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Experimental Study of Crack Growth Behavior of Circumferentially Cracked Pipe under Cyclic Loading using SEM

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***Abstract:** This is the age of nuclear power and the safety of nuclear power plants is very important to prevent the release of radiation to the public domain. The design of pipe using in primary heat transport system is very critical because pipes are subjected to fluctuating pressure and maximum pipes are failed due to fatigue failure. There are many techniques such as ultrasonic, potential drop, eddy current, acoustic emission, photography and compliance technique to measure crack length during fatigue crack growth test.*

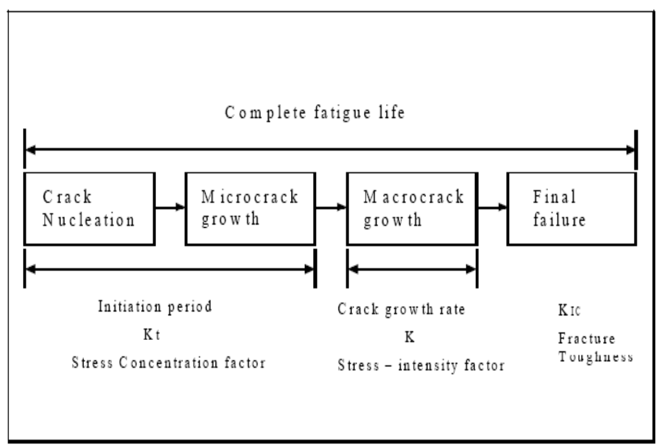
This study demonstrates the use of scanning electron microscope (SEM) to measure circumferential crack length in fatigue crack propagation testing of circular pipes. Fatigue crack growth test were conducted on four point bend specimens (SA53 Gr. B galvanized steel pipe) initially notched circumferentially at mid-span. Crack was propagated in three dimensions with respect to the long axis of the pipe; transverse, longitudinal, and radial. Specimen compliance was determined for a crack from the load-CMOD data. Both compliance and crack length is normalized. The results shows relationship between normalized compliance and normalized crack length is unique. Also the good agreement between crack growth rate and stress intensity factor in Paris regime is found.

1. INTRODUCTION

The fatigue failures occur in many forms. Mere fluctuations in externally applied stresses or strains result in mechanical fatigue. Cyclic loads acting in association with high temperatures cause creep-fatigue; when the temperature of the cyclically loaded component also fluctuates, thermomechanical fatigue (i. e. a combination of thermal and mechanical fatigue) is induced. Recurring loads imposed in the presence of a chemically aggressive or imbrittling environment give rise to corrosion fatigue. The repeated application of load in conjunction with sliding and rolling contact between materials produces sliding contact fatigue and rolling contact fatigue, respectively, while fretting fatigue occurs as a result of pulsating stresses along with oscillatory relative motion and frictional sliding between surfaces. The majority of failures in machinery and structural components can be attributed to one of the above fatigue processes. [1]

Failure of member under fatigue loading can be classified into five steps based on crack propagation as mentioned below. [1].

1. Crack nucleation caused by sub structural and micro structural changes
2. The creation of microscopic cracks
3. Formation of dominant crack from the movement of dislocations and slip bands which eventually lead to cat strophic failure.
4. Stable propagation of dominant crack so produced.
5. Structural instability and complete failure of member.



Total fatigue life of a component is defined as number of cycles or time to induce fatigue damage and to initiate a dominant fatigue flaw which propagates until final failure. As mentioned above load required to fail a component under cyclic loading is far less than that of load required for static loading. This phenomenon of decreased loading that is required for failure the component was first studied by

Bauschinger and the corresponding effect is known as Bauschinger effect as described below.

According to Bauschinger's effect, if a material is subjected to forward plastic deformation in tension or compression and afterwards if the direction of application of load is changed then the material will yield at lower loads than the load required for forward plastic deformation. So during the application of cyclic loading the load requirement will gradually decreases and may reach even less than that of operating cyclic loading because of which the material will fail. Many aluminum alloys containing non-sharable strengthening properties are stretched prior to temper treatments to relieve thermal residual stresses. Since many of these materials exhibits Bauschinger effects they will exhibit low flow stresses if stretching direction is reversed. Due to the decreased flow stress or due to damage caused by cyclic strain the flaws or micro structural irregularities will cause to initiate the fatigue crack. [3].

