Estimation of Crack Growth Properties of High Strength Metallic Materials by a Novel Technique

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***Abstract*-This research work proposes a novel technique based on fracture mechanics approach for the quick determination of fatigue crack growth rate and threshold stress intensity factor range (ΔK_{th}) of metallic materials using circumferentially cracked round bar (CCRB) specimen geometry. The literature survey indicates that the fatigue crack growth rate data generated using ASTM E-647 standard test specimens were strongly dependent on specimen size and its configuration. Also the standard test procedure is more cumbersome and time consuming requires costly instrumentation. Aluminum 2014T6 alloy is used as the test specimen because of its wide application in automobiles and aero plane industry. It is found that the test procedure is simple, reliable, less time consuming and uses simple instrumentation. The obtained fatigue crack growth rate is found to be very close to the values obtained by using standard specimens. This methodology can be widely applied in industries for rapid determination of ΔK_{th} any metallic materials.**

Keywords: Fracture mechanics, Stress intensity factor, Fatigue crack growth, Compact tension C(T)specimen.

I. INTRODUCTION

Structural components should be designed to prevent the fatigue failure which needs fracture mechanics parameters like fracture toughness, threshold stress intensity factor or fatigue crack growth rate etc. The geometric stress raisers like holes, fillets and notches develop very fine cracks under different loading conditions. These cracks start growing and propagate due to repeated loads and finally failure. Critical assessment of fatigue crack growth behaviour of cracks in metallic materials which are used in engineering structures is necessary. The fatigue crack growth rate is expressed in terms of average crack extension per cycle. Crack growth can take place under both static and fatigue loading. ASTM E647[1] is the standard which explains fatigue crack growth rate (da/dN) test procedure using compact tension or single edge notched bend specimens etc. Expressing da/dN as a function of stress intensity range (ΔK) provides results that are independent of planar geometry, thus enabling exchange and comparison of data obtained from a variety of specimen configurations and loading conditions. This Feature enables da/dN versus ΔK data to be utilized in the design and evaluation of engineering structures. ASTM E1681(2008) e1 is standard test method for determining a threshold stress intensity factor for environment-assisted cracking of metallic materials. Several modifications and adaptations of LEFM have been reported as an attempt to predict the fatigue behaviour of short fatigue cracks [2], [3]. The fatigue crack growth rate curve is used as a material property because fracture mechanics theory is fundamentally based on the assumption that the relationship between (da/dN) and ΔK is independent of geometric configuration, termed similitude. Jingu.T and K. Nezu[4] proposed different crack growth models using a round bar specimen with a V-notch with circular shaped crack front across the bar. One among these is a ring shaped crack model creating a circular periphery at the notch bottom, and then propagating towards the center of the fracture section. Laiarinandrasana.L et al.[5] conducted creep crack growth test using different specimen geometries including CCRB, and found no any effect of specimen geometry over a large temperature range on the nature of master curve da/dt versus C* for a given crack depth. Based on constant amplitude fatigue data and mean crack growth rates, predictions of variable amplitude fatigue crack growth using notched tensile specimens were done [6]. Murthy.A.R.C et al.[7] suggested that the fatigue crack growth models need to be more generalized in order to use them for the realistic loading situations straightaway. Hiroshi Tada et al.[8] proposed various equations for determination of SIF for number of specimen configurations in different loading conditions. The K_{IC} value obtained using CNT specimen is very close to the K_{ISCC} values obtained by centre cracked (CC), surface flaw (SF), and cantilever bend(CB) standard specimens, which indicates that the CNT specimen can provide K_{ISCC} data similar to the other standard specimens[9].The strong dependence of the crack growth rate on specimen width, thickness and environment makes C(T)specimen a poor choice for developing standard material response data. But the standard procedure is more cumbersome and time consuming. Industry requires a simple straightaway approach to investigate the failed members. The present work explains a new methodology for the rapid determination of fatigue crack growth rate of metallic materials.

