FRACTURE TOUGHNESS PREDICTION OF BRITTLE & DUCTILE MATERIALS

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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 intensity factor calculated and next which the Residual stress is calculated to the ductile and brittle, And finally calculates the life prediction for the ductile and brittle materials and Results to be compared, Good agreement to the materials.

Keywords— Brittle and Ductile materials, Stress intensity factor, Residual strength, 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 enhanced degradation under stress. The statistical aspect of strength derives from the distribution of the most severe defects in the components (i.e., the strength-determining 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 discussion will 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 $K_c$ in any metallic alloy when cyclic loading is applied. In simplified concept, it is the accumulation of damage from the cyclic plastic deformation in the plastic zone at the crack tip that accounts for the intrinsic mechanism of fatigue crack growth at $K$ levels below $K_c$. 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 Al₂O₃ ceramics (99.5%)

<table>
<thead>
<tr>
<th>Property</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>Kg/m³</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>-</td>
</tr>
<tr>
<td>UTS</td>
<td>MPa</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>GPa</td>
</tr>
<tr>
<td>Flexural strength</td>
<td>Mpa</td>
</tr>
</tbody>
</table>
3.2 Mechanical properties of 1045 steel:

<table>
<thead>
<tr>
<th>Material</th>
<th>Density</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>Kg/m³</td>
<td>7.872×10³</td>
</tr>
</tbody>
</table>

3.3 Mechanical properties of Aluminium:

Material: 2024-T3 Al alloy:

<table>
<thead>
<tr>
<th>Material</th>
<th>Density</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>Kg/m³</td>
<td>2.70×10³</td>
</tr>
</tbody>
</table>

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, $K_I$, 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.

4. Stress Intensity factor:

The local stresses near a crack depend on the product of the nominal stress ($\sigma$) 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

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.
5.2. Stress intensity factor figs

Stress strain characteristics for brittle materials 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 $S_{yp}$ value of brittle material is greater than $S_u$ (2) Brittle materials are generally stronger in compression than in tension and consequently, for brittle materials $S_u$ in compression ($S_{uc}$) is greater than $S_u$ in tension ($S_{ut}$). As a result of this $S_{uc}$ and $S_{ut}$ are the limiting stresses in mechanical design 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 the following equation.

For Mode-I (Opening Mode):

5.3.1 FOR CERAMICS

\[ K_I = \frac{3PL}{2SW^2} Y(\alpha) \]

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

\[ Y(\alpha) = \frac{\sqrt{3(1.99+\frac{2}{\alpha})(-0.09+H(\alpha))}}{(1-\alpha)^{3/2}(1+3\alpha)} \]

\[ F(\alpha) = 0.83\alpha - 0.31\alpha^2 + 0.14\alpha^3 \]

\[ H(\alpha) = -0.42\alpha + 0.82\alpha^2 - 0.31\alpha^3 \]

5.3.2 FOR STEEL:

For Mode-I (Opening Mode)

\[ K_I = \frac{P}{BW^2} f \left( \frac{a}{w} \right) \]

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.

5.3.3 FOR ALUMINIUM:

For Mode-I (Opening Mode)

\[ K_I = \frac{f(a)}{B\sqrt{W}} \]

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

where: \( P = \) critical applied load = 705 N, \( S = \) length of the rectangular bar, \( f(a) = \) 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.

<table>
<thead>
<tr>
<th>Crack Lengtha ((\text{mm}))</th>
<th>Theoretical CERAMICS</th>
<th>Theoretical STEEL</th>
<th>Theoretical ALUMINIUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.412</td>
<td>717.810</td>
<td>360.58</td>
<td>728.55</td>
</tr>
<tr>
<td>1.414</td>
<td>717.814</td>
<td>361.11</td>
<td>727.63</td>
</tr>
<tr>
<td>1.416</td>
<td>717.816</td>
<td>361.64</td>
<td>726.71</td>
</tr>
<tr>
<td>1.418</td>
<td>720.090</td>
<td>362.17</td>
<td>725.79</td>
</tr>
<tr>
<td>1.420</td>
<td>720.090</td>
<td>362.17</td>
<td>725.79</td>
</tr>
<tr>
<td>1.422</td>
<td>722.098</td>
<td>363.23</td>
<td>723.95</td>
</tr>
<tr>
<td>1.424</td>
<td>723.102</td>
<td>363.76</td>
<td>723.03</td>
</tr>
<tr>
<td>1.426</td>
<td>724.106</td>
<td>364.29</td>
<td>722.11</td>
</tr>
<tr>
<td>1.428</td>
<td>725.108</td>
<td>364.82</td>
<td>721.18</td>
</tr>
<tr>
<td>1.430</td>
<td>726.113</td>
<td>365.35</td>
<td>720.27</td>
</tr>
</tbody>
</table>
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.
\[ \sigma_{fc} = \frac{3P}{2Wt^2} \]

