THE INFLUENCE OF SERVICE AND MANUFACTURING DEFECTS ON CYCLIC LIFE OF GAS TURBINE ENGINE BLADES

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Fatigue tests of turbine rotor blades with manufacturing defects and compressor rotor blades with notches simulating in-service defects were performed. It was shown that in the presence of manufacturing defects the scatter of fatigue characteristics of turbine blades increases. The defects which have the biggest effect on fatigue characteristics of turbine blades at room and operating temperatures were determined. For compressor blades of various types the sizes of the defects which have no influence on their fatigue limits were defined. This is associated with the pattern of stress distribution along the blade length. Allowable defects in compressor rotor blades should be defined experimentally due to possible changes in the oscillation mode of blades with defects. Design engineers should take into account the regularities found in their calculations of the reliability and lifetime of blades.

INTRODUCTION

As it was shown by Kuznetsov (1), in many cases fatigue failures of gas turbine engine (GTE) rotor blades occurring in service are associated with the presence of initial (manufacturing or metallurgical) or in-service defects.

For rotor blades of an axial-flow compressor, typical in-service defects are dents and scratches occurring as a result of entrapment of foreign objects into the engine air inlet.

Both the manufacturing and in-service defects in blades can become a cause of their failure. Therefore, when checking the blades after manufacturing and during operation, one should have the information on the level of danger of various defects. The authors studied the influence of two types of defects on the fatigue of blades (compared to the defect-free blades):

- manufacturing: for rotor blades of GTE turbines:
- in-service: for rotor blades of GTE compressors.

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EXPERIMENTAL PROCEDURES AND TEST OBJECTS

The influence of manufacturing defects on the fatigue of blades was studied using the rotor blades of the 3d stage of a GTE turbine manufactured by machining from die
forgings of the EI 437BVD alloy. The tests were performed at temperatures of 293K and 843K on a test bench with an electrodynamic excitation of vibrations. Bending vibrations of the first mode were excited in the blades. The stresses in a blade were prescribed in accordance with the range of the blade-end vibration calibrated with respect to the stresses in the vicinity of the root section.

Selected blades without defects were tested, as well as those with the defects of limited size within the tolerances of the manufacturing practice:

- burnup sites from grinding on the blade in the vicinity of the blade locking piece;
- marks on the blade after grinding;
- residual stresses induced by an additional operation - polishing of the blade surface near the root.

The fracture of a blade was taken to be the appearance of a crack which lowers the frequency of natural vibrations by 1...2% as compared to the initial one. The fracture of blades occurred along the leading and trailing edges. The influence of in-service defects was studied on two types of rotor blades of on low-pressure compressor (LPC) of GTE:

- the blades of the 1st and 4th stages of an airplane GTE of the VT3-1 titanium alloy;
- the blades of the 1st stage of an helicopter engine of the VT8 titanium alloy.

The analysis of the distribution of in-service defects along the blade surface revealed that 70% of them are dents located in the upper half of the blade length. The depth of the dents is within 0.5 - 1.2mm. It is difficult to select a required number of blades with identical defects. Therefore, a notch in the form of a triangular cut out of depth 0.5 - 1.2 mm and with a rounding off radius of 0.1 mm was made on the blades, which simulates in-service damage on the leading edge. The concentrator (notch) was located in the midlength of the blade and in testing the account was taken of the stress distribution along the blade length for each type of blades. Strains were measured in different sections of the blade. The distribution of stresses along the leading and trailing edges for the vibrations of the 1st mode is presented in Figure 1.

EXPERIMENTAL RESULTS AND DISCUSSION

Investigation into the Influence of Manufacturing Defects on Cyclic Life of GTE Turbine Rotor Blades

Figures 2 and 3 present the results of fatigue testing of GTE turbine rotor blades at room and operating temperatures. In view of the scatter of the results of testing and calibration of various batches of blades, statistical processing of the data was carried out by the relationships of Sachs (2). From these results (Table 1) it follows that all the defects tested increase the dispersion of the samples at high and room temperatures. In this case, the biggest effect on this parameter is produced by the additional polishing operation at 293K and by burnups at 843K. The same defects at corresponding temperatures lead to the biggest reduction in life and fatigue limit of the blades compared to the reference batch.

