FRACTOGRAPHIC INVESTIGATION OF THE FAILURE OF SECOND STAGE GAS TURBINE BLADES

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ABSTRACT

This paper deals with a fracture investigation of second stage turbine blades in a 32 MW unit in a thermal power plant. The premature failure of the blades, made of nickel based superalloy Udimet 500, occurred after a service life of 50000 h and caused extensive damage to the unit. Several fractured blades were retrieved from the unit to identify the cause of failure. The investigation included visual examination, SEM fractography, chemical analysis, hardness measurement, and microstructural characterization. Detailed examinations of the blades indicated that the primary failure event was related to the fracture of a turbine blade at the top firtree root. The fracture surface morphology exhibited features characteristic of slow stable crack growth by crystallographic faceted cracking and striation formation that was terminated by interdendiritic fracture at the final stage of failure. These together with the results of macrofractographic observations identified high cycle fatigue as the primary contributing fracture mechanism. The main fatigue crack initiated on a surface that was damaged by fretting wear as evident from the debris on the contact surfaces of the firtree joint. The physical characteristics of fretting damage in relation to crack initiation are discussed based on the microstructural and fractographic findings presented.

Keywords: Firtree joint, Fractography, Fretting fatigue, Turbine blade, Udimet 500.

1. INTRODUCTION

Gas turbine blades are made of nickel-base and cobalt-base superalloys principally. During the past few decades, the operating temperatures of gas turbine engines have been on the rise to achieve higher and higher engine power and efficiency. This has necessitated a continuing advancement in the temperature withstanding capabilities of materials used in their construction [1]. Gas turbine blades are critical components in power plants which in the event of their failure the power plants will shut down. This case can cause long time current failure and economic loss. Therefore, it is necessary to settle the failure analysis of turbine blades in order to increase the reliability of turbine systems [2,3].
Turbine blades are susceptible to damage and crack formation in regions of component contact that experience both centrifugal and oscillatory vibrations [4]. A component subjected to fatigue in the presence of mating component under a contact load experiences micro-slip along the contacting interface, and causes a significant reduction in fatigue life. This is commonly referred to as fretting fatigue that results in an increase in tensile and shear stresses at the contact surface, which acts as a damage generator leading to crack nucleation, growth,

and eventually failure faster than that under the conventional fatigue condition without fretting (plain fatigue). The reduction in life of machine components under fretting fatigue as compared to plain fatigue has been demonstrated by a number of researchers [1,2]. The blade/disk attachment at the firtree joint, in gas turbine engines is one of critical components which can fail due to fretting fatigue. This component is subjected to high cycle fatigue (HCF) condition that involves high frequencies and vibrational type loads often superimposed on a high mean stress [3-5].
During the fretting fatigue process, cracks will nucleate and propagate according to severe stress gradients that are generated from of the effective shape of contact, coefficient of friction, and the applied loads [1]. These fretting cracks are initially very small, but may eventually lead to severe component damage [4]. Different signs have been introduced for fretting fatigue conditions which include: formation of wear products on contact surface and crack opening, presence of wear track on contact surface, crack nucleation in vicinity of wear tracks, micro plastic deformation in nucleation site and the slant orientation of crack in the nucleation region [6].
This paper reports the fracture investigation of second stage turbine blades in a 32 MW unit in a thermal power plant. The premature failure of the blades occurred after a service life of 50000 h and caused extensive damage to the unit. The primary failure event, which was related to the fracture of a turbine blade at the firtree joint, under the influence of fretting fatigue conditions, is analyzed based on fractographic studies of crack initiation and growth on the turbine blade failure surface and physical characterization of fretting damage in relation to crack nucleation.

2. EXPERIMENTAL METHODS

A damaged turbine blade which was retrieved from the accident site is shown in Figure 1. The firtree joint is also separately presented in the above mentioned figure. The remaining portion of the main fractured turbine blade under investigation which only includes the firtree root region, due to complete separation of the air foil section of the blade in the fracture process, is shown in Figure 2.

