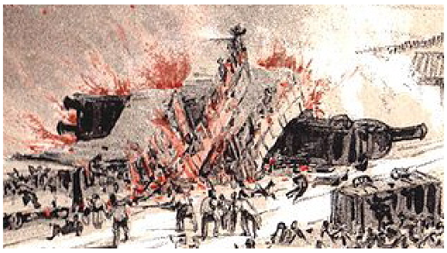
SureScreen Scientifics Division

Technical Bulletin
Issue 2 - Fatigue

Even though fatigue can be prevented by design and operation, it is said that four out of every five metal failures occur by fatigue cracking. It therefore ranks as the most important failure mode and every engineer and designer should understand fatigue.

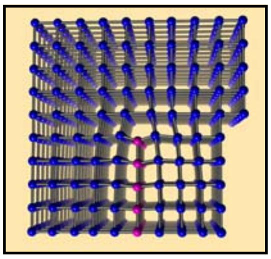
Attachments like car fog lights, street lighting columns that waft about in the breeze, and that screwdriver you always use to remove paint tin lids are all likely to fail by fatigue eventually. This is because fatigue occurs when the material progressively weakens from an applied fluctuating stress. Vibration, stress cycling, thermal cycling, repeated overloading, and repetitive use can all initiate fatigue. The most common causes of these stress cycles are rotation and vibration because they are applied so many times. The first article on failure caused by cyclic stress was published in 1837 by Wilhelm Albert. His mine chains failed and so he made what was probably the first machine to simulate fatigue. He then went on to design the first braided steel rope. The term 'fatigue' began with Jean-Victor Poncelet, in 1839 when he described metals as getting tired. One of the first disasters reported as a consequence of fatigue was the Versailles train crash, which killed up to 200 people, made worse by the system of locking passengers in the carriages for their own safety. After that, passengers were allowed to open doors themselves. It was Braithwaite reporting on common service fatigue failures and coins the term fatigue in 1854.



The Versailles rail crash (artists impression)

DISLOCATIONS

Fatigue only occurs when stresses vary, so the dead weight of a bridge on the suspension ropes will not cause fatigue, but wind loading and changes in load as traffic uses the bridge will.



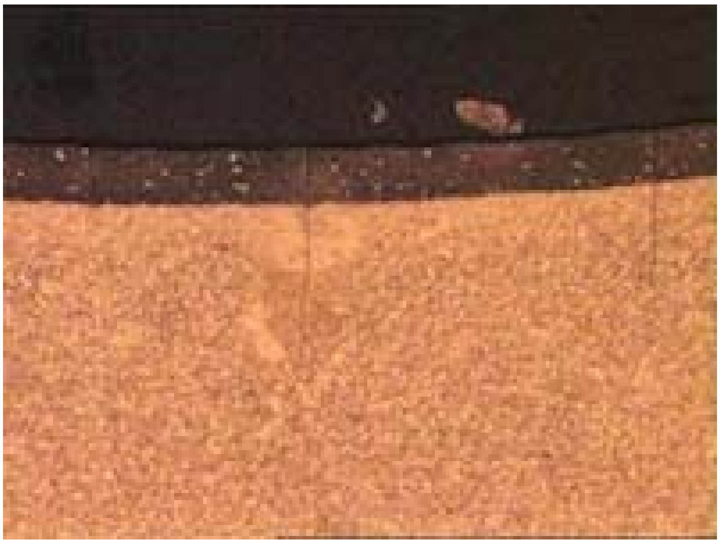
Metals are made up from atoms that sit in an organised lattice structure, but unless the metal is made from a single crystal there are numerous defects in that lattice where planes of atoms don't fit together. These are known as dislocations and we can think of them as a half sheet of paper in a paper stack. There are some 1,000,000,000,000 dislocations per cm^3. As metals deform these dislocations travel through the metal, allowing it to distort. Increasing the number of dislocations by deformation raises its strength through work-hardening. Heating the metal allows dislocations to dissipate through diffusion and one result is that the metal softens.

