Titel:

"MTU solutions against erosive attack and loss of EGT margin in turbo engines - ERCoat^{nt}"

Authors:

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1 Introduction and synopsis

Compressors of gas turbine engines are certain to suffer premature performance losses when in service they ingest sand, fly ash, salt and ice crystals and volcanic ashes carried in the air. The performance losses noted after erosive exposure and an accompanying rise in the fuel consumption of commercial compressors are attributed to the removal of blade material over time. This in 2002 caused MTU Aero Engines to launch the development of a new category of erosion-inhibiting coatings that are now being offered under ERCoat^{nt} for use on new parts and for MRO applications (without necessitating redesign).

At the present state of the art, thin vapor-deposited TiN coatings provide best possible protection against erosive attack on compressor blades. ERCoat^{nt} coatings, applied by physical vapor deposition (PVD), excel by their multi-layer structure and special chemical composition (several patents pending), the structure being achieved by the alternating deposition of hard-material layers and soft intermediate layers. ERCoat^{nt} coatings will appreciably delay if not entirely suppress erosive attack on blades. Thanks to the modest thicknesses of 5 µm to 50 µm and the moderate surface roughness of ERCoat^{nt}, negative effects on aerodynamics can be ruled out also when the coating is deposited subsequently during shop visits.

The company has tested the effect ERCoat^{nt} has on the mechanical properties of compressor blades in nickel and titanium alloys in elaborate test series on coated material specimens and engine components. The test series importantly demonstrated that, among other findings, modern erosion-inhibiting coatings may accelerate crack initiation under LCF load when a critical strain level is exceeded, an insight that needs to be considered in the selection and introduction of erosion-inhibiting coatings for compressor applications.

Altogether, MTU's knowledge of typical erosion damage and available coating options, plus the validation work it has done on these coatings, alleviate the risk users are taking with the introduction of this novel coating category on their engines. Apart from the economics, these coatings also actively contribute to the environmental protection effort.

2 Erosion on gas turbine engines

The compressors of gas turbine engines are particularly prone to premature performance losses when in service they ingest sand, fly ash, salt and ice crystals or volcanic ashes carried in the air (***Fig. 1***). It is especially in regions known for their dust and sand-laden atmosphere that the rapid onset of erosion on compressor blades is a constant threat.

The performance degradations noted on commercial compressors in the aftermath of erosive exposure are attributed to the removal of blade material. ***Fig. 2*** compares a virgin blade with a compressor blade damaged by erosion. The eroded blade shows material loss primarily in the upper airfoil area (tip). In the leading edge area, the erodent impinges almost vertically on the edge, wearing away material there and so reducing the blade chord. Whereas in the trailing edge area, owing to the narrow impingement angle of the erodent, material is removed over a wider surface area, reducing blade thickness. Generally, it is observed that erosion-induced loss of material only affects certain areas of compressor blades, while on other areas the erosive attack remains marginal.

Erosion-induced material loss on compressor blades aggravates surface roughness especially on the pressure side of the blade, causing aerodynamic disadvantages, such as reduced efficiency. Compiled in ***Fig. 3*** are roughness measurements taken on a 10-stage compressor. These roughness measurements were conducted on virgin blades versus service-exposed blades that had been operated in a heavily erosive environment (4,000 flight hours approx.). The roughness measurements here shown were all taken on the blade pressure side in the trailing edge area of the blade tip. They indicate that the used blades exhibited increased surface roughness compared with new parts. Erosion-induced roughness increase is more severe on the forward compressor stages than on those further downstream, which among other things is attributed to the fact that larger erosion particles fracture through collision in the forward compressor stages, so that the mean size of the erosive particles decreases further towards the rear compressor stages. MTU's observations and insights such as these also point out ways to preferentially coat only part of the compressor for improved cost-effectiveness.

3 Erosion protection

3.1 Erosion protection systems

At the present state of the art, thin (5 µm to 50 µm) vapor-deposited TiN layers provide best possible protection against erosive attack on compressor blades. High-velocity oxy-fuel flame-sprayed, aluminized and slurry coatings have proved less suitable for the purpose.

