

Creep failure of low pressure turbine blade of an aircraft engine

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ARTICLE INFO

Article history:

Received 14 December 2010
Received in revised form 8 March 2011
Accepted 23 March 2011
Available online 31 March 2011

Keywords:

Fatigue
Creep
Udimet 500
Aircraft
Turbine

ABSTRACT

A low pressure turbine blade of an aircraft engine was fractured during the ground test run. The failed as well as neighboring unfailed blades were studied during failure investigation. Microstructure of a virgin blade was also analyzed for reference.

The material of the blade was Udimet 500, a high strength Ni-base super alloy. The investigation revealed that the triple point creep cracks were initiated on the trailing edge of blade-airfoil near root region. Grain dropping was also observed within these cracks. One of these cracks was propagated under the high cycle fatigue mechanism, circumscribing almost 50% of the fracture area. When this fatigue crack might have propagated to a critical length, the airfoil of the blade fractured catastrophically under overload condition. The primary cracking was due to creep. Such cracks were also present on the same location of neighboring blades indicating that they were also prone to failure.

Microstructural study of the failed and unused blades revealed that except the creep crack problem at specific location, there was no other microstructural degradation typical of high temperature exposure in the failed blade. Hardness of the failed blade was closer to that of unused blade as well. The edges of the airfoil of blades were found grinded which was carried out on the instructions of the OEM. It is assumed that the stresses in the turbine region might gone higher either due to engine operating parameter or due to the change in original design of blade.

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1. Background

After a general overhaul, during the test bed run of an aircraft engine, severe vibration and change in the engine noise were observed. In the visual inspection, airfoil of a low pressure (LP) blade was found fractured near the root region. The hours since new (HSN) of the engine was 270 h. The failed blade, its two neighboring unfailed blades and an unused blade were analyzed during the study.

2. Experimental results

2.1. Macroexamination

The failed and a neighboring unfailed blade were inspected visually. The observations are summarized in the following sub-sections.

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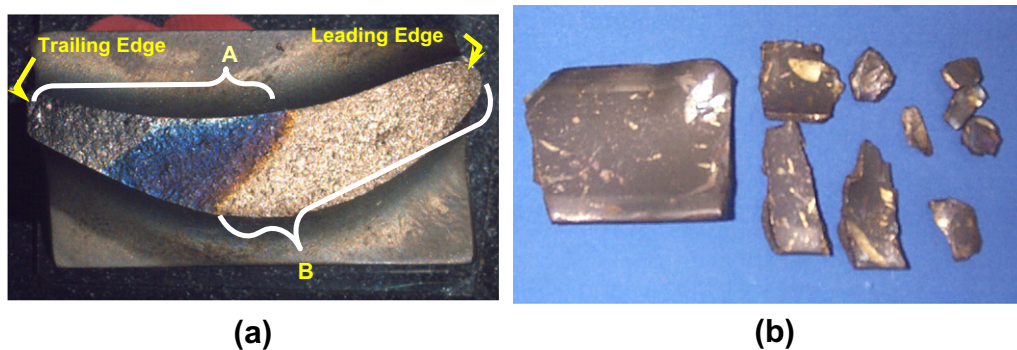


Fig. 1. Failed blade, (a) fracture surface, (b) remains of the airfoil.

2.2. Failed blade

Fig. 1a shows the fracture surface of the failed blade. Two distinct regions were observed on the fractured surface; one was bluish colored region A, covering approximately half of the fractured area, and the remaining light-grayish colored region B. Based upon the variation of color density, the region-A further incorporated into two regions. The airfoil was recovered in severely damaged condition, see **Fig. 1b**. The complement fracture surface on the damaged airfoil was smeared probably due to rubbing with other parts of the engine.

2.3. Unfailed blade

Fig. 2 shows the front and rear views of an un-failed turbine blade. The blade surface was dark grayish in color. On the airfoil, approximately 5–6 mm wide grinding marks were observed on the trailing and leading edges. They were observed on both pressure and suction side of the airfoil. Damage was observed on the airfoil tip of the blades.

