FRACTURE TOUGHNESS PREDICTION OF BRITTLE & DUCTILE MATERIALS

Dr.B.Balakrishna[1], S.Hari krishna[2]

[1]*Associate professor, Department of mechanical engineering, University College of engineering, JNTU Kakinada, A.P, INDIA.*
[2]*PG student, Department of mechanical engineering, University College of engineering, JNTU Kakinada, A.P, INDIA.*

Abstract

The mechanisms of fatigue-crack propagation are examined with particular emphasis on the similarities and differences between cyclic crack growth in ductile materials, such as metals, and corresponding behavior in brittle materials, such as ceramics. Which promote crack growth, and mechanisms of crack-tip shielding behind the tip (e.g., crack closure), which impede it. Brittle & ductile materials fail in a time-dependent manner in service and how to estimate the lifetimes that can be expected for such materials. In addition, we describe procedures to evaluate the confidence with which these lifetime predictions can be applied. The widely differing nature of these mechanisms in ductile and brittle materials and their specific dependence upon the alternating and maximum driving forces (e.g., ΔK and Kmax) provide a useful distinction of the process of fatigue-crack propagation in different classes of materials; moreover, it provides a rationalization for the effect of such factors as load ratio and crack size.Major aspect of the failure is stress intensty factor calculted and next which the Residual stress is calcuated to the ductile and brittle,And finally calculates the life prediction for the ductile and brittle materials and Results to be compared ,Good agrement to the materials.

Keywords— *Brittle and Ductile materials, Stress intensity factor, Residual stregth, Fracture toughness**,** Fracture mechanics, Life prediction*.

1. Introduction

Techniques to determine reliability of components fabricated from brittle materials (e.g., ceramics and glasses) have been extensively developed over the last 30 years.[1–7] Reliability is generally defined as the *probability* that a component, or system, will perform its intended function for a specified *period of time*.[8] Accordingly, the two overarching principles influencing reliability are the statistical nature of component strength and its time-dependent, environmentally en- hanced degradation under stress. The statistical aspect of strength derives from the distribution of the most severe defects in the components (i.e., the strengthdetermining flaws).[9–15] The time-dependent aspect of strength results from the growth of defects under stress and environment, resulting in time-dependent component failure.[16–19]. These concepts have lead to a lifetime prediction formalism that incorporates strength and crack growth as a function of stress. Predicted reliability, or lifetime, is only meaningful, however, when coupled with a confidence estimate. Therefore, the final step in the lifetime prediction process must be a statistical analysis of the experimental results.[2, 20–22].

1. General Considerations

The most basic assumption made in this is that the material whose lifetime is of interest is truly brittle; that means there are no energy dissipation Mechanisms (e.g., plastic deformation, internal friction, phase transformations, creep) other than rupture occurring during mechanical failure. It has been well documented that brittle materials fail from flaws that locally amplify the magnitude of stresses to which the material is subjected.[9, 10,14,15,23] These flaws, e.g., scratches, pores, pits, inclusions, or cracks, result from processing, handling, and use conditions.

For a given applied or residual stress, the initial flaw distribution determines whether the material will survive application of the stress or will immediately fail. Similarly, the evolution of the flaw population with time determines how long the surviving material will remain intact.

1.1 Strength:

Because the flaw population under stress defines the initial strength of a brittle material, it is necessary to characterize this distribution or, equivalently, the Distribution of initial strengths.

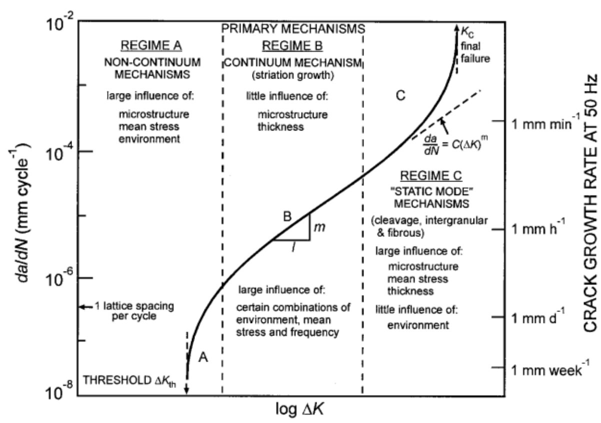
2. FUNDAMENTALS OF FRACTURE:

