ISSN: 1231-4005
e-ISSN: 2354-0133
DOI: 10.5604/12314005.1213899

INFLUENCE OF THE CRACK PROPAGATION VELOCITY ON HEAT RELEASE IN COMPRESSOR BLADES DURING FATIGUE TESTS

Arkadiusz Bednarz, Michał Kuźniar

Rzeszow University of Technology
Department of Aircraft and Aircraft Engines
Powstancow Warszawy Street 8, 35-959 Rzeszow, Poland
tel.: +48 17 7432348
e-mail: abednarz@prz.edu.pl, mkuzniar@prz.edu.pl

Abstract

In this work, the influence of the crack propagation velocity on heat release in blade was shown. Research was be performed during fatigue test of the compressor blade. In the investigations, the blade with the V-notch was examined. The blades during experiment were entered into transverse vibration by a vibration system Unholtz-Dickie UDCO-TA-250. The crack propagation process was conducted in resonance condition. The blades were periodically bended what simulates geometry changes during operation of the engine. The main part of the work is based on research of fatigue. During investigations both the amplitude of the crack length and also the blade tip displacement were controlled. Additional velocity of crack propagation was measured by change of a crack length in time. In the same time temperature, distribution pictures were observed. The taken picture was used to exhibit the phenomenon and shown the heat propagation direction. The main results of presented investigation are both the parameters of a crack and the crack growth dynamics in the compressor blade subjected to vibrations. An additional original result of the work is connection between velocity of crack propagation and temperature distribution taken from picture. The result of above analysis can be used in determining the amount of energy released during the cracking process and evaluate the amount of energy required for the growth of a gap. In this work, the capabilities of the proposed method and the problems associated with it were defined. The results presented in this paper have theoretical and practical value.

Keywords: *crack propagation velocity, notch, thermovision, turbine engine, heat distribution*

1. Introduction

The turbine aircraft engines works in difficult environment. On its parts acts complex state of loads. Many parts from the engine were subjected to various loads and stresses. One of the most important turboshaft engine parts are compressor blades. Forces acting on the blade stem from centrifugal forces (induced by rotation of compressor) and they cause elongation. Additionally, on blades acts forces associated with pulsation of the air flow which goes through the engine. A complex state of stress causes bending. The blades have a low flexural resistance, due to the small thickness of the profile. For this reason, they are susceptible to mechanical vibrations. Dangerous type of blade vibrations was named resonant. When vibration frequency will achieve value associated with a resonance then blade would start vibrate with a large amplitude what is cause formation of stresses. Main principle of operation of the aircraft engine is based on high rotational speed. Rotation of compressor (and a fan) causing the suction of air into inlet. Along with the air sucked in are small objects, e.g. grains of sand. These objects may cause a collision with blades and vanes. Blades after impact of foreign object have various mechanical defects, located on the leading edge of the blade (Fig. 1a). These defects are named notch. The particular interest from the constructor point of view is behaviour of turbine engine blades in resonance condition and progressive process of crack propagation of the blades. Cyclic dynamic loads causing an energy release (in form of heat) which was distributed in whole blade. The speed of crack propagation process could affect to temperature distribution on compressor blades. To observe this phenomenon could be used thermographic methods – by observing temperature distribution on blade during resonant condition. The heat generated in areas of high stresses, which correlate, with the area of propagation of gap, will be the basis to test a thermovision image in order to characterize the dynamic behaviour of the blade. This test was taken in this study.

In many investigations problem of foreign object damage (FOD) were considered. The basis of this work was article [7]. In this paper problem related with FOD and methodology of fatigue tests of compressor blade were described. Additionally, in this work FEM analysis of blades were prepared. In work [1], method of measuring crack length by using thermography image was described. The compressor blades were subjected into fatigue tests in resonant condition. Received temperature distribution was illustrated by thermography camera. Obtained thermographic pictures were subjected in image processing (with MATLAB software). After using edge detection algorithm, obtained images show the temperature distribution around the gap. Heat located in the vicinity of the crack derived by adhesive friction between the rubbing surfaces. Adhesion [4] is consisted in contact between the surfaces of the bodies as a result of the setting force field between them. Friction between the surfaces of the gap was produce heat energy. This energy was dissipated on the blades. Dissipated energy was observed as a heat distribution in body can be observed as an emissivity. Emissivity [5] is a phenomenon of emitting energy as a thermal radiation.

