ORAL/POSTER REF. ICF100104PR

Experimental and Finite Element Analysis of Fracture Criterion of Extra Deep Drawn Steel Sheets

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ABSTRACT

The efforts made over the last three decades to understand fracture behaviour of structural material in elastic and elasto-plastic fracture mechanics regimes are numerous, whereas investigations related to fracture behaviour of materials in thin sheets or gross yielding fracture regimes are limited in number. The prevention of failure in stressed structural components currently requires fracture mechanics based design parameters like fracture toughness or critical crack-tip opening displacement. The present attempt would aim to fulfill this gap and generate more information thereby increased understanding on fracture behaviour of sheet metals. In the present investigation, using a recently developed technique for determining fracture criteria in sheet metals, results are generated on fracture toughness and verified with Finite Element analysis. At the end it is concluded that magnitude of fracture toughness of thin sheets increases with increase in thickness, unlike that for thick plates.

KEY WORDS

Extra Deep Drawn Steel Sheets, Fracture Criterion, Gross Yielding Fracture Mechanics, Crack-tip opening Displacement.

INTRODUCTION

In recent years, there have been considerable emphasis in the production of Deep Drawing and Extra Deep Drawing (EDD) steel in industries. The wide applications of EDD steel are not only well known for domestic appliances like storage containers, household utensils but also for automobile industries for manufacturing car bodies. With increasing global competition for quality materials, there is a need to understand the fundamentals of crack initiation in these bulk products. The characterization of thin sheets is presently being done with the help of empirical engineering simulative tests like Erichsen cup test, Olsen cup test and hole expansion test. The principle of the above tests, in general, attempt to search for an engineering parameter which indicates the mechanical environment for crack initiation and/or propagation [1] under the corresponding experimental conditions for each of these tests. The event of crack initiation and propagation is commonly dealt with using fracture mechanics principles; but so far little attention has been paid in this direction.

OBJECTIVES

The insufficient attention on studies related to fracture behaviour of sheet metals originates from the fact that engineering materials with thinner sections are not considered as load bearing structural parts. Only Liu and his co-workers [2-4] have suggested some guidelines to assess fracture criteria of thin and tough plates of structural materials. The objectives of this study are (i) to present a simple technique for obtaining fracture criteria of EDD steel sheets in line with the studies of Liu [2], Ray [1] and verify the same with FE analysis. (ii) to examine the effect of the variation of thickness of such steel sheets on their fracture criteria.

BACKGROUND

The basic principle for obtaining fracture criteria of thin and tough sheets / plates according to Liu and his co-workers [2-4] is related to examinations of a strip necking zone which remains embedded inside the plastic zone ahead of a crack tip in a deformed specimen. The investigators have contended that such strip necking phenomenon is governed by the ratio of the plastic zone size and the plate thickness (B), and thus a physical parameter $(K/S_Y)^2/B$ controls the occurrence of crack tip necking. The parameter henceforth will be referred to as the strip necking parameter. In addition, Liu [2], and Liu and Kuo [4] have observed that the crack tip opening displacement in the strip necking zone is equal to the thickness contraction. This observation led them to conclude that the thickness contraction at the crack tip is equal to the crack tip opening displacement (CTOD), which in turn is related to the stress intensity factor. Thus, a measurement of the thickness contraction at the critical point of surface crack initiation leads to the assessment of a fracture criterion for thin and tough sheets and plates. But these investigations have not indicated any rationale for detecting the crack initiation event.

METHODOLOGY

The determination of fracture criterion for thin sheets in the present study was made using compact tension type specimens as per ASTM standard E399-91 [5] and with the help of a fabricated grip. The various tests are conducted to summarize the results.

SPECIMEN PREPERATION

Specimen is fabricated according to ASTM standard E399-91 [5] by wire electric discharge machining to maintain the exact relationship between all the dimensions. The configuration of the test specimen is shown in Fig.1. The specimens were ground with emery papers following 1/0 (coarse), 2/0, 3/0, 4/0 (fine). These were then polished first using alundum and finally using 0.25μm diamond paste. The mechanical grip was fabricated suitable to the Universal Testing Machine.

