State of Arts: Fracture Toughness

Prof. Ketul Brahmbhatt, Prof. Satish Shah, Mr. Mohit Pambhar

Abstract— **Fracture mechanics is the branch of science which characterizes the crack in a component. Fracture mechanics applied to crack growth under fatigue loading. Fracture toughness is a property which describes the ability of a material containing a crack to resist fracture, and is one of the most important properties of any material for many design applications. There are various parameters which describe the fracture toughness in the quantitatively like stress intensity factor (K), J-integral, crack tip opening displacement (CTOD) and crack tip opening angle (CTOA). This material property varies with the variation of different factors which is studied in this paper.**

Index Terms— **Fracture toughness, Stress Intensity Factor, CTOD, J-integral.**

I. INTRODUCTION

Fracture mechanics applied to crack growth under fatigue loading. Initially, the fluctuating load nucleates a crack, which then grows rapidly and finally the crack growth rate per cycle picks up speed. Thereafter the stage comes when the crack-length longs enough to be considered as a fracture failure.

While cutting a tree, we should make a notch with an axe at its trunk and then pull it down with a rope. Wohler was one of the earliest investigators (1860), who investigated fatigue of locomotive axles by applying controlled cyclic loads. This led to development of S-N diagram and finding endurance limit of steel.

The ships, which were earlier made by joining plates together through the process of riveting, were changed to welded frames. Many of these failed in the cold temperatures of the North Atlantic Ocean. In the construction of passenger planes, it was found that the planes were exploded in the air. It was found that a fatigue crack, initiated near an opening in the fuselage, ran through its entire body especially at high altitudes, where the outside pressure was low and the interior pressure of the airplane was pressurized for the comfort of passengers.

For all practical purposes, modern fracture mechanics was born in 1948 when Irwin formulated fracture mechanics by devising workable parameters like stress intensity factor and energy release rate. Fracture mechanics is now applied extensively to important fields like nuclear engineering, piping, space ship, rockets, offshore structure etc.

II. MODES OF FRACTURE FAILURE

There are mainly three modes of fracture failure as shown in fig. 1. The opening mode, Mode I, is characterized by local displacements that are symmetric with respect to the x-y and x-z planes.

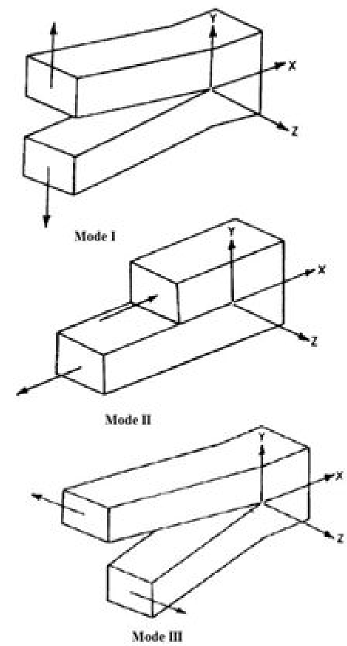

Fig. 1 Three modes of fracture failure

Local displacements in the sliding or shear mode, Mode II, are symmetric with respect to the x-y plane, and skew symmetric with respect to the x-z plane. The two fracture surfaces slide over each other in a direction perpendicular to the line of the crack tip. Mode III, the tearing mode, is associated with local displacements that are skew symmetric with respect to both x-y and x-z planes. The two fracture surfaces slide over each other in a direction parallel to the line of the crack front. Each of these modes of deformation corresponds to a basic type of stress field in the vicinity of crack tips. In any analysis, the deformations at the crack tip can be treated as one or a combination of these local displacement modes.

III. STRESS INTENSITY FACTOR (K)

The stress intensity factor (K) is used to predict the stress state near the crack tip because of remote load or other residual stresses. Stress intensity factor is mainly used for Linear Elastic Fracture Mechanics (LEFM) problem. It is given by Irwin [10] as

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$K_I = \sigma\sqrt{\pi a}$
(1)
where σ is far field stress and a is crack length.