Correlation between a heat dissipation and a fatigue crack propagation were a main subject in several works. Paper [2] present the description of heat dissipation in titanium blade (Ti-6Al-4V) subjected to cyclic loads. Additionally were shown how crack length impact on the temperature field around gap.

In the experimental test, the blade from first stage of a compressor was used. This part was taken from PZL-10W turboshaft engine. This engine was developed to drive a helicopter PZL W3 Sokol. Its alternative propeller version PZL-10S was used in the aircraft PZL M28 Bryza. This engine was produced and developed by PZL-WSK Rzeszow.

The main objective of the work is determination impact of velocity of crack propagation on a temperature distribution. An additional objective is also the dynamics of the crack growth in the blade with the notch created by machining.

2. Test in resonant condition

The fatigue test in resonant condition was executed on a compressor blade. The blade was made of EI-961 steel and has the following parameters: compounds (0.11C, 11Cr, 1.5Ni, 1.6W, 0.18V, 0.35Mo, 0.025S, 0.03P), ultimate tensile strength in the range of 900-1000 MPa, yield stress is 800-900 MPa, Young's modulus is 200 GPa, and Poisson's ratio value is equal to 0.3. These parameters correspond to the temperature of 20°C. The compressor blade was attached to the shaker head which causes action of a variable loads. These loads were generated by a vibrating system Unholtz-Dickie TA-250. To measure the amplitude of the blade tip a laser vibrometer Polytec PSV-H400S was used.

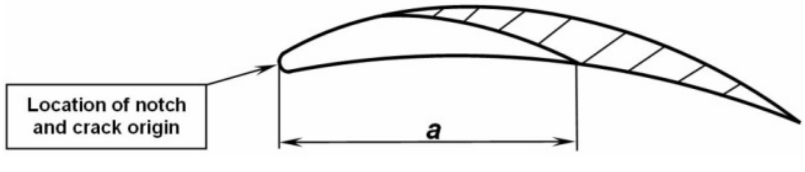

Fig. 1. Sketch of the broken blades with defined (a) the length of the crack

To identify length of the crack a method from work [1] was used. First step was to measure dimension of a gap by using fluorescent penetrant and UV light. Fluorescent fluid was applied on the inner surface of the blade. The used liquid enters into the gap, and after removing rests, it is still inside. UV light released the places where fluid is. Each measurement requires stopping the attempts what may reduce the reliability of results. Therefore, this method is imperfect.

The distribution of temperature around crack may show length of crack and also influence of crack length on speed of propagation. The images used in work were taken by thermography camera. In tests, VarioCam were used (example on Fig. 2). The VarioCam have sensitivity on level 0.03 K and geometric resolution equal to 640x480 pixels. Adhesive friction between both parts of newly established crack causes the release of energy around the gap. This energy was monitored as a local temperature gradient.

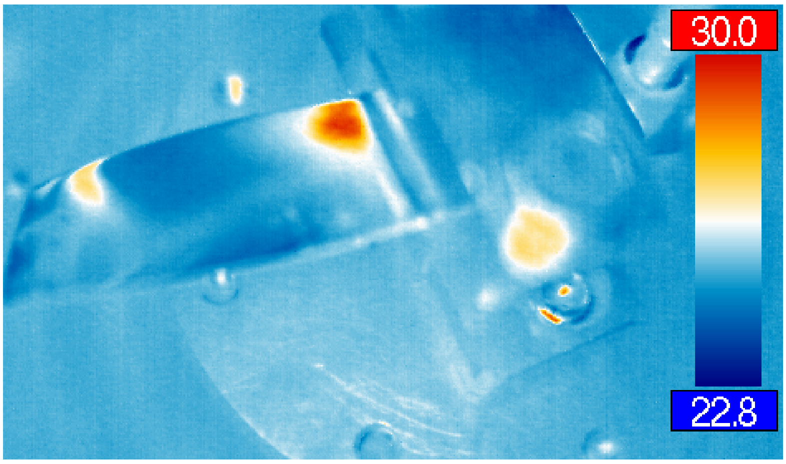

Fig. 2. View of temperature distribution image taken by VarioCAM

3. Results

The blade used in research has the same geometrical parameters of the notch like the blade in work [1]. The distance between the notch and foot of the blade is equal 3 mm, what is shown on picture (Fig. 3). Amplitude of displacement during research was equal to A = 1.8 mm.

