Engineering Failure Analysis 18 (2011) 2111–2125

Contents lists available at ScienceDirect

Engineering Failure Analysis

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

# Numerical stress and crack initiation analysis of the compressor blades after foreign object damage subjected to high-cycle fatigue

Lucjan Witek

*Department of Aircraft and Aero Engines, Faculty of Mechanical Engineering and Aeronautics, Rzeszów University of Technology, 35-959 Rzeszów, 8 Powstańcow Warszawy Ave., Poland*

ARTICLE INFO

*Article history:*
Received 29 January 2011
Received in revised form 20 June 2011
Accepted 1 July 2011
Available online 6 July 2011

*Keywords:*
Compressor blade
Fatigue crack initiation
Stress analysis
Finite element method
Foreign object damage

ABSTRACT

This paper presents results of the complex stress and crack initiation analysis of the PZL-10 W turbo-engine compressor blade subjected to high cycle fatigue (HCF). A nonlinear finite element method was utilized to determine the stress state of the blade during the first mode of transverse vibration. In this analysis, the numerical models without defects and also with V-notches were defined. The quality of the numerical solution was checked by the convergence analysis. Obtained results were next used as an input data into crack initiation ($\varepsilon$–$N$) analyzes performed for the load time history equivalent to one cycle of the transverse vibration. In the fatigue analysis the different methods such as: Neuber elastic–plastic strain correction, linear damage summation and Palmgreen–Miner rule were utilized. As a result of $\varepsilon$–$N$ analysis, the number of load cycles to the first fatigue crack appearing in the compressor blades was obtained. Moreover, the influence of the blade vibration amplitude on the number of cycles to the crack initiation was analyzed. Values of the fatigue properties of the blade material according to Baumel–Seeger and Muralidharan methods were calculated. The influence of both the notch radius and values of the UTS of the blade material on the fatigue behavior of the structure was also considered. In the last part of work, the finite element results were compared with the results of an experimental vibration HCF tests performed for the compressor blades.



## 1. Introduction

High cycle fatigue failures typically have a root cause which stems from flaws in the material (impurities or voids), abusive machining which creates high stress concentrations, or wear between components. However, even “perfect” components have a finite life, and will fail after a certain number of cycles. If a problem arises in the compressor section it will significantly affect the whole engine function and, of course, safety of the aircraft. The broken blade could cause the puncture of the engine casing. Failures of any high speed rotating components (jet engine rotors, centrifuges, high speed fans, etc.) can be very dangerous to passengers, personnel, and surrounding equipment and must always be avoided.

The failure analysis of the compressor blade has received the attention of several investigations. The problem of fatigue fracture of the compressor blade was described by: Lourenço et al. [1], Kermanpur et al. [2], Silveira et al. [3], Poznanska et al. [4]. The stress and failure analysis of the compressor blades were also described in [5,6]. The work condition of the turbine blade are heavier by occurrence of the thermal and mechanical stress, thermal degradation of material, creep, erosion etc. For this reason more causes of the turbine blade damage are reported (Troshchenko and Prokopenko [7], Park et al. [8], Song et al. [9], Vardar and Ekerim [10], Xu and Yu [11], Xiaolei and Zhiwei [12], Xie et al. [13], and works [14,15]).

