CLEAVAGE INITIATION MECHANISM IN NOTCHED SPECIMENS OF STEEL WITH CARBIDES AND INCLUSIONS

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ABSTRACT

Cleavage initiation mechanism in notched specimens of steel with carbides and inclusions is investigated at -196 ^{o}C and -130 ^{o}C. The mechanical tests, microscopic observations and measurements, and FEM calculations are carried out. Two types of cleavage initiation sites are found. One is related to approximately spherical inclusions ahead of notch root (IC initiation), the other is related to spherical inclusions situated ahead of elongated larger string inclusions (SIC initiation). In both IC and SIC initiation mechanism, the crack nucleation is induced by inclusions and the final fracture is controlled by propagation of a ferrite grain-sized crack into matrix grain. In the case of SIC initiation, a plate-like defect caused by the early debonding of the elongated larger string inclusions promotes the cleavage fracture, and the cleavage initiates in front of the plate-like defect. Temperature has pronounced effect on the type of the cleavage initiation site. At -196 ^{o}C the fractures are mainly the IC initiation mechanism, and at -130 ^{o}C all the fractures are the SIC initiation mechanism. The reason for this has been analyzed. The notch toughness of the steels tested is mainly determined by the cleavage initiation occurring in the weak constituents composed of inclusions and matrix grains, and is independent on the sizes and numbers of carbide particles.

1 INTRODUCTION

Smith model [1] assumed that a cleavage crack could initiate when grain boundary carbide is fractured by impingement of dislocation pile-up, and the final fracture is controlled by the carbide-sized crack propagation into the neighboring ferrite. Many researchers accepted this model, and the carbide size was regarded as a major factor controlling cleavage fracture in various steels [2,3]. However, some authors have proposed the influence of both matrix grain size and particle size on cleavage fracture [4]. In some works of present authors [5,6], it has been suggested that grain size is the controlling microstructural feature that determines the critical cleavage fracture stress in notched specimens.

On the other hand, examples of inclusion-initiated cleavage fracture have also been found in weld metal and various steels [7,8]. In some recent studies, TiN inclusion-induced cleavage in steels has also been reported [9]. However, for some steels in which carbide particles coexist with inclusions, the mechanism of cleavage fracture initiation has not still been identified. Especially, to author's knowledge, little evidence has been found for the possible influence of larger non-metallic inclusions, such as manganese sulfides, on cleavage fracture initiation.

In this study, by the microscopic observations, measurements and FEM calculations, the mechanism of cleavage fracture initiation in notched specimens of a C-Mn steel in which carbide particles coexist with inclusions is investigated.

2 EXPERIMENT AND CALCULATION

The material used was a rolled C-Mn pressure vessel steel (16MnR) with elongated larger string inclusions (MnS). The heat treatments included austenitizing specimens at 900 ^{o}C for 2 hours, then quenching in water to obtain uniform matrix grain microstructure. Then some of the specimens were tempered at 685 ^{o}C for 24 hours and the remaining for 96 hours to obtain the same ferrite grains with fine (FC) and coarse (CC) carbide particles, respectively. Eight millimeter diameter round bars with 50 mm gage length were used for the tensile tests. Notched specimens for four point bending (4PB) test were cut in the L-T orientation, and the orientation of elongated string inclusions in relation to the specimen orientation is shown in Figure 1. The 4PB specimens have thickness W =12.7mm, width B =12.7mm, notch depth a = 4.25mm, notch root radius ρ = 0.25mm, and notch flank angle θ=45^{o}. The double notch specimens are used for observing the remaining micro cracks. Tensile and 4PB tests were carried out at a cross head speed of 1mm/min at -130 ^{o}C and -196 ^{o}C.

Fracture surfaces of all specimens were observed in detail with a scanning electron microscope (SEM) S-520. The initiation site of cleavage fracture was located by tracing the river pattern strips back to their origin with the similar method used by previous researchers [12-16]. The distance of the cleavage initiation site from the tip of the blunted notch was measured as X_f. For doubly notched specimens, fracture occurred at one notch and the critical condition was reached in the vicinity of the survived notch. The six metallographic sections perpendicular to the survived notch root were cut, and were grouped together in a single bakelite mount and polished using standard metallographic techniques. The metallographic sections were etched with 2% natal to observe the remaining crack and identify the critical event of cleavage using the SEM [6].

