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THE EFFECT OF NOTCH ANGLES ON THE FRACTURE PARAMETERS OF ALUMINUM THREE POINT BEND SPECIMENS

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ABSTRACT

Stable Crack Growth in ductile materials like aluminum, occurs prior to instability. The instability happens at higher load than the crack initiation load. A usual design based on the crack initiation load may lead to an under utilization of the material. In order to realize the full potential of the material, it is better to characterize the stable crack growth. n this work, the effect of notch angle on the critical stress intensity factor K_{Ic} is investigated for aluminum 6061 grade. A standard three point bend test is carried out on a rectangular bar with notch angles 30^0, 45^0 and 60^0 on a servo hydraulic machine. The specimen is precracked under cyclic loads and later tested under monotonic non cyclic loads. American Standard for Testing of Materials (ASTM) guidelines were used to fabricate and experiment the specimens to determine the critical Crack Tip Opening Displacement (CTOD) values. Compliance based approach was used to compute the Elasto-Plastic Fracture Toughness, J integral at different Crack Mouth Opening Displacement(CMOD) values.

Keywords: *Stress Intensity Factor, Compliance based approach, J-integral, Linear Elastic Fracture Mechanics, Elasto Plastic Fracture Mechanics*

1. Introduction

Fracture mechanics plays a vital role in predicting the failure of materials in use. The most familiar Linear Elastic Fracture Mechanics (LEFM) theory estimates the failure of brittle materials comfortably. But for the ductile materials, the LEFM theory hardly characterizes the fracture behavior. Another theory, called as, Elasto Plastic Fracture Mechanics (EPFM) which is based on the J-integral or crack opening displacement (COD) [1], is used to characterize fatigue cracks in ductile materials.

Other than sharp cracks, there are possibilities for the structures to have notches. And these notches are stress raisers which will cause fracture latter. There is no established theory available to forecast fracture initiation at notch stress raisers [2]. But, the case of fracture initiation at notch stress concentrations is a problem of increasing importance in many engineering applications. Though many theories are available to predict damages, no much experimental data are available to characterize fracture ahead of blunt V notches in ductile materials [3].

The fracture toughness parameters J integral and CTOD are equally good in characterizing the vicinity of the crack [4,5].

2. Experimental Work

2.1 The test case

Three point bend specimens of Aluminum 6061 with different notch angles are loaded and the fracture toughness is studied.

The experiment is done in two phases. The first phase is pre-cracking in which notched specimens are fatigue pre-cracked in limited load range. And the second is actual loading with load vs. Crack Mouth Opening Displacement (CMOD) recording. The experiment is done on an Instron 8802 servo hydraulic Universal Testing

Machine. A load cell of Dynacell make with a dynamic rating of +/- 250 kN is used. A COD gauge of make Instron, travel 4mm and gauge length 10 mm is mounted to get crack line displacements. This test is performed on aluminum grade 6061 flat specimens

2.2 Specimens

In this investigation, 6061 Grade Aluminum flat specimens were used. All the specimens were fabricated from the same plate with dimensions 20 X 10 X 500 mm flat plate. Table 1 provides the composition for the plate used.

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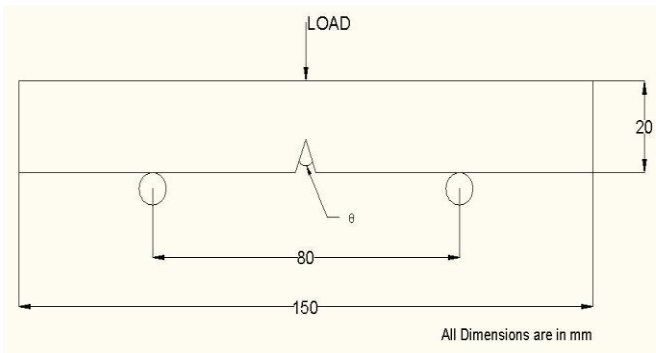

Fig. 1 Three point bend specimen

Table 1: Composition of the specimen

Cu	Si	Mg	Mn	Fe
0.35	0.43	0.75	0.22	0.38

Specimens were fabricated with three different notch angles (θ), viz. 30^0, 45^0 and 60^0 and five specimens in each category. The notches were cut using wire cut in V shapes in a CNC machine. The specimens, shown in Fig. 1, had the design recommended by ASTM Standard E1290-99[6] for three-point-bend specimens [7], except that they contained a straight-face notch terminated by a semicircular tip instead of a sharp crack. The ratio of crack depth to specimen width (a/W) was more than 0.45 for all specimens. All other dimensions match the nominal ones as specified by the ASTM Standard [6] to within the accuracy of the measurements (0.03 mm).

