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VALIDATION OF CESI BLADE LIFE MANAGEMENT SYSTEM BY CASE HISTORIES, ON LINE MEASUREMENTS AND IN SITU NDT

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ABSTRACT

A Life Management System was developed for hot components of large industrial gas turbines, in the form of a software tool for predicting component lives under typical operational transients (normal and also abnormal) and steady-state periods. The method utilises results of previous thermo-mechanical finite element and finite volume fluid mechanics analyses. The basic idea of this method is using data from structural and aero-thermal analyses (pressures and temperatures), blade life theory and material properties as an input to algorithms, and using operational and historical data to validate the predicted damage amounts. The software developed in this project, of general applicability to all GT models, has been implemented with reference to the geometries, materials and service conditions of a Fiat-Westinghouse model.

Keywords: life management, failure analysis, hot component, computer code.

NOMENCLATURE

B	Strain ratio
C_i	Material parameters
D_{CR}	Creep damage
D_{OX}	Cyclic oxidation damage
D_{TMF}	Thermo-mechanical fatigue damage
$D_{m,tot}$	Total mechanical damage
N	Number of expended load cycles
N_f	Number of load cycles to failure for thermo-mechanical fatigue
N_{ox}	Number of load cycles to failure for cyclic oxidation
Q	Activation energy (J/mol °K)
R	Gas constant (J/mol)
T	Absolute temperature (°K)
t	Expended time (hours)
t_h	Hold time (hours)
t_{ox}	Time to complete aluminium depletion (hours)
t_r	Creep time to rupture (hours)
$\Delta\varepsilon_{tm}$	Range of mechanica strain in a load cycle
ε_{min}	Minimum value of mechanical strain in a load cycle
ε_{max}	Maximum value of mechanical strain in a load cycle
σ	Von Mises equivalent stress (MPa)

INTRODUCTION

To obtain a reliable, cost–effective and efficient energy production with a low polluting level it is very important that the engine remains as long as possible in a good condition. Normally maintenance and overhaul intervals are prescribed by the gas turbine manufacturer based on the design know how and on the feedback collated from users' experience. A sufficiently wide statistics to make reliable prediction of component lives is normally available only to the manufacturer; on the opposite each individual user is generally unable to obtain a sufficient statistics on a particular GT model, unless he has several similar machines in his fleet and several years of operation experience.

Moreover in several plants gas turbines are operated in variable conditions, so that the scheduled maintenance time intervals originally suggested by the OEM do not result to be the best ones to minimise maintenance costs while optimising plant availability and safety. To obtain a convenient tool to optimise life of hot parts in a GT, a code can be prepared which has capability to calculate their residual life by combining turbine operational history with mechanical analysis algorithms and measured engine parameters. With the support of such a system it is possible for a user to predict the consequences of the different types of turbine operation (start/stop, baseload, trip etc.). This concept [1-3] was originally proven with General Electric Frame 7 and 6 gas turbines in EPRI developments in the last decade, leading to the development of the so called Life Management System (LMS) called REMLIF.

A life prediction methodology for large industrial gas turbines was developed also in CESI, dedicated at present to the first stage rotating blades of gas turbines widely used in Italy. In this study, the CESI approach is presented, implemented in a

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LMS as a PC software tool useful to calculate spent life fraction and to predict residual components lives under typical operational condition. Secondly the application of this code is described to a number of real case histories, with the comparison between software predictions and experimental findings in the most damaged regions of the blades.

Finally the results of in situ NDT measurements performed during maintenance plant stops with the frequency scanning eddy current technique (F-SECT) were successfully compared with the prediction of the LMS software, run with the plant history as input.

These results will be described and the future perspectives of the use of this LMS tool will be discussed

CESI LMS APPROACH

The Life Management System (LMS) developed at CESI is a PC software tool able to predict the gas turbine components lives under steady-state and transient conditions. The LMS development work was consisting of a comprehensive list of actions as follows.

A) Damaged components and damage mechanisms identification: based on service experience, the critical regions on components and the relevant damage modes (creep, fatigue, TMF, coating damaged features, role of hot corrosion, embrittlment etc.) are analised in order to identify the correct approach in the development of a LMS; attention has to be paid to the refurbishement cycles, repair and heat treatment features and coating details.

B) Computational fluid dynamics: geometrical parameters are retrieved for original component, including the inner cooling channels details, and the operating conditions are reviewed and collected, both normal steady-state service and the most typical start up and shut down transients; these data are then processed by means of fluid dynamics codes to obtain thermodynamic data distribution in gas flow around the component.

