Understanding Fatigue

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In the gas turbine industry, whether it is in the power generation or propulsion sectors, durability is perhaps the most significant attribute a gas turbine can possess. The nature of the tasks performed dictate the impact of premature wear or failure. In the commercial land/sea based arena (power generation, pipeline pumping, land or sea propulsion) the consequences of service interruption are at minimum a loss of revenue. In the commercial aviation sector safety is of paramount concern, while military engines must meet force readiness as well as safety demands.

Figure 1. The airfoil tip and a portion of this turbine blade platform came apart due to high cycle fatigue (HCF) during an ultrasonic cleaning operation. The blade material is a single crystal alloy.

The repetitive or "cyclic" loading of turbine components associated with generator/pump duty cycles, airline take-off/cruise, or combat mission throttle excursions is a principal source of degradation in turbomachinery. Even manufacturing processes can cause fatigue damage (Figure 1), commonly referred to as "metal fatigue."

Actually, fatigue degradation is not confined to metals. Most engineering materials (ceramics, composites, aggregates, etc.) are also susceptible to fatigue damage. To understand the nature of fatigue it is first necessary to consider some basic aspects of material behavior.

Fundamental Material Properties

The strength of a material is a measure of its ability to resist deformation (i.e. being stretched, bent, etc.). Engineers and technicians determine strength by conducting a "tensile" test. In this test a specimen similar to that shown in Figure 2 is employed.

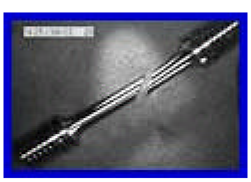

Figure 2. This tensile specimen has been tested to rupture. The metal is a "single crystal" turbine blade alloy and has separated along a crystallographic slip plane.

The test is conducted in a tensile test machine (Figure 3). The tensile specimen is pulled apart lengthwise (loaded in axial tension) until fracture occurs. The tensile machine can continuously record incremental values of load and the resultant elongation of the test specimen. A load versus deflection curve is obtained from the tensile test.

Figure 3. A servo hydraulic test machine capable of conducting tensile and fatigue tests, and a variety of other material evaluation tests, including those in aggressive environments.

From load we can determine stress. From deflection we can determine strain. The tensile strength of a material is illustrated in a stress versus strain curve. Stress is expressed in units of pounds per square inch (psi) and is calculated by dividing pounds of applied load by the specimen's cross sectional area. Engineering strain is obtained by dividing the change in specimen length by the initial specimen length. The result is expressed as % strain. The results of the test are shown graphically in the stress vs. strain curve (Figure 4) where stress is plotted on the vertical axis and strain is plotted on the horizontal axis.

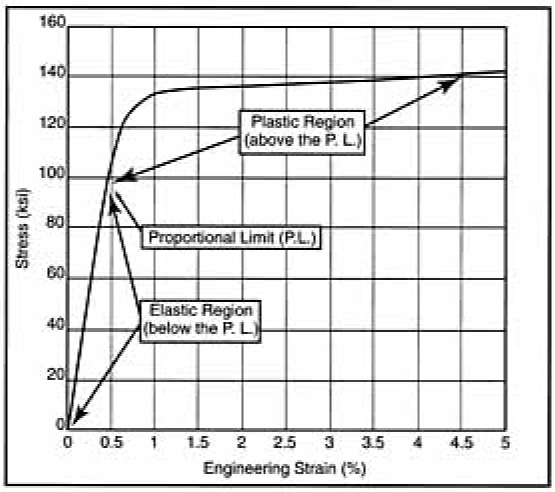

Figure 4. The stress vs. strain curve for a typical gas turbine alloy. The sample starts to deform plastically at about 100,000 psi and breaks at just over 140,000 psi (140ksi). This curve indicates the strength of the alloy under a static (non-cyclic) load. It would break much sooner (from fatigue) under a vibratory load.

As indicated in Figure 4, there are two distinctly different regions of the stress versus strain curve. In the "elastic" region stress and strain increase linearly up to the proportional limit (P.L.). In this region, removing the load allows the strain to return to zero. Beyond the elastic region we enter the "plastic" region where increases in stress result in disproportionately large increases in strain. Removing the load from the tensile specimen in this region will not result in the strain returning to zero. The specimen is said to be plastically deformed or yielded.

Fatigue

There are three commonly recognized forms of fatigue: high cycle fatigue (HCF), low cycle fatigue (LCF) and thermal mechanical fatigue (TMF).

The principal distinction between HCF and LCF is the region of the stress strain curve where the repetitive application of load (and resultant deformation or strain) is taking place.

