Aerospace Science and Technology 33 (2014) 65–75

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Foreign object damage on the leading edge of gas turbine blades

Seyed Masoud Marandi, Kh. Rahmani, Mehdi Tajdari

Department of Energy and Mechanical Engineering, Power and Water University of Technology, Vafadar Exp'Way, Shahid Abbaspour Boulevard,
P.O. Box: 16765-1719 Tehran, Iran

ARTICLE INFO

Article history:
Received 29 July 2011
Received in revised form 4 December 2012
Accepted 2 January 2014
Available online 15 January 2014

Keywords:
Foreign object damage
Stress concentration factor
Residual stress
Experimental stress analysis

ABSTRACT

The severe damages to the leading edge of aircraft blades occur when millimeter-sized particles such as sands, gravels or even the pieces of the engine components impact those of blades, which is called hard body impact or foreign object damage. This damage produces the geometry discontinuity such as the notch on the blades which becomes the site for fatigue crack initiation.

FOD on the leading edge of the turbine blade is done by using the finite element method in this paper. Experimental stress analysis is performed for investigating the stress concentration factor at the crater base and is compared with the data from the finite element and the analytical method. The comparison shows that the finite element method results agree well with the experimental and analytical data at the crater base. Then the residual stress along the largest blade length is obtained for the potential crack initiating regions, and at the end, the analysis focuses on the comparison between the quasi-static indentation and fully dynamic impact for three critical locations where the tensile residual stresses cause crack initiation.

1. Introduction

Foreign object damage (FOD), taking the form of small hard particle ingestion during takeoff and landing of aircraft, can cause significant damage to airfoils in the fan, compressor and turbine stages of aero-engines. The size of these objects such as gravel or sand is typically in the millimeter regime, with impact velocities determined primarily by the blade speed and in the range of 100–350 m/s, depending on the specific engine [17]. Damage to the blades of the engine is normally caused when a particle hits the rotating blade. There is a high relative velocity due to the motion of the blade and acceleration of the particle causing high forces and local damage to the blade. Often this damage is at or close to the leading edge of the blade and takes the form of a dent or notch in the leading edge [5].

The history FOD phenomenon can be divided into two categories:

(i) Foreign object damage occurs on the leading edge of compressor blades or low-temperature turbine stages which are both made of titanium alloy [10,11].

(ii) Sometimes this type of damage happened to the high-temperature turbine stages which are made of Ni-based superalloy. Papers have published in this field are about blades with TBC coating [4,6]. Coated turbine blades mostly use in airplanes, working with low thermal fatigue stresses conditions, but uncoated turbine blades are used in some aircrafts which thermal fatigue stresses are high which cause the blade coating becomes useless. So far, there has not been any history of works about FOD on the leading edge of real case uncoated gas turbine blades. In this paper, the investigation about foreign object damage on the leading edge of uncoated gas turbine blades was performed by FEM, and then validated by photoelastic and quasi-static methods. There are several superalloy blades that have microcracks at three regions, which are scrutinized by Kh. Rahmani et al. Due to finding these microcracks initiation reasons at mentioned sites, FEM is applied in this paper. It is obtained that these reasons are residual stresses and elastic stress concentration factor. FOD on the several uncoated gas turbine blades of the jet engine is shown in Fig. 1(b), while the undamaged gas turbine blade is shown in Fig. 1(a).

The high-temperature turbine engine blades, which are typically made of Ni-based superalloy, experience low-cycle fatigue (LCF) loading due to normal start-flight-landing cycles, and high-cycle fatigue (HCF) loading due to vibration and resonant airflow dynamics, often superimposed with a high mean stress. Under such cyclic loads, smaller indentation craters created by FOD can become sites for fatigue crack initiation and thus severely decrease the lifetime of the blade, often by several orders of magnitude [2].

Perhaps one of the biggest challenges in the prevention of FOD-related failures lies in understanding the nature of the damage caused by the FOD impact. A better understanding of this damage would provide valuable insight into the formation and propagation of FOD-initiated fatigue cracks allowing a more realistic lifetime estimate [1]. To develop an understanding of how FOD degrades the fatigue life of a component, two factors need to be addressed: (I) the stress concentration factor associated with the geometry of

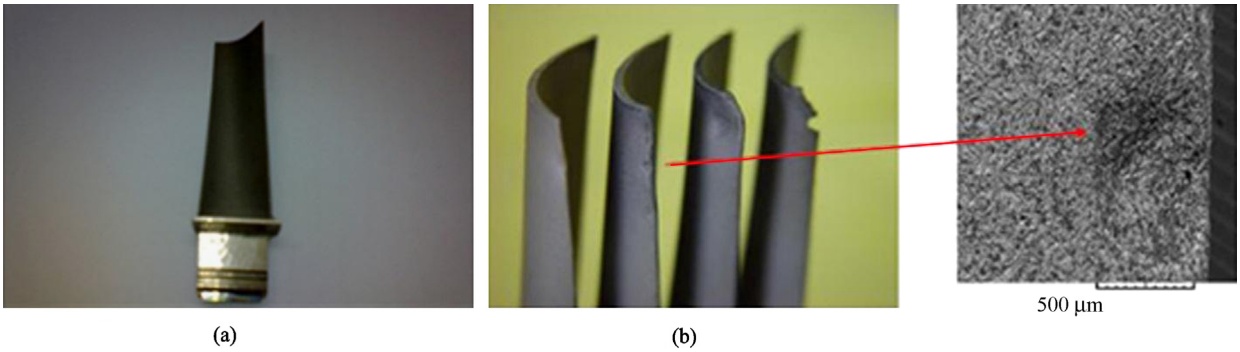
---

E-mail address: marandi1362@gmail.com (S.M. Marandi).

