DEGRADATION OF ALUMINIDE COATED DIRECTIONALLY

SOLIDIFIED SUPERALLOY TURBINE BLADES

IN AN AERO GAS TURBINE ENGINE

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Abstract

The conventional polycrystalline nickel based superalloys for gas turbine blade application are gradually replaced by the newer and more advanced directionally solidified (DS) superalloys due to their improved mechanical properties. In spite of this development, cheaper aluminide coatings are still widely used on the DS superalloys to protect them from high temperature oxidation and corrosion attack. This paper discusses the modes of service induced degradation such as oxidation, thermal fatigue (TF) and interdiffusion in a DS nickel based superalloy with a diffusion aluminide coating which is currently being used in the high pressure turbine (HPT) of an advanced aero engine. The presence of complex internal cooling passages in the blade along with poor TF properties of the aluminide coating give rise to the initiation of a large number of cracks in the coating. Ingress of oxidants through these cracks leads to the failure of the component.

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Introduction

Directionally solidified (DS) superalloys are generally superior to polycrystalline counterparts because of their improved high temperature mechanical properties. This has been achieved as a result of better control on grain morphology and crystallographic texture, lower levels of porosity and a significant difference in the nature and distribution of precipitating phases during directional solidification As a means of protecting these advanced superalloys from the aggressive turbine environment, coatings are applied by a variety of processes (2). In advanced aero engines, NiCrAlY or NiCoCrAlY type overlay coatings are most commonly used although ceramic type thermal barrier coatings are finding increasing application in the turbine hot section particularly in stationary components. However, aluminide coatings obtained by pack cementation process, at a much lower cost are still widely used by aero engine manufacturers.

This paper describes the modes of service induced degradation in several prematurely retired directionally solidified high pressure turbine (HPT) blades. The blades were air cooled DS René 80H with a diffused aluminide coating on the airfoil and platform surfaces applied by a pack cementation process. The modes of coating degradation in these blades were examined and the influence of coating degradation on the substrate alloy was investigated.

Experimental

Several prematurely retired DSRené 80H HPT blades of chemical composition given in Table 1 were retrieved from the service engines. The blades were electroless nickel plated to preserve the corrosion products on the surface. Blade sections were cut and metallographic examination was carried out using a Novascan 30 scanning electron microscope. Energy dispersive X-ray analyses were done using a Tracor Northern energy dispersive X-ray analyzer attached to a scanning electron microscope.

Table 1

Approximate Composition in Weight % of Alloy René 80H* (3)

Ni	Cr	Со	Мо	W	Ti	Al	В	Zr	Нſ
Base	13	9.6	4.0	4.9	4.5	3.0	0.015	0.01	0.74

^{*} Trade Mark of General Electric Company

Results and Discussion

Figure 1(a) and (b) respectively show the front and top view of a service exposed HPT blade illustrating A) tip oxidation, B) tip cracking as well as C) thermal fatigue cracking in the leading edge area. The aluminide coating showed signs of oxidation, thermal fatigue and interdiffusion between the coating and substrate alloy. These degradation modes are discussed individually in the following.

The DSRené 80H blade has several cooling holes in the blade tip region as shown in Figure 1(b). These cooling holes were found in the partially or fully plugged state after service exposure (Figure 2). As high as 6 to 9 tip cooling holes were plugged in a single blade. The debris was identified as nickel and aluminum rich oxides. Minor quantities of other elements such as titanium, chromium and cobalt were also found in these oxides.

