Determination of Fracture Toughness in Tensile Fracture and Fatigue Fracture of Steels

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Abstract: *Steels are the common high strength metallic materials used in various engineering applications. The mechanical components in service have to bear severe stresses. This paper focuses on the study of behavior of steels under tensile fracture and fatigue fracture. Centre notched cylindrical specimens of EN8 and EN31 are used. The fracture toughness and crack growth rate of these materials are determined. It is observed that the fracture toughness determined in tensile load (mode-I) and fatigue bending load (mixed mode) were in close range. The stress intensity factor range in fatigue test resembles with the fracture toughness values of the test material. The obtained crack growth rates are found to be in a comparable range of values. The scanning electron micrographs (SEM) are also analyzed and support this conclusion.*

Keywords: *Fatigue, Fracture toughness, Crack growth rate, Fractography, Mixed mode of fracture.*

1. Introduction

Fracture mechanics is the branch of solid mechanics. It explains the mechanical behaviour of bodies having cracks under different loading conditions. Varieties of steels are used in mechanical engineering applications. The mechanical members used in severe loading conditions have to bear the stresses. If the structural member contains a crack, then the component becomes weak and cannot be used upto its design life. There are different reasons for fracture failures. Fracture may occur due to tensile loads or fatigue loads. The studies of fracture properties in these both types of fracture failures are important to understand the material behaviour. This may be useful for selection of suitable materials for suitable applications in machine design [1]. Number of comparative studies of the various fracture toughness test methods and estimation procedures have been carried out in the literature.[5-8]. Circumferentially cracked cylindrical bar specimens are used to find the fracture toughness and crack growth rate by various researchers [7-11].

1.1. Materials: Alloys of Steel

Medium carbon steels find applications in the manufacturing of gears, axles, shafts, fasteners and other similar components [14]. The extensively used steels such as EN8 and EN31 which are available commercially are used. EN8 (BS970080M40) is a low carbon unalloyed steel. EN8 steel has superior tensile properties is suitable for stressed pins, shafts and keys etc. The silver steel or EN31 (BS1407) is a high carbon alloy steel which achieves a high degree of hardness [12]. The chemical composition of steels used for the tests are shown in the following Table I.

TABLE I: The Chemical Composition of Steel Alloys (Wt. %)

Alloy	C	Mn	Cr	Si	S	P	Ni	Mo	Balance
EN8	0.41	0.50	13.5	0.35	0.03	0.01	0.10	0.005	Fe
EN31	1.00	0.31	1.71	0.28	0.003	0.013	0.21	0.01	Fe

2. Experimentation

2.1. Hardness

Hardness is an important mechanical property. Fracture properties of a material are closely related to hardness of the material [2]. In the present investigation, experimentally determined Vickers hardness of each test material and the tensile properties are tabulated as shown in the following Table II.

TABLE II: Hardness and Tensile Properties of Test Materials Determined at Room Temperature

S.No.	Material	Vickers Hardness Number (VHN)	Yield Strength σ_{ys} (MPa)	UTS σ_{UTS} (MPa)	% Elongation
1	EN8	132	537	721	13.62
2	EN31	146	512	717	15.25

2.2. Specimen preparation

The notched round bar with a V-groove of 60º has been cut to a radial depth of 1mm circumferentially at the center of the cylindrical bar [8-10]. The specimen is machined to have good surface finish. The notch root radius is machined to a close tolerance limit of ±0.01 mm with a mean notch root radius ρ about 0.2 mm.

