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STRESS CORROSION MODELING IN STEAM TURBINE BLADES

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Abstract

This article is a proposition of mathematical model of stress corrosion. Model has been implemented into Abaqus FEA code. This paper contains results of stress corrosion simulation of steam turbine blade and inluence of degradation material for vibrational blade propetries and its kinetostatic work parameters.

1. Introdution

We present in this paper results of numerical simulations of 16th stage blade stress corrosion of 100 MW steam turbine. The 100MW turbine is an oryginal design prepared at Gen. K. Świerczewski Mechanical Works (currently ALSTOM Power Sp. z o. o.) in Elbląg at the end of seventieth. As a result of visual inspection of the steam paths of corrosion was found both on rotor blades and disks. The most endangered areas of rotor blades are upper parts of root where steam has acces. As a result of analisys [2] it was found that causes of failures originate in poor quality of steam. A conclusion from analysis [5] is that the direct reason of rotor blades cracking initiation is stress corrosion caused by simultaneous action of corrosive processes and tensile kinetostatic stresses. A steel used for blades is susceptible for corrosion and in agresive enviroment exhibit a large decrease of mechanical properties (drop in the value of elastic moduls and yield stress).

2. Mathematical modeling of stress corrosion in steam environment.

Let us consider a stress corrosion mathemathical model that assumes existance of two parts:
a) reactive – diffussive part which describes transport of agresive compounds in metal. It is based on the following equations:

$$J_i^k = D_{ij}^{km} \frac{\partial}{\partial x_j} c^m , \tag{1}$$

where: J_i^k is flux of k th aggressive chemical compound, D_{ij}^{km} is diffusion coefficient of k th aggressive chemical compound in steel and c^m is mass concetration of given chemical compound

$$D_{ij}^k = D_0^k \exp\left(\frac{-Q^k}{RT}\right)\delta_{ij}\left(1 + A_1^k \varepsilon_{ij}^{el} + A_2^k \varepsilon_{ij}^{pl} + A_3^k \varepsilon_{ij}^{cr}\right) + \omega D_0^{\omega} \exp\left(\frac{-Q_{\omega}}{RT}\right); \tag{2}$$

where: Q^k - activation energy of k th chemical compound in steel, R - gaz constant, T - temperature in $[^oK]$, $\varepsilon_{ij}^{el}, \varepsilon_{ij}^{pl}, \varepsilon_{ij}^{cr}$ - elastic, inelastic and creep strains tensors, A_1^k, A_2^k, A_3^k - constants, ω, Q_ω - local damage parameter and activation energy for damage parameter. Bounduary conditions for reactive – difussive part of model represents following equation:

$$c = \left| pH_{envirom.} - 7 \right| A_4^k c_0 \tag{3}$$

, where c_0 - given concetrations of ions at $pH = 7$, $\left[H_3O^+\right] = \left[OH^-\right] = 1 \cdot 10^{-7} \left[mol/dm^3\right]$, A_4^k - constant.

b) mechanical – this part discribes mechanical properties of material as a function of local damage parameter and local concentrations of chemical compounds.

- elastic material behaviour

$$(1-\omega)^n \cdot \begin{bmatrix} \left(\sigma_{11} + {}^{E}\!/_{2}\left(1 + \frac{c^H}{c_g}\right)\right) when\left(c^H \geq c_g\right); \left(\sigma_{11}\right) when\left(c^H < c_g\right) \\ \left(\sigma_{22} + {}^{E}\!/_{2}\left(1 + \frac{c^H}{c_g}\right)\right) when\left(c^H \geq c_g\right); \left(\sigma_{22}\right) when\left(c^H < c_g\right) \\ \left(\sigma_{33} + {}^{E}\!/_{2}\left(1 + \frac{c^H}{c_g}\right)\right) when\left(c^H \geq c_g\right); \left(\sigma_{33}\right) when\left(c^H < c_g\right) \\ \sigma_{12} \\ \sigma_{23} \\ \sigma_{31} \end{bmatrix} = \begin{bmatrix} \lambda + 2\mu & \lambda & \lambda & 0 & 0 & 0 \\ \lambda & \lambda + 2\mu & \lambda & 0 & 0 & 0 \\ \lambda & \lambda & \lambda + 2\mu & 0 & 0 & 0 \\ 0 & 0 & 0 & \mu & 0 & 0 \\ 0 & 0 & 0 & 0 & \mu & 0 \\ 0 & 0 & 0 & 0 & 0 & \mu \end{bmatrix} \cdot \begin{bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ \varepsilon_{12} \\ \varepsilon_{23} \\ \varepsilon_{31} \end{bmatrix} \tag{4}$$

