

A Practical Discussion on *Fatigue*

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Introduction

According to independent studies by Battelle in 1982, between 80-90% of all structural failures occur through a fatigue mechanism, with an estimated annual cost in the US of about \$1.5B. Furthermore Battelle concluded this could be reduced by 29% by application of current fatigue technology.

In this paper we overview the physical behaviour responsible for fatigue from initiation to final component failure.

The Physics of Fatigue

Fatigue is defined as 'Failure under a repeated or otherwise varying load, which never reaches a level sufficient to cause failure in a single application.' Fatigue cracks always develop as a result of cyclic plastic deformation in a localised area. This plastic deformation often arises, not due to theoretical stresses in a perfect part, but rather due to the

... between 80-90% of all structural failures occur through a fatigue mechanism. However, the adoption of fatigue prediction in the finite element community, where most structural engineering decisions are made, has been limited.

presence of a small crack or pre-existing defect on the surface of a component, which is practically undetectable and clearly unfeasible to model using traditional Finite Element techniques.

August Wöhler was the first to study fatigue and propose an empirical approach. Between 1852 and 1870, Wöhler studied the progressive failure of railway axles. He constructed the test rig shown in Figure 1, which subjected 2 railway axles simultaneously to a rotating bending test. Wöhler plotted the nominal stress versus the number of cycles to failure, which has become known as the SN diagram. Each curve is still referred to as a Wöhler line. The SN method is still the most widely used today and a typical example of the curve is shown in Figure 1.

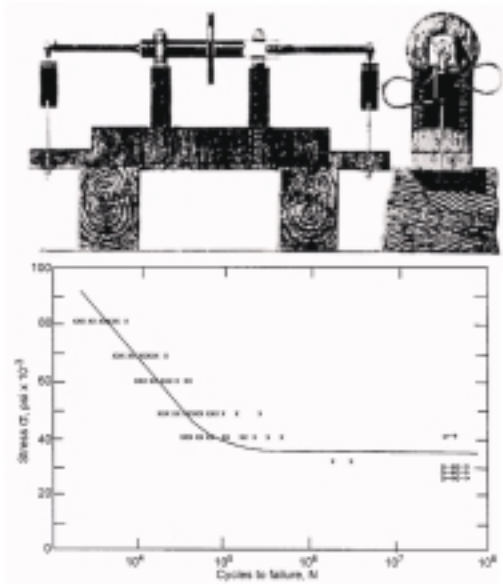


Figure 1 Wöhler's Rotating Bending Fatigue Test

Several effects are notable about the Wöhler line. First, we note that below the transition point (approximately 1000 cycles) the SN curve is not valid because the nominal stresses are now elastic-plastic. We will show later that fatigue is driven by the release of plastic shear strain energy; therefore above yield, stress loses the linear relationship with

strain and cannot be used. Between the transition and the endurance limit (approximately 10^7 cycles), SN based analysis is valid. Above the endurance limit the slope of the curve reduces dramatically and as such this is often referred to as the 'infinite life' region. In practice, however, this is not really the case. For example, Aluminum alloys do not exhibit infinite life, and even steel does not exhibit infinite life when subjected to variable amplitude loading.

With the advent of modern magnification techniques, fatigue cracks have been investigated in more detail. We now know that a fatigue crack initiates and grows in a two-stage process. In the early stages a crack is seen to grow at approximately 45° to the direction of applied load (following the line of maximum shear stress). After traversing two to three grain boundaries its direction changes and then propagates at approximately 90° to the direction of the applied load. These are known as Stage I and Stage II cracks and are illustrated in Figure 2.

