Damage of protective coating due to unstable engine running

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Abstract
The paper deals with damage of rotor turbine blades in condition of unstable engine running as engine surging or sudden engine stop. Three aircarft engines after the service with a different history were studied. In all cases, an overheating of the engines accidentally appeared during the service. Representative blades were chosen from every engine and studied by light microscopy, scanning electron microscopy, energy and wave dispersion spectroscopy. The blades were produced from JS6K superalloy and coated by Al and Si. This protect layer is ranked among diffusion coatings. The limiting factor of the engine operation lifetime is the state of the coatings; therefore, an attempt to correlate the damage level of the coating with the service parameters, especially with the overheating temperature and the duration of this event, was made. It was found that the exposure to high temperature above the critical value only for several seconds substantially decreases the engine-power and its durability.

1. Introduction

Majority of hot component are made from superalloys with protect coatings which are the function of the engine operating conditions. Thus alloys are developed to improve their creep resistance, resistance to fatigue, oxidation and hot corrosion [1,2,3]. Coatings focus on serving as physical barriers between aggressive compounds of environment and the substrate. However, no coating has been found to these days that would survive the aggressive environment of a gas-path in turbines.
Excluding the base modes of failure as high-temperature oxidation, high-temperature hot corrosion and low-temperature hot corrosion, there are several other damage modes leading to cause coating loss and accelerate the overall failure mechanism [4,5,6]:

- Mechanical distress to the coating.
- Solid state diffusion of elements between the coating and substrate.
- Spallation due to differential thermal expansion of coating and substrate.
- Rumpling of coatings.

As the temperature increases above the critical temperature of outgoing gas, diffusion plays a great role in damage and subsequently the differential thermal expansion between coating and substrate can cause spallation of coating.

A motivation for this work comes from a demand for an extension of knowledge concerning a degradation of diffusion AlSi coatings protecting rotor blades of the aircraft engine DV2.
This aircraft is appointed for light training combat aircraft, where sudden changes of engine output are in progress during flight maneuvers. Owing to surging, failure of the fuel system or a human factor, the work temperature of blowing gases can exceed its critical value T_{4C} = *760 °C*. If this exceeding happens under starting, the critical value T_{4C} = *705 °C.*

2. Failures of rotor blades

2.1 Material and heat treatment of blades

The subject of study was the cooled rotor blades of the first stage of the high-pressure turbine (Fig. 1). Polycrystalline rotor blades are made of nickel-based superalloys JS6K (Table 1) by a precise casting. Their heat and chemical-thermal treatment is described in the Table 2. AlSi coating is used for service temperature in the range 815-1150 °C.

Table 1 The chemical composition of JS6K alloy

Chemical element	Ni	C	Co	Cr	W	Mo	Ti	Al	Nb	Fe	B
mass. %	base	0.12 0.20	4.0 5.0	9.5 12.5	4.5 5.5	3.5 4.8	2.5 3.2	5.0 6.0	5.5	2.0	0.02

Table 2 Heat and chemical-thermal treatment of JS6K superalloy

Type of treatment	Technological procedure of treatment
Homogenization annealing	In vacuum, at 1225 ºC, 4 h dwell at temperature, cooling by argon stream at an overpressure of 1.5 – 2 bar.
Annealing to remove residual stress after mechanical treatment	At 950 ºC, 2 h dwell at temperature in dry argon environment; cooling in air.
Creation of AlSi layer	Stage 1: spraying a layer of AS2: 350 ml coloxyline solution, 112 g Al powder, 112 g Si powder
	Stage 2: diffusion annealing at 1000 ºC 3 h dwell at temperature; slow cooling in a retort.

The microstructure of AlSi layer is shown in the Fig. 2 and it is composed of two sublayers. The outer Al-sublayer is created by NiAl with content of Al<50 at.% and lower amount of phases containing refractory elements. The inner Si-sublayer creates Ni-Al matrix and higher amounts of phases of elements as: Si, Cr, Mo, Ti, W and Co. The thickness of layer varies in the range of 20–50 μm.