2.3. Pre-cracking

Precracking of the specimen at the root of V-notch is achieved using R. R. Moore rotating bending fatigue testing machine. The precracking is done at a suitable bending load such that the maximum stress intensity factor (K_{max}) should not exceed 60% of minimum expected fracture toughness K_{IC} of the test material during precracking.[3,4] Cyclic tensile-compressive load of equal amplitude is applied and the stress ratio being R equal to minus one($R= -1$). During precracking, the crack is allowed to grow only up to a finite radial length by subjecting the specimen to undergo definite number of fatigue cycles at that initial load. Annular precrack around the V-notch root is developed circumferentially. The following equation is used to determine the stress intensity factor (K_I) at the notch root of the specimen in fatigue bending [14].

$$K_I = \sigma_N \sqrt{\pi a F_1\left(\frac{r}{R}\right)} \tag{1}$$

$$\sigma_N = \frac{4M}{\pi r^3}$$

$$F_1\left(\frac{r}{R}\right) = G\left(\frac{r}{R}\right)\left(\sqrt{1-\frac{r}{R}}\right)$$

$$G\left(\frac{r}{R}\right) = \left(\frac{3}{8}\right)\left[1 + 0.5\left(\frac{r}{R}\right) + \left(\frac{3}{8}\right)\left(\frac{r}{R}\right)^2 + \left(\frac{5}{16}\right)\left(\frac{r}{R}\right)^3 + \left(\frac{35}{128}\right)\left(\frac{r}{R}\right)^4 + (0.531)\left(\frac{r}{R}\right)^5\right]$$

Where M is the bending moment applied in fatigue, r is the radius at the notch root, R being the radius of round bar.

2.4. Notch Tensile Test

The specimen is loaded monotonically in tension on a 400 kN Universal testing machine with a crosshead displacement rate of 0.5 mm/min until failure. The displacement is measured using two extensometers and average value is calculated. The applied load acts in a direction perpendicular to the crack plane at the V-notch root. It is nothing but opening mode or Mode-I loading. A minimum of four specimens of the material are tested for fracture toughness. The maximum loads for all the specimens are tabulated.

2.5. Fracture Toughness Calculations From Notch Tensile Test

The precracked specimen breaks at the root of V-notch when the stress intensity factor reaches critical value. The fracture toughness can be determined using equation for stress intensity factor under mode-I loading [1, 7, 10, and 14]. Knowing the maximum load P and the crack length, the fracture toughness (K_{IC}) can be calculated as,

$$\mathrm{K_{IC}} = \left\{\frac{\mathrm{P}}{(\mathrm{D})^{3/2}}\right\} \left[1.72\left(\frac{\mathrm{D}}{\mathrm{d_{eff}}}\right) - 1.27\right] \tag{2}$$

The valid range for the use of above equation is $0.46 < (d_{eff}/D) < 0.86$ where d_{eff} is the effective ligament diameter and D is the diameter of round bar. The average of experimental fracture toughness value of the given test material is calculated. Fracture toughness of each specimen is calculated using (2) and results are tabulated as shown in following Table III and Table IV.

TABLE III Fracture Toughness (K_{IC}) Test Material: EN8

S. No.	Length of precrack a_f(mm)	Bending moment during pre-cracking (N-m)	Crack length a (mm)	Avg.Effective Ligament diameter d_{eff} (mm)	d_{eff}/D	Max. Load (kN)	Load at failure (kN)	Fracture Toughness K_{IC} (MPa√m)
1	0.40	9.81	2.80	9.20	0.767	58.00	52.50	42.91
2	0.50	9.81	3.00	9.00	0.751	59.00	52.50	45.79
3	0.70	9.81	3.40	8.60	0.717	54.00	52.75	46.37
4	1.10	9.81	4.20	7.80	0.650	49.25	48.75	51.56
					Average value of K_{IC} = **46.66** MPa√m			

TABLE IV Fracture Toughness (K_{IC})Test Material: EN31

S. No.	Length of precrack a_f(mm)	Bending moment during pre-cracking (N-m)	Crack length a (mm)	Avg. Effective Ligament diameter d_{eff} (mm)	d_{eff}/D	Max. Load (kN)	Load at failure (kN)	Fracture Toughness K_{IC} (MPa√m)
1	0.16	14.72	2.30	9.70	0.808	63.00	62.50	41.15
2	0.27	14.72	2.50	9.50	0.792	54.50	53.50	37.38
3	0.53	14.72	3.00	9.00	0.750	48.00	47.00	37.37
4	0.64	14.72	3.30	8.70	0.725	47.00	46.50	39.41
					Average Value of K_{IC} = **38.83** MPa√m			

