

Fracture Toughness Evaluation of Carbon Steel Alloy for Pressure Vessel Manufacturing

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ABSTRACT

This article is to evaluation of fracture toughness of carbon steel based on the testing Standards. ASTM Standards ASTM E399-90 “Plane-Strain Fracture Toughness of Metallic Materials”. E1290–70 “Test Method for crack Tip Opening Displacement (CTOD) fracture toughness Measurement”. E1820–80 “Test Method for Measurement of Fracture Toughness”. And British Standard, BS 4762 “Fracture Mechanics Toughness Tests. Method for determination of KIC, critical CTOD and critical J values of metallic materials”. This Standards give a method for determining plane strain fracture toughness values KIC, for carbon steel specimens. The method uses fracture pre-cracked specimens.

تقييم مقاومة الكسر لسبائك الصلب الكربوني المستخدمة في تصنيع أوعية الضغط

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المُخلص

تتناول هذه المقالة تقييم مقاومة الكسر للفولاذ الكربوني استناداً إلى معايير الاختبار. تشمل هذه المعايير معايير الجمعية الأمريكية لاختبار المواد (ASTM) التالية: E399-90 "مقاومة الكسر في حالة الإجهاد المستوي للمواد المعدنية"، و E1290-70 "طريقة اختبار قياس إزاحة فتح طرف الشق (CTOD) لمقاومة الكسر"، و E1820-80 "طريقة اختبار قياس مقاومة الكسر". بالإضافة إلى المعيار البريطاني BS 4762 "اختبارات مقاومة ميكانيكا الكسر. طريقة لتحديد قيم KIC و CTOD الحرجة و J الحرجة للمواد المعدنية". توفر هذه المعايير طريقة لتحديد قيم مقاومة الكسر في حالة الإجهاد المستوي (KIC) لعينات الفولاذ الكربوني، وذلك باستخدام عينات مُشققة مسبقاً.

الكلمات المفتاحية: صلابة الكسر، سبيكة الصلب الكربوني، التكامل J، إزاحة فتح الشق، تصنيع أوعية.

1 Introduction

Fracture mechanics R.W. Nichols (1984), Anderson, T. L (1994). is mainly focused on a single crack. It is generally used to describe a material's resistance to crack extension and applicable to both to fracture testing and fracture control, helping characterize the property of material that determines how well it resists fracture. Measuring and standardizing fracture toughness is essential for applying mechanics of fracture methods R.W. Nichols (1984).

The toughness of fracture values can also support characterization of the material, performance evaluation, and assurance the quality for typical structures of engineering, including pressure vessels and piping, petrochemical vessels and tanks, oil and gas pipelines,

and automotive, ship, and aircraft structures. Therefore, measurement, testing and assessment of fracture toughness are the key topics in advancing fracture mechanics methods and their engineering applications Zhu, Xian-Kui and Joyce, James A (2012) . Fracture toughness is an indication of the amount of stress required to propagate a preexisting flaw. Flaws may appear as cracks, voids, metallurgical inclusions, weld defects, design discontinuities, or some combination thereof.

Standardized techniques for resistance testing of crack growth structural for steel following ASTM E1820 ASTM E1290-70 , typically uses three p0int bend and compact tension methods. The defect assessment procedures under development recommend using geometry dependent values of fracture toughness to

ensure that crack tip constraint in the test of specimen closely matches that in the structural components . In particular, fracture toughness of fracture values from notch of single edge tension specimens are more suitable for assessing the resistance of fracture for pressurized pipelines and cylindrical vessels than deep notch specimens under bending S. Cravero, C. Ruggieri (2005) . the evaluation procedures of J integral focus primarily on developing estimation schemes for components of plastic.

The first Approach uses a plastic factor (Sumpter and Turner) to relate macroscopic crack driving forces, such as J integral and Crack-Tip Opening Displacement CTOD to the area of the load displacement curve or crack mouth opening displacement for cracked geometries.

Since the load displacement data are obtained easily from standard test specimens, this method is well suited for fracture toughness testing procedures, including ASTM E1820 Zhu, Xian-Kui and Joyce, James A (2012), ASTM International (2018), S. Sedmak and Z. Radakovic (2004).

2 The fracture mechanics Approach

It contrasts the mechanics of fracture approach with traditional of structural design and material selection . Traditionally, the expected design stress is compared to the flow properties of candidate materials, and a material is considered acceptable if its strength exceeds the applied stress. To reduce the risk of brittle fracture, designers may use a factor of safety on stress and set minimum tensile elongation requirements. Mechanics of fracture , however, quantifies the critical combinations of these variables. Two main analysis approaches of fracture are the criterion of energy and the approach of stress intensity T.L. Anderson (2005) . they are equivalent under certain conditions.