Ming-Zhi XING, Yong-gang WANG and Zhao-Xiu JIANG [2] have found that fracture toughness (K_I) of aluminium alloys of 25 mm circular rod are dependent on loading rate. 2024-T4 has better crack initiation tolerance whereas 7075-T6 has better crack growth tolerance which is related with different fracture modes. The fracture mode of 2024-T4 is transgranular fracture with high density small sized dimples and the fracture mode of 7075-T6 is mainly intergranular fracture with many intermetallic particles in bottom of the void located in fracture surface. The variation of K_d with time for 2024-T4 and 7075-T6 in three point bending test is shown in fig. 2.

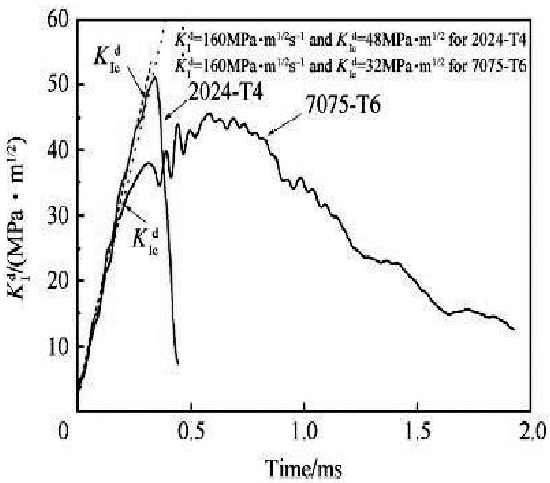

Fig.2 The variation of K_d with time for 2024-T4 and 7075-T6 in 3PB test

Nenad Gubeljaka, Andrej Likeba and Yury Matvienkob [3] have found that apparent fracture toughness ($K_{I,app}$) depends on ρ and specimen size (b and B) and also critical radius ρ_c under which fracture toughness $K_{I,app}$ become independent ρ. They proposed four different models (empirical equations) for evaluation of fracture toughness considering the effect of ρ and specimen size. The 1st model predicts $K_{I,app}$ as a function of ρ. The 2nd model considers plastic zone size (r_p) as well as ρ. The 3rd model predicts $K_{I,app}$ as a function of b. In the 4th model account both B and b. They have found that there is in good agreement between predicted models and experiment results.

I.Souki, D.Delagnes and P.Lours [4] have found that changing in the austenitizing temperature from 990°C to 1050°C has no influence on both the crack propagation rates and the fracture toughness (K_I) of 5% Cr martensitic steel. But the modification of tempering changes the fracture toughness and crack propagation rate.

Maria Jesus Perez-Martina, Borja Ericeb and Francisco Galveza [5] have done the experiments on Al 7017-T73 by using the subsequent apparatus ordered from lowest to highest load application velocity: a servo-hydraulic universal testing machine, a free-drop tower, a modified Split Hopkinson Pressure Bar and an explosive load testing device. Fig. 3 shows the dynamic stress intensity factor for aluminium 7017-T73 alloys all the specimens with different testing methods. The experiment result gave conclusion that the fracture-initiation toughness of the aluminium 7017-T73 alloy remained constant regardless of the velocity at which the load was applied.

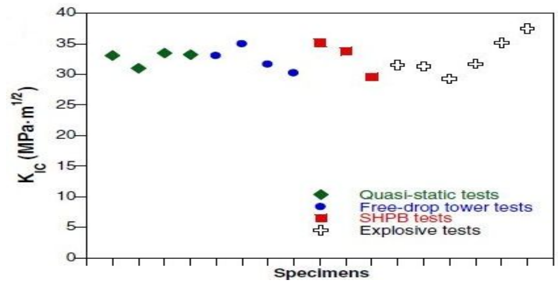

Fig. 3 Fracture toughness for aluminium 7017-T73 alloy all the specimens with different test

Yu Xiaa, Li Yulonga and Li Lia [6] have found that fracture toughness depends on grain size. They measured the fracture toughness of AZ31 magnesium alloy after the grain refinement. They concluded that K^C of AZ31 was increased 21.1 to 28.6 MPa$\sqrt{m}$ with average grain variation from 16.47 to 1.75 µm. Also fracture mechanics was changed to mixture of cleavage fracture and dimple fracture from only dimple fracture.

