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THE WEAR MECHANISMS OCCURRING IN ABRADABLE SEALS OF GAS TURBINES

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Metallographic investigations of worn abradable coatings have been carried out to identify and characterize the main wear mechanisms occurring in turbomachine seals. The following mechanisms have been found: cutting, smearing, adhesive transfer, crushing, melting and tribo-oxidation. Three other mechanisms occur without blade–seal interaction: erosion, corrosion and high-temperature oxidation. Using the data from these investigations as a reference, rub tests have been conducted on a specially designed high-speed–high-temperature rig. The many correlations obtained between test values and wear mechanisms allow the generation of 'wear mechanism maps' for coatings of the AlSi–plastic family. Mechanism orientated model tests are needed to understand the correlations between structural parameters and coating behaviour during blade–coating interactions. Wear mechanism maps will help modelling coating systems to be able to withstand severe service conditions. Avoiding the onset of adhesive or melting wear and simultaneously favouring cutting wear produces better abradable seals which will help improve both the operational safety and the economy of modern turbomachines.

1. Introduction

Modern turbomachines need very small clearances between rotating components (blade tips, labyrinth seals) and the stator case in order to minimize gap losses and so increase efficiency. For this purpose, different types of abradable seals are deposited on the stator case to cope with rotor misalignment, thermal and centrifugal dilatations, and unbalanced parts. The primary requirement of abradable seals is to allow for wear without damage to the blade tip. A secondary requirement, gaining in importance, is that the surface remains smooth after wear in order to reduce aerodynamic losses. Different coating systems have been developed over the past years or are being evaluated at present. In general, the development of abradable systems has taken place empirically and relies on very little knowledge of the actual situation in service. In this work, a more systematic approach to the development of material systems is applied. As a first step, the wear mechanisms occurring in service are identified by examining worn components. The second step consists of laboratory material trials where by widely varying the test parameters, the different wear mechanisms identified in practice are simulated. The conditions leading to mechanism transitions are then analysed and related to the material properties. This step ends with the generation of 'wear mechanism maps' [1]. In the third step, a model is formulated for the relationship between material microstructure and in-service wear mechanisms. Using this model, material systems for improved performances can be designed (owing to its early development stage, this step will not be discussed here).

2. Investigation of worn service parts

In order to identify wear mechanisms that the coatings are subjected to, worn abradable seals that had been run in service were investigated. In the preliminary work only abradable seals from non-turbine stages were inspected ($T < 500$ °C). The worn materials (AlSi–plastic and nickel–graphite coatings) were examined non-destructively and destructively where possible. The main characteristics of each identified wear mechanism are described below.

2.1. Erosion, corrosion and oxidation

The erosion, corrosion or oxidation of a coating can be detected in that no contact (rub interaction) has taken place and/or the roughness, surface chemistry and colour has changed. No surface interaction takes place as the abradable surface retreats thereby increasing the gap between blade tip and coating.

The erosion, corrosion and oxidation of a coating are undesirable as they increase the blade gap so reducing engine efficiency.

2.2. Cutting

The high-speed blade tip can act as a cutting tool when it interacts with the coating. The new surface generated by cutting is very smooth and the coating takes on a shiny appearance. A surprising feature is the efficiency of the cutting (material removal) as the coating material at or around the cut shows very little or no deformation (Fig. 1). When cutting occurs, chip separation takes place in a brittle manner even in highly ductile materials such as polymers.

Cutting is a desirable means of abradable seal wear as the blade tip is not damaged, no material transfer takes place and the coating is left with a smooth surface that has favourable aerodynamic properties.

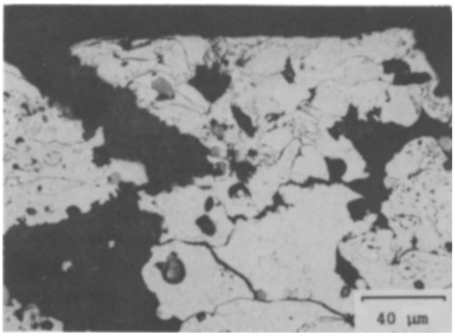

Fig. 1. Microsection through a nickel–graphite coating worn in the pure cutting mode. The subsurface zone is free of deformation.