C) Thermo-mechanical analyses: data obtained from the aerothermal analyses (point B) are used as boundary conditions in a thermal-structural finite element (visco-elasto-plastic) code to provide patterns for temperature, stress and strain at almost all locations in the component.

D) Materials relevant data gathering: in a few cases, sufficient material information can be found in literature (traditional alloys and simple physical and mechanical parameters, such as thermal conductivity, Young modulus...); on the opposite, materials resistance to high temperature damage mechanisms, particularly for coated elements, have to be determined by important testing activities: creep, TMF and cyclic oxidation mainly.

E) Damage models: the materials data have then to be processed by suitable methods to provide all the numerical coefficient (temperature, stress, strain and time dependent) in the damage growth rate models and end-life criteria, specific for the damage mechanisms and maintenance philosophy under consideration (e.g. end life defined as component failure, or maximum tolerated damage suitable to be repaired, ...).

F) LMS software: the several damage models and end life criteria are implemented in a software tool, also containing the input and output interfaces for a friendly use by the plant operator; it is pointed out that this software carries out a number of different damage evaluations, for a preselected grid of component conditions (new/refurbished) and operational scenarios (including transients), as provided by the user.

G) Flexibility: within the LMS software, some options exists to take advantage of directly measured (or better to say, experimentally obtained) parameters; for example, the results from the aerothermal analysis can be tuned to the actual temperature values obtained by a pyrometer or estimated from metallurgical studies.

H) Validation: at last, the code and its prediction capability have to be verified against actual case histories, namely damage evidence found after certain operational histories, for which the LMS tool is applied to derive comparative damage evaluations.

As regard point D, in CESI laboratories several cyclic oxidation tests were performed at different temperatures (1 hour cycle); through metallography, quantitative image analysis and X-ray microanalysis; an analytical model was formulated, taking into account all the aluminum depletion mechanisms active during operation and based on literature studies [4].

In this paper, aspects of the CESI activity for the development of LMS for the TG50D5 gas turbine are described. Due to space limitations, items A to D and G in the above list will not be further treated, short descriptions will be given of item F, and special focus will be put to the validation studies only (item H).

DAMAGE EVALUATION

The CESI Life management System (LMS) takes into account three damage mechanisms:

- thermo-mechanical fatigue (coated base material);
- creep (bare base material);
- cyclic oxidation (coated material).

The first two mechanism act on mechanical properties of turbine component materials, while the last is related to protection capabilities of coatings.

The value D_{TMF} of damage for thermo-mechanical fatigue is given by the ratio between the number N of expended load cycles e the number N_f of cycles to rupture:

$$D_{TMF} = \frac{N}{N_f} \tag{1}$$

where N_f is a function of turbine operating conditions and mechanical properties of materials [3, 9-11]:

$$N_f = C_1 \left(\Delta\varepsilon_{tm}\right)^{C_2} \left(t_h\right)^{C_3} \exp(C_4 B) \tag{2}$$

In Eq. (2), C_i are function of material and load cycle shape, $\Delta\varepsilon_{tm}$ is the total mechanical strain range during a load cycle, t_h the hold time and B is given by:

$$B = \frac{\varepsilon_{max} + \varepsilon_{min}}{\varepsilon_{max} - \varepsilon_{min}} \tag{3}$$

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If turbine is subjected to different type of load cycles (transient speed, hold time, ...), for each of them Eq. (1) is applied and the total fatigue damage is the linear sum of partial damages:

$$D_{TMF} = \sum_i D_{TMF,i} = \sum_i \frac{N_i}{N_{f,i}} \tag{4}$$

The value D_{CR} of damage due to creep is given by the ratio between the exposure time t and the time t_r to creep rupture:

$$D_{cr} = \frac{t}{t_r} \tag{5}$$

Time t_r can be evaluated by mean of relation:

$$t_r = C_1\, \sigma^{C_2} \exp\left(\frac{Q}{RT}\right) \tag{6}$$

where C_i and Q are material parameters, R is the gas constant, and σ and T are, respectively, stress and temperature in steady-state condition. Again, when different types of load cycles are present, linear sum of damage is adopted:

$$D_{cr} = \sum_i D_{cr,i} = \sum_i \frac{t_i}{t_{r,i}} \tag{7}$$

At present, fatigue and creep damages are treated separately, neglecting influence of one mechanism on the other; the total mechanical damage $D_{m,tot}$ is then:

$$D_{m,tot} = D_{TMF} + D_{cr} \tag{8}$$

At last, two models are implemented for cyclic oxidation damage. In the former, the value D_{OX} of cyclic oxidation damage is given by the ratio between the number N of expended load cycles and the number N_{ox} of cycles to get an Al content in coating not enough to assure protection on base material:

$$D_{OX} = \frac{N}{N_{ox}} \tag{9}$$

The number N_{ox} is given by an empirical fit to published test results in literature [4, 6, 7] for a similar coating system:

$$N_{ox} = \left[\frac{C_4}{C_1\, t_h \exp\left(\frac{-Q}{RT}\right)}\right]^{\frac{1}{C_2 + C_3 \exp\left(\frac{-Q}{RT}\right)}} \tag{10}$$

where C_i, are coating material parameters, and other parameters t_h , R and T were defined above.