Mohd Ahadlin Mohd Daud, Nurulhilmi Zaedah Nasir, Ahmad Rivai and Mohd Zulkefli Selamat [7] have done three point bend impact experiments on AZ61 magnesium alloy on impact testing machine. The dynamic fracture toughness determined at sharp crack with five different thicknesses of 2,4,6,8 and 10 mm. A sharp crack was initiated and propagated to half of specimen width at a constant crack propagation rate of $1x10^{-8}$ m/cycle before specimen was loaded by impact force until maximum force is reached. This test was conducted at an impact velocity of 3.85 m/s. The dynamic fracture toughness of AZ61 K_d was determined from force displacement history. From the result it was founded that K_d value decreases with increasing the specimen thickness.

IV. J-INTEGRAL

The J-integral is also a factor which characterize a crack. It is very useful to characterize material which exhibit elastic-plastic behavior near crack tip. For plane problems, consider an arbitrary path around a crack tip as shown in fig. which starts from one face of the crack and ends to the other crack face. It was first defined by Rice [16] based on the deformation theory of plasticity called J integral and given by:

$$J = \oint w\, dy - T_i \frac{\partial u_i}{\partial x} ds \quad (2)$$

w is the strain energy density, T_i is the components of the traction vector, u_i is the displacement vector components, ds is the length increment along the contour, x and y are the rectangular coordinates with the y direction taken normal to the crack line and the origin at the crack tip.

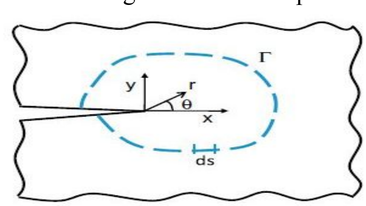

Fig. 4 An arbitrary path around crack tip

M. Berganta, A. Yawnyb and J. Perez Ipiñac [8] gave fracture characteristic using J-R curve of the steam generator tube of nuclear power plant. For this, they considered elastic-plastic fracture mechanics (LEFM) methodology for analysis. They gave the new experimental technique for the nonstandard specimen of Steam Generator tubes for evaluating J-R curve. The specimens were made of Incoloy 800 (Ni: 30.0-35.0; Cr: 19.0-23.0; Fe: 35.5 min, % in weight). They made two different specimens one with circumferential wall crack and two opposite circumferential wall crack. The notches were made by electro discharge machining. The testing was done using servo-hydraulic testing machine. The applied load P, and the load-line displacement were recorded. After the evaluation of eta factor J-R curve is estimated. The stable crack growth was measured during the test applying an optical method, and also allows simultaneous measurement of the CTOD fracture toughness parameter.

V. Fracture Toughness Parameter Testing Methods

A. Crack Tip Opening Displacement (CTOD)

It is another parameter suitable to characterize a crack. It can be used for both linear elastic fracture mechanics (LEFM) and elastic-plastic fracture mechanics (EPFM). It was given by Wells [9]. Using the Irwin's [10] estimate of plastic zone size and the elastic displacement solutions for a center-cracked infinite plate, the CTOD (δ) was approximated as:

$$\delta = \frac{4}{\pi}\frac{K_I^2}{E\sigma_{ys}} \quad (3)$$

Wells [9] recognized that the factor 4/ π is inconsistent with the energy balance approach (which would require a factor of unity), and subsequently omitted this factor.

The plastic hinge model was developed by Hollstein and Blauel [11] to determine CTOD by assuming that two arms of the specimen rotate rigidly about a plastic hinge point in the uncracked ligament.

