DAMAGE OF DIFFUSION COATINGS ON TURBINE BLADES

Marta Kianicová a, Karel Slámečka b, Jaroslav Pokluda b

a Alexander Dubček University in Trenčín, Trenčín, Slovakia, kianicova@tnuni.sk
b Brno University of Technology, Brno, Czech Republic, slamecka@fme.vutbr.cz
b Brno University of Technology, Brno, Czech Republic, pokluda@fme.vutbr.cz

Abstract

Nickel- and cobalt-based superalloys have been developed and are used in the hot sections of gas turbines in order to meet complex high-temperature phenomena. The gas temperature in modern engines exceeds 1650 °C in the turbine section and its cooled parts reach temperatures as high as 1200 °C. During operation, the structural materials degrade by fatigue, creep, oxidation, corrosion and erosive wear. Protective coatings provide barriers between the alloys and outer environment and, in particular, they enhance a resistance to oxidation and hot corrosion. The metallic coatings can be divided into two categories: diffusion and overlay coatings. Diffusion aluminate coatings (DAC) are based on the intermetallic compound β-NiAl that forms under the influence of the substrate. Although DAC have been enjoying wide application, they have a limitation which arises from no deliberate changes of their properties to meet requirements of specific service conditions. This article is focused on a detection of damage that formed in the diffusion coatings on first stage turbine blades after two different short-term overheating events. Motivation for this study came from demands for an extension of our knowledge of degradation mechanisms. A possibility of a non-destructive assessment of the damage level using suitable damage parameters is also briefly described.

Keywords: Diffusion aluminate coating, overheating, degradation parameter, creep, aircraft engine.

1. INTRODUCTION

Surface engineering and coatings technology play a crucial role in the operation at high temperatures, particularly for gas turbines, which are subjected to complex thermal and mechanical strain/stress cycling. Depending on the specific component, thin-walled sections can experience widely different thermal fatigue cycles. Coatings are applied with a specific aim to improve the base material resistance mainly to hot corrosion, oxidation and to provide a barrier against high temperatures. These can be achieved by properly bonded coatings to the substrate. The choice of protective coating depends on the operating environment. The main types of protective coatings used for gas turbine components can be defined as follows [1,2]:

- Diffusion aluminate coatings – formed by the surface enrichment with Al, and can be modified by Cr, Pt or Si.
- Overlay coatings – they are commonly known as MCrAlX coatings, where M is the base metal, Cr is chromium, Al is aluminum and X (often yttrium) is represented by components to improve the adhesion to the substrate.
- Thermal barrier coatings – were designed to insulate the component from the hot gas path and generally consist of ceramic topcoat of the zirconia type bonded to the diffusion or overlay bondcoat.

Operating any system beyond the design limits can often cause irrecoverable failure of components, e.g. due to overload or overheating. Stress rupture, creep or thermal shocks are the most important life-limiting factors. Creep degradation during overheating is one of the most serious degradation modes of coated turbine blades in service. This article is focused on a detection of damage that forms in the diffusion coatings after overheating events.
Moreover, a possibility of a non-destructive assessment of their damage level using a suitable damage parameter is briefly described. Motivation for this study came from a demand for a substantial extension of our knowledge of rare degradation mechanism as overheating and request of producer to assess the degradation by overheating from basic data extracted from performance properties.

2. ENGINE SPECIFICATIONS AND REFERENCE CASES OF OVERHEATING

The damage of rotor blades of the first stage of the high-pressure turbine (1VTT) of the DV2 aircraft engine made of the JS6K nickel superalloy was studied after different overheating events during service. This alloy is predetermined for operating temperatures of 800 – 1050 °C and has been, for a long time, utilized in the manufacture of aircraft engine blades by the company Walter Prague. Further details concerning the JS6K nickel superalloy can be found in [3]. The 1VTT blades of the DV2 engine are protected from the high temperature of combustion products by an oxidation, corrosion and creep-resistant Al-Si layer denoted AS2. The 1VTT blades of the DV2 aircraft engine, produced by HTC-AED a.s., Považská Bystrica, Slovakia, are located behind the combustion chamber. They are cooled internally by air, which is taken from the 4th stage of the high-pressure compressor. Internal cooling of blades makes it possible to increase the temperature of combustion products entering the turbine by about 100 °C. At the maximum engine mode, the temperature of gases prior to entering the turbine is 1096 °C. Rotor blades of the high-pressure turbine are the most heavily loaded components of the runner wheel. Owing to surging, a short-time (5 to 20 s) overheating shock can appear so that the working temperature $T$ of outlet gases (behind the turbine) exceeds its critical values $T_{4C,s} = 705 °C$ for the engine starting and $T_{4C,o} = 760 °C$ for the operation modes [3]. This shock causes a creep-based damage of coatings and a subsequent reduction of service life of the gas turbine rotor blades when compared to the planned life of 1500 flight hours. The overheating data (time over the critical temperature $T_{4C}$ and temperature of outlet gases) were registered by thermocouples positioned behind the last stage of the three-stage turbine. Up to now producer of investigated engines remarked 28 cases of different overheating events. After their macroscopic and microscopic analyses we can found direct relevance between failure of blade coating and overheating event as shown in the following examples.