METALLOGRAPHIC AND MECHANICAL TESTS

The composition of the investigated steel is given as (C-0.06, Mn-0.38, S-0.03, P-0.017, Si-0.05, Fe-Bal., all in weight %). The microstructure of the material revealed ferrite plus pearlite (~5.1%), and the average ferrite grain size was found to be 7.2μm. The average tensile properties of the material were as follows: yield strength (S_Y) = 355.9MPa, ultimate tensile strength = 387MPa. The average hardness of the steel in the Rockwell-B scale was obtained as 71.3.

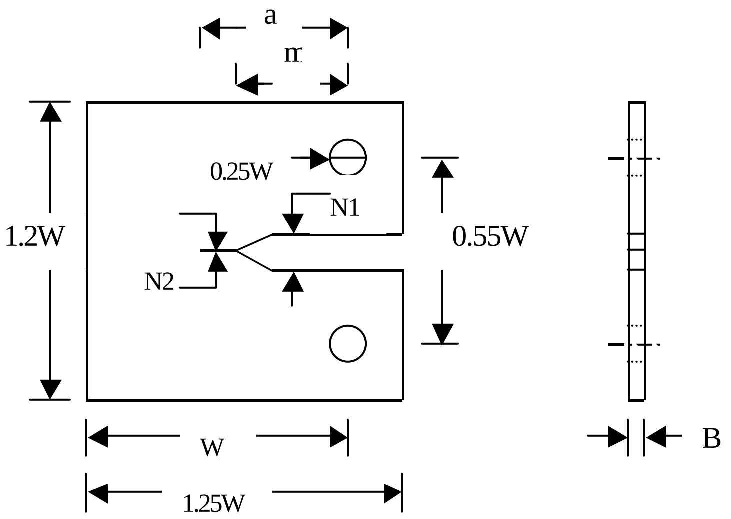

Fig.1. Geometry of the test specimens used for determining fracture criteria of thin sheets. (W = 24 mm, B = 1.18 - 1.69 mm, N1 = 0.8 mm, and N2 = 0.2 mm, a = actual crack length, m = major slot)

FRACTURE TEST

The fracture tests were carried out using an Instron (Model 4204) Universal Testing Machine with a loading rate corresponding to the constant crack head displacement of 0.2 mm/min at the room temperature of 300K. During such tests, the magnitude of load and displacement were recorded together with time. It was observed that load dropped at a particular instance during such a test, when butterfly-shaped surface cracks initiated. At that instance of time the loading of a specimen was discontinued, and the specimen was taken out for subsequent measurement of *CTOD* and analysis of alternate fracture criteria. Four specimens with thickness 1.18, 1.58, 1.64 and 1.69 mm were tested. The detailed dimensions of the specimens together with the critical loads (P_c) at the point of crack initiation obtained during their tests are given in Table 1.

Table 1.

Dimensions of the tested specimens and the Maximum Load (P_c) attained During the Fracture Tests.

Specimen Code	Thickness B (mm)	Crack Length a (mm)	Critical Load P_c (kN)
S1	1.18	10.16	1.194
S2	1.58	10.15	1.829
S3	1.64	10.22	1.773
S4	1.69	10.16	1.855

ESTIMATION OF FRACTURE TOUGHNESS

The critical crack-tip opening displacement during the loading consists of elastic CTOD ($\mathbf{d}_e$) plus plastic CTOD ($\mathbf{d}_p$) following report of You and Knott [6].

