Aircraft jet engines have to be able to withstand infernal conditions. Extreme heat and bitter cold tax coatings to the limit. Materials expert Dr Ir. Wim Sloof fits atoms together to develop rock-hard coatings. The latest invention in this field is known as ceramic matrix composites. Sloof has signed an agreement with a number of parties to investigate this material further.

Rock-hard coatings

Jet engines require super strong material

Christian Jongeneel

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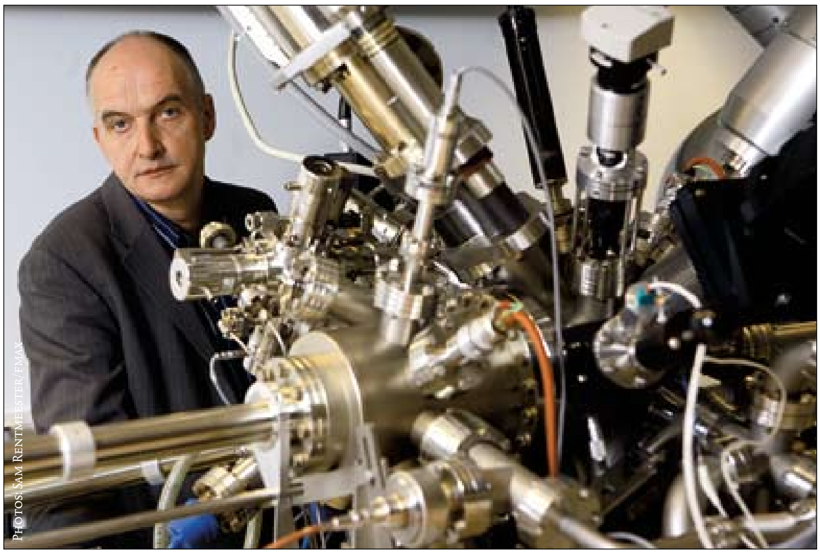
The Paris Air Show is one of the leading events in the aircraft industry. Not only do hundreds of thousands of people flock to the show to gape at the latest aircrafts, it is also the place to be for signing production contracts. This summer Wim Sloof attended on behalf of Delft University of Technology. In Paris he presented a research agreement with a number of partners, including Rolls Royce, one of the world's largest manufacturers of aircraft engines. The subject was coatings. "We are working on high-temperature coatings for use in gas turbines, where temperatures can reach one thousand degrees Celsius," Sloof explains. "When people hear the word coatings, most of them think of some type of paint, but we're talking about a very thin protective coating of a very hard material. These coatings are indispensable inside aircraft jet engines. The conditions they have to tolerate are much more extreme than they are for say, gas turbines used to generate electricity." Because of these exceptional operating conditions (and the safety risk if an engine were suddenly to fail) jet engines are a great challenge to materials scientists. To begin with they have to withstand higher temperatures because these enable the engine to burn its fuel more efficiently. In addition, saving weight is of the utmost importance. This is a general trend in aircraft construction, prompted by the need for more efficient use of fuels. Service life also plays a major part. Engine maintenance is one of the main reasons why very expensive aircraft are grounded on a regular basis. Sloof: "The limitations of jet engines currently stem purely from the materials used."

Aluminium oxide

There are various types of engines in use, but their main principle is the same. The engine sucks in air at the front, compresses it, adds fuel, and ignites the mixture. This creates a high-pressure mixture of gases that escape through the rear of the engine to provide thrust. The escaping gases also drive a turbine, which taps off some of the engine's power to drive the fan that sucks in and compresses the air at the front of the engine. Due to the mechanical stresses and heat involved, the turbine wheels form the most vulnerable part of the engine. As the temperature inside the turbine increases, the number of suitable materials for its construction decreases. Materials scientists therefore have to solve increasingly complex conundrums, taking into account a material's resistance to enormous temperature changes. The interior of a running jet engine soon reaches temperatures in excess of one thousand degrees Celsius, but on the other hand the engine also has to withstand temperatures far below zero, as an aircraft might become grounded in a Moscow blizzard. On top of that the materials have to be lightweight and affordable, two reasons why tungsten, the most heat-resistant metal available and used to manufacture light bulb filaments, doesn't make the grade. Aircraft turbines are made of a strong nickel alloy, which although very heat-resistant cannot withstand temperatures in excess of one thousand degrees Celsius. The constant battering with hot oxygen causes rapid oxidisation, which weakens the structure. One good way of preventing this is to apply a protective oxide coating which keeps the hot oxygen away from the nickel surface. The best candidate for such a coating is a ceramic material, aluminium oxide. However, aluminium oxide and the nickel alloy have different coefficients of expansion. The repeated heating and cooling of the turbine components result in stresses between the coating and the substrate, causing the coating to peel away. This can be solved by adding an adhesion layer consisting of aluminium and nickel, which works by damping the stresses. The problem is that a mix of just nickel and aluminium also tends to oxidise internally. This can be countered by adding chromium. And since all these metals usually contain pollutants, yttrium must also be added to act as a scavenger element, binding sulphur for example. Finding the optimal ratios for this quartet of metals takes ▸▸