A. Determination of Stress Intensity Factor

The equation for determination of SIF for a CCRB specimen in bending [8].

$$K_I = \sigma_N \sqrt{\pi r}\, F_1(r/R) \qquad (1)$$

where $\sigma_N = 4M / \pi r^3$

$$F_1(r/R) = G(r/R)\,[\sqrt{1-(r/R)}]$$

$G(r/R) =$

$$(3/8)[1+0.5(r/R)+(3/8)(r/R)^2+(5/16)(r/R)^3+(35/128)(r/R)^4+(0.531)(r/R)^5]$$

B. Estimation of Fatigue Crack Growth Rate (da/dN)

Based on constant amplitude fatigue data and mean crack growth rates, predictions of variable amplitude fatigue crack growth using notched tensile specimens were done. Lijustell.P and F.Nilsson [6] determined the crack growth rates by following equations.

$$\{\Delta a_{i,\,mean} / \Delta N\} = (a_{i+1} - a_i / N_{i+1} - N_i) \qquad (2)$$

where $\Delta a_{i,\,mean} = (a_{i+1} + a_i) / 2$

$\{\Delta a_{i,\,+1} / \Delta N\} = (\delta/\delta N)\mathrm{Lsqfit}\,(a_{i,+2}, a_{i,\,+1}, N_{i,\,+2}, N_{i,\,+1})$ where

a = crack length; N= No. of cycles; i= Iteration number

Crack growth rate is usually determined by measuring the length of the longest crack and then dividing this length by the time of the test. This approach is rather simplistic since it assumes that the cracks initiate at the start of the test, including the longest crack. The crack growth rate increases linearly with increasing K_I.

II. EXPERIMENTAL WORK

A. Material

Extruded rods of Al 2014-T6, an aluminum alloy were used for the present investigation as a test material. Al2014 is an Al-Cu alloy available in a wide variety of product forms. The chemical composition of the material is reported in Table 1. This material is suitable for high strength performance in various lightweight mechanical members such as in aerospace vehicles. For applications requiring high strength and hardness even at elevated temperatures, Al 2014-T6 is used.

TABLE I
CHEMICAL COMPOSITION OF MATERIAL AL 2014T6 (WT.%)

Cu	Fe	Mn	Si	Mg	Others	Al
4.15	0.9	0.84	0.82	0.43	0.45	Balance

Helicopters have critical structural requirements for rotor blades. Alloys 2014-T6, 2024-T3 and 6061-T6 in extruded or drawn hollow shapes are utilized extensively for the main spar member. In transport aircrafts for wing tension members, shear webs and ribs, alloys 2014-T6, 2024-T4 and 7075-T6 are used extensively. For these applications, fatigue performance and fatigue toughness, combined with high strength are the alloy characteristics of chief concern. Alloys of 2014-T6 are employed for forged products located in heat-affected areas in supersonic aircrafts.

Radhakrishnan V.M[10] has collected a number of data from various and proposed the following least square fit relationships (ΔK being MPa√m and da/dN in m/cycle).

$$\log C = \log(2.5\times10^{-6}) + m\log(4.26\times10^{-2}) \qquad (3)$$

for Aluminum alloys.where *C* and *m* are Pari's Law parameters in Eqn. $da/dN = C(\Delta K)^m$

B. Specimen preparation

The round bar specimens of test material were prepared by machining in ordinary lathe. A 60^0 V- groove has been cut to a radial depth of 1mm circumferentially at the centre of the cylindrical bar of radius *r*. A good surface finish is given on the specimen surface as well at the notch. Multiple round bar specimens were prepared with dimensions as shown in Fig.1.

Max dia. D =12mm, Dia. at notch d =10mm,
L = 238mm V notch angle $\alpha = 60^0$,
Mean notch root radius $\rho = 0.18$mm

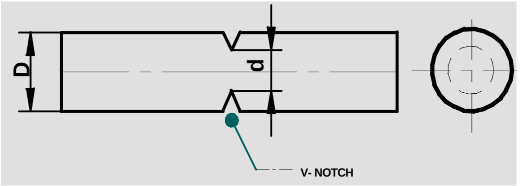

Fig.1. Schematic of V- notched round bar specimen

C. Method

In the present work the estimation of fatigue crack growth rate is done by a simple technique. A CCRB specimen of above said dimensions was fatigued till failure under a pre set fatigue load in a rotating bending fatigue testing machine for at R equal to-1. The number of cycles to failure (N) was noted and the experiment was repeated for different bending moments and the readings were tabulated as shown in Table 2.

III. RESULTS AND DISCUSSION

Three prominent regions can be seen on the fractured surface of the test specimen. The outermost being the machined surface, innermost surface, and the middle surface generated due to stable propagation of fatigue crack front. The inner surface will not be an exact circular one, but will be near circular with irregular circumference generated during final fracture as shown in Fig.2. Also the inner ligament will not be a concentric one. The stable fatigue crack propagation will generate a relatively smoother flat surface.