1270-9638/$ – see front matter © 2014 Elsevier Masson SAS. All rights reserved.
http://dx.doi.org/10.1016/j.ast.2014.01.001

Nomenclature

ρ	density
E	Young's modulus
υ	Poisson coefficient
D	projectile particle diameter
v_b	ricochet velocity
w	crater width
δ	depth of penetration
t	plate thickness
b	bulge width
KE	kinetic energy
$\varOmega$	dimensionless impact energy
k_t	elastic stress concentration factor
σ_{applied}	cyclic stress
$\Delta\sigma_{\text{applied}}$	applied load range
R_{applied}	applied load ratio
$\varepsilon^{\cdot}$	strain rate
σ_Y	yield stress
r	curvature radius
σ_{xx}/σ_Y	dimensionless residual stress in x-direction of the plate
I	index of refraction
Δ	linear phase shift
$\varLambda$	wave length
N	isochromatic fringe order
M_f	material fringe value



(a)

(b)

Fig. 1. (a) The undamaged blade. (b) FOD on the several uncoated gas turbine blades of the jet engine [19].

the damage site, and (II) the residual stress field resulting from the impact.

A number of different approaches have been tried in order to simulate FOD in the laboratory. Early approaches often employed a quasi-static chisel indenter to introduce a notch on the leading edge of a blade or specimen [12]. In this method, the normal impression of a hard spherical particle into a thick elastic–plastic substrate is considered. A rigid sphere of diameter D is pushed into a thick substrate by a static load P. The indent diameter, w, and the indentation depth, δ, both were measured after unloading. Although indent existing in this method is simpler than dynamic impact, residual stress resulting from that is not exactly similar to real state, dynamic impact, especially at the bottom of the notch. In quasi-static chisel, the dynamic impact substitutes with the static problem but with the same notch profile, which is why this is superficially an impact. Other work can be performed by hitting the leading edge with a swinging pendulum. More recent work has therefore concentrated on the use of small particles fired at specimens using a gas gun [8]. Although using a gas gun for simulating FOD is more real than other approaches, the costs of using that seem unreasonable.

2. Model description and material property

For modeling foreign object damage on the leading edge of a gas turbine blade, the following items are done:

1. The piece of the turbine engine is impacted on the leading edge of the turbine blade. The impacted piece is considered nickel based superalloy (In617) at 300 °C. The mechanical properties of it at 300 °C are: Young's modulus $E = 190$ MPa, Poisson's coefficient $\upsilon = 0.3$ and density $\rho = 8360\ \text{kg/m}^3$ [9].
2. The turbine blade is considered nickel based superalloy René 80. The temperature of the turbine blade is assumed 871 °C that agrees with the impacted place. The impacted place is at $\frac{1}{3}$ of the end of the turbine blade compatible with real cases. The stress–strain curve of René 80 superalloy is given in Fig. 2. The mechanical properties of René 80 superalloy are: Young's modulus $E = 130$ MPa, density $\rho = 8160\ \text{kg/m}^3$ and Poisson's coefficient $\upsilon = 0.3$ [19].
3. The spherical particle is impacted on the leading edge with three different diameters $D_1 = 3.2$ mm, $D_2 = 2$ mm, $D_3 = 1.27$ mm and different velocities are in the range of 100–350 m/s.
4. For simplifying the modeling, the turbine blade is modeled rectangular cross-sectional features with the plate length $L_1 \gg t$, the plate width $L_2 \gg t$ ($L_1 = 3.5L_2$ which is not very important) and thickness $t < 1.3$ mm (for $\frac{1}{3}$ of end of the turbine blades leading edge).

The In617 spherical particle with diameter D is impacted normal to $\frac{1}{3}$ end of the leading edge of René 80 superalloy plate as the blade which its left side is clamped. This model is sketched in Fig. 3(a). Deformed specimen after impact is shown in Fig. 3(b), and Fig. 3(c) depicts the cross section of Fig. 3(b). Potential crack initiation regions are also depicted in Fig. 3(c) which are at the bottom of the indent (A), outside the crater rim (B), one crater radius away from the crater (C), and at the bulge tip (E). The depth of penetration, δ, the crater width, w, measured in the central plane of the 3D model is sketched in Fig. 3(d), and the maximum bulge width, b, are also illustrated. Although the bulge tip seems to be the fatigue crack initiation site, cracks are not observed in this region in real FOD which will be explained by the FEM results.