Innovative technical developments predominantly base on multi-layer hard-material coatings deposited by means of PVD techniques. Building on this state of the art, MTU Aero Engines has developed its erosion inhibiting coatings ERCoat^{nt} for compressor applications. Shown in ***Fig. 4*** is a partial view of a blisk (bl̲ade i̲ntegrated dis̲k̲) with some low-temperature ERCoat^{nt} coated blades readily apparent. ***Fig. 5*** depicts various compressor components having high-temperature ERCoat^{nt} coated blades.

ERCoat^{nt} coatings deposited by PVD technique excel by their multi-layer structure and special chemical composition (several patents pending). The structure is achieved by the alternating deposition of hard-material layers and soft intermediate layers. The overall thickness of the multi-layer coating ranges from about 5 µm to 50 µm. In the presence of particle erosion, the multi-layer structure advantageously permits crack branching to occur, extending the life of the coating and component.

Theoretical considerations and experiments alike have demonstrated that the multi-layer structure will affect the erosion and mechanical properties to be expected in service. There are many options of choosing among many different numbers and thicknesses of individual layers. Apart from their high resistance to erosion, the individual layers of the multi-layer structure are associated with further desirable properties. Among these are high crack resistance, crack blunting and crack stopping, stress transfer and supporting action.

Exemplified in ***Fig. 6*** is the multi-layer structure of an ERCoat^{nt} coating in a transverse microsection. ***Fig. 6a*** shows a metallographic microsection clearly displaying the 25-µm overall thickness and the approximately 3-µm ceramic and metallic intermediate layers. **Fig. 6b** is a high-resolution scanning electron microscope exposure showing the nanostructure of the ceramic intermediate layer. The chemical composition of successive nanolayers varies only slightly, and each nanolayer is merely 20 nm to 50 nm thick. This nanodesign again appreciably reduces the potential critical crack or defect size as compared to conventional materials. Overall, it is essentially the chemical composition, nanodesign and multi-layer structure that cooperate to produce the desirable ERCoat^{nt} properties.

3.2 Erosion tests

ERCoat^{nt} coatings can appreciably slow down if not fully suppress erosive attack on the blades. Any negative effect ERCoat^{nt} might have on aerodynamics is precluded owing to the small 5 µm to 50 µm thickness of the coatings and the marginal surface roughness they have.

Erosion tests were made on an erosion rig. As an erodent, silica sand with particle sizes between 75 µm and 200 µm was used, as it would typically occur in a compressor environment. On the rig, the particles were accelerated with compressed air to between 200 m/s and 350 m/s and targeted at the surfaces under test at an angle of 20°.

Fig. 7 compares the weight loss curves of a version 1 and a version 2 ERCoat^{nt} coated coupon with that of an uncoated coupon (base material Ti-6-4). The weight loss measured for the base material coupon in the Ti-6-4 titanium alloy occurs in direct proportion to time. The ERCoat^{nt} coated coupons sustain the erosion loading for a certain duration without suffering any measurable weight loss. In this phase, called the initiation phase, protection against erosion is 100%. As the erosive load continues, the erosion-inhibiting coating is gradually attacked until completely worn off the base material. During this phase, called the transition phase, the erosion rate (mass loss over time) increases. During a third phase, removal of base material sets in, the erosion rate having reached that of the unprotected base material.

The initiation times for the two ERCoat^{nt} coated coupons shown in ***Fig. 7*** are comparatively long. Whereas the titanium base material exhibits no initiation phase and material removal by erosion begins the moment the erosive loading sets in. A notable difference is found in the duration of the transition phase between low-temperature and high-temperature ERCoat^{nt}. Compared with the low-temperature coating, the transition phase of the high-temperature ERCoat^{nt} coating is nearly 4 times as long, raising the time to reach the removal rate of the base material from 1.5 time units for the low-temperature coating to about 7 time units for the high-temperature ERCoat^{nt} coating.

The erosion parameters selected represent a heavy erosion loading intended to simulate, time-lapse fashion, typical erosion in a compressor environment. In the course of the test series, the test parameters were set to permit a prompt comparison to be made of the erosion properties of various coating systems. Still, it remains the aim of erosion protection development to maintain full protection (or a longest possible initiation phase) over the entire service time of a compressor component.

