Engineering Failure Analysis 45 (2014) 234–244

Contents lists available at ScienceDirect

Engineering Failure Analysis

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

Failure analysis of gas turbine rotor blades

Sweety Kumari *, D.V.V. Satyanarayana, M. Srinivas

Defence Metallurgical Research Laboratory, PO: Kanchanbagh, Hyderabad 500 058, India

A R T I C L E I N F O

Article history:
Received 13 March 2014
Received in revised form 16 June 2014
Accepted 16 June 2014
Available online 15 July 2014

Keywords:
Failure analysis
Turbine blade
Superalloy
Fatigue
Internal object damage

A B S T R A C T

The failure of the stage I, II and III turbine rotor blades of an aircraft engine was investigated by metallurgical analysis of the failed/damaged blades. The blades were made out of Ni-based superalloys of different grades. The aeroengine has completed about 80% of the assigned life since new and several hundred hours since the last overhaul before the failure of the blades. Two blades of I stage were found broken at the top and several blades of this stage were also found with deep cuts on one of the edges. Further, several II and III stage turbine blades have dents and nicks on their leading/trailing edges. Detailed investigation including visual examination of the blade surfaces, fractography, micro structural examination, chemical analysis and hardness measurement was carried out to identify the cause of the failure of the blades. The investigation has revealed that the damage of surface coating has caused severe localized oxidation attack to I stage blade 'A', leading to the formation of oxide at interface between coating and substrate and pits as well as dislodgement of surface coating at several locations on the surface of the aerofoil. Fatigue cracks have initiated at these pits and propagated during service and led to the fracture of the first stage blade. Subsequently, the broken pieces of the first stage blade has caused further damage (internal object damage) to other first stage as well as the second and the third stage turbine blades in the form of dents and nicks on leading/trailing edges by impact.

1. Introduction

Turbine rotor blades are important components of aeroengines with complex geometry whose performance is directly related to the reliability and life of engines [1–3]. Gas turbine blades are principally made out of nickel-base and cobalt-base superalloys. Nickel-based superalloys are the most complex and the most widely used alloys for various gas turbine components which operate under high temperature and high pressure conditions. A noteworthy feature of nickel-base alloys is that they can be used for load-bearing applications at temperatures up to 0.8 T_m, (T_m is melting point in Kelvin), and where no other class of engineering alloys can be used. Ni-based superalloys commonly used as turbine disc and blade material are strengthened by precipitation of γ' phase ($Ni_3(Al,Ti)$). Mechanical properties, in particular creep properties, of these alloys depend upon the volume fraction of γ' as well as precipitation of carbides along the grain boundary. These alloys are prone to microstructural degradation during service exposure, which affects the load bearing characteristics of the superalloy adversely. The microstructural changes during high temperature exposure or service include coarsening or directional growth of γ' particles (known as rafting), formation of continuous carbide film along grain boundaries and excess precipitation of carbides within the grains.

* Corresponding author. Tel.: +91 040 2458 6545; fax: +91 040 2434 0683.
E-mail address: sweety24_k@yahoo.com (S. Kumari).

http://dx.doi.org/10.1016/j.engfailanal.2014.06.003
1350-6307/

The blades and other components of gas turbines suffer service induced damage which may be natural or accelerated. The degradation may have metallurgical or mechanical origin. The factors responsible for damage in turbine blades are: (i) operating environment (high temperature, fuel and air contamination, solid particles, etc.), (ii) high mechanical stresses (due to centrifugal force, vibratory and flexural stresses) and (iii) high thermal stresses (due to thermal gradients). In general, blade failures can be grouped into two categories (a) fatigue including both High Cycle Fatigue (HCF) and Low Cycle Fatigue (LCF) [4–8] and (b) creep/stress rupture [9,10]. Further, these damages can be categorized: (i) external and internal surface damage such as corrosion, oxidation, crack formation, erosion, foreign object damage (FOD), and fretting, and (ii) internal damage of microstructure such as γ' [Ni_3(Al,Ti)] phase coarsening or rafting, grain growth, grain boundary creep voiding, carbide precipitation and brittle topologically close packed (TCP) phase formation. There are generally three possible damage mechanisms affecting the life of turbine blades; mechanical damage through creep, multiaxial fatigue and high temperature corrosion. Impact damage or foreign object damage (FOD) is a common failure mechanism in the compressor blades but not so common in turbine blades. However, these can suffer impact by the lost fragments of other broken off parts of the engine, known as internal object damage (IOD).

In this paper, the results of the detailed metallurgical investigation undertaken to identify the cause of the failure of turbine blades of different stages of an aeroengine of a military transport aircraft, are presented.

2. Experimental procedure

A set of four blades from all the three stages of a gas turbine were examined. Detailed metallurgical analysis including visual examination, stereo, optical and scanning electron microscopy, chemical analysis and hardness measurement, was undertaken. The fracture as well as damaged portions of blades of different stages I, II and III were cut cleaned ultrasonically and examined using stereo and scanning electron microscopy for recording fracture features. Also, samples were cut from aerofoil region of blades of different stages, mounted in Bakelite, polished following standard metallographic practice and etched using a chemical reagent for microstructural examination. Krolls agent was used for etching stage I and II blade samples, while 5% nital for (electrolytic etching) stage III blade samples.

3. Results

3.1. Chemical composition

Chemical analysis of one blade from each stage was carried out using instrumental analysis method. The concentration of elements present in I, II and III stage blades are given in Tables 1–3, respectively.

3.2. Hardness

Bulk hardness measurements were made on the polished samples extracted from aerofoil region of I, II and III stage blades using a universal hardness testing machine at a load of 30 kgf. The average hardness of I, II and III stage blades in the aerofoil section were found to be ~420, ~380 and ~275 HV, respectively.

3.3. Visual examination

During defect investigation after stripping of engine, one blade of turbine rotor of I stage was found broken (designated as blade 'A') and other had a deep cut at the trailing edge (designated as blade 'B') as illustrated in Fig. 1. The blade 'A' had fractured at a height of about 4 cm from the blade root platform (Fig 1a). A piece of about 1 cm size was found chipped off at the trailing edge of blade 'B' (Fig. 1b). Also, several blades of II and III stages were found to have nicks and dents on their leading/trailing edges as illustrated in Fig. 2. It can be seen that the extent of damage i.e., the depth of cut/dent/nick on edges of the blades has progressively reduced from stage I through stage II to stage III.

3.4. Stereographic examination

Stereographic examination of the fracture surface of blade 'A' revealed two distinct fracture regions as shown in Fig. 3. Region I i.e., fracture surfaces near the leading (Fig. 3a) and the trailing edges (Fig. 3b), reveals beach marks a characteristic of progressive fracture, while region II i.e., the region between leading and trailing edge has rough and dull appearance. Stereo micrograph of the damaged region of stage I blade 'B' reveal both rough and rubbed features as shown in Fig. 4.

Table 1
Chemical composition of I stage blade (wt%).

C	Mo	Nb	Cr	Al	Ti	W	Co	Ni
0.16	3.5	0.032	9.60	5.0	2.3	13.0	5.10	Balance