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Brittle Fracture Validation Through Crystallographic Deformation for the Characterization of Cleavage in Carbon Steel

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Abstract: This study describes the necessary steps to perform a valid fracture test for the characterization of cleavage in carbon steel. The testing is based on the methodology published in the ASTM Standard, coded E-399-90, by using the compact tension geometry. Predominant elastic fracture or plane-strain fracture toughness K_{IC} is designed in this particular test geometry for the classification of suitable materials. Micrographic analysis of pre-cracking stage by fatigue to cleavage crack initiation and gross plasticity of fracture surfaces are investigated. Validation of elastic or brittle fracture by cleavage of carbon steel has been identified through the characterization using scanning electron microscopic fractography observation. Unique microstructure pertaining to brittle and cleavage failure characteristic has been observed through river patterns and feather marks on the crack initiation zone surface.

Key words: Cleavage, compact tension, plane-strain fracture toughness K_{IC}, microstructure, river pattern, feather mark

INTRODUCTION

Failure in steels can occur in a variety of mechanisms. Brittle fracture, particularly in cleavage mode is of a priority concerned, since such failure induces severe catastrophe with the least sustained load. Cleavage initiates from the stress raiser by opening mode loading tends to propagate a crack along a specific crystallographic plane that involves the breaking of the atomic bonds. Through the Linear Elastic Fracture Mechanics modeling (Inglis, 1913; Griffith, 1920; Irwin, 1957), a material property called the fracture toughness has been derived to measure the resistibility of material against such crack-induced fracture. For a known material category and fracture toughness value, the fracture by brittle or elastic deformation through cleavage mode can be subsequently defined (Wells, 1961). A standard approach has been well accepted in a testing methodology as in described in the ASTM E 399-90 (1991).

In fracture processes, telltale marks appearing on the cracked surfaces can offer a wealth of information related to the fracture mechanism and the material characteristics. For polycrystalline solids like steels, the grains are randomly oriented with respect to each other. Under cleavage loading, a cracking path can be induced to change its direction when come across the grain boundaries, which results in the creation of distinct faceted cracked surfaces. At the onset of crack propagation in particular, cleavage failure leaves unique marks that appears like river and feather patterns (Anderson, 1995). The achievement to trace these trademarks will be the evidences to verify the cleavage mechanism on brittle material fracture.

FRACTURE TOUGHNESS MODEL

Irwin (1957) has derived the K- factor to characterize the intensity of local stress such that the stress state of a material is expressed by

$$\sigma_{ij} = \frac{K_I}{\sqrt{2\pi r}}.f_{ij}(\theta) \tag{1}$$

where, the K_I is the Mode-I stress intensity factor, r is the distance of any entity originating from the crack-front, θ is an angle measured from the crack plane and $f_{ij}(\theta)$ is a known function of θ. From the dimensional analysis (Anderson, 1995), the only parameters defined in a fracture loaded body is the loading stress σ and the crack length α, which is related as

$$K_I = \gamma\left(\sigma\sqrt{a}\right) \tag{2}$$

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where:

γ = An undetermined dimensionless factor.

Considering the relationship between K_I and the ratio of crack length over the width of a body a/W, the dimensionless factor is thus related to the geometric function f(a/W). Since the function consists of a factor $\sqrt{p}$ for any size of a/W, the equation is alternately written as

$$K_I = \sigma\sqrt{\pi a}.f\left(a/W\right) \tag{3}$$

where:

$$f\left(a/W\right) = \frac{\left(2 + a/W\right)\begin{pmatrix}0.886 + 4.64a/W - 13.32a^2/W^2 \\ +14.72a^3/W^3 - 5.6a^4/W^4\end{pmatrix}}{\left(1 - a/W\right)^{3/2}} \tag{4}$$

for Compact Tension geometry (Sih, 1973; ASTM E 399-90, 1991). These relations are defined for prediction of elastic fracture by cleavage mode, which utilizes a geometric body confined by the plain-strain deformation of Compact Tension specimen. Therefore, the K_I is defined as measurement of a fundamental material fracture toughness or resistance to crack propagation.