2.3. Deformation

During interaction the coating may be deformed plastically by the blade tip. This deformation can take on many forms even within one coating as these are heterogeneous materials and their individual components deform in different ways.

The surface can become striated on a scale varying from micrometers to millimetres (Fig. 2). Extensive flow of the coating can also take place, leading to large-scale smearing of the metallic phase with the non-metallic components appearing to have fractured in a brittle fashion.

Incursion stresses lead to unwanted densification of the material. When incursion speeds are particularly high and most of the deformation is radial, the term crushing is used [2].

The process of deformation is not favourable as it roughens the surface so leading to aerodynamic losses and compacts the coating. Densification of the coating is unfavourable as this makes future interactions more violent as the coating cannot readily give way to the advancing blade.

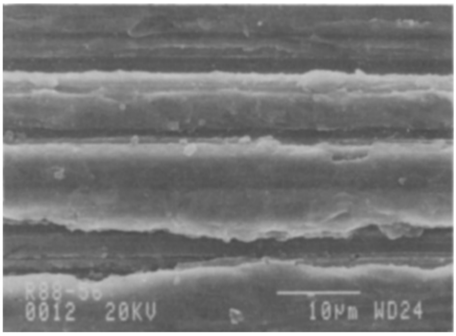

Fig. 2. Scanning electron microscope image of the surface of an AlSi–plastic coating subjected to smearing. Minute surface striations of wave length about 10 μm are present.

2.4. Adhesive transfer

This is the transfer of material from the coating onto the blade or vice versa and is often associated with the above process of deformation. The non-metallic particles of the coating may be covered by compacted surface layers that detrimentally affect the behaviour of the abradable seal as they lead to overheating and the formation of thick hard transfer layers. These transfer layers have a horizontal layered substructure due to the successive smearing of the coating and blade tip materials (Fig. 3). Great amounts of frictional heat are released during the metallic transfer so that the substrate may undergo thermal cracking and densification.

Adhesive transfer is detrimental and should be avoided.

2.5. Melting

The transferred layers mentioned above can have complex chemical compositions. This *in-situ* mechanical alloying may result in a newly formed alloy having a lower melting point than its original constituents. These alloys then melt during the following rubbing interactions forming hard and compact areas upon solidification.

The sectioning of these hard spots shows that local melting followed by rapid solidification takes place. In nickel–graphite coatings, melted layers of up to 125 μm have been seen to form. These layers had a columnar solidification structure that was extensively cracked (Fig. 4).

The melting of the materials at the rubbing interface is harmful as the transfer of the molten material onto the blade is favoured, and the molten mass forms a hard layer on solidification that can lead to serious blade damage, should a second interaction take place.

2.6. Tribo-oxidation

This is a minor wear mechanism that does not seem to play a significant role during blade tip coating–interactions but was found to occur at labyrinth seal contacts. At these contacts the labyrinth segments seal against

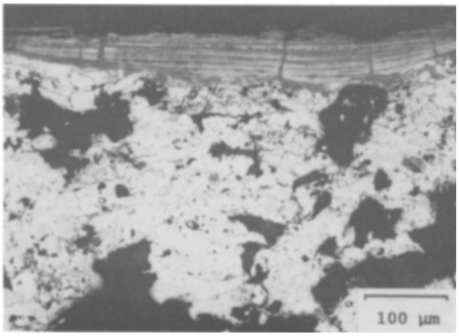

Fig. 3. Microsection through a nickel–graphite coating showing adhesive transfer. The transferred blade material exhibits a layered structure. The coating underwent radial densification (crushing).