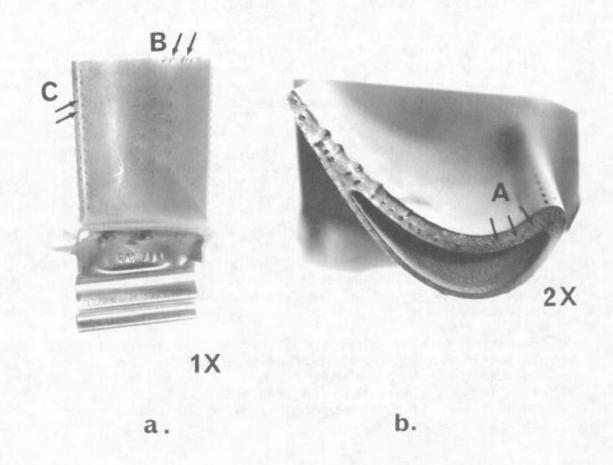


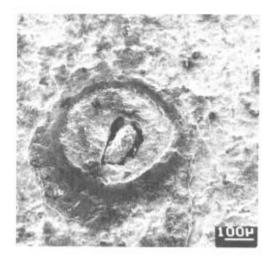
Figure 1. a) Front and (b) top view of a service exposed HPT blade showing regions of: A. Tip oxidation. B. Tip cracking. C. TF cracking in the leading edge.

The implications of partially blocked cooling holes are that these oxides have a lower thermal conductivity than the blade material and act as thermal insulators between the internal cooling air and the hot internal blade surface, while fully blocked holes limit the flow of cooling air into the blade. Consequently, both conditions would act to increase the blade temperature which in turn can lead to a higher oxidation rate of the substrate alloy if exposed directly to the gas turbine atmosphere. This condition was actually observed in the service exposed turbine blades. Since the new blades were "tip ground" prior to engine installation and/or were allowed to cut through the high pressure turbine shroud during testing, the aluminide coating in both cases was removed thus exposing the bare tip surface. As a result, severe oxidation of the DSRené 80H substrate alloy was observed at the tip in the vicinity of cooling holes as depicted in Figure 2.

Tip Oxidation and Cracking

The high pressure turbine blade had undergone catastrophic oxidation and radial cracking at the blade tip, specifically between the mid-chord and trailing edge regions. The damage to the blade trailing edge was found to be much more severe than in other regions. This damage is illustrated in Figure 3. The tip degradation found by examination of a number of service exposed blades is summarized as follows:

- (i) The number of tip cracks ranged from 6 to 12 per blade.
- (ii) The tip was heavily oxidized. Since the tip cooling holes were partially coated during the aluminide coating process, they were little affected by oxidation compared to the surrounding base surface. The evidence that the cooling hole walls stand above the oxidized substrate alloy supports this view point, (Figure 1(a)).
- (iii) The tip cracks usually have a broad mouth (1-3 mm) towards the trailing edge of the concave surface. Some of these cracks extended up to the convex surface i.e., across the entire trailing edge thickness. Such cracks were in fairly advanced stages, therefore their origin could not be established.
- (iv) It is suggested that these cracks were of thermal fatigue nature resulting from the variation in temperature across the trailing edge region of the blade. Loss of aluminide coating due to tip grinding before installation and/or tip rubbing against the turbine shroud during engine operation may also have contributed towards initiation of such cracks.
- (v) Extensive loss of substrate alloy in the tip cracks by exidation followed by scale evaporation, spalling or erosion contributed towards the widening of these cracks. In the HPT blades examined so far, it is believed that the predominent mode of material loss from these cracks is by evaporation since no visible signs of erosion or spalling were observed.



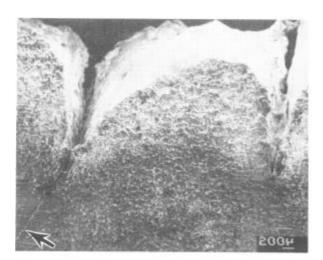


Figure 2. SEM micrograph showing tip oxidation and plugged cooling hole.

Figure 3. SEM micrograph showing the oxide morphology on the blade tip surface.

- (vi) The tip cracks ranged from 0.1 to 6 mm in length and propagated into the substrate alloy downwards in the radial direction. Some of these radial cracks have been observed to turn to become axial. This could have a serious consequence such as blade tip separation.
- (vii) The radial cracks proceeding downwards gave rise to a number of fine axial cracks.