*E-mail address:* lwitek@prz.edu.pl

1350-6307/$ - see front matter 
doi:10.1016/j.engfailanal.2011.07.002

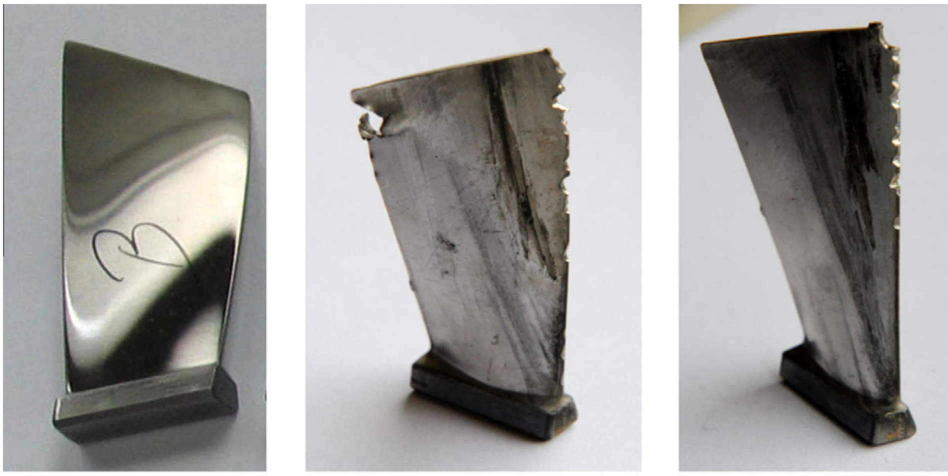
(a) (b) (c)

**Fig. 1.** View of the Ist stage compressor blade used in PZL-10 W turbo-engine (a), and blades after foreign object damage (b and c).

This paper is the continuation of work [6] in which undamaged blades were tested in the fatigue conditions. The main objectives of presented investigations are to determine both the stress state and also the number of fatigue cycles to the first crack appearance in the compressor blades (without defects and also including artificially created V-notch), subjected to separate high cycle fatigue. These defects (notches) simulate foreign object damage of the blade. The numerical results were compared with the results of experimental fatigue test performed for the first stage compressor blades of the PZL-10 W turbo engine.

## 2. Object of investigations

The compressor blade (Fig. 1a) is susceptible to foreign object damage (FOD). The ingestion of foreign objects into aircraft jet engines can lead to severe structural damage of the fan or compressor airfoils. The high airflow required to operate such engines creates a powerful suction effect which tends to draw in small objects from area around the aircraft.

Damage of the compressor blades of engine is normally caused when a particle is hit by the rotating blade. There is high relative velocity due to the motion of the blade and acceleration of the particle causes high forces and local damage to the blade. Often this damage is at or close to the attack (leading) edge of the compressor blade and takes the form of a dent or notch in the leading edge (Fig. 1b and c). Foreign object damage is a prime reason for maintenance and reparation of military jet engines which operate on landing grounds. The damage induced by small hard objects of millimeter size in conjunction with the typical load spectra experienced by airfoils can lead to non-conservative life prediction and unexpected fatigue failures.

The first stage blade of the PZL-10 W turbo engine (Fig. 1a) is made out of EI-961 steel (0.11C; 11Cr; 1.5Ni; 1.6 W; 0.18 V; 0.35Mo; 0.025S; 0.03P) with the following properties (measured in temperature 20 °C): Ultimate tensile strength 900–1090 MPa (depending on heat treatment), Yield stress 800–900 MPa, Young modulus 200 GPa, Poisson ratio 0.3 [17].

## 3. Finite element models of the compressor blades

Parametric geometry models of the blade were made using the MSC-Patran program [16]. The finite element (FE) models used in this work can be divided into two groups. The first group consists of the models which do not have any defects. These models were consisted of different number of finite elements. For example, the model presented in Fig. 2a consists of 60477 nodes and 13440 HEX-20 elements. The HEX-20 isoparametric finite element has quadratic shape functions and gives a good convergence of the numerical solution.

A few blades with different notch radius belong to the second group of FE models (Fig. 2b and c). In the stress and fatigue analysis, models with the following notch radius: 0 mm; 0.02 mm and 0.075 mm were considered. The V-notch in FE model was located about 5 mm above the blade locking piece (dovetail) (Fig. 3a). During analysis the blade was fixed on the bottom surface of the dovetail.

The blade under vibration is periodically bent towards left and right side (Fig. 3b). Because of the fact that the cross-section of blade is non-symmetric, the stress levels under left and right deflection of blade will be quite different. In description of figures and results, the information about blade deflection will be given.