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Mechanisms of Crack-Closure During Fatigue of Metals and Alloys for Technology Specific Applications

Review Article

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Abstract

The closure mechanisms of plasticity-induced crack closure, roughness-induced crack closure and oxide-induced crack closure are briefly examined and discussed. Mention is made of the factors or reasons favouring the occurrence of a specific closure mechanism. The role and contribution of applied stress intensity in governing crack growth through the microstructure of the chosen material ids emphasized. Plasticity-induced crack closure is predictable based on applied load, resultant stress intensity and growth rate of the fatigue crack be it under conditions of plane stress or plane strain. However, prediction of roughness-induced crack closure and oxide-induced crack closure is not straight forward primarily because it is governed by the mutually interactive influences of the intricacies specific to microstructure of the chosen material and both nature and aggressiveness of the environment, be it gaseous or aqueous, to which the material or structure is exposed to during service.

Keywords: Fatigue Crack Growth, Plasticity-Induced Crack Closure, Roughness-Induced, Crack Closure, Oxide-Induced Crack Closure, Stress, Stress Intensity, Microstructure, Environment

Introduction

Cracks that develop in a structure that is subject to fatigue loading, or cyclic loading, spend a considerable portion of their life-time in the near-threshold region during both stress-controlled high cycle fatigue (HCF) and very high cycle fatigue (VHCF) tests. Approaches, or methods, to accurately characterize the propagation of damage through the microstructure of the chosen material during these conditions is often the objective of the fatigue-crack-growth rate (FCGR) data that is generated and collected during testing of a standard specimen that conforms well with specifications detailed in the appropriate ASTM Standard. Test data at both the threshold and near-threshold conditions are essential and critical for subsequent numerical modelling of the crack growth behavior. An ability to accurately predict the service life of a component containing a crack while concurrently establishing proper inspection intervals does depend a lot on the fatigue crack growth rate (FCGR) data.

Linear elastic fracture mechanics (LEFM) quantifies the fatigue crack growth rate (FCGR) data [da/dN] in terms of stress-intensity factor range [ΔK], at a given load ratio [R= minimum stress/maximum stress] as was first shown and documented in the published literature by Paris and Erdogan [1]. The relation between stress intensity factor range (ΔK) and crack growth rate (da/dN) was shown to be nearly linear on a log (ΔK) versus log(da/dN) plot in 'region-2', which is called or referred to as the Paris region. The prediction of fatigue life in this region is quite simple and is essentially governed by the expression:

$$da/dN = C\,(\Delta K)^m$$

In this expression, both C and *m* are regarded as Paris constants.

As the crack grows through the microstructure of the chosen material, be it a pure metal or an alloy counterpart and even a composite material, it eventually becomes unstable eventually culminating in failure of the chosen test specimen by fracture.

Background

The entire life of a fatigue crack was well explained by J. M. Barsom [2]. The region of unstable crack growth was referred to as 'Region-3' in the variation of fatigue crack growth rate (FCGR) data with stress-intensity factor range (ΔK). $K_{Maximum}$ is the only useful data that is obtained from this region primarily because life of the fatigue crack is far too short to extract any other useful information. However, the fatigue crack does spend a significant amount of its life span in Region-1 and does eventually come out of its dormancy to exhibit observable growth through the microstructure of the material during repeated cyclic loading. The minimum value of ΔK (stress intensity factor range), which is needed for the crack to begin growing is referred to as the *threshold stress-intensity factor range* [ΔK_{th},] and is an important information for purpose of design that is obtained from 'Region-1'. Generally, Region 1 is a nonlinear region since growth of the crack during fatigue loading does depend on mutually competitive influences of microstructural parameters and environmental parameters. This was well documented by McEvily Jr. and co-workers in their independent study [3]. One of the significant mechanisms that influences crack-growth behavior in 'Region-1' and early stages of 'Region-2' is "crack closure".

Observations and Discussion

Crack closure is a phenomenon during fatigue loading, wherein the opposing faces of a crack tends to remain in contact even when an external load is acting on the chosen material. Upon gradual increase in the load, a critical value is reached at which point the crack is now fully open. Crack closure often occurs or arises due to the presence of material propping open the crack faces and can arise as a direct consequence of many sources to essentially include the following:

(i) plastic deformation

(ii) corrosion of crack surfaces

(iii) presence of fluid in the crack

(iv) roughness of the crack surfaces

All of these aspects are well reviewed by R. Pippan and co-workers [4].

Plasticity-Induced Crack Closure

The phenomenon of plasticity-induced crack closure (PICC) is associated with the occurrence and presence of plastically deformed material on the flanks of an advancing fatigue crack and was first shown in a study conducted by R. Pippan and co-workers [5]. The degree of plasticity at the crack tip is influenced by both magnitude of constraints and severity of constraints in the chosen material. Under plane stress condition, the piece of material in the plastic zone gets elongated, which is primarily balanced by an out-of-plane flow of the material. This was first shown by N. Ranganathan [6]. Under plane strain conditions and constant amplitude loading, there is an absence of plastic wedge at a large distance behind the crack tip. However, the material in the plastic zone, or wake, is plastically deformed and acts as a "local" wedge in the immediate vicinity of the crack tip. This places a hinderance, or suppresses growth of the crack through the microstructure of the chosen material. This was first shown by F. Antunes and co-workers [7].