2. CHARACTERIZATION OF FATIGUE CRACK GROWTH

Under cyclic loading conditions, the onset of crack growth from a pre-existing flaw or defect can occur at (maximum) stress intensity values that are well below the quasi-static fracture toughness. For conditions of small-scale yielding, where the nonlinear zone at the crack tip is a mere perturbation in an otherwise elastic material, Paris, Gomes & Anderson and Paris & Erdogan postulated that the growth of a crack under cyclic loading should be governed by the 'law' [6, 7]

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

Where da/dN is the change in the length of the crack per load cycle (a is the crack length and N is the number of fatigue cycle) and ΔK is the stress intensity factor range defined as

$$\Delta K = K_{max} - K_{min}.$$

Kmax and Kmin, respectively, are the maximum and minimum stress intensity factors corresponding to the load, Pmax (or maximum nominal stress, σ_{max}) and the minimum load, Pmin (or minimum nominal stress, σ_{min}), also $K_{max} = Y\sigma_{max}\sqrt{\pi a}$ and $K_{min} = Y\sigma_{min}\sqrt{\pi a}$ for a center-cracked plate containing a crack of length 2a which is subjected to tensile fatigue with a far-field stress range, $\Delta\sigma = \sigma_{max} - \sigma_{min}$. Y is the finite size correction factor for the plate. The C and m are empirical constants which are functions of the material properties and microstructure, fatigue frequency, mean stress or load ratio, environment, loading mode, stress state and test temperature. The empirical crack growth law, due to Paris et al. is the most widely used form of characterizing fatigue crack growth rates for a vast spectrum of materials and test conditions.

Elber argued that only the stress range from σ_o to σ_{max} is responsible for the crack propagation. So the effective stress range will be $\Delta\sigma_{eff} = \sigma_{max} - \sigma_o$ and corresponding stress intensity factor will be modified to $\Delta K_{eff} = K_{max} - K_o$. Thus Paris law will take a form of

$$\frac{da}{dN} = C(\Delta K_{eff})^{m}$$

3. THEORY ANALYSES

The crack lengths during four point bend test on pipe have to determined using Scanning Electron Microscope (SEM) and incorporate them to determination of crack growth rate. Fatigue crack growth test will conduct on four point bend specimens (SA53 Gr. B galvanized steel pipe) initially notched circumferentially at mid-span. Crack propagates in three dimensions with respect to the long axis of the pipe; transverse, longitudinal, and radial, hence measurement in three directions and at different lengths will very difficult.

Fatigue crack growth analysis will be carried out based on the Paris law given by [11, 12]

$$da/dN=[C\,(\Delta K)^{m}] \quad (1)$$

Where C and m are constants.

Stress intensity factor range can be calculated from

$$\Delta K = \Delta\sigma_o\sqrt{\pi a}\,(F_G) \quad (2)$$

$$\Delta\sigma_o = \Delta M/Z$$

$$\Delta M = [\Delta P\,(Lo - Li)]/4$$

$$Z = \frac{\pi}{32 d_0}[d_o^4 - d_i^4]$$

ΔM = range of applied moment

ΔP =range of applied load.

d_o is outer diameter and d_i is inner diameter

Lo and L_i is outer and inner span respectively

Five pipe specimen (having app. 30 deg) are loaded below (18.8%) limit load (P_L) and five specimen (having app. 45 deg) are loaded with limit load. The limit load/moment is computed using the following equations: [25]

$$M_L = 4R_m^2 t\sigma_f[\cos\left(\frac{\theta}{2}\right) - 0.5\sin\theta]$$

Where, R_m is the mean radius of the pipe cross-section, t is the wall thickness, σ_f is the pipe material flow stress taken as the average of yield and ultimate stress and θ the semi-crack angle.