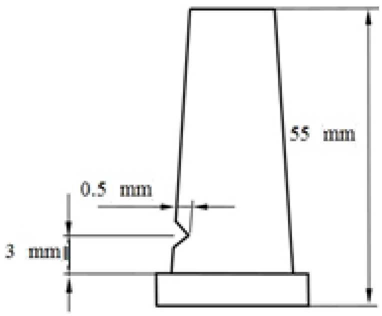

Fig. 3. View of a geometrical dimensions of object of study

The results of test in resonant condition were shown on Tab. 1. This table consist information about a number of cycles counted for different crack length in damaged blade. The first column contains initial frequency at which the test was started. Second column gives information about the final frequency of the test. The rate of change of frequency was determined as a change of frequency during the test and time of the test. Every step of research has the same parameters, for example, intensity of excitation and an amplitude of a blade tip. During tests increase in length of the gap were observed. Additionally, a table with amplitude and resonant frequency for subsequent part of test was prepared.

Information about frequency, amplitude (from amplitude-frequency characteristics) and velocity of crack propagation were shown in Tab. 2. Intensity of excitation was the same in every case of study, it was equal to 1 g. Unit g is the gravitational acceleration, and it is equal to 9.81 m /s2. The resonant frequency was decreased while crack propagates. Change of frequency in first part of tests is about 2-3%. This change in frequency is related to the appearance of cracks. Number of load cycles required to initiation of crack equals 144000. Until total destroying of the blade 371 thousands of cycles were counted.

Tab. 1. Control parameters of vibration system and results of fatigue test of the blade (A=1.8 mm)

Initial frequency	Final frequency	Time of test	Rate of change of frequency	Partial no. of cycles	Total no. of cycles	Total no. of cycles (CP)	Intensity of excitation	Crack length	Amplitude of blade tip
F_{init}, Hz	F_{fin}, Hz	s	dF/dt, Hz/s	$N_{part} \times 10^6$	$N \times 10^6$	$N_{cp} \times 10^6$	g, m/s^2	a, mm	A, mm
817.59	813.89	177	0.020	0.144	0.144	0	15	1	1.8
813.6	803	86	0.123	0.07	0.214	0.069	15	4.2	1.6
803.03	780.53	105	0.214	0.083	0.297	0.153	15	6.8	1.8
777.44	751.44	41	0.634	0.031	0.328	0.184	15	10	1.8
750	705	28	1.607	0.02	0.348	0.204	15	11.6	1.8
700	500	184	1.087	0.110	0.459	0.315	15	14.7	1-1.5
500	200	160	1.875	0.056	0.515	0.371	15	17.2	1-1.5

Tab. 2. Result of resonant vibration peaks from amplitude-frequency characteristics for different crack length

Resonant frequency	Amplitude of dispacement	Crack length	Intensity of excitation	Velocity of crack propagation
F_{rez} Hz	A mm	a mm	g	mm/s
822.4	0.35	0	1	0.00565
816.6	0.28	1	1	0.037209
804	0.28	4.2	1	0.024762
785.4	0.23	6.8	1	0.078049
769.2	0.11	10	1	0.057143
711.4	0.054	11.6	1	0.016848
492.2	0.26	14.7	1	0.015625
178.6	0.39	17.2	1	0.00565

On Fig. 4 was shown velocity of propagation crack on function length of crack. Additionally, the information about the frequency change with increasing length of gap was given. With lower values of frequency (lower than 300 Hz), blade achieves smaller amplitude of displacement. Related with this phenomenon velocity of crack propagation was decreased. A red line (rate of change of frequency) in theoretical way should have exponential course. The different course features obtained an experiment was due to change of amplitude in two last attempts. The amplitude change resulted in a decrease of stress, and thus slowed the frequency change.