3.3 Effect of erosion coatings on base material properties

Elaborate test series were run on coated material specimens and components to explore the effect ERCoat^{nt} has on the mechanical properties of compressor blades in nickel and titanium alloys.

Overall, it was noted that the erosion protection coatings under study have no appreciable effect on the mechanical properties of the Inconel 718 nickel alloy investigated. The thermal service limits for the use of ERCoat^{nt} coated components in a nickel-base alloy are dictated by the oxidation resistance of the coating.

For the Ti-6-4 and Ti-6-2-4-2 titanium alloys under study, however, limitations became apparent to the use of ERCoat^{nt} coated test specimens and components under cyclic loading. The mechanical tests here conducted primarily investigated the effect ERCoat^{nt} coatings have on HCF (high cycle fatigue) and LCF (low cycle fatigue) strength. It is generally assumed that apart from the ERCoat^{nt} protective coatings here involved, also other erosion-inhibiting, hard-material based coatings will exhibit the noted effects on fatigue strength.

Fig. 8 are diagrams showing the effect ERCoat^{nt} coatings have on the HCF and LCF strength of titanium alloys. The test data indicated that depending on the coating system, blade material and geometry selected, HCF strength may drop as much as 15%.

A further essential insight gained from the test series is that modern erosion protection coatings may accelerate crack initiation under LCF load when a critical strain level is exceeded, a fact that needs to be considered in the selection and introduction of erosion protection coatings for compressor applications. Still, MRO customers of MTU won't have to worry: the use of the coating marketed by the MTU Maintenance Group under the trade name MTU^{Plus} ERCoat^{nt} is amply tested and approved considering all potential effects.

4. Use of erosion protection coatings

In the coming years, MTU and its customers are pushing ahead with the introduction of erosion protection coatings for primarily two reasons:

The blisk construction of the next compressor generation results in appreciable performance gains but also in costly integral components the erosion-induced loss of which may become a commercial hazard. In this connection, the temperature requirements for the protective coatings run as high as 650°C and beyond.

The retrofitting of erosion protection coatings in current compressor programs to individual blades and blade clusters of varying geometries proves a cost-effective solution because as a result of improved airfoil stability and the sustained smoothness of blade surfaces, fuel consumption comes down. Also, it cuts spare parts costs over extended lifecycles and reduces scrap rates, improving availability in service by the operators. So, apart from the logistics involved, if for instance the need for a single premature or unscheduled shop visit of a commercial 10-stage compressor for blade replacement is obviated, economies may run in the neighborhood of €1,000,000.

Additionally, if the erosion tendency of compressors is reduced, they will be safer in operation considering they are running longer in a safe region of their operating envelope, so that negative regimes (e.g. surging) can be avoided. Also, in-flight shutdowns can be avoided that are necessitated by eroded, mechanically deteriorated stator vanes that develop cracks and are then caught in the rotor stages.

On veteran compressors, alloys like steel are often used for blades and these need to be protected also against corrosion. This is where the concomitant corrosion resistance of ERCoat^{nt} coatings comes in handy.

In the case of nick-type FOD or other damage, the affected areas can be repaired by blending within allowable limits, and without necessarily requiring recoating.

ERCoat^{nt} coated rotor blades can readily be brought to specified dimensions using blade tip grinding. The coated surfaces can also be smoothened inexpensively by techniques such as vibratory finishing to achieve a superfinish.

Under certain circumstances, these coatings, when present, can be stripped and redeposited during repair events.

In all, MTU's introduction of ERCoat^{nt} erosion protection coatings mark another milestone in the company's quest to provide customers with a new MTU^{Plus} repair technique that will help airlines save millions long-term. The technique at once contributes importantly to active environmental protection achieved by reducing fuel and material consumption.

