ENGINEERING NOTE

FRETTING FAILURE OF TURBINE BLADES IN A TURBOJET ENGINE: A CASE STUDY

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Abstract

Gasturbines operate at extreme conditions, often at the design limits of turbine blades which are more likely to experience failures than other less stressed parts. Cases of blade failures are studied for a turbo jet engine in service. Small-amplitude relative oscillatory sliding displacements between the contacting surfaces of blade and disc are known as fretting and it arises as a result of cyclic loading of one of the contacting members. The paper presents case studies of fretting failure in turbine blades and suggests remedial measures to prevent such failures.

Introduction

Turbine blades typically fail because of creep, oxidation, low-cycle fatigue (LCF) and high-cycle fatigue (HCF). Fatigue failure accounts for about 50% of all component damages in jet engines. HCF is responsible for nearly half of all these failures while LCF and all other modes of fatigue lead to remainder of fatigue failures in almost equal proportions. Failure by HCF affects a variety of engine components but dominantly to turbine blades. Contributing factors often include environmental attack, corrosion, cyclic loads, over firing, or inadequate refurbishment. The origin of HCF in gas turbine engines can be attributed to one or more of the reasons such as mechanical vibration arising from rotor imbalance and rub, aerodynamic excitation occurring in upstream vanes, downstream struts and blades whereby engine excitation frequencies and component response frequencies corresponding to different modes of vibration may overlap. Aeromechanical instability, primarily in blades, accompanying aerofoil flutter and acoustic fatigue of sheet metal components in the combustor, nozzle and augmenter also can attribute to HCF in gas turbine engines [1].

Various damage processes such as foreign object damage, internal object damage and fretting fatigue which create microscopic notches and other sites at which fatigue cracks can nucleate and advance sub-critically to catastrophic proportions. These case studies investigate the causes of turbine blade failures and recommend remedial measures to prevent such occurrences in future. Residual stress analysis considering the mission cycle of the engine after certain period of service can be carried out to limit the engine critical components so that engines or components can be withdrawn and replaced prior to any catastrophic failure takes place in service [2].

Engine Configuration

The configuration of an aero gas turbine engine without air intake is shown in Fig.1. It is a straight flow single spool turbojet engine of 17 kN thrust class with multi stage

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axial compressor driven by a single stage turbine. It has a can-annular type combustion system incorporating duplex atomizers.

The main rotating assembly comprises a single unit in which the compressor rotor is coupled by a rigid shaft to turbine wheel with maximum rotational speed of 10000 rpm and the rotor system is mounted on two bearings.

Turbine wheel assembly comprises the disc and blades. The blades have roots of "fir tree" form which mate with corresponding slots in the disc, each being retained by a hollow split dowel driven through a diagonal hole in the disc to engage a slot in the blade root as shown in Fig.2.

The blades are of impulse section at the root and develop towards a section at the tip. The material used for turbine blades is Nickel base super alloy and the disc material is of high alloy steel.

Turbine Blade Failure Cases

The engine is in service and during periodic boroscopic inspection of turbine rotor blades; cases of blade cracks and failure on fir-tree location are noticed. The details of these three cases are given in Table-1. These engines are withdrawn prematurely for detail investigation. As a precautionary measure, NDT crack detection checks are suggested on all engines at the earliest. One of the typical blade failure cases is shown in Fig.3.

Investigation of Failures

Systematic investigations of these failures were carried out to isolate the root cause of the failure before corrective measures could be taken. The step-by-step examination of the cases is as follows

Forensic Investigation

- History of components, previous work carried out and any defects etc
- Engine exploitation hours since overhaul
- Review of operating and maintenance records
- Details of engine sortie prior to this failure
- Visual examination of the engine air intake, inlet guide vanes
- Hand rotation of the engine rotor
- Measurement of tip clearance followed by strip examination
- Dimensional checks of fir tree serrations of failed blades
- Any evidence of internal object release that caused the damage
- Evidence of any foreign object entry into the air passage
- Chordal width of the blades
- Trailing edge thickness of the blades

Table-1 : Turbine Failure Cases Under Study

	Hours in Service	No of Blades Cracked/Failed
Case-1	100	2
Case-2	290	1
Case-3	310	3

Metallurgical Examination

- Mechanical and chemical tests to determine the material's properties
- Coating details
- Microscopic examination to determine the failure mechanism
- Fluorescent penetration inspection (FPI) on all blades
- Examination of corresponding turbine discs for any possible cracks
- Hardness test of blades

Findings of the investigation

Visual examination of the engine and compoents did not show any abnormality. Engine was found free to rotate on hand rotation. Material composition analysis was found to meet the specification. The hardness of the blades was found within the allowable limits specified by the designer.

