

METALLURGICAL MINUTES

Materials Testing and Engineering ■ Failure Analysis ■ Manufacturing Problem Solving ■ Physical and Chemical Analysis

Fatigue Failure

On May 11th, 1842 the first major railroad disaster in history set off a chain of events which led to the discovery of the phenomenon that we now know as fatigue failure. The Paris – Versailles Express, hurtling down the tracks at the then astounding speed of 50 miles per hour, exploded in flames when the drive axle on the lead locomotive broke, digging its front end into the railbed. The second locomotive in the tandem drive set smashed into the firebox of the lead engine along with the first three cars, killing 57 passengers outright and injuring over a hundred more. It was the 1800's equivalent of a jumbo jet crash, and the great scientific minds of the day focused their collective wisdom on perhaps the first major failure analysis in history. The result of their decade long investigation produced the beginnings of our understanding of fatigue.

Fatigue is the most common type of fracture in engineered components. Fatigue fractures are also particularly dangerous because they can occur under **normal** service conditions, with no warning that a progressively growing crack is developing until the final catastrophic failure. The component, whether it's the outer aluminum skin of a commercial jet or a simple tubular chair leg, often **appears** to be perfectly sound with no visible distortion to warn of impending failure.

A **technical** understanding of fatigue requires a comprehensive knowledge of metallurgy, physics, and phenomena like plastic deformation, slip planes and dislocation theory. In fact, there are several competing theories on exactly what happens at a microscopic level when a fatigue crack initiates. But a **practical** understanding of the process is extremely beneficial and has direct application to its prevention, and the manufacturing environment, as discussed below.

To the non-technically inclined, the term "fatigue" suggests this type of failure is related to the age of a component, that the material is "tired". In fact, fatigue fracture can occur within hours of a component going into service. Conversely, even



large, highly stressed components can operate for decades with no fatigue cracking or failure.

Fatigue fractures result from repeated, or cyclic, stresses. These stresses can take a variety of forms, such as bending (in one direction), reverse bending (back and forth in two directions), torsion (twisting in one or more axis) and rotation. Regardless of the variation in direction, the stress on the component at the point of fatigue fracture is always tensile stress, in which the fracture initiation site is being "stretched", or pulled in opposite directions. To illustrate this, visualize a tube which is being repeatedly bent in one direction. The side of the tube that is concave when it is bent is being compressed. The side of the tube which is convex is being "stretched", or subjected to a **tensile stress**. This is the side on which a fatigue crack will initiate.

Fatigue cracks initiate at stresses below the tensile strength of the material. Tensile strength is the stress, or load, at which a material breaks when pulled in two opposing directions. This load is a specific value for each metal alloy, varying somewhat depending on heat treating and other processing operations. These values are widely available in engineering reference manuals, typically expressed as pounds per square inch in American references. The fact that fatigue cracks can occur at stress levels below the tensile strength of a material is difficult to explain. Theories on this focus on

Continued on page 2

Fatigue

Continued from page 1

physical and structural changes at the microscopic (0.0001” or less) area of crack initiation.

Fatigue is a progressive fracture mechanism. Once a fatigue crack initiates, it is driven further into the component with each stress cycle. This crack growth process continues as long as the component is subjected to cyclic stress. Depending on the magnitude and frequency of these stresses, the crack may grow over time ranging from hours to years. Eventually, the crack advances to a point where the remaining intact cross section of the component can not sustain the next cyclic stress load – “the straw that breaks the camels back” – and complete fracture of the component occurs.

Fatigue in the “Real World”

In the “real world” fatigue *usually* – that’s usually, not always – initiates at a location that acts as a stress concentration, or focal point, to the stresses imposed on a component. Stress concentrations take a wide variety of forms. They include geometric features (such as holes, slots, corners and radii), rough areas of surface finish, welds, corrosion pits, and microstructural defects such as inclusions.