2.4. Material chemistry

The materials of the blades were analyzed using Emission Spectrometer, Inductively Coupled Plasma (ICP) and carbon sulfur analyzer. The result of chemical analysis is given in **Table 1**. The composition was closest to the standard Udimet 500 [1,2].

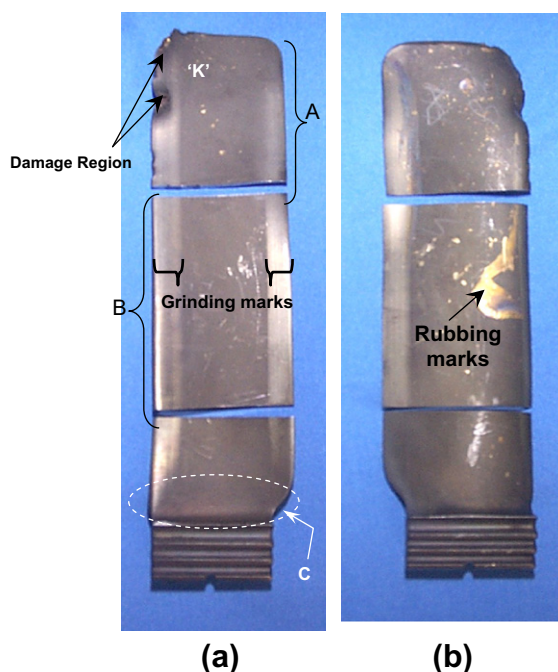


Fig. 2. Un-failed blade, (a) pressure side, (b) suction side.

Table 1
Chemical composition.

Element	Blade	Udimet 500
C	0.07 ± 0.01	0.08
Cr	18 ± 0.5	18.0
Co	17 ± 0.5	18.5
Mo	3.8 ± 0.2	4
Ti	2.7 ± 0.2	2.9
Al	3.0 ± 0.2	2.9
B	<0.01	0.006
Zr	≤0.04	0.05
Ni	Bal.	Bal.

2.5. Hardness

Hardness of the airfoil of blades was measured using Vicker's hardness tester. The results are given in the Table 2.

2.6. Microscopy

Sample of airfoils of failed and un-failed blades were prepared for metallography. In the polished condition carbides were observed, see Fig. 3a and b. Fig. 3c shows the optical micrograph of the region 'C' (as marked in Fig. 2) of un-failed blade. Intergranular cracking was observed in the surface grains. Such cracking was not present in the mid-airfoil region (region 'B' as marked in the Fig. 2), see Fig. 3d. Cracks were also observed in the region 'C' of the neighboring blades; see Fig. 3e and f. These cracks were seemed to be of mixed type i.e., Intergranular as well as transgranular. The grains at the cracks regions were seemed to be dislocated from their initial locations.

Samples were etched using Marbles reagent. Fig. 4a and b shows the general microstructure of the mid region of the un-failed adjacent blade revealing grain boundaries structure and primary carbides. Grain-boundary secondary carbides were also observed using scanning electron microscope, see Fig. 4c and d. At higher magnification gamma prime (γ') in the matrix was also revealed, see Fig. 4e. Similar microstructural features were observed in the failed and unused blade samples. The size of γ' was measured using an image analyzer; its diameter was 0.1 μm in the failed as well as unused blade, see Fig 4e and f.

At region 'C' (as marked in the Fig. 2) triple point wedge type cracks were observed in the failed and un-failed neighboring blades; see Fig. 5a and b. They were present up to ~2 mm deep from the surface as observed after progressive grinding followed by polishing. Such cracks were not present at the middle and top region of the blade airfoil (marked as 'A' & 'B' in the Fig. 2).

Surface of the unfailed blades were also observed using scanning electron microscope. At trailing edge of one of blade, opened wedge type cracks were observed at region 'C', see Fig. 6. Grains dropping were also evident at this location (Fig. 6).