In the latter model, the value D_{OX} of cyclic oxidation damage is given by the ratio between the exposure time t and the time t_{ox} to the end of coating life (i.e. when coating aluminium content decreases to the value of the base material):

$$D_{OX} = \frac{t}{t_{ox}} \tag{11}$$

The value of t_{ox}, function of a great number of parameters, has been evaluated by means of a computer code [15] for several operating conditions; in LMS code data bank, the coefficients of a surface interpolating those t_{ox} values are stored.

Also for cyclic oxidation the total damage is the sum of damages due to different load cycles:

$$D_{OX} = \sum_i D_{OX,i} \tag{12}$$

THE LIFE MANAGEMENT SYSTEM COMPUTER CODE

The LMS software was developed since the beginning as a small, flexible and self-contained software package for a personal computer, allowing efficient answers for any wish of scenarios asked by the user. Therefore it is running fast and providing great steps of view, based on a huge amount of pre-existing knowledge and calculations. Such characteristics are provided by two features.

First of all, as already mentioned, the LMS software does not carry out any aerothermal or structural analysis to determine the needed values of temperature, stress and strain at every point in the component; all such analyses were indeed made previously, during extensive simulations and modelling of several transients and steady-state operations; only their final results are stored in the LMS software. Moreover, in the code data bank also all needed material parameter values, temperature dependent, are contained.

Second, due to the wide variability of real operations, a scheme was adopted allowing a simple classification; not only simple for the subsequent analysis by the LMS software, but also simple for the realistic possibility of the plant user to have the needed records of the operational data available. The simplifications here adopted were the following:

- only two types of start up modes do exist, “Normal” (as prescribed in the machine manual of operation) or “Fast” (accelerated);
- similarly the shut downs can be “Normal” or “Fast” (trips).

When starting an analisys, the LMS software asks the user to choose a machine type, a component in it (first stage blade, vane, ...) and other data like new or refurbished material, coating type, and so on; all available component/material combinations are shown to the user by means of a tree view. In the current version, the software contains data and damage coefficients suitable for life analysis of first stage blades of two GTs, Fiat-Westinghouse TG50D5 and GE MS9001E; however, thanks to code modularity, as long as additional GTs and/or components will be investigated leading to the necessary algorithms matched to their characteristics (blade geometry, aerothermal conditions, stress-strain patterns, materials strength characteristics), the code will be easily implemented for such

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additionals too.

Then the operational history is requested to be entered by the user:

- the past operation, in terms of percent normal transients and trips, percent of weekly operation ($t_h \cong 100$ hr) or daily ($t_h \cong 15$ hr), and so on, to be considered for the computation of the accumulated damage amounts (fatigue, creep and cyclic oxidation);
- the planned scenario of future GT utilisation, in a form quite similar to one for the past operation (daily, or weekly, etc.), in order to evaluate damage accumulation rates specific for the planned future use.

Two options are available for planned future use: the user may wish to request the needed operational life up to the accumulation of a selected amount of component damage (e.g. up to a total damage of 100%, or coating damage up to 90% still suitable to allow blade refurbishement, any sort of special damage...), or may wish to insert a desired plant operation period, and asking therefore what would be the damage accumulated in that period (this would be typically the residual component life, or the interval up to next planned inspection during a major overhaul for maintenance).

Damage analysis results are provided by the LMS software in three formats:

A) a simple text page with a summary of input data and of most relevant output results, namely the maximum levels of damage (creep, fatigue, cyclic oxidation, and total summed damage contributions) and the estimated remaining life for safe operation;
B) detailed information in tabular form (a bit massive, so tedious to consult, essentially intended to allow special careful views when needed), presenting the values of the temperature, stress, strain, damages, etc., for each individual position in the component (the several nodes in the finite element mesh);
C) dynamic graphical view of the component, in which the levels of the several quantities (e.g. the stresses, or the temperatures, or the cyclic oxidation accumulated damage, ...) are displayed by means of iso-curves (in “banded form”, i.e. with regions between two iso-curves filled with a solid color).

When using graphical output, view of turbine component can be panned, rotated and zoomed simply by dragging the mouse; also is available an option to query all input and output data in a single point of the component by clicking in the desired position.

CODE VALIDATION

The code validation was possible using several failure analysis studies performed on first stage blades in the first years of operation of the gas turbine fleet, before that the LMS system could be realised. In such studies metallographic analyses were performed on sections of the blades at different blade heights. Both optical microscopy and scanning electron microscopy and EDS (energy dispersive spectroscopy techniques) were used to evaluate coating damage and base material ageing (γ’ coarsening and oxidation/corrosion). Among the different NDT techniques used in evaluating the blade after operation or during outages the F-SECT (frequency scanning eddy current technique [16]) resulted to be very powerful in measuring both coating thickness and coating damage.

Table 1 – Case histories for CESI LMS validation.

Case History	Turbine Inlet Temperature	N° of start-ups	Trips %	Total firing hours	Mean hold time
1	Design	180	5	19800	110
2a	Design	480	10	14200	29
2b	Design	650	10	15500	24
3	Design+50°C	450	40	8800	19

Table 2 – Damage levels evaluated with CESI LMS for case histories in Tab. 1.

Case History	Damage level (%)		
	Fatigue	Creep	Cyclic Oxidation
1	24	18	80
2a	43	12	74
2b	54	14	84
3	59	8	81

In the following some applications of the code are described; the respective operating conditions introduced into the input screen of the LMS code are shown in Tab. 1, while summaries of analyses results (maximum value of each type of damage, usually happening at different positions on the component) are reported in Tab. 2. These are calculated with a mean value of coating thickness of 200 µm for case 1 (original new blade), while a mean coating value of about 170 µm was used for the other cases (refurbished blades), because this was the typical minimum thickness of the coating, measured in the hottest regions the by F-SECT technique in the coating shop.

CASE HISTORY 1

This case history is representative of a TG50D5 turbine normal operating period with a prevalence of weekly operating cycles. The MCrAlY coating was produced by the OEM.

As shown in Tab. 2, the creep damage level is generally rather low, as expected, while the coating life (Fig. 1) is near its end along the leading edge and on a small region of the pressure side, near the trailing edge and at mid height of the blade probably because of lower cooling as holes start to be placed only along one row instead of two. It can be noticed that these are the hottest zones of the calculated temperature distribution of the component (shown in Fig. 2). Secondly a considerable thermo-mechanical fatigue damage is found at the platform edge in a particular position of the suction side (Fig. 3); relevant TMF damage is also observed along the leading edge.

The analyses performed by NDTs on operated components showed that in the regions indicated by the code actually the coating was exhausted (very low equivalent beta thickness obtained by measurement with the F-SECT system) in about 85% of the blades. A confirmation of the code results came also by residual stresses measurements performed on the component: significant tensile stress values were measured in the region of

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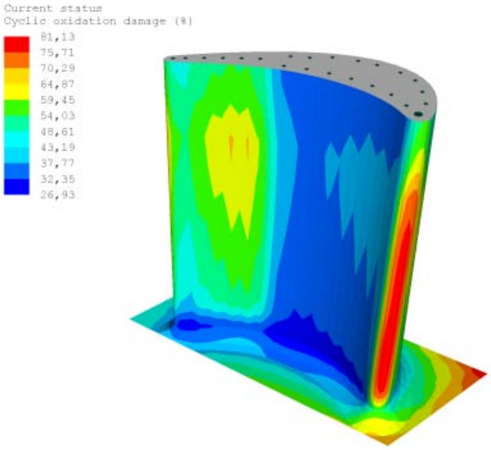

Figure 1 – Case history 1: distribution of cyclic oxidation damage.

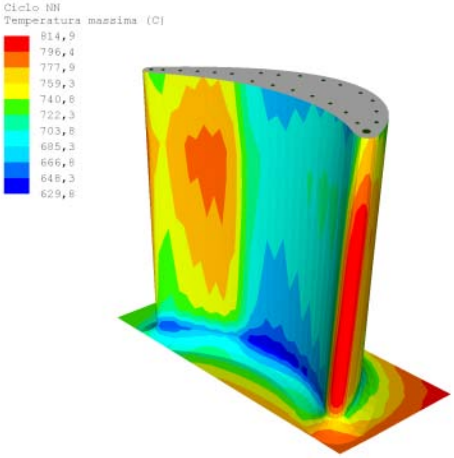

Figure 2 – Case history 1: distribution of steady-state temperature.