The oxidation of substrate alloy DSRené 80H was not confined to the tip regions, but also extended into the interior of the blade through the tip cracks. Figures 4 (a) and (b) show longitudinal cross-sections of a blade in which cracks extended from the tip and propagated in the radial direction. Some of these cracks originated at the grain boundaries near the blade tip and some far away from it, suggesting that the grain boundary channels of the DS alloy did not have any major impact on the material degradation process.

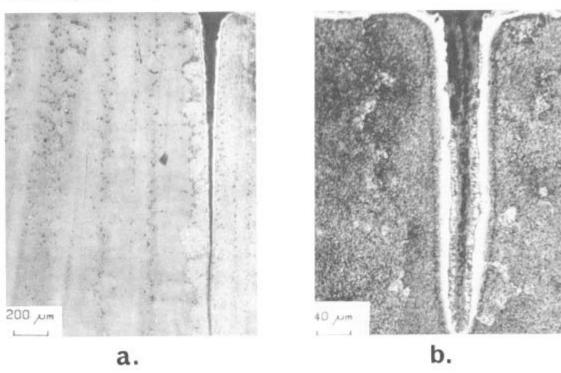


Figure 4. Scanning electron micrographs showing a crack originating from the blade tip (a) near a grain boundary, b) in the bulk grain.

Figure 5 shows a general morphology of the oxidized layer at the blade tip in a longitudinal cross section. No trace of the aluminide coating was found near the tip. The outer scale layer contained Ti and Cr rich oxides and the inner layer contained small elongated internal oxide particles rich in Al and Ti. The morphology of oxidation products in a growing crack was quite similar to the general tip oxidation morphology except in certain regions where the internal oxides had formed a complete layer (Figure 6).

Elemental X-ray analyses near the internal oxidation zone revealed a depletion of Al, Ti and Cr in the alloy matrix. Absence of gamma prime (γ ') was noticed in this depleted zone. The severity of the depletion was best judged by comparing the morphology, size and volume fraction of the γ ' phase in the depleted zone and the alloy underneath. Figure 7 shows the size and distribution of γ ' precipitates in the substrate alloy just below the depleted zone. Loss of Al and Ti in this region resulted in a loss of gamma prime phase in the alloy.

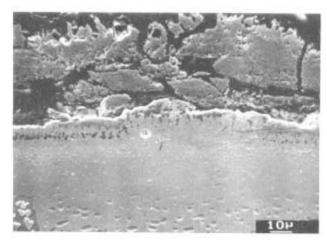


Figure 5. SEM micrograph showing the oxide morphology on the blade tip surface.

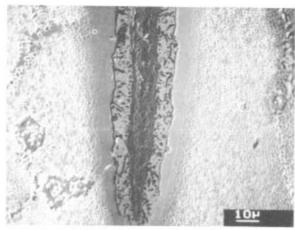
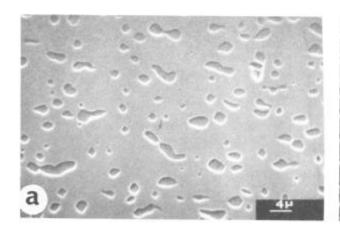


Figure 6. SEM micrograph showing oxide morphology in the vicinity of a tip crack.



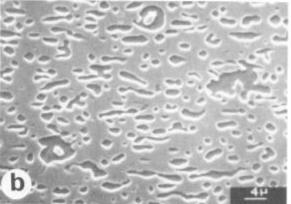


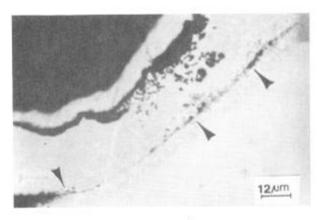
Figure 7. SEM micrograph showing variation in morphology and distribution of γ' (a) immediately below the depleted layer as shown in Fig. 5. (b) well below the region shown in Fig. 7(a).