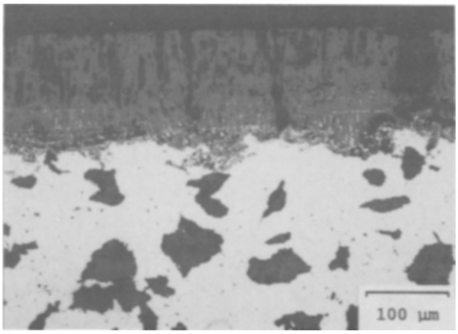

Fig. 4. Microsection through a nickel–graphite coating after melting wear. Molten blade material was transferred to the coating, mixed with the coating surface and quenched by the substrate. Diffusion bonding of the coating particles also occurred.

plasma sprayed coatings. The intermittent rubbing at high speeds and temperatures causes the contacting points to oxidize strongly with the resulting oxide films spalling from time to time [3]. This rubbing induced oxidation is called tribo-oxidation.

Although not a spectacular wear mechanism, it can be responsible for significant wear in short periods of time.

3. Rig tests

3.1. Test rig description

To be able to run tests under conditions that produce different wear mechanisms, a rig was designed and constructed that allows for a wide range of all test parameter settings. The following requirements are fulfilled

- Tangential speed range $V_t = 50 - 500\ \mathrm{m\ s^{-1}}$
- Incursion speed range $V_{\mathrm{inc}} = 0 - 3000\ \mu\mathrm{m\ s^{-1}}$
- Coating temperature range $T = \mathrm{RT} - 800\ °\mathrm{C}$

The incursion speed, temperature and interaction force are controlled via a digital voltmeter. The incursion of the coated sample is actuated by a computer controlled step motor, so that absolutely reproducible tests can be run. Two diagonally opposed blade dummies are fitted in quick change holders. The simple dummy form allows for easy manufacturing of various tip geometries from almost any material. The rotor is driven by an electric motor which has the advantage, over turbine driven systems, that no corrosion affects the wear picture.

Due to the full computer control of the test and rapid exchange of samples a turn around time of 10 - 15 min per test is normally achieved with three to four personnel.

3.2. Test results

A short test duration is an essential condition when parametric correlations have to be examined. During the first hundred tests the dependence of wear mechanisms on V_t, V_{inc}, specimen temperature, rub duration, coating heat treatment, blade material and tip geometry were investigated. Certain relationships are discussed in the following.

3.2.1. Coating temperature dependence on wear mechanism

Figure 5 shows the temperature measured on the reverse side of the coating, as a function of rub time during two different tests. In test A, the temperature increased by 3 °C from 353 °C initially. Massive metallic transfer of the coating to the blade tip occurred typical of an adhesive wear mechanism. During test B, the temperature increased by about 40 °C without any metallic transfer to either the coating or the blade with a wear mechanism of cutting being observed.

3.2.2. The correlation between coating roughness, blade weight variation and the wear mechanism

The data measured for three coatings, AlSi–polyimide, nickel–graphite and AlSi–polyester have been plotted in Fig. 6 using a weighted roughness value ($R = aR_a + bR_z + cR_{max}$) as a function of the mass variation of the blade used in the test (ΔG).

