Crack Path in Turbine Blades for Transition from Very- to High-Cycle-Fatigue Regime

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ABSTRACT. *Blades of the superalloy IN738 (CrMoTiAl LC) were tested on two cyclic stress levels, less and higher of the material fatigue limit. Fatigue cracking some blades took place on the second stage of the test at the blades airfoil base and in some distance from the base at the leading edge. Fractographic analyses have shown that in all sections crack origination was subsurface from inclusions because of sliding. This problem of the crack path has discussed and shown that the material state with high percent of inclusions caused earlier blades fatigue pre-cracking in very-high-cycle-fatigue regime during less level of cyclic loading. It has recommended and introduced new technology with less percent of inclusions for the superalloy that has increased its fatigue limit on 20% and fatigue cracking of blades have tested by the same program has seen on the second stage in the arifoil base section only.*

INTRODUCTION

It is well-known phenomenon of in-service fatigue cracks origination in turbine blades of aircraft engines [1]. Their fatigue fracture takes place at the leading edge, primary, because of material intergranular. There are two cause of this cracking – creeping or thermo-fatigue mechanisms. Second, after the intergranular cracking there is drastically transition to the transgranular cracking because of fatigue mechanism.

Applicably to in-service long time of structural components recent studies revealed [2] that conventional fatigue limits do not exist for many engineering alloys, with fatigue failures occurring in Very-High-Cycle-Fatigue (VHCF) regime (lifetime more than 10^7 cycles). For materials with a high density of defects such as inclusions, internal defects are the primary crack initiation sites in VHCF regime [3]. In the VHCF regime, fatigue crack initiation is the life-determining process.

Better understanding of the fatigue crack path of superalloys in the VHCF regime can therefore directly benefit safe extension of the residual life of the turbine engine components and power-generation supplies to support the development of new alloy systems.

In this study, the fatigue crack path of a polycrystalline nickel-based superalloy, IN738 LC, has analysed in transition area from VHCF to High-Cycle-Fatigue regime using resonance type of cyclic loading. The crack initiation features and crack propagation subsurface is described based on fractographic analysis.

MATERIAL AND EXPERIMENTAL PROCEDURES

Material and fatigue tests

The blades presented for investigation are made of heat resistant superalloy IN738 LC (CrMoTiAl LC). Commercial chemical composition in Weight (%): (3.2-3.7)Ti; (3.2-3.7)Al; (0.6-1.1)Nb; (1.5-2.0)Ta; (2.4-2.8)W; (1.5-2.0)Mo; (8.0-9.0)Co; (15.7-16.3)Cr; 0.1Mn(max); 0.003S(max); Ni-balance.

Blades cast material has been prepared in the precipitation-hardened condition. Mechanical properties at the temperature 20^0C and 850^0C were respectively Tensile Strength 860 and 500MPa, Yield Strength 730 and 375 MPa.

Cast blades of 400 mm in airfoil size, manufactured by the older procedure, have tested on the special rig at the frequency 250 Hz of the first form under bending by the symmetrical cycle. Two stages of fatigue tests have used. First stage with stress level of 210 MPa and stress ratio near zero was some below of the material fatigue limit determined for not failed specimens up to durability 2.10^7 cycles. After this number of cycles exceeded in testes, the new stress level, which was some higher of the fatigue limit, introduced and specimens were fatigued up to their visible cracking. At the moment when tests were finished at the $1.5\text{x}10^5$ cycles, in some blades cracks have occurred at the airfoil base and one crack more took place the leading edge.

Investigation procedures

The crack appearance by the airfoil leading edge on some distance from the base was in contradiction with results of numerical estimations of blades stress-state. The numerical estimation of the blade stress-state in different sections has shown that during blade stressing by the first bending form the most intensive stress-state has the airfoil base section. That is why the blade cracking by the leading edge on some distance from the base was very strange.

To explain the contradiction between numerical simulation material durability for blades and revealed blabes cracking in two sections, the fractographic and local X-ray analyses were performed on the scanning electron microscope of Karl Zeiss firm and device “Inca” of Cambridge instruments respectively.