When the gap is longer and velocity of crack propagation increased then the energy of break will increase. It was visible on thermal photography. With increasing emitted energy the temperature gradient on thermal images were observed.

The picture presented below (Fig. 5, 6 and 7) were taken during the test. The image showed different thermal distribution related with propagation of the crack. The image from left side presents view of thermal distribution from thermographic camera. Images on the right side were prepared by processing in Photoshop software (edge detection). The cracks were marked inside the ellipse. Heat in metals spreads quickly. Based on the phenomenon of heat dissipation the energy emitted during the crack propagation can be observed. The area with higher temperature in upper part of blade was result of the reflection of light rays.

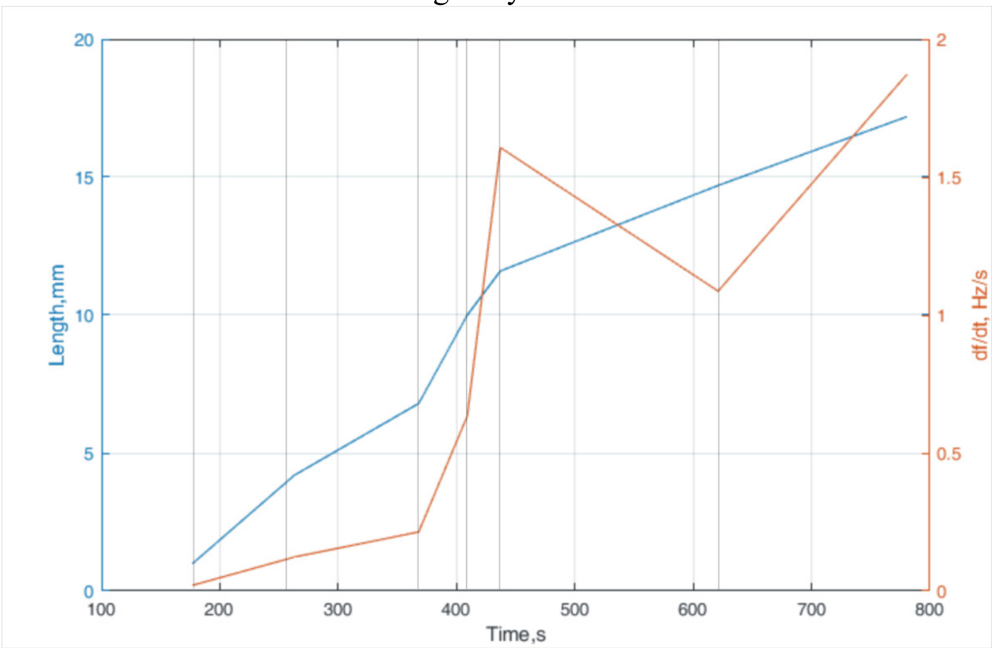

Fig. 4. With time of grown length of crack (blue) comparison to acceleration frequency