If fluctuating stresses are sufficient they also cause dislocation movement and they concentrate where stresses are greatest, forming small steps in the surface that develop into embryo fatigue cracks. As stresses continue, these embryo cracks continue to grow until one of them starts to accept a greater proportion of the load, it then grows leaving the embryo cracks behind. Even when the fractured face is damaged beyond recognition after the fracture, these embryo cracks can be detected to provide strong evidence that the failure occurred by fatigue. Fatigue cracks are very often transgranular—they travel across grains not round them; although embryo cracks can sometimes be intergranular - around grains not across them.

HIGH STRESS, LOW CYCLE; LOW STRESS, HIGH CYCLE

Once an embryo crack has formed, the two main features that affect the fatigue are the magnitude of stress changes, and number of times it has been applied. As the fatigue crack grows through the metal, it progressively weakens it, until only a small portion remains when it breaks, because the remaining metal can no longer resist the applied stress. The applied load must have been high when the fatigued area is small and the final fracture is a large proportion of the cross-section. When the remaining metal is small, the applied loads must have been modest. Our advice on stress level and cycles helps designers avoid the problem next time. Stress levels are usually significantly affected by changes in section, hard spots, damage, and any other feature that results in a stress concentration.

Four out of every metal failures are thought to be due to fatigue



Several embryo cracks in the surface of a component

In high-cycle fatigue an *S-N curve* or Wohler curve plots the magnitude of a cyclic stress (*S*) against the logarithmic scale of cycles to failure (*N*). Designers can use this to calculate an acceptable stress for components to prevent fatigue, provided none of the damaging effects of stress concentrations develop.

However, stresses are rarely uniform, so M. A. Miner popularised a rule in 1945 that had first been proposed by A. Palmgren in 1924. The *Miner's rule* or the *Palmgren-Miner linear damage hypothesis*, states that if we add up the different stress cycles at the difference amplitudes, once this adds up to 1 failure is almost certain. This allows us to calculate the life left, by taking away the stress cycles that the component has already undergone on its S-N curve..C is experimentally found to be between 0.7 and 2.2. Usually for design purposes, C is assumed to be 1. These simple formulae have formed the basis of modern computerised CAD systems that incorporate fatigue data.

$$\sum_{i=1}^{k} \frac{n_i}{N_i} = C$$

Although finite element analysis has made systems more accurate, they cannot accommodate metal defects, manufacturing variance, surface texture, damage and corrosion. There is also sometimes an effect in the order in which the reversals occur. Cycles of low stress followed by high stress can cause more damage than would be predicted by the rule. It also fails to consider the effect of overload or high stress which may result in a compressive residual stress. High stress followed by low stress may have less damage due to the presence of compressive residual stress.

DE HAVILLAND DH 106 COMET ACCIDENTS

The ambitious first jet propelled passenger aircraft, the de Havilland Comet used new lightweight alloys, had the first riveted and bonded fuselage, and was extensively tested before being put into service. But its square windows and access doors became its Achilles heel, resulting in 26 hull-loss accidents and 426 fatalities. Fatigue from the corner stress concentrations should have been identified, but expensive test fuselages were filled with water bags for over-pressurisation tests before being fatigue tested. We now know that local deformations can result in longer fatigue life because of the presence of compressive stresses; in this case strengthening or 'coaxing' the corners of the Comet's square doors and windows.

Comet disasters in the 1950's helped knowledge of fatigue

Chief test pilot John Cunningham likened the Comet to Concorde in the way it changed aviation for ever. A greater understanding not only of the causes of fatigue, but of fatigue investigations in general was accompanied by redesigns for Comet 2 and subsequent models and the Comet even became the basis of Nimrod and a nuclear bomber but the name and its reputation never recovered. However, we now apply compressive stresses to metal surfaces deliberately by peening or bead blasting, and this considerably improves fatigue resistance of critical components like today's jet engine parts.