Fig.2. Cross sectional view of a fatigue failed CCRB specimen

During the test, only after few cycles of rotation a fine circumferential crack gets generated at the V-notch root which depends on the material property. The crack starts propagating radially inwards. As the crack front propagates the cross section area of ligament decreases gradually. This ligament cross section will not be a circular one but with slightly deformed boundaries. Usually this ligament cross section will be eccentric with reference to the axis of the CCRB specimen. The radius ***r*** of CCRB at the V-notch root after machining to an average crack depth of 1mm would be *(r-1)* mm.

As explained in ASTM E-647, the minimum initial fatigue crack length should be at least 1mm by precracking. In a CCRB specimen under fatigue loading, when the ligament diameter is about 8 mm, we can consider that as a precracked specimen with 1 mm fatigue crack length. From literature it is understood that the crack initiation takes more time which belongs to the region-I of the sigmoidal curve (da/dN versus ΔK plot) for any metallic material. Once the crack gets generated, stable crack propagation (region-II) starts and the crack growth rate increases gradually. In the regime III the crack growth rate would be very high leading to sudden unstable fracture failure. It is observed that when the radius of ligament is about 2.5 mm, this sudden fracture occurs because of rapid increase of stress intensity factor.The specimen ligament of radius (*r*) at the V-notch root reduces to zero when specimen fails. Stress intensity factors at a radius of (r-*1*) and at *2.5* mm were being maximum value and minimum values were calculated for each bending moment using the Eq(1) and tabulated as shown in Table 2. A plot of da/dN versus ΔK was drawn as shown in Fig.3 below. From this plot the threshold SIF range of the test material can be determined at 10^{-8} range of da/dN. For Al 2014T6 this value found out to be ΔK_{th} = 4.12MPa√m from the plot Fig.3.

TABLE 2
THE STRESS INTENSITY FACTOR AT THE NOTCH ROOT FOR DIFFERENT FATIGUE CRACK LENGTHS (a_f) UNDER VARIOUS FATIGUE BENDING MOMENT (M) VALUES

1	2	3	4	5	6	7
S. No	**Bending Moment M Nm**	**da/dN mm/cycle**	**N_f Cycles**	**K_I at r = 4mm**	**K_I at r =2.5mm**	**ΔK Col.6-Col.5**
1	19.62	4.03E-07	6205	29.33	54.14	24.81
2	17.17	2.54E-07	9837	25.67	47.38	21.71
3	16.19	2.27E-07	10996	24.20	44.67	20.47
4	14.72	2.09E-07	11954	22.01	40.62	18.61
5	14.23	1.97E-07	12715	21.27	39.27	18.00
6	13.24	1.84E-07	13560	19.79	36.53	16.74
7	12.75	1.69E-07	14784	19.07	35.18	16.11
8	12.26	1.63E-07	15320	18.33	33.83	15.50
9	11.77	1.48E-07	16855	17.60	32.48	14.88
10	10.79	1.41E-07	17727	16.13	29.77	13.64
11	9.81	1.16E-07	21578	14.67	27.07	12.40
12	8.83	8.10E-08	31011	13.20	24.37	11.17
13	7.36	5.10E-08	49100	11.00	20.31	9.31
14	5.89	4.10E-08	61685	8.81	16.25	7.44
15	4.91	1.40E-08	185434	7.34	13.55	6.21

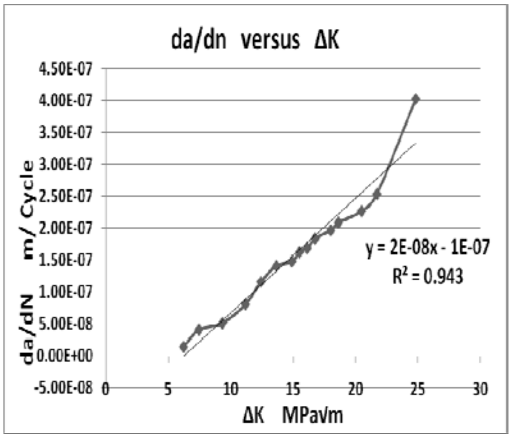

Fig.3. Fatigue crack growth rate curve for Al2014 T6 at R= -1

IV CONCLUSION

The following conclusions were done on the basis of this research work.

- Rapid estimation of fatigue crack growth rate and threshold stress intensity factor range ΔK_{th} is possible using CCRB specimens and hence can be readily adapted by industries for any high strength metallic materials.
- The test procedure supports use of CCRB type specimens in FCGR tests and the resulting values are not dependent on the specimen size or its configuration as in standard test method.
- Less instrumentation required for the test and cost of the test is relatively less.
- The test method results are within the valid range of values as obtained by standard methodologies.

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