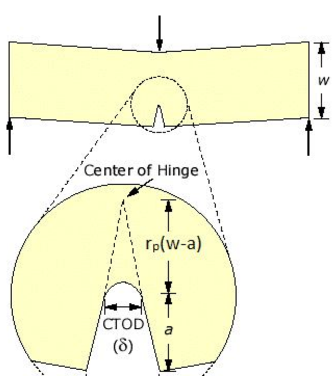

Fig.5 Plastic hinge model for calculation of CTOD

$$\delta = \frac{K^2(1-\nu^2)}{2\sigma_{ys}E} + \frac{[r_p(W-a)+\Delta a]V_{pl}}{[r_p(W-a)+a+Z]} \quad (4)$$

where a is the crack length, Δa is the crack extension, Vpl is the plastic component of CMOD, Z is the distance of knife edge measurement point from the front face of specimen, r_p (W-a) denotes the distance of the plastic hinge point from the crack tip, and r_p is the plastic rotation factor that was obtained from the limit load analysis as given by Wu SX [12]. It was accepted that $r_p \approx 0.44$ for deep-cracked SE(B) specimens, and $r_p \approx 0.46$ for C(T) specimens. This plastic hinge model is described in ASTM E1290.

B. Crack Tip Opening Angle (CTOA)

The crack tip opening angle (CTOA) is defined as the average angle of the two crack surfaces measured at a point 1 mm behind the crack tip. The CTOA fracture mechanics method was developed primarily to characterize the stable crack extension behavior for thin-walled materials in low constraint conditions. A standard test method for the critical CTOA testing was developed recently ASTM with a designation as E2472–06e1

Nenad Gubeljaka, Andrej Likeba and Yury Matvienkob [13] have done the experiment on standard specimen of SEN(B) and C(T) and one nonstandard pipe ring specimen according to ASTM E1820. CTOD-R curve was obtained using normalization method by remote measurement of CMOD for all specimens and these curves for all three specimens shows similar fracture toughness in stable crack initiation range. They concluded that the piping specimen can be suitable for fracture toughness testing of pipeline with axial flaws when standard's requirement of fracture toughness test is not possible.

Tetsuya Tagawa, Yoichi Kayamori and Mitsuru Ohata [14] have calculated CTOD value using plastic hinge model according to British Standards BS5762 in 1979 and the ASTM standard E1290. They have concluded that the ASTM E1290-08 tends to give a smaller value of the critical CTOD, $\delta_{(c,ASTM)}$ than that evaluated by BS7448, $\delta_{(c,BS)}$ and $\delta_{(c,ASTM)}$ was occasionally about 60% of $\delta_{(c,BS)}$ in cleavage cracking for low yield-to-tensile ratio steels. This inconsistency in $\delta_{(c,ASTM)}$ and $\delta_{(c,BS)}$ is mainly caused by the mismatch between $2\sigma_{ys}$ and $m\sigma_Y$, in the calculation of CTOD, where σ_{ys} is the yield stress, m is the constraint factor in ASTM E1290-08 and σ_Y is the effective yield strength.

L.M. Plaza [15] measured the uncertainty in the determination of CTOD of Metallic materials. The CTOD measures according to standards: British standard BS7448 and ASTM E1290-93. All the sources of uncertainty are listed out for ex. in apparatus, method, environment, operator test, piece, measuring instrument etc. These all are classified according to uncertainty type. After all these, the combined uncertainty is estimated. The expanded uncertainty is estimated from combined uncertainty which will add to the measures CTOD value. This CTOD value is very accurate the initial value of CTOD.