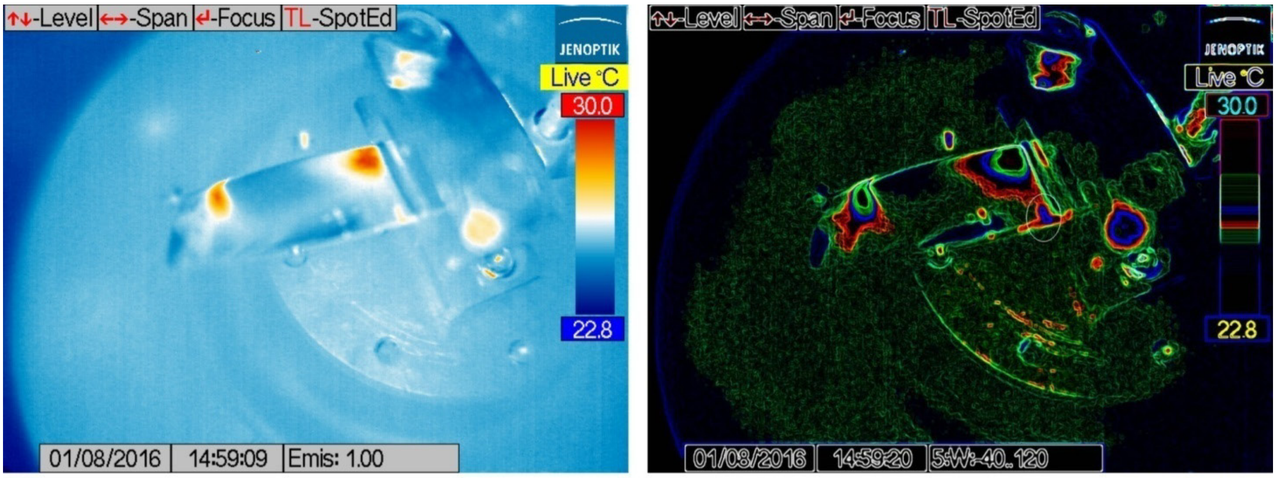

Fig. 5. View of a crack and thermal distribution related with length of crack selected 6 mm

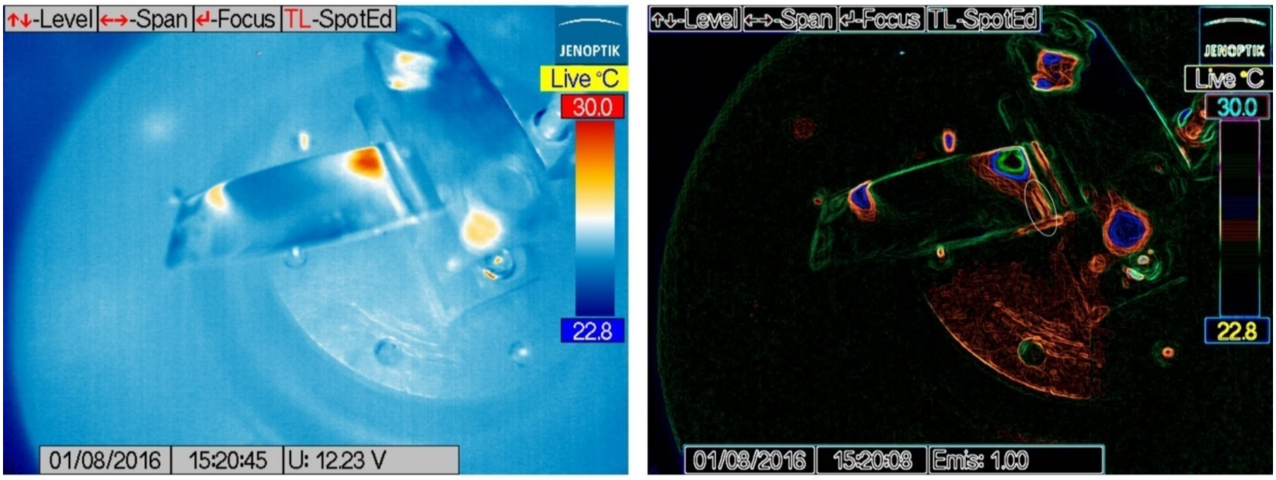

Fig. 6. View of a crack and thermal distribution related with length of crack selected 11.8 mm