where c^H is the concetration of hydgrogen (if present), c_g is a limit of concetration above which recombination of hydrogen or reaction $Fe_3C + 4H \rightarrow 3F + CH_4$ occurs. As a result of both mentioned process bubbles of gas in metal appears. Then material damage is a superposition of external forces and internal pressure from gasous H_2 and(or) CH_4, λ, μ are Lame constants and they are also connected with local damage parameter:

$$\lambda = \frac{\nu^* E^*}{(1+\nu^*)(1-2\nu^*)} \quad \mu = \frac{E^*}{2\left(1+\nu^*\right)} \quad E^* = E\omega \quad \nu^* = \nu\omega \tag{5}$$

- plastic material behaviour

$$f\left(\sigma - \alpha\right) = \sigma_0 = \sqrt{{}^{3}\!/_{2}\left(S_{ij} - \alpha_{ij}\right) : \left(S_{ij} - \alpha_{ij}\right)} \qquad \frac{d}{dt}\varepsilon_{ij}^{pl} = \frac{\partial f\left(\sigma - \alpha\right)}{\partial \alpha} \frac{d}{dt}\bar{\varepsilon}^{pl}$$
$$\frac{d}{dt}\bar{\varepsilon}^{pl} = \sqrt{{}^{3}\!/_{2} \frac{d}{dt}\varepsilon_{ij}^{pl} \frac{d}{dt}\varepsilon_{ij}^{pl}} \qquad \frac{d}{dt}\alpha_{ij} = C \frac{d}{dt}\bar{\varepsilon}^{pl} \frac{\left(\sigma_{ij} - \alpha_{ij}\right)}{\sigma_0} + \frac{1}{C}\alpha \frac{d}{dt}C \tag{6}$$

where α_{ij} - is backstress tensor, C – is hardening parameter $C = \frac{d\sigma}{d\bar{\varepsilon}^{pl}}$, σ_0 - is yield Huber – Misses stress, its value is also a function of damage parameter :

$$\sigma_o = (\sigma_o)_{start} - b\omega, \tag{7}$$

$(\sigma_o)_{start}$ - is the yield stress Huber – Misses stress of material at begining of analysis, b - constant parameter.

The damage ω parameter represets porosity of material due void nucleation and growth. Following equations for evolution of damage parameters have been originaly proposed by Gurson[4]:

$$\frac{d}{dt}\omega = \frac{d}{dt}\omega_{gr} + \frac{d}{dt}\omega_{nucl}, \tag{8}$$

$$\frac{d}{dt}\omega_{gr} = \lambda(1-\omega)N_{kk}, \tag{9}$$

$$\frac{d}{dt}\omega_{nucl} = \frac{f_N}{s_N\sqrt{2\pi}}\exp\left[-\frac{1}{2}\left(\frac{\bar{\varepsilon}^p - \varepsilon_N}{s_N}\right)\right]\frac{d}{dt}\bar{\varepsilon}^p. \tag{10}$$

In Eq. 8 – 10 damage is connected directly with inelastic strains, but in our work we would like to propose modified function for damage as function of local concentrations of chemical compoudns too. The total evolution for damage parameter represent following equation:

$$\frac{d}{dt}\omega = \lambda(1-\omega)N_{kk} + \frac{f_N}{s_N\sqrt{2\pi}}\exp\left[-\frac{1}{2}\left(\frac{\bar{\varepsilon}^p - \varepsilon_N}{s_N}\right)\right]\frac{d}{dt}\bar{\varepsilon}^p + A_5 c^k \exp\left(c^{H_2O}\right). \tag{11}$$

c^k - local concentractions of agressive enviroment, c^{H_2O} - local concentration of water, part $\exp\left(c^{H_2O}\right)$ describes influence of water which make material degradaction faster and more intensive, A_5 - constant variable, f_N, ε_N, s_N - material constants.

3. Calibration of the model constants

All model constants requires calibration on experiments $\sigma-\varepsilon$ data for normalized sample under external mechanical force. The sample is placed in steam enviroment. Calibration is prosess in which we change values of model constants and simultaneously compare experimental curves $\sigma-\varepsilon$ with those recived from calculations. The calibration process ends when good agreement is recived. Figure 1 shows the sample result of calbraction.