2.7. Fractography

Fractured surface of the failed blade was examined using scanning electron microscope. Crack origin was located at the trailing edge next to the root section on the fractured surface as shown in Fig. 7a. This was the thinnest curve shape region of the airfoil; see Fig. 2a, region 'C'. Grain was found dropped/missed from the crack initiation region as shown in Fig. 7a. High concentration of oxygen was detected in EDS (energy dispersive spectroscopy) analysis on the surface of missed grain region, see Fig. 7b.

Two flat regions (facets) were observed in the vicinity of this missed grain. These facets could be developed during the stage-I of the fatigue crack propagation. Very next to this region striations were observed along with tear ridges as shown in Fig. 8a and b. This is the stage-II crack propagation under fatigue. This region (region-II of the fatigue) of the crack succession had covered almost 50% of the fracture surface area. Relatively coarse striations were observed near the end of the stage-II fatigue region as shown in Fig. 9a and b.

Fig. 10a shows the transition from stage-II crack propagation to stage-III. Dotted line in Fig. 10a separates the two regions. Stage-III is the final overstress area. The magnitude of the cyclic stress increases with the crack propagation in a stage-II mode. The overstress area shown in Fig. 10b is mixed type having intergranular and dimpled fracture surface.

Table 2
Hardness.

Blade	Hardness, HV
Unfailed blade	360 ± 6
Failed blade	360 ± 5
New blade	365 ± 4

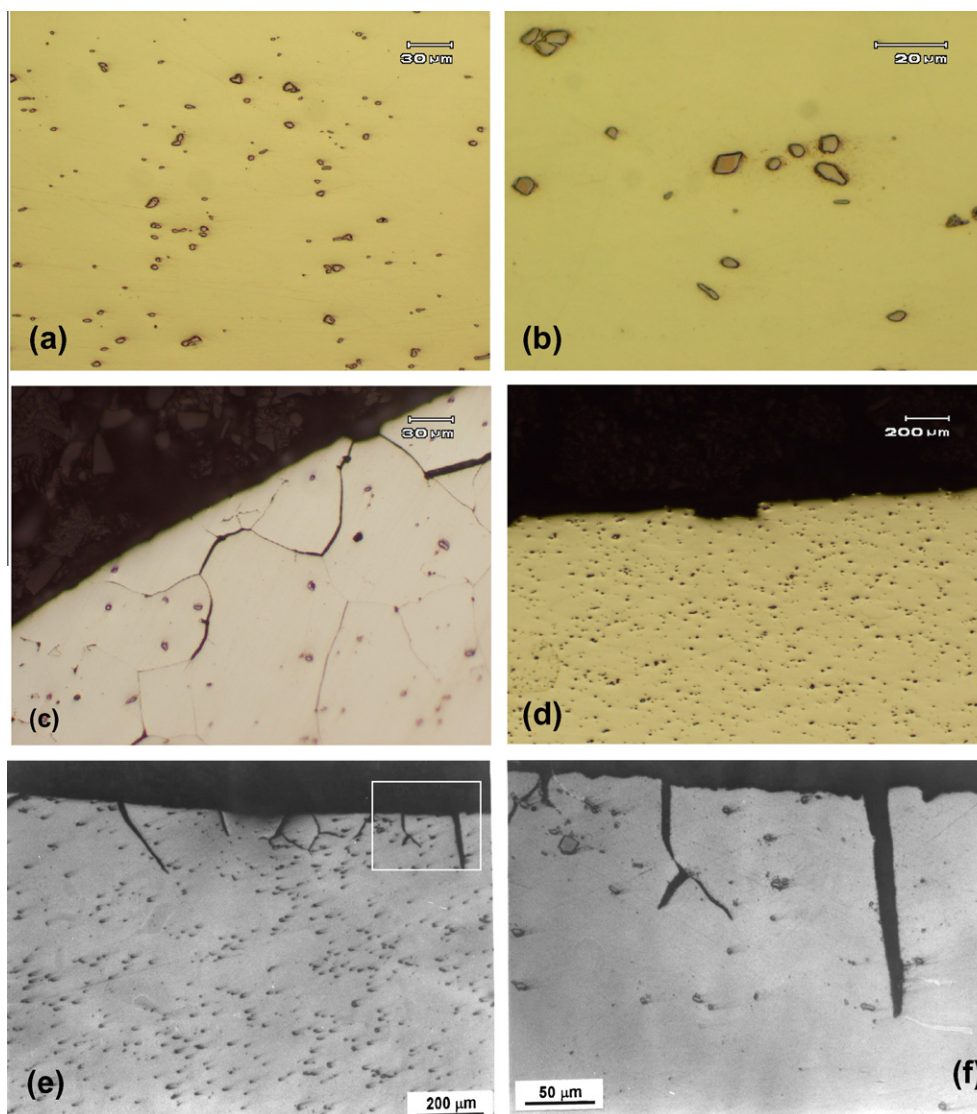


Fig. 3. Polished sample of failed blade, (a) revealing primary carbides, (b) same as (a) at high magnification, (c) cracks at the grain boundaries at region 'C' (see Fig. 2), (d) region 'B', (e and f) neighboring blade at region 'C'.