Degradation of Aluminide Coating

The aluminide coating on the HPT blade consisted of a coarse grain β -NiAl structure in the outer layer and a diffusion zone containing TiC, M23C6 carbides and sigma phases. Three modes of coating degradation have been observed in the service exposed turbine blades. They are respectively oxidation, thermal fatigue and interdiffusion.

Oxidation

Oxidation of the aluminide coating leads to the formation of Al₂O₃ which if mechanically stable can provide very good oxidation resistance. In actual service operation, cyclic variation in turbine blade temperature results in spalling of the Al₂O₃ from the coating. In the HPT blades investigated, the aluminide coating provided moderate oxidation resistance in the regions where the coating was undamaged. Localized oxidation attack of the coating occurred near the diffusion zone which resulted in coating delamination (Figure 8). In some instances, the coating had spalled from the leading edge region of the blade due to oxidation attack at its diffusion zone (Figure 9).



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Figure 8.

SEM micrograph illustrating preferential oxidation attack at the coating/substrate interface.

Figure 9.

SEM micrograph illustrating coating loss at the leading edge due to oxidation attack at the diffusion zone.

The role of hafnium in providing oxide scale adhesion on MCrAl alloys is well known (4). Hafnium in a directionally solidified MM-200 alloy has been observed to diffuse into the EB-PVD NiCoCrAlY coating and provide better Al203/coating adhesion than on a NiCoCrAlY coated Hf free alloy (5). The theory is that hafnium diffuses into the overlay coating and forms a higher density of hafnium rich oxide "pegs". Similar behaviour could be expected from the DSRené 80H/aluminide coated blades which contains an equivalent amount of Hf. However, in this investigation service exposed blades did not show any such pegs. Recent Auger and SIMS analyses on these blades also confirmed the absence of Hf enriched oxide pegs (6). This observed difference could be due to the limitations imposed on diffusion of Hf through various carbide and intermetallic phases present in the coating diffusion zone.

Thermal Fatigue

The HPT blade experiences a complex thermal and mechanical history during a typical mission of the aircraft. Temperature gradients and mechanical constraints during such complex cycles give rise to cyclic thermal stresses and therefore induce thermal fatigue (TF) damage in the HPT blade. Since the aluminide coating on the HPT blade has a fairly high brittle to ductile transition temperature, the coating can be somewhat brittle at near service temperatures. Any thermal fatigue crack formed in the coating can then be propagated into the substrate alloy.

Figures 10(a) to (d) illustrate the thermal fatigue cracks present in various regions of an HPT blade. Depending on the location of the crack, minor to extensive substrate alloy attack has been observed. Figure 10(a) shows the initiation of a TF crack in the coating whereas Figures 10(b) and (c) show attacked regions near the blade leading edge. It should be noted in Figure 10(d) that near the leading edge of the blade, the diffusion zones of the external airfoil coating and the internal coating on the cooling hole surface have completely overlapped each other. In other words, no substrate alloy was found to be present in between these two coating interfaces. As a result of this and poor TF properties of the coating, a crack that had initiated in this region of the coating propagated through the entire blade wall thickness. Gamma prime depletion zones beneath the interior oxidized surfaces were also observed in these cracks.

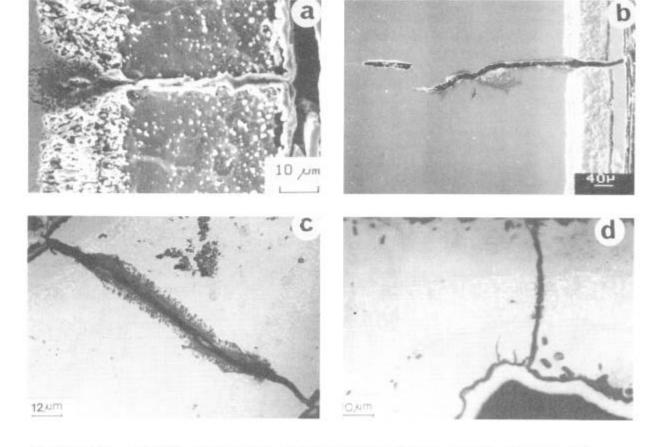


Figure 10. a) SEM micrograph showing TF cracking of the coating and b) subsequent substrate alloy attack, c) optical photomicrograph showing complete attack on a thin blade wall d) TF cracking at the region where coating diffusion zones overlapped.