HCF is characterized by low amplitude high frequency elastic strains. An example would be an airfoil subjected to repeated bending. One source of this bending occurs as a compressor or turbine blade passes behind a stator vane. When the blade emerges into the gas path it is bent by high velocity gas pressure. Changes in rotor speed change the frequency of blade loading. The excitation will at some point match the blade's resonant frequency causing the amplitude of vibration to increase significantly.

To clarify this concept we need to return to the stress strain curve. When a tuning fork is struck it vibrates at its resonant frequency. As the beams of the fork bend back and forth at hundreds of cycles per second the amplitude of the bending results in strains that are confined to the elastic portion of the stress strain curve. As the vibrations die down and stop the fork returns to its original shape. Only elastic strains have occurred so no permanent deformation has taken place.

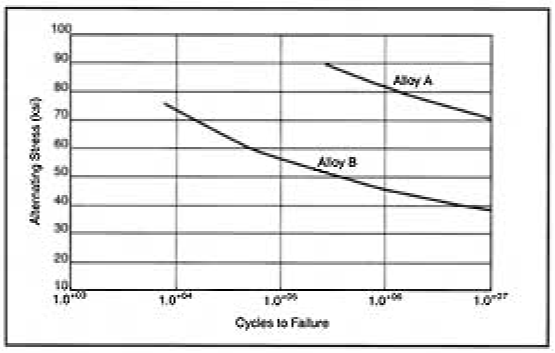

Figure 5. **A typical plot of HCF test data. Alloy A can withstand alternating stresses of up to 70ksi for 10 million cycles (almost forever) without breaking. Alloy B can withstand such stresses for only about 40,000 cycles before failure. For Alloy B not to fail, it would have to be exposed to alternating stresses of less than 40ksi.**

The tuning fork can endure tens of millions of cycles under these conditions but eventually it will fail due to HCF. A typical plot of HCF test data is shown in Figure 5. The example of how a turbine, fan or compressor airfoil can become elastically stressed describes one source of HCF excitation.

LCF is the mode of material degradation when plastic strains are induced in an engine component due to the service environment. The results of a typical LCF comparison are shown in Figure 6.

LCF is characterized by high amplitude low frequency plastic strains. If we pull the beams of the tuning fork apart until they are permanently bent we have imparted one half of an LCF cycle. The act of permanently bending means that we have exceeded the elastic limit point on the stress strain curve and have crossed over into the plastic region. Forcing the beams back into the original position will require them to bent or "yielded" thereby completing one LCF cycle. The tuning fork can endure only a very few of these cycles before it will fail due to LCF. In a turbine blade these large strains occur in areas of stress concentration.

Most turbine blades have a variety of features like holes, interior passages, curves and notches. These features raise the local stress level to the point where plastic strains occur. Turbine blades and vanes usually have a configuration at the base referred to as a dove tail or fir tree. This feature is used to attach the blade to the turbine disk. As engine rotational speed increases centrifugal forces result in local plastic strains at the attachment surfaces resulting in LCF damage.

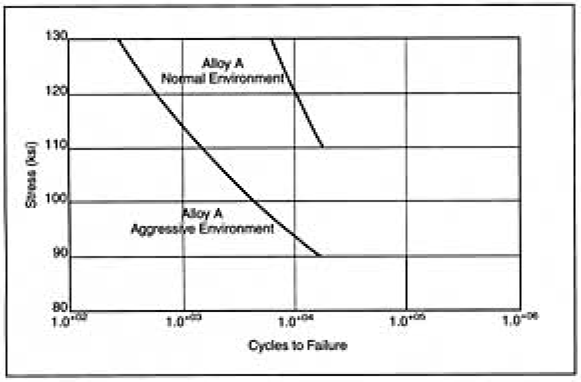

Figure 6. This LCF data was developed to determine the effects of an aggressive environment (such as extreme heat, cold, etc.) on fatigue life. Fatigue test results in the aggressive environment (left curve) were an order of magnitude lower than the baseline fatigue life tested in air (right curve). For example, in a normal environment, under 120ksi alternating stress, Alloy A would fail at about 10,000 cycles. In an aggressive environment, the same Alloy would fail at about 600 cycles.

Thermal Mechanical Fatigue (TMF)

So far we have discussed strains that result in a material when it is stressed. In the case of TMF (present in turbine blades, vanes and other hot section components) large temperature changes result in significant thermal expansion and contraction and therefore significant strain excursions. These strains are reinforced or countered by mechanical strains associated with centrifugal loads as engine speed changes. The combination of these events causes material degradation due to TMF.

