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Influence of leading edge damage of aircraft engine compressor blades on their fatigue strength

Wpływ uszkodzenia krawędzi natarcia łopatek sprężarki silnika lotniczego na ich wytrzymałość zmęczeniową

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Article presents the research results of the influence of aircraft compressor blade damage length and its position on fatigue strength under high number of cycles conditions. The criteria for blade damage detection classification and test research methodology were developed. The instrumentation for compressor blades fatigue tests was designed and constructed. Fluorescent method was used to determine the fatigue crack initiation sites and its propagation direction during fatigue test.

KEYWORDS: aircraft engine, compressor, blade, fatigue tests, fatigue strength

In order to ensure safety in the flight and striving to reduce aircraft operating costs, it is necessary to look for innovative solutions for the control of components and the rotating assembly, especially the critical elements of these constructions. At the same time, the adopted solutions must meet the highest standards of operational safety of aircraft drives [1].

The current tendency to build aircraft engines with high power and efficiency, and definitely lower mass leads to increased loads of individual subassemblies and their components. For example, the compressor's working vanes are more loaded and, at the same time, have a smaller blade thickness and complex shapes of the working surface. In addition, during use, there is intensive erosive wear of the blades and their corrosion caused by operating conditions. Taking into account these factors, the design requirements for compressor blades of aircraft engines meeting high safety criteria are increasingly rigorous [1].

At the turn of the 20th and 21st centuries, progress was made in the theoretical analysis of the gas stream moving in the compressor and turbine components of aircraft engines. Improved models of new engine designs as well as their loads and working conditions have been developed. Modern computational methods have been introduced in numerical simulation processes. Despite the development of numerical simulation methods, however, they do not take into account all the phenomena characteristic of the work of aircraft engine components. Therefore, experimental studies of models and real objects are still of great importance at the design and construction stages as well as the operation of aircraft engine structures. The results of the experiments form the basis for the verification of accepted models. They are also indispensable for identification and theoretical justification of physical phenomena typical for the work of aircraft engines [2].

The analysis of the literature data and the results of own research shows that the majority of failures of aircraft engine compressors are caused by damage to the vanes and their insufficient strength under conditions of permanent and variable loads [3]. It was found that fatigue cracks are the cause of approx. 70÷80% of engine failures. Analysis of the process of initiation and propagation of these cracks confirmed that their main cause are severe working conditions of the blades. Shoulders are, among others exposed to damage by foreign objects [4] – particles with high hardness, most often of mineral origin. They are present in the air sucked into the flow channels of the engine and cause erosive wear of structural elements [5]. Also, larger solid objects, e.g. fragments of airport pavements, cause damage. The blades during operation of the engine are therefore heavily exposed to a foreign object damage (FOD).

Due to the nature of the operation of the blades during their work, the useful properties determined at the design stage of the engine must be maintained. Compressor blades of aircraft engines work under loads causing both low-cycle fatigue (change of rotational speed) and high-cycle fatigue (vibrations of blades, change of gas flow dynamics).

Analysis of the causes of engine failures indicates that in the majority of cases, the fatigue strength of the blade after impact by the foreign objects is reduced. The effect of the plastic deformation of the material in the impact zone is the notch in which the stress concentration takes place and the fatigue strength decreases. It was stated that depending on the value of the FOD impact energy, the initiation and propagation of fatigue crack are of different nature [6]. In addition, the continuous change in the shape of the curved surface of the blade and the change of the cross-sectional area of the blade poses difficulties in determining the degree

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of impact of damage to these elements by solid objects. These issues are still at the center of interest for the constructors of aircraft propulsion [7, 8].

The aim of the undertaken research is an attempt to develop a methodology for assessing the impact of damage to the leading edges of an aircraft engine's compressor blades on their fatigue strength.

Material and methodology of research

The first stage air compressor vanes were made of martensitic steel with chemical composition: 11% Cr; 1.6% W; 1.5% Ni; 0.35% Mo; 0.18% V; 0.11% C; 0.03% P and 0.025% S. In order to realize the main objective of the research, the criteria for the classification of blades defects were developed depending on their length and position on the leading edge in relation to the blade lock. Five zones of blade height and eight groups of defects length were identified (fig. 1, fig. 2, tab. I and tab. II) [9].

