FATIGUE AND FRACTURE TESTING

FOR THE RAIL INDUSTRY

CONTENTS

element

INTRODUCTION

Fatigue of metals was first noted in the 19th century when Jean-Victor Poncelet, a French engineer, and mathematician served most notably as the Commanding General of the prestigious École Polytechnique, described parts as becoming “tired” in his lectures at the military school at Metz. In the wake of the Versailles rail accident in May 1842, the cause of which was the failure of an axle in the leading locomotive, the first scientific investigations into the little-understood phenomenon was launched. In 1870, In 1870, German railway engineer August Wöhler published his work on the relationship between the stress applied to a part and its fatigue life. The S-N curve, often referred to as a Wöhler Curve, allowed the relationship to be quantified for the first time, leading to better engineering design by limiting the stress at critical areas.

Fatigue in metals caused by cyclic loading progressively damages a localized area of a structure, eventually leading to the formation of cracks. Once a crack is formed, it will grow with each application of load. The growth rate will depend on a variety of factors; the magnitude of the load, the length of the crack and the remaining portion of un-cracked material, and the geometry of the crack. The crack will continue to grow until it reaches a critical size, which occurs when the stress-intensity factor exceeds the material’s fracture toughness. At this point, the crack growth will very rapidly, and the structure may fracture completely.

Today, fatigue mechanisms are generally considered to be well understood, at least for materials that are widely used, such as steel, aluminum, and nickel super-alloys. The stages of fatigue can be broadly broken down in the following:

1. Crack Initiation
2. Crack Propagation
3. Fracture

CRACK INITIATION

Stress or strain-controlled fatigue tests allow an investigation into how long a material may remain undamaged when subjected to a certain amount of cyclic deformation. That is to say, the repeated application and removal of said deformation. Typically, this is either defined as fixed stress (load) or strain (extension). The deformation level for each cycle is the same, and the test is continued until either the specimen fractures or a specified number of cycles have been completed (runout). The majority of the cycles performed during the fatigue test are spent forming a crack or cracks, and only the very final stages of the test are spent in propagating the crack. This is why many fatigue failures of in-service parts can appear to happen so quickly and why it is so essential to understand the behavior.

Under test conditions, the material can be very closely monitored for changes in response signals. For example, during a stress-controlled test, the change in the test piece's extension can be monitored. As a crack forms, the sample's total extension will increase even though the same force is applied. These changes in the material are not easily detectable outside of the laboratory, but understanding the effects of deformation on the material can help engineers make well-informed design and service decisions.

There is a number of factors that can affect the results of the test, and these need to be carefully considered and controlled:

- **Surface Finish** - Most fatigue cracks form at the surface. A rougher surface may have more points for a fatigue crack to initiate from. Their presence may also act as stress raisers, which may cause cracks to initiate sooner.
- **Residual Stress** - can either reduce or improve fatigue performance. Excessive polishing of the surface can result in sub-surface tensile stresses, which will reduce performance.Peening the material can generate compressive residual stress at the surface albeit while creating tensile stress deeper in the specimen. The overall effect will improve fatigue resistance as cracks cannot form in a compressive environment. Peening can also work-harden the material – this increases the number of dislocations in the material, which hinders plastic deformation meaning the material will behave elastically beyond the elastic yield stress of the non-hardened material.
- **Temperature & Environment** - Temperature and environment will have a dramatic effect on the mechanical properties of a material. Higher temperatures generally lead to a lowering of material properties and results in shorter fatigue lives. Certain atmospheres can also lead to a reduction in material properties and will have a detrimental effect on fatigue performance.
- **Microstructure** - The uniformity of the material microstructure is essential. In two-phase structures, pockets of softer material can lead to the early crack formation or faster crack propagation rates reducing the fatigue life. These can be the result of non-uniform heat treatment. The presence of large carbide or inclusions at or near the surface can result in early fatigue crack initiation.

Some materials such as steel and titanium alloys exhibit a theoretical fatigue limit, where cycling the material below a certain stress will not lead to fracture by fatigue. High cycle fatigue strength (about 104 to 108 cycles) can be described by stress-based parameters. A load-controlled servo-hydraulic test rig is commonly used in these tests, with frequencies of around 20–50 Hz. Other sorts of machines, such as a resonant magnetic frame, can also be used. Such rigs can achieve frequencies up to 250 Hz.