2.6. Fatigue Crack Growth Test

On a standard R.R.Moore rotating bending fatigue testing machine, the precracked specimen is mounted and allowed to rotate under suitable bending load till failure and number of fatigue cycles (N_f) are tabulated. The radial crack at the notch root propagate radially inward towards its centre. The mean crack lengths and diameter of final ligament at the time of fracture in the cracked surfaces are measured under optical microscope. The ratio of crack length to the number of cycles to failure is calculated. This value of (da/dN) is the fatigue crack growth rate. The ratio of average steady crack length (a_f) to the number of cycles to failure (N_f) in fatigue of the precracked specimen is the crack growth rate.

$$\frac{da}{dN} = \frac{a_f}{N_f} \qquad (m/cycle) \tag{3}$$

K_{min} is the minimum stress intensity factor at the beginning of fatigue loading whereas the K_{max} is the maximum stress intensity factor at fracture. The difference of stress intensity factors gives the range of stress intensity factor ΔK. The crack growth rate of EN8 and EN31 steel are determined using five similar specimens of each type of steel. The calculated values of ΔK and (da/dN) based on the experimental results are tabulated as shown in Table V.

Table V : Fatigue Crack Growth Test R= **-1**

Material	K_{min} (MPa√m)	K_{max} (MPa√m)	Average of SIF range ΔK (MPa√m)	Average value of crack growth rate da/dN (m/cycle)
EN8	6.553	55.81	**49.26**	0.862E-07
EN31	7.806	47.046	**39.24**	0.216E-07

3. Results and Discussions

The test results are summarized and reported in the Table VI.

TABLE VI: Summary of Test Results

1	2	3	4	5	6	7	8
Material	VHN	Yield Strength MPa	UTS MPa	% Elongation	Fracture Toughness by Tensile Fracture (MPa√m)	Fracture Toughness by Fatigue Fracture (MPa√m)	Average value of crack growth rate da/dN (m/cycle)
EN8	132	537	721	13.62	**46.66**	**49.26**	0.862E-07
EN31	146	512	717	15.25	**38.83**	**39.24**	0.216E-07

It is observed that EN8 steel is stronger and less ductile than EN31 from its tensile properties. The unstable fracture occurs when the SIF at the crack tip reaches a critical value which is called as fracture toughness K_{IC}. Column 7 is the fracture toughness in mixed mode fracture. It is because in fatigue bending load at the V-notch root, the crack experiences opening (mode-I) due to bending load and also tears due to rotation (mode–III) once the radial crack propagates half the way. It can be seen that the values of fracture toughness (K_{IC})values obtained from tensile test(column 6) of Table 6 and SIF range(ΔK) obtained through fatigue fracture(column 7) of Table 6 are in a comparable range. The crack growth rate in tougher material is less than that in brittle material. It is true by the results obtained as seen in column 8.

3.1. Micrographs

A. Material: EN8 steel: The overall cross sectional views and SEM pictures of fractured surfaces of the specimen in tensile fracture and fatigue fracture are shown in Fig.1 and Fig.2 respectively where; a) The microstructure of precracked surface b) Surface due steady crack growth c) Surface of sudden fracture.