3. Discussion

The alloy of the low pressure turbine blades was Udimet 500 which is a nickel base super alloy. The surface of the blades was unprotected i.e., without any coating. The operating temperature of the LP turbine region was $\sim 760\text{--}800\text{ }^{\circ}\text{C}$ as specified by the OEM (original equipment manufacturer).

The microstructure including the gamma prime size of the failed as well as adjacent un-failed blades was similar to that of unused blade. It shows that there was no basic microstructural degradation in the failed blade. However, at region 'C' of the airfoil of the un-failed blades as well as on the complement airfoil section of the failed blade wedge type triple point creep cracks were observed. These cracks were present up to $\sim 2\text{ mm}$ depth from the surface and were confined to trailing edge at region 'C'. Surface grains were also observed dropped probably due to these cracks. Fig. 11 shows the schematic of a blade and the gas flow. The region 'C' may be considered as a critical region of the airfoil of blade, as maximum stresses are applied there due to its cantilever state.

Intergranular creep usually occurs by either of the two fracture processes [3]; (1) triple point cracking, and (2) grain boundary cavitations. Fig. 11c and d shows how the triple point crack and grain boundary cavitations occur due to grain boundary sliding at high temperature under conditions of stress. The small arrows in figures show the grain boundary sliding direction. Further, the strain rate and temperature determine the dominating fracture mode. Relatively high strain rates and