Fig. 1 The rotor blade

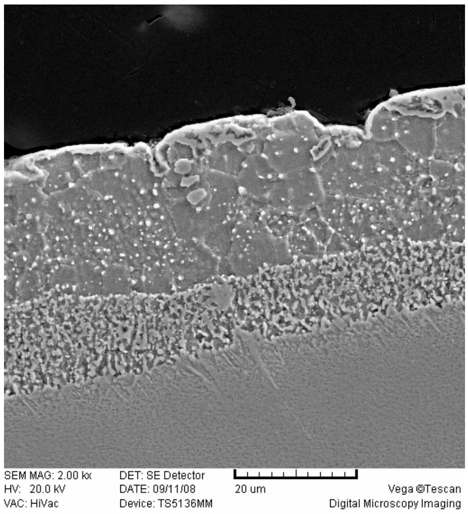

Fig. 2 Microstructure of AlSi layer

2.2 Damage of blades due to overheating

2.2.1 Engine 92040

Significant microstructural changes of coated blades depend on the degree and time of overheating. A few of examples of these changes are described below. Engine 92040 had 167 hours and 37 minutes of flight operation when surging performed at the Egyptian operator. The critical temperature of outlet gases T_{4C} rose to 997 ºC and the duration of critical temperature excess was 12 s (Table 3, Fig. 3). This short overheating caused degradation of coating blades. Their microstructure is visible in the Fig. 4.

Table 3 Data of local analysis taken in flight real time

Time	AR [deg]	VTK [%]	NTK [%]	CLH [l/h]	TEG [°C]	Time	AR [deg]	VTK [%]	NTK [%]	CLH [l/h]	TEG [°C]
00:09:28	26	54.6	31.3	***319***	561	00:09:36	27	43.3	21.2	248	972
00:09:29	26	52.9	28.3	***343***	659	00:09:37	52	42.3	20.6	248	976
00:09:30	26	51.3	26.5	***343***	753	00:09:38	69	41.4	20.1	248	980
00:09:31	27	49.7	25.3	***378***	841	00:09:39	64	40.3	19.8	236	989
00:09:32	27	48.5	24.2	331	922	00:09:40	1	39.4	19.2	201	997
00:09:33	27	47.1	23.3	296	951	00:09:41	1	36.1	17.7	0	877
00:09:34	27	45.7	22.5	272	960	00:09:42	1	32.9	16.3	0	773
00:09:35	27	44.5	21.8	260	964	00:09:43	1	30.3	14.9	0	690

Where:

AR - Control stick position
VTK - High-pressure compressor revolutions
NTK - Low-pressure compressor revolutions
VNA - Tilting mechanism
TV - Outer temperature
TEG - Temperature of outlet gases
CLH - Fuel flow

Data from Table 3 document that the fuel flow was increasing from 28th to 31st second of operating time while pressure compressor and turbine revolutions were decreasing (blades of compressor and turbine are on the same rotary shaft).