Simple fracture is the separation of a body into two or more pieces in response to an imposed stress that is static (i.e., constant or slowly changing with time) and at temperatures that are low relative to the melting temperature of the material. The applied stress may be tensile, compressive, shear, or torsional; the present discussionwill be confined to fractures that result from uniaxial tensile loads. For engineering materials, two fracture modes are possible: **ductile** and **brittle.** Classification is based on the ability of a material to experience plastic deformation. Ductile materials typically exhibit substantial plastic deformation with high energy absorption before fracture. On the other hand, there is normally little or no plastic deformation with low energy absorption accompanying a brittle fracture. ‘‘Ductile’’ and ‘‘brittle’’ are relative terms; whether a particular fracture is one mode or the other depends on the situation. Ductility may be quantified in terms of percent elongation and percent reduction in area . Furthermore, ductility is a function of temperature of the material, the strain rate, and the stress state. The disposition of normally ductile materials to fail in a brittle manner

Any fracture process involves two steps—crack formation and propagation —in response to an imposed stress.

2.1 Fatigue-crack propagation in ductile metallic materials

Subcritical crack growth can occur at stress intensity K levels generally far less than the fracture toughness Kc in any metallic alloy when cyclic loading is applied. In simplified concept, it is the accumulation of damage from the cyclic plasticdeformation in the plastic zone at the crack tip that accounts for the intrinsic mechanism of fatigue crack growth at K levels below Kc. The process of fatigue failure itself consists of several distinct processes involving initial cyclic damage (cyclic hardening or softening), formation of an initial ‘fatal’ flaw (crack initiation), macroscopic propagation of this flaw (crack growth), and final catastrophic failure.



3.MATERIALS TO BE USED TO OUR WORK & MATERIAL PROPERTIES

3.1 Mechanical properties of Al_2O_3 ceramics (99.5%)

	Units	
Density	Kg/m^3	3.90
Poison’s Ratio	-	0.22
UTS	MPa	262
Young’s modulus	GPa	370
Flexural strength	Mpa	379

3.2 Mechanical properties of 1045 steel:

	Units	
Density	Kg/m^3	7.872×10^3
Poison's Ratio	-	0.29
UTS	MPa	621
Yield strength	MPa	382
Young's modulus	GPa	210
Elongation	%	16
Reduction in area	%	35

3.3 Mechanical properties of Aluminium: Material: 2024-T3 Al alloy:

	Units	
Density	Kg/m^3	
Poison's Ratio	-	0.3
Yield strength	Mpa	355
Young's modulus	GPa	71
Tensile stress	Mpa	80
Fracture toughness	Mpa	70.6

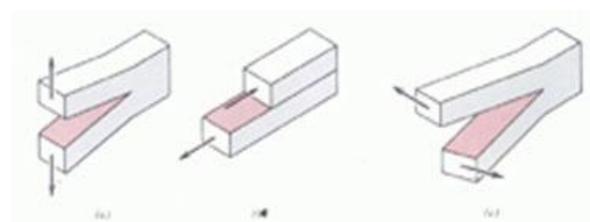
4. Stress Intensity factor:

The local stresses near a crack depend on the product of the nominal stress (σ) and the square root of the half-flaw length. The relationship is called the "stress intensity factor" (K).

Units: - $MNm^{-3/2}$ or $MPam^{1/2}$

Geometry and loading conditions influence this environment through the parameter K, which may be determined by suitable analysis. This single parameter K is related to both the stress level and crack size. The determination of stress intensity factor is a specialist task necessitating the use of a number of analytical and numerical techniques. The important point to note is that it is always possible to determine K_I to a sufficient accuracy for any given geometry or set of loading conditions.

Thus, the form of fracture of ceramic materials is fundamentally brittle, with Mode I, Mode II,Mode III. The Mode-I stress intensity factor, K_{Ic} is the most often used engineering design parameter in fracture mechanics. Typically for most materials if a crack can be seen it is very close to the critical stress state predicted by the "Stress Intensity Factor". Various modes of failures are shown in fig



Modes of crack surface displacement

5. Fracture Analysis

5.1 Description of the Model:

The rectangular bar having dimensions of length 30 mm, height 5.75mm and width 2.88 mm. The crack was poisoned at the middle of the rectangular bar and it is an edge type. The length of the crack is 1.412 mm and the width is 3.23mm.

