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FRACTURE TOUGHNESS EVALUATION USING CIRCUMFERENTIAL NOTCHED TENSILE SPECIMENS BY THE TENSILE TEST AND ANSYS SOFTWARE

N. MEYDANLIK
Mechanical Engineering Department, Trakya University, 22180 Edirne/TURKIYE

Abstract

Fracture toughness (K_{Ic}) is the most important parameter that defines mechanical behaviour of the materials using machine design. Since, fracture tests are both difficult and time consuming, the researchers have been investigating for the easier evaluation of K_{Ic} for many years. In this work; K_{Ic} values have been obtained by using ANSYS software based on the experimental values evaluated in the previous studies. It was shown that there is no significant difference between the experimental ones and the ones obtained by ANSYS. This procedure can provide an important advantage on obtaining of the K_{IC} values.

Key words: *Fracture toughness (K_{Ic}), circumferential notched tensile specimens, ANSYS.*

1. INTRODUCTION

Fracture toughness (K_{Ic}) is the most important parameter that demonstrate mechanical behaviour (against to loads) of the materials using real structural components' design and it is a measure of a given material's resistance to crack growth. Determination of stress intensity factor (K_I) and its threshold value for crack propagation (i.e., K_{Ic}), is major materials selection criterion. K_{Ic} is usually determined using bulky specimens (CT compact tension test specimens) by the tests (ASTM E-399) based on appropriate fracture mechanics theories. Unfortunately, these fracture mechanics tests are complex and expensive to conduct, and very few laboratories are equipped to conduct all of the various types of tests. In addition, the required thickness for a standard plane strain fracture toughness test is not always available due to its relatively large dimension. The required machining cost, fatigue pre-cracking, and testing standard specimens for fracture toughness (K_c, J_c, etc.) and the size requirements necessary to ensure valid K_{Ic} test results sometimes render the tests impractical as quality-control tests (Abdel-Hamid et al.,2012) .

For this reason, many number of studies have been done for the easier evaluation of K_{Ic} with a rapid and at the same time reliable technique for many years. Last decade, nonstandart circumferentially notched tensile (CNT) specimens have been widely used for this purpose (Li et al.,(1997), Ule et al., (2000), Bayram et al., (2001), Rihan et al., (2005), Nath et al., (2006)). Ule et al., (2000) worked on AISI M2 high speed steels and argued that the measured fracture toughness was affected by the eccentricity of the fatigued area. They measured the eccentricity of the fatigue precracked region and found an underestimation of fracture toughness with increasing eccentricity. Rihan et all. (2005) have developed a uniform pre-crack ahead of the notch of the CNT specimen by subjecting the specimen to a controlled fatigue in a bending-rotating set-up and showed advantages of CNT testing technique. CNT specimen is one of the smallest possible specimens that can produce valid plane strain crack loading conditions. Bayram et al., (2001) measured fracture toughness K_C of various steels and aluminum alloys with CNT specimens and summarized that the experimentally measured fracture toughness values using CNT specimens are accurate and reliable considering some correction factors. The finite element studies on fatigue precracked round bar specimens confirmed that this specimen

geometry even of very small size ensures plane-strain condition for fracture toughness test (Ibrahim et al., 1987). In this work, evaluated K_{Ic} values on previous studies has been evaluated again with modelling of the CNT specimens and tensile test by using ANSYS software and results have been compared with experimentially evaluated K_{Ic} values.

2. THEORITICAL BACKGROUND

Stress intensity factor is given as below relation for the circumferentially notched tensile (CNT) specimen (Buechkner et al, (1965)). There are different expressions for K_I used in the fracture mechanics literature. However, in this presentation K_I values has been used estimated values with the expression (1) by the various researchers in order to compare results. Schematic presentation of the CNT specimen used in this work is shown in Fig.1.

$$K_I = \frac{P}{D^{1.5}}\left[1.72\left(\frac{D}{d}\right) - 1.27\right] \qquad (1)$$

where P is load, D is outside diameter and d is diameter of the minimium net section after fatigue crack growth. Plane strain fracture toughness K_{Ic} is the lowest value of the stress intensity factor. The most important limitation to obtain of the K_{Ic} is the ratio of plane strain fracture toughness to yield strength. This has been explained as the form given below by different researchers (Ule et al., (2000), Nath et al., (2006), Ibrahim et al.(1987), Londe et al., (2010), Wei et al., (1982)) for CNT specimens,

$$D \geq k \left(\frac{K_{Ic}}{\sigma_y}\right)^2 \qquad (2)$$

where σ_y is the yield stress and k is a numerical constant. k value varies between 1 and 2, depending on materials. An additional requirement is that the length of specimen L which should be at least 4D.