If we observe the development of a Stage I crack at high magnification we see the alternating stress leads to persistent slip bands forming along the planes of maximum shear. These bands slip back and forth, much like a deck of cards, and give rise

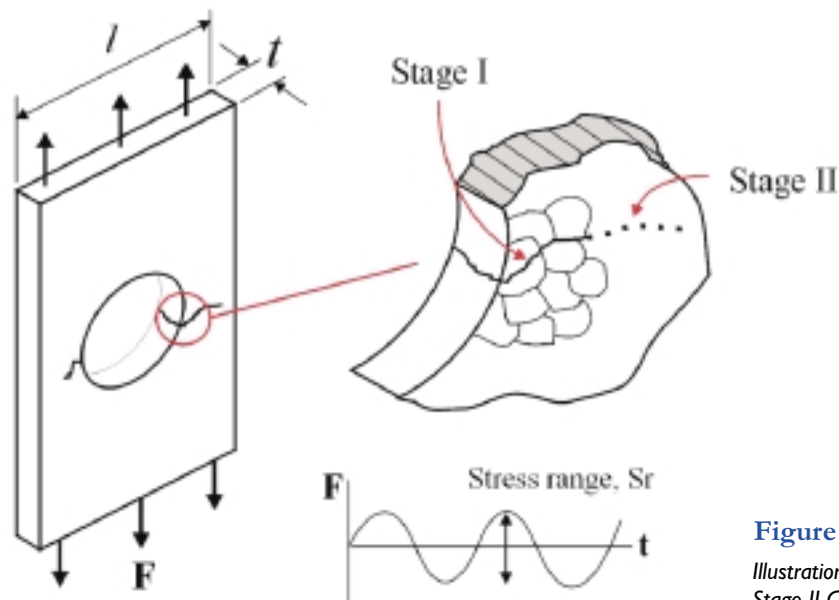


Figure 2
Illustration of Stage I and Stage II Crack Growth

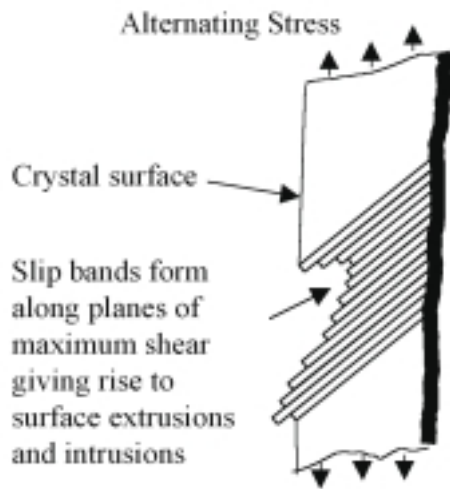


Figure 3 Illustration of persistent slip bands

to surface extrusions and intrusions. The surface intrusions essentially form an 'embryonic' crack and are illustrated in Figure 3. The Stage I crack propagates in this mode until it encounters a grain boundary, at which point it briefly stops until sufficient energy has been applied to the adjacent grain and the process continues.

After traversing two or three grain boundaries the direction of crack propagation now changes into a Stage II mode. In this stage the physical nature of the crack growth is seen to change. The crack itself now forms a macroscopic obstruction to the flow of stress that gives rise to a high plastic stress concentration at the crack tip. This is illustrated in Figure 4. It should be noted that not all Stage I cracks evolve to Stage II.

To appreciate the Stage II growth mechanism we need to consider what happens at the cross section of a crack tip during a stress cycle. This is illustrated in Figure 5.

The fatigue cycle starts when the nominal stress is at point 'a'. As the stress increases in tension through point 'b' we notice the crack tip now opening giving rise to local plastic shear deformation giving rise to local plastic shear deformation while the crack extends into the virgin metal at point 'c'. As the tensile stress now decreases through 'd' we observe the crack tip