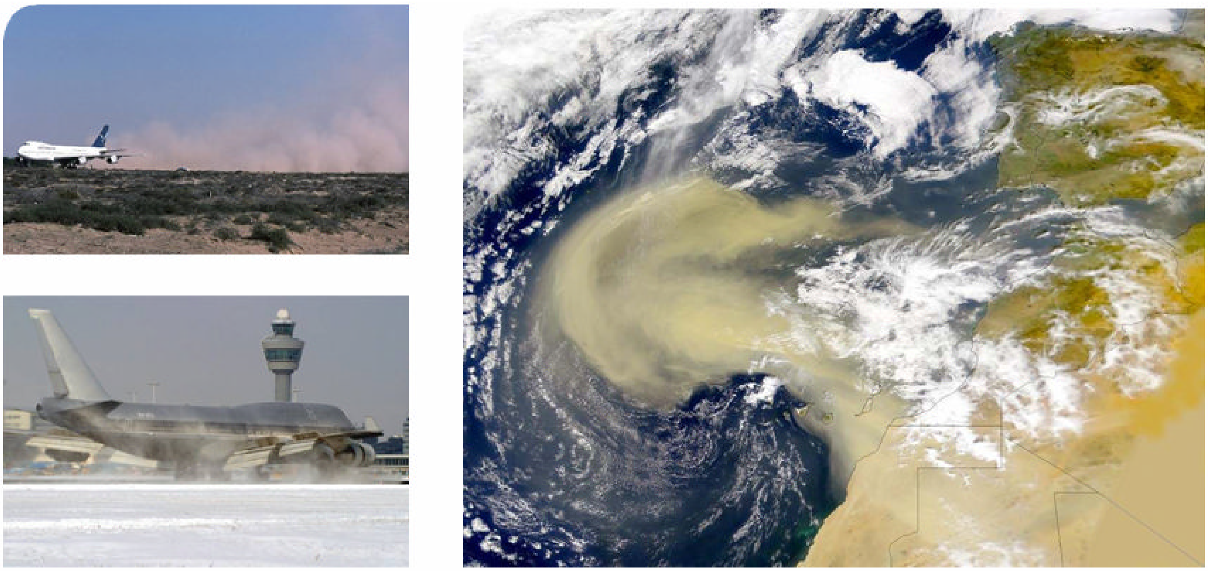

Fig. 1: Sands, volcanic ash particles, salt and ice crystals may erosively attack engine components.