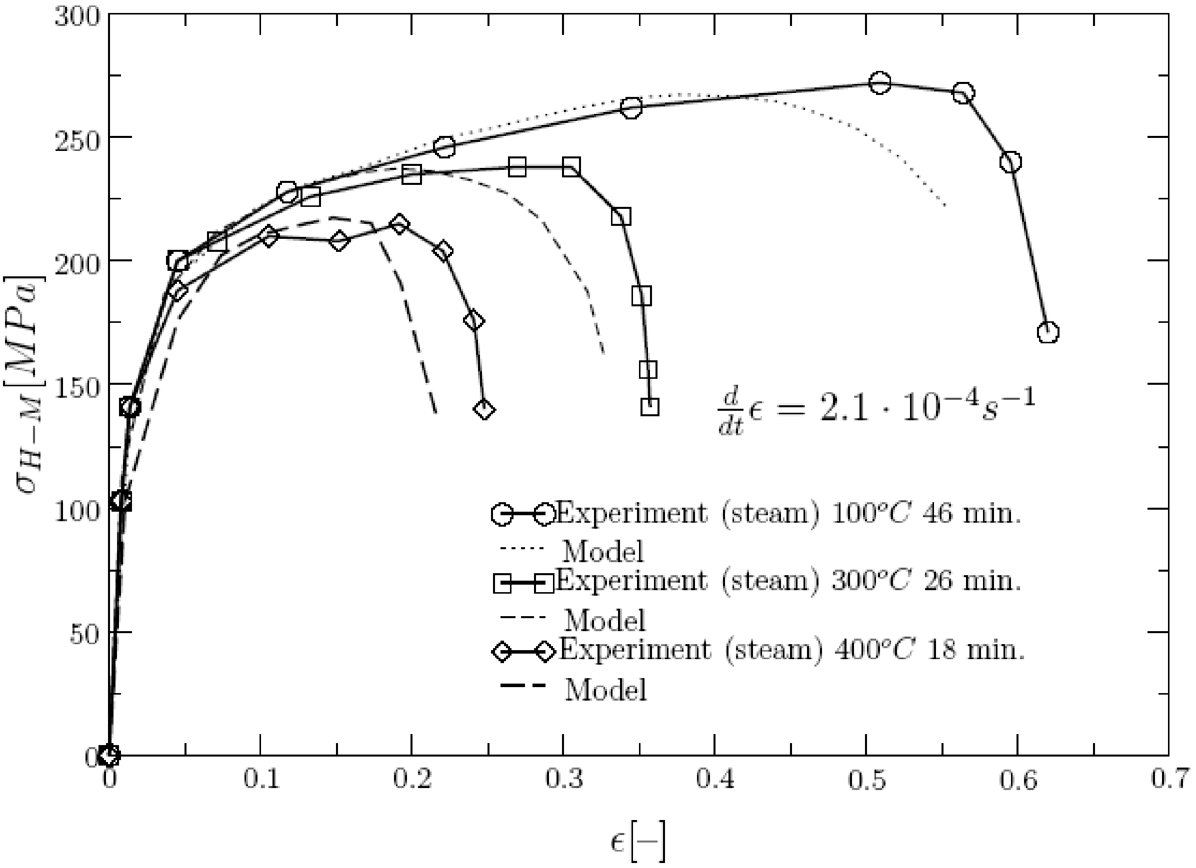

Fig. 1 Example result of calibration for different steam temperatures (ST12TE stainless steel). [7]

Table 1 shows the model constant recived from calibration for blade corrosion simulations.

Table 1 Values of model constants for ST12TE.

Constant	Value	Constant	Value
A_1	12.5	D_0	$10^{-15}\ m^2/s$
A_2	78.3	k	$34.2\,kJ/mol$
A_3	0	$(\sigma_o)_{start} = R_e$	210 MPa
A_4	1	c_0	$2.38\,mol/kg$
c_g	$0.23c_0$	f_N	3e-3
ε_N	0.3	s_N	0.1

2. Degradation of rotor blades

Figure shows the geometry of 16 th stage of 13UC100 blade and its numerical model.