Roughness-Induced Crack Closure

In the years that followed S. Suresh and co-workers [8] showed roughness-induced crack closure (RICC) to occur during in-plane shear type of loading, which is essentially due to the occurrence of a misfit of the rough fracture surfaces of the upper crack lip and the lower crack lip. Due to the conjoint and mutually interactive influences of anisotropy and heterogeneity of the material microstructure, the out-of-plane deformation is favoured to occur locally when the crack-tip is loaded, and thus favouring the occurrence of microscopic roughness of the fatigue fracture surfaces. Roughness-induced crack closure (RICC) is valid when roughness of the surface is of same order as the crack opening displacement (COD). It is often influenced by the conjoint and mutually interactive influences of a few factors to include the following:

a. grain size

b. loading history

c. mechanical properties of the material

d. loading ratio and

e. specimen type

Oxide-Induced Crack Closure

Oxide induced crack closure (OICC) is favoured to occur when rapid corrosion is favoured to occur during crack propagation. It is caused when the base material at the fracture surface is exposed to either a gaseous environment or an aqueous environment and becomes oxidized. Although the oxidized layer is initially thin to start with, under continuous and repetitive deformation both the contaminated layer and the base material tend to experience repetitive breaking or rupturing. This favours the occurrence of exposing more of the base material to the aggressive environment, and thereby aiding in the formation and presence of oxides on the surface. S. Suresh and co-workers [9] have shown that oxide-induced crack closure (OICC) does occur at both room temperature and elevated temperatures, and the oxides that are formed and present on the crack surfaces are more noticeable at the low load-ratios [R] and resultant low crack growth rates.

Among the various techniques for measuring 'crack-closure', the crack opening displacement (COD) gauges are popular due to the overall ease they offer in both mounting and data acquisition. In many applications, crack growth is often measured using sensors, such as strain gauges, since it would be practically impossible to mount a crack opening displacement (COD) gauge. Use of strain gauges around the immediate vicinity of a crack tip is another technique that can be safely used for quantifying 'closure'. However, it was J.C. Newman [10] who did notice difficulties in measuring closure in the near-threshold regime and attributed this to very low displacements. The problem is compounded in elastic-plastic deforming materials, such as the families of both alloy steel and carbon steel, that are known to exhibit 'crack-closure' due to a combination of phenomenon to include the following:

i. Plasticity-induced crack closure

ii. Oxide-induced crack closure

iii. Roughness-induced crack closure and

iv. Viscosity-induced crack closure.

Elber adopted a COD-meter to measure crack opening as a function of the applied load (P). The non-linear portion of the load (P) versus crack opening displacement (COD) curve was taken to be representative of 'crack closure'. Over the years, various methods have been adopted by different authors to accurately determine and record 'closure' from a load (P) versus crack opening displacement (COD) plot. The methods were based on the following:

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I. Slope variation
II. Intersection of two tangent lines
III. Deviations from linearity and
IV. Maximum correlation factor

This was initially shown by J.E. Allison and co-workers [11]. The 'tangent point' method is quite popular and a similar such approach was followed by W. Yusheng and co-workers [12].

Challenges and Approach

An experimental measurement of the load during 'crack closure' can be challenging especially for small crack lengths, due essentially because of a low change in compliance during loading. A number of experimental techniques have been proposed to include piezo-electric sensors apart from the conventional potential drop technique and the strain gauge technique as was first reported in the published literature by C. Wallbrink and co-workers [13] and Van Kuik and co-workers [14]. One technique for recording crack opening displacement for small cracks is the laser-based interferometric strain/ displacement gage. This method essentially measures a change in length between two small indentations placed across a fatigue crack. This was successfully used by W.N. Sharpe and co-workers [15] for small cracks in a 2.3-mm thick specimen of aluminum alloy 2024-T3, which is widely chosen for use in the aircraft industry for the purpose of outer skins of an airplane. The piezoelectric strain sensor was suggested for automatic identification of crack closure using the compliance-based method in the work conducted by A.L. Gama and co-workers [16]. However, this approach is limited to small strain values and is affected and/or influenced by variation in test temperature.

Not much information is available in the published literature on 'closure' measurements using strain gauges, which continues to be the best option based on a thorough review of the published literature. In real time applications, such as hull of a ship or air craft wings, crack opening displacement (COD) gauges can seldom be used. Hence, the strain gauge sensor is one technique, which is preferred for measuring 'crack closure' during studies of crack growth in both ductile metals and their alloy counterparts.

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