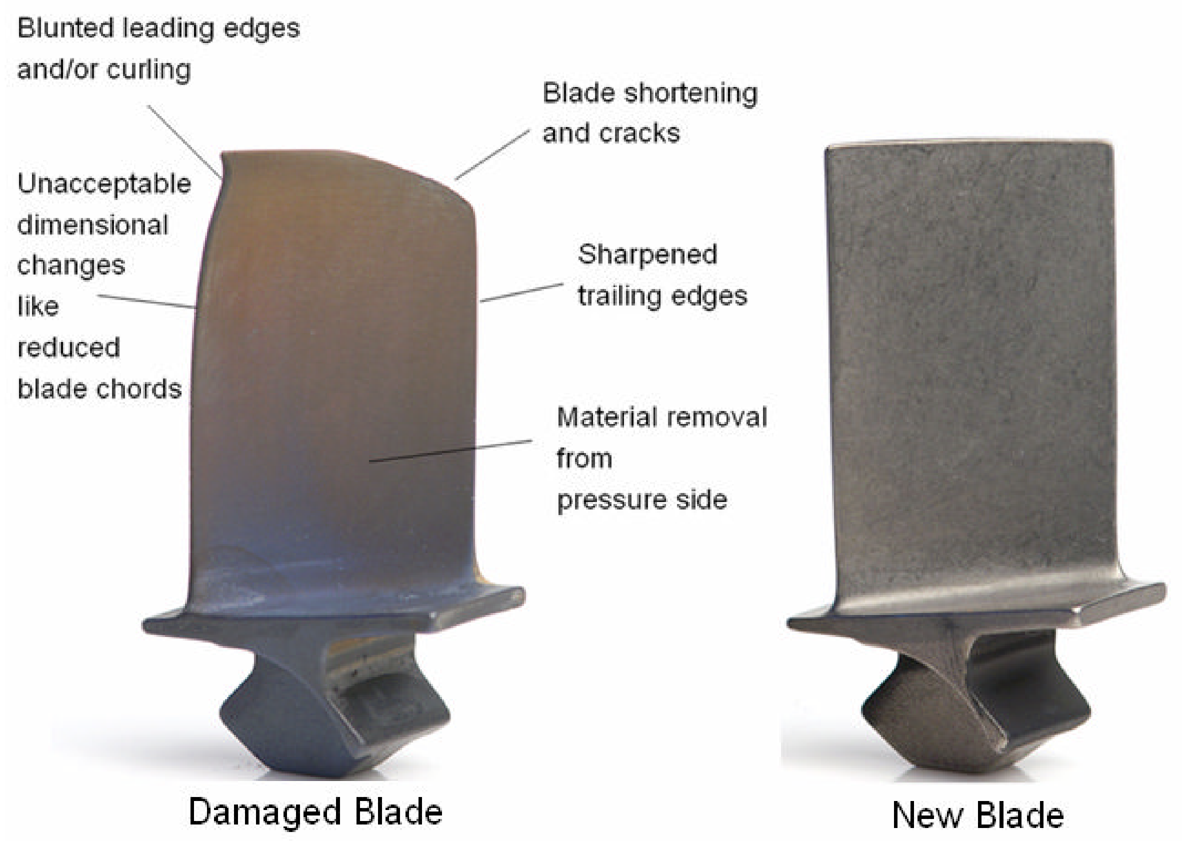

Fig. 2: Comparison of an eroded compressor blade with a virgin blade.

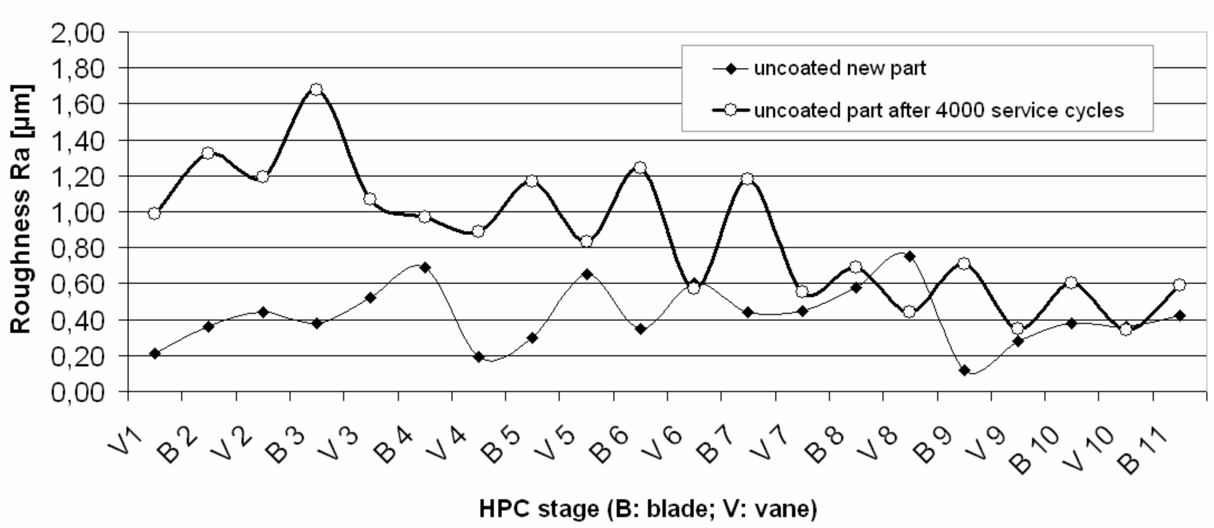

Fig. 3: Surface roughness of eroded compressor blades (after 4,000 flight cycles approx.) compared with the surface finish of virgin parts.

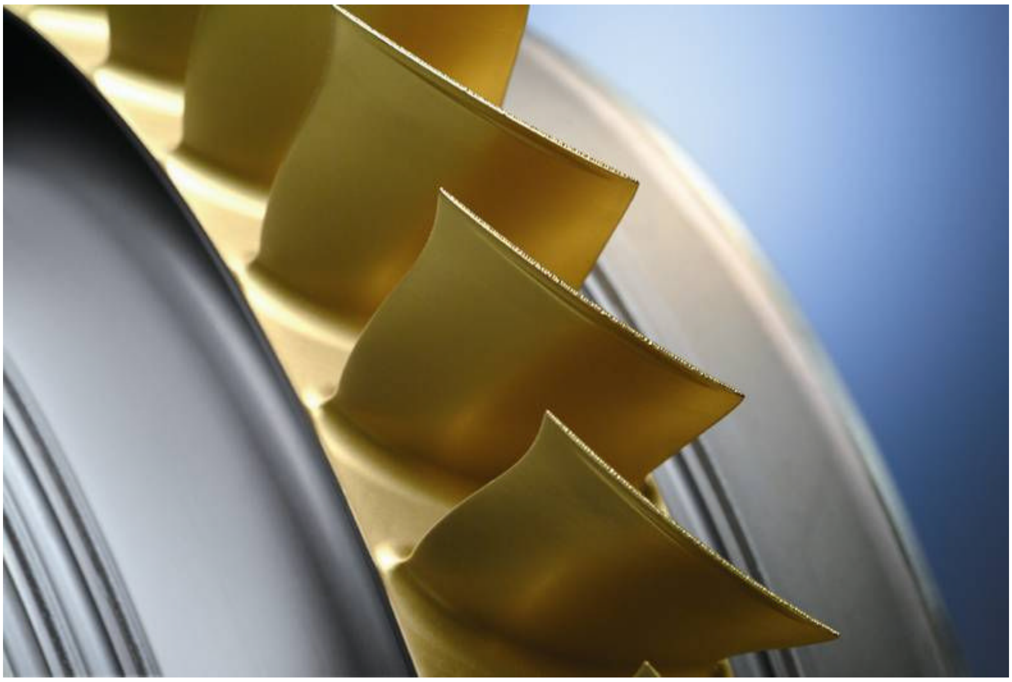

Fig. 4: Partial view of a blisk (blade integrated disk) with version 1 ERCoat^{nt} coated blades.

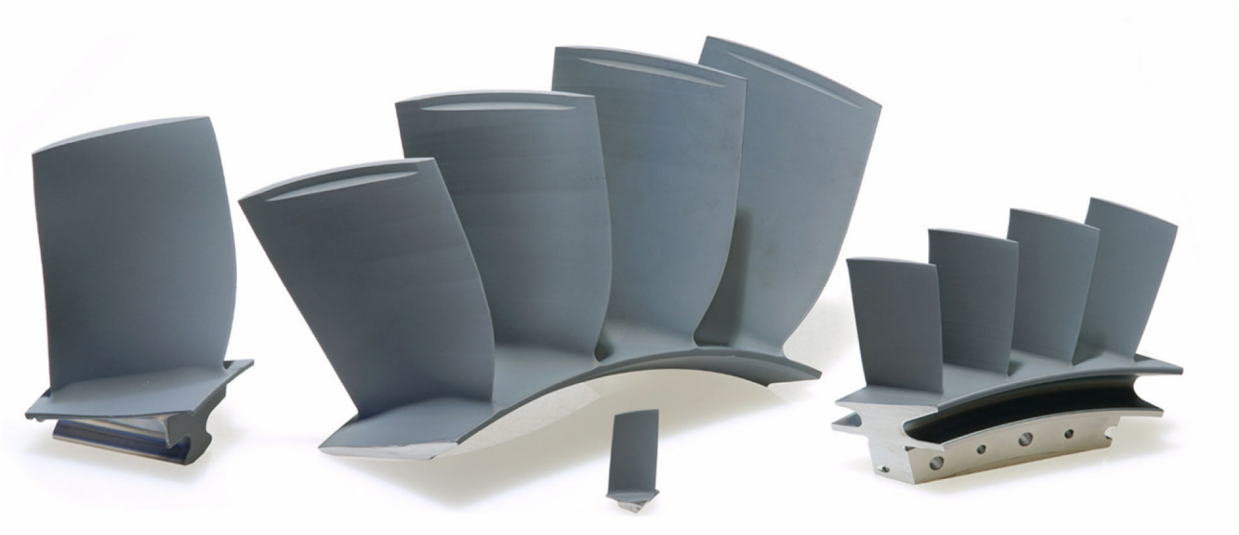

Fig. 5: Compressor components with version 2 ERCoat^{nt} coated blades.

