Fracture Analysis of Pressure Vessel Component - Arc Shaped Tension Specimen

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Abstract—There are many components of machines, process plants and household goods that fail through over loading improper utilities. Tradition failure criteria cannot adequately explain many structural failures that occur at stress level consider lower than the ultimate strength of the material. Some of failures occur due to deficiency of construction, but many due to material deficiencies in the form of pre-existing flaws that initiated cracks and thus caused fracture. However, no material in reality is flawless and all materials or material produced by fabrication processes contain flaws which constitutes the modes of failure initiation. Essentially, if the crack reach the certain size and is subjected to highly strained region, which are regarded as potential cause of failure. Here it is need to understand the characteristics of crack and its developments. Stress Intensity Factor (K) is used in fracture mechanics to more accurately predict the stress intensity near the tip of a crack caused by a remote load or residual stresses. The testing of material SA 516 Gr 70 and IS 2062 will be carried out with different thickness viz. 12, 16, 18 and 20 mm and critical stress intensity factor of Arc Shaped Tension (AT) specimens were performed which were having crack to width ratio 0.5 as suggested by ASTM E-399.

Keywords: - Crack tip opening displacement, Energy release rate, Fracture analysis, Pressure Vessel, Stress Intensity Factor.

I. INTRODUCTION

A pressure vessel is a closed container designed to hold gases or liquids at a pressure substantially different from the ambient pressure. The pressure differential is dangerous and fatal accidents have occurred in the history of pressure vessel development and operation. Consequently, pressure vessel design, manufacture, and operation are regulated by engineering authorities backed by legislation. For these reasons, the definition of a pressure vessel varies from country to country, but involves parameters such as maximum safe operating pressure and temperature.

There are many components of machines, process plants and household goods that fail through over loading improper utilities. Tradition failure criteria cannot adequately explain many structural failures that occur at stress level consider lower than the ultimate strength of the material.

Some of these failures occur due to deficiency of construction, but many due to material deficiencies in the form of pre-existing flaws that initiated cracks and thus caused fracture. However, no material in reality is flawless and all materials or material produced by fabrication processes contain flaws which constitutes the modes of failure initiation. Essentially, if the crack reach the certain size and is subjected to highly strained region, which are regarded as potential cause of failure. Fracture Mechanics is a set of theories describing the behavior of solids or structures with geometrical discontinuity. The discontinuity features may be in the form of line discontinuities in two dimensional media & surface discontinuities in three-dimensional media. Fracture mechanics is the establishment of a new design philosophy "damage tolerance design methodology". Major advantage of fracture mechanics is fracture parameter stress intensity factor. Fracture mechanics is based on the implicit assumption that there exists a crack in a work- component. The crack is artificial prepared in different shapes, i.e. a hole, a notch, a slot, a re-entrant corner, etc. The crack may exist within a component due to manufacturing defects like slag inclusion, cracks in a weldment or heat affected zones due to uneven cooling and presence of foreign particles. Some years ago, when accurate analysis for predicting the growth of a crack was not available, a reasonably high factor of safety was chosen to account for unforeseen factors.

The strain energy release rate is the energy dissipated during fracture per unit of newly created fracture surface area. This quantity is central to fracture mechanics because the energy that must be supplied to a crack tip for it to grow must be balanced by the amount of energy dissipated due to the formation of new surfaces and other dissipative processes such as plasticity.

The stress intensity factor is used in fracture mechanics to predict the stress intensity near the tip of a crack caused by a remote load or residual stresses. It is a theoretical construct usually applied to a homogeneous, linear elastic material and is useful for providing a failure criterion for brittle materials, and is a critical technique in the discipline of damage tolerance.

II. LITERATURE REVIEW SUMMARY

Webster G A et al. investigated the failure of thick walled tubing subjected to internal pressure. Thick-walled tubing is used for variety of applications in the chemical, nuclear and armaments industries where high internal pressure has to be withstood. If this pressure is cyclic, initiation and propagation of cracks by fatigue may take place with the ultimate risk of failure by fast fracture. Usually fatigue crack in thick walled cylinders initiate at the bore and propagate in a radial plane in the manner illustrated in figure 1.