An appreciable influence of defects in the form of residual stresses induced by polishing on the fatigue characteristic dispersion is observed only at 293K, since at 843K thermally activated processes of residual stress relaxation and removal of the cold work extending to the depth of 40...100 mm reduce somewhat the dispersion of the experimental results. The lowest fatigue characteristics and the highest scatter of the results at 843K are observed in the blades with burnups. This is related to irreversible changes in the material properties in the zones of these defects. At a temperature of 273K the presence of burnups on the blades induces the changes in the slope of the fatigue curve (Figure 2). At 273K in the blades of the reference batch and in the blades with burnups the cracks initiate from the leading and trailing edges, whereas in the blades after polishing and in those with scratches the biggest part of fractures occurs from the trailing edge.

TABLE 1 - Results of Fatigue Investigation on Rotor Blades of GTE 3d stage at 293K and 843K

Temperature K	Type of Defects	Number of Blades Tested	Fatigue Limit MPa	Dispersion of Results
293	Reference blades	9	220	36.4
293	Burnup sites	10	210	225.6
293	Grinding marks	10	220	138.8
293	Residual stresses	13	190	517.1
843	Reference blades	10	220	92.6
843	Burnup sites	10	200	560.2
843	Grinding marks	9	210	180.6
843	Residual stresses	11	210	273.8

Investigation of the Influence of In-Service Defects on Cyclic Life of Compressor Rotor Blades

Testing of the blades of the first stage of the GTE LPC with defects at the stresses in the controlled section above 130 MPa revealed two types of defects: curling of the upper part of the blade and asymmetry of the blade ends oscillation with respect to neutral position which is caused by the loss of stability of the blade edges when the blade moves towards the pressure face. For this reason, the stress state of a blade with a defect was studied additionally using the method of lacquer coatings and strain measurement. The data obtained revealed that the maximum stresses in a blade without a concentrator are acting on the back and on the leading edge of the blade lower part, whereas in a blade with a concentrator - in the concentrator zone.

Quantitative assessment of the blade stress state was performed according to Serensen's procedure (3) which makes it possible to calculate the principal stresses and strains from the data of strain measurement. On the basis of these data and the results of the calculation of equivalent stresses in the section with a concentrator, calibration relationships were obtained between the equivalent stresses and oscillation amplitude of the blade end.

The degree of the influence of a defect was estimated by the magnitude of the effective stress concentration factor:

$$k_\sigma = \sigma_{-1b} / \sigma_{-1d} \qquad (1)$$

where σ_{-1b} is the fatigue limit of a defect-free blade; σ_{-1d} is the fatigue limit of a blade with a defect.

Fatigue limits were determined by the method of Locati (4). To evaluate the fatigue limit of blades of titanium alloy with an error within 3...5%, in standard (5) it is recommended to test no fewer than 10 blades. The tests results of those are listed in Table 2.

TABLE 2 - Results of Fatigue Testing of Rotor Compressor Blades with Defects by Lokati's Method.

Type of Engine	Type of Blade	Notch Depth mm	Number of Blades Tested	Fatigue Limits of Blades, MPa	Mean Value of Fatigue Limit MPa	Root-Mean-Square Deviation MPa	Fatigue Notch Factor k_σ
Aircraft engine	1st stage	0	10	185, 188, 234, 257, 258, 262, 262, 268, 293, 299.	250.6	38.4	1.0
Aircraft engine	1st stage	1± 0.1	10	219. 5, 223, 223.5, 246.5, 252, 259.5, 255, 271.5, 295, 305.5.	255	29.4	~1.0
Aircraft engine	4th stage	0	10	350, 370, 371, 371, 400, 400, 403, 433, 483, 495.	407.6	48.9	1.0
Aircraft engine	4th stage	1± 0.1	10	356.5, 369.5, 379.5, 383.5, 393, 405, 411, 429, 431, 436.	399.4	27.5	1.02
Heli-copter engine	1st stage	0	12	400, 446, 475, 467..3, 475.3, 476.7, 485.3, 492, 495.3, 496, 496, 498.	476.8	27.6	1.0
Heli-copter engine	1st stage	0.5 ± ± 0.1	10	244, 306, 260, 269.3, 258.7, 274, 286.7, 290, 297, 299.	278.5	20.4	1.71

Analysis of the fatigue limits obtained and their root-mean-square deviations reveals that the concentrators chosen do not influence the fatigue limits of airplane GTE compressor blades and the fatigue limit of a helicopter GTE blade decreased by 42% which is associated with a special pattern of stress distribution along the blade length. To find the critical size of a defect which does not lower fatigue resistance characteristics of a compressor rotor blade, the authors studied the blades of the first stage of the GTE LPC with concentrators of depths 1, 2.5, and 3.5 mm (samples of 10 blades).