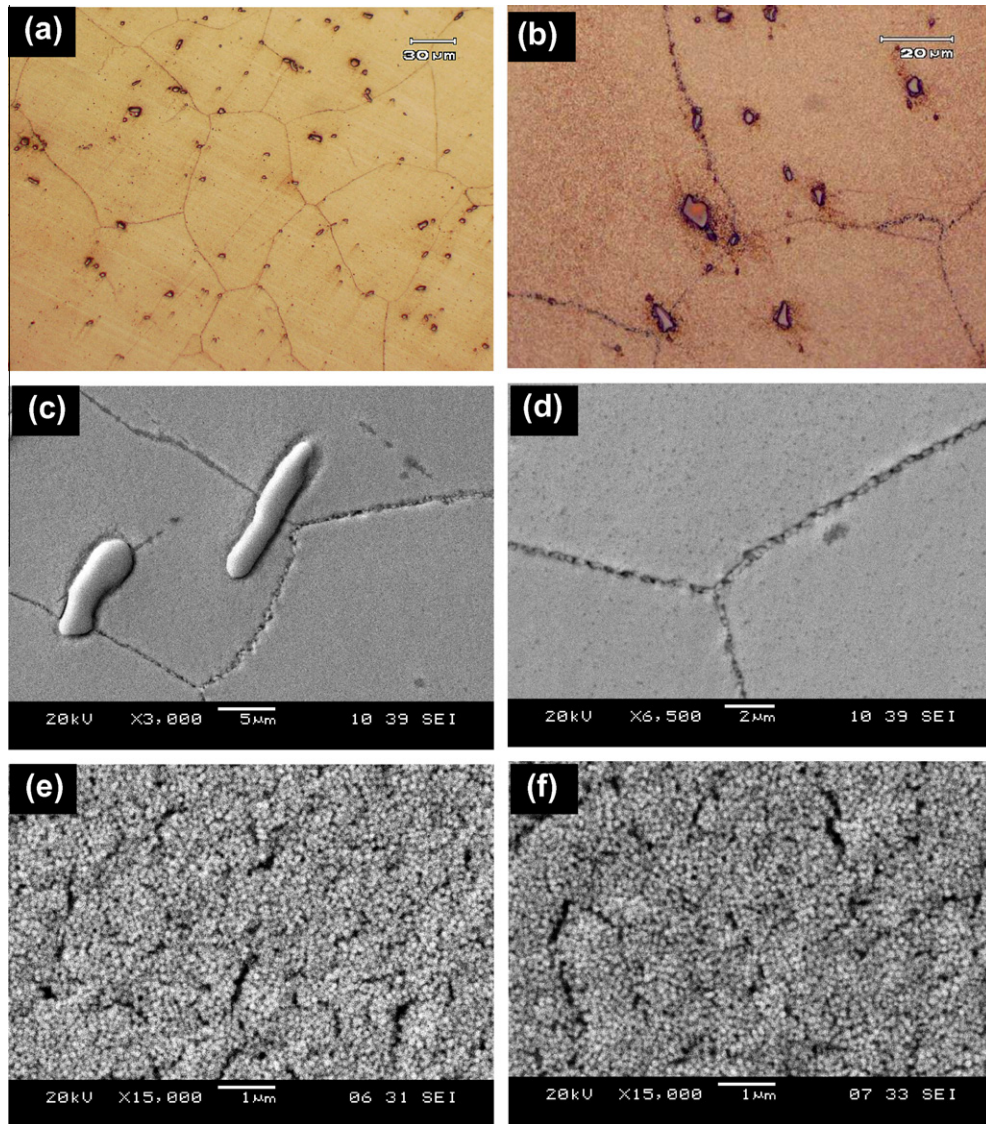


Fig. 4. (a and b) optical micrographs revealing the general microstructure, (c and d) high magnification revealing secondary carbides at the grain boundaries, (e) high magnification revealing the gamma prime, (f) gamma prime in the new blade sample.

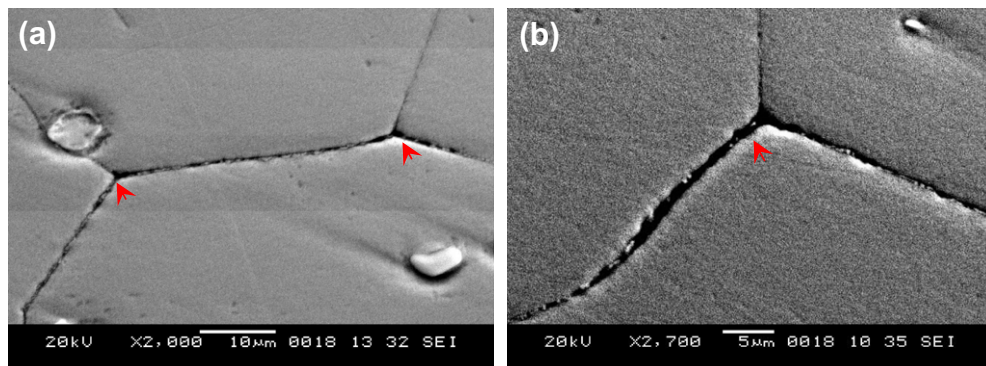


Fig. 5. Triple point wedge type cracks near the root region of airfoil in, (a) failed blade, (b) adjacent unfailed blade.