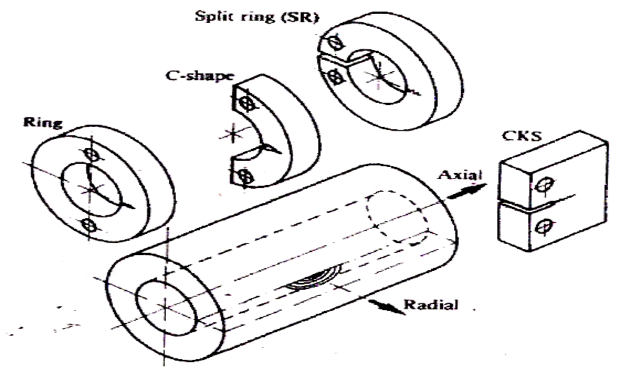

Fig. 1: Test pieces for fatigue crack growth studies of thick walled tubing

M.A. Guerrero et al. calculated the behaviour of a pressure vessel (PV) made of high strength steel (P500) subject to the design loads and assuming the existence of the ''worst case'' crack allowed by the European standards in order to demonstrate the safe use of these steels and the too conservative design rules currently applied by the pressure vessel manufacture codes.

K.F. Nilsson et al. have studied that a series of fracture tests were performed on large scale bend beams, which were fabricated from a reactor pressure vessel steel and contained simulated sub-surface defects.

Xian-Kui Zhu et al. have studied that technical review of fracture toughness testing, evaluation and standardization for metallic materials in terms of the linear elastic fracture mechanics as well as the elastic–plastic fracture mechanics.

Rolf Sandstrom et al. have studied that a model for design against brittle failure based on recent fracture mechanics findings is proposed of wide plate tests have been performed for two materials: P500 and P690 high strength low alloy steels.

Xudong Qian et al. have studied that Fracture assessment procedures for nuclear reactor pressure vessels (RPVs) will combine non-linear analyses of crack front response with stochastic treatments of crack size, shape, orientation, location, material properties and thermal pressure transients.

Nikhil Gupta et al. studied an experimental and computational study of EN-31 steel Compact Tension specimen was performed. Compact Tension specimen was considered in the experimental portion of the study.

V. G. Degiorgi at al have discussed An experimental and computational study of HY-100 steel three-point bend fracture specimens.

III. Experimental Setups And Method

The American Society for Testing and Materials (ASTM) Committee E 24 on Fracture Mechanics developed the first standard for fracture testing standard; it is ASTM standard E 399 the standard method for Stress Intensity Factor(K_{1C}) testing. The critical stress intensity factor of a material depends on thickness of the plate. However, for a thick plate it is independent of thickness because the material in front of crack tip deforms in plane strain. Then, critical stress intensity factor can be treated as the property of the material. Thus, the experiment should be controlled so as to have its loading in plane strain only; that is the plastic zone size in front of the crack tip is quite small in comparison to the specimen thickness. In this work, critical stress intensity factor has been found experimentally for pressure vessel steels i.e. IS 2062 and SA 516 Gr.70 using arc shaped tension specimen as suggested in ASTM E399.

As suggested in ASTM E-399, Load Vs Load line displacement is needed for the calculation of the force P_Q. Hence, the UTM 600 kN which is shown in Fig.2

Fig. 2: Universal Testing Machine 600 kN capacity

In ASTM E-399 there are different specimens are

– Bend SE(B) Specimen
– Compact Tension CT Specimen
– Disk-Shaped Compact DCT Specimen
– ARC-Shaped Tension A(T) Specimen
– ARC-Shaped Bend A(B)Specimen

In the present work the Arc Shaped Tension A(T) specimen is selected and total 16 specimens are fabricated out of having thickness of 12, 16, 18 and 20 mm respectively of IS 2062 and SA 516 Gr 70 materials.

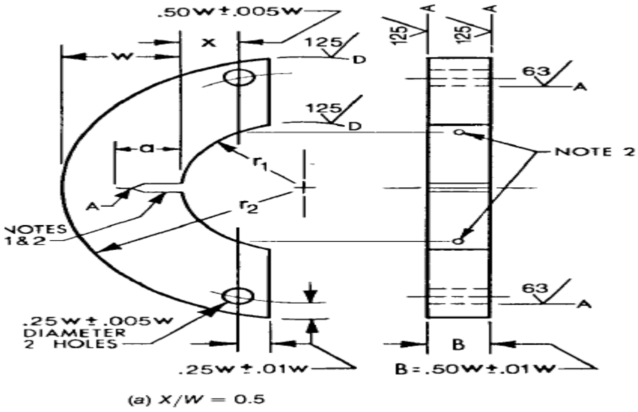

Fig. 3: Arc Shaped Tension A(T) Specimen

ASTM suggested ratio of width of specimen and thickness of the specimen, in the range of 2 to 4, i.e., 2 ≤W/B≤ 4. Here for the ease in manufacturing and cost effectiveness the ratio of W/B was taken as 2. The dimensional drawing of specimen having 12, 16, 18 and 20 mm.