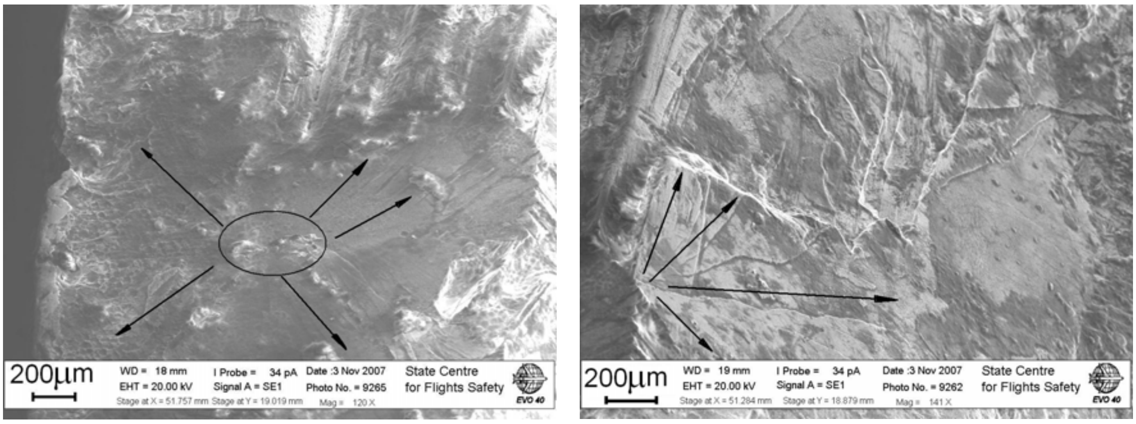
Primary, the investigated blade has subjected to surface microetching to reveal element distribution character over material structure. After etching the crack №1 (placed in the airfoil base) was opened, and fractographic analysis of fatigue crack path have been performed.

Second, the blade zone including the crack №2 (placed at the airfoil leading edge) has been cat out, and the surface segment adjoining to this crack has subjected initially to metallographic analysis using an electron microscope. Then, the local spectral analysis of material has performed in the crack region crossing the crack line. After that, the crack has been opened and fracture surface has subjected to fractographic analysis.

INVESTIGATION RESULTS

Crack path in the section of the airfoil base

Fatigue crack occurred in two zones at some distance from the suction side surface (SSS). The initial area of origin, dominated crack propagation is located nearly in the middle SSS, Fig.1.



a) b)

Figure 1. Fracture surface relief (a) near the origin area situated under the suction side suface, and (b) fracture serface pecularities formed in the progress (indicated by arrows) of initial fracture facet generation. The boundary of the origin has indicated by dotted line.

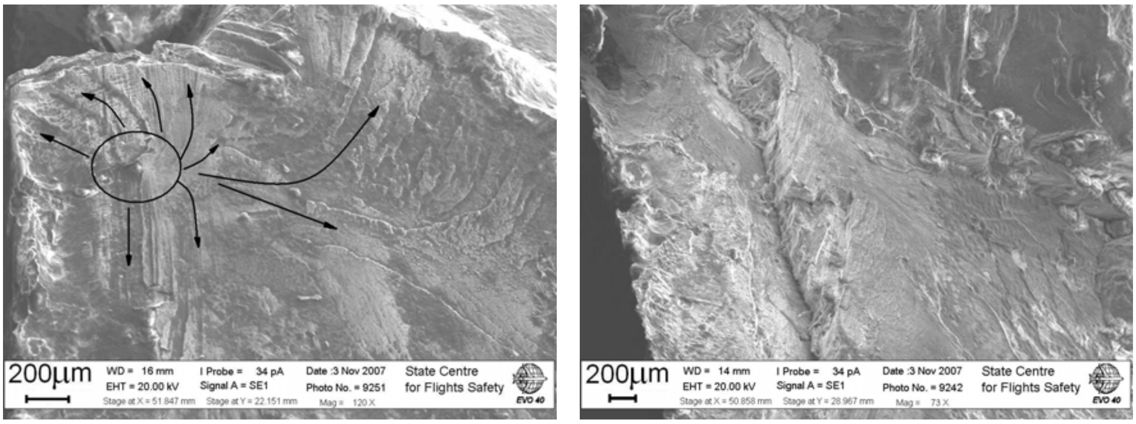
Unfortunately, due to initial blade surface etching, its fracture has been turned to be partially etched. Consequently, the fracture in its portion directly adjoining to the SSS has been covered with material etching products, and this makes it impossible to trace crack initiation peculiarities taking place just below the surface. Nevertheless, steps that have observed to diverge in fan-shaped directions from the fracture origin allow to considere them in such manner that the crack initiation occurred subsurface at the distance of about 0.9mm below it.

Then crack propagation proceeded within the range of the facet reflecting material fracture along one of crystallographic planes by dominating shear or mode II of the crack opening. New crack initiation has occurred at the boundary of this facet from several sources, one of which has concentrated focus, Fig.1b.