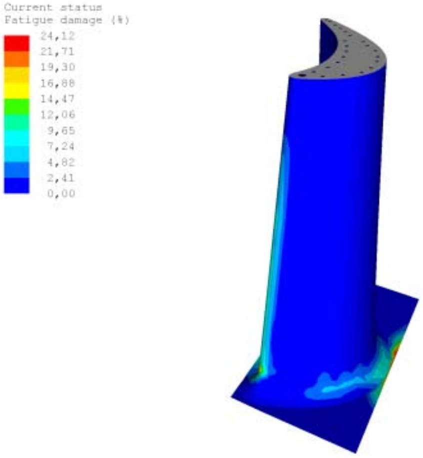

Figure 3 – Case history 1: distribution of thermo-mechanical fatigue damage.

the platform around the position where the code indicates relevant thermomechanical fatigue damage. Moreover the calculated plastic deformation levels and measured residual stresses gave the explanation of some accident (stress corrosion cracking of several millimetres) happening during the stripping process when this was performed without a previous solution heat treatment [14].

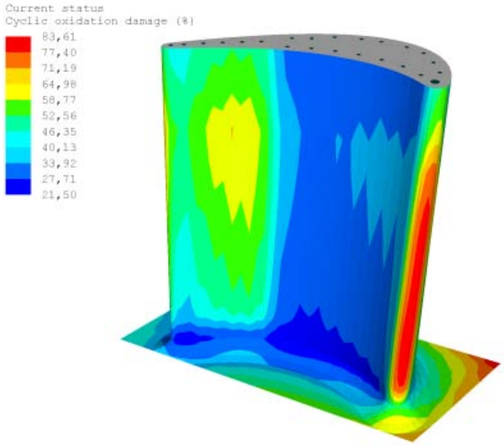

Figure 4 – Case history 2: distribution of cyclic oxidation damage.

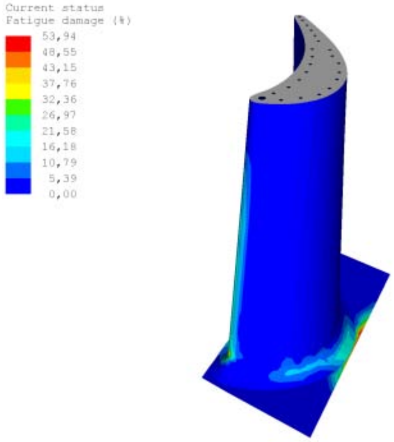

Figure 5 – Case history 2: distribution of thermo-mechanical fatigue damage.

CASE HISTORY 2A AND 2B

Some GTs of the fleet were operated cycling more often (almost daily), so that the maximum equivalent operating hours (EOH) value indicated by the OEM was reached with about 14000÷15500 firing hours and about 500-650 start-ups (see Tab. 1).

As shown in Tab. 2, in these cases the creep damage level is even lower than in the previous case, as expected due to the lower firing hours, while the coating life is near its end in regions located along the leading edge and on the pressure side (similar positions as in the previous case where cooling is reduced from two to one row of holes – Fig. 4).

At the platform edge in the position of the suction side previously noticed, the thermo-mechanical fatigue damage was about 50% (indication of possible crack presence – Fig. 5).

One blade (case 2A) was analysed with F-SECT in several positions and after that sectioned to perform metallography; F-SECT results, shown in Fig. 6, confirm the level of coating damage calculated by the LMS. The comparison between Fig. 4 and Fig. 6 shows an interesting agreement between the coating damage level evaluated by the NDT technique F-SECT and the damage calculated by LMS:

- in positions 1 and 15 the coating is still protective (β phase

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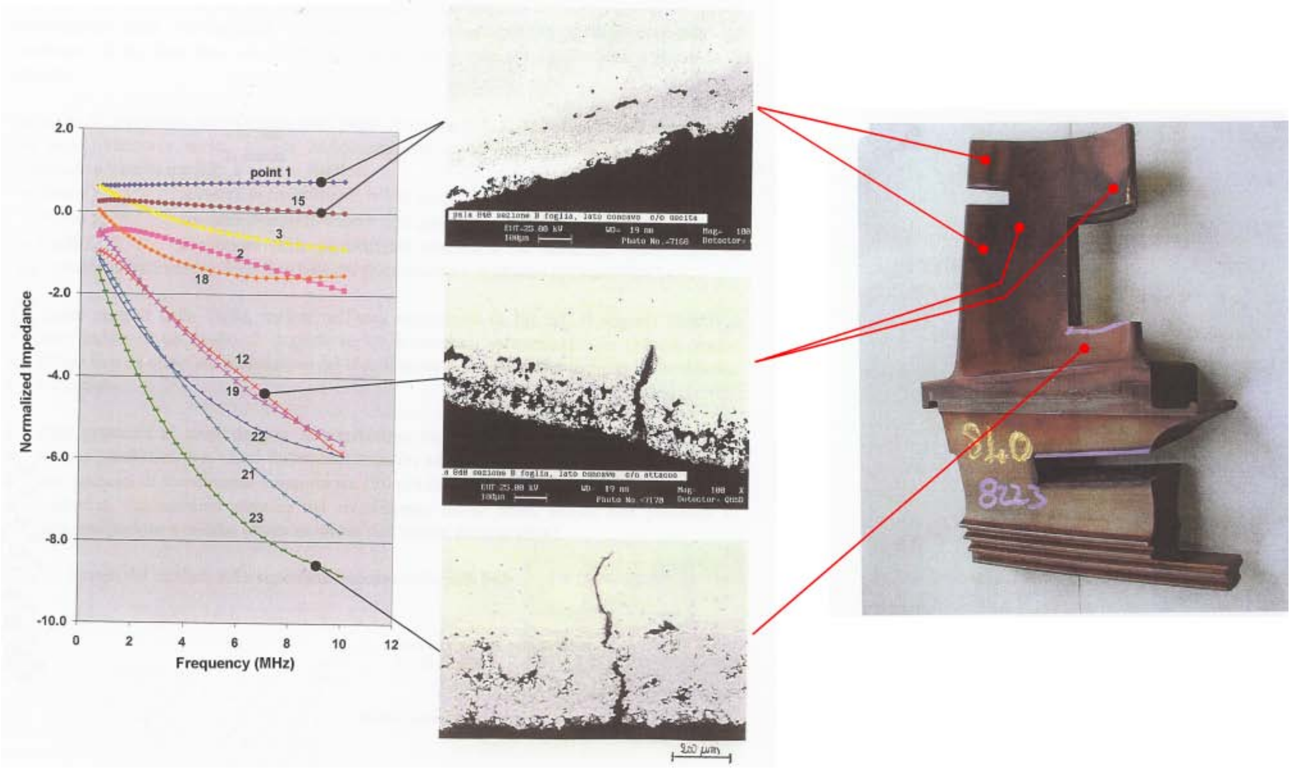

Figure 6 – F-SECT results for blade of case history 2A in Tab. 1.

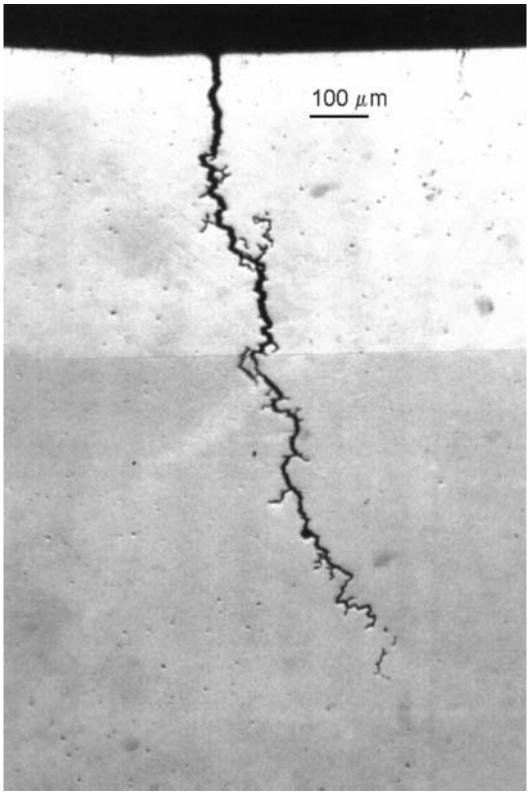

Figure 7 – Long intergranular stress corrosion cracks at platform edge of blade of case history 2B in Tab. 1 (see Fig. 8).

is present) and the code evaluates about 50% of residual life;

- in the hottest positions (e.g. 12, and towards the leading edge) the coating is thin, no more protective and also base material is damaged;
- near the platform (position 23) the coating is present but no more protective.

Figure 8 – Position of platform crack shown in Fig. 7.

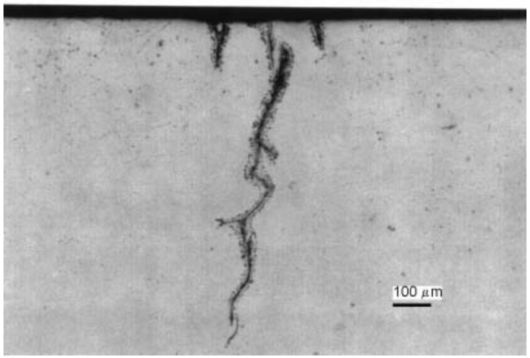

Figure 9 – Transgranular cracks at platform edge on blade of case history 2B in Tab. 1.