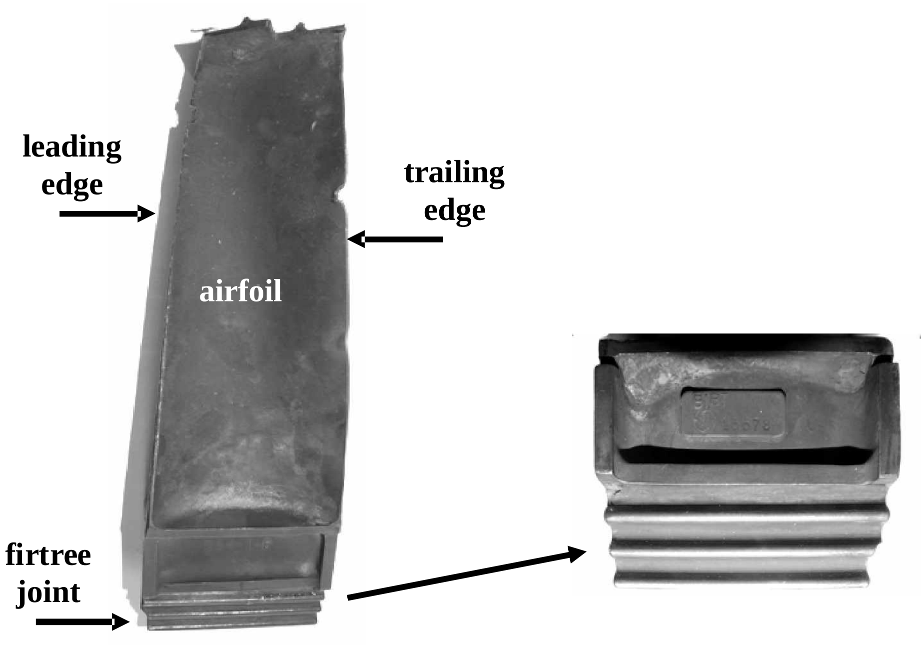


Figure 1. Blade geometry and the firtree joint of a damaged turbine blade.

Figure 2. The remaining firtree root region of the fractured blade.

Following visual examination and digital camera photo documentation, portions of the fracture surface were cut for microfractographic studies by scanning electron microscope equipped with an energy dispersive spectroscopy, EDS analysis facility. The specimens were subjected to SEM examinations in the as received condition as well as following ultrasonic cleaning. All the specimens used for material characterization were prepared from locations beneath the fracture surface. Chemical analysis was carried out using optical emission spectroscopy method. Specimen preparation for macroscopic and microscopic metallurgical evaluations on longitudinal and transverse sections was carried out using standard metallography techniques, followed by etching the specimens with Marbel reagent. Macrohardness measurements were performed using Rockwell C hardness testing method.

3. RESULTS AND DISCUSSION

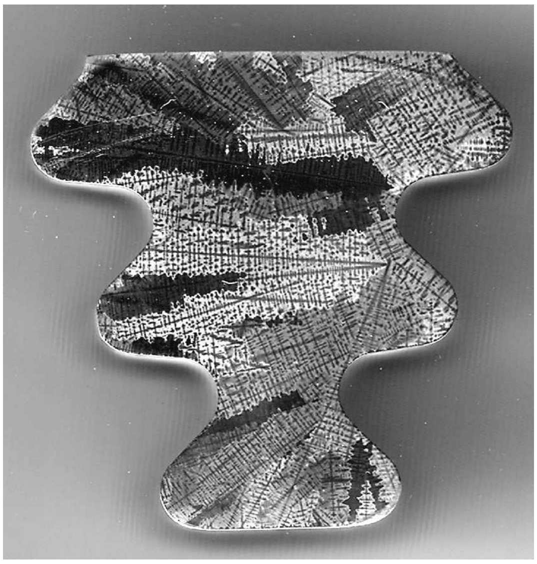
3.1 Material characterization

Chemical analysis was conducted using optical emission spectroscopy method on specimen cut from the firtree root region beneath the fracture surface. The results of chemical analysis are shown in Table 1, which are in good agreement with the standard chemical composition for Udimet 500 superalloy [7].