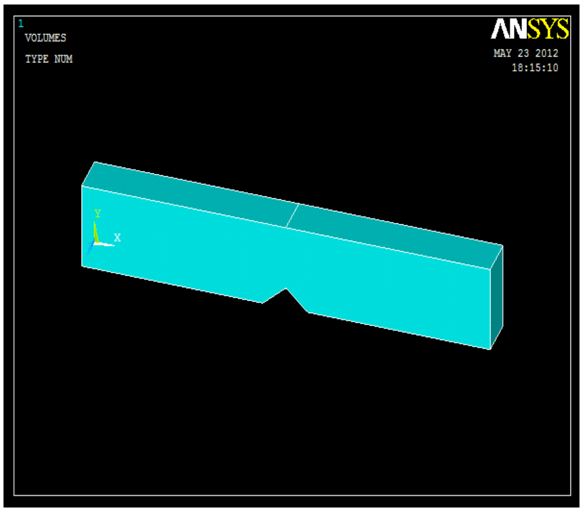


Figure 1: Shows the rectangular bar

5.2. Stress intensity factor figs

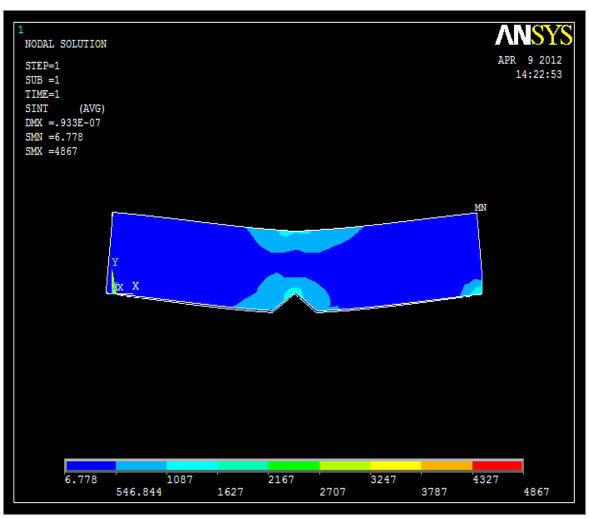


Figure 2: Nodal solution of a SEVNB specimen with a crack Length of a=1.412(CERAMICS)

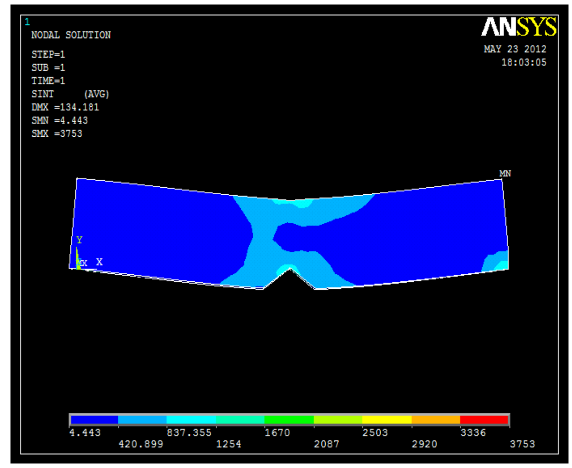
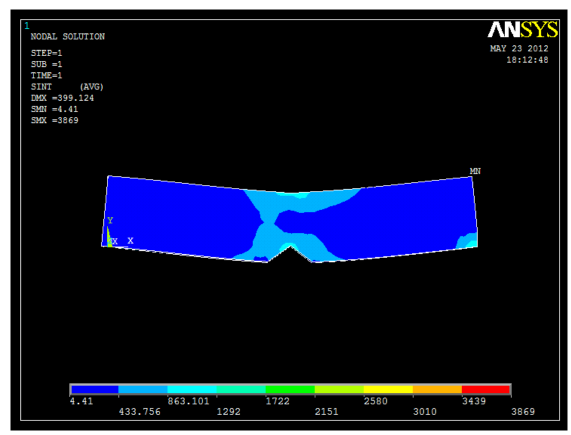


figure 3. Nodal solution of a SEVNB speimen with a Crack length of a=1.412mm(STEEL)