Low-cycle fatigue (loading that typically causes failure in less than 104 cycles) is associated with localized plastic behavior in metals; thus, a strain-based parameter should be used for fatigue life prediction in metals. Testing is conducted with constant strain amplitudes typically at 0.2 - 2 Hz.

There are a number of commonly used internationally recognised recognized test standards for generating good quality fatigue data:

General Fatigue:

- ASTM E1823: Standard Terminology Relating to Fatigue and Fracture Testing
- BS 3518 – 1: Guide to general principals

Force Controlled:

- ASTM E1823: Standard Terminology Relating to Fatigue and Fracture Testing
- BS EN 6072: Constant amplitude fatigue testing
- BS ISO 1143: Rotating bar bending fatigue testing
- BS ISO 1143: Rotating bar bending fatigue testing
- ASTM E466: Standard Practice for Conducting Force Controlled Constant Amplitude Axial Fatigue Tests of Metallic Materials

Strain Controlled:

- BS ISO 12106: Fatigue testing - Axial-strain controlled method
- ASTM E606: Standard Test Method for Strain-Controlled Fatigue Testing

CRACK PROPAGATION

Once a defect is present in the material, the rate at which the crack propagates is a critical design parameter. The magnitude of the cyclic load is the main factor driving the crack growth, however, there are other factors that play a role:

- **Stress-Intensity Factor** - Rather than relying on just stress to define the driving force behind the crack, stress-intensity is used instead. This is a function of the applied force, the sample geometry, and the size of the defect.
- **Mean Stress** - A higher mean stress will increase the rate of crack propagation.
- **Temperature & Environment** - Higher temperatures generally lead to faster growth rates. Cracks exposed to humid environments can propagate faster, whereas cracks growing inside a structure or vacuum may grow much slower.
- **Overloads** - Initially, an overload will increase the rate of growth, however, if the maximum force is great enough, it can cause a large area of plastic deformation, which may retard the crack growth for a large number of cycles.

Unlike a stress or strain-controlled fatigue test, a fatigue crack growth rate test is conducted on a specimen with a pre-existing fatigue crack. The specimen is prepared with a starter notch and is subjected to cyclic loading to initiate a crack from the starter. This crack is grown for several reasons; to remove the effect of the machining process, attempt to replicate a real-world defect, ensure the crack is growing within the measurement field, and ensure the initial conditions of each test are consistent.

In the laboratory, there are several methods of monitoring crack propagation. The most common methods are:

- **Visually:** Either manually with an operator making crack length measurements every nth cycle or by use of a digital camera synchronized to the test frame. The image will contain a calibrated reference for correlation to the crack length.
- **Compliance:** This is the reciprocal of the specimen stiffness and can be correlated to the crack's length. It is usually monitored by measuring the crack mouth opening displacement, although there are other accepted methods.
- **DCPD:** Direct Current Potential Drop uses a pulsed, constant current to monitor the increase in electrical resistance as the crack propagates. Probe wires are attached to the sample on either side of the crack; the voltage and cycle count are recorded as the current is pulsed. The voltage response is then related to the crack length.

Fatigue crack growth data shows 3 three distinct regions:

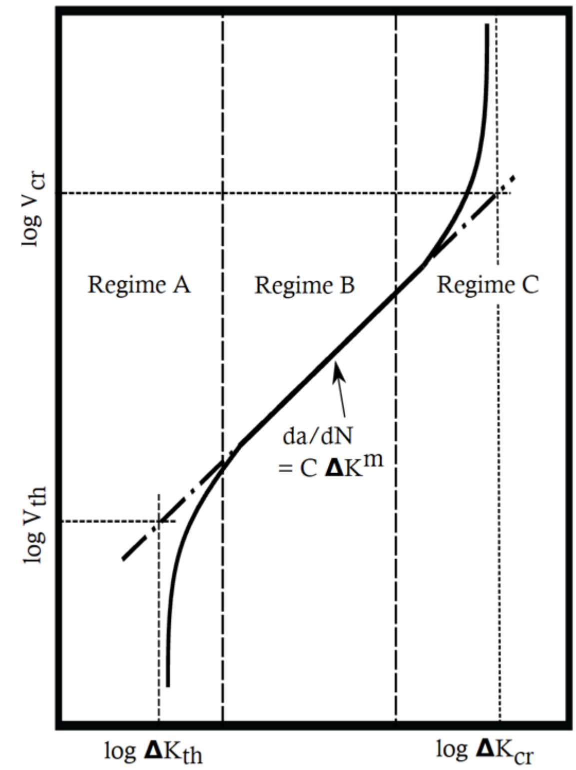
A. Threshold: low stress-intensity factor (ΔK) values give rise to slow rates of crack propagation. The threshold is defined as the point at which the rate of growth is slower than a certain level. ASTM E647 defines this point as 10-10 m/cycle.