2.3 Experimental arrangement

A fixture is fabricated to load the three sizes of specimens with scaled support and loading pins and to accommodate selected transducers for measurements during the tests. The fixture with the specimen is tested in a 50-ton Instron servo hydraulic testing machine. Dynacell load cell is used to measure the applied load, two linearly variable differential transducers to measure the displacement of the load application point and a clip gage to measure the Crack Mouth Opening Displacement (CMOD). The position of the transducers is indicated in figure 2.

To establish the suitable crack-tip condition, the stress intensity factor (SIF) level at which specimen fatigue precracking is conducted is limited to a relatively low value.

This test method involves the determination of the CTOD fracture toughness (K_{Ic}) of metals by increasing load tests of fatigue precracked specimens. Load versus Crack Mouth Opening Displacement (CMOD) is digitally noted. The load at a 5 % secant line offset from the initial slope (corresponding to about 2.0 % apparent crack extension) is established by a particular deviation from the linear portion of the record. The value of K_{Ic} is calculated from this force using equations that have been established by elastic stress analysis of the specimen configurations specified in this test method. The validity of the K_{Ic} value determined by this test method depends upon the establishment of a sharp-crack condition at the tip of the fatigue crack in a specimen having a size adequate to ensure predominantly linear-elastic, plane-strain conditions.

The specimens are then tested under static load. The Load vs. CMOD record is obtained and graphed. The Compliance formula is used to obtain potential energy as follows.

3. Determination of CTOD Toughness

Crack Tip Opening Displacement (CTOD) is considered to be an equally powerful parameter in characterizing the crack development. Here, CTOD is calculated using a relation given in ASTM E1290-99[6] and followed by Kudari et al [7]. This method uses a rotation factor as given by [6].

$$\text{CTOD}, \partial = \frac{(CMOD).r.b}{a + r.b}$$

where r is rotation factor, a the crack length and b the width. The value of r according to ASTM E 1290-99[6], is 0.44 for Single Edge Notched Bend Specimens.

The relationship is given in figure 2.

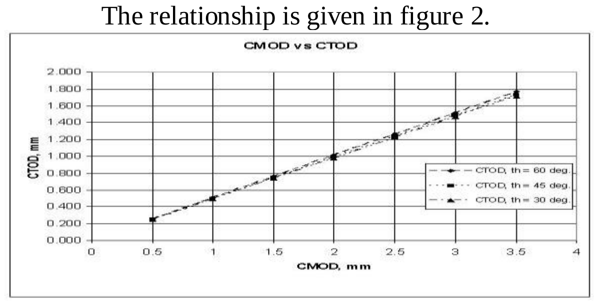

Fig. 2 CMOD vs CTOD

4. Determination of J Integral

J integral is a commonly accepted parameter to be an effective criterion for the initiation of crack extension. Though there are several methods to find the J integral, an energy based method is used here.

With reference to Derbalin [9], the J integral based on energy method,

$$J = \frac{1}{B}\frac{\partial U}{\partial a}$$

where U is the potential energy, a is the crack length and B is the specimen thickness. Graphically, the potential energy difference, dU, for two specimens with crack lengths a and (a+da) is the area between the load versus load-point displacement curves.

In this compliance approach, the difference in the potential energy between two specimens with small difference in crack lengths a and (a+da). The J integral calculated for specimens with different notch angles vs. CTOD, are compared in figure 3.

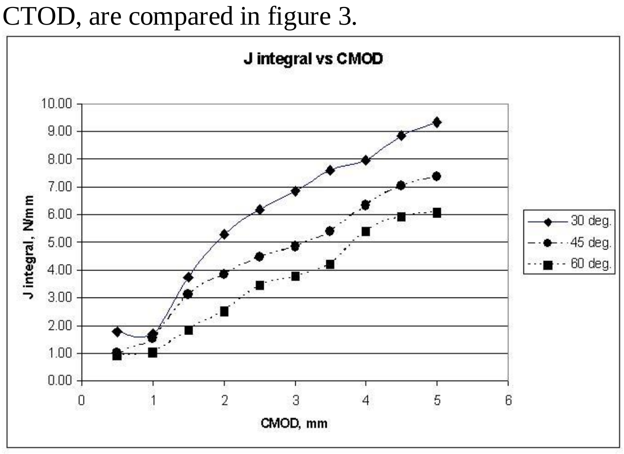

Fig. 3 J integral vs CMOD for notch angles 30^0, 45^0 and 60^0

5. Results

The fracture toughness, K_{Ic} and results are obtained as following. The K is calculated [6] as follows.