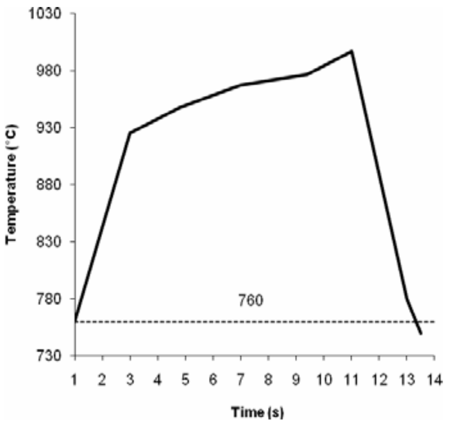

Fig. 3 Waveform of critical temperature excess of engine 92040

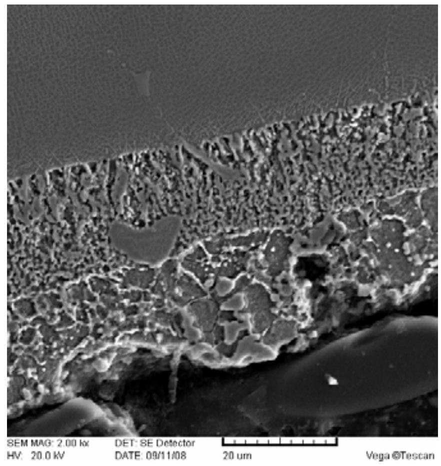

Fig. 4 Microstructure of AlSi layer on the convex side of 92040

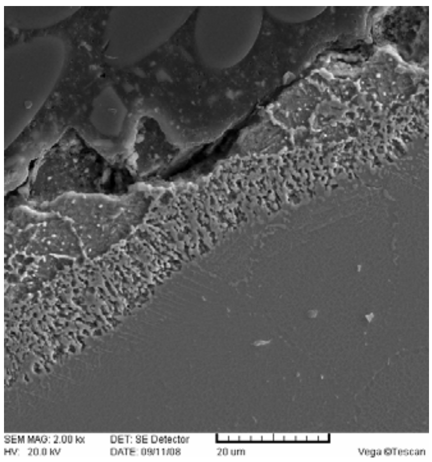

Fig. 5 Microstructure of AlSi layer on the concave side of 92040

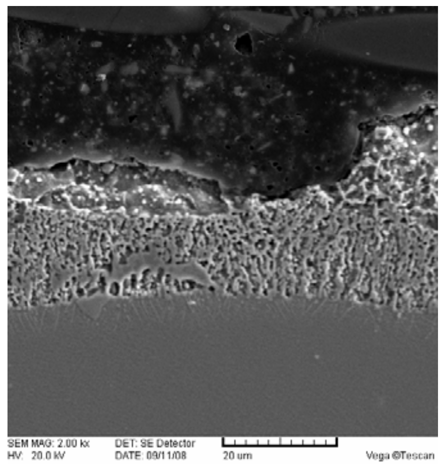

Fig. 6 Microstructure of AlSi layer on the leading edge of 92040

In the Fig. 4,5,6 are clearly visible difficulties of damage on individual parts of blade 92040.

The leading edge and the concave side were more loaded than the convex side and their outer zones are more damaged, some of outer areas were removed from surface.

2.2.2 Engine 91016

The engine 91016 ran 25 hours and 18 minutes when overheating was caused by surging at the Egyptian operator during 7 seconds. Another 27 s of overheating occurred due to a control fault. The temperature peaks reached 1094 °C (Fig. 7). Microstructure of engine blade is presented in the Fig. 8.

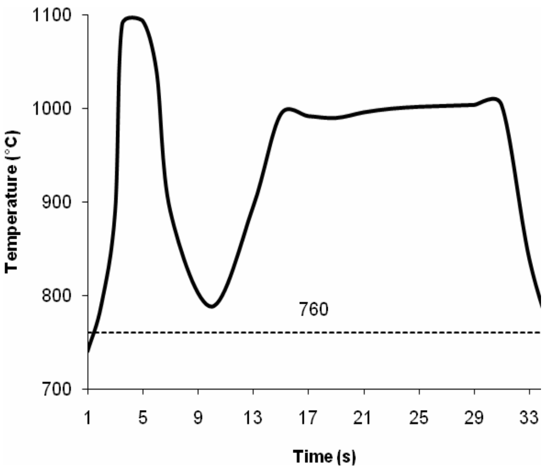

Fig. 7 Waveform of critical temperature excess of engine 91016

In spite of that the engine had only 25 hours and 18 minutes of flight operation, surging and consequently a control fault in total duration time 34 seconds caused complete loss of coating. This example of overheating approves very rapid damage of coating by spallation and surface of JS6K alloy underwent the state of plastic flow (Fig. 9).

The microstructure illustrated in the Fig. 9 proved that unstable service conditions and thermal-mechanical overloading caused very rapid and non-permissible damage of coatings. The engine can not be in working operation under these aspects and is subjected to repair.

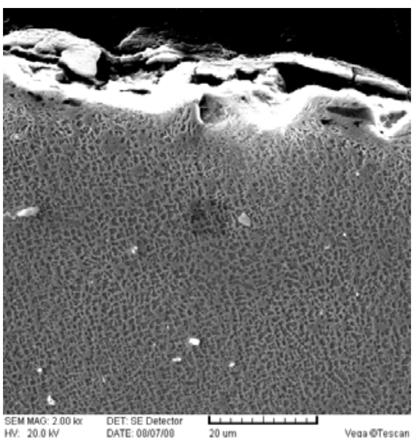

Fig. 8 Microstructure of 91016 engine blade

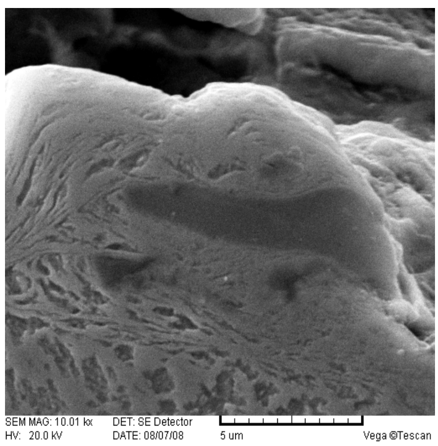

Fig. 9 Microstructure of damaged blade

2.2.3 Engine 94076

Compared to the previous analysed blades, engine 94076 had the highest number of hours of flight operation, i.e. 342 hours and 7 minutes when suddenly the engine stopped in the range of 10 seconds. The maximum overheating temperature reached 1079 ºC and the duration of temperature excess was 20.6 s (Fig. 10). Microstructure of the blade on the convex side (Fig. 11) is different from the one on the concave side (Fig. 12).