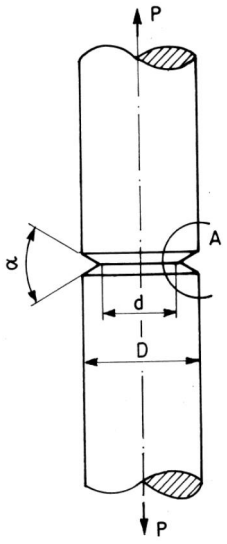

Fig.1. Schematic presentation of the CNT specimen for fracture toughness, α=60° (Ule et al, 2000).

The CNT specimen achieves plane strain conditions and low plasticity despite its small size (Pickles et al., (1983)). This is important because, for valid K_I testing, it is required that the conditions appropriate to linear elastic fracture mechanics exist. For this condition to be the case, only a minimal amount of plastic flow during fracture is permitted. In tests conducted earlier at Monash University, acceptable results have been achieved using 9.5 and 15 mm diameter CNT specimens, whereas for the same material, fracture toughness (K_{Ic}) determination, using standard CT specimens, requires widths up to 80 mm. (Rihan et al., (2004)). Moreover, it has been known that crack initation and propagation occur at maximum load (or at around maximum load) in the high strength metallic materials (Li et al., (1997)). Therefore K_{Ic} values determining the fracture instant has been estimated at maximum load point throughout these examined papers (Londe et al., (2010 and 2011), Wu et al., (2009), Alaneme (2011), Meydanlık (2012)).

3. ANSYS MODELLING AND ANALYSIS

In this study, the commercial finite element software ANSYS was used for the geometric modelling and the finite element analysis. ANSYS calculates the stres intensity factors (K_I, K_{II} and K_{III}) associated with homogeneous isotropic linear elactic fracture mechanics. A displacement extrapolation method is used in the calculation. This method assumes that the displacement calculations are for the plane strain state. The fracture toughness K_{Ic} values have been evaluated by means of ANSYS analysis at the maximum load on the tensile (fracture) tests and the results were compared with ones obtained by analytical equation (1) on previous literature. Firstly, axisymmetrical CNT specimens have been modelled on the plane (x,y). All the FE models were developed using six nodes triangular axisymmetric PLANE2 element which is shown in Fig.2. The element has a quadratic displacement behavior and is well suited to model irregular meshes (such as produced from various CAD/CAM systems). An axisymmetric structure may be represented by a plane (x,y) finite-element model. The use of an axisymmetric model greatly reduces the modeling and analysis time compared to that of an equivalent 3-D model. Due to the axisymmetric geometry and the symmetry about the plane of the crack, only one-quarter of the specimen was modelled. The boundary conditions used in the models are shown in Fig. 3a and 3b. A uniform stress of ($P_{max.}$/A) MPa applied on the end of bar and K_{Ic} values obtained by using ANSYS analysis.

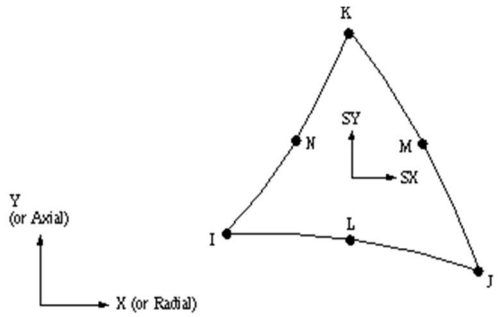

Fig. 2. 6-node triangular axisymmetric ANSYS PLANE2 element (ANSYS 12.0) .