The exception to “usually”, the cases where fatigue fractures initiate from component surfaces that are free of stress concentrations, typically result from one of two causes; under-design of the component, or abusive service conditions. Just as all materials have an ultimate tensile strength, they also have a **fatigue strength**, sometimes called the fatigue limit or endurance limit. Once a component is subjected to cyclic stresses that exceed this limit, fatigue fracture occurs.

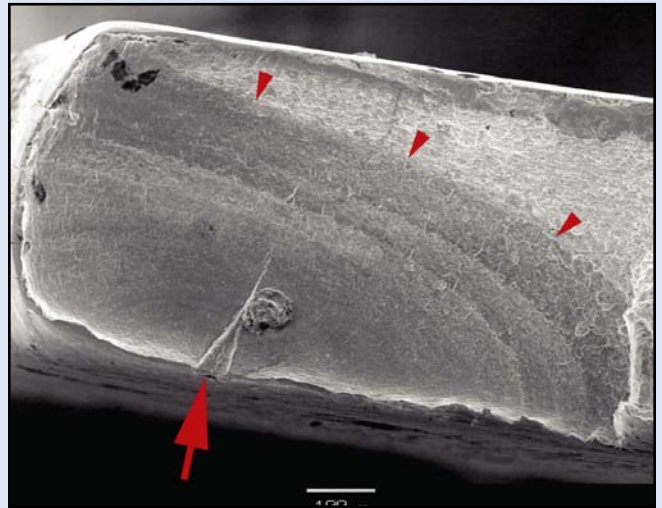
Fatigue failures of this type are less common than fatigue failures initiating from stress concentrations. Usually components are intentionally over-designed to deal with stresses several times greater than what they would be subjected to in service as a safety margin.

Fatigue Crack Initiation - The Critical Event

If the initiation stage can be prevented, fatigue fracture will not occur. It sounds so obvious and simple. It’s not. As noted above, initiation is the most complex stage of fatigue fracture. A low magnitude load, which would have no effect whatsoever on a component in a single application, can be devastating when repeatedly applied as thousands or millions of cycles. The cumulative effect of these cyclic loads are microscopic “shifts” in the material’s structure which ultimately produce a “dislocation” – at this scale it is too small to be called a crack – and the focal point of stress concentration is born. Corners, holes, rough surface finish, welds and other features only

Analyzing Fatigue

A variety of analytical tools and techniques are used to identify fatigue fractures and their root cause. These include macroscopic examination, microstructural analysis, hardness testing, chemical analysis, microprobe chemical analysis and scanning electron microscopy (SEM).



There are three stages in the life of a fatigue failure: **1 Initiation**, **2 Crack Growth (propagation)**, and **3 Final Fracture**. These stages are illustrated in the SEM image of a fractured rectangular wire above. The Initiation is indicated by the large red arrow at the lower left. The area of progressive Crack Growth extends from this arrow to the line indicated by the three smaller red arrows. Final Fracture, the point at which the remaining intact cross section of the wire could not sustain the next cyclic stress load – “the straw that breaks the camels back” – and complete fracture occurred, is the light area above the three arrows. This fracture is an example of **bending fatigue** (in one direction) initiating from a single point of origin.

Continued on page 3

accelerate the process. To further complicate the issue, vibration harmonics, dampening of the system and the environment in which the component functions add a large unknown factor. Collectively, these affects become difficult to predict in the design stage.

Confronting Fatigue - Attack and Defense

From a practical standpoint, fatigue failures present a danger to you, the manufacturer, at three points in a components life. These are the design stage, the manufacturing process, and the service environment.

Design

The design engineer is the first line of defense against fatigue fracture. He or she can't prevent failures originating in the manufacturing process or service environment, but the designer lays the foundation of prevention.

In an ideal world, each design would be subjected to extensive stress calculations and fatigue testing. In the real world this is rarely cost effective for non-critical components. Instead, accepted and "proven" parameters are applied. These typically include safety margins which are more than adequate. Typically, but not always.

Computer Aided Design (CAD), Finite Element Analysis (FEA) and a variety of other computer driven design and predictive technologies can greatly enhance the fatigue resistance of a component at the design stage. But they can not prevent fatigue failures. That's because the next two threats of fatigue failure are beyond the designer's control.