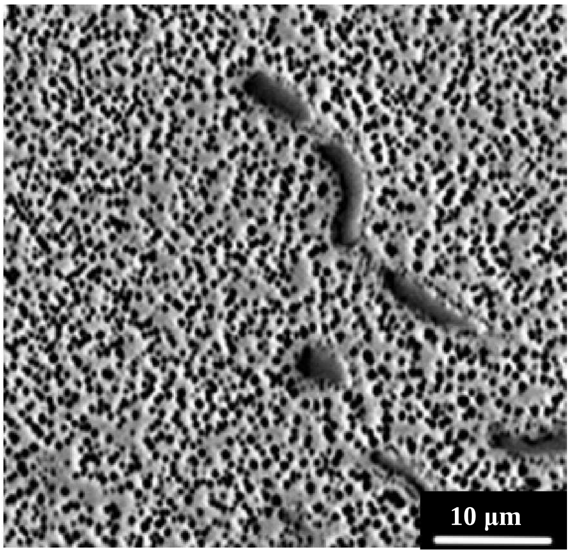
Table 1. Chemical composition of turbine blade

Source of data	Composition (wt. %)								
	Ni	Cr	Co	Mo	Al	Ti	Ta	C	B
Chemical analysis	52.99	18.98	17.25	3.93	3.40	3.17	0.366	0.080	0.006
Udimet 500 [7]	53	18	17	4	3	3	0.02	0.1	0.02

Metallographic observations were carried on transverse and longitudinal sections prepared from the firtree root region of the turbine blade beneath the fracture surface. A macroethed metallographic section of the firtree root showing the coarse dendritic structure of the cast Udimet 500 superalloy is presented in Figure 3(a). Distribution of fine gamma prime particles and interdendritic carbides in the matrix can be seen in a higher magnification SEM micrograph in Figure 3(b). The common strengthening mechanism of this alloy is precipitation hardening through gamma prime precipitation in the matrix. The gamma prime phase is an intermetallic compound of nominal composition [$Ni_3(Al,Ti)$] which is stable over a relatively narrow range of composition. The morphology of the gamma prime particles in the firtree root region does not seem to have been abnormally affected by the long term service of the turbine blade. The average hardness number of the blade material was found to be 32 HRC which was fairly uniform across the various metallographic sections.



(a)



(b)

Figure 3. (a) Macroetched section of the firtree root, (b) SEM micrograph showing gamma prime particles and interdendiritic carbides.

3.2 Fractography

The side view of the fractured blade presented in Figure 2 shows that the failure surface is located at the top firtree root. The general orientation of the fracture surface is nearly normal to the longitudinal axis of the blade. Visual examination of the fractured blade indicates that the fracture process involved minimal gross plastic deformation with no visible sign of any change in the cross section area at the fracture location. Thus the failure of the blade can be considered as a macroscopically brittle fracture process.

Macroscopic appearance of the fracture surface is shown in Figure 4. Two distinct regions denoted as A and B, which is delineated by a curved superposed boundary line, can be identified on the fracture surface. Region A has a more shiny appearance and extends from the boundary to the trailing edge side of the blade and covers about 40% of the fracture surface. Region B located in the opposite side extends up to the leading edge side of the blade. The fracture mechanisms in these regions are analyzed by SEM fractography.

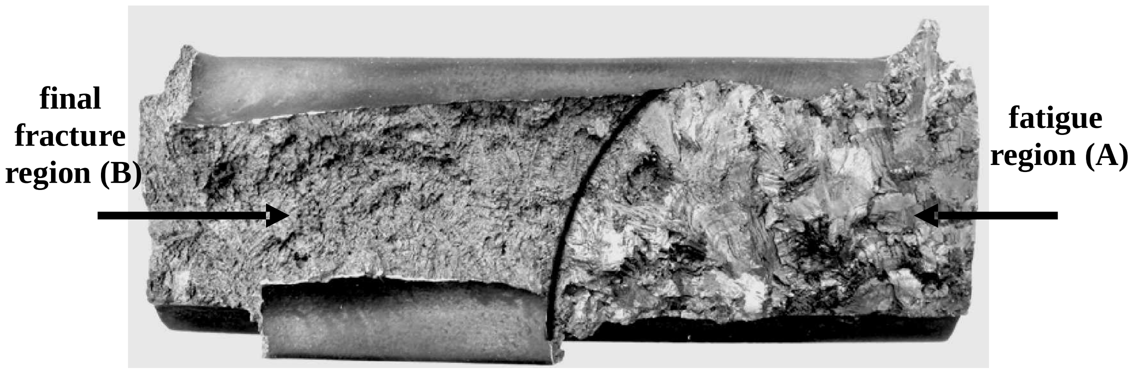


Figure 4. Fracture surface of the blade.