2.1 Engine 94072

Engine 94072 had 327 hours and 45 minutes of flight operation. The critical temperature excess of outlet gases occurred when starting the engine and switching over to the basic control system, with the maximum overheating temperature reaching 748 °C and the duration of 5.1 s corresponding to of permitted critical temperature excess. Blade 94072 has a much degraded outer sub-layer, corrosive products of fuel combustion damaged it down to the diffusion sub-layer level. The average thickness on this concave side of blade is 14.6 μm (Fig. 1.). The two-layer coating on the convex side of less stressed blade is non-uniform and covered by corrosive phases at lower thickness. The average coating thickness of convex side is 19.3 μm (Fig. 2.). Excessive thickness of corrosive phases and melting of secondary carbides on the grain boundaries of substrate JS6K indicate the event of short-time overheating.
In the process of high-temperature exploitation tensile stresses evolving in the area of corrosion products can lead to generation of cracks parallel to the interface coating/substrate (Fig. 3.). These cracks in the gradual exploitation interconnect and consequently lead to the degradation mode of spalling. This mechanism causes a gradual or total loss of upper parts of coating after overheating.

2.2 Engine 94074

Engine 94074 had 166 hours and 15 minutes of flight operation. The critical temperature excess of outlet gases occurred when the engine was starting. The temperature \( T_{4,C} \) reached 858 °C and the period of overheating was 6.1 s. The microphotographs of blade 94074 document a very pronounced degradation of not only the DAC but also its base nickel alloy.

The blade on the concave side is without coating (Fig. 4.). DAC on the convex side of the blade consists only of the degraded diffusion sub-layer (Fig. 5.). Its average thickness value reaches 9.4 μm. As regards the microstructure, the coating is formed by the \( \gamma \) matrix and a small amount of fine carbide particles. Needle-shaped particles based on creep-resistant elements occur beneath the diffusion zone of coating and has been termed secondary reaction zone or SRZ [4]. For many nickel-base alloys it is typical to observe these precipitates in the interface coating/substrate after high temperature exposures. Ni-base superalloys are prone to precipitate \( \sigma \)-phases of needle-shaped morphology which occur in the range of 650-950 °C.

Surface roughness, creep deformation, the presence of scaling and extent of interdiffusion between the coating and substrate are the main degradation characteristics due to higher then normal operating temperature. At the same time rapid environmental attack (oxidation and hot corrosion) induces cracks perpendicular to the interfaces and leads to spalling and finally loss of coating.
2.3 Engine 94076

Compared to all the analysed blades, engine 94076 had the highest number of hours of flight operation, i.e. 342 hours and 7 minutes. The critical temperature excess of outlet gases occurred while the plane was landing, when training manoeuvre of touchdown was accompanying by abrupt burnout in the combustor chamber for 10 s with corresponding decreasing of revolutions. The reaction of the pilot trying to increase these revolutions led to shifting the engine control lever towards higher degrees. This elemental operation increased the flow of fuel into the no-longer burning combustion chamber and repeated mixture ignition did not to starting run and increasing of revolutions of high pressure turbine. Instead the maximum temperature, measured in back of turbine achieved 1079 °C, the duration of permitted temperature excess was of 20.6 s. From basic engine parameters depicted in Fig. 6 is evident that revolutions despite excess of temperature are increasing. Relation between revolutions of high pressure turbine and temperature of outgoing gases sustains that in the turbine did not spring to the change of thermal energy to mechanical work. This phenomenon gives us information that engine experienced burning outside the combustion chamber what corresponds with no significant macroscopic changes detected in the coating (Figs. 7, 8). The average respective thicknesses of coatings 18.8 μm and 21.1 μm on the concave and convex sides correspond well with the number of flight hours of operation. Fig. 8 gives another confirmation of initialization and propagation of cracks from the areas of corrosive attacks with superimposed thermal and mechanical cycling.
2.4 Discussion of Results

Microphotographs of analysed blades after overheating event showed a complex influence of creep, increasing oxidation and corrosion, interdiffusion of elements into coating and between substrate and coating, as well as precipitation and grow of undesirable phases at the interface substrate/coating. Microstructures of blades 94072 and 94074 expose that excessive service temperature produces a great amount of corrosive phases which, due to cyclic stresses, lead to the cracks parallel to the interface.

Gradual loss of upper parts of coatings is a consequence of this mechanism. Because higher both the temperature field and the temperature gradient are on the concave side of blades, these sides are always degraded with higher intensity. Cracking near the sub-zone interface (Fig. 3) means a start of the spalling processes that cause a gradual reduction of the coating thickness. Such cracks are a result of local tensile stresses perpendicular to the interface caused by a gradient of tensile stresses directed along the interface during overheating and/or by rumpling of the sub-zone interface under high compressive stresses in the diffusive subzone during cooling (similarly as on the TGO/TBC interface of thermal barrier coatings [5]). Due to the latter process, the tensile stresses develop at the concave site of the diffusive sub-zone while the compressive stresses appear at the convex site. Shear stresses are induced at inclined sections. The magnitude and the sign of these stresses depend on both the mismatch of elastic moduli of sub-zones and the ratio of the amplitude to the wavelength of the wavy interface. The cracking of this type is augmented by the thermal cycling that is normally prevalent in service.

