Engineering Failure Analysis 47 (2015) 89–101

Contents lists available at ScienceDirect

Engineering Failure Analysis

journal homepage: www.elsevier.com/locate/engfailanal

An investigation of premature fatigue failures of gas turbine blade

Wassim Maktouf [a,b], Kacem Saï [b,*]

[a] Mechanical ATA, BG Tunisia
[b] UGPMM, National Engineering School of Sfax, Tunisia

ARTICLE INFO

Article history:
Received 4 July 2014
Received in revised form 26 September 2014
Accepted 30 September 2014
Available online 20 October 2014

Keywords:
Turbine blade failures
Metallography and chemical analysis
Finite element analysis

ABSTRACT

A failure of a first stage compressor blade of a Gas Turbine Generator in a Gas Treatment plant caused severe mechanical damage to the compressor section and power supply troubles. In this paper, the blade failure is investigated by mechanical, metallography and chemical analysis. A finite element analysis is performed on the blade geometry to identify the stress concentration areas and the stress/strain values. The investigation outcomes provided the most probable cause of the premature blade failure and the recommendations to mitigate such incidents.

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1. Introduction

Despite the new designed engines became more efficient and durable, blade failures often lead to loss of all downstream stages and can have a dramatic effect on the availability of the turbine engines. In fact, the majority of gas turbo-generators are used as an auxiliary compensator to generate electric power at the peak of load demand. Therefore they are often utilized in discontinuous conditions of commissioning which leads to a lot of shocks, risks and premature blades' failures.

Several GT (Gas Turbine) engineering handbooks and technical papers indicate that the conditions which influence the blade lifetime are the high mechanical stresses due to centrifugal force, vibratory and flexural stresses; the operation environment (high temperature, fuel and air contamination, solid particles, etc.) and the high thermal stresses due to thermal gradients. However the degree of deterioration in an individual blade differs due to several factors such total service time and operation history (number of start-ups, shut-down and trips), engine operational conditions (temperature, rotational speed, mode of operation: base load, cyclic duty, etc.) and manufacturing differences (forging, casting, heat treatment, grain size, porosity, alloy composition, etc.) [1,2].

Statistics on industrial GT [3] indicate that blade failure represents 62% of the total damage costs for heavy duty GT. High cycle fatigue (HCF) occurs for 12% of compressor blades [2]. Thus, several technical papers have been interested in the fatigue aspects of the GT blades. Kargarnejad and Djavanroodi [4] have performed an assessment of a failed GT blade and noticed that the maximum stress due to centrifugal force and fluid pressure is located near the connection point of the airfoil and the root. Crack initiation and propagation in the base metal was due to mixed fatigue/creep mechanism and grain boundary brittleness caused by formation of a grain boundary continuous film of carbides. Qu et al. [5] have investigated the fracture surface of a failed first stage blade in GT engine and found that during initial fracture stage, the crack propagates slowly and the fracture surface is generally quite flat. Accordingly, the fracture surface becomes gradually rougher because of the

* Corresponding author. Tel.: +216 74 274088; fax: +216 74 275595.
E-mail addresses: wassim.maktouf@bg-group.com (W. Maktouf), kacemsai@yahoo.fr (K. Saï).

http://dx.doi.org/10.1016/j.engfailanal.2014.09.015
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increasing crack propagation rate at higher real stress and smaller carrying area. Fracture veins/striations and clam shell markings of the fracture morphologies displays a fatigue fracture features and indicate the propagation direction of the fatigue crack. On other hand dendrite morphology of the surface indicates instantaneous fracture features mainly due to last stage of the fracture process or aroused by hitting the initial broken blade at high rotating speed.

Other studies focused on determining the vibrational characteristics of the first row blades by static and dynamic finite element (FE) analysis [6–9]. The dynamic behavior of the blade was investigated using modal and harmonic analysis and the drafted campbell diagram reveals the coincidence points between the rotor exciting harmonics and the natural frequency modes of the blade which are the critical conditions causing the cracking problems. It was then concluded that the dynamic stress distribution in conjunction with the magnitude of the maximum static stress on the blade, resulting from the centrifugal force, causes HCF to occur in the blade [6].