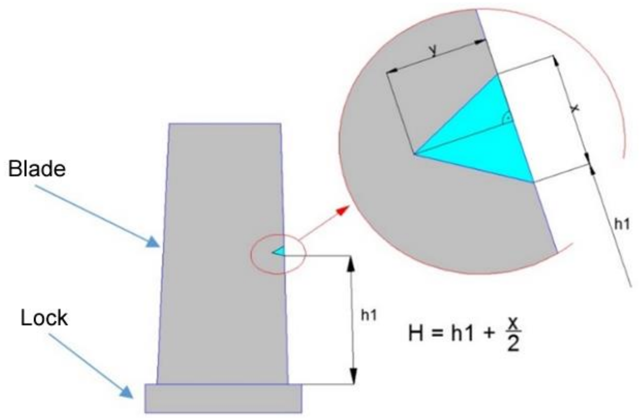

Fig. 1. Scheme of the compressor blade and defect measurement methodology

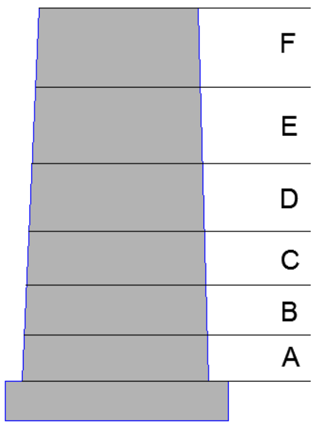

Fig. 2. Zones of the position of the blade defects

TABLE I. Groups of blade defects depending on the length

Defect group	Defect lenght *y*, mm
I	0÷0,099
II	0,1÷0,199
III	0,2÷0,299
IV	0,3÷0,499
V	0,5÷0,999
VI	1÷1,999
VII	2÷2,999
VIII	> 3

TABLE II. Zone of location of the blade defects depending on the distance from the blade lock

Defect location zone	Distance from the blade lock *H*, mm
A	0÷5,99
B	6÷12,99
C	13÷23,99
D	24÷43,99
E	44÷54,5

In a special station, model defects were made on the blades. The length of each of them was measured and assigned to a specific group (fig. 3).

The high cycle fatigue test was carried out using a testing machine - Brüel&Kjær LDS V830 vibration exciter. A 30-sample fatigue test was carried out to develop the Wöhler plot. The average value of the fatigue limit was determined on the basis of 15 samples. The method of increasing loads was applied. The tests assumed the basis of the fatigue test $N_G = 1 \cdot 10^7$ cycles and the initial stress amplitude σ_1 = 363 MPa. The amplitude of the stress was increased by $\Delta\sigma$ = 29.4 MPa. Fatigue strength was determined under conditions of periodic sinusoidal stress [10].

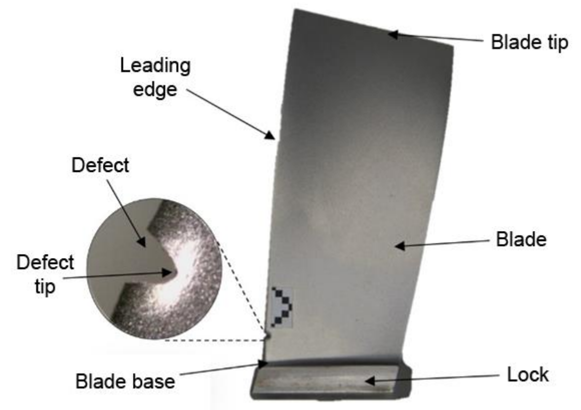

Fig. 3. Blade leading edge with defect in zone *A*; defect group – *V*

Methodology of non-destructive testing of blades after the fatigue test was developed. A non-destructive penetrant-fluorescence method was adopted. The UVF-4 fluorescent penetrant, BRE-S cleaner, UVE fluorescent developer and ultraviolet light source were used.