3. Crack loading modes

Equation (1) S. Cravero, C. Ruggieri (2005) , shows the stress filed near a crack in an isotropic linear elasticity for mode I (K_I), and modes II (K_{II})and modes III (K_{III}) are the modes of loading and study the behavior of crack.

$$\begin{aligned}
 & \text{Mode I} \\
 \sigma_{xx} &= \frac{K_I}{\sqrt{2\pi r}} \cos\left(\frac{\theta}{2}\right) \left[1 - \sin\left(\frac{\theta}{2}\right) \sin\left(\frac{3\theta}{2}\right)\right] \\
 \sigma_{yy} &= \frac{K_I}{\sqrt{2\pi r}} \cos\left(\frac{\theta}{2}\right) \left[1 + \sin\left(\frac{\theta}{2}\right) \sin\left(\frac{3\theta}{2}\right)\right] \\
 \tau_{xy} &= \frac{K_I}{\sqrt{2\pi r}} \cos\left(\frac{\theta}{2}\right) \sin\left(\frac{\theta}{2}\right) \cos\left(\frac{3\theta}{2}\right) \\
 \sigma_{zz} &= 0 \text{ (Plane stress)} \\
 & \nu(\sigma_{xx} + \sigma_{yy}) \text{ (Plane strain)} \\
 \tau_{xz}, \tau_{yz} &= 0
 \end{aligned}
 \tag{1}$$

Note: ν is Poisson's ratio.

Where r is the distance to the point of interest from the Crack -Tip (where the stresses are evaluated), and θ is the angular orientation of that point relative to the Crack -Tip.

Stress variation in the y-direction around the crack tip for isotropic linear elasticity under Mode I, is used for analysis of stresses around crack tip.

$$\sigma_{yy} = \frac{K}{\sqrt{2\pi r}}
 \tag{2}$$

Equation (1) is only valid near crack tip where asymptotic stress fields are developed i.e., where $1/\sqrt{r}$ dominates the stress field. The value of b_y cannot be lower than applied stress, σ [3].

The crack extension after loading is calculated according to the stress perpendicular to the crack level in the first position, which is as follows:

$$\Delta a = a - a_0
 \tag{3}$$

Where: a is the crack growth size after loading and a_0 the nominal crack length.

4. Basics Of Fracture Strength

Fracture toughness measures a material's ability to resist brittle fracture when a crack is present. High fracture strength tends to make ductile fracture more likely, while the fracture of brittle is typical of materials in lower fracture toughness.

The Fracture toughness is calculated using the following equation:

$$KQ = \frac{FQS}{B W^{1.5}} f(a_0/W)
 \tag{4}$$

Where W is the width of specimen , B is the thickness and S is the support and $f(a_0/W)$, are given in standards by tables for easier calculation of K_Q . The purpose Of a toughness of fracture test is to evaluate the

strength for material to crack growth by measuring the load needed to extend a brittle or ductile crack Anderson, T. L (1994).

5. Crack-Tip Opening Displacement (CTOD)

CTOD has several definitions, the most common are the displacement at the original of Crack-Tip and the 90° intercept T.L. Anderson (2005) . CTOD measurements often use edge cracked specimens in three-point bending, where the hinge model is inaccurate if displacements mainly elastic. Therefore, the methods standard split displacement into elastic and plastic parts, and CTOD for this specimen is estimated as:

- For elastic region.

$$CTOD_{el} = \frac{KQ^{2*}(1-\nu^2)}{(2\sigma F * E)} \tag{5}$$

Where: ν is the Poisson’s ratio, σF is the flow stress and E is the Young’s modulus.

- For plastic region.

$$CTOD_{pl} = \frac{0.4 (W - a_0) C_{MODpl}}{(0.4 W + 0.6 a_0)} \tag{6}$$

Where: a_0 is the nominal crack length and W is the specimen width.

Thus,

$$CTOD = CTOD_{el} + CTOD_{pl} \tag{7}$$

Where: $CTOD_{el}$ is the Crack-Tip Opening Displacement for elastic region. $CTOD_{pl}$ is the Crack-Tip Opening Displacement for plastic region.

6. J Integral

The growth of crack can be predicted by calculating the factor of the intensity of stress or rate of energy release. The J - integral is determined from the curves of the load line displacement LLD and the load displacement T.L.

Anderson (2005). First, express J as the sum of the components of plastic and elastic.

$$J = \frac{2A_t}{B (W - a)} \tag{8}$$

Where: A_t is the total of area for overall load applied (F) and (LLD) curves,

7. Material And Specimen Geometry

In order carbon steel as metal alloy processed for testing. The geometry of specimen and the properties of mechanical is given in Table 1.

Table 1. Mechanical properties & geometry of specimen.

Specimen	Basic Metal SM80-1
B (mm)	14.961
W (mm)	15.037
a_0 (mm)	8.79602
a_0/W	0.585
$f(a_0/W)$	3.5629
S (mm)	60
σ_F (MPa)	780.00
σ_{YS} , (MPa)	750.00
E, (MPa)	206,000

Specimens were fabricated according to the ASTM (E 1820) method for standard test of measuring toughness of fracture, except for the initial crack Zhu, Xian-Kui and Joyce, James A (2012).