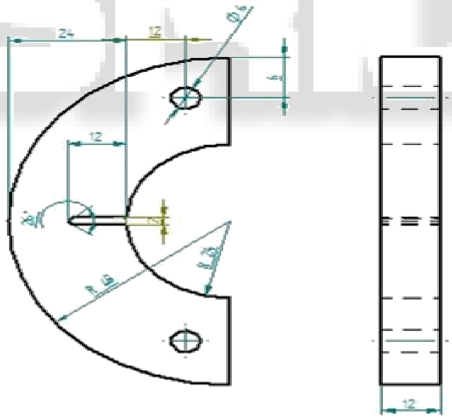

Fig. 4: Dimensional Drawing of 12 mm thick AT Specimen

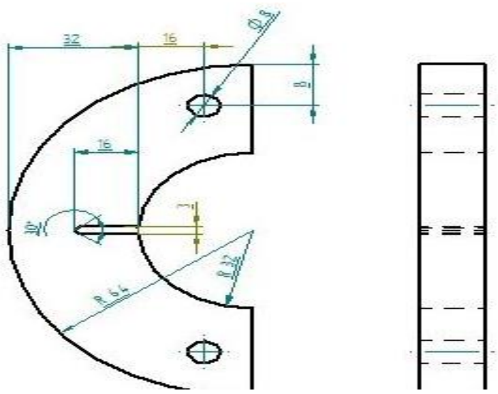

Fig. 5: Dimensional Drawing of 16 mm thick AT Specimen

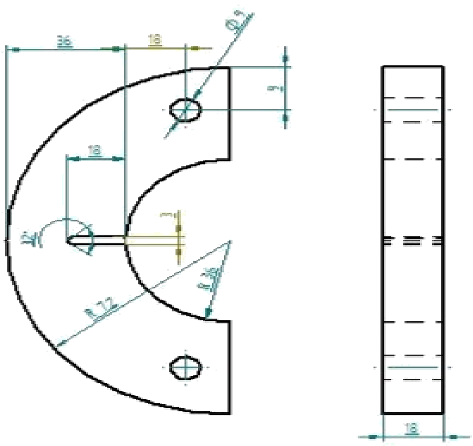

Fig 6 Dimensional Drawing of 18 mm thick AT Specimen

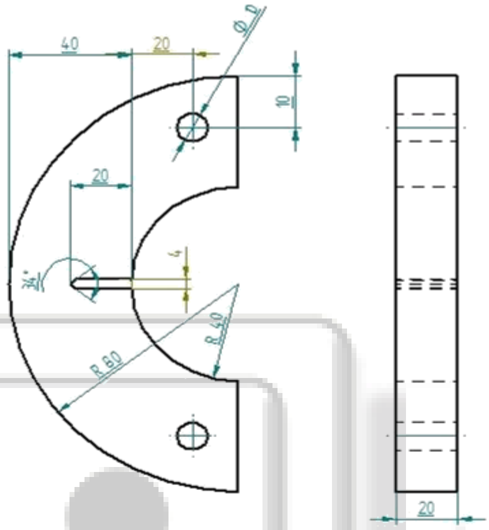

Fig. 7: Dimensional Drawing of 20 mm thick AT Specimen

A loading clevis suitable for testing standard compact C(T), arc-shaped tension A(T), and disk-shaped compact DC(T) specimens is shown in Fig 8. Both ends of the specimen are held in the clevis and loaded through pins in order to allow rotation of the specimen during testing. The clevis holes are provided with small flat on the loading surfaces to provide rolling contact. The size, proportions, and tolerances for the clevis shown in Fig 8. are scaled to specimens.