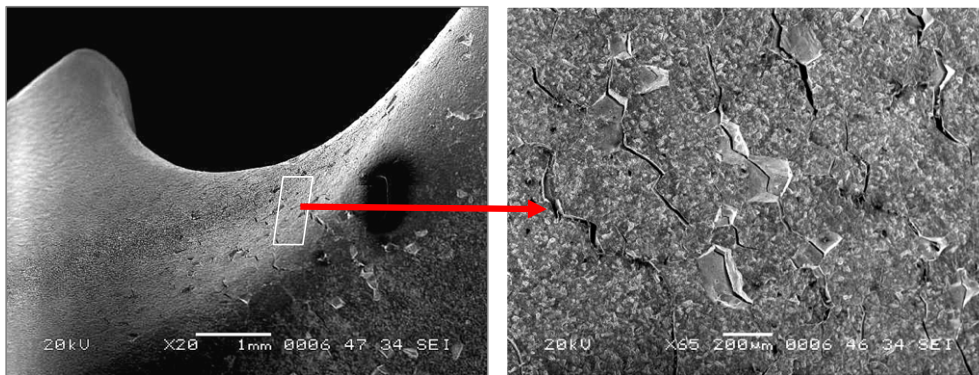


Fig. 6. Opened cracks with dropped grains at the 'C' region of an unfailed blade.

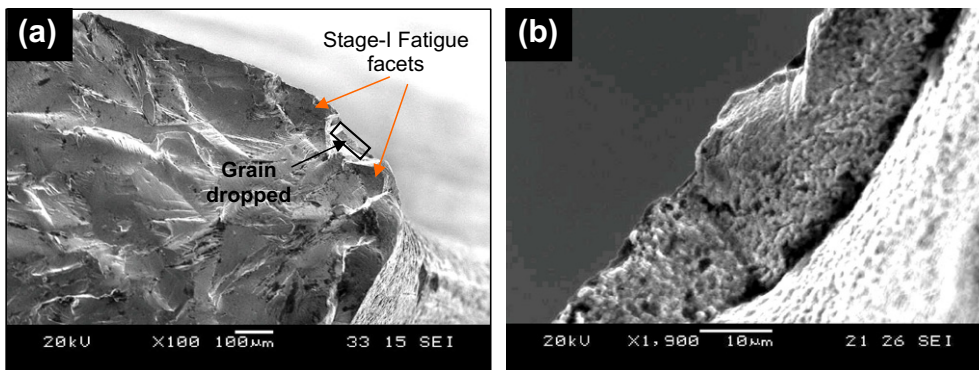


Fig. 7. Failed blade fractured surface revealing crack initiation from a dropped grain region as well as stage-I fatigue facets; (b) is the high magnification of boxed region in the (a).

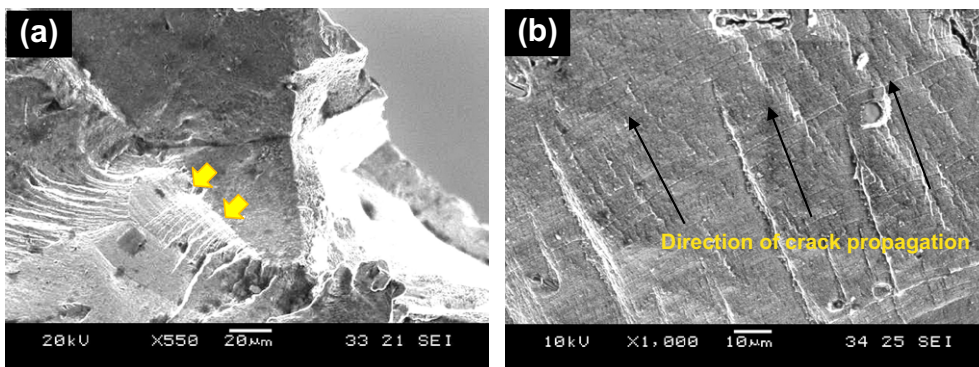


Fig. 8. Failed blade fractured surface showing start of stage-II fatigue, (a) fatigue striations (arrows) next to the stage-I fatigue along with tear ridges, (b) high magnification showing striations and tear ridges.

intermediate temperatures promote the formation of wedge cracks. Such cracking fall in the crack dominated failure in which cyclic initiation and propagation proceed under influence of creep cavitations [4].