The blades were washed ultrasonically in a solution of isopropyl alcohol (for degreasing) for 120 s and dried in compressed air. The UVF-4 penetrant was applied to the surface of the blade – its interaction time ranged from 5 to 6 min. The blade was then immersed in the BRE-S remover and dried with compressed air. A UVE developer was applied to the prepared surface of the blade.

Research results and their analysis

The fatigue test for the new, unpolluted vanes was the basis for the Wöhler plot illustrating the stress level σ_a as a function of the number of cycles to failure N_f (fig. 4) [11]. The fatigue strength of non-damaged blades σ_Z = 563 MPa was assumed as the main criterion in the assessment of the effect of the degree of damage on the fatigue strength of the blades.

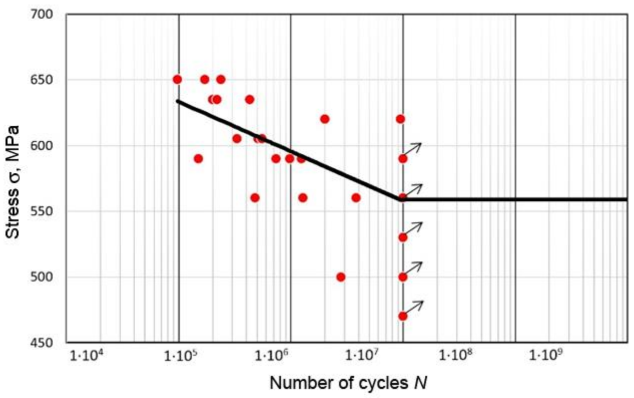

Fig. 4. Wöhler plot for the first stage vanes of an aircraft turbine compressor

TABLE III. Fatigue strength of damaged blades depending on the length and location of defects on the leading edge of the blade

No. of blade	Defect group	Defect location zone	Fatigue strength σ_a, MPa	No. of blade	Defect group	Defect location zone	Fatigue strength σ_a, MPa
L0059	II	E	545	L0113	IV	A	305
L0060	I	E	545	L0114	IV	A	305
L0061	V	E	575	L0115	V	A	305
L0062	VI	E	485	L0116	V	A	275
L0063	IV	E	545	L0117	V	A	215
L0064	VII	E	455	L0118	V	A	245
L0065	VIII	E	455	L0119	VI	A	215
L0066	III	E	545	L0120	III	C	215
L0067	I	D	575	L0121	IV	C	395
L0068	I	D	575	L0122	I	C	485
L0069	I	D	575	L0123	I	C	485
L0070	I	D	455	L0124	I	C	545
L0071	II	D	545	L0125	I	C	485
L0072	II	A	455	L0126	II	C	425
L0073	II	D	215	L0127	II	C	425
L0074	II	D	365	L0128	IV	C	305
L0075	III	D	455	L0129	IV	C	275
L0076	III	C	245	L0130	III	C	275
L0077	III	D	545	L0131	V	C	215
L0078	III	D	545	L0132	IV	C	245
L0079	IV	D	545	L0133	II	C	425
L0080	IV	D	515	L0134	II	C	395
L0081	IV	D	575	L0135	III	C	365
L0082	IV	D	545	L0136	III	C	425
L0083	V	D	575	L0137	I	B	605
L0084	V	D	545	L0138	I	B	575
L0085	V	D	575	L0139	I	B	515
L0086	V	D	545	L0140	I	B	605
L0087	VI	D	545	L0141	II	B	485
L0088	VI	D	545	L0142	II	B	515
L0089	VI	D	575	L0143	II	B	455
L0090	VI	D	545	L0144	II	B	485
L0091	VII	D	575	L0145	III	B	335
L0092	VII	D	515	L0146	III	B	335
L0093	VII	D	575	L0147	III	B	395
L0094	VII	D	545	L0148	III	B	305
L0095	VIII	D	455	L0149	IV	B	245
L0096	VIII	D	455	L0150	IV	B	305
L0097	VIII	D	455	L0151	IV	B	365
L0098	VIII	D	455	L0152	IV	B	365
L0099	I	A	515	L0153	VII	E	575
L0100	I	A	605	L0154	VIII	E	605
L0101	II	A	515	L0170	III	D	545
L0102	II	A	485	L0171	III	D	545
L0103	I	A	545	L0172	V	D	575
L0104	II	A	515	L0173	V	D	575