Moreover the critical root position was analysed. Very tiny transgranular oxidised cracks (some tenth of millimetre deep)

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Figure 10 – Case history 3: cyclic oxidation damage on mounted first stage blades, leading edge side.

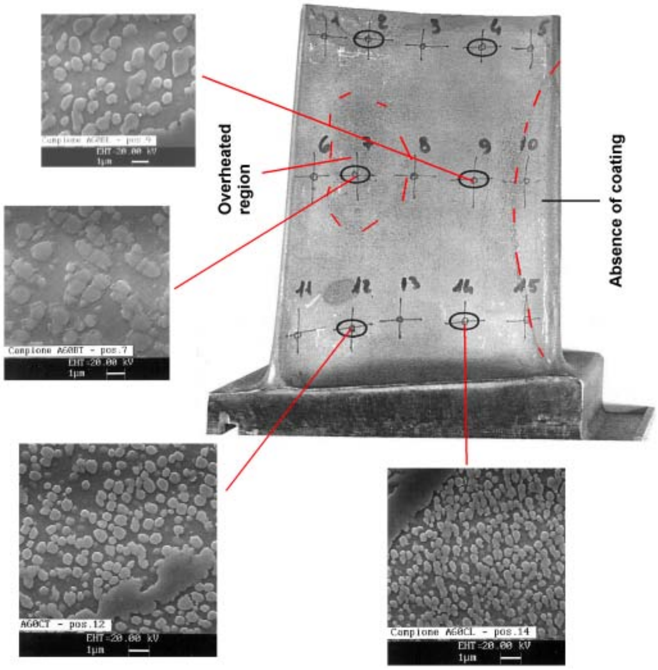

Figure 11 – Case history 3: damage on first stage blades.

could be actually found. It must be noticed that usually such cracks are too small to be detectable with NDTs on the operated and sand blasted blade during the inspection for deciding component repairability after operation.

On some blades of case 2B (sent to refurbishment after the operation period) unacceptable platform cracks (longer than 2 mm) were found after stripping as shown in Fig. 7. Careful metallographic examination demonstrated the presence of pre-existent small transgranular cracks due to thermo-mechanical fatigue (Fig. 9). This finding validates code calculations.

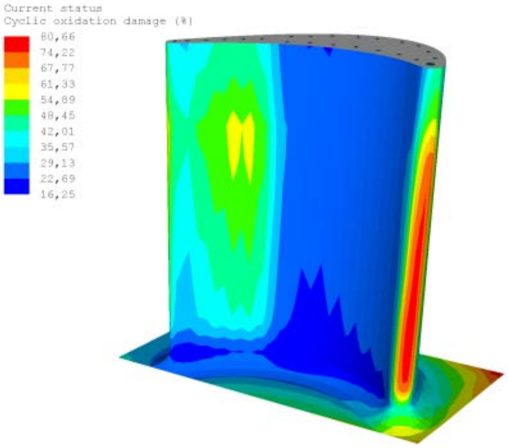

Figure 12 – Case history 3: distribution of cyclic oxidation damage.

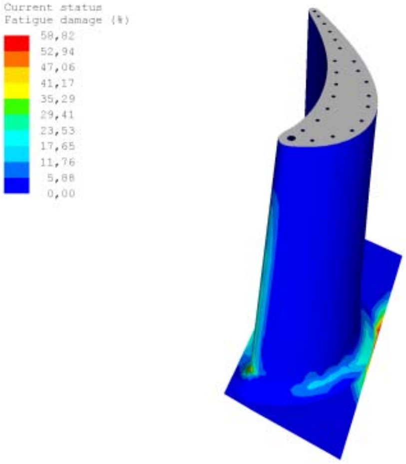

Figure 13 – Case history 3: distribution of thermo-mechanical fatigue damage.

CASE HISTORY 3

The third case is related to an abnormal operating period, with a lot of component scrapping due to heavy damage of the coating, its complete failure and hot corrosion damage of the base alloy at the leading edge and on the pressure side (see the blades as operated and still mounted in Fig. 10). This happened at the beginning of the plant history, trying to reach the nominal efficiency levels and when the LMS code was not yet prepared.