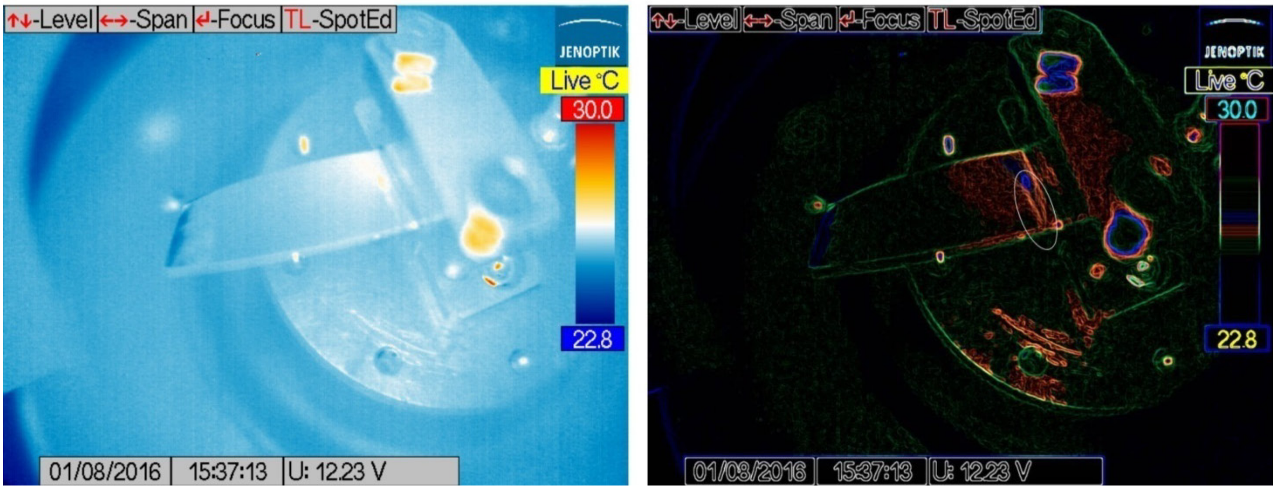

Fig. 7. View of a crack and thermal distribution related with length of crack selected 17.2 mm

4. Calculation of energy

In the following part of research the analysis were focused on numerical method of calculating released energy. The first part K-factor was calculated. Calculation of K was made based on the basic formula (1). K-factor (stress intensity factor) at a known length of crack and the critical strain is called a fracture toughness:

$$K = \sigma \times \sqrt{\pi \times l}, \tag{1}$$

where:
K – stress intensity factor,
σ – ultimate tensile stress,
π – mathematical constant 3.14,
l – characteristic length (length of crack in this case).

Coefficient of energy release called G is calculated with using K-factors for different length of crack. Equation (2) used to computation G value has the following mathematical syntax:

$$G = (1 - \upsilon^2) \times \frac{K^2}{E}, \tag{2}$$

where:
G – coefficient of energy release,
K – stress intensity factor,
υ – Poisson ratio,
E – Young modulus.

Amount of energy (3) from cracking process in the blade was determined based on the following equation:

$$\mathbf{E} = G \times A, \tag{3}$$

where:
E – energy,
G – coefficient of energy release,
A – cross sectional area of blade on crack plane, amounting A = 36.5 mm^2.

The energy emitted during the crack propagation process was increased. Higher value of emitted energy was observed on thermal images as a field of higher temperature. This area is around a tip of the crack. The observed increase in temperature quickly disappears after stopped the test. This phenomenon is associated with rapid propagation of heat in the metal. Comparing the results from Fig. 5 and 6, the increase in energy is connected by an increase in the speed of crack. It is visible as the elongation of the higher temperature area.

Tab. 3. Value of K, G factor and Energy of crack propagation

Stress intensity factor $K \times 10^7$, $Pa \times m^{1/2}$	Coefficient of energy release $G \times 10^4$, kg/s^2	Energy E, J
5.0432	1.157	0.423
10.335	4.860	1.778
13.152	7.869	2.879
15.948	11.572	4.233
17.177	13.424	4.911
19.336	17.012	6.223
20.916	19.904	7.281

5. Conclusions

Presented work show correlation between the velocity of crack propagation and energy release during crack propagation. On thermal images this were observed as a greater area of higher temperature (local gradient). Simple numerical methodology of calculation of the energy shows that higher velocity indicates increase in release of the energy. This finding is important from a scientific and practical point of view. In future works relation between energy and velocity of crack propagation could be used to determine the level of damage to the blade.

The indicated method could be used during the inspection of the engine. The use of slow motion thermographic camera will detect faults and their degree of advancement without having to remove elements. Additionally, the presented method can be used while testing various types of elements, which develops a crack.

Acknowledgement

The research leading to these results has received funding from the People Programme (Marie Curie International Research Staff Exchange) of the European Union's Seventh Framework Programme FP7/2007-2013/ under REA grant agreement n° PIRSES-GA-2013-610547.

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