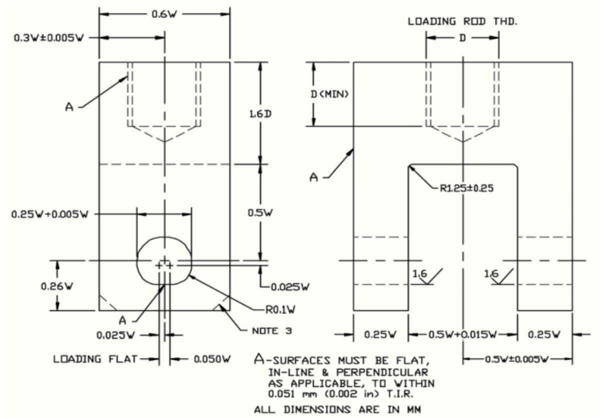

Fig. 8: Loading Clevis for Arc-Shaped A(T) Tension Specimen

Fig. 9: Loading of Arc Shaped Tension Specimen

Fig. 10: Crack propagate in loaded specimen

Fig. 11: Fractured AT specimens after completion of test

The values of apparent K_{Ic} will me much lower than the real K_{Ic}. Hence the ASTM E-399 suggested that the both B and a i.e., the thickness and crack length should be larger than $2.5K_{Ic}^2/\sigma_{ys}^2$. ASTM E- 399 has suggested the following dimensions of Arc Shaped Tension Specimen as W = 2a, and also 2B ≤ W ≤ 4B. The Stress Intensity Factor is calculated from equation

$$K_Q = \frac{P}{B\sqrt{W}}\left(3\frac{X}{W} + 1.9 + 1.1\frac{a}{W}\right)\left[1 + 0.25\left(1 - \frac{a}{W}\right)^2\left(1 - \frac{r_1}{r_2}\right)\right] f\left(\frac{a}{W}\right) \quad (3.1)$$

$$\text{Where, } f\left(\frac{a}{W}\right) = \frac{\sqrt{\frac{a}{W}}}{\left(1-\frac{a}{W}\right)^{3/2}}\left[3.74 - -6.30\frac{a}{W} + 6.32\left(\frac{a}{W}\right)^2 - 2.43\left(\frac{a}{W}\right)^3\right] \quad (3.2)$$

IV. EXPERIMENT TABLE

Material	Specimen	P_Q (kN)	B (cm)	W (cm)	X (cm)	a (cm)	r_1 (cm)	r_2 (cm)	K_{1c} ($MPam^{1/2}$)	K_{1C} (avg) ($MPam^{1/2}$)
IS 2062	12 mm - 1	22.02	1.2	2.4	1.2	1.2	2.4	4.8	179.97	178.99
	2	21.78	1.2	2.4	1.2	1.2	2.4	4.8	178	
IS 2062	16 mm -1	26.76	1.6	3.2	1.6	1.6	3.2	6.4	142.06	140.26
	2	26.07	1.6	3.2	1.6	1.6	3.2	6.4	138.4	
IS 2062	18 mm-2	22.41	1.8	3.6	1.8	1.8	3.6	7.2	99.70	99.70
IS2062	20 mm-1	25.8	2.0	4.0	2.0	2.0	4.0	8.0	98.0	97.78
	2	25.68	2.0	4.0	2.0	2.0	4.0	8.0	97.55	
SA 516 Gr 70	12 mm-1	27.15	1.2	2.4	1.2	1.2	2.4	4.8	221.90	203.51
	2	22.65	1.2	2.4	1.2	1.2	2.4	4.8	185.12	
SA 516 Gr 70	16 mm-1	21.09	1.6	3.2	1.6	1.6	3.2	6.4	111.97	112.36
	2	21.24	1.6	3.2	1.6	1.6	3.2	6.4	112.76	
SA 516 Gr 70	18mm-1	29.52	1.8	3.6	1.8	1.8	3.6	7.2	131.32	128.59
	2	28.29	1.8	3.6	1.8	1.8	3.6	7.2	125.86	
SA 516 Gr 70	20 mm-1	64.62	2.0	4.0	2.0	2.0	4.0	8.0	245.45	227.51
	2	55.17	2.0	4.0	2.0	2.0	4.0	8.0	209.56	

V. OBSERVATIONS

This review presents the views, experimental results obtained and conclusions made in the field of fracture failure. After performing experiment, that the stress intensity factor has been calculated for different material (IS 2062 and SA 516 Gr 70) for different thickness (12mm, 16mm, 18mm and 20mm) specimens and find that if material thickness is increases then stress intensity factor (fracture toughness) is reduces excepts in case of material SA 516 Gr 70 for thickness of 18 mm and 20 mm.

Stress intensity factor of IS 2062 material for 12 mm thickness specimen is 178.99 $MPam^{1/2}$. This defines that material sustain stress upto 178.99 $MPam^{1/2}$. After increasing stress crack will be propagated.

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