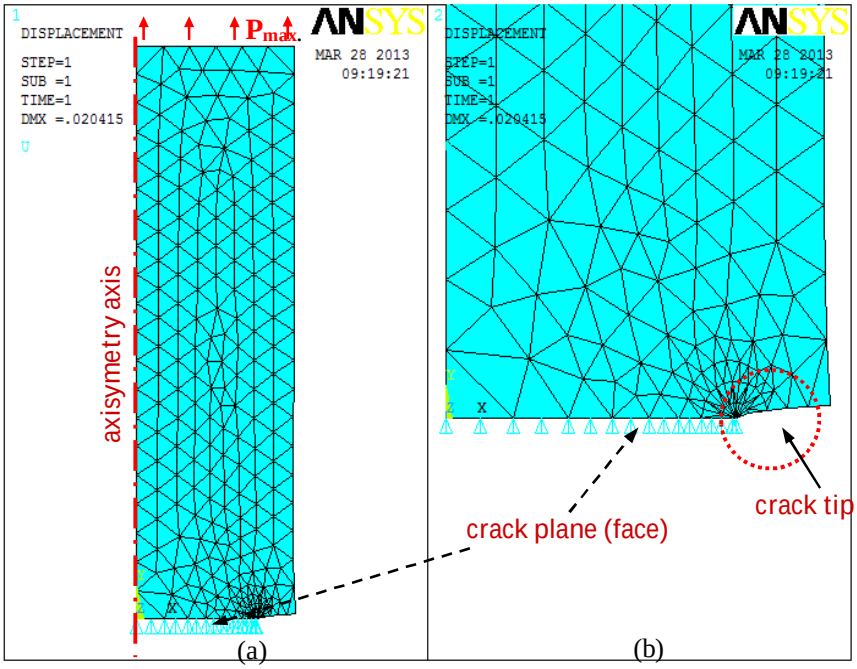

Fig. 3. (a) Modelled one-quarter CNT specimen, (b) Detail of the crack plane and crack tip.

4. ANSYS RESULTS AND DISCUSSION

Results of the five different works which has done using five different materials have given on the Tables 1-5. The K_{Ic} values obtained by Eq.(1) in the works of Londe et. al., (2010 and 2011) are compared with the ANSYS results on Tables 1 and 2. They used two different aluminium alloys, 6082-T6 and 2014-T6. On the tables 3, 4 and 5 the K_{Ic} values again obtained by Eq.(1) in the works of Wu et. al. (2009), Alaneme (2011) and Meydanlık (2012) are compared with ANSYS. In obtaining the results (Alaneme (2011)) there was no fatigue precrack and d/D ratio was constant.

Table 1. Comparison of K_{Ic} in (Londe et al., (2011) with that obtained ANSYS analysis.

Specimen No	d/D (mm/mm)	Max. Load (kN)	K_{Ic} calculated using Eq.(1) *(MPa m^{½})*	K_{Ic} evaluated by ANSYS *(MPa m^{½})*	Difference with (Eq.1) (%)
No1	9.54/12	36.80	25.02	25.46	1.8
No2	9.46/12	37.25	25.86	26.13	1.0
No3	9.20/12	34.60	25.62	26.80	4.6
No4	8.66/12	27.30	23.06	23.68	2.7

Table 2. Comparison of K_{Ic} in (Londe et al., (2010) with that obtained ANSYS analysis.

Specimen No	d/D (mm/mm)	Max. Load (kN)	K_{Ic} calculated using Eq.(1) *(MPa m^{½})*	K_{Ic} evaluated by ANSYS *(MPa m^{½})*	Difference with (Eq.1) (%)
No1	9.84/12	33.00	20.77	20.66	0.1
No2	9.72/12	32.25	20.94	20.82	0.1
No3	9.56/12	31.50	21.30	21.96	0.3
No4	9.35/12	30.75	21.93	22.46	0.2
No5	9.16/12	30.00	22.44	22.95	0.2
No6	9.21/12	29.50	21.79	22.60	0.4
No7	8.74/12	29.00	24.08	24.96	0.4
No8	8.52/12	28.00	24.55	25.12	0.2
No9	8.11/12	25.00	24.25	25.67	0.6
No10	7.66/12	23.75	25.74	26.27	0.2

Table 3. Comparison of K_{Ic} in (Wu et al., (2009)) with that obtained ANSYS analysis.