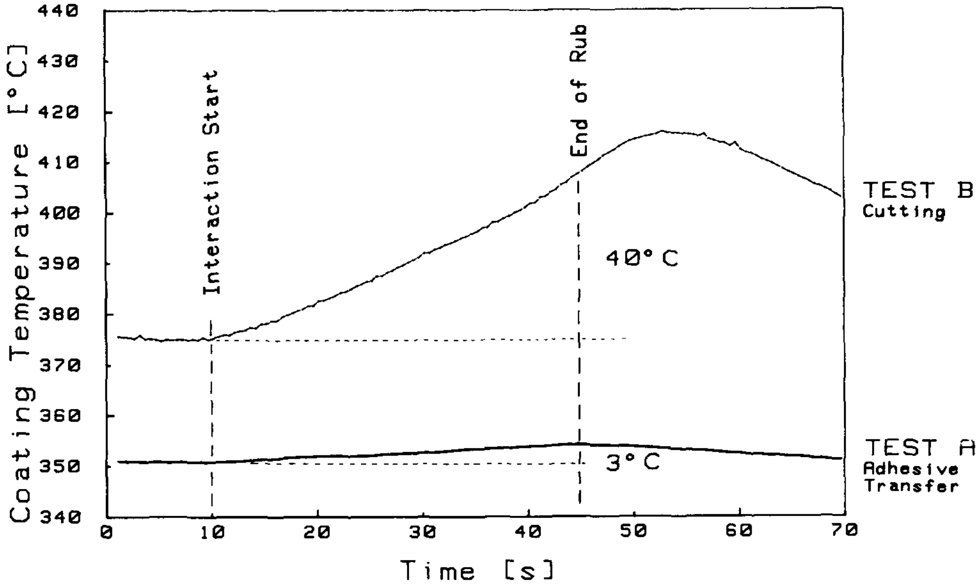

Fig. 5. Specimen temperature *vs.* time for two different rub tests. Test A: adhesive wear with metal transferred from the coating to the blade. The sample temperature remains almost constant. Test B: cutting wear (brittle mode). A temperature increase of more than 40 °C takes place during the rubbing interaction.

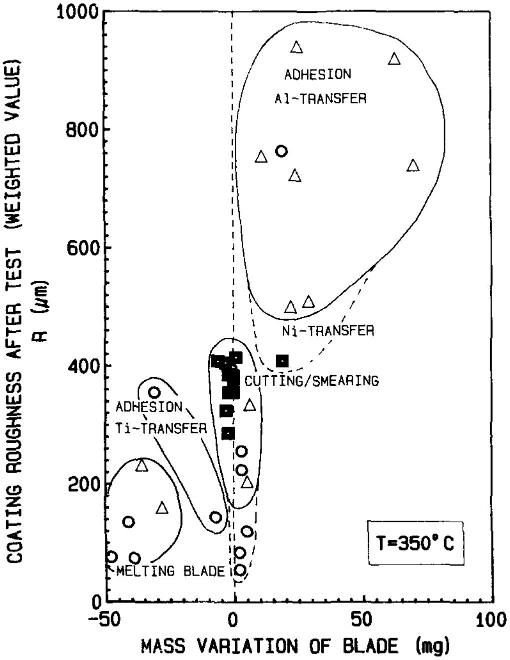

Fig. 6. Plot of the coating roughness, after the test, *vs.* the mass variation of the blade, for the three coating families tested under many different combinations of (V_t, V_{inc}). Each area on the graph corresponds to a major wear mechanism. ○, AlSi–plastic (solid); Δ, AlSi–plastic (melted); ■, nickel–graphite.

(1) The points in the upper right area of the plot correspond to samples where adhesive transfer from the coating to the blade took place.

(2) Adhesive transfer from the blade to the coating was observed when titanium blades were rubbed at high incursion speeds in the intermediate area at the bottom left.

(3) In the central region, no material transfer takes place ($\Delta G = 0$) and cutting or smearing were identified.

(4) In the lower left area, blade tip melting wear occurred during very high speed tests carried out with comparatively low melting point Nimonic blades.

4. Discussion of results

The metallographic investigation of abradables worn in service has shown that different wear mechanisms [4] can be easily identified by either destructive or non-destructive methods. However, the history of in-service interaction conditions cannot be accurately determined as external influences are often superimposed on the wear pattern, thus making any conclusion as to the wear behaviour of the investigated coatings rather uncertain.

Performing model wear tests on a well instrumented test rig is an efficient solution to this problem. It has been shown that systematic correlations exist between the wear mechanisms and the measured test values. From this, 'wear mechanism maps' [1] can be drawn for some of the tested materials (Fig. 7). The tangential speed V_t, is plotted on the horizontal axis and the incursion speed V_{inc}, on the vertical axis. Mechanisms occurring at a set of conditions are plotted using the initial letter of the relevant mechanism. In wear maps drawn from classical wear experiments, wear rate changes define the mechanism boundaries. In the case of the abradable tests, the wear rate is almost equal to V_{inc}, so that other values such as the temperature increase of the coating during the rub, the wear track roughness R or the blade mass variation ΔG have to be used to determine the wear mechanism.

The results presented in Fig. 6 are summarized in Fig. 7 in the form of two 'wear mechanism maps'. Two AlSi–plastic materials with different plastic filler melting points are compared at a testing temperature of 350 °C. At this temperature, one plastic filler is molten (Fig. 7a) and the other solid (Fig. 7b).