Figur 4.Nodal solution of a SEVNB specimen with a crack length of a= 1.412 mm (ALUMINIUM)

Stress strain characteristics for brittle mate rials are different in two ways. (1) They fail by rupturing (separation of atomic planes) at the ultimate stress (Su) without any noticeable yielding (slip phenomena) before the rupture. It can be presumed that Syp value of brittle material is greater than Su (2) Brittle materials are generally stronger in compression than in tension and consequently, for brittle materials Su in compression (Suc) is greater than Su in tension (Sut). As a result of this Suc and Sut are the limiting stresses in mechanical de sign with brittle materials

5.3 STRESS INTENSITY FACTOR FORMULAS:

For ceramics:

There are numerous expressions which make it possible to calculate the Mode I critical stress intensity factor in bending tests, starting from the test load and the geometry of the notched beam. Guinea et al. [24] proposed the use of thefollowing equation.

For Mode-I (Opening Mode) :

5.3.1 FOR CERAMICS

K_I is given for rectangular bar as follows:

$$K_I = \frac{3.P.L}{2.B.W^{\frac{3}{2}}}.\mathrm{Y}(\alpha)\text{……………………….1}$$

where: P =critical applied load =705 N, S = length of the rectangular bar, Y(α)=geometry parameter for different crack length ,

, w = the height of the beam, B = beam depth.

Where

$$\mathrm{Y}(\alpha) = \frac{\sqrt{\alpha}(1.99+\mathrm{F}(\alpha)+4\left(\frac{W}{L}\right).(-0.09+\mathrm{H}(\alpha))}{(1-\alpha)^{3/2}\,(1+3\,\alpha)}\text{................2}$$

$$\mathrm{F}(\alpha) = 0.83\alpha - 0.31\alpha^2 + 0.14\alpha^3 \text{ ....2a}$$

and

$$\mathrm{H}(\alpha) = -0.42\alpha + 0.82\,\alpha^2 - 0.31\alpha^3\text{.....................2b}$$

5.3.2 FOR STEEL :

For Mode-I (Opening Mode)

K_I is given for rectangular bar as follows:

$$K_I = \frac{P.\ S.}{B\ w^{\frac{3}{2}}} f\left(\frac{a}{w}\right)$$

where: P =critical applied load =705,
S = length of the rectangular bar
$f\left(\frac{a}{w}\right)$=geometry parameter, l= for different crack lengths, w = the height of the beam, B = beam depth,

for different crack lengths, w = the height of the beam, B = beamdepth Where

$$f\left(\frac{a}{w}\right) = \frac{3.\left(\frac{a}{w}\right).\left[1.99-\frac{a}{w}.\left(1-\frac{a}{w}\right).(2.15-3.93.\frac{a}{w}+2.7.\frac{a^2}{w^2})\right]}{2.\left(1+2.\frac{a}{w}\right).(1-\frac{a}{w})^{3/2}}$$

5.3.3 FOR ALUMINIUM:

For Mode-I (Opening Mode)

K_I is given for rectangular bar as follows:

$$K_I = \frac{P}{B\sqrt{W}} f\ \alpha$$

$$f\ \alpha = \frac{3\frac{S}{W}\sqrt{\alpha}}{2\ 1+2\alpha\ \ 1-\alpha^{3/2}}\left[1.99-\alpha\ 1-\alpha\ \ 2.15-3.93\ \alpha\ +2.7\ \alpha^{\ 2}\right]$$

where: P =critical applied load = 705 N, S = length of the rectangular bar, $f(\alpha)$=geometry parameter for different crack length, w = the height of the beam, B = beam depth.

5.4 STRESS INTENSITY FACTOR:

TABLE 1: for stress intensity values for 3 materials .