Where \( \sigma_{fc} \) = 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 \( K \) =370 MPa√m, \( \beta \) =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 \( \sigma_{fc} \) = residual strength, \( W \) = width of the plate, \( a \) = crack length, \( \sigma_y \) = stress 350 N/mm\(^2\) for steel (assumed)

Case2: Fracture toughness condition
\[ \sigma_{fc} = \frac{K}{\beta \sqrt{\pi a}} \]

Where \( K \) =280 MPa√m, \( \beta \) =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)

<table>
<thead>
<tr>
<th>Crack Length (mm)</th>
<th>Residual strength (N/mm(^2)) CERAMICS</th>
<th>Residual strength (N/mm(^2)) STEEL</th>
<th>Residual strength (N/mm(^2)) ALUMINUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.412</td>
<td>31.308</td>
<td>2.3696</td>
<td>2.3696</td>
</tr>
<tr>
<td>1.414</td>
<td>31.352</td>
<td>2.3685</td>
<td>2.3685</td>
</tr>
<tr>
<td>1.416</td>
<td>31.397</td>
<td>2.3674</td>
<td>2.3674</td>
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<tr>
<td>1.418</td>
<td>31.441</td>
<td>2.3664</td>
<td>2.3664</td>
</tr>
<tr>
<td>1.420</td>
<td>31.485</td>
<td>2.3653</td>
<td>2.3653</td>
</tr>
<tr>
<td>1.422</td>
<td>31.530</td>
<td>2.3642</td>
<td>2.3642</td>
</tr>
<tr>
<td>1.424</td>
<td>31.574</td>
<td>2.3631</td>
<td>2.3631</td>
</tr>
<tr>
<td>1.426</td>
<td>31.618</td>
<td>2.3620</td>
<td>2.3620</td>
</tr>
</tbody>
</table>
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 \( (da/dN \text{ or } da/dt) \) to the applied stress intensity \( (1K \text{ or } K_{\text{max}}) \) in order to estimate the time or number of cycles \( N_f \) to grow the largest undetectable initial flaw \( a_i \) to critical size \( a_c \), 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),  
\( \Delta K = \) Stress intensity factor.
\[
\Delta K = \frac{p \cdot \sigma}{W} f \left( \frac{a}{W} \right), \quad f \left( \frac{a}{W} \right) = \text{Geometry factor}
\]

where
\[a = \text{crack length}, \quad da = \text{increment in crack length} = 0.002, \quad dN = \text{increment in crack life}.
\]

6.1.2 FOR ALUMINIUM:

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

where
\[N = \text{Crack life which is initialized to zero,} \quad c, \quad m = \text{Material constants (2 to 4),} \quad \Delta K = \text{Stress intensity factor}.
\]

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

\[a = \text{crack length}, \quad da = \text{increment in crack length} = 0.002, \quad dN = \text{increment in crack life}.
\]

6.1.3 FOR CERAMICS

\[\frac{da}{dN} = C(K_{\text{max}})^n(\Delta K)^p
\]

Where: \(C = \text{Constant (2 & 4),} \quad K_{\text{max}} = 370, \quad \Delta K = \text{Stress intensity factor value,} \quad n = 3.6 \quad \text{&} \quad p = 1.9
\]

\[dN = \text{increment in crack life}.
\]

Table 4: LIFE PREDICTION FOR 3 MATERIALS

<table>
<thead>
<tr>
<th>Crack Length (mm)</th>
<th>Life prediction</th>
<th>Life prediction</th>
<th>Life prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ceramics</td>
<td>Steel</td>
<td>Aluminium</td>
</tr>
<tr>
<td>1.412</td>
<td>1.87E-05</td>
<td>1.457E-15</td>
<td>3.56E-04</td>
</tr>
<tr>
<td>1.414</td>
<td>1.85E-05</td>
<td>1.448E-15</td>
<td>3.53E-04</td>
</tr>
<tr>
<td>1.416</td>
<td>1.83E-05</td>
<td>1.440E-15</td>
<td>3.51E-04</td>
</tr>
<tr>
<td>1.418</td>
<td>1.81E-05</td>
<td>1.432E-15</td>
<td>3.48E-04</td>
</tr>
<tr>
<td>1.420</td>
<td>1.79E-05</td>
<td>1.424E-15</td>
<td>3.46E-04</td>
</tr>
<tr>
<td>1.422</td>
<td>1.77E-05</td>
<td>1.407E-15</td>
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<td>1.424</td>
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<td>1.426</td>
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<tr>
<td>1.430</td>
<td>1.69E-05</td>
<td>1.376E-15</td>
<td>3.34E-04</td>
</tr>
</tbody>
</table>

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 calculated & concentrated step to my work is stress intensity 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:
