 (Chen [14]) shows the mechanism of transform of critical event for cleavage process from crack propagation to crack nucleation due to increasing of grain sizes. For a fine grain steel a high σ_f makes critical $Q=\sigma_f/\sigma_y$ as high as 1.84 for propagating a grain sized crack (Figure 7(a)). At an applied load in term of $P/P_{gy}=0.3$, the plastic strain is sufficient to nucleate a crack, but the normal stress is insufficient to propagate it and the critical event for cleavage presents as the crack-propagation model. Until the applied load increases to $P/P_{gy}=0.5$, both plastic strain and the normal stress are sufficient to trigger a cleavage fracture (Figure 7(c)). For a coarse grain steel with a low $\sigma_{f,}$ a critical Q as low as 1.20 is sufficient to propagate a grain sized crack at an applied load of $P/P_{gy}=0.2$(Figure 7(b)). But the plastic strain is insufficient to nucleate a crack and the critical event for cleavage presents as the crack-nucleation model. At an applied load of $P/P_{gy}=0.3$, the normal stress just at the notch root is sufficient to propagate a crack nucleated by the high plastic strain (Figure 7(d)) and produces a crack initiated and propagated directly at the notch root.



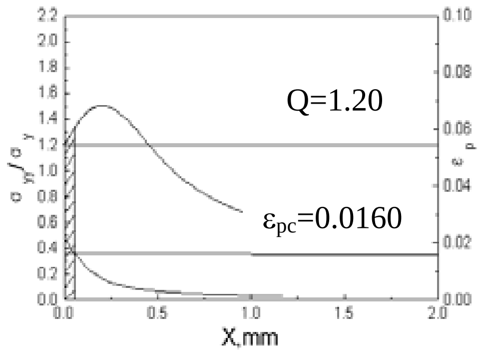
(a) P/P_{gy}=0.3



(b) P/P_{gy}=0.2



(c) P/P_{gy}=0.5



(d) P/P_{gy}=0.3

Figure 7 Schematic mechanism of transform of critical event for cleavage process from crack propagation to crack nucleation due to increasing grain sizes

6 REFERENCES

1. A.N.Stroh, The formation of cracks as a result of plastic flow, *Proceedings, Royal Society* A223, 405-432, 1954.
2. J.F.Knott, Some effects of hydrostatic tension on the fracture behaviour of mild steel, *J. Iron Steel Institute,* 104-111,1966.
3. C.J.McMahon and M. Cohen, Initiation of cleavage in polycrystalline iron. *Acta Metallurgica*, 13, 591-605, 1965.
4. E. Smith, The nucleation and growth of cleavage microcracks in mild steel. *Proc. Conf. Physical Basis of Yield and Fracture, Inst. Phys. and Phys. Soc.*, Oxford, 36-53, 1966.
5. G.Z.Wang and J.H.Chen, Cleavage Fracture Criterion of Low Alloy Steel and Weld Metal in Notched Specimens, *Inter. J. Fract*, 89, 296-284,1998.
6. G.Z.Wang and J.H.Chen, A Statistical Model for Cleavage Fracture in Notched Specimens of C-Mn Steel, *Fatigue Fract. Engng. Mater. Struct*, 24, 451-459, 2001.
7. G. Oates and J. R. Griffiths, Mechanisms of cleavage fracture initiation in notched and smooth specimens of 3% silicon iron, *Metals Science Journal*, 13, 341-345,1969.
8. Tsann Lin, A.G. Evens and R. O. Ritchie, Stochastic modeling of the independent roles of particle size and grain sizes in transgranular cleavage fracture, *Metall. Trans.*18A, 641-651, 1987.
9. J. H. Chen, Q. Wang, G.Z. Wang, and Z.Li, Fracture behavior at crack tip - a new framework for cleavage mechanism of steel, *Acta Mater.* 51, 1841-1855, 2003.
10. G.R.Griffiths and D.R.Owen, An elastic-plastic stress analysis for a notched bar in plane strain bending, *J. Mech. Phys. Solids*, 19, 419-431, 1971.
11. J.H.Chen, G.Z.Wang etal, Advances in the Mechanism of Cleavage Fracture of Low Alloy Steel at Low Temperatures. Part. I : Critical event, *Int. J Fract*, 83, 105-120, 1997.
12. J.H.Chen, Z.Li and G.Z.Wang, Effects of tensile Prestrain on the Notch Toughness of Low-alloy Steel, *Metall. Mater. Trans*. 34A, 1055-1068, 2003.
13. G.Z.Wang, X.C.Ren and J.H.Chen, Change of critical events of cleavage fracture with variation of loading rate in notched specimens of steel, *Int. J Fract*. 119, 61-66, 2003.
14. J.H.Chen, G.Z.Wang and Q.Wang, Change of Critical Events of Cleavage Fracture with Variation of Microscopic Features of Low-Alloy Steels, *Metall. Mater. Trans*, 33A, 3393-3402, 2002.