How Fatigue Data are Obtained

Engineers and technicians obtain fatigue data much as they do tensile data. The test machines are similar to that shown for tensile tests and similar specimens are used. The chief difference lies in the application of load. In an HCF specimen test, the load is applied to the specimen at 30 to 60 cycles per second and often at much higher frequencies.

In engine components where HCF is a concern, turbomachinery designers observe what is referred to as a material's fatigue strength. This is determined by running multiple specimen tests at a number of different stresses. The objective is to identify the highest stress that will produce a fatigue life beyond ten million cycles. This stress is also known as the material's endurance limit. Gas turbines are designed so that the stresses in engine components do not exceed this value including an additional safety factor.

LCF testing is conducted in a similar fashion, the chief difference being the need for higher (plastic) loading and lower frequencies. As shown earlier, the graphic results appear similar but the lives are much lower and there is no "fatigue strength" per se. Still, components subjected to

LCF loading are designed such that stresses remain well below the average lives determined in the LCF tests.

The fatigue life graphs are informative in a number of ways. In addition to determining the maximum stress allowed for a component life to meet ten million cycles, they can also be used to compare the durability of different alloys and show temperature and other environmental effects.

Tensile (stress vs. strain) curves and fatigue (stress vs. life) curves also show us why fatigue is such a concern. If we look at the tensile behavior shown in Figure 4, we can see that the breaking strength is over 140,000 psi. This means that 140,000 lbs. can be hung from a bar with a one square inch cross section indefinitely. If we look at the HCF plot in Figure 5, we can see that the fatigue strength for Alloy B is less than 40,000 psi. This tells us that for infinite life a material's ability to resist a cyclic (vibratory) load is much lower than its ability to resist a sustained load.

Fatigue Mechanisms

But how and why do fatigue cracks start? To understand the micromechanics of fatigue crack initiation, we need to know something about metals. Metals are crystalline in nature. Metal crystals are referred to as grains and are composed of uniform layers of atoms stacked one upon another like eggs in a crate. The atoms occupy regular positions in what is called a lattice structure. Atomic forces keep the atoms in place.

When a grain deforms these layers attempt to slide past each other in a shearing process called slip. If the slip displacement is small (confined to the elastic portion of the stress vs. strain curve) the deformation will be reversible. If the slip is large enough (exceeding the P.L.) plastic deformation will occur along the slip plane and the slip will be irreversible. As fatigue cycles accumulate, the number and intensity of the bands increase and the microstructural damage is concentrated (localized) onto a few intense slip bands. The process continues until a persistent slip band (light diagonal band in Figure 7) forms.

Figure 7. Multiple slip bands can be seen in this HCF specimen test that was suspended at ten million cycles. An intense slip band has formed (lower left to upper right) and a distinct offset in the gage section (lower left edge of sample) can be seen. The specimen material is a single crystal (a single large grain) turbine blade alloy. The dark lines are primary dendrites, a part of the alloy microstructure.

Eventually a fatigue crack will form along these slip bands. The previous discussion is somewhat simplified in that metals are non-homogeneous, containing numerous microscopic discontinuities such as grain boundaries, microscopic pores, carbides and other hard particles generically called defects. These discontinuities inhibit slip and act as local stress concentrators. These features ultimately become fatigue crack initiation sites.

The Importance of Defects

If we look at our stress strain and fatigue curves it would appear that higher alloy strength equates to superior fatigue life. But alloy microstructure can be more important than strength. LCF and HCF cracks frequently initiate at the intrinsic defects previously mentioned. This is not to say that the material is defective. Intrinsic defects can be likened to the knots in knotty pine boards. Defects are a normal feature of an alloy's microstructure. Still, as boards can be selected with fewer knots, alloys can be produced with fewer defects. In the alloy comparison shown in Figure 5, "Alloy A" exhibits clearly superior durability (70ksi vs <40ksi). What is not shown, but is especially interesting, is that Alloy A is significantly lower in strength than "Alloy B." The improvement stems from a low defect content obtained in Alloy A by special heat treatments.

Summary

Although this discussion has been directed toward non-engineers, some more advanced issues have been touched upon for the benefit of those readers working in the field. Comparisons drawn between wood and superalloy defect distributions are a simplification, but are useful in conveying a concept.

That being said, for the layman, in a sense, fatigue can be likened to a jackhammer constantly pounding on a concrete sidewalk. A concrete slab can indefinitely support a tremendous constant load; but a relatively small load, applied at a high frequency, can cause failure in a surprisingly short time.

For those non-engineers, and engineers new to this area, it is hoped that you now have a better understanding of fatigue and how fatigue life is determined. For those engineers working in Life Prediction, Materials Behavior, Design and Structures Technology, it is hoped that some of this information has been helpful to you as well.