Further crack development has realized from the above-discussed origin along another crystallographic plane by shear. The crack had extended reorientation so that its further propagation was in all directions.

The second fracture origin positioned at some depth under SSS is located at a considerable distance from the primary origin. Its initiation has occurred subsurface at a depth of approximately 0.6mm below the SSS, Fig.2.

The main-line crack, which has started with its propagation from the above-mentioned primary origin, has arrived at the secondary origin. Nevertheless, it should be noted that there are two additional fracture origins located close to the secondary, both at some depth from SSS. Both are concealed from observation by that material segment which had not been destroyed when the crack No.1 was opened. There is a scarcely expressed system of slipping blocks along the fracture facets reflecting material fracture through dominated mechanism of shearing, Fig.2b.



a) b)

Figure 2. General view (a) of fracture relief in the secondary origin (indicated by circle) of fatigue fracture under the blade suction side surface and (b) extended segments of quasi-cleavage of dendrite body on various fracture segments.

Thus, analysis of fatigue crack initiation sources implemented so far has showed that:

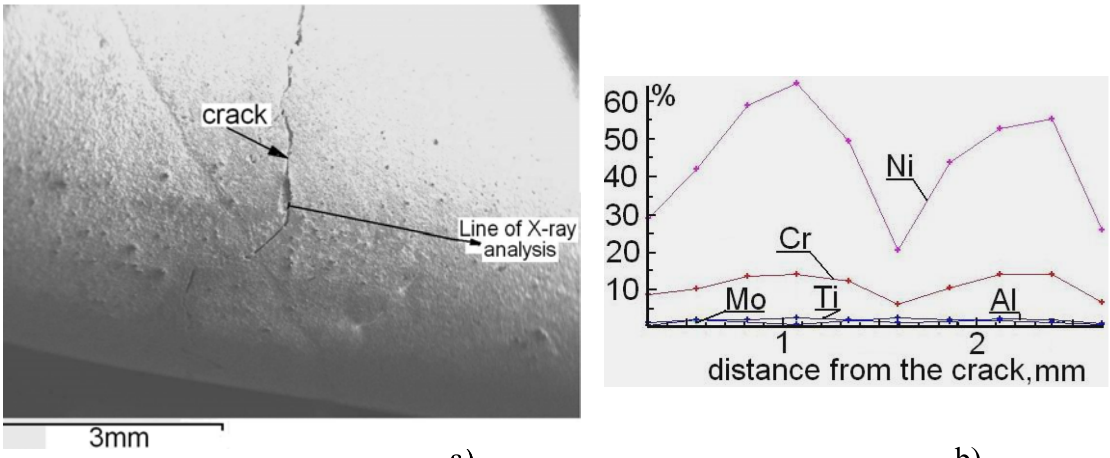
- crack initiation has occurred in several zones located along the blade SSS at some depth subsurface;
- initial crack development is related to a mechanism of shear along one of crystallographic planes formed an initial facet of fracture;
- main-line crack propagation has occurred as a result of concentrated source generation from the initial fracture facet subsurface.

Crack path in the blade airfoil section

Study of the etched blade surface in the region of the crack No.2 has showed as follows. The surface is uniform without any signs showing presence of material precipitations or deposits, which could be geometrically discernible on etched surface, Fig.3. Crack boundaries include segments of hardly expressed zones with opening its edges, and simultaneously with these, there are drastic geometric changes in other segments at the blade edge. No additional material cracking has revealed near the main crack path along the blade edge on both the suction side and the pressure side.

Local X-ray spectral analysis performed point-by-point at a distance from the crack path has showed that no fundamental differences in distribution of basic elements are there (see Fig.3b). Governing laws of changing in both ratio and percentage of chemical elements are typical for the composition of this material. Avaliable variations, e.g. some decrease, and then increase of nickel content at a distance from the crack explaines by the fact that strengthening particles dominate near the grain (dendrite) boundaries.

