LIFE MANAGEMENT SYSTEM FOR HOT-GAS-PATH COMPONENTS OF GAS TURBINES

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ABSTRACT
Recently the number of gas-turbine-powered combined-cycle plants has been increasing because of their efficiency and environmental compatibility. Gas turbine operating conditions are severe, especially for hot-gas-path components. To improve the reliability of such components and to extend their life, we have developed a life management system based on a residual-life-assessment method. The system makes possible integrated residual-life-assessment based on numerical analyses, material destructive-tests, nondestructive inspections, statistical analyses of field machine data, and the use of a database. To develop the system, the primary damage mechanism for each component is clarified and material degradation is evaluated. For nozzles, the system describes a method of predicting the maximum surface crack growth. The validity of the methods is verified by assessment of the inspection data. This paper also describes optimization of operating cost and RAM (reliability, availability and maintainability).

INTRODUCTION
Most of newly built fossil fuel power plants are combined-cycle plants, a configuration chosen because of its efficiency and its compatibility with the environment. Several of the hot-gas-path components within a gas turbine, such as the combustion devices, nozzles, and buckets, operate under particularly severe conditions caused by high gas turbine inlet temperatures and frequent startups and shutdowns. These conditions can damage strong Co-based and Ni-based superalloys usually used for these components. To reduce maintenance costs and to reliably operate gas turbines, residual life assessment methods that estimate component damage are required.

This paper therefore describes a life management system for improving the reliability of the hot-gas-path components of gas turbines and extending their life. The system is based on the residual-life-assessment methods using a database and it recommends optimal maintenance procedures and scheduling. The system consists of numerical analyses, material destructive-tests, nondestructive inspections, statistical analyses of field machine data, and the use of a database. It makes possible integrated residual-life-assessment based on results of these residual life assessment methods and, it can also be used widely with an Internet browser over an Intranet.

CONFIGURATION OF LIFE MANAGEMENT SYSTEM FOR HOT-GAS-PATH COMPONENTS
Figure 1 shows the system configuration of the life-management system for gas turbine hot-gas-path components. This system consists of a man-machine-interface subsystem, residual-life-assessment subsystems, a database, an integrated residual-life-assessment subsystem, and a life management subsystem. Some features of the system are described below.

In the man-machine-interface subsystem, the hot-gas-path components of interest can be selected, using indexes of the gas turbine machine name, plant name, and so on. The life management system makes possible integrated residual-life-assessment consisting of residual-life-assessment based on analysis, field data, sample tests, and a database. In the residual-life-assessment based on analysis subsystem, a component residual life is calculated using numerical damage estimation models that describe the damage mode and using a finite element analysis that calculates the metal temperature and stress. In the residual-life-assessment based on field data subsystem, the...
records of crack length, deformation, and so on, which are collected in the database are analyzed using statistical methods. This subsystem gives the damage tendency curve which is derived from regression. In the residual-life-assessment based on the sample-test subsystem, material degradation information for the operation is derived from results of testing a few sample components extracted from gas turbines.

The residual-life-assessment subsystems calculate the lifetimes of the hot-gas-path components. The integrated residual-life-assessment subsystem then synthesizes the results and estimates the life of the component more accurately than by a single residual life assessment method. All the results are accumulated in the database.

In the life-management subsystem, maintenance optimization is surveyed by varying some parameters that affect the life span of the component.

The system hardware configuration is shown in Fig. 2. The system is a client-server system, and the client can use it with browser software, over the Internet and Intranet. This system consists of two servers. One is a web server for control, display and database. The other is an analysis server which has residual-life-assessment programs, a statistical-analysis program, and a life management program. Client 1 has only a browser software and can do basic analysis of the system. The system supports maintenance planning. Client 2 has a browser and analysis programs and can do further analysis. The system supports R&D users for life extension study. Client 3 has browser and field data input program and can accumulate field data in the database. The system supports field service users for data storage.

EXAMPLE OF APPLICATION TO FIRST-STAGE NOZZLE

The system was applied to the life management of gas turbine first-stage nozzles. The first-stage nozzles are exposed to the hottest part of the gas stream in the turbine and thus require forced cooling. The temperature gradient generated in the cross-section of the airfoil causes thermal stress, which is repeated at the startups and shutdowns. The nozzles often crack because of the thermal stress, as shown in Fig. 3. Cracking is considered to be their principle damage mode because crack penetration leaks cooling air in the nozzles and raises their metal temperature causing their failure. Therefore the damage and the residual life of the nozzle were evaluated by using the crack growth behavior.

Prediction of the crack growth in crack depth is important in assessing the residual life of the nozzle airfoil section. Currently, total crack length is used as a criterion for nozzle repair, but penetration of even one crack in the thickness of the airfoil cross section would reduce the reliability of a nozzle. Consequently, the maximum crack depth is a more appropriate parameter for estimating the damage in nozzles than is either the total crack length or the crack density. We developed a crack growth prediction method by applying fracture mechanics and a simplified thermal stress distribution model.
Man-machine Interface

The initial system displays are shown in Fig. 4. The man-machine interface is consisted of GUI (Graphical User Interface) using HTML (Hypertext Markup Language) and easy to operate. The system for the nozzle starts after a click at the nozzle button. The nozzle of interest is selected from the database relating with plant name, gas turbine name and so on.

Residual Life Assessment Based on Analysis

The residual life assessment based on the analysis subsystem is consisted of