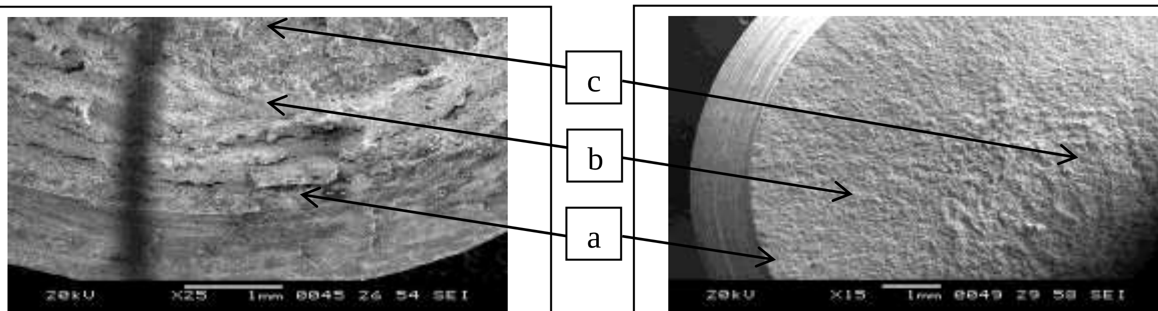

Fig.1.SEM views of Tensile Fractured Surface of EN8

Fig.2.SEM views of Fatigue Fractured surface of EN8

B. Material: Silver Steel (EN31): The overall cross sectional views and SEM pictures of fractured surfaces of the specimen for tensile fracture and fatigue fracture are shown in Fig.3 and Fig.4 respectively, where; a) The microstructure of precracked surface b) Surface due steady crack growth and c) Surface of sudden fracture.

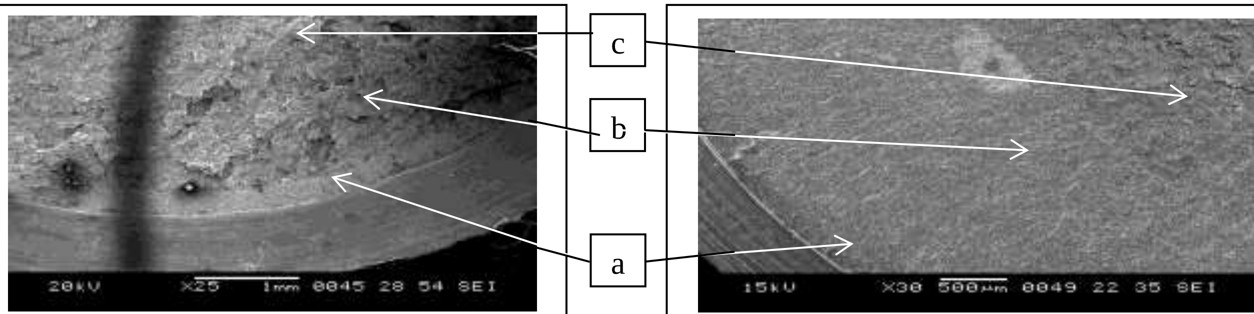

Fig.3.SEM views of Tensile Fractured Surface of EN31

Fig.4.SEM views of Fatigue Fractured Surface of EN31

3.2. SEM analysis

Microstructures influence the fracture properties of materials. The fine grained structure improves fracture toughness [15, 16]. Unstable fracture at the end produces a different surface morphology. Fractographs at higher magnification revealed features of locally ductile and brittle mechanisms. In the circumferential zone a shear mode fracture is seen. But at the centre, a fibrous region due to final unstable sudden fracture is observed. The overall sectional views of fatigue fractured surface show smooth surface finish. Bright regions are observed where the structure is different from the surrounding phase. The SEM study of the fatigue fractured surface reveals the presence of micro cracks with inclusions which is an important root for the stress concentrations. More striation like features were seen in region (b) may be because of lower crack growth rate during steady crack propagation.

4. Conclusions

Notch tensile test of round bar specimens is conducted to get the fracture toughness (K_{IC}) in tensile fracture. The experimentally obtained fracture toughness values are within the comparable range of K_{IC} values of low and medium carbon steels. The values of stress intensity factor range (ΔK) determined through fatigue tests resemble with the fracture toughness values obtained in notch tensile test. This is true for both the tested materials EN8 and EN31 steel alloys. The SEM of tensile fractured and fatigue fractured surfaces also resembles closely in the three regions namely, a). in precracked regions, b). in steady crack growth region and c). in sudden fracture region. The fatigue fractured surfaces are smoother than the tensile fractured surfaces.