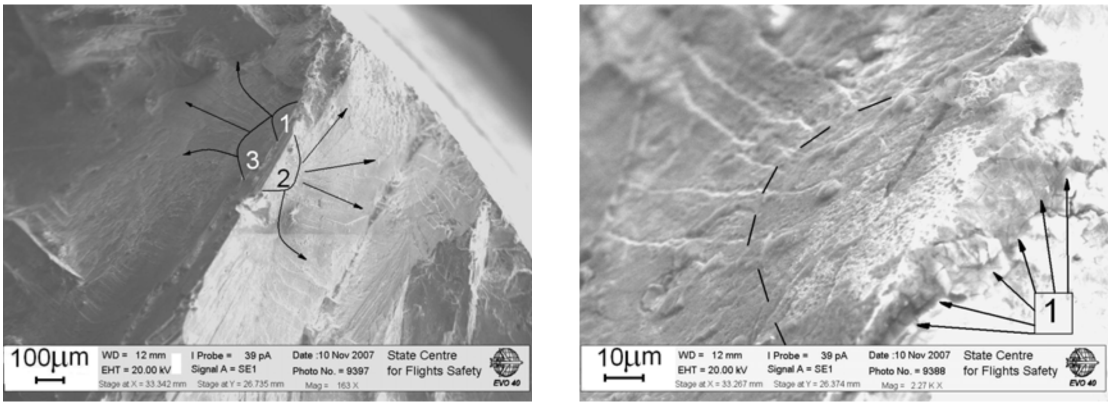
Density of these is higher than that inside grain body, and consequently nickel content turned to be (locally) lower than that within the grain body.



a) b)

Figure 3. View of the crack path (a) located at the blade edge in the segment of the most pronounced variation of its track, and (b) weight distribution of basic elements over its length to the right hand of the crack (shown by arrow).

After implementing the above-mentioned investigations crack edges have been opened to study character of its origination and growth. It has found that fatigue crack initiation zone has clearly positioned in space according to two slipping planes, which correspond to two conjugated dendrites, Fig.4. Both planes are positioned in the space so that rupture source zone is moved away to a significant distance from the fracture plane which correspondes to main-line crack development at a distance from these source-bound rupture plane.



a) b)

Figure 4. Overview (a) of the fatigue crack initiation zone with indication of three failure origins ("1"-"3") and (b) first of the origin area with a cascade of brittle inclusions (shown by arrows) placed in its focus.

Fracture relief analysis along the above-discussed slipping planes has made it possible to show that the fracture focus is located at some depth, about 0.35mm under the blade surface. Originally segments “1” and “3” were generated as it shown shematically (see Fig.4); and then initiation and propagation of the crack from the source “2” has occurred.

Fracture relief analysis in the zone of crack origination has showed that an agglomerate of brittle inclusions, Fig.4b, generates it. It follows therefore that fatigue crack initiation has occurred as a resule of high stress concentration caused by the zone where brittle inclusions have been accumulated.

Initial crack path occurred under conditions where shear strain dominated. The discovered relief reflects the process of cleavage dislocations along those slipping planes arranged close one by another, and joining those cracks generated in each plane as a result of destruction of bridges between rupture planes and give rise to that path, which is commonly desined as “streamlet-like” relief.

The discussed manner of the crack intiation subsurface was seen [4] in the nickel-based superalloy Rene 88 DT tested in VHCF regime at 593^0C. Cristallographic facets at crack initiation sites without inclusions had selected into to groups according to their geometry: single plane of facet and chevron facet. Cristallographic facet with shevron shape has reconstructed in space by the 3D method. Results indicate that facet planes one and second are orientated with respect to the loading axis about 45 degree and 46 degrees, respectively.

In the considered case of the blade leading edge failure, the facet planes have approximately the same orientations that shown for the superalloy Rene 88 DT.

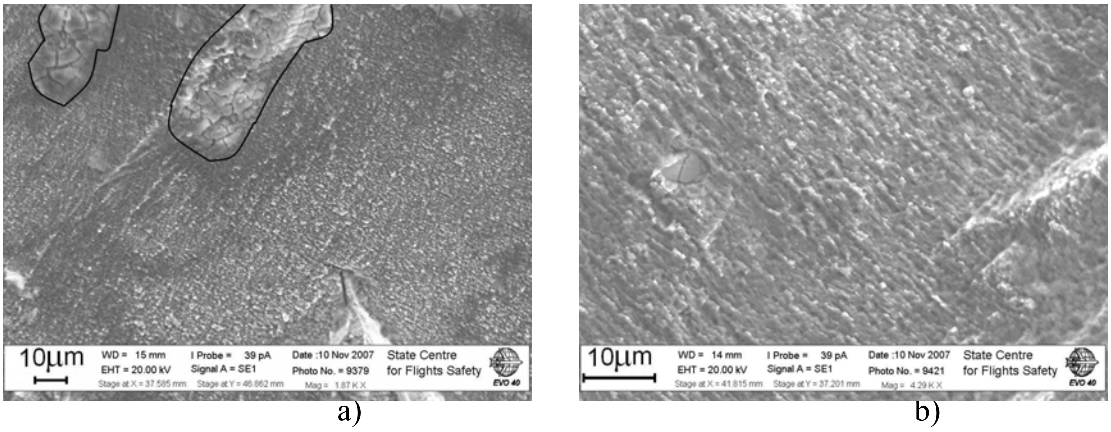
Thransition from two above mentioned facet planes is associated with crack development which orientation has change with its transition into the plane where the maximum tensile stress acted in the loading progress. Therefore, the segment of the transition from the zone of crack origination to main-line development of the crack has crystallographic character of the fracture surface in the shape of quasi-shear steps streamlet-like relief.