The material containing the low-melting-point plastic underwent

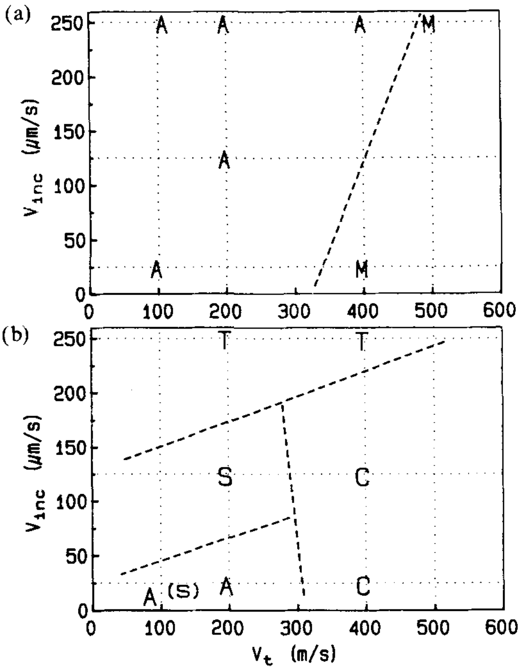

Fig. 7. Wear mechanism maps of two different AlSi–plastic coatings tested at $T = 350°C$. a, Coating with low-melting-plastic (molten at 350 °C); b, coating with higher-melting-plastic (solid at 350 °C). The letters show where tests were run and which mechanism occurred: A, adhesive transfer from the coating to the blades; M, melting wear of blade tip; S, smearing; C, cutting; T, adhesive titanium transfer from the blade to the coating.

adhesive transfer (Fig. 7a, "A") over the major part of the tested speed range. Under adhesive conditions, no temperature rise of the coating occurred during the rub. AlSi was transferred from the coating to the blades, resulting in a high track roughness and a blade mass increase. Although not favourable from a sealing efficiency point of view, this behaviour may be qualified as being safe and unproblematic.

At high blade tip speeds ($V_t \geqslant 400 \text{ m s}^{-1}$), strong frictional heating caused the blade tips to melt ("M") resulting in unwanted blade mass losses and a low track roughness. The liberated particles oxidized and produced heavy sparking. As it results in blade damage, melting wear is harmful and should be avoided in engines.

The material containing the higher-melting-point plastic had a more complex wear behaviour (Fig. 7b). At small V_t and V_{inc} adhesive wear ("A") with coating transfer to the blade tip occurred. These conditions are unlikely to occur under normal operating circumstances. At larger incursion speeds, more material must be removed, in each blade pass, leading to a substantial modification of the stress field under the leading edge of the passing blade. These changing conditions also resulted in a change of wear mechanism. At intermediate incursion speeds, smearing ("S") with a very small amount of coating transfer onto the blade tip took place. As the incursion speeds increased further the mechanism changed to titanium transfer ("T") onto the coating. At very large tangential speeds, ($V_t = 400 \text{ m s}^{-1}$), the coating probably reached its strain rate limit and experienced pure cutting wear ("C"). When this occurred, the coating temperature increased and a very low blade mass variation and track roughness, which are favourable in service, were recorded.

5. Conclusions

(1) An investigation of in-service worn abradable seals found the wear mechanisms to comprise the following: cutting, smearing, adhesive transfer, crushing, melting and tribo-oxidation.

(2) The coating temperature during rub testing has been found to depend on the wear mechanism. Adhesive wear induces a small temperature increase while cutting wear causes strong heating of the coating.

(3) Good correlations were observed between wear track roughness, mass variation of the blades and the occurring wear mechanism. The material system (coating–blade) has little effect on these correlations.

(4) The wear mechanisms found on service parts can all be produced on test specimens by varying the velocity (V_t, V_{inc}) combinations.

(5) Wear mechanism maps have been drawn for several abradable systems. These maps can be used for modelling wear mechanisms and the design of coating systems to provide enhanced performance at elevated temperatures.

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