Crack Lengtha (mm)	Theoretical CERAMICS	Theoretical STEEL	Theoretical ALUMINIUM
1.412	717.810	360.58	728.55
1.414	717.814	361.11	727.63
1.416	717.816	361.64	726.71
1.418	720.090	362.17	725.79
1.420	720.090	362.17	725.79
1.422	722.098	363.23	723.95
1.424	723.102	363.76	723.03
1.426	724.106	364.29	722.11
1.428	725.108	364.82	721.18
1.430	726.113	365.35	720.27

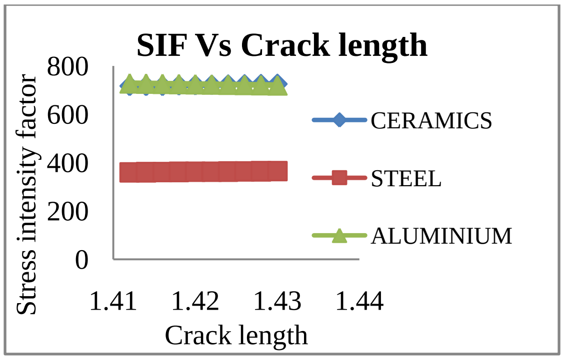


Figure 5 : shows the stress intensity values for CERAMICS, STEEL, ALUMINIUM.

5.5 Residual bending Strength:

5.5.1 for CERAMICS

Case1: Plastic collapse condition.

$$\sigma_b = \frac{3.P.l}{2.w.t^2}$$

Where σ_b= residual bending strength (Mpa), P = maximum load at specimen breakage (N), W = width of the plate (mm),t = test specimen thickness, l= various crack lengths (mm)

Case2: Fracture toughness condition

$$\sigma_{fc} = \frac{K}{\beta.\sqrt{\pi.a}}$$

Where K=370MPa√m ,β=geometry factor

$$\beta = (1 - 0.025.\alpha^2 + 0.06.\alpha^4).\sqrt{\sec\frac{\alpha\pi}{2}}$$

5.5.2 FOR STEEL:

Case1: Plastic collapse condition

$$\sigma_{fc} = \frac{(w-a)}{w}.\pi$$

Where σ_{fc}= residual strength, w= width of the plate, a= crack length,σ_y= stress 350 N/mm^2 for steel (assumed)

caseII: Fracture toughness condition

$$\sigma_{fc} = \frac{K}{\beta.\sqrt{\pi.a}}$$

$$\beta = (1 - 0.025.\alpha^2 + 0.06.\alpha^4).\sqrt{\sec\frac{\alpha\pi}{2}}$$

Where K=300 MPa√m , β=geometry factor.

5.5.3 FOR ALUMINIUM:

Case1: Plastic collapse condition

$$\sigma_{fc} = \frac{(w-a)}{w}.\pi$$

Where σfc= residual strength, w= width of the plate, a= crack length, σy= stress 350 N/mm2 for steel (assumed)

Case2: Fracture toughness condition

$$\sigma_{fc} = \frac{K}{\beta.\sqrt{\pi.a}}$$

Where K=280 MPa√m, β=geometry factor,

$$\beta = (1 - 0.025.\alpha^2 + 0.06.\alpha^4).\sqrt{\sec\frac{\alpha\pi}{2}}$$

Table 2 : Fracture collapse condition (case I)

Crack Length a (mm)	Residual strength (N/mm^2) CERAMICS	Residual strength (N/mm^2) STEEEL	Residual strength (N/mm^2) ALUMINIUM
1.412	31.308	2.3696	2.3696
1.414	31.352	2.3685	2.3685
1.416	31.397	2.3674	2.3674
1.418	31.441	2.3664	2.3664
1.420	31.485	2.3653	2.3653
1.422	31.530	2.3642	2.3642
1.424	31.574	2.3631	2.3631
1.426	31.618	2.3620	2.3620

1.428	31.663	2.3609	2.3609
1.430	31.707	2.3598	2.3598

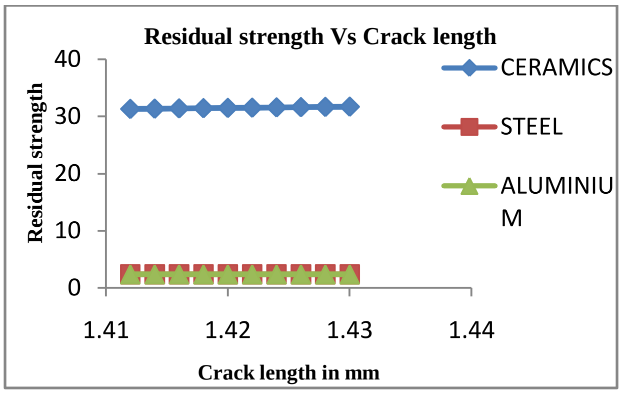


Figure6 :shows the Residual strength Vs Crack length(case I)

