Loads and materials

The parts in a gas turbine are subject to several kinds of loads. To cope with these loads, the right materials need to be used. In this chapter, we'll take a look at the loads and materials used.

1 Loads and failures

We will take a look at the load types that are present in a gas turbine. We also examine how these load types can cause failure.

1.1 Load types

A lot of types of loads occur in the gas turbine. Let's take a look at a few

- **Centrifugal loads** are caused by high rotational speeds. The centrifugal force is proportional to $m\omega^2 r$.
- **Thermal loads** are caused by temperature changes. These loads are only present if parts can't expand freely. This can be caused by two reasons. Either the two connected parts are heated differently, or the parts have a different **coefficient of thermal expansion** (CTE).
- **Vibrational loads** occur when an object is excited by a frequency close to its **natural frequency**. We generally want to prevent vibrational loads. Therefore, components need to be designed such that their natural frequency isn't near to a frequency occurring in the gas turbine.
- **Pressure loads** occur due to pressure differences. They mainly occur in the compressor and the turbine. This causes bending of the blades. To prevent this, the blades are usually made such that the pressure loads are cancelled out by the centrifugal loads.

1.2 Types of failure

There are many ways in which a part of a gas turbine can fail. Again, we examine a couple of them.

- **Static failure** (or **overload**) is quite simple. The present load is bigger than the material strength. To make sure that static failure does not occur, the right material needs to be selected. Special attention has to be payed to the **yield strength** and the **ultimate strength**. These parameters often depend on the temperature T. Also, a (usually big) safety margin has to be taken into account.
- **Fatigue** is a failure type caused by a cyclic load. We can make a distinction between **High Cycle Fatigue** (HCF) and **Low Cycle Fatigue** (LCF). In HCF, a lot of cycles (usually over 10^6) are needed to cause fatigue failure. Only elastic stresses are present. HCF failure is often caused by vibrations. LCF is fatigue due to inelastic stresses.

  An important parameter for fatigue is the number of cycles until failure. This can be derived from a **Wöhler curve**. In this curve, the number of cycles until failure is plotted for various stress levels. The Wöhler curve generally depends on the temperature.

  Fatigue failure is caused by growing cracks. Cracks can be initiated by **foreign object damage** (FOD), like dirt or birds hitting the gas turbine. After the crack has been initiated, it will grow. The **crack growth** da/dN is expressed in the increase in crack distance da per cycle dN. Crack growth occurs in three stages. First, there is the **slow grack growth region**, in which the crack growth is low. Second, there is the **power law region**. In this region, the crack growth increases. It does this according to the **Paris law**

$$\frac{da}{dN} = C\left(\Delta K\right)^n, \tag{1.1}$$

where C and n are constants. ΔK is the **load factor**. The third and last step is **final failure**, in which the growth rate diverges.

- **Creep** is inelastic deformation, caused by low forces at high temperatures. The magnitude of the **creep rate** $\dot{\varepsilon}_{cr}$ highly depends on the temperature T. It depends on the stress level σ as well. The **creep strain** ε_{cr} shows a similar behaviour as the crack growth. Again, there are three stages. This time, the second stage is characterised by a power law like

$$\dot{\varepsilon}_{cr} = AT^n\sigma^m. \tag{1.2}$$

- In **corrosion**, a corrosive medium (like oxygen, nitrogen or sulfur) reacts with the metal surface. Due to this, an embrittled layer is formed, from which large flakes can break away. Corrosion generally doesn't cause failure itself, but it encourages the other failure types.

Different parts are subject to different types of failure. Fatigue mainly occurs in rotating/moving parts, like the compressor and the turbine. Damage caused by **thermal degredation** is mostly present in parts with high temperatures, like the combustion chamber and the turbine.

2 Building the gas turbine

Let's take a look at how we build a gas turbine. What materials do we select? What coatings do we apply? And how do we make sure that the gas turbine stays in working order?

2.1 Materials

First, we look at the compressor blades. They are subjected to high mechanical loads, due to the high rotational speed. We thus want to have materials with a high **specific strength** σ_{UTS}/ρ and a high **specific stiffness** E/ρ. Stainless steel, titanium and nickel alloys are suitable for this. Of these three, titanium gives the largest weight savings. Drawbacks are the high cost of titanium and its flammability.

Now we examine the turbine blades. The first stage turbine rotor blades are the most severely loaded components in the gas turbine. We thus want to have a high quality material. It should have a high specific strength, a high thermal mechanical fatigue resistance, a high creep resistance, sufficient ductility (to sustain FOD) and a reasonable oxidation and corrosion resistance. All these properties need to be maintained at high temperatures. Although **blade-cooling systems** limit the temperature as much as possible, the turbine blades will still get quite hot.

2.2 Manufacturing

Manufacturing gas turbine parts can be quite difficult. This especially holds for the turbine blades. Due to the high-strength materials, forging is not possible. **Casting** techniques are therefore used. To be precise, the method of **investment casting** is used.

Coatings are also often applied. This can be done for different reasons. First of all, coatings protect against oxidation/corrosion. A second reason for applying coatings, is for thermal protection. These so-called **thermal barrier coatings** (TBCs) have a low thermal conductivity. They therefore thermally insulate the part they're covering.

When applying coatings, either **diffusion coating** or **overlay coating** is used. In diffusion coating, a chemical reaction is used to put the coating onto the metal part. In overlay coating, the coating is simply sprayed/deposited onto the part.

2.3 Design philosophies

Let's ask ourselves an important question: When do we replace parts? The answer to this question depends on the **design philosophy** we apply.

In the **safe-life** philosophy, no inspections are applied. The part is simply replaced after it has reached its **life limit**. The life limit is determined using Wöhler curves. A downside of this method is that parts are often replaced, that do not need replacing yet. Also, components are often found damaged before the life limit is reached.

In the **damage tolerance** philosophy, the possibility of cracks/flaws is taken into account. Therefore, regular inspections are performed. These inspections are performed such that cracks are detected before they can cause serious harm. However, at the end of the life limit, the parts are replaced, no matter if damage has occurred or not.

In the **retirement for cause** (RFC) philosophy, life extension beyond the life limit is applied. To do this, **risk assessments** are used. First, the allowable risk is set. This allowable risk then determines the increase of the life limit. In the RFC philosophy, it is exactly known how much risks are taken. This is an advantage.