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6. References

[1] John M. Barsom and Stanley T. Rolfe, *Fracture and Fatigue Control in Structures, Applications of Fracture Mechanics*, Inc, Englewood Cliffs, New Jersey 07632, Prentice Hall, 2nd Edition, 1987, ch.3-8, pp. 64-274.

[2] *Fracture Toughness Values For Al and Steel Alloys, Design for Fracture Toughness, Material Selection and Design*, ASM Handbook, vol. 20, 1997, pp. 537-538.

[3] *Standard Test Method for Measurement of Fatigue Crack Growth Rates,* Annual Book for ASTM Standards, American Society for Testing and Materials, ASM International, West Conshohochen, PA, Vol 3(01), 2001 ASTM-E647-01.

[4] *ASTM Testing and Evaluation*, 10th edition, ASM Handbook, ASM International, vol. 8, 2000, pp. 1270-1283.

[5] Susil. K. Putatunda, "A Comparison of Various Fracture Toughness Testing Methods", *Engineering Fracture Mechanics*, vol 25(4), pp. 429-439, 1986.
http://dx.doi.org/10.1016/0013-7944(86)90257-2

[6] K. K. Ray and G. P. Poddar, "Estimation of Fracture Toughness of Steel Using Chevron Notched Round Bar Specimens", *Fatigue Fracture Material structure,* Blackwell Publishing Ltd, vol. 27, pp. 253-261, 2004.

[7] R. N. Ibrahim and H. L. Stark, "Validity Requirements for Fracture Toughness Measurements Obtained From Small Circumferentially Notched Cylindrical Specimens", *Engineering Fracture Mechanics*, vol. 28(4), pp. 465-460, 1987.

http://dx.doi.org/10.1016/0013-7944(87)90190-1

[8] D. M. Li, A. Bakker, "Fracture Toughness Evaluation Using Circumferentially Cracked Cylindrical Bar Specimens", *Engineering Fracture Mechanics*, vo.l 57(1), pp. 1-11, 1997.

[9] K. Hojo, I. Muroya, A. Bru¨ckner - Foit, "Fracture Toughness Transition Curve Estimation From a Notched Round Bar Specimen Using The Local Approach Method", Japan, *Nuclear Engineering and Design*, vol. 174, pp. 247–258, 1997.

http://dx.doi.org/10.1016/S0029-5493(97)00125-8

[10] M. Scibetta, R. Chaoudi and E. Van Walle," Fracture Toughness Analysis of Circumferentially- Cracked Round Bars", *International Journal of Fracture*, vol. 104, pp. 145-168, 2000.

http://dx.doi.org/10.1023/A:1007625612644

[11] T. Nakamura, C. F. Shih and L. B. Freund, "Elastic-Plastic Analysis of A Dynamically Loaded Circumferentially Notched Round Bar ", *Engineering Fracture Mechanics*, vol. 22(3), , pp. 437-452, 1985.

http://dx.doi.org/10.1016/0013-7944(85)90144-4

[12] *The Atlas specialty metals*- Technical handbook of bar metals, 2005.

[13] B. Farahmand and K. Nickbin, "Predicting Fracture and Fatigue Crack Growth Properties using Tensile Properties", *Engineering Fracture Mechanics*, vo.l 75, pp. 2144-2155,2008.

http://dx.doi.org/10.1016/j.engfracmech.2007.10.012

[14] Hiroshi Tada, Paul. C. Paris and George. R. Irwin, *The Stress Analysis of Cracks Handbook, Three Dimensional Cracked Configuration*, American Society of Mechanical Engineers, New York, Professional Engineering Publishing, 3rd Edition, 2003.

[15] S.K.Nath and Uttam Kr Das, " Effect of Microstructure And Notches on The Fracture Toughness of Medium Carbon Steel", *Journal of Naval Architecture and Marine Engineering*, vol. 3, pp. 15-22, 2006.

[16] Vojteh Leskovsek, Boris Ule, Bozidar Liscic, The Influence of Microstructure on Fracture Toughness of Vacuum Heat Treated HSS AISI M2, *Materiali in tehnologije*, vo.l 35(5), pp. 211-217, 2001.