$$CTOD_c = \mathbf{d} = \mathbf{d}_e + \mathbf{d}_p \quad (1)$$

$$\mathbf{d}_e = [K^2(1-\mathbf{u}^2)] / 4\, S_Y\, E \quad (2)$$

where, the elastic modulus (E) and the Poisson's ratio ($\mathbf{u}$) were taken as 211 Mpa and 0.33, respectively. However, to know the value of $\mathbf{d}_e$ the magnitude of stress intensity factor K needs to be estimated. The value of K is found from the Dugdale model [7] using the relationship:

$$G = K^2 / E = S_Y . CTOD \quad (3)$$

where, G = strain energy

The $CTOD$ is taken as $\mathbf{d}_p$, estimated with the help of an optical microscope and substituting this value in equation (3), the value of K is determined. Now the value of K gives the value of $\mathbf{d}_e$, which on substitution in equation (1) gives the value of critical CTOD ($\mathbf{d}$). Now the critical strain energy is given by

$$G_c = CTOD_c . S_Y = \mathbf{d} . S_Y \quad (4)$$

and subsequently the value of fracture toughness K_c is calculated by:

$$K_c = \sqrt{(G_c . E)} \quad (5)$$

FINITE ELEMENT FORMULATION

The same study was simulated in ANSYS program using same dimensions, material and loading situation. The crack-tip deformation consists of elastic deformation and plastic deformation. Elastic deformation is based on linear analysis and plastic deformation is based on non-linear analysis.

SOLID MODELLING AND MESH GENERATION

A block is modeled with the dimensions as per ASTM standard, however one axes symmetry is considered for mode I type loading. Material properties are incorporated for linear & nonlinear analysis.

The solid model is then discertized into number of elements and nodes by automatic generation. Meshing is graded from fine at the crack-tip to coarse at the solid boundary. The element is defined by 20 nodes having three degrees of freedom per node: translations in x, y, and z directions. The element has plasticity, stress stiffening, large deflection and large strain capabilities. The most important region in a fracture model is the region around the edge of the crack. A prism shaped element may be formed by collapsing the top plane of a brick element along the surface diagonal. To pick up the singularity in the strain, the elements around the crack-tip should be quadratic, with the mid-side nodes placed at the quarter positions. Such an element called as a singular element was derived by Blackburn [8].

LOADING AND BOUNDARY CONDITIONS

In experiment, pins are inserted through the hole and are held through grip by the jaws of Instron machine. To simulate the practical situation, at the top of a cylindrical hole a line is defined and the total load is distributed along the line. To simulate the support condition, all the bottom face nodes are restricted for x and y direction movement.

LINEAR ANALYSIS

In this analysis, quarter shifting of the mid node is done to get singularity effect. For a particular specimen related critical load P_c is applied and the node of maximum displacement is located. For the particular node, 'θ', the angle made by the direction of maximum displacement with crack plane and the stress value, either s_x or s_y is noted. Then following the basic equation (5), the exact value of K is calculated.

$$s_x = K_I / (2\pi r)^{1/2} \cos\theta/2 \, (1 - \sin\theta/2 \sin 3\theta/2) + \ldots$$
$$s_y = K_I / (2\pi r)^{1/2} \cos\theta/2 \, (1 + \sin\theta/2 \sin 3\theta/2) + \ldots \qquad (5)$$

where, r is the radius of the node from the crack tip. Now substituting value of K in equation (2), the value of elastic deformation d_e is determined.

NONLINEAR ANALYSIS

Elastic-plastic finite element analysis can be considered as an extension of elastic analysis by incorporating extra conditions pertaining to nonlinear plasticity conditions. The elastic-plastic finite element analysis was carried out by Gdoutos et al [9]. Nonlinearity includes material nonlinearity and geometric nonlinearity. The elastic-plastic process requires a continuous assessment of stress and plastic strain at all points of the structure as the applied load increases. Hence the load is applied in sequence of relatively small increments, and within each step checks on stress and equilibrium are made. As the loading starts, the program starts to iterate the stress above the yield stress to consider the plastic effects. The whole nonlinear curve is considered to consist of number of straight lines, each being designated as a load step. With the help of this analysis, the value of plastic CTOD d_p and crack-tip necking d_n is determined at the same node considered in linear analysis to find the value of K_C. The values of d_e and d_p given by FE analysis are used in equation (1), (4) and (5) to find fracture toughness.

