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Alloys and aircraft

Few people think about what an aircraft is made from, but new metal alloys could be part of the key to make making jet engines quieter and more efficient. At any one time, there are over 500 000 people in the air flying! As ***Divya Vadegadde Duggappa*** *of Cambridge University explains, one of the things that make this possible is metallurgy.*

Key words
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If you have boarded a flight, you might have noticed large, spinning blades that resemble a big fan. This is a jet engine, which makes it possible for an aircraft to fly. The big fan at the front constantly spins and sucks in large volumes of air from the atmosphere. The compressor blade squeezes the air to 1/50 of its volume. The compressed air is mixed with the jet fuel and an electric spark ignites the mixture creating a small explosion in the combustion chamber. This causes the squeezed gas to expand and shoot out at the nozzle passing through another group of blades called turbine blades, at the back of the engine. This drives the plane forward.

The temperature of the air that passes over the turbine blades is higher than 1500°C. To protect the turbines from such extreme temperatures they are coated with ceramics, which have low thermal conductivity. However, the temperature experienced by the turbine blades is still as high as 1100°C so the materials used in this part of the jet engine need to be able to withstand these high temperatures.

Figure 1 shows the parts of a jet engine. The fan and compressor blades are made of titanium-based materials and the turbine blades are nickel-based.

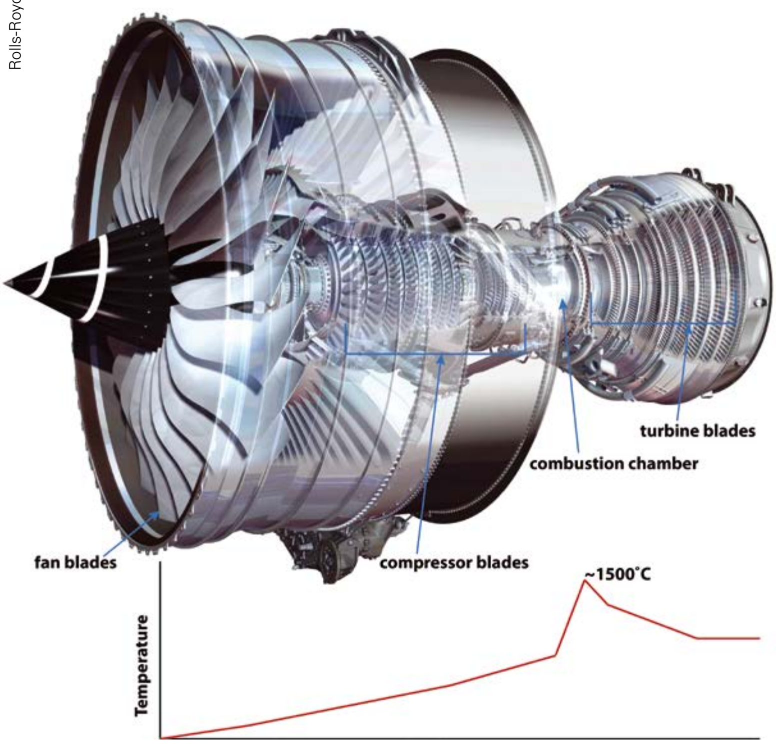

Figure 1 *The parts of a jet engine; the turbine blades must withstand the highest temperatures.*

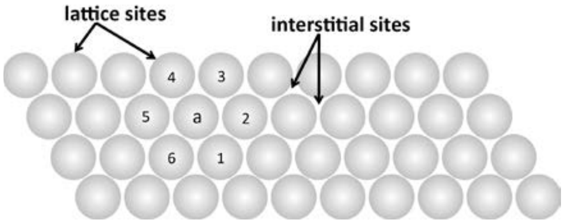

Figure 2 *The arrangement of atoms in two dimensions in a pure metal.*

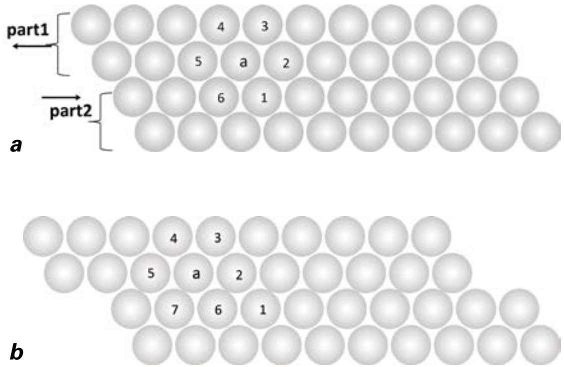

Figure 3 ***a*** *A shear force pulls adjacent layers of atoms in opposite directions;*
b *After the force is removed, atom 'a' is bonded to a different set of neighbouring atoms.*

Metals for high temperatures

There are metallic elements in the periodic table which have melting temperatures higher than 1500°C. However, they cannot be used in the jet engines because of their other properties such as high density, high cost, high reactivity and lower strength at high temperatures. None of the elements in the periodic table has the combination of the properties desired for high temperature applications. However, the required properties can be achieved by mixing different metals or adding non-metallic elements to metals in a process known as *alloying*. Alloying does not have much effect on the electrical and thermal conductivities, but it has significant impact on the strength, which is the most important property for engineering applications.