8. Rustles And Discussion

Multiple specimens carbon steel metal was monotonically loaded following the ASTM Standards. Tests were conducted for all specimens in the same circumstances and conditions.

The tests are performed under displacement-controlled loading. Each specimen is loaded to the maximum of force corresponding to plastic collapse. The results for the metal alloy, obtained after the tests and J integral calculations, are derived from the load–displacement LD and load load-line displacement LLD curves in Figure 1.

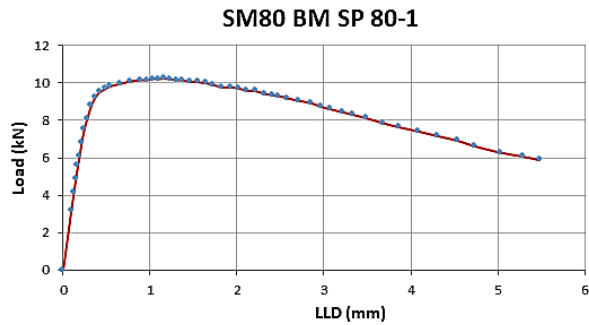


Fig. 1: The load &(LLD) of metal alloy

The obtained values of J used as a measure of crack driving force, are presented as a function of crack growth size Δa . Figure 2 shows values of J, Figure 3, shows J integral and CTOD relationship.

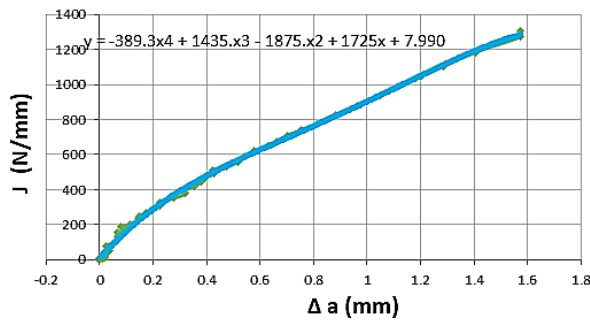


Fig. 2: Estimated J values corresponding to crack extension Δa SM PS BM

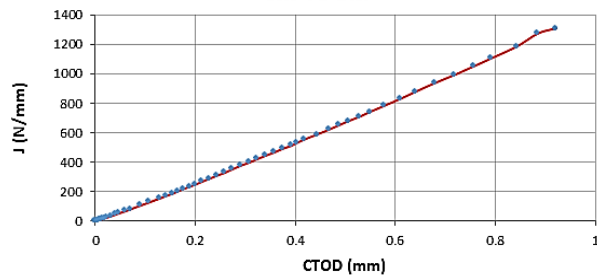


Fig.3: J integral and CTOD relationship

Figures 2 and 3, it can be noted that metal alloy of carbon steel has ascendable relation, if increases J values increases the values of Δa , as well as increasing the values of CTOD to become almost linear relationship.

Overall, the carbon steel exhibits an increasing trend in both J integral and Crack-Tip Opening Displacement CTOD with crack extension Δa Therefore, higher applied loading produces larger crack-tip deformation and a stronger crack driving force, which results in greater crack extension. Such behaviour supports that

the material’s fracture resistance can be effectively characterized using J and CTOD.

9. Conclusion

In this article, Multiple specimens of carbon steel were monotonically loaded following the ASTM Standards. Tests were conducted for all specimens in the same circumstances and conditions. the higher values of J integral and CTOD are obtained for metal. The results obtained after the tests, given the different curves was observed that with increased load will increases crack extension, thus increasing the values of both J-integral and CTOD to metal alloy of carbon steel.

The results confirm that evaluating the fracture toughness characterization of carbon steel using J integral and CTOD provides a consistent description of crack growth resistance. Therefore, the evaluated both can support engineering fracture assessment by linking applied loading to crack extension behaviour for pre-cracked metallic component.

References

R.W. Nichols (1984) The use of fracture mechanics as an engineering tool. The 1984 ICF Honour Lecture. ICF 6, New Delhi, India.
 Anderson, T. L (1994). Fracture Mechanics - Fundamentals and Applications. 2nd ed., Boca Raton: CRC.,
 Zhu, Xian-Kui and Joyce, James A (2012) "Review of fracture toughness (G, K, J, CTOD, CTOA) testing and standardization". U.S. Navy Research. 97
 ASTM Standard “Test Method for Crack – Tip Opening Displacement Fracture Toughness Measurement” ASTM E1290–70
 S. Cravero, C. Ruggieri (2005) Engineering Fracture Mechanics, 72 1344
 ASTM International (2018) “Standard Test Method for Measurement of Fracture Toughness,” ASTM E1820.
 S. Sedmak and Z. Radakovic (2004) Form Fracture Mechanics to Structural integrity Assessment
 T.L. Anderson (2005) Fracture mechanics- Fundamentals and a applications, third Edition