The maximum normal stress σ_{yy} on the plane directly ahead of the notches ahead of notches were calculated by Finite Element Method (FEM) for 4PB specimens tested at -130 ^{o}C and -196 ^{o}C. A two dimensional model with 8-node biquadratic plane strain reduced integration elements (CPE8R) was used with the ABAQUS code. Using the measured P_f/P_{gy} and the distances X_f of the cleavage initiation sites, the cleavage fracture stress σ_f were determined accurately from the curves of stress σ_{yy} distribution.

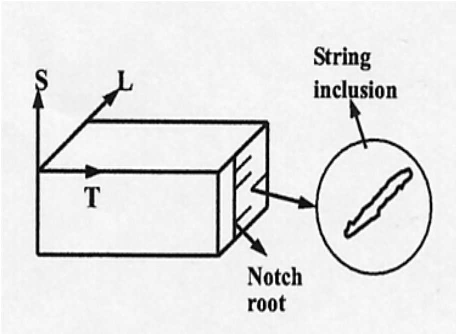

Figure 1: Orientation of elongated string inclusions and specimen

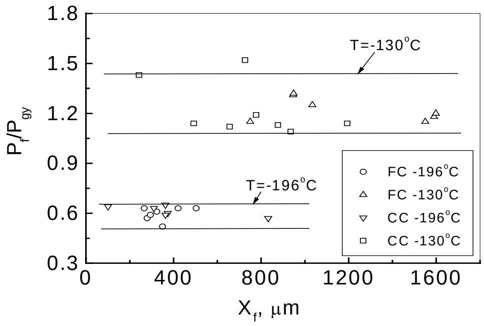

Figure 2: P_f/P_{gy} and X_f for FC and CC microstructures

3 RESULTS

The following ideas are summarized from experimental data and observations:

(1) The notch toughness (characterized by the ratio of the fracture load to the general yield load, P_f/P_{gy}) of the CC and FC steels with different sizes of carbide particles are almost the same at the same temperature. But the toughness at -130 ^oC is higher than that at -196 ^oC (Figure 2).

(2) The fracture modes in the specimens of the two steels with different sizes of carbide particles are also the same. All specimens tested at -196 ^oC and the most specimens tested at -130 ^oC are the cleavage fractures with one principal initiation site ahead of notch root. The distance X_f of the cleavage initiation site from the tip of the blunted notch in the specimens tested at -130 ^oC is larger than that at -196 ^oC (Figure 2).

(3) Two types of cleavage initiation sites could be distinguished for all the specimens of both steels tested at -196 ^oC and -130 ^oC. One is related to approximately spherical inclusions ahead of notch root, as typically shown in Figure 3, and is marked as IC. The other is related to spherical inclusions situated ahead of the elongated larger string inclusions. The spherical inclusions interacted with the string inclusions, and the cleavage is promoted by the string inclusions and initiated in front of the string inclusions, as typically shown in Figure.4, and is marked as SIC. The EDS point analysis shows the approximately spherical inclusions as cleavage initiation particles are often composed of MnS or complex oxides containing Al, Mn, Fe, Ca and Ti , and their diameters are about 1 - 4 μm, and the elongated larger string inclusions are mainly MnS. No carbides are found as cleavage initiators in the notched specimens of both steels.

(4) Temperature has a pronounced effect on the type of cleavage initiation site. At -196 ^oC both IC and SIC initiation sites are found, but the most (about 80% in FC and CC specimens) is IC

type. At -130 ^oC all the cleavage initiation sites are SIC type.

(5) In metallographic sections of fractured doubly notched specimens at -196 ^oC and -130 ^oC for CC and FC microstructures, ferrite grain-sized remaining cracks related to inclusions were found in front of the surviving notch, as typically shown in Figure.5 (indicated by the IFC). These cracks situated in a range of 60-800 μm ahead of notch root. These cracks indicate that the normal tensile stress is not sufficient to propagate the just nucleated micro-crack in a cleavage manner, and the cleavage fracture shows the crack-propagation-controlled mechanism [6].