Metallic structures

Pure metals contain identical atoms arranged in a regular pattern. A two-dimensional arrangement of atoms in a pure metal is shown in **Figure 2**. The positions that are occupied by the atoms are called *lattice sites*. Each atom in the lattice site is attached to the neighboring atoms by metallic bonds. For example, in two-dimensions, the atom labelled 'a' is bonded with atoms 1 to 6. But metals are 3-dimensional and in three dimensions, atoms can be thought as spheres. When layers of spheres pack together there are spaces between them which in a metal structure are called *interstitial sites*.

What happens when a force is applied to a metal? **Figure 3a** shows a force (known as a shear force) pulling part 1 and part 2 in opposite directions. If this force is not enough to break the bonds, the atoms get back to their original position after the force is removed.

When higher forces are applied, the layers of atoms can slide over one another by breaking the existing bonds and making new bonds with other atoms. This is shown in **Figure 3b**, where for atom 'a' the bond has broken with atom '1' and a new bond formed with atom '7'. In this situation, atoms do not get back to their original positions after the removal of the force. There is a permanent change in the shape of the material.

If the forces are continuously applied for a longer period of time, sustained shape change can result in breaking of the metal. So in order to inhibit the shape change, sliding of the layers of atoms needs to be made difficult, which is known as *strengthening*. Alloying can be used to strengthen a metal.

Adding extra atoms

A metal can be alloyed with an element of smaller atomic size. If the atoms are small enough, they prefer to sit in the interstitial site as shown in **Figure 4a**. This is why steel, the most commonly used alloy in structural applications, is so strong. Steel is a mixture of iron with less than 0.2% of carbon atoms in it. The carbon atoms are about half the size of the iron atoms. They act as a barrier preventing easy sliding of the layers of metal atoms, thus making it harder to change the shape compared to pure iron. This is because with the carbon atoms present more force is required to break the existing bonds. This is always the case when nonmetallic smaller elements such as boron, oxygen, nitrogen or carbon are alloyed with metals.

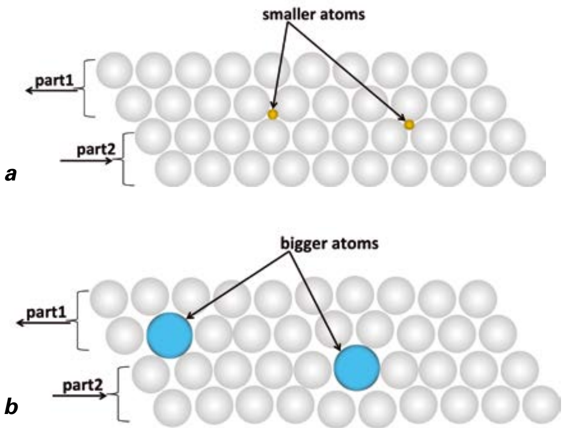

Figure 4 *Arrangements of atoms in the presence of*
a *smaller atomic size alloying elements*
b *larger atomic size alloying elements.*

If another element with a larger atomic size is added to iron it will occupy the regular lattice site **(Figure 4b)** rather than the interstitial site. Brass is one such alloy, a mixture of copper and zinc where the atomic sizes are very similar.

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Metal solutions

In order to form an alloy, a metal needs to dissolve other elements in it to form what is called a solid solution. The ability to dissolve something is known as solubility, the same as it is for a liquid dissolving a solid. The solubility depends on several factors but for the best solubility the atoms should be of similar sizes and the elements must have the same crystal structure and similar reactivity. In addition to these factors, temperature is the most important variable that determines the solubility of elements. For example, nickel cannot dissolve any molybdenum at room temperature. However, it can dissolve 25 weight percent of molybdenum at 1250°C. On the other hand, nickel can dissolve copper completely above 322°C.

If an element added to a metal exceeds its solubility limit at a given temperature then it will separate from the original metal and form another state (*phase*) with different crystal structure. For all the elements in the periodic table graphs called *phase diagrams* are available, which show the limit of solubility of each element in other elements at different temperatures. This can be used to design the alloys depending on the application requirements.

High temperature alloys

One of the important factors in engineering applications is the temperature at which materials are used. When atoms get hot they become more mobile and sliding of layers of atoms becomes easier, leading to failure of parts. Compared to any other commercially existing alloys, nickel alloys are the best at keeping their strength at high temperatures and hence they are called *superalloys*. Nickel is one of the elements in the periodic table and it can dissolve many elements. Nickel based superalloys are used for the turbine blades and turbine disks of jet engines. The alloying elements that are normally present in Ni-based superalloys are cobalt, chromium, aluminum, titanium, iron, molybdenum, niobium, tantalum, tungsten, ruthenium, and hafnium. Small amounts of boron and carbon are also often included. Apart from strengthening, these alloying elements also help to reduce the alloy's reactivity.

A single jet engine like this can generate a thrust force of 400 000 N.

Research is on-going to increase the efficiency of jet engines. This could be done by burning the air-fuel mixture at higher temperatures, which requires the turbine to sustain higher temperatures. However, nickel based superalloys that are currently in use are operating close to their melting points (1500°C) so part of the research is to try to find alloys which can operate at higher temperatures. This is done by altering the alloying element additions, playing with amount of alloying elements being added and by changing the manufacturing processes. Alloys which can operate effectively at higher temperatures may contribute to the development of aircraft which are more fuel efficient and quieter.

Divya Vadegadde Duggappa is a Post-Doctoral Research Associate at the Rolls-Royce University Technology Centre, Department of Materials Science and Metallurgy in Cambridge. She works on designing new alloys and manufacturing them through advanced fabrication techniques. These offer design freedom, so that complicated designs which could enhance the efficiency can be manufactured.