Usually much microstructural degradation such as gamma prime coarsening, conversion of primary carbides to secondary carbides, coalescence of secondary carbides at grain boundaries and formation of creep cavitations and sigma phases are reported [5–7] to be observed in the U-500 alloy during high temperature exposures, whereas in the present case only triple point cracking was observed.

Hardness of the failed blade was also closer to the unused, unused blade. It showed that the strength of blades was also not degraded, leading to the conclusion that it has not failed due to loss of material strength.

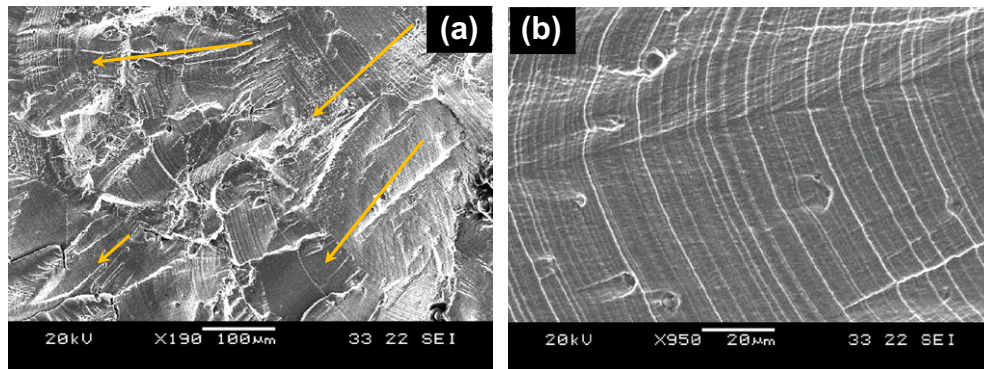


Fig. 9. Failed blade; fractured surface revealing coarse striations near overload region, (a) low magnification, (b) high magnification.

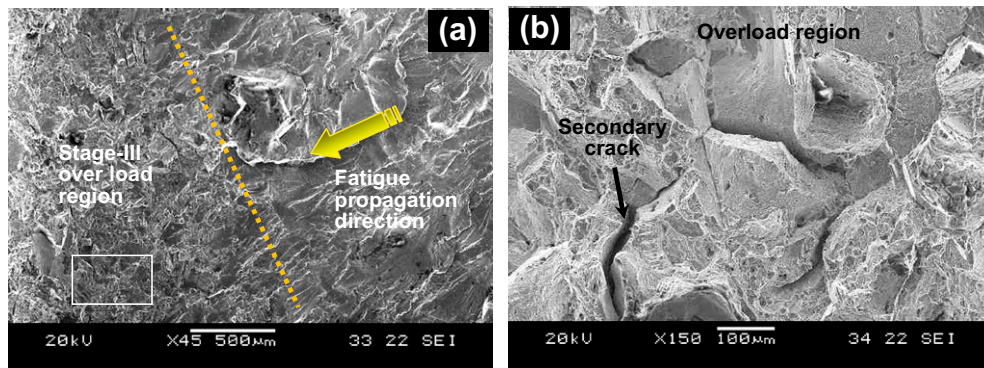


Fig. 10. Failed blade; fracture surface showing, (a) transition between fatigue crack propagation and final overload area, (b) stage-III over load region (high magnification of boxed area in (a)).