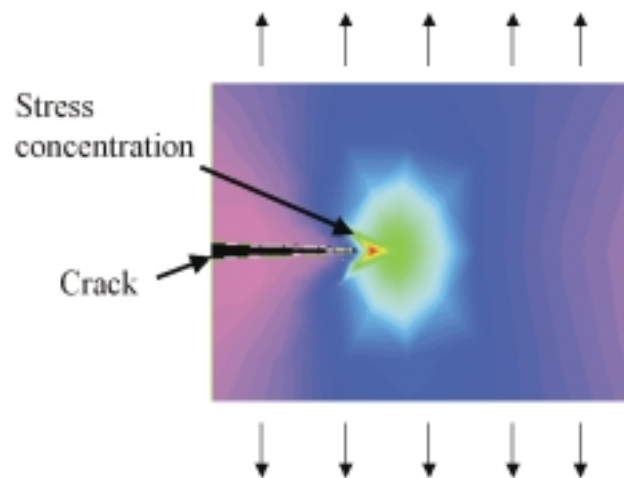


Figure 4 High plastic stress concentration at the tip of a Stage II crack

closing and the permanent plastic deformation gives rise to a distinctive saw tooth profile known as a 'striation'. On completion of the cycle at point 'e', we observe that our crack has now advanced through length Δa , and has formed an additional striation. We can also appreciate that the extent of crack growth is proportional to the range of elastic-plastic crack tip strain applied. Higher cycle ranges give rise to greater Δa .

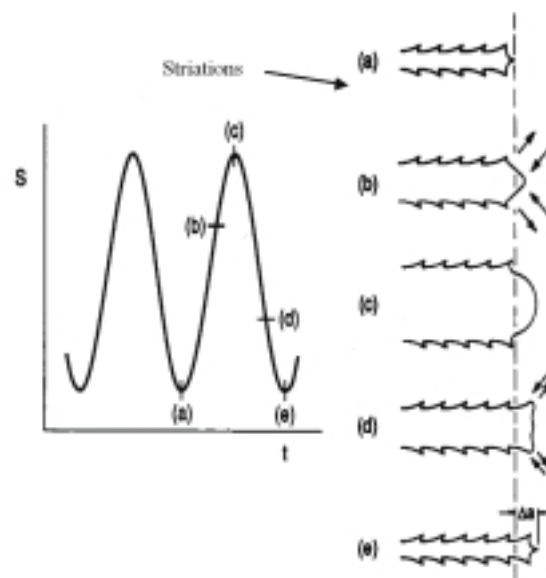


Figure 5 Illustration of Stage II crack growth

Factors Affecting the Rate of Fatigue Crack Growth

In this section we investigate and explain conceptually the effect of the following parameters on fatigue crack growth rate:

- Stress or Strain Range
- Mean Stress
- Surface Finish and Quality
- Surface Treatments
- Sequence effects

We will see that Stress or Strain range has the most important influence.

Stress or Strain Range

From the previous description we notice that in both Stage I and Stage II growth, crack development arises through plastic shear strain on a microscopic scale. Consider, therefore, the plastic shear strain forming along the Stage I slip planes or at the tip of a Stage II crack as a result of the nominal stress time history shown in Figure 6.

In Figure 6a, we see the nominal stress rise with time. On a microscopic level, in the presence of a crack or pre-existing defect, the stress and strain become plastic and can be plotted in the stress vs strain diagram shown. Figure 6b now shows what

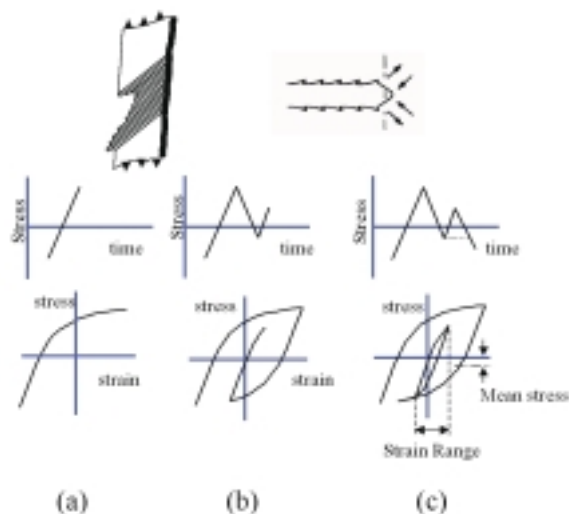


Figure 6 Elastic-plastic stress and strain along a slip plane and at the root of a crack