> *Finding the right coating is an endless conundrum in which each new solution appears to introduce a new snag*



Dr Ir. Wim Sloof uses the electron microscope to understand the atomic basis of hardness

a lot of research, for other variants are also possible, using zirconium or hafnium instead of yttrium. And even when you find the ideal composition, you're still not finished, as Sloof warns: "The microstructure of the crystals in both the underlying alloy and the coating is also very important. As the oxide structure become coarser, it gives better protection to the nickel alloy substrate."

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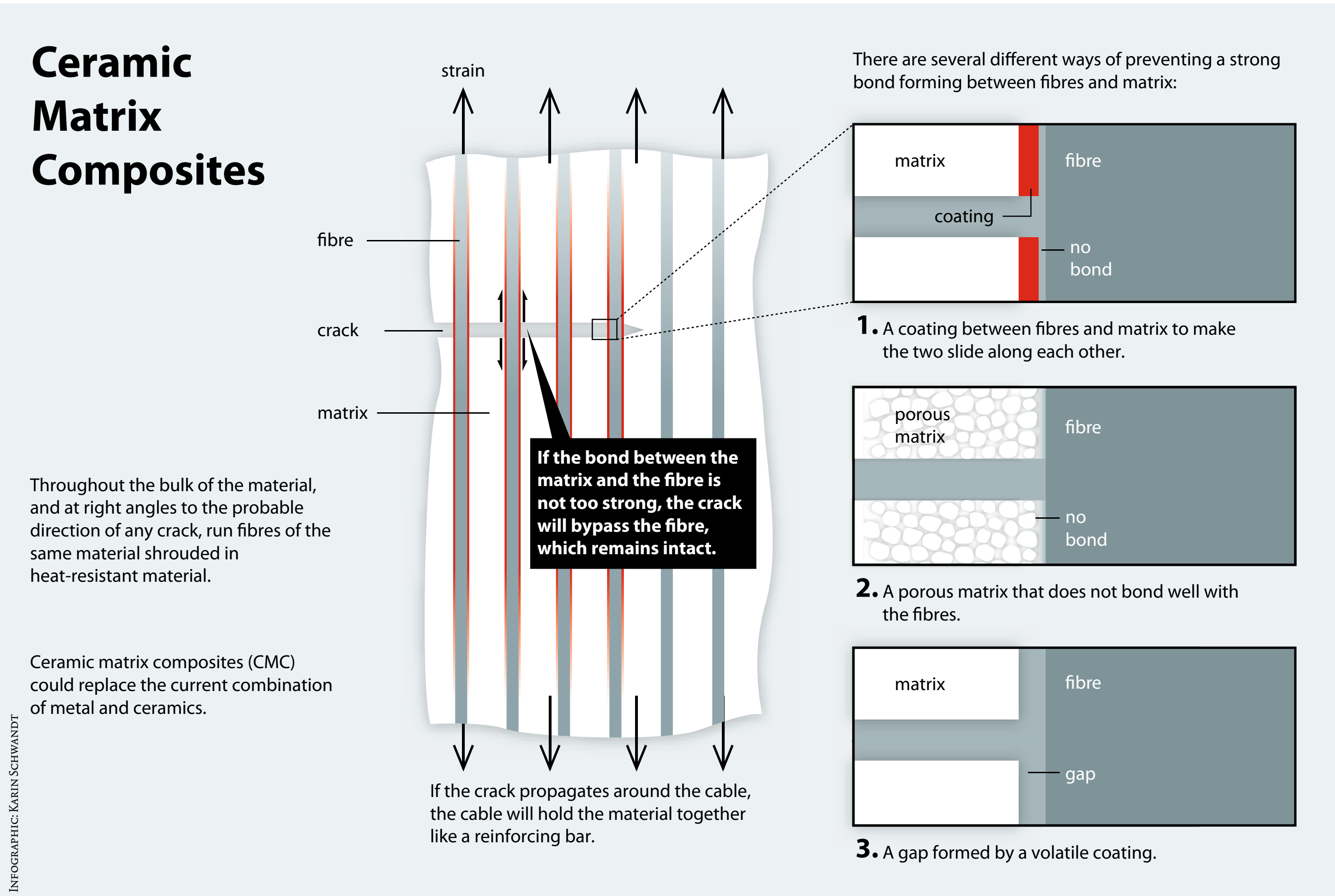
Self-healing