The local spectral analysis of the material for its element composition in the fracture origins with cascade of inclusions has shown that a high content of sulphur and oxygen is there in inclusion zones. The fracture zone itself contains no sulfure, and oxygen content is sufficiently lower (natural fracture oxidation).

As an intermediate summing up the implemented investigation of the area of the crack origination, one can conclude that:

- initiation of the main-line rupture has occurred at a distance of about 0.35mm from the surface, and it has been generated by several sources located in a close proximity (within the range of 0.2mm) one to another;
- crack initiation has been caused by aggregation of brittle inclusions in the material with a high content of sulphur and oxygen where this have formed a segment shaped as a truncated cone; initiation of the fatigue crack has just occurred from its boundary;
- begining phase of crack propagation has proceeded along slipping planes of two dendrites in the quasi-brittle manner subsurface without going outwards.

Relief elements analogous to those described as applied to fracture relief because of crack growth under the material tension at the blade airfoil base, revealed in the direction of crack propagation, Fig.5.



a) b)

Figure 5. Fracture relief (a) positioned in the crack growth direction with a cascade of opened brittle inclusions (indicated by dotted lines) and (b) blocks of slip bands under magnified view.

First, relief morphology reflects crack development under conditions when mutually intersected slipping systems area formed. It keeps futher as a basic kind of blade rupture over the whole course of crack growth up to the zone, which corresponds to the maximum depth of the crack growth up to in the progress of tests.

The fact has engaged our attension that aggregates of brittle inclusions have got into the fracture located in the crack growth direction (see Fig.5). The X-ray analysis has shown that a high content of sulfure and oxygen is there in inclusions zones. The fracture zone itself contains no sulphur with natural fracture surface oxidation. The brittle inclusions and their aggregates observed at a significant distance from the crack origins and over the course of the crack development support the fact that fatigue crack initiation subsurface has just occurred from an aggregate of those inclusions, which are inherent for this material.

DISCUSSION

Fracture zone generation indications revealed in the initial phase of blade rupture in different sections allow making conclusion that preliminary loading of material resulted in depletion of its fatigue strength subsurface according to the mechanism of VHCF. Transition to an icreased stress level, some more than material fatigue limit, during tests has resulted in new initiation of the fatigue crack at an enlarged depth subsurface. The source and/or the focus of new crack initiation have turned to be located on the boundary of the initial facet, which has become the geometrical (or physical) stress concentration.

The above considered pecularities of fracture relief generation in the fracture surface have been observed previously [5] during tests of steel JIS SUJ2. Following facts have revealed at moments of programm transitions from the high stress level to the lower and vice versa. In the case of initial accumulation of critical level of damages in the VHCF regime with a lower stress level to higher stress level have resulted in formation of fracture origin subsurface. If, however, material damage accumulation with a lower stress level did not reach its critical value, then transition to a higher stress level has resulted in formation of a fracture origin at the specimen surface.

Therefore, fracture surface analysis of the blade performed within areas of fatigue crack origination in two sections shows that formation of the initial rupture sources has occurred during the first loading phase subsurface. Transition to the higher stress level has resulted in secondary formation of a fracture origin subsurface at the boundary of the initially formed rupture facet, which has generated because of material depletion at the low loading phase.

Lowering probability for aggregation of brittle inclusions in the blade material near its edge results in increased durability and can exclude crack initiation in the blade airfoil.

This recommendation has introduced in the new manufacturing procedure for blades and new tests by the same programm have shown increseased fatigue limit on 20% and crack initiation on the second loading phase at the blade surface in the airfoil base only.

CONCLUSION

Crack initiation along the blade airfoil edge and at the base of its airfoil has revealed to formation of several sources located subsurface in each section. The crack has occurred at the edge and at the airfoil base in VHCF regime caused by an aggregation of brittle inclusions.

Depletion of fatigue crack durability subsurface has occurred during the first loading phase under the lower stress level.

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