Rama Rao and Dutta [7] presented a new on-condition monitoring approach of the GT's rotor based on signal analysis of the casing vibration (outer casing instrumented with standard accelerometer). The response of the casing due to the excitation by the blade passing frequencies (BPF) of different stages is analyzed to diagnose the condition of the blades. During any load drop or transient regime of the turbine, the vibration amplitude peaks at the harmonic rotor frequencies are interacted with blades' natural frequencies causing disturbance of the functional regime and inducing high vibration and noise in the entire engine. When a rotating blades vibrate, the amplitude of the BPF show significant variation. Therefore looking at the waterfall graph, any unusual side bands close to the BPF excitation peaks is indicating abnormal dynamic loading on the blade such axial loading by pulsating air and this could indicate crack in the blades. In some cases, significant unbalance of the machine component reveals also second side band on either sides of BPF. Investigations revealed that the proactive finding of the root cracks identified in five blades of rotor stage #2 (R2) of 210 MWe GT were based on appearance of side band to the BPF of blades in rotor stage R2.

FOD (Foreign Object Damage) is also a failure's root cause of the first row of compressor blades [10,11]. In fact, the inlet duct of the GT engine ingests large amounts of air sucked-in by the compressor during the GT operation period. Therefore, any solid material entrained with the air will cause damage through either erosion or impact. Nevertheless, FOD is infrequent for the industrial GT contrarily to the aviation GT engines. In fact, industrial GTs are equipped with highly efficient air filtration systems for operation in a variety of environments. The available technologies (static, self cleaning, etc.) provide barrier filtration against dust, pollen, dirt and other airborne particulate with more than 99% efficiency on sub-micron particles.

Other studies revealed that the environment must be considered when evaluating any blade failure. Environmental problems do not normally result in catastrophic failures, but work in conjunction with other failure modes leading to the compound premature failure. Compressor blades (with uncoated airfoils) are frequently affected by corrosion and pitting, that can be severe if the ambient air contains salts or other contaminants [12–14]. Thus, the blade fatigue strength is significantly reduced by corrosion in which the stress versus number of cycles (S–N) curve loses its validity and blade failures caused by crevice corrosion will show symptoms typical of stress corrosion fatigue or stress corrosion.

Ziegler et al. [13] investigated a turbine blade failure of a power plant. Their analysis revealed that damage initiated by the presence of pits found on the tail of the blade profile caused by corrosive atmosphere, mainly sodium and chloride salts. The formation of pits lead to residual stresses which give rise to the initiation of intergranular micro-cracks type. Bhagi et al. [14] found that the fractographic investigation of a failed blade was also initiated by corrosion pits. In fact, the oxides of silicate and sodium were detected on the fractured surface which leads to formation of corrosion pits/attacks. The transgranular cleavage fracture mode and the fatigue marks show that the cause of failure is corrosion fatigue. For both case studies, examination of the fractured surfaces by energy dispersive spectrometry X-ray (EDS) revealed ample amounts of nonmetallic inclusions. The solubility of these foreign particles in the air, decreases but condense onto the surface of blades at higher concentration enhancing the corrosion phenomena.

The above studies and investigations provide an overview of the probable root causes of the turbine blade's premature failures, and offer support to analyze the case study subject to this work.

This paper starts by presenting the occured incident and subsequent damages (Section 2). Section 3 focus on the blade material's chemical composition, mechanical properties, and required manufacturing process. Section 4 is devoted to the failure identification: Visual Inspection, Fluorescent Penetrant Inspection (FPI), Stereo-Microscopy, Metallography, Chemical Analysis, Scanning Electron Microscopy (SEM), Energy Dispersive X-ray Spectroscopy (EDS), and Hardness Testing. A FE analysis will then be performed on the blade geometry to identify the stress concentration areas, stress/strain values, vibration modes, ...and compare results with the fractured material. The last section aims at providing the most probable cause of failure and recommendations to mitigate such incidents.

2. Failure background

A failure of a first stage compressor blade of a GTG in a Tunisian Gas Treatment plant operated by BG Tunisia caused severe mechanical damage to the compressor section and power supply troubles. The subject engine was operating in an island load share capacity where two engines, units A and B, were operating with approximately 30% load. The failure of unit B occurred immediately following a 60% load increase when unit A suddenly shutdown. The failed engine accumulated only (5996) hours of service but (102) starts since new installation (Fig. 1).

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