B. Paris Region: A steady state of crack propagation which can be described by the power law relationship:

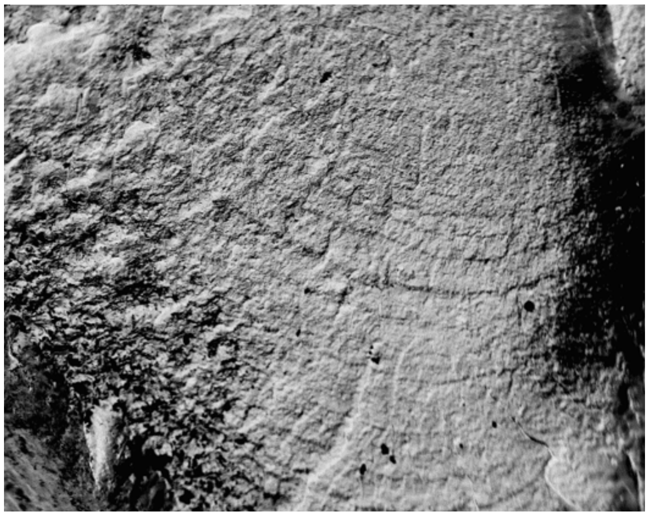
$$da/dN = C(\Delta K)^n$$

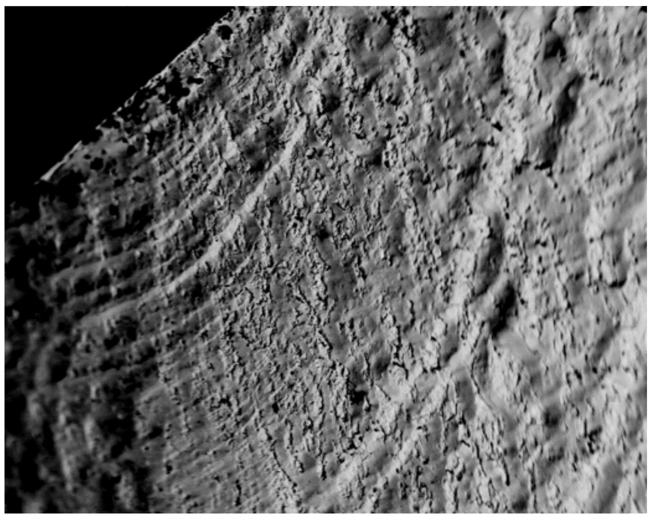
The growth rate (da/dN is the change in crack length (da) per change in cycle (dN)) is defined as a function of the stress-intensity factor and the material coefficients C and n. C and n can depend on a number of variables such as material, temperature, environment, frequency, and stress ratio.

C. Near fracture: The remaining ligament is small relative to the crack length, and the stress-intensity is very high and approaching the fracture toughness of the material. The growth rates in this region may be unstable and unpredictable.



Below are Images of Striations, areas that mark the position of the crack tip; the width indicates the growth from one loading cycle. Each image is approximately 300 μm wide.





There are a number of commonly used internationally recognized test standards for generating good quality fatigue crack growth rate data:

General Fatigue

- ASTM E1823: Standard Terminology Relating to Fatigue and Fracture Testing
- BS 3518-1: Guide to general principals