Following detailed SEM examinations of region A, a semielliptical crack region which originated at the top firtree root was found as shown in Figure 5(a). Fine radial markings emanating from the crack nucleation zone can be seen in this fractograph. The fracture surface appearance in the early stages of crack growth near the initiation site is shown in Figure 5(b).

Faceted crystallographic crack growth characterizes the fracture surface morphology in this region. This type of crack growth has been previously reported for many planar slip and low stacking fault energy FCC alloys, including many of the nickel based superalloys, under cyclic crack growth conditions at relatively low stress intensity amplitudes [2]. Further examination of the fracture surface, in the middle parts of region A, reveals the formation of typical striation markings characteristic of progressive crack growth under high cycle fatigue conditions [8]. A fine band of dense striations can be seen in Figure 5(c). The fracture surface morphology in region B is indicative of a distinctly different type of fracture mechanism. The interdendiritic and typically rough morphology of the fracture surface in this region is shown in Figure 5(d). This change in fracture surface morphology is associated with a transition from stable cyclic crack growth to unstable fast fracture due to the exhaustion of the load carrying capacity of the blade. From the fractographic point of view the change in fracture mode from transdendritic to interdendiritic is considered as one of the typical features of fracture of cast materials by a fatigue mechanism.

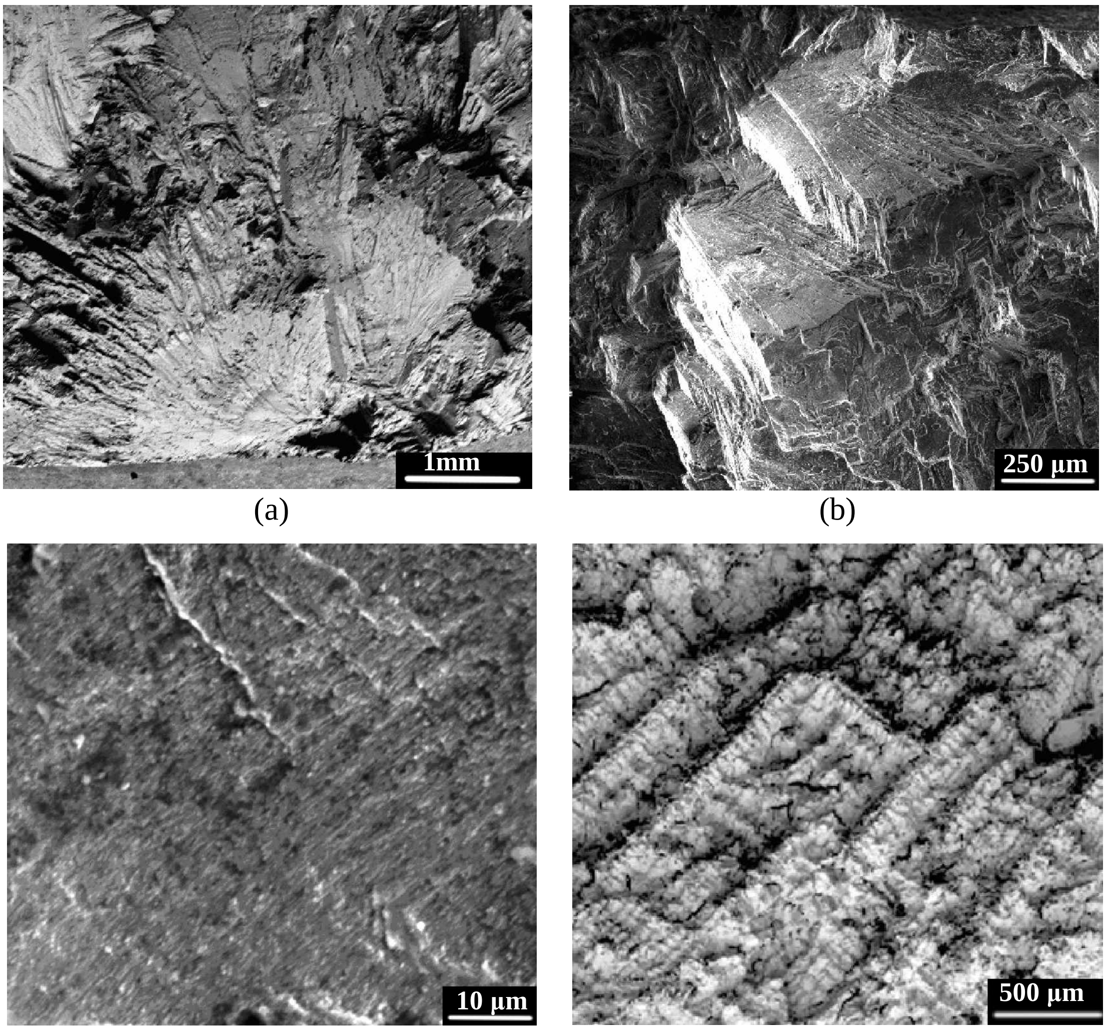


Figure 5. SEM fractographs showing (a) semielliptical crack in the iniation region (b) crystallographic fatigue crack growth, (c) characteristic fatigue striations and (d) interdendritic fracture morphology in the final fracture region.

A magnified view of the fatigue facture region of the turbine blade root failure surface is shown in Figure 6. The partially discolored region corresponds to the roughly thumb nail shape crack extending from the crack initiation zone and is indicative of the exposure of the cracked blade to gas flow process. Close examination of the contact surfaces of the firtree joint reveals the formation of continuous tracks of about 3 mm wide across the entire contact surfaces (Figure 6). The magnified morphology of the tracks is shown in a SEM micrograph in Figure 7.

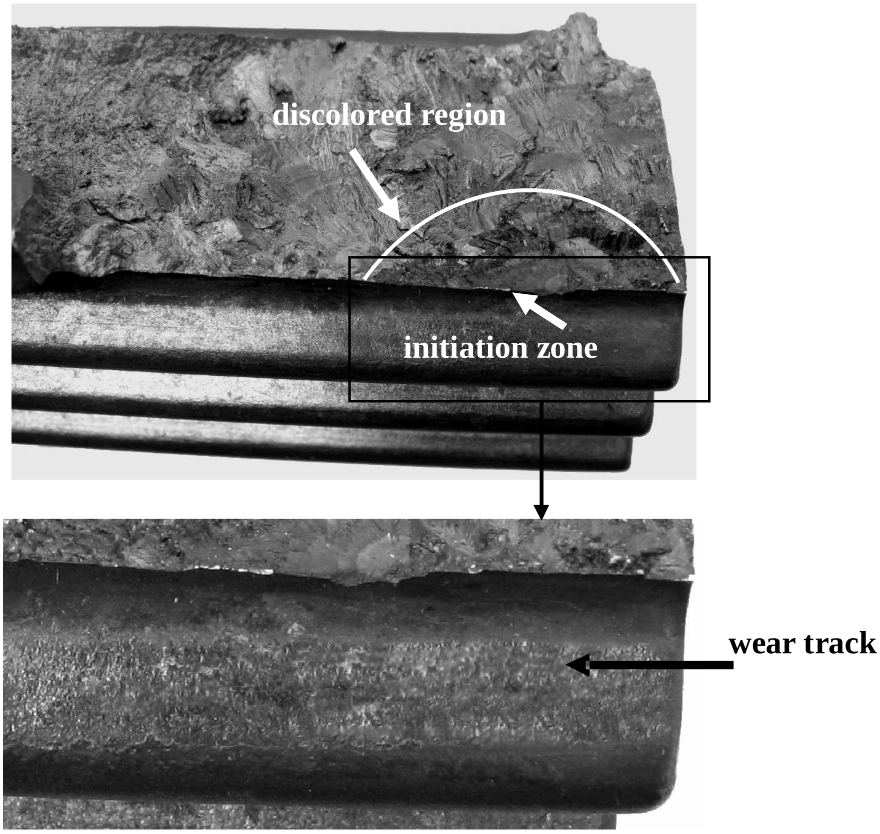


Figure 6. Magnified views of fatigue facture region and a wear track .