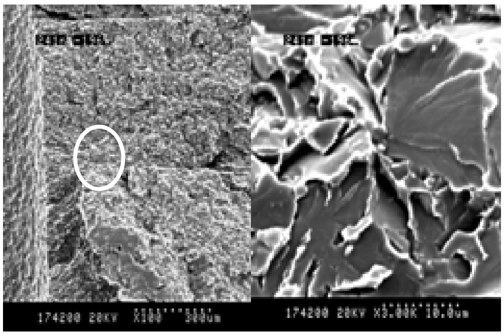

Figure 3: Typical fracture surface showing IC type of cleavage initiation site

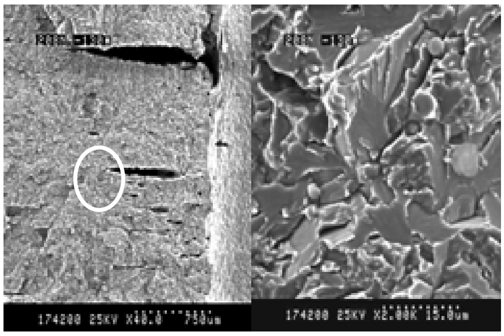

Figure 4: Typical fracture surface showing SIC type of cleavage initiation site

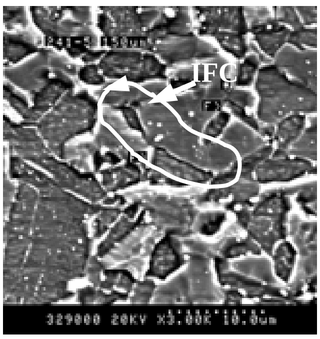

Figure 5: Ferrite grain-sized remaining microscopic cracks

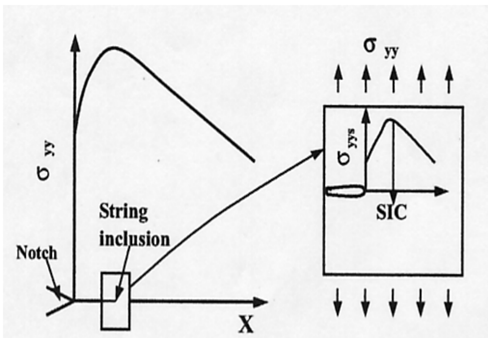

Figure 6: A schematic diagram showing a local high stress zone σ_{yys} ahead of the defect tip

4 DISCUSSION

The finding of the two types of cleavage initiation site (IC and SIC) means that the inclusions are more active in inducing cleavage fracture than carbide particles in these steels. The finding of the ferrite grain-sized remaining cracks means that the critical event of the cleavage process is the propagation of a grain-sized crack into the neighboring matrix. For the case of SIC initiation site observed, it means that the elongated larger string inclusions promote the cleavage fracture. The mechanism could be analyzed as follows:

The orientation of the elongated string inclusions in relation to the specimen orientation is schematically shown in Figure 1. Because the interfacial strength between the string inclusions and matrix is rather low, an early debonding occurs during the loading process [8]. This will result in a plate-like defect, as typically shown in Figure 4. Because the tip of the plate-like defect is similar to a blunted notch tip, the defect could not directly propagate due to insufficient stress concentration. But it can cause a local high stress zone in front of its tip under the action of the applied maximum normal stress σ_{yy}, as schematically shown in Figure 6. If a spherical inclusion is sampled in the local high stress zone, and a grain-sized crack is induced as in the case of IC, the crack propagation into matrix grain under the combined action of the maximum normal stress σ_{yy} and the local high stress σ_{yys} will cause the final cleavage fracture of the specimen.

Temperatures have pronounced effect on the type of the cleavage initiation site. At -196 ^{o}C the fractures are mainly the IC initiation mechanism, and at -130 ^{o}C all the fractures are the SIC initiation mechanism. The reason for this is that at -130 ^{o}C the lower stress σ_{yy} ahead of notch is insufficient to propagate a crack ($\sigma_{yy} < \sigma_f$), a local high stress σ_{yys} is provided by the plate-like defect related to the elongated string inclusion. Because the σ_f value is independent on temperature [31,39], the difference of the measured σ_f value between -196 ^{o}C (IC) and -130 ^{o}C (SIC) should be the local high stress σ_{yys} (Fig.6) for SIC at -130 ^{o}C, and the difference of the measured σ_f value between -196 ^{o}C (IC) and -196 ^{o}C (SIC) should be the σ_{yys} for SIC at -196 ^{o}C. From the measured σ_f data by FEM, the σ_{yys} value is estimated to be in a range of about 350-650MPa for the SIC at -130 ^{o}C, and in a range of about 100-150MPa for SIC at -196 ^{o}C.

On the other hand, because the notch toughness is mainly determined by the cleavage initiation occurring in the weak constituents composed of inclusions and matrix grains, and is independent on the sizes and numbers of carbides, the notch toughness of the CC and FC steels are almost the same at the same temperature (Fig.2).

5 CONCLUSIONS

(1) In cleavage fractures of notched specimens of steels in which carbide particles with different sizes (FC and CC) coexist with inclusions, two types of cleavage initiation sites are found. One is related to approximately spherical inclusions ahead of notch root (IC initiation), and

the other is related to spherical inclusions situated ahead of the elongated larger string inclusions (SIC initiation). In both IC and SIC initiation mechanism, the crack nucleation is induced by inclusions and the final fracture is controlled by propagation of a ferrite grain-sized crack into matrix grain. In the case of SIC, the plate-like defect caused by the early debonding of the elongated larger string inclusions promotes the cleavage fracture, and the cleavage initiates in front of the plate-like defect.

(2) Temperatures have pronounced effect on the type of the cleavage initiation site. At -196 ^{o}C the fractures are mainly the IC initiation mechanism, and at -130 ^{o}C all the fractures are the SIC initiation mechanism.

(3) Because the notch toughness is mainly determined by the cleavage initiation occurring in the weak constituents composed of inclusions and matrix grains, and is independent on the sizes and numbers of carbide particles, the FC and CC microstructures shows the same notch toughness.

REFERENCES

[1] Smith E. Proc. Conf. “Physical basis of yield and fracture”, Inst. Phys. and Phys. Soc., Oxford, p.36, 1966.

[2] Ritchie RO, Knott JF, Rice JR. On the relationship between critical tensile stress and fracture toughness in mild steel. J. Mech.Phys.Solid., vol.21, pp.395-410, 1973.

[3] Bowen P, Druce SG., Knott JF. Effects of microstructure on cleavage fracture in pressure vessel steel, Acta Metall. vol.35, pp.1121-1131, 1987.

[4] Echeverria A, Rodriguez-Ibabe JM. The role of grain size in brittle particle induced fracture of steels, Mater. Sci. Eng. vol.A346, pp.149-158, 2003.

[5] Wang GZ, Chen JH. A statistical model for cleavage fracture in notched specimens of C-Mn steel. Fatig & Fract Engng Mater & Struct., vol.24, pp.451-459, 2001.

[6] Wang GZ, Wang JG, Chen JH. Effects of geometry of notched specimens on the local cleavage fracture stress σ_f of C-Mn steel. Engineering Fracture Mechanics, vol. 70, pp.2499-2512, 2003.

[7] Balart MJ, Davis CL, Strangwood. Cleavage initiation in Ti-V-N and V-N microalloyed ferritic-pearlitic forging steels, Materials Science and Engineering, vol.A284, pp.1-13, 2000.

[8] Mantyla M, Rossoll A, Nedbal I, Prioul C, Marini B. Fractographic observations of cleavage fracture initiation in a bainitic A508 steel, Journal of Nuclear Materials vol.264, pp.257-262, 1999.

[9] Fairchild DP, Howden DG, Clark,WAT. The Mechanism of brittle fracture in a microalloyed steel: Part I. Inclusion-induced cleavage. Metall. Mater. Trans. vol.31A, pp.641-651, 2000.