There was no evidence of over heating of blades and disc. Tip clearances were within allowable limits. However, FPI confirmed the cracks on blade fir-tree serrations and non- uniform loading. Dimensional checks on the blade fir-tree serration sections have shown deviations from the overhaul limits which are presented in Table-2.

Table-2 : Deviations in Fir-Tree Serrations

Blade Nomenclature	Slot-1	Slot-2	Slot-3
Acceptance Limits (mm)	5.316 +0.152	3.391 +0.152	1.468 +0.254
Case-1/Bld 1	0.127	0.107	0.305
Case-1/Bld 2	0.030	0.040	0.234
Case-2/Bld 1	0.102	0.097	0.304
Case-3/Bld 1	0.119	0.009	0.335
Case-3/Bld 2	0.102	0.104	0.343
Case-3/Bld 3	0.119	0.114	0.335

The slots in the disc corresponding to blade serrations are defined in Fig.4.

The microscopic examination has confirmed the failure as high cycle fatigue (HCF). The factographic picture is presented in Fig.5. Fretting scars were also visible in the slots of partial slip regime at the outer rim of the contact area.

Failure Analysis

Optical electron microscope examination has identified the failure mode as fatigue in all three cases. The cause of fatigue is determined as cyclic load arising from fretting and is due to the dimensional deviation in serration slots. Fretting damage generally occurs at blade and disc attachment surfaces at fir tree section, bolt flanges and shrink fit areas [3][4].

Fretting Fatigue

When two different members of a component are in contact, small-amplitude relative oscillatory sliding displacements between the contacting surfaces may arise as a result of high-frequency, low amplitude vibrations in the component or due to cyclic loading of one of the contacting members [5].

Differences in thermal expansion or contraction between the members during temperature fluctuations in service or repeated impact of one member on the other in the presence of a fluctuating mechanical load may also lead to small-amplitude oscillatory contact between surfaces. When the repeated tangential displacement facilitates a reduction in the fatigue endurance limit and promotes an earlier nucleation and subsequent growth of fatigue crack, the resulting damage is referred to as fretting fatigue. Since the occurrence pattern is similar in the current cases, the failure is attributed to fretting failure. The deterioration in the fatigue resistance of a material due to fretting occurs by complex synergetic interactions from such factors as [6]

- Amplitude of the cyclic slip displacement
- The mismatch in the elastic and plastic properties between the contacting surfaces
- Cyclic frequency, wave form and dwell time
- Normal contact pressure
- Coefficient of friction between the fretted surfaces which is strongly influenced by the roughness of the surfaces
- Operating temperature and environment
- Residual stresses induced by surface modification techniques such as shot-peening or coating or by heat treatments, welding etc
- Mechanical loads imposed on one or both members engaged in fretting
- Micro structural changes and phase transformations due to temperature rise in the vicinity of the fretted surfaces

Remedial Measure

Several approaches are commonly employed in gas turbine industries to combat the failure arising from fretting fatigue. The following remedial measures are recommended to prevent such type of occurrences in future [6].

- To introduce a layer of compressive residual stresses in the vicinity of the surface that undergoes fretting fatigue. Methods such as shot-peening, cold working and laser shock peening may be followed.
- Coefficient of friction between the fretted surfaces to be reduced by introducing lubricants such as polyte trafluoroethylene, molybdenum disulphide etc.
- To increase the frequency of in-situ NDT check.
- To select efficient lapping tools and processes during lapping of blade fir-tree in the disk slot.

Conclusion

Fatigue failure of turbine blades is a dominant failure mode in gas turbine engines. Relative oscillatory sliding displacements between the blade and disc at fir-tree serration surfaces arise as a result of high-frequency, low amplitude vibrations in the component and also due to cyclic loading of one of the contacting members. Remedial measures such as introduction of a layer of compressive residual stresses in the vicinity of the surface which undergoes fretting fatigue and methods to reduce the coefficient of friction between the fretted surfaces may be adopted to avoid such failures in future.