Table 3: Fracture toughness condition(case II):

Crack length (mm)	Residual Strength (N/mm2) CERAMICS	Residual Strength (N/mm2) STEEL	Residual Strength (N/mm2) ALUMINIUM
1.412	175.903	0.9596	0.8956
1.414	175.779	0.9604	0.8975
1.416	175.654	0.9612	0.8996
1.418	175.530	0.9620	0.9016
1.420	175.405	0.9628	0.9036
1.422	175.281	0.9636	0.9056
1.424	175.156	0.9644	0.9076
1.426	175.032	0.9652	0.9096
1.428	174.907	0.9660	0.9116
1.430	174.783	0.9668	0.9136

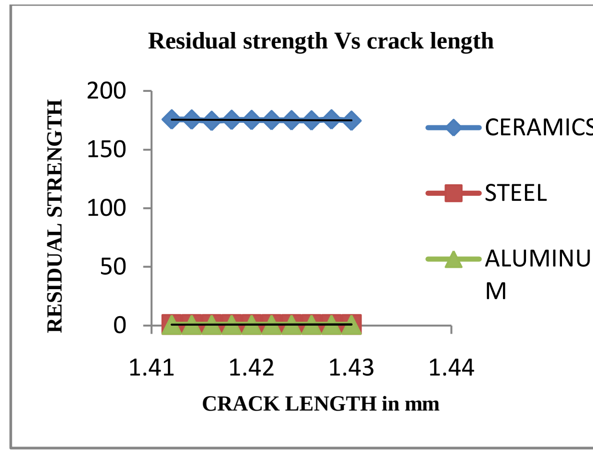


Figure7:shows the Residual strength Vs Crack length(case II)

6.LIFE PREDICTION

6.1 Fatigue design and life prediction:

The marked sensitivity of fatigue-crack growth rates to the applied stress intensity in intermetallics and ceramics, both at elevated and especially ambient temperatures, presents unique challenges to damage-tolerant design and life-prediction methods for structural components fabricated from these materials. For safety-critical applications involving most metallic structures, such procedures generally rely on the integration of data relating crack-growth rates (d*a*=d*N* or d*a*=d*t*) to the applied stress intensity (*1K* or *K*max) in order to estimate the time or number of cycles *Nf* to grow the largest undetectable initial flaw *ai* to critical size *ac*, viz.

6.1.1 For steel:

Crack growth life has been predicted using Paris law. The formula for predicting the life:

$$dN = \frac{da}{c(\Delta K)^m}$$

where N= Crack life which is initialized to zero,
c, m= Material constants (2 to 4),
ΔK= Stress intensity factor.

$$\Delta K = \frac{P.\,S.}{B\,w^{\frac{3}{2}}} f\left(\frac{a}{w}\right) \quad , \quad f\left(\frac{a}{W}\right) = \text{Geometry}$$

a = crack length , da = increment in crack length =0.002, dN = increment in crack life.

6.1.2FOR ALUMINIUM:

$$dN = \frac{da}{c(\Delta K)^m}$$

where
N= Crack life which is initialized to zero, c,
m = Material constants (2 to 4),
ΔK= Stress intensity factor.

$$\Delta K = \frac{P}{B\sqrt{W}} f\left(\frac{a}{W}\right), \quad f\left(\frac{a}{W}\right) = \text{Geometry factor.}$$

a = crack length , da = increment in crack length =0.002, dN = increment in crack life.