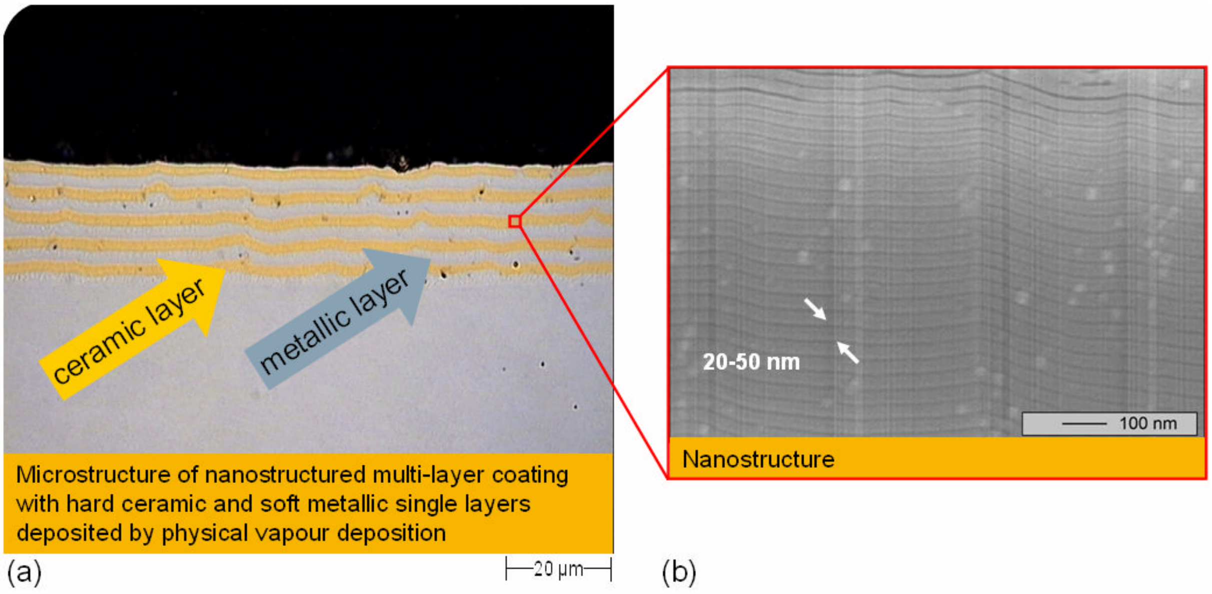

Fig. 6: Multi-layer structure of an ERCoat^{nt} coating in section

(a) transverse microsection

(b) high-resolution scanning electron microscope exposure of transverse section

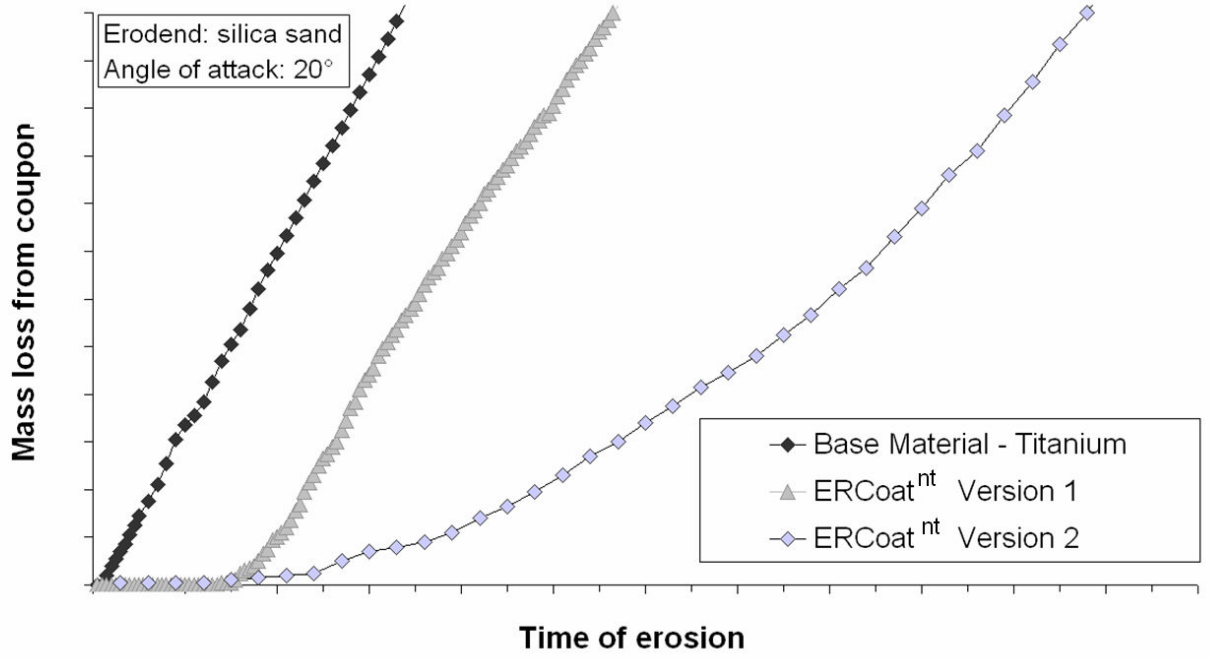