Table 2

Comparative Assessment of Experimental and FE Results on Different Fracture Parameters

Specimen Code No.	Thickness B (mm)	Crack-Tip Opening Displacement $CTOD_c$ (d) (mm)		Fracture Toughness K_c MPa $m^{1/2}$	
		Experiment	FEM	Experiment	FEM
S1	1.18	0.631	0.640	211.5	212.8
S2	1.58	0.699	0.712	222.6	224.4
S3	1.64	0.778	0.783	234.8	235.4
S4	1.69	0.945	0.843	258.8	244.3

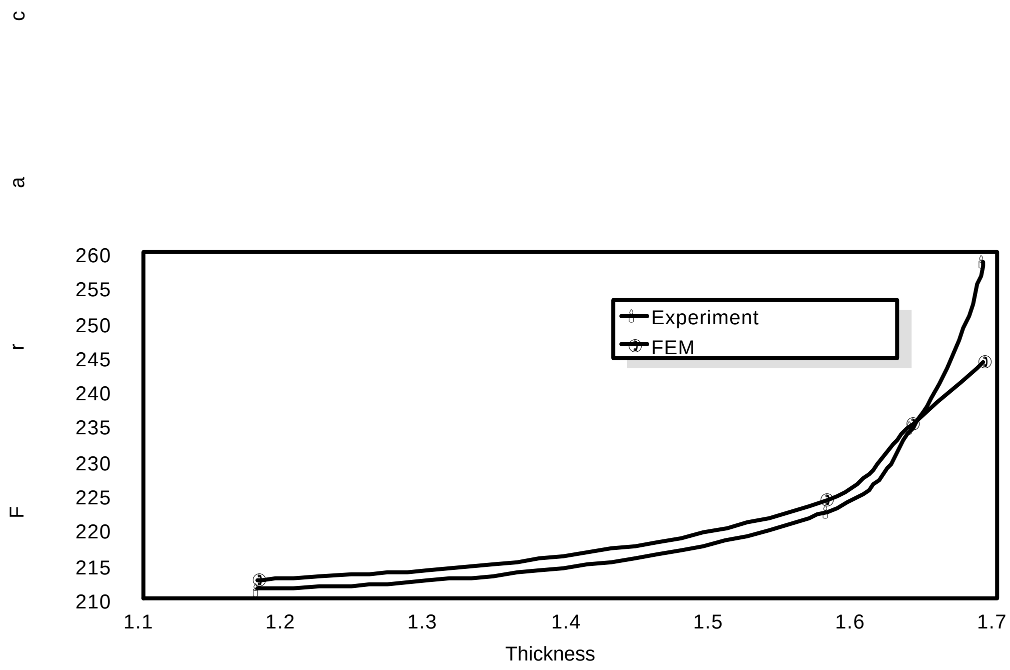

Fig. 2. Variation of Fracture Toughness for EDD (0.06%) Steel Sheet

CONCLUSIONS

1. The variation of d and K_c with the thickness of steel sheets are given in Table 2. and Fig. 2. Figure 2 indicates that the trend of the present results by experiment and FE analysis is in agreement with those obtained by Liu [2], and in both the reports the magnitude of fracture toughness of thin sheets increases with increase in thickness, unlike that for thick plates as reported by Brown and Srawley [10].

2. One of the key observations in this study is the detection of the crack initiation in thin sheets from the phenomenon of load-drop, as illustrated with the help of Fig. 6. The detection of this event eliminates the elaborate effort required by Moire fringe technique for the estimation of $CTOD_c$ ($=d$) and replica technique for the estimation of crack tip contraction d_n [2-3] because $CTOD_c$ can be simply estimated with the help of an optical microscope.

3. The plastic zone size for all the tested sheets extends upto the ligament boundary of the specimens.

4. The amount of crack-tip necking could be determined by FE analysis, which otherwise a difficult task to measure.

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