6.1.3 FOR CERAMICS

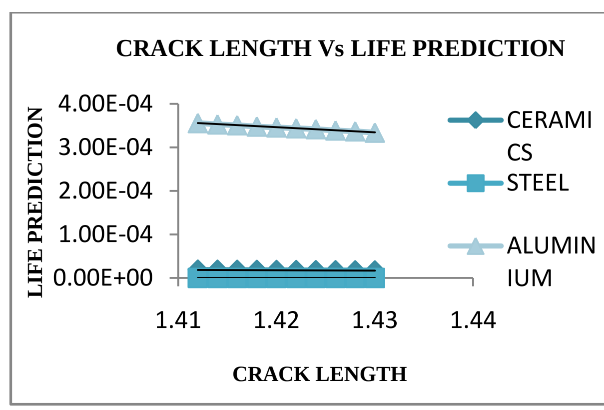
$$da/dN = C(K_{\max})^n(\Delta K)^p$$

Where: C = Constant (2 & 4), $K_{max} = 370$,
ΔK =Stress intensity factor value, n= 3.6 & p= 1.9

dN = increment in crack life.

Table 4 :LIFE PREDICTION FOR 3 MATERIALS

Crack Length (mm)	Life prediction Ceramics	Life prediction Steel	Life prediction Aluminium
1.412	1.87E-05	1.457E-15	3.56E-04
1.414	1.85E-05	1.448E-15	3.53E-04
1.416	1.83E-05	1.440E-15	3.51E-04
1.418	1.81E-05	1.432E-15	3.48E-04
1.420	1.79E-05	1.424E-15	3.46E-04
1.422	1.77E-05	1.407E-15	3.44E-04
1.424	1.75E-05	1.399E-15	3.42E-04
1.426	1.73E-05	1.391E-15	3.39E-04
1.428	1.71E-05	1.384E-15	3.37E-04
1.430	1.69E-05	1.376E-15	3.34E-04



Figur 8 : shows the Life prediction Vs Crack length

7.Summary and conclusions:

Although the mechanisms of cyclic fatigue in brittle materials are conceptually different from the well known mechanisms of metal fatigue, First we calculted & consentrated step to my work is stress itensity factor. Finally, the marked sensitivity of growth rates to the applied stress intensity in ceramics and intermetallics implies that projected lifetimes will be a very strong function of stress and crack size; this makes design and life prediction .

8.Acknowledgment:

It is with a feeling of great pleasure that I would like to express my most sincere heartfelt gratitude to **Associate Prof, Dr.B.Balakrishna** Dept. of Mechanical Engineering, JNT University, Kakinada .for suggesting the topic for my work and for his ready and noble guidance throughout the course of my Preparing the work. I thank you Sir for your help, inspiration and blessings. Last but not least I would like to express my gratitude to my parents and other family members, whose love and encouragement have supported me throughout my education.

References:

1. *S. M. Wiederhorn and L. H. Bolz, ''Stress Corrosion and Static Fatigue of Glass,'' J. Am. Ceram. Soc.,* ***53,*** *543 (1970).*
2. *S. M. Wiederhorn, ''Reliability, Life Prediction, and Proof Testing of Ceramics,'' in Ceramics for High Performance Applications, J. J. Burke, A. G. Gorum, and R. N. Katz (eds.), Brook Hill, Chestnut Hill, MA, 1974, pp. 633–663.*
3. *S. M. Wiederhorn, E. R. Fuller, Jr., J. Mandel, and A. G. Evans, ''An Error Analysis of Failure Prediction Techniques Derived from Fracture Mechanics,'' J. Am. Ceram. Soc.,* ***59****(9–10), 403–411 (1976).*
4. *J. E. Ritter, Jr., ''Engineering Design and Fatigue Failure of Brittle Materials,'' in Fracture Mechanics of Ceramics, Vol. 4, R. C. Bradt, D. P. H. Hasselman, and F. F. Lange, (eds.), Plenum Press, New York, 1978, pp. 667–686.*
5. *J. E. Ritter, Jr., S. M. Wiederhorn, N. J. Tighe, and E. R. Fuller, Jr.,''Application of Fracture Mechanics in Assuring Against Fatigue Failure of Ceramic Components,'' in Ceramics for High Performance Applications, III, Reliability, Vol. 6, E. M. Lenoe, R. N. Katz and J. J. Burke (eds.), Plenum New York, 1981, pp. 49–59.*
6. *E. R. Fuller, Jr., B. R. Lawn, and R. F. Cook, ''Theory of Fatigue for Brittle Flaws Originating from Residual Stress Concentrations,'' J. Am. Ceram. Soc.,* ***66****(5) 314–321 (1983).*
7. *S. M. Wiederhorn and E. R. Fuller, Jr., ''Structural Reliability of Ceramic Materials,'' Mater. Sci. and Eng.,* ***71****(1–2), 169–186 (1985).*
8. *K. C. Kapur and L. R. Lamberson, Reliability in Engineering Design, Wiley, New York, 1977.*
9. *A. A. Griffith, ''the Phenomena of Rupture and Flow in Solids,'' Phil. Trans. Roy. Soc. London A,* ***221,*** *163–198 (1921).*
10. *A. A. Griffith, ''The Theory of Rupture,'' C. B. Biezeno and J. M. Burgers, Eds., Intl. Cong. Appl. Mech., Delft, 1924, pp. 55–63.*