Formation of through-the-thickness cracks, perpendicular to the surface, manifests some significant cyclic changes of residual stresses in the coating also during the external overheating event. In the case of the engine 94076 one can imagine that, after an extreme cooling down and a repeated heating to the working temperature, a sequence of rather high compressive and tensile stresses appeared in the coating bulk which, most probably, led to a creation of these cracks. The overheating produces a sequence of compressive and high tensile stresses in the coating [6] leading to a formation of through-the-thickness cracks. Although these cracks were, in fact, not a direct reason for the coating destruction, they could serve as channels for penetration of external corrosive environment into the protective layer and substrate.

3. NONDESTRUCTIVE ASSESSMENT OF COATING DAMAGE

Because the producer always has to decide about a further performance till the next general repair, he used following empirical parameter based on an extract of preceding overheating data.
\[
D = (t_2 - t_0)(T_{\text{max}} - T_c)^3 \int_{t_0}^{t_2} [T(t) - T_c] \, dt
\]

where \( t_0 < t < t_2 \) is the overheating duration, \( T > T_c \equiv T_{\text{4C}} \) and \( T_{\text{max}} \) is the maximal overheating temperature. The critical values of that parameter are related to the service measures so that the producer can meet a statement concerning the performance capability [Manual, Africa].

In order to verify the reliability of the parameter \( D \), the reduction of the thickness of AS2 layers was analyzed for four overheating events. It was found that the relative thickness of the degraded surface layer was a monotonically decreasing function of the parameter \( D \). The best fit of that function was achieved by a quadratic dependence of the relative thickness on the logarithm of \( D \). The critical parameters of \( D \) corresponded well with the expected geometrical shapes of the coatings. Thus, the description of blade damage using the parameter \( D \) according to eq. (1) seems to be very plausible.

The parameter \( D \) possesses an interesting physical meaning. When assuming a creep work done by tensile misfit stresses during the overheating event, one can show that this parameter is directly proportional to the specific Hamiltonian’s action.

Consequently, the damage function can be expressed in a more general form as

\[
D = (t_2 - t_0)^{1+q} [T_{\text{max}} - T_c]^{q(n+1)} \int_{t_0}^{t_2} [T(t) - T_c] \, dt
\]

where \( p + q = 1 \) and \( n \in (1, 6) \).

The parameter \( D \) defined by eq. (1) represents a special case of eq. (2) for \( p = 1/4, q = 3/4 \) and \( n = 3 \). The value \( n = 3 \) indicates a plausible mixture of diffusion and dislocation mechanisms of the creep damage during the overheating events.

Thus, one can examine other forms of the damage parameter when retaining its physical meaning in terms of the unit \( (^\circ \text{C} \cdot n^{1}s^2) \) and avoiding both fractions and negative values of powers in eq. (2). After examination of 18 various permissible sets of parameters \( n, p \) and \( q \) a much simpler damage parameter

\[
D' = (t_2 - t_0)^2 (T_{\text{max}} - T_c)^4
\]

was found as a nearly equivalent to \( D \). However, this new damage parameter would need a further verification. The assessment procedure based on the parameter \( D \) does not provide correct data in the special cases when the overheating is caused by a gas burning outside the combustion and repeated overheating of the engine. Nevertheless, these cases can be easily identified when analyzing records of the engine data during service.

4. **CONCLUSION**

Microphotographs of analyzed blades represent the complex influence of degradation modes typically occurring at high temperatures. Consequences of high temperature and heat drop by sudden cooling below the critical temperature \( T_{\text{4C}} \) we can summarize subsequently:

- The high temperature exploitation together with creep deformation induces the mechanism of accelerated oxidation on the top of the coating and diffusion of elements in the system coating/substrate. At the same time a decomposition of carbides of type \( M_{23}C_6 \) occurs in the substrate along with a tendency towards stigmatization of the alloy at the coating/alloy interface (Fig. 3. and 5.).
• Rapid decreasing of the high temperature on the surface due to cooling via air-cooling channels lead to a creation of tensile stresses in the coating (as consequence of mismatch of coefficients of thermal expansion) and subsequently to cracks perpendicular to the interface coating/substrate. Coactive cooling results in the surface condensation of exhaust gases and accelerated hot corrosion (Fig. 1.). These areas serve as initiators for generation and propagation of cracks not only perpendicular to the interface (Fig. 8.) but also parallel with interface (Fig. 3.). Their effect is a partial (Fig. 5.) or a total loss of the coating (Fig. 4.) that is known as spalling.

The empirical parameter \( D \) defined by eq. (1) is a useful tool for a non-destructive assessment of the damage level. The more simple parameter defined by eq. (3) seems to work as well but this would need a further experimental verification.

ACKNOWLEDGEMENT

This work was supported by the Ministry of Industry and Trade of the Czech Republic in the frame of the Project FR-TI1/237 099.

LITERATURE