Interdiffusion

The difference in chemistry of the aluminide coating and the substrate DS René 80H alloy gives rise to chemical potential gradients of Al, Ni and other alloying elements. Predominant processes are the diffusion of Al from the coating into the substrate alloy and diffusion of Ni, Co, Ti and Cr in the opposite direction.

Compositional variation of different alloying elements such as Ni, Al, Co, Ti and Cr were determined across the coating on a qualitative basis by a line scan technique using an Energy Dispersive X-ray analyzer attached to a scanning electron microscope. The results are shown in Figures 11(a) and (b). Figure 11(a) shows a gradual depletion of Al from the coating due to its diffusion zone into the substrate alloy. Sigma phase formation beneath the coating diffusion has been observed quite extensively, particularly towards the trailing edge of the blade. This is shown in Figures 12(a) and (b) which represent respectively, longitudinal and transverse section of the blade a substrate/coating interface region. Sigma phase is formed as a result of Al diffusion from the coating into the substrate alloy and enrichment of elements like Cr, Mo, W and Ti at the coating/substrate alloy interface. Formation of sigma phase in thin wall sections of the blade can offer an easy path for crack propagation from the coating into the substrate alloy, although no such phenomenon was observed in the present investigation (7).

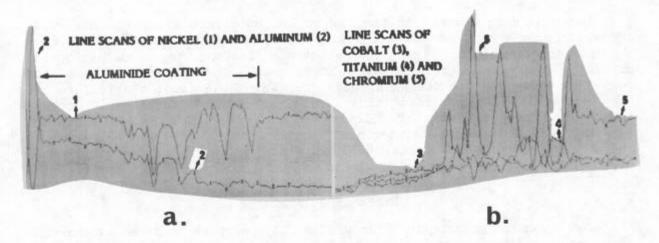


Figure 11. Elemental X-ray intensity profiles of a) Ni, Al and b) Co, Ti and Cr obtained by an energy dispersive X-ray analyzer.

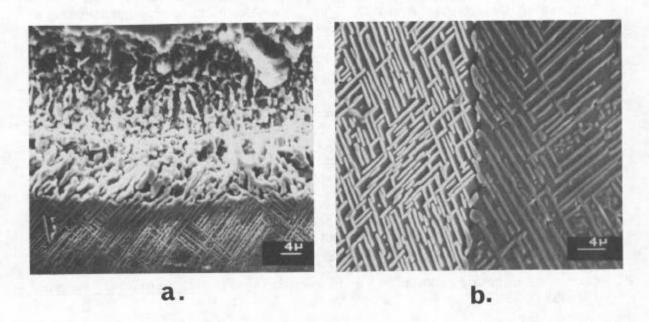


Figure 12. SEM micrographs illustrating the sigma phase formation below the coating diffusion zone, a) longitudinal section and b) transverse section through the region containing the sigma phase.

Summary and Conclusions

Investigation of several prematurely retired HPT blades showed extensive tip damage such as cracking and oxidation particularly towards the trailing edge region. The initiation of this damage is believed to have started from the tip surface due to the loss of the protective aluminide coating by tip grinding and/or rubbing against the HPT shroud. Initiation and propagation of TF cracks at the trailing edge subsequently accelerated the substrate alloy attack by oxidation. Resistance of the DSRené 80H substrate alloy to oxidation at the turbine operating temperature was observed to be poor. The plugging and oxidation of tip cooling holes also were attributed to tip grinding and/or rubbing against the turbine shroud. The oxide in the cooling hole can act as an insulator and limit heat transfer from the blade to the internal cooling air.