Lei Zhenkun, Bai Ruixiang, Deng Lino and Quiet Wei [16] have used in digital image correlation method to measure the displacement in DCB test with interfacial crack. They have bounded two materials together: a carbon fiber laminate and a piezoelectric ceramic plate for a bi material cantilever beam test with initial interface crack length a_0= 20 mm. The experimental results show that extension process of crack is divided into two phases stable and unstable crack extension. The crack growth rate remains constant within stable phases CGR increases gradually with time. According to graph of results the different phases of loading history have different effects on crack parameters and thus both parameters are not mutually increase during the loading process. The CTOA parameter increased rapidly from the first unstable crack extension phase while the CTOD began to increase after entering into second unstable crack growth phase. The interface crack propagation behavior of bi material corresponds to the transition of loading condition. The interface crack starts from the pairing mode-I and gradually transforms into mixed mode-I/II until it fully deboned last.

Conclusion

We concluded that fracture toughness parameters K, CTOD and J-integral depends on many factors. There are various specimens and methods available to measure fracture toughness parameters. There are many parameters which geometry of specimen, materials, types of loading, grain size, type of methodologies, size of notch and temperature on which fracture toughness depends.

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References

[1] *A path independent integral and the approximate analysis of strain concentration by notches and cracks.* JR., Rice. s.l. : J Appl Mech, 1968, pp. 379-86.

[2] *Dynamic Fracture Behaviors of Selected Aluminum Alloys Under.* Ming-zhi XING, Yong-gang WANG and Zhoa-xiu JIANG. 2013, Defence Technology 9, pp. 193-200.

[3] *Notch Radius and Specimen Size Effects on Fracture Toughness of Low Alloy Steel.* Abdel-Hamid I. Mourada, and Aly El-Domiatya. 2011, Procedia Engineering 10, pp. 1348-53.

[4] *Influence of heat treatment on the fracture toughness and crack propagation in 5% Cr martensitic steel.* I.Souki, D.Delagnes, and P.Lours. 2011, Procedia Engineering 10, pp. 631-37.

[5] *On the loading-rate dependence of the Al 7017-T73 fracture-initiation toughness.* Maria Jesus Perez-Martina, Borja Ericeba and Francisco Galveza. 2014, Procedia Materials Science 3, pp. 1026-31.

[6] *Effect of grain refinement on fracture toughness and fracture.* Yu Xia, Li Yulong and Li Li. 2013, Procedia Materials Science 3, pp. 1780-85.

[7] *Dynamic Fracture Toughness of Magnesium Alloy under Impact.* Mohd Ahadlin Mohd Daud, Nurulhilmi Zaedah Nasir, Ahmad Rivai and Mohd Zulkefli,. 2013, Procedia Engineering 53, pp. 639-44.

[8] *Estimation procedure of J-resistance curves for through wall cracked steam generator tubes.* M. Berganta, A. Yawnyb and J. Perez Ipinac. 2012, Procedia Materials Science 1, pp. 273-80.

[9] *Application of fracture mechanics at and beyond general yielding.* Wells AA. 1963, Br Weld J , pp. 563-70.

[10] *Analysis of stresses and strains near the end of a crack traversing a plate.* . Irwin GR. 1957, J Appl Mech, pp. 24:361-64.

[11] *On the relation of the crack opening displacement to the J-integral.* Hollstein T, Blauel JG. 1977, Int. J Fract, pp. 385-90.

[12] *Plastic rotation factors of three-point bend and compact tension specimens.* . Wu SX, Mai YW, Cotterell B. 1988, J Test Evaluat, pp. 555-7.

[13] *Fracture Toughness Measurement by Using Pipe-Ring Specimens.* Nenad Gubeljaka, Andrej Likeba, Yury Matvienkob. 2014, Procedia Materials Science 3, pp. 1934-40.

[14] *Comparison of CTOD standards: BS 7448-Part 1 and revised ASTM E1290.* Tetsuya Tagawa, Yoichi Kayamori, Mitsuru Ohata. 2009.

[15] *The determination of uncertainty in CTOD testing.* L.M. Plaza. 2000, UNCERT COP.

[16] *Noncontact optical measurement of CTOA and CTOD for interface crack in DCB test.* Lei Zhenkun, Bai Ruixiang,Deng Libo, Qui Wei. 2012, Optics and Lasers in engineering, pp. 964-70.