L0105	II	A	515	L0174	VI	A	185
L0106	I	A	605	L0175	VI	A	215
L0107	III	A	455	L0176	V	C	155
L0108	III	A	455	L0177	V	C	125
L0109	III	A	425	L0178	VI	C	95
L0110	III	A	365	L0179	VI	C	65
L0111	IV	A	395	L0180	VI	C	75
L0112	IV	A	395				

The fatigue strength of the blade, determined on the basis of the fatigue test, during which data on the stress value and the number of stress cycles was obtained (figs. 5-7), was used to determine the trend line (using the least squares method). The aim was to show the tendency to decrease the fatigue strength of the blade in the individual zones.

Analysis of the results of the fatigue test also allowed to determine the degree of impact of the damage - depending on its position on the leading edge in relation to the base of the pen (lock) - on the fatigue strength of the blade. The results of the fatigue test of fractures with defects of groups I-VIII were taken into account (fig. 7). It was found that defects lying within 24 mm from the base of the blade lock (zones A-C) have the greatest impact on reducing the fatigue strength of the blade.

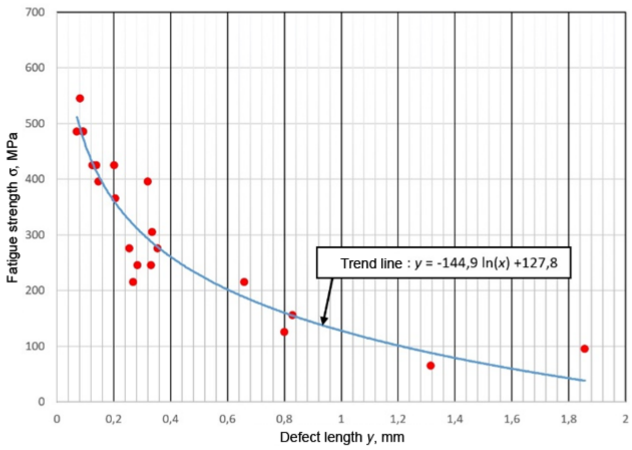

Fig. 5. Average fatigue strength of the blade as a function of defect length - zone C

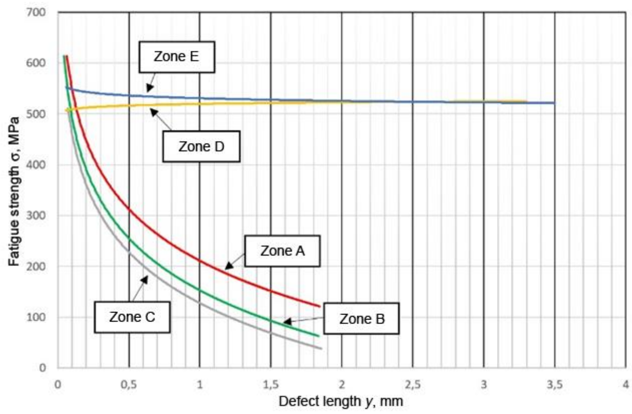

Fig. 6. Average fatigue strength of the blades depending on the length of defect - zone A-E

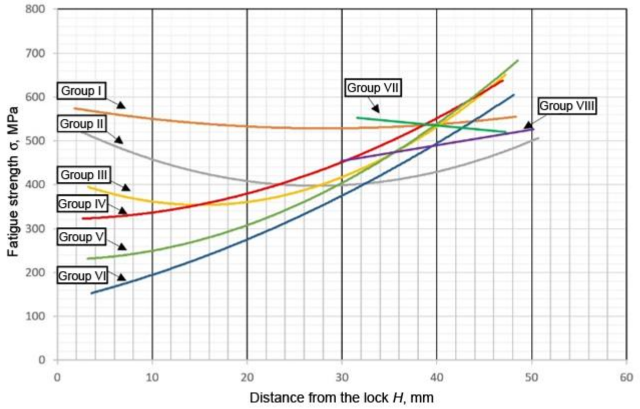

Fig. 7. Fatigue strength of the blades as a function of defect distance from the lock - defect group I-VIII