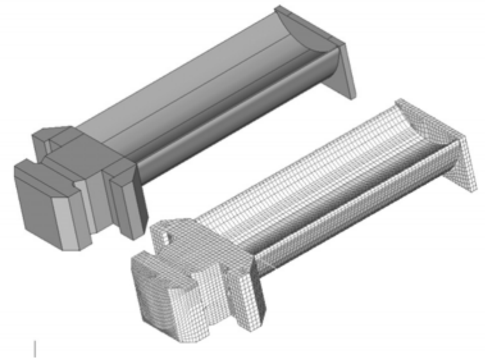

Fig. 2 Geometry and numerical model of 16 th stage of 13UC100 blade.

Blade has about 70.000 degrees of freedom. Mesh consists 20 – node elements C3D20T. The chosen element is well known and definied thermal – stress element from library of Abaqus FEA software. To simulate blade work conditions the degrees of freedom on root of blade have been fixed. Blade is loaded by rotational body force (rotations 3000 rev./min.) and steam flow (about 16 kPa). On the blade surfaces loaded a concentration of aggresive enviroment. Balde is working at 160^{o}C. The calculations have been made also for initial material state and for chosen example states of corrosion. The results are shown in Table 2 and on following figures.

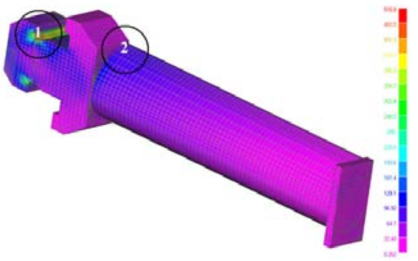

Figure 3 Huber – Misses stress. Initial state 1 – 515MPa and 2- 129MPa. Initial state.

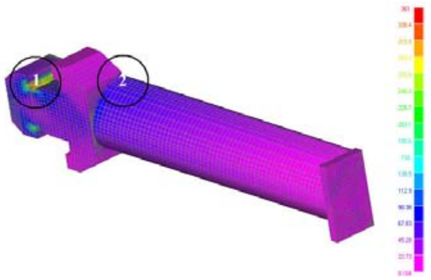

Figure 4 Huber – Misses stress. 30% blade material degradaction.1 – 361MPa and 2- 92MPa.

Table 2 Redistribution of maximal H –M stress loaded blade versus level of blade material degradation.

Points on Fig 3 and 4 H –M [MPa]		Level of material degradaction [%]	Points on Fig 3 and 4 H – M[MPa]	
1	2		2	1
515	129	0	62	550
501	125.1	3	60.1	533.5
485	121.2	6	58.2	517

470	117.3	9	56.3	500.5
465	113.4	12	54.4	484
442	110	15	53.2	469
425	105.6	18	50.6	451
410	103	21	48.9	434.5
398	97.8	24	46.8	420
380	93.9	27	45.3	401.5
361	90	30	43	385

Values of H – M stresses presented in Table 2 are decreasing during the progress of the corrosion. This result means that dergradated material transmits lower forces. In the same time stresses at the centre of blade significantly increases leading to a stress redistribution.

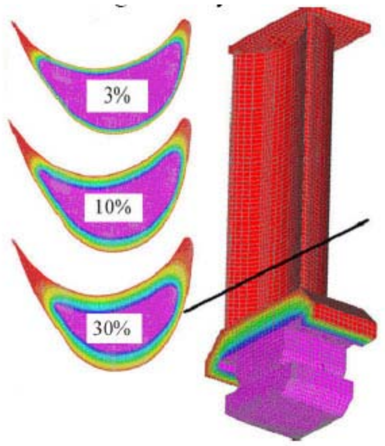

Figure 5 The example of evolution of damage parameter for different corrosion levels. Black line means a position of cross-section area.

The Figure 5 presents example of levels of blade corrosion. Material degradation took place only on unshielded surfaces of blade which have contact with steam. In the next step the vibrational analysis and influence of stress corrosion process for the natural frequencies of blade have been made.

It is well known (from operating characteristics of steam turbine) that to prevent vibrational hazard the first five natural frequencies of blade have to be outside of dangerous range of frequencies. Dangerous ranges for 16th stage are:

- For fow frequency : H_2=[85,115]; H_3=[138,162]; H_4=[188,212]; H_5=[238,262]; H_6=[288,312]
- For high frequency H_1=[2185,2415]; H_2=[4370,4830]; H_3=[6555,7245]

The first step is calculation of first five natural frequencies of given blade. Results of calculations are placed in Table 3 and following figures.