The Manufacturing Process

Manufacturing processes are a rich, though unintended, source of stress concentrations from which fatigue cracks can initiate. The list is almost endless, and includes rough machined surfaces from dull tooling or excessive feeds and speeds, burrs from cutting or drilling operations, and insufficient chamfers or corner radiuses. Welds, even when technically faultless, provide geometric stress concentrations. Defective welds and welding procedures may result in porosity and high hardness heat affected zones from which fatigue can initiate. Mechanical fasteners – bolts, screws, studs, and rivets – are highly prone to fatigue failure, either due to defects in the fastener itself, or to insufficient tightening torque during the assembly stage of the manufacturing process.

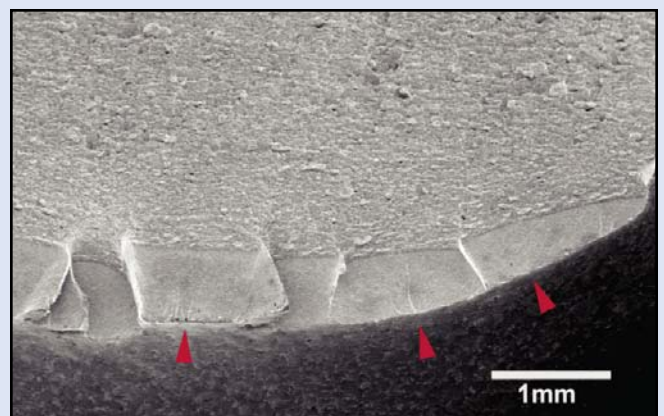
Care in manufacturing and a good quality control program will avert many of these potential sources of fatigue initiation. However, despite the best quality control program, the manufacturer is often at the mercy of their raw material supplier. These suppliers may open the door to fatigue failure through castings which contain excessive porosity or microstructural defects, mill products which are work hardened, forgings with undetected laps or seams, or gross non-metallic inclusions in any of these products. Appropriate specifications on outsourced stock and components are vital in guaranteeing their quality, but as with so many aspects of production, they are a compromise. Loose specs solicit low cost bids, but a potentially high percentage of defective products, while tight specs limit the number of vendors capable of meeting them and drive costs higher, cutting into profits.

Analyzing Fatigue Continued



The fractured crane lifting hook above is an example of **reverse bending fatigue** (back and forth in two directions). In this case, the major bending stress was applied from the bottom of the fracture as oriented in this photo, and a minor stress from the top. The darker gray area indicates final fracture in a single stress cycle. The thin horizontal band at mid fracture indicates a significant "jump" in the fracture progression that occurred in the cycle proceeding final fracture which almost, but not quite, resulted in complete fracture. This fatigue fracture initiated from multiple origins. Multiple origins are indicated by the steps, or "ratchet marks", at the outer diameter of the fracture indicated by the arrows. Ratchet marks occur when multiple fatigue cracks initiate at slightly different planes on a component's surface. As these multiple cracks progress into the component, they eventually join into a single fracture plane as show above.

Rachet marks resulting from multiple fatigue origin locations are shown at high magnification in these images (see image below and at the top of the adjacent column) taken on our Scanning Electron Microscope (SEM). Fatigue cracking penetrated only a short distance into this NASCAR Racing suspension component before