Specimen No	d/D (mm/mm)	Max. Load (kN)	K_{Ic} calculated using Eq.(1) *(MPa m^{½})*	K_{Ic} evaluated by ANSYS *(MPa m^{½})*	Difference with (Eq.1) (%)
No1	4.32/9.50	34.77	94.54	94.89	0.4
No2	4.54/9.50	38.00	95.67	95.77	0.1
No3	4.41/9.50	36.70	95.85	96.39	0.5
No4	4.46/9.50	37.20	94.04	94.54	0.5

Table 4. Comparison of K_{Ic} in (Alaneme (2011)) with that obtained ANSYS analysis.

Specimen No	d/D (mm/mm)	Max. Load (kN)	K_{Ic} calculated using Eq.(1) *(MPa m^{½})*	K_{Ic} evaluated by ANSYS *(MPa m^{½})*	Difference with (Eq.1) (%)
No1	4.5/6.0	14.16	31.2±0.8	31.84	2.0
No2	4.5/6.0	16.15	35.5±0.5	36.33	2.3
No3	4.5/6.0	18.56	40.9±0.1	41.75	2.0
No4	4.5/6.0	15.65	34.5±0.1	35.22	2.1
No5	4.5/6.0	14.60	32.1±0.9	32.87	2.4
No6	4.5/6.0	18.50	39.7±1.3	41.64	4.8
No7	4.5/6.0	19.71	43.4±0.2	44.37	2.2
No8	4.5/6.0	16.90	37.2±0.3	38.01	2.2

Table 5. Comparison of K_{Ic} in (Meydanlık (2012)) with that obtained ANSYS analysis.

Specimen No	d/D (mm/mm)	Max. Load (kN)	K_{Ic} calculated using Eq.(1) *(MPa m^{½})*	K_{Ic} evaluated by ANSYS *(MPa m^{½})*	Difference with (Eq.1) (%)
No1	6.9/10.0	44.6	54.5	55.2	1.3
No2	6.8/10.0	43.3	54.3	55.3	1.8
No3	6.8/10.0	41.4	53.9	54.9	1.8
No4	5.9/10.0	34.2	54.1	55.1	1.8
No5	5.6/10.0	27.4	55.8	55.6	0.4
No6	6.8/10.0	42.6	54.2	55.2	1.8
No7	6.8/10.0	42.3	54.0	55.5	2.7
No8	6.8/10.0	40.9	53.9	55.2	2.4

It is shown that there is no very big difference between results evaluated with equation (1) and ANSYS. It is shown that ANSYS results are larger than the results obtained by Eq. (1) about % (1-2). The reason for the results are so close to each other can be due to the fitness of the fracture mechanics theory to the method of calculating K_I of ANSYS software. Namely, fracture toughness has been defined at the immediately crack tip. In linear elastic problems, it is known that the displacement near the crack tip vary as $(r)^{½}$. r is the distance from the crack tip. The stresses and strains are singular at the crack tip, varying as $1/(r)^{½}$. To resolve the singularity in strain, crack faces should be coincident, and the elements around the crack tip should be quadratic, with midsides nodes placed at the quarter points. Such elements are called singular elements as shown on Fig. 4. ANSYS has these elements, automatically generates singular elements around the specified keypoint, allow you to control the radius fo the first row elements in the circumferential direction and K_I calculation is done at a few node away from the crack tip in accordance with the theory of fracture mechanics.

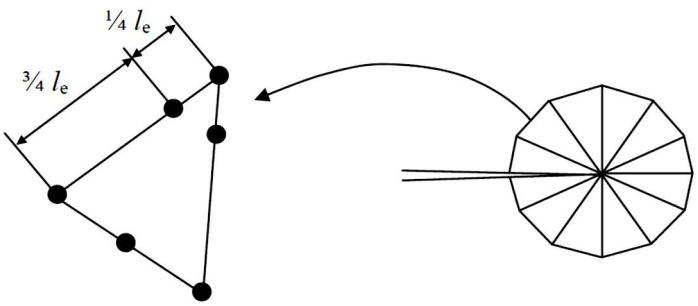

Fig.4. Example of a 2D singular element and element- division around a crack tip.

5. CONCLUSIONS

In this study; evaluated K_{Ic} values at the previous works has been calculated again by using ANSYS. Looking all over the results, we can say that non-standart CNT type specimens could be used to determine of the K_{Ic} values. The more works have to be done on CNT specimens by using the more different materials and CNT type specimens can be standardized. Additionally, ANSYS software could be used with right modelling and applied load for the simulating fracture tests and CNT specimens or to confirm experimental results.

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