Table 3 First five natural frequencies of loaded and unloaded blade (Initial state $\omega = 0$).

Natural frequency	Rotations 0 [obr./min]	Rotations 3000 [rev./min.]
1	706	719
2	1294	1305
3	3119	3142
4	4068	4147
5	6313	6343

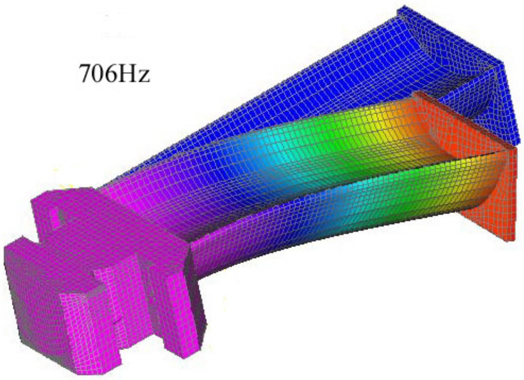

Figure 6 Natural frequency no 1. Damage parameter $\omega = 0$.

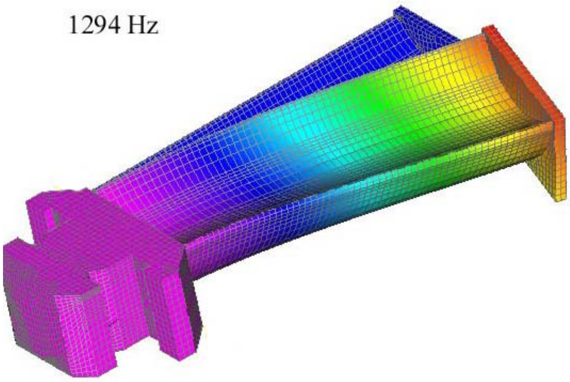

Figure 7 Natural frequency no 2. Damage parameter $\omega = 0$.

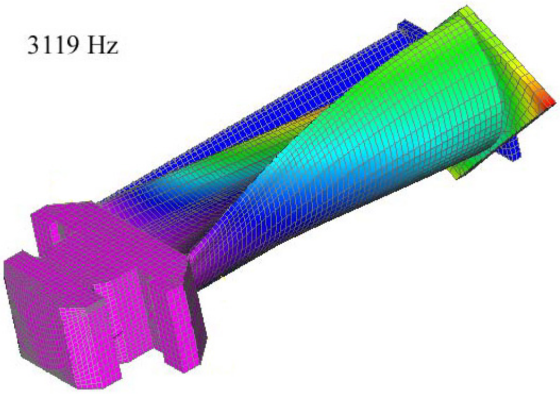

Figure 8 Natural frequency no 3. Damage parameter $\omega = 0$.

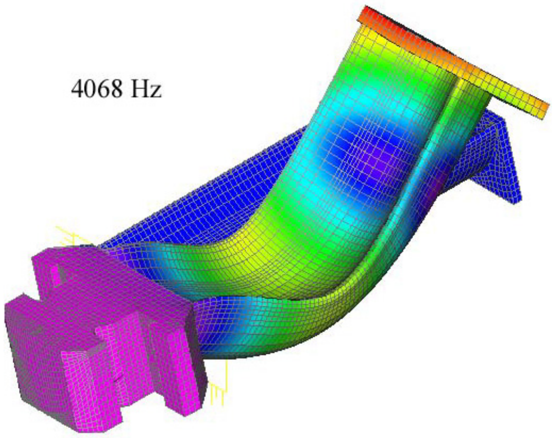

Figure 9 Natural frequency no 4. Damage parameter $\omega = 0$.

The next step the calculations of natural frequencies of loaded blade have been made during stress corrosion calculation. Results are presented in Table 4.

Table 4 Depence of natural frequency versus level of material degradation level in [Hz].

Free frequency	Level of material degradation										
	0%	**3%**	**6%**	**9%**	**12%**	**15%**	**18%**	**21%**	**24%**	**27%**	**30%**
1	719	697	674	652	630	608	585	563	541	519	496
2	1305	1265	1224	1184	1143	1103	1062	1022	981	941	901
3	3142	3045	2947	2850	2752	2655	2558	2460	2363	2265	2168
4	4147	4018	3890	3761	3633	3504	3376	3247	3119	2990	2861
5	6343	6147	5951	5755	5559	5363	5167	4971	4775	4579	4377

The calculated values with dangerous ranges are shown on Figure 10.