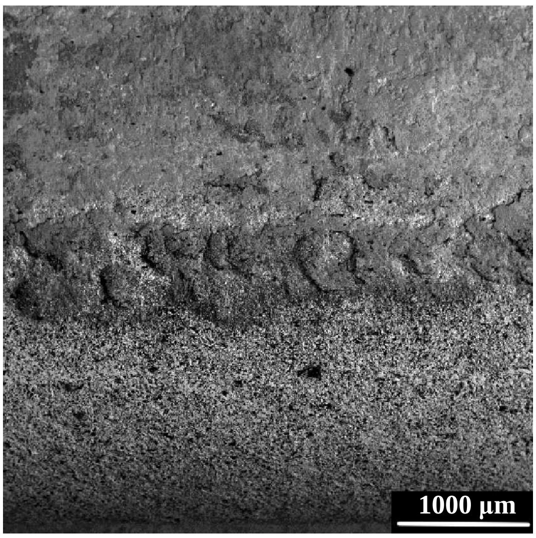
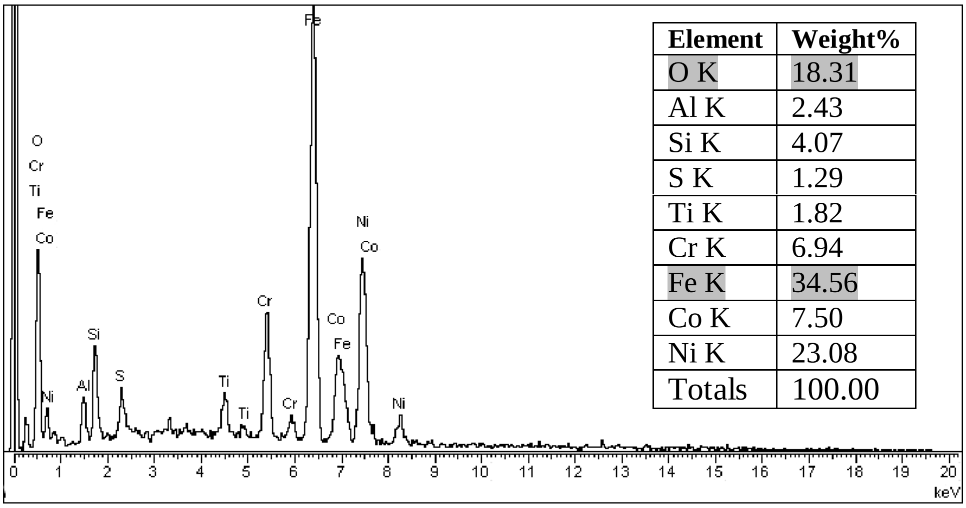


Figure 7. SEM micrograph of trapped debris forming a wear track.

The tracks seem to consist of accumulated wear debris particles trapped between the contact surfaces. EDS analysis of the wear debris shown in Figure 8 reveals a high concentration of iron, which is the base element in the chemical composition of the Cr-Mo-V steel disc material.



Element	Weight%
O K	18.31
Al K	2.43
Si K	4.07
S K	1.29
Ti K	1.82
Cr K	6.94
Fe K	34.56
Co K	7.50
Ni K	23.08
Totals	100.00

Figure 8. EDS analysis of wear debris particles on the wear tracks.

This entrapment of wear debris normally occurs under fretting wear conditions when opposing local surface regions in tightly held components undergo a small localized relative displacement for long periods. These conditions are typically encountered in the firtree roots of the rotating turbine blades. The firtree roots are also subjected to vibratory loads and high centrifugal forces leading to elevated contact and bulk stress, which combined with the relative displacements during operational cycles, compels them to endure fretting fatigue conditions. It can be seen from the magnified views of the crack initiation region and the wear tracks shown in Figure 6 that crack initiation region is located in close proximity of the wear track on the top firtree root. Furthermore the crack orientation in the initiation region is at an inclined angle with respect to the blade axis as shown in the SEM fractograph in Figure 9.