Continued on page 4

The Service Environment

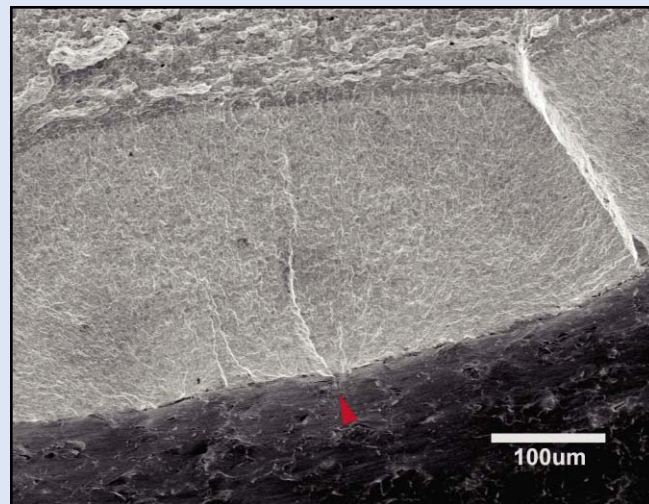
Once a product leaves the factory you, the manufacturer, have lost control and all bets are off. Abuse and inadequate maintenance are leading sources of failure by fatigue, as well as other failure modes. Failure of components or assemblies “up stream” from your product may introduce higher loads than the product or component was designed to sustain. Service environments, such as road salts or ocean front installations may instigate corrosive attack, with corrosion pits providing a fatigue initiation sight. Analysis and identification of the root cause of fatigue failures in these cases is critical in educating your customer in the appropriate use and maintenance of your product and getting them back on track as a satisfied customer.

Identifying the root cause of service environment initiated fatigue failures can be challenging. Some years ago, we provided analytical support on a lawsuit which was filed after an individual sustained a back injury when the metal leg of a “stacking chair” fractured. Stacking chairs are the type of institutional chairs you often see in school auditoriums, government office waiting rooms, etc. and are designed to be stacked, one upon the other, for more compact storage when not in use. This particular chair came from a college in Ohio. Our analysis proved low stress, high cycle fatigue as the failure mode. In other words, low magnitude stresses applied at high frequencies, in this case over a million cycles.

The chair had been in use for a relatively brief time, and even if it had seen longer service, it seemed unlikely that it had been sat in on a million occasions. This presented something of a mystery, as the failure mode was indisputable. Investigation of the service environment revealed that the chairs were used sporadically and when not in use, were stacked in a storeroom. The college staff was methodical in setting up the chairs in orderly rows in an adjacent auditorium, then stacking them from the same row end when they were no longer required, with the same chair ending up on the bottom of the stack before going back into storage. The stack was higher than the maximum specified by the manufacturer, providing a load in excess of the design limit. A survey of the area revealed that the storeroom was immediately above the main HVAC installation, the key and final piece of the puzzle. Vibration from the HVAC system, transmitted through the storeroom floor, and loads from the weight of chairs stacked in excess of the design limit provided the stresses required to initiate the fatigue crack. Once the crack grew to the point at which the remaining intact tubular leg could no longer sustain the load of a sitting person, final fracture occurred.

As with all failure analyses, the analyst must provide **specific answers** to three critical questions when evaluating a fatigue failure. They are: **1 How did it fail?** **2 Why did it fail?** and **3 What will prevent future failures?** If you have commissioned a failure analysis, and **all three** of these questions are not answered, all you have paid for is some interesting pictures and a possible lawsuit when your product fails again.

Analyzing Fatigue Continued



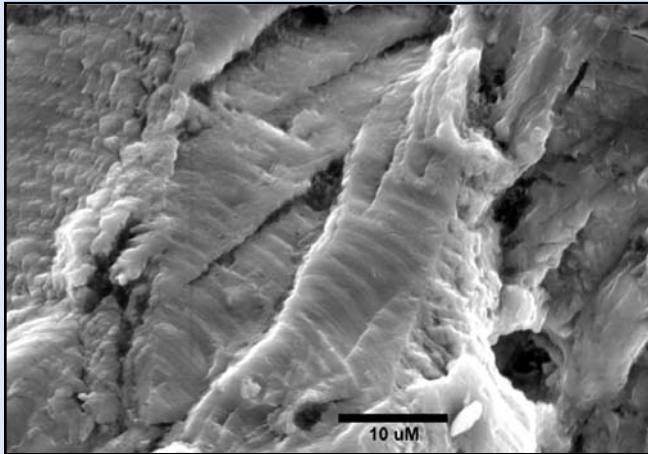
it failed completely in a single load cycle. As a result, the multiple origin fatigue cracks never progressed far enough to coalesce into a single fracture plane. Several of the individual origin sites are indicated by arrows.