Compact Tension, Single Edge Tension, and Middle Tension

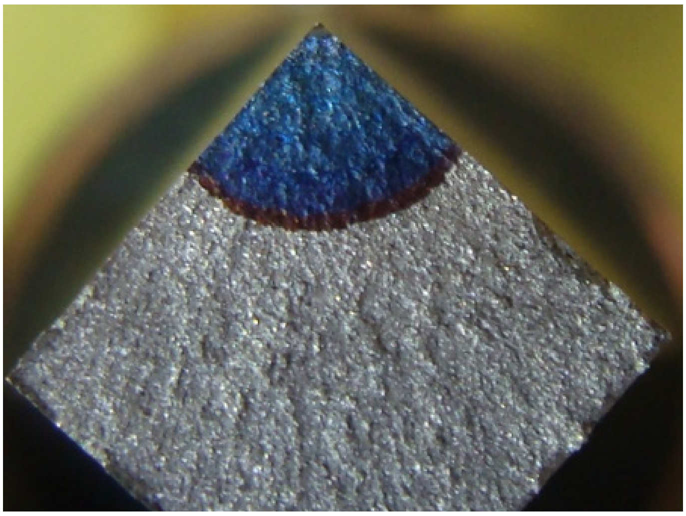
- ASTM E647: Standard Test Method for Measurement of Fatigue Crack Growth Rates
- BS ISO 12108: Fatigue testing — Fatigue crack growth method

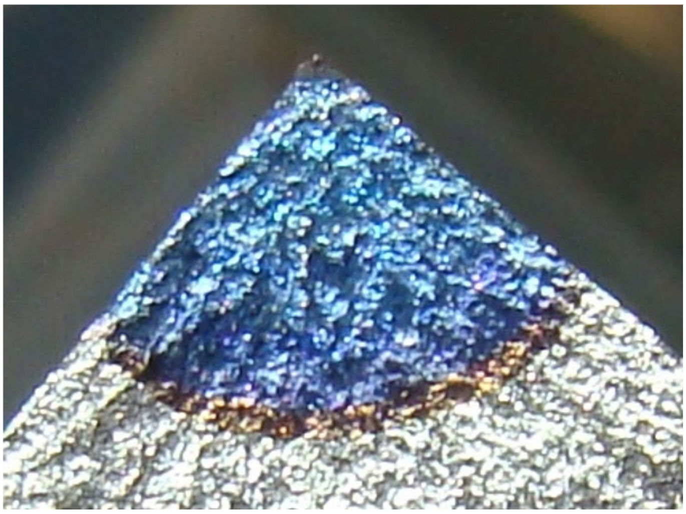
3, 4 and 8 point Single Edged Notched Bend, Centre Cracked Tension, Single Edged Notch Tension

- BS ISO 12108: Fatigue testing — Fatigue crack growth method

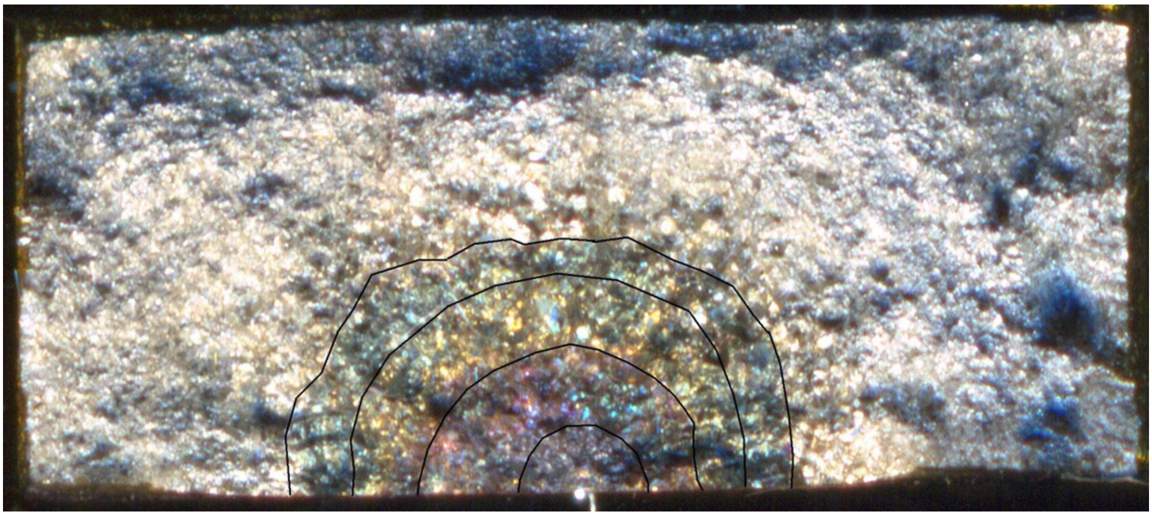
Corner Crack

- BS EN 3873: Test methods for metallic materials — Determination of fatigue crack growth rates using Corner-Cracked (CC) test pieces





Beachmarks are often observed in fracture faces. They are caused by changes in the load regime or environmental conditions. They are often induced to mark the crack length without damaging the test piece. The images are approximately 10 mm wide.