So, the coating of a turbine wheel consists of two layers. On top is a thin oxide layer, below which is a thicker adhesion layer. The resulting structure has self-healing properties, as tests conducted by Sloof revealed. Each cycle of heating and cooling increases the damage to the oxide coating," he says, "but there comes a point when damage starts to repair itself. This happens when aluminium from the adhesion layer starts to form a new aluminium oxide coating."

Although the coating with an oxide layer and an adhesion layer offers robust protection against the incessant pounding of the turbine with hot oxygen, it doesn't mean that the ideal coating has been found. True, the oxidising action of the hot air is held at bay, but the pure heat is not. The turbine wheel could even start to melt. In order to prevent this from happening, a third, insulating layer is needed to cover the other two layers. This layer is known as the thermal barrier coating (TBC). The TBC consist of feather-like crystals oriented at right angles to the coating surface and made from a material that does not conduct heat very well, like zirconium oxide. The size of the crystals and the distance between them are very important, since any space between the crystals could be used by the hot air to reach the oxide layer. Finding the right material and the right way to grow the crystals also requires a lot of research.



If the turbine wheel is cooled from within, the TBC can maintain a temperature difference of 150 degrees between the turbine blades and the hot air. In other words, if a turbine wheel can withstand a temperature of 1100 degree without a TBC, adding the thermal barrier will make the

'Jet engines need to be resistant to extreme temperatures, as well as weight-saving and reliable'

turbine suitable for temperatures up to 1250 degrees. This is a considerable improvement, although a useful property is lost in the process. "The TBC has no self-healing properties," Sloof explains, "so if a crack starts to form at the base of a crystal, the whole feather structure can come away." In order to make the material self-healing Sloof added a mix of molybdenum and silicon to the material. Now if oxygen penetrates the material through a crack, molybdenum oxide and silicon oxide are formed; the first evaporates, and the second repairs the crack. All in all, finding the right coating involves a seemingly endless juggling with atoms, with each new solution appearing to introduce a new snag. The conundrum relates not only to the chemical composition, but also to the production conditions that will produce the optimum material structure.

A mechanic inspects a blade of the turbine of the F-100 engine, the engine of the F16 fighter

Cracks

The aircraft industry currently stands on the threshold of a new development: ceramic matrix composites (CMC). This is the research for which Delft University signed an agreement with Rolls Royce, the Dutch National Aerospace Laboratory, and Sulzer-Eldim, a part Swiss, part Dutch high-tech company with a reputation in the field of heat-resistant materials. CMC is like a woven fabric of ceramic material, e.g. silicon carbide, that could replace the current combination of metal and ceramics. Pure ceramics are fragile. CMC is a combination of ceramics with ceramic fibres that make the material tougher. Sloof: "CMC can take up more stress before it breaks." Through the bulk of the material run cables of the same material at right angles to the probable direction of any cracks. These cables are shrouded in a thin coating of another heat-resistant material. This coating prevents the cable from sticking to the rest of the silicon carbide. All this happens at micro and nano levels.

The effect is like that of stitching in textiles. As a tear forms in the bulk material, at some point it meets one of the ceramic fibres, a cable. This makes it difficult for the crack to propagate. And even if the crack does continue around the cable, the fibres will hold the material together, rather like a reinforcing bar in concrete. This process can only succeed if the shrouding coating ensures that the bulk material does not adhere too strongly to the cable, for if the cable and the matrix form a whole, the mechanism's value will be limited.

"However, silicon carbide is an expensive material, which also oxidises quickly at high temperatures," Sloof says. "We think that it is possible to create CMCs using aluminium oxide. This would be cheaper as well as being resistant to oxidisation, but would have the drawback of being less strong."

CMC is already being used in gas turbines for power stations, but the reliability has not yet been sufficiently tested for use in aircraft engines. Sloof estimates that this will take another five years or so of research. Nonetheless, the first application is already known, the advanced F-136 jet engine that will power the Joint Strike Fighter.

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