The experimental results are given in Figure 4 from which it follows that a concentrator of depth below 1.5 mm does not decrease fatigue characteristics of the tested blades. This conclusion has been confirmed by comparing mean values of the fatigue limits with the use of Student's statistical t-criterion.

CONCLUSIONS

1. The investigated manufacturing defects of the turbine rotor blades have only a slight effect on the fatigue characteristics of blades at room and operating temperatures but increase appreciably the dispersion of the experimental results. The biggest reduction of the fatigue characteristics and increase of their dispersion at 293K are caused by the defects in the form of nonuniform residual stresses on the blade surface and at 843K by the defects in the form of burnups.

2. When determining the level to which the manufacturing defects in the compressor rotor blades are dangerous, it is imperative to consider both the site of the defect location on the blade, which is dictated by the pattern of stress distribution during oscillation, and the defect size. Allowable defects in compressor rotor blades should be defined experimentally due to possible changes in the oscillation mode of blades with defects.

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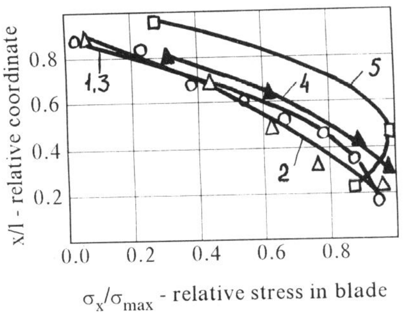
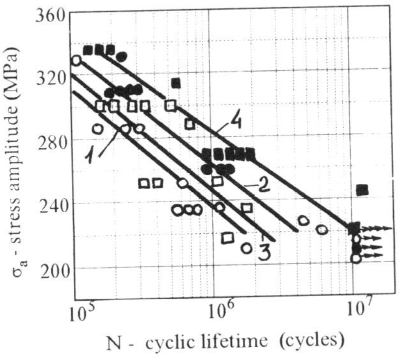


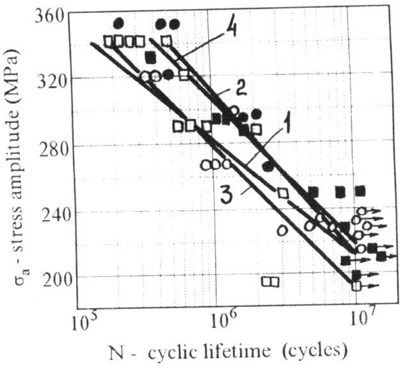
1- 1-st stage of the airplane engine LPC (leading edge); 2 - 1-st stage of the airplane engine LPC (trailing edge); 3 - 4-th stage of the airplane engine LPC (leading edge); 4 - 4-th stage of the airplane engine (trailing edge); 5 - 1-st stage of the helicopter engine LPC (leading edge);

Figure 1. Stress distribution along the rotor blades



1. o - blades with burnup sites;
2. ● - with grinding marks; 3. □ - with residual stresses; 4, ■ - reference blades; → - nonfailed blades

Figure 3. Fatigue curves for rotor blades of GTE 3-rd stage at 843K



1. o - blades with burnup sites;
2. ● - with grinding marks; 3. □ - with residual stresses; 4, ■ - reference blades; → - nonfailed blades

Figure 2. Fatigue curves for rotor blades of GTE 3-rd stage at 293K

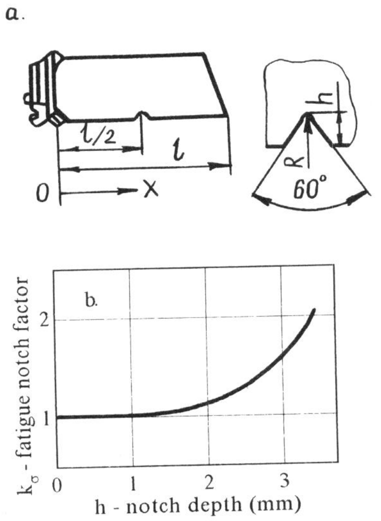


Figure 4. The appearance of a notch in blades (a) and k_σ vs h relation (b)