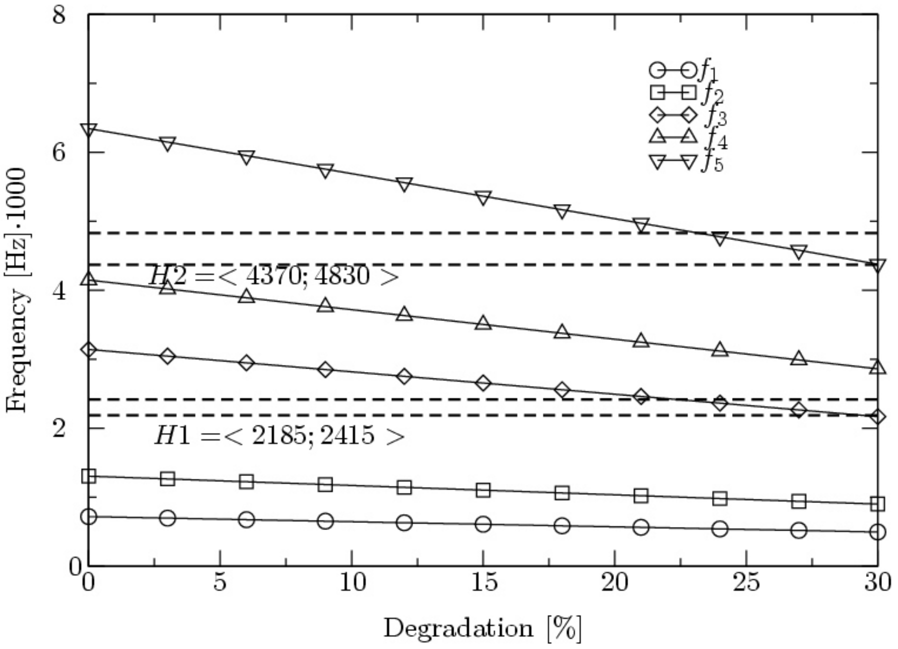

Fig. 10 Depence of natural frequency versus level of material degradation level.

From above results one can see that at 22.5% level of material degradation third natural frequency is in danger range H1 and at 24% fifth one is in interval H2. This proces leads to corrosion fatigue of blade and in concequence of this proces blade may break off.

4. Conclusions

Corrosion process leads to stresses redistribution in blade, outer stresses of blade become smaller and simultaneously stresses of inner blade part becomes higher.

Results of dynamics calculations demonstrates that undegradated blade frequencies are outside of dengerous ranges. Situation changes when the corrosion takes place. At 22% degradation level first natural frequency is in dangerous interval and amlitude of blade vibrations increase. This leads to accelerated fatigue damage and as a concequence blade breaks off. Figure 11 confirms proposed mechanism of blade damage.

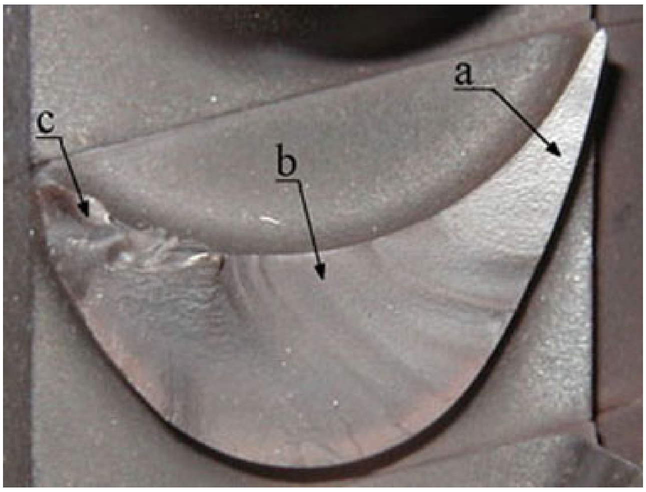

Figure 11 Real damage of 13UC100 16 th stage.[2]

a – rough, brittle fracture from trailing edge
b – fracture of fatigue nature encompassing the central part of the airfoil
c – fracture of immediate nature (blade break off with plastic strains)

5. Reference

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