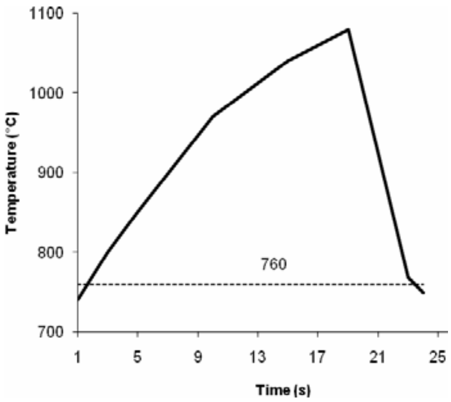

Fig. 10 Waveform of critical temp. excess for engine 94076

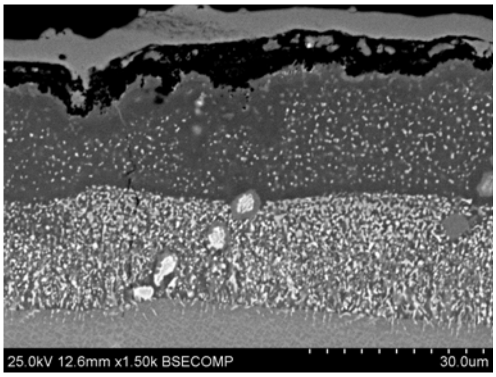

Fig. 11 Convex side of 94076 blade

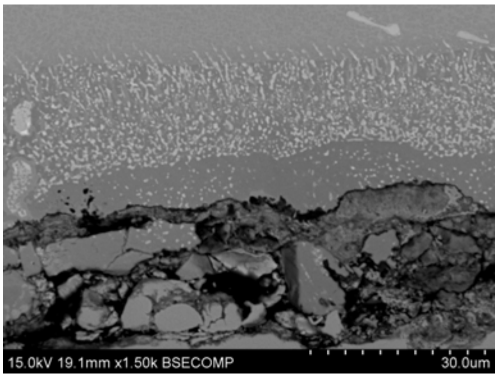

Fig. 12 Concave side of 94076 blade

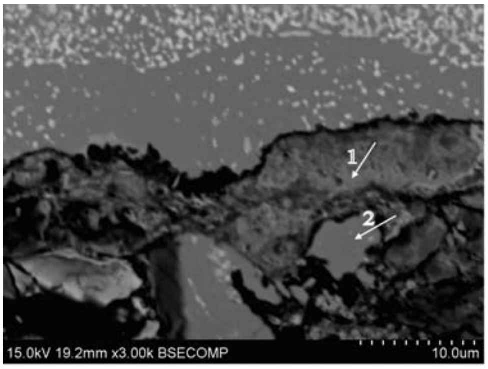

Fig. 13 Analyzed areas on the concave blade side

The concave side of the blade is covered by corrosion phases and so the damage is different from the previous mentioned blades 92040 and 91016. Corrosion products occupied a half of AlSi zone, while surging of 92040 and 91016 engines caused removal of AlSi coating. The microchemical analysis of corrosion products (Fig. 13) is presented in the Table 4.

Sudden stopping of engine 94076 and its temperature excess caused wider range of deterioration in the outer zone of AlSi concave side. The AlSi coating of the convex side is without damage besides inconsiderable phase changes.

Table 4 Microchemical analysis of corrosion products

At. %	Mg-K	Al-K	P-K	Ca-K	Ti-K	Cr-K	Fe-K	Ni-K	Mo-L	W-L
Pt1	1.49	16.15	8.36	2.06	5.19	3.22	-	60.87	2.66	-
Pt 2	-	38.36	-	-	0.53	2.58	0.55	57.26	-	0.71

3. Method for Assessment of blades and performance capability of engine

The producer of engines DV2 provided 6 pieces of damaged blades by overheating to investigate. Measurements of their relative width on the both sides and limitation for performance capability from basic data about overheating event enabled to plot the graph as a function of the degradation level *D* and the relative width *h_r* (Fig. 14). Data of two investigated blades are not included in Fig. 14 because the burning of the gas was made up outside the combustor chamber and so they were not damaged by high temperature. Among them just belongs analyzed 92040 engine blade.