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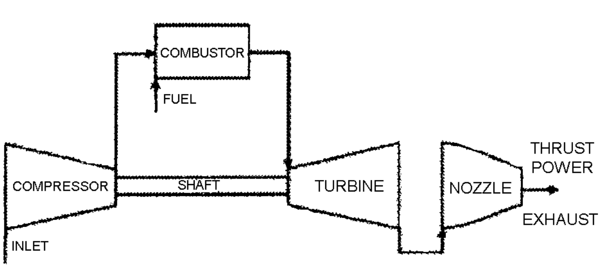

Fig.1 Schematic Layout of Gas Turbine Engine

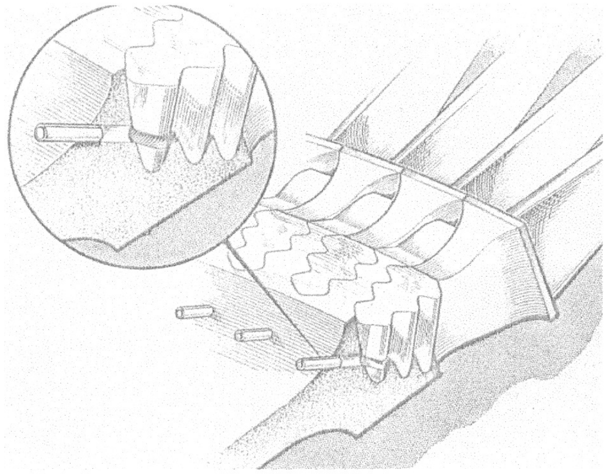

Fig.2 Turbine Disc and Blade Attachment

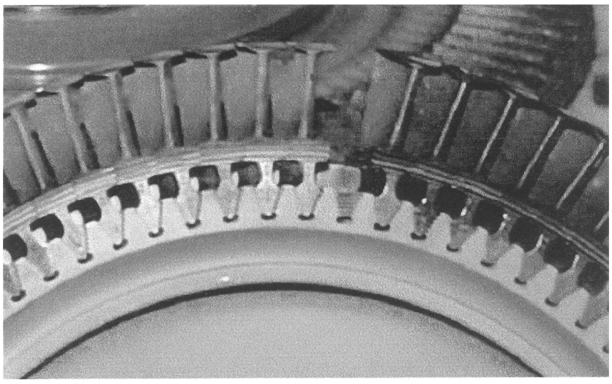

Fig.3 Turbine Blade Failure : A Typical Case

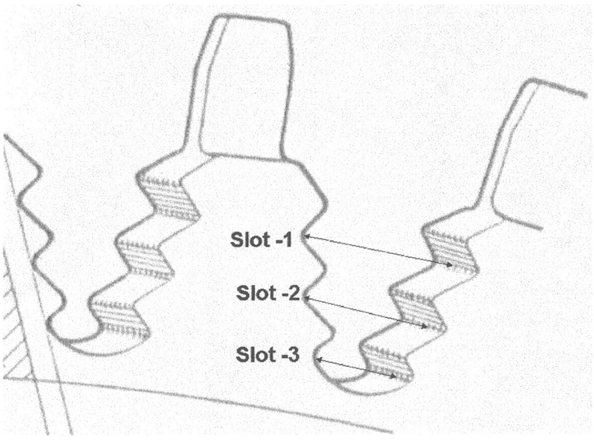

Fig.4 Definitions of Disk Slots w.r.t Blade Serration

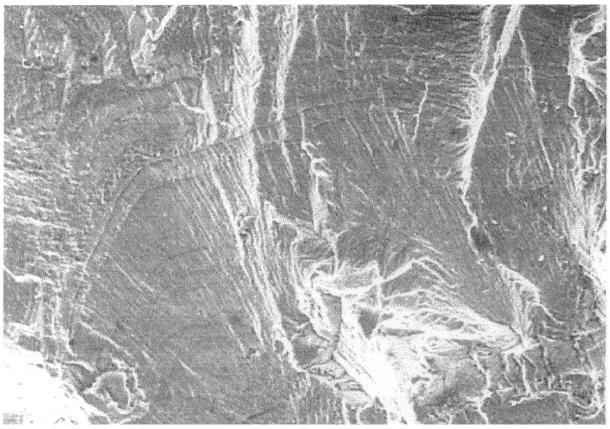

Fig.5 Factographic Picture of the Failed Blade Section