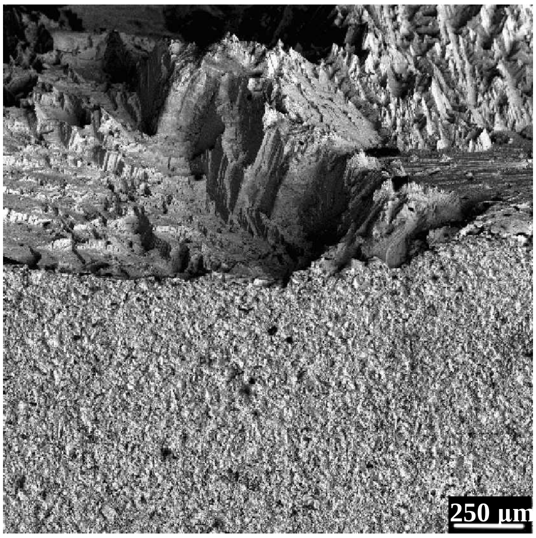


Figure 9. SEM micrograph showing slant crack orientation at the initiation region.

The above findings which include the formation of wear products on contact surfaces of firtree root, presence of wear tracks, crack nucleation in the vicinity of wear tracks and the slant orientation of the crack in the nucleation region are indicative of the strong influence of the fretting fatigue mechanism [9,10] on the failure of the blade under investigation.

4. CONCLUSIONS

1- Based on fractographic observations three distinct stages including, crack initiation, crack growth and final fracture were identified on the failure surface of the fractured blade which had failed at the top firtree root in the blade/disc joint.
2- Formation of wear products on the contact surfaces of firtree root, presence of wear tracks, crack initiation in vicinity of wear tracks and the slant orientation of crack in the nucleation region are indicative of primary contributions of fretting fatigue mechanism to the failure process of the blade.
3- Stable cyclic crack growth regions by crystallographic faceted cracking and striation formation were identified on the fatigue fracture surface.
4- The transition from stable cyclic crack growth to unstable fast fracture was accompanied by a change from transdendritic to interdendiritic fracture mode.

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REFERENCES

1. Bhaumik S. K., Sujata M., “Failure of a low pressure turbine rotor blade of an aeroengine”, Journal of Engineering Failure Analysis, Vol.13, pp. 1202-1219, 2006.
2. Wang W., Xuan F., “Failure analysis of the final stage blade in steam turbine”, Journal of Engineering Failure Analysis, Vol.14, pp. 632-641, 2007.
3. Vardar N., Ekerim A., “Failure analysis of gas turbine blades in a thermal power plant”, Journal of Engineering Failure Analysis, Vol.14, pp. 743-749, 2007.
4. Garcia D.B., Grandt A.F., “Fractographic investigation of fretting fatigue cracks in Ti–6Al–4V”, Journal of Engineering Failure Analysis, Vol.12, pp. 537–548, 2005.
5. Mall S., Namjoshi S.A., Porter W.J., “Effects of microstructure on fretting fatigue crack initiation behavior of Ti-6Al-4V”, Journal of Materials Science and Engineering, Vol.383, pp. 334–340, 2004.
6. Nowell D., Dini D., Hills D.A., “Recent developments in the understanding of fretting fatigue”, Journal of Engineering Fracture Mechanics, Vol.73, pp. 207-222, 2006.
7. ASM, **Metals Handbook: Properties and Selection**, Vol. 2, 10^{th} ed., Materials Park, OH, pp. 436-444, 1990.
8. Brooks C. R., **Metallurgical Failure Analysis**, McGraw-Hill, New York, USA, pp. 140-170, 1993.
9. Rajasekaran R., Nowell D., “Fretting fatigue in dovetail blade roots: Experiment and analysis”, Journal of Tribology International, Vol.39, pp. 1277–1285, 2006.
10. Jin O., Mall S., “Effects of slip on fretting behavior: experiments and analyses”, Journal of Wear, Vol.256, pp. 671–684, 2004.