Macroscopic examinations using fluorescence method enabled observation of the source and nature of initiation and direction of fatigue cracks propagation of damaged blades. It was found that damaged blades after fatigue test are characterized by cracks between 6 and 14 mm long. Fatigue cracks most often are located on the upper (convex) surface of the blade. The direction of propagation of these cracks is parallel to the base of the blade lock (fig. 8) [12].

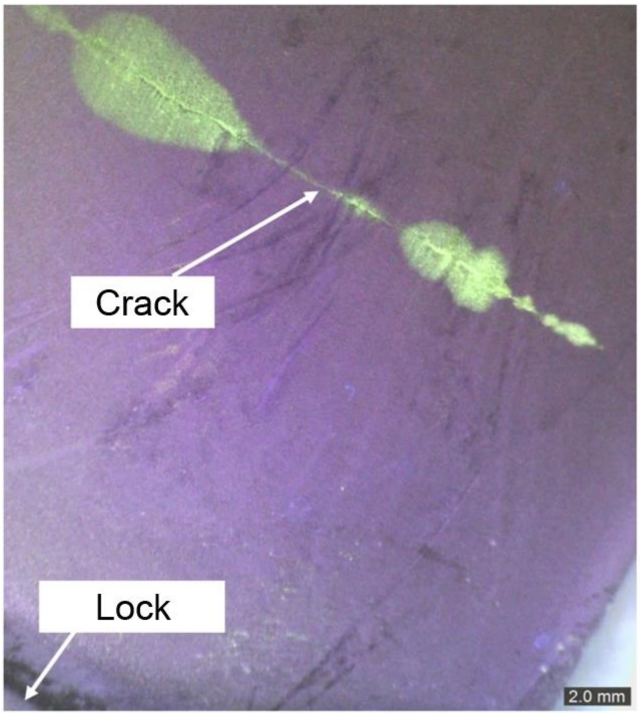

Fig. 8 The crack on the upper surface of the blade after a fatigue test

It was found that the sites of the crack initiation were usually found at the tip of the defect (fig. 3) - this was the case for all the blades after the fatigue test with defects in zones B and C. At the same time it was found that cracks on the upper surface of the blade were initiated in its central part - this was characteristic for all blades after fatigue test with defects in zone E (tab. IV). The cracks formed in the central part of the blade ran at the distance from 5 to 12 mm from its lock.

TABLE IV. Fatigue cracks initiated at the tip of the blade defect depending on the position

Damage zone	Initiation of break at the defect tip, %
A	82
B	100
C	100
D	42
E	0

Conclusions

Analysis of the test results allowed to determine that the length and location of the blade defects on its leading edge strongly, although to a different degree, affect its fatigue strength. It was found that the fatigue strength was most diminished in the case of blades with leading edge damage located within 24 mm from the base of the lock. Damage to the edge of the blade with a depth of 0.1 mm, located in zones A-C, causes a marked decrease in fatigue strength. In turn, damage located at a distance >24 mm from the base of the lock has little or no effect on the fatigue strength of the blades.

It has been shown that the smallest fatigue strength is characteristic for blades with defects on leading edge located at a distance of 13 to 24 mm from the lock. For example, damage with a length of 1.3 mm reduces the fatigue strength to 65 MPa.

Macroscopic examinations after the fatigue test of the blades with defects on the leading edge located at a distance of less than 24 mm from the lock indicate a tendency to initiate fatigue cracks on the upper surface of the blade at the tip of the defect. The propagation direction of the cracks is perpendicular to the leading edge of the blade.

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