FRACTURE

Once the combination of crack length and load reaches a critical point, a material will fracture. The purpose of the fracture toughness measurement is to estimate the relationship between failure stress and crack size and characterize the material's resistance to fracture under a specific set of circumstances. There are various methods for measuring this value, and the technique employed often depends on how the material behaves. For example, where the failure is expected to be brittle, a plane-strain fracture toughness measurement, KIC, may be made; where the failure mode is expected to be more ductile, the JIC or CTOD values may be more representative.

Plane-strain fracture toughness testing is unusual in that there can be no advanced assurance that a valid KIC will be determined in a particular test. Therefore compliance with the specified validity criteria of the specific method is essential. In particular, limits on the stress employed during fatigue pre-cracking or the ideal specimen size can only be calculated once the test result is known; consequently, estimates on the material performance must be made which can prove to be inaccurate.

Similar to a fatigue crack growth rate test, fracture toughness measurements are made on specimens with a pre-existing fatigue crack. They are prepared for a test in a similar way as crack propagation samples and for the same reasons.

The procedures for measuring toughness can vary in complexity. One of the simplest methods is plane-strain fracture toughness measurement conducted to ASTM E399. The measurement is made by deforming the test piece at a constant displacement rate. The crack opening displacement (COD) is recorded along with the load response. The test is continued until the sample has completely fractured. Once the sample has been broken open, the crack length is measured and the crack geometry assessed for compliance with the requirements.

The load vs. COD data is plotted, and a line of best-fit is drawn through the linear loading portion. A secant with a gradient of 95% of the best-fit (or other convenient reduction) is drawn. The point at which the secant intersects the test data gives the PQ value. The KQ is calculated from PQ and the initial crack length to give a preliminary fracture toughness result. This value is then qualified as the material property KIC if all of the validation criteria are met. If they cannot be met, the result is reported as a KQ value.

There are four main categories or validation criteria for ASTM E399:

- **Specimen Geometry** - For the crack to be in a state of plane-strain, the geometry must conform to the requirements of the test standard.
- **Crack Geometry** - The fatigue crack must be between 45 and 55% of the sample width. The crack front must not exhibit excessive bowing.The fatigue crack must stay within the plane of the starter notch.
- **Fatigue Pre-cracking Conditions** - The choice of initial and final loads for the fatigue pre-crack is generally at the discretion of the test house, however, they must meet the validation criteria given by the standard. The crack length must lie in the envelope given by the test standard.
- **K-Calculation** - The ratio of K_{Max}/KQ must be less than 1.10 to ensure the fracture is classified as brittle. The value of $2.5(KQ/\sigma_{YS})^2$ must be greater than the ligament length to ensure the fracture is linear-elastic. If one or more of these conditions is not met, a larger sample is recommended.

Other requirements may be stipulated within specific test standards or specifications; these are broadly highlighted as the most common points.

There are many commonly used internationally recognized test standards for generating good quality fracture toughness data:

General Fracture Toughness

- ASTM E1823: Standard Terminology Relating to Fatigue and Fracture Testing

Plane-Strain

- ASTM E399: Linear-Elastic Plane-Strain Fracture Toughness of Metallic Materials

Multiple Methods

- ASTM E1820: Standard Test Method for Measurement of Fracture Toughness
- BS 7448-1: Method for determination of KIc, critical CTOD, and critical J values of metallic materials

Understanding the relationship between crack formation, crack propagation, and failure is critical to good damage tolerant design. However, this relationship can be affected by a considerable number of variables. It is essential to understand as broadly as possible the relationship when setting maintenance schedules, predicting the service life of parts and structures, or when designing new parts or considering new materials.

Element has one of the most comprehensive ranges of materials testing services available in the TIC sector that covers materials selection, application, and performance testing, as well as failure analysis testing services. We are a world leader in the provision of high-volume routine mechanical testing services such as tensile testing, impact testing, or hardness testing for both metals and polymeric materials. We also have highly specialized mechanical testing services including fatigue testing, fracture mechanics, crack metal testing, crack propagation testing, creep testing, corrosion testing and chemical analysis services using OES, XRF, ICP, EDS, MS and other analytical techniques.

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