11. *W. Weibull, ''A Statistical Theory of the Strength of Materials,'' Ing. Vetenskaps Akad. Handl.,* ***151,*** *45 (1939).*
12. *W. Weibull, ''Phenomenon of Rupture in Solids,'' Ing. Vetenskaps Akad. Handl.,* ***153,*** *55 (1939).*
13. *W. Weibull, ''A Statistical Distribution Function of Wide Applicability,'' J. Appl. Mech.,* ***18****(3), 293–297 (1951).*
14. *F. W. Preston, ''The Mechanical Properties of Glass,'' J. Appl. Phys.,* ***13,*** *623–634 (1942).*
15. *R. E. Mould and S. D. Southwick, ''Strength and Static Fatigue of Abraded Glass Under Controlled Ambient Conditions: II, Effect of Various Abrasions and the Universal Fatigue Curve,'' J. Am. Ceram. Soc.,* ***42****(12), 582–592 (1959).*
16. *S. M. Wiederhorn, ''Influence of Water Vapor on Crack Propagation in Soda-Lime Glass,'' J. Am. Ceram. Soc.,* ***50,*** *407 (1967).*
17. *S. M. Wiederhorn, ''Subcritical Crack Growth in Ceramics,'' in Fracture Mechanics of Ceramics, Vol. 2, R. C. Bradt, D. P. H. Hasselman, and F. F. Lange (eds.), Plenum, New York, 1974, pp.613–646.*
18. *S. W. Freiman, ''Stress-Corrosion Cracking of Glasses and Ceramics,'' Stress-Corrosion Cracking, R. H. Jones (ed.), ASM International, Materials Park, OH, 1992, pp. 337–344.*
19. *G. S. White, ''Environmental Effects on Crack Growth,'' in Mechanical Testing Methodology for Ceramic Design and Reliability, D. C. Cranmer and D. W. Richerson (eds.), Marcel Dekker, Inc., New York, 1998, pp. 17–42.*
20. *D. F. Jacobs and J. E. Ritter, Jr., ''Uncertainty in Minimum Lifetime Predictions,'' J. Am. Ceram. Soc.,* ***59****(11–12), 481–487 (1976).*
21. *C. A. Johnson and W. T. Tucker, ''Advanced Statistical Concepts of Fracture in Brittle Materials,'' in Engineered Materials Handbook, Vol. 4, Ceramics and Glasses, ASM International, Materials Park, OH, 1992, pp. 709–715.*
22. *E. R. Fuller, Jr., S. W. Freiman, J. B. Quinn, G. D. Quinn, and W. C. Carter, ''Fracture Mechanics Approach to the Design of Glass Aircraft Windows: A Case Study,'' in SPIE Proc.,* ***2286,*** *419– 430.*
23. *A. Zimmermann, M. Hoffman, B. D. Flinn, R. K. Bordia, T.-J. Chuang, E. R. Fuller, Jr., and J. Ro¨del, ''Fracture of Alumina with Controlled Pores,'' J. Am. Ceram. Soc.,* ***81****(9), 2449–2457(1998).*
24.*G.V. Guinea, J.Y. Pastor, J. Planas, M. Elices. "Stress intensity factor, compilance and CMOD for a general three-point-bend beam". Int. J. Fract. 89 103-116 (1998)*