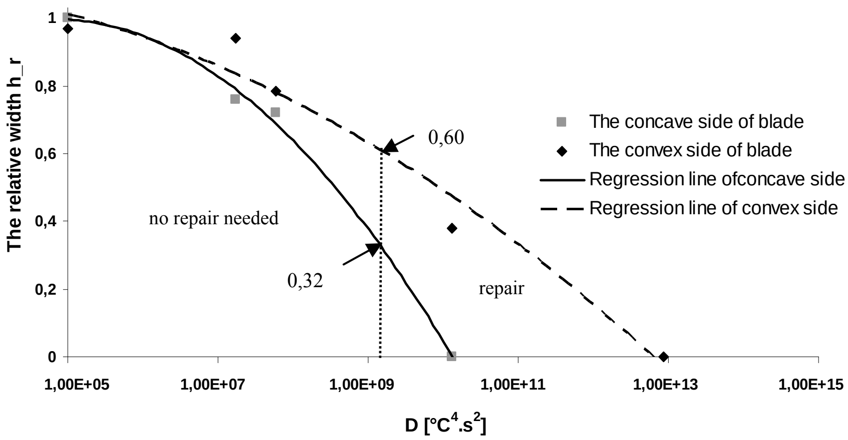

Fig. 14 Dependence of the layer width h_r on the parameter *D* for the concave and the convex side of investigated blades.

Relative width *h_r* of the residual layer was introduced as follows (Eq. 1- 4);

$$h\_r = \frac{h}{h_0}, \tag{1}$$

Degradation level is appointed as following:

$$D = PQ, \tag{2}$$

$$P = \int_{t_1}^{t_2} T(t)dt, \tag{3}$$

$$Q = (T_{\max} - T_c)^3 (t_2 - t_1), \tag{4}$$

where $t \in < t_1, t_2 >$ is the overheating duration defined by $T > T_c$, T_{max} is the maximal overheating temperature and T_c is the critical temperature T_{4C}.

By means of this procedure the producer meets a statement concerning the performance capability. The limit between operation and repair of engines was appointed by producer to be $D < 1.5 \times 10^9$ °C^{4}s^2. These relations and limit has been verified and established. There has been detected that the degradation level D does not able to provide reasonable information in two special cases:

(i) the burning of the gas outside the combustion chamber due to a sudden decrease of turbine revolutions;

(ii) a repeated overheating of the engine.

All data of the dependence and investigations of more blades are in references [7,8].

4. Conclusions

The aim of this paper was to point the fact of a danger of overheating. As it has been shown above, complete or partial degradation of fireproof coatings for high temperature applications depend on different circumstances and conditions concerning the gas temperature at the turbine inlet, the pressure, speed and composition of the gas flow. Engine transitions and due to it dynamic forces, the irregularity of the temperature field cause high stresses and finally deterioration of blades. In addition aggressive environment, for example grit inducted to the gas-air channel, accelerate loss of coating by erosion [9,10,11]. During service coatings degrade at two fronts: the coating-gas path interface and the coating-substrate interface. Deterioration of coating-substrate interface occurs at the high temperatures. However if high temperature and dynamic forces co-exist, damage may have catastrophic effect. These above mentioned causes of blades are evidence of it. It must be taken into consideration, that evolution and changes of protective oxides are in a dynamic flux, so their composition, morphology and thickness are a function of time.

The coating failure of investigated blades we can explain as following:

I. Surging of 91016 engine has very destructive effect. Sudden pressure changes of compressor, the unstable conditions of heating and loading, difference in pressure, very abrupt thermal changes at the concave and convex surfaces, large stress amplitudes and vibrations significantly reduce coating life expectancy and impair the safety. Surging has features of low-cycle fatigue. Engine 91016 has run only 25 hours before the overheating and degradation of its coating could not be significant. One of interpretation is that the amount of silicon of undamaged inner layer is sufficient to formation of brittle or low-melting phases under conditions of excess temperature and their spallation during the cooling part of the cycle.

II. Surging of 92040 compressor caused blowing-out of flame in combustor chamber. This is established by decreasing of turbine revolutions in despite of increasing amount of fuel flow (see Table 3). Damage of these rotor blades was not such expressive as the 91016.

III. Abrupt interruption of performance 94076 engine in the range of 10 seconds does not result loss of layer. We can note the corrosive products that result from high temperature hot corrosion.

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