Calculation of K_Q—Bend specimen K_Q is calculated in SI units of N/mm$^{3/2}$ as follows

$$K_Q = \frac{P_Q S}{BW^{3/2}} f\left(\frac{a}{W}\right)$$

for which,

$$f\left(\frac{a}{W}\right) = 3\sqrt{\frac{a}{W}}.\frac{1.99-\left(\frac{a}{W}\right)\left(1-\frac{a}{W}\right)\left[2.15-3.93\frac{a}{W}+2.7\left(\frac{a}{W}\right)^2\right]}{2\left(1+2\frac{a}{W}\right)\left(1+\frac{a}{W}\right)^{3/2}}$$

where P_Q = force N (lbf),

B = specimen thickness m (in.),

S = span as determined m (in.),

W = specimen width (depth) as determined, m (in.), and

a = crack size as determined in, m (in.).

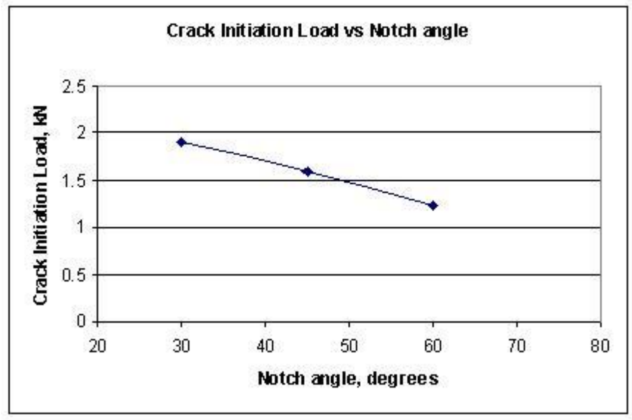

Fig. 4 The effect of notch angle on crack initiation load

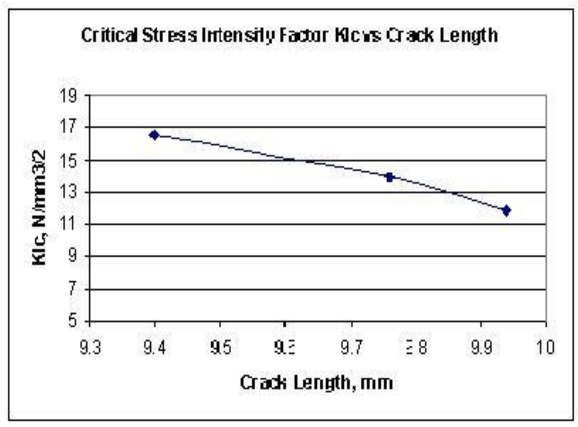

Fig. 5 The effect of crack length on the critical stress intensity factor, K_{Ic}

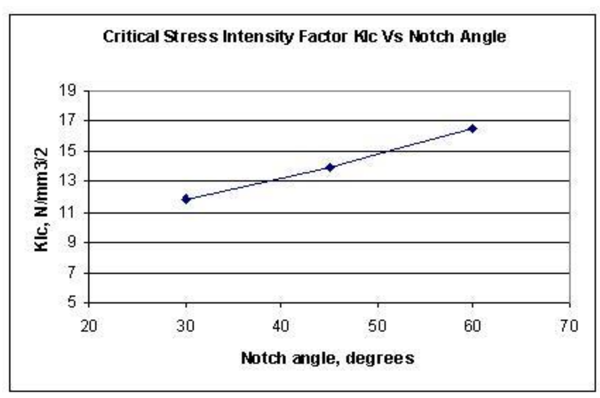

Fig. 6 The effect of notch angle on stress intensity factor, K_{Ic}

6. Conclusions

After analyzing the results carefully, the following conclusions are drawn from the present investigation.

i. The relationship between CTOD and CMOD is found conveniently using the plastic hinge method using a rotation factor as given in ASTM E1290 -99. The CTOD (fig. 2) is observed to be around half of the CMOD for all the notch angles.

ii. The relationship between elasto plastic fracture toughness J and CTOD (fig.3) are linear. The slope of the lines is found to be greater for acute notch angle. The relationship between J and CTOD is observed as linear and the slope of the line is inversely proportional to the notch angle.

iii. The crack initiation load is observed to be indirectly proportional to the notch angle. (Fig. 4)

iv. The Critical Stress Intensity Factor, K_{Ic} is inversely proportional to the crack length and directly proportional to the notch angle. Hence it is understood that specimens with larger notch angles are tougher than specimens with acute notch angle.(Fig.5 & Fig.6)

Future research is to be carried out to go beyond the so far obtained results presented here and to clear further doubts. In particular, the tests on different loading angles with a range of setup changes are desirable to establish if and how the present results can be generalized. We hope that this paper will provide a starting point and more interest to continue this line of investigation.

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Nomenclature

Symbol	Description	Units in SI
K_{Ic}	Critical Stress Intensity Factor	$N / mm^{3/2}$
J integral	Path independent integral	$N.mm/mm^2$
CTOD	Crack Tip Opening Displacement	Mm
CMOD	Crack Mouth Opening Displacement	Mm
θ	Angle of the V notch	degrees