The diagonal bands exhibited by the fatigue fracture of this compressor connecting rod are commonly called “arrest lines”. These indicate a change in the frequency of cyclic stresses, such as “stop-start” sequences, changes in RPM, or variations in load. The initiation site at the crankshaft journal bore (arrow) is heavily damaged. This is not uncommon in fatigue failures. As the first location to crack, the initiation site is exposed to potential relative movement of the two sides of the crack during propagation. This presents a significant challenge to the analyst in determining the root cause of fatigue cracking.

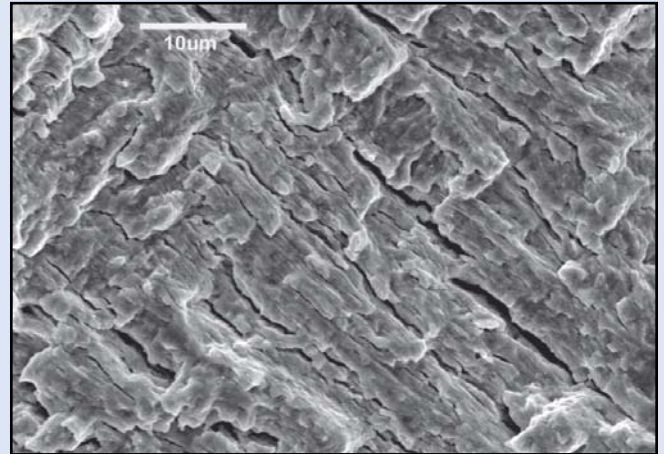
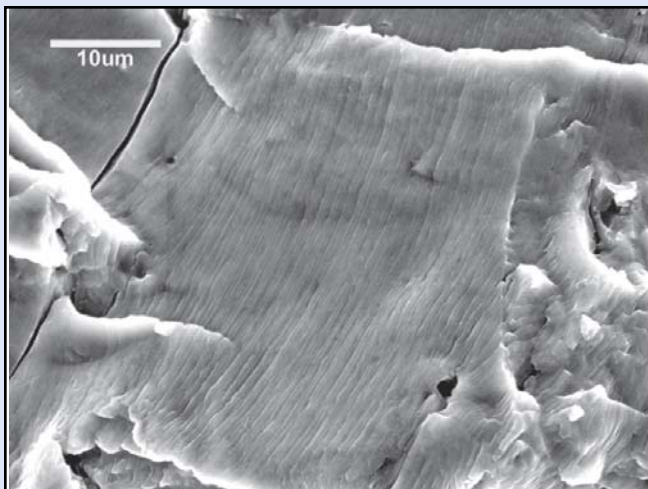
Continued on page 5

Analyzing Fatigue Continued

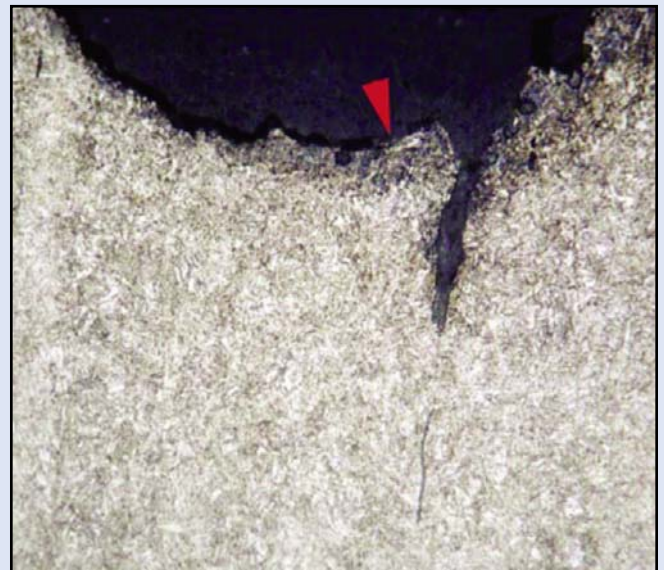


Fatigue fractures exhibit distinct features, called striations, when viewed at high magnification using Scanning Electron Microscopy. Striations appear as relatively evenly spaced parallel lines. Each striation is actually a shallow crack that results from a single load, or stress, cycle. Repetition of these cycles produces an advancing repetition of shallow cracks as shown above in this fatigue fracture in a hydraulic valve body. This process is characterized by the term, “fatigue crack propagation”.