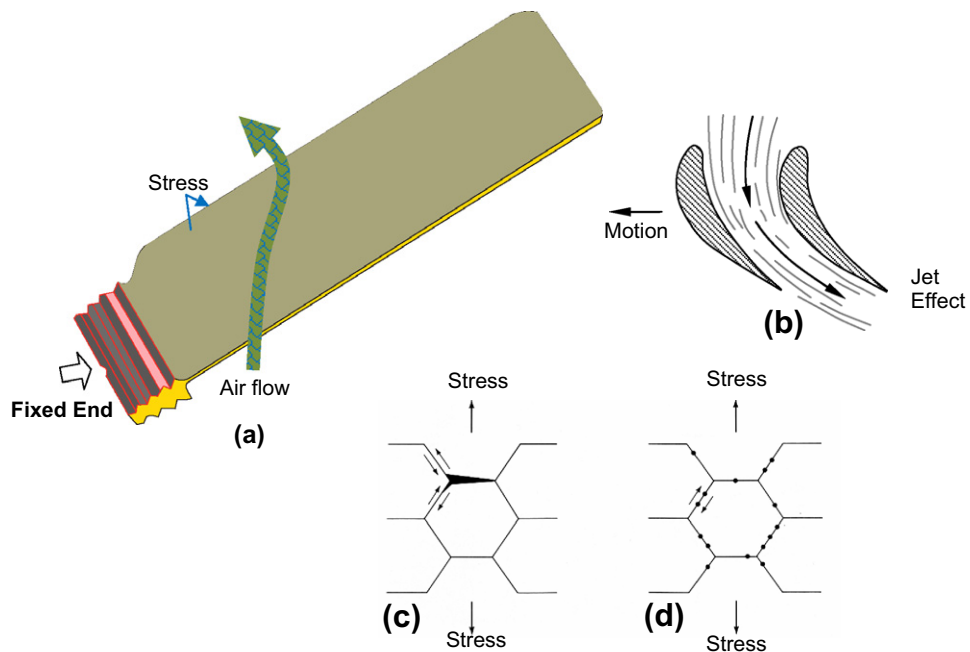


Fig. 11. Schematic revealing, (a) blade pressure side, (b) movement of the gases and motion of the turbine, (c and d) triple point cracking and cavitation, respectively in intergranular creep; small arrows show the grain boundary sliding direction.

Moreover, the trailing/leading edges of the blades were observed grinded. According to user, as per OEM directions, the edges are grinded up to 1 mm for safer operation after some specified operating hours of the blades.

The fractured surface of the failed blade was found colored blue which changes gradually from light blue to dark blue in the stage-II fatigue region; It could be due to successive exposure of the opened crack to hot gases.

On the fractured surface, crack started from the trailing edge next to the root region. A grain was found dropped from the crack initiation region. It shows that the primary crack was triple point creep crack as was also observed in the adjacent un-failed blades. On the fractured surface of the failed blade two flat regions was observed in the vicinity of dropped grain region. It would be the stage-I fatigue facets [8,9]. It often resembles cleavage, and do not exhibit fatigue striations. Next to the stage-I fatigue region, fatigue striations along with tear ridges were observed. The mode of fracture was transgranular, typical of stage-II fatigue [8,9]. It covered almost 50% of the fracture area on the failed fractured surface. When the crack had progressed to critical depth or size, the airfoil fractured in the overstress mode [8,9]. Triple point cracks were also present on other locations but depending upon service conditions, only one crack was favored to grow under fatigue.

4. Sequence of failure

The possible sequence of the failure is as follows:

- Wedge type triple point creep cracks were initiated at the trailing edge of the airfoil near root region of the blade leading to the grains dropping.
- The creep crack proceeded under the high cycle fatigue mechanism; when crack propagated to a critical length (~50% of the fracture area) in stage-II fatigue, the airfoil fractured in over load condition.

5. Conclusions

- Blade failed primarily due to creep crack(s) at region C.
- Besides the triple point creep cracking at the region C, no microstructural degradation typical of high temperature exposure was observed. As the hardness could be taken as the crude indication of strength, the hardness of the failed blade was also closer to that of unused blade revealing no degradation in the strength of material.
- The grinding of the edges of the blades may contribute in the change of the original geometry of the blade airfoil which might have augmented the stress condition at the region C. It may be assumed that the stresses in the turbine region might gone higher either due to engine operating parameter or due to change in the original design of the blade.

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