EVIDENCE OF FATIGUE


Fatigue in a bolt, from several starting points

When fatigue cracks travel across a surface, the crack front advances in a series of striations like concentric ripples, often showing various colours from oxidation or corrosion unless the component ran in oil. To the expert, these striations reveal where the crack started, which direction it grew, and where the final overload fracture began. Sometimes, abrupt changes in striations reveal altered stress patterns, or relocation of the component. Subtle striation changes are indicative of variations in duty responsible for the fatigue. This might allow us to differentiate between service loads and incidents. For example storm damage on a tower crane will probably show differently to service fatigue through repetitive lifting.

THE FATIGUE LIMIT

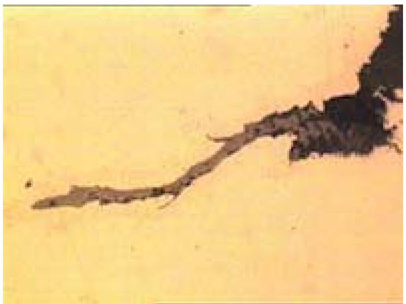
The ordering of atoms is different in different materials. Austenitic stainless steels and brasses have a lattice structure that is face centred cubic (fcc), whereas carbon steels and ferritic stainless steels have a lattice that is body centred cubic (bcc). Others, like magnesium and zinc are hexagonal close packing (hcp). Metals that are fcc or hcp have the potential to fatigue at any stress variation, no matter how low it is. However, a bcc lattice is more difficult to propagate dislocations, that is why bcc metals such as steel are usually stronger and harder. As a consequence, these materials will not fatigue if the stress change is below a certain value, known as the fatigue limit. By designing components that operate below the fatigue limit, it should be possible to prevent fatigue completely. But corrosion can remove the fatiguie limit even in bcc metals because the corrosion activation removes the resistance to develop embryo cracks. In these components, surface protection is important.

This effect of corrosion can dominate the progression of fatigue, resulting in a similar mechanism known as corrosion fatigue. Here, there is a balance between the fatigue stress and the number of

cycles, and the effects of corrosion in propagating the crack. Those failures that have deeply penetrating fatigue cracks that are filled with oxide and relatively blunt-tipped are mostly driven by corrosion, whereas those which retain a sharp tip are more likely to be dominated by fatigue, with corrosion being a secondary effect. Understanding these features helps designers overcome the problem in replacements. Notable corrosion fatigue situations we have encountered in our work include railway lines, (especially on dock railways where there is salty water), water towers, car chassis, boilers and power stations.

WHY THE LOOSE BOLT FAILS FIRST

Despite much being known about fatigue these days, some aspects still confound engineers. For example consider a set of bolts that hold things together, such as the bolts holding your car wheel in place. Only loose bolts will fail by fatigue. This seems counter-intuitive until we consider how the stresses are applied to the bolt.



Each bolt is used to clamp the joint together and at each position the stress in the bolt is balanced by the clamping force between the two plates. Tight bolts develop a high clamping force, but undertight bolts develop a modest clamping force. However the bolt only sees changes in its stress once the working force overcomes the clamping force, fluctuating, fatigue stress only affect the bolt once applied stresses exceed the clamping force. So only undertight bolts see fatigue.

Conversely, if the bolt is tightened to a high torque, the clamping force is very high, and the working stress is unlikely to unseat the joint, and so the bolt stress will not be affected by fatigue stresses. In fact it has been argued that all failures in bolts are due to under-tightening, and if they are tightened correctly fatigue cannot occur. From a practical point of view this is not quite correct since the joint can be affected by corrosion, thermal cycling etc,. Sometimes the bolt is too small for the application so it cannot generate enough clamping force, or there could have been excessive shock loading that stretched the bolt.

Therefore, while the appearances of fatigue can be readily apparent to the inexperienced, most fatigue failures are quite complex and require an expert examination. In fact some fatigue failures don't show striations at all, and require an electron microscope and magnifications of 25,000 plus to see them. Gearbox components can fit into this category because the oil film prevents the colouration on striations that usually reveals them.

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