The appearance, or morphology, of fatigue fracture striations varies depending on the magnitude and frequency of the applied load and the physical characteristics of the affected component such as hardness, microstructure and chemical composition of the alloy. These SEM images illustrate fatigue striations in an aluminum valve body (image below) and an alloy steel high pressure hydraulic cylinder (image at the top right of the adjacent column).

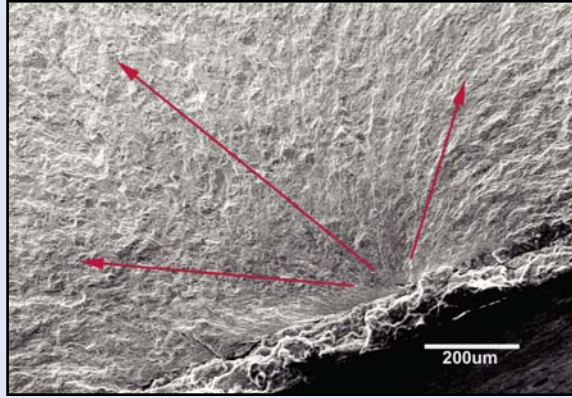


In some cases, the root cause of a fatigue failure can only be discovered by an analysis of internal characteristics of a component at the crack location. In this example below, a metallographic cross section revealed decarburization (dark phase at arrow) of the surface of a steering arm due to faulty heat treating. This carbon depleted layer has significantly reduced hardness and strength, as well as residual tensile stress, conditions highly conducive to fatigue crack initiation.

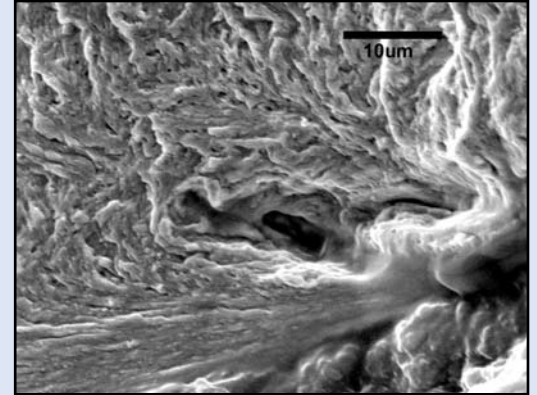


Continued on back page

Analyzing Fatigue Continued



Other types of internal defects which act as initiation sites for fatigue are apparent on the fracture surface. Examination of this brake return spring by SEM revealed fracture features which radiate from a single initiation point. Viewed at higher magnification, this initiation point exhibits a void containing a non-metallic inclusion which acted as a stress concentration.



Metallurgical Associates Inc. is an independent materials testing and engineering facility accredited by the American Association for Laboratory Accreditation (A2LA-ISO/IEC 17025). Our expertise includes failure analysis, process problem solving and process/material certification and selection. For a quote or discussion of your analytical requirements, contact Tom Tefelske (tomt@metassoc.com), Dan Kiedrowski (dank@metassoc.com) or Rob Hutchinson (robh@metassoc.com), or call (262) 798-8098 or Toll Free (800) 798-4966. Visit MAI's web site at www.metassoc.com.



PRSRF STD
US Postage
PAID
Milwaukee, WI
Permit No. 1275



2325-B Parklawn Drive
Waukesha, WI 53186
262-798-8098 • Fax 262-798-8099
Toll Free 800-798-4966
E-Mail: info@metassoc.com
Web Site: www.metassoc.com