happens when the nominal stress is reduced and then raised again by a smaller amount. Again the local stress vs strain can be plotted showing the effect of local yielding. Finally Figure c shows another reduction in the nominal stress. From the stress vs strain plot we now see the formation of a hysteresis loop. A loop in the stress vs strain plot indicates release of strain energy where the total energy released is equal to the area of the loop. Essentially we have released a quantity of shear strain energy and this has been expended in sliding the slip planes or advancing the Stage II crack.

From this illustration we therefore see that a 'quantum' of shear strain energy is released when the nominal stress is cycled into tension and then back again. Also, the larger the stress cycle, the greater the energy released. From the SN curve shown in Figure 1, we see that fatigue life drops exponentially as the stress cycle range increases.

Mean Stress

The mean stress (residual stress) will also affect the rate of fatigue damage. Viewed conceptually, if a mean tensile stress is applied to a Stage II crack then the crack is being forced open and any stress cycles applied will therefore have a more pronounced affect. Conversely, if a mean compressive stress is applied then the crack will be forced shut and any stress cycle would first of all have to overcome the pre-compression before any growth could ensue. A similar concept applies for a Stage I crack.

Surface finish

Since fatigue cracks usually initiate from a pre-existing defect at the surface of a component, the quality of the surface will greatly influence the chance of a crack initiating. While most material test specimens have a mirror finish and therefore achieve the best fatigue lives, in practice most components are seldom as good and so we need to modify the fatigue properties. Surface finish has a more significant effect on the fatigue of components subjected to low amplitude stress

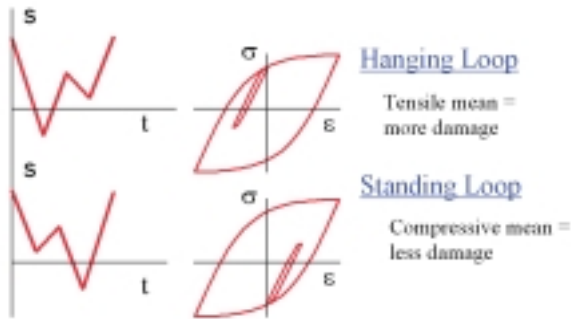


Figure 7 Illustration showing the effect of cycle sequence

cycles. The effect of surface finish can be modelled by multiplying the SN curve by the surface correction parameter at the endurance limit.

Surface Treatments

Surface treatments can be applied to improve the fatigue resistance of a component. These usually work by inducing a residual compressive stress at the surface. Under low amplitude cycles the stresses at the surface are significantly lower or even remain compressive. Therefore the fatigue life is greatly improved. We note, however, that this effect is only true for components subjected to low amplitude stress cycles. If large amplitude cycles were applied then these would start to overcome the pre-compression and the benefit would be lost. The effect of surface treatments can be modelled in the same way as surface quality.

Sequence effects

The sequence in which cycles are ordered can influence the fatigue life. Consider the two time histories shown in Figure 7. Both appear to consist of two cycles having the same range and mean stresses. However, if we plot the elastic-plastic response we see that the smaller cycle has a tensile mean in the first example and a compressive mean in the second. Therefore the first example will create more damage than the second. For most practical analyses, sequence effects are insignificant because the probability of one sequence occurring

is equal to that of the other. However, it is worth bearing in mind when planning some simplified and idealised loading sequences.

Conclusions

In this paper we have attempted to discuss the physics behind fatigue analysis in a practical and conceptual way. The main effects that influence fatigue performance have been addressed. We hope this paper has helped form a clearer picture on the key issues related to fatigue failure.