Destructive metallographic examinations were performed on two scrapped blades (sections at 10%, 50% and 90% of blade height). The coating was absent in two regions outlined in Fig. 11 (blade surface appearance after sand blasting). In the same picture examples of γ' morphology at different locations are shown: based on the measure of the γ' particle size and the reference curves of γ' coarsening versus temperature and time for UD 520 alloy [21] the evaluation of the operated metal temperature was performed. In the hottest regions of the blade an over temperature of about 50°C was estimated.

The code shows that actually the component life is passed over both for the cyclic oxidation and the fatigue damage mechanisms, even if in different regions. The damage maps are shown in Figs. 12-13. The comparison between Fig. 12 and the picture of the real component (Fig. 11) demonstrates a very

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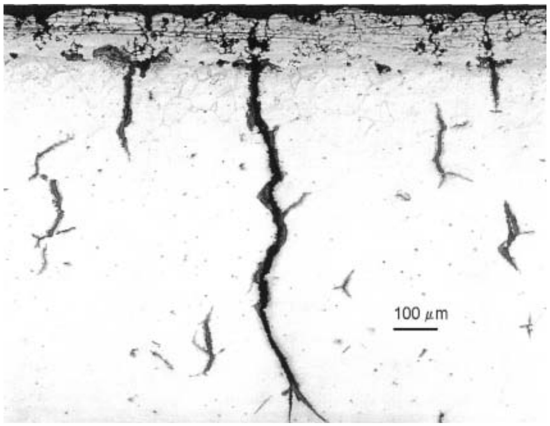

Figure 14 – Case history 3: platform TMF cracks at the same location where maximum fatigue damage is shown in Fig. 13.

good agreement between real and calculated damaged regions in the hottest zones of the component airfoil (pressure side) and at the leading edge. Some cracks were also found in some components at the platform edge in the same position of the suction side (see also previous cases) as shown in Fig. 14 for this case.

DISCUSSION

Currently the LMS developed at CESI is still in the validation phase, i.e. it is intended that a number of details will be checked and progressively optimised by the feedback from experience gained in actual damage findings on service exposed GT components. Nevertheless, from the comparative analyses of predicted and actual damage amounts obtained in this paper, the prediction capability seems quite significant already at this stage. It has to be pointed out that creep and cyclic oxidation damage models are to be regarded as reasonably well established. On the other hand, the larger uncertainties might be expected within the TMF damage prediction part, as the TMF strength model presently included in the LMS software was determined from a limited source of TMF data, from tests carried out at CESI in a previous programme. As in that experiments no account was made for investigating hold time (t_h) nor strain ratio (B) effects, the numerical coefficients for such terms in Eq. (2) above for TMF life evaluations were not available for our alloy U520, and had to be taken identical to those reported in the EPRI [3], for another Ni-base alloy, in non coated condition (as most TMF cracking evidence were found in non coated parts of the blades investigated). Predicted results were not bad in our TMF analyses, but clearly an experimental programme devoted to define the t_h and B dependence of the TMF damage equation specifically for the alloy here considered, U520, is intended to remove this marginal lack of knowledge.

The LMS here developed was targeted to the main damage mechanisms for the first blades row in industrial gas turbines. Extending this package to other hot-parts would appear a useful development. However this would require consideration of different damage phenomena not addressed here, e.g. aerothermal and mechanical vibrations which are often important for last stage rows blades performance.

CONCLUSIONS

The two tools (LMS and F-SECT technique) can be used together in a complementary and collaborative way to optimise GT maintenance policy (costs minimization and efficiency increase).

The capability of the LMS system coming out of the previous section can be summarised in the following:

A) prediction of different levels of cyclic oxidation and fatigue damage associated to different GT operation regimes (weekly, daily, ...);
B) evaluation of life reduction (for thermo-mechanical fatigue) due to an unexpectedly high number of trips;
C) residual life estimation for the actual conditions which the plant was operated in.

Most of all, the system is able to indicate the most critical locations on the components for each damage mechanism; this information can be a useful guide in several occasions:

- during quality control of the coating process, it allows a better choice of locations where the F-SECT measurements must be done to assure that a sufficient compact coating thickness is present;
- during plant stops those critical positions will be more carefully observed by visual inspections and premature damage discovered;
- during the scheduled maintenance stops (open turbine case) the F-SECT control of the coating degradation by cyclic oxidation can be more effectively concentrated on the most critical positions;
- decision to send components to refurbishment can be better supported by the use of code calculations and experimental measurements by F-SECT.

The experience done on the old machines analyzed in this paper give a strong indication of how useful such a versatile LMS system can be and that it can be worth to afford the big effort required to extend such methodology to the latest generation GTs.

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