Fig. 7: Results from erosion experiments on coated and uncoated titanium specimens.

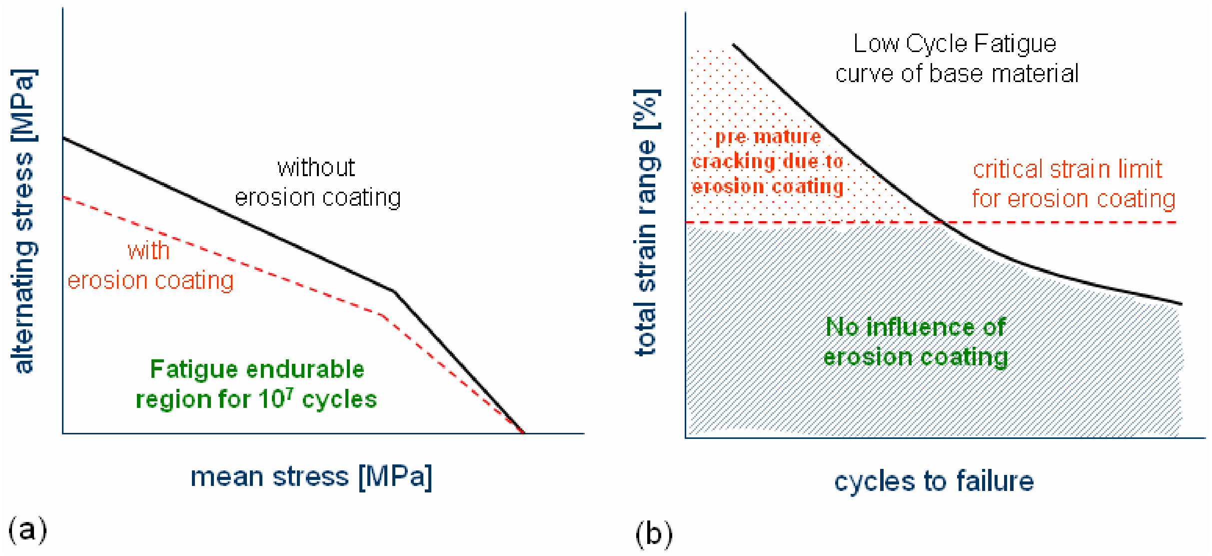

Fig. 8: Effects of advanced erosion protection coatings on the HCF and LCF strength of titanium alloys.

(a) Effect on HCF strength

(b) Effect on LCF strength