MATERIAL AND PROPERTIES

The elemental composition of the carbon steel was obtained by performing the Glow Discharge analysis. The main elements concern was accurate up to a coefficient of variation of no more than 5% and the average data composition is tabulated in the Table 1. Microstructural details of the material was also obtained by selecting, grinding, polishing and etching to review the pearlitic and base iron grains as shown in the Fig. 1. The pearlitic structure constitutes up to about 36% of the material. Further mechanical tensile testing, determined by ASTM E8-01 (2002), of the material was conducted using a servo hydraulic tensile testing machine. The material deformation characteristic results were also obtained and analyzed to yield the average tensile properties as tabulated in the Table 2 below; coefficient of variation ranges from 3.7% to 5.6%.

Table 1: Elemental material composition obtained by glow discharge analysis

Elements	Percentages of composition
Iron	98.50000
Carbon	0.15000
Manganese	0.94867
Phosphorus	0.00872
Sulfur	0.01307
Silicon	0.22767
Cuprum	0.01803
Nickel	0.01023
Chromium	0.03743
Vanadium	0.00423
Molybdenum	0.00387
Titanium	0.01397
Aluminum	0.04053
Niobium	0.00427
Zirconium	0.02667
Boron	0.00036
Cobalt	0.01987
Tin	0.00428
Lead	0.00141

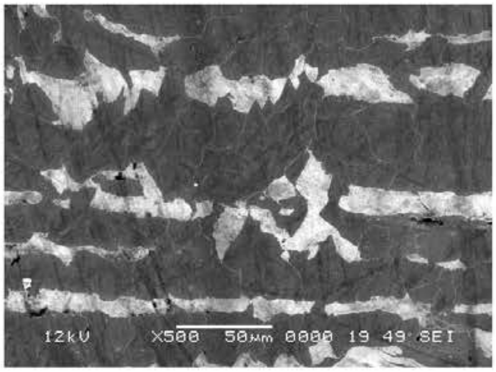


Fig. 1: Pearlitic (light) and base-iron (dark) microstructure

Table 2: Mechanical tensile properties derived from tests conducted using the Universal Tensile test machine

Tensile properties	Average values
Modulus of elasticity (MPa)	210.000
Yield strength (MPa)	328.330
Ultimate strength (MPa)	536.670
Ductility (%)	21.630
Poisson ratio	0.295

TESTING COMPACT TENSION GEOMETRY

The Compact Tension geometry for mode-I plain-strain linear elastic fracture characterization was adopted as determined by the ASTM E399-90 (1991). The geometrical dimensions of the compact tension specimen were as shown in the Fig. 2. The standard dimensional profiles had been derived based on the constraint of elastic material characteristic properties in order to achieve plain-strain fracture toughness criterion. In particular, to ensure validity of linear elastic fracture mechanics application, the critical sharp crack tip is necessary to constraint the initiation of crack by separation of elastic atomic bonds. At the macro-mechanical level, a macro scale V-shape profile of the crack tip was machined out using the wire cutting technique. In order that fatigue pre-cracking could be conducted to create fine hairline crack ahead of the V-notch tip.

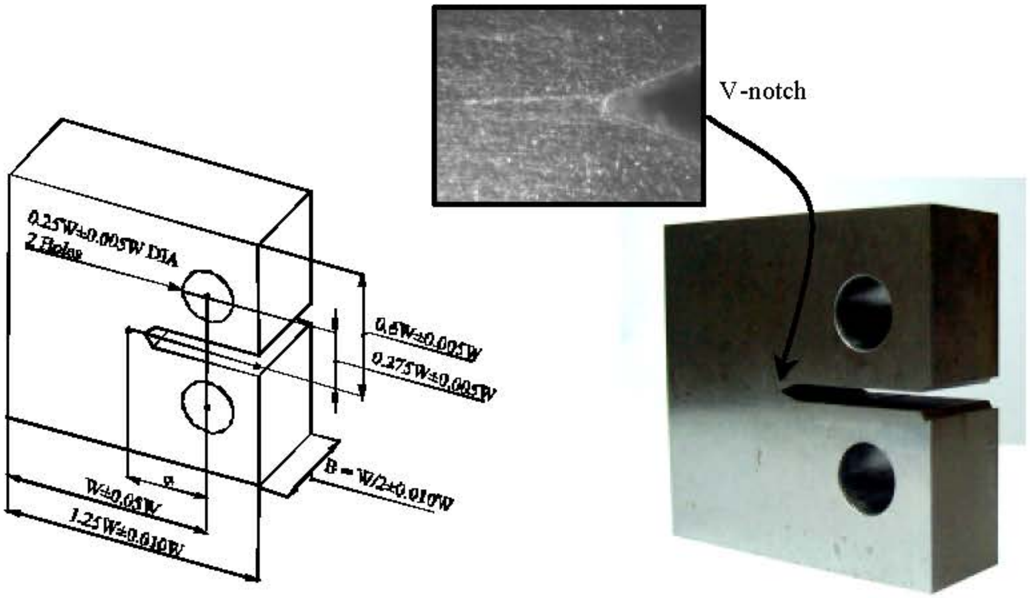


Fig. 2: ASTM E399-90 compact tension specimen geometry

A total of five specimens were prepared following the proportional dimensions for one critical thickness of about 26 mm such that the effective elastic fracture toughness could be achieved at plain strain constraint of $B \geq 2.5\ (K_{IC}/\sigma_{ys})^2$. Characteristic load-displacement at fracture initiation and reduction of data were obtained via standard unidirectional tensile loading by cleavage to the specimen using a servo hydraulic tensile machine. The applied loads and corresponding Crack Opening Displacements (COD) were recorded by the machine-integrated load cell and an externally-mounted clip gage spanning at the starter notch mouth.

DETERMINATION OF K_{IC}

The load versus COD curve (P-COD curve) provides the characteristic signature of the fracture resistibility to crack development under cleavage load. The reduction of data based on ASTM standard derives a 5% deviated slope-line that intersects the characteristic curve provides the fracture load point at initiation is presented in Fig. 3. At the same time, initial linear slope must be within the constraint of $0.7 \leq$ liner slope ≥ 1.5 or $P_{max}/P_Q \leq 1.10$, in order to satisfy plain strain condition. As a result of determining the fracture load point at initiation, the stress intensity factor K_{IC} or fracture toughness value can now be determined. The resultant experimental K_{IC} for a range of thickness is shown in the Fig. 4. Plain strain elastic fracture toughness free from thickness effect is

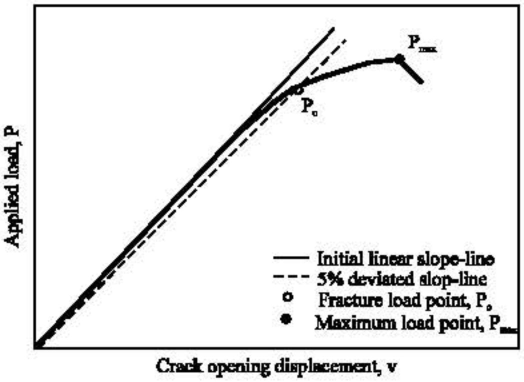


Fig. 3: Characteristic P versus COD plot

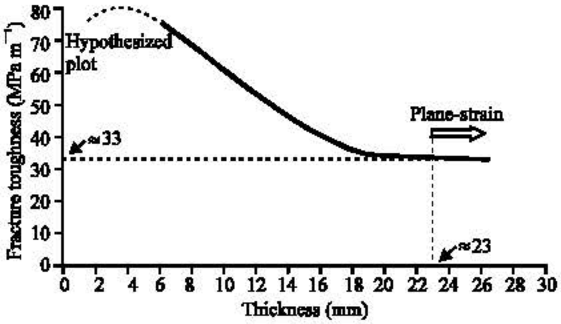


Fig. 4: Fracture toughness versus thickness characteristic plot

experimentally derived at the value of about 33 Mpavm with a coefficient of variation of 5.9%. While the limiting thickness for this K_{IC} value is estimated at a minimum value of 23 mm for this particular carbon steel material.

FRACTOGRAPHIC ANALYSIS

The fractographic analysis of the fractured surface provides important insights as to the mode and mechanisms of failure. Three characteristic fractured zones, fatigue pre-crack, crack initiation and gross fracture, were prepared and subjected to Scanning Electron Microscopic (SEM) observation. Their characteristic micro-failure behaviour and mechanism were obtained as shown in the Fig. 5. In the pre-crack zone, wave-like striation patterns were observed had been a result of planar slippage deformation due to the fatigued-loading effect. At the onset or crack initiation zone, flat and faceted microstructure surfaces were distinctly observed. Following the onset, gross plastic failure by separation of specimen produces microstructures with characteristic dimpled together with coalescence of microvoids were wide spread. The interest of the SEM analysis was focused at the instant onset of crack propagation as this provides an indication of material characteristic and cleavage. Corresponding trademarks of cleavage; were identified by river and feather deformation patterns observed at the onset zone as shown in the Fig. 6 and 7, respectively.

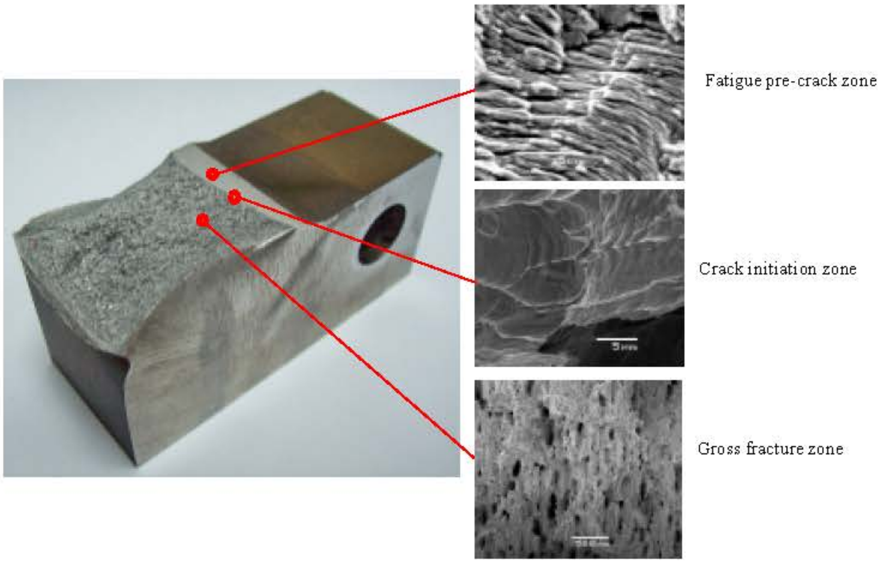
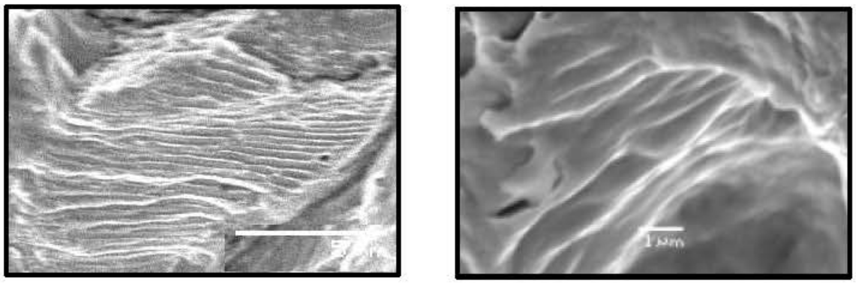
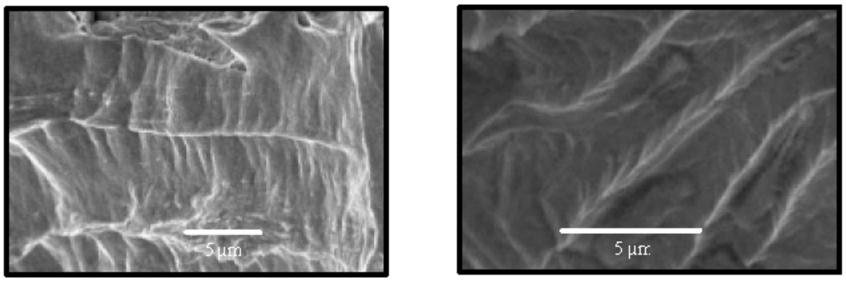


Fig. 5: Fractographs of distinctive zones in pre-crack, initiation and gross failure


(a) Magnification at 5000xs

(b) Magnification at 10,000xs

Fig. 6: River patterns at crack onset



(a) ‘Open-feather’ at 3000xs (b) ‘Closed-feather’ at 5000xs

Fig. 7: Feather marks at crack onset

CONCLUSIONS

Plane-strain fracture toughness value of about 33 MPa√m had been obtained experimentally at a limiting thickness of at least 23 mm for the carbon steel material utilized in the investigation. In addition, the fractography analysis had illustrated in the micro-structural deformation patterns, distincted to river and feather marks at the crack onset, as a commonly trademark found on the cleavage and brittle failure surfaces. Hence the characterization of cleavage in carbon steel was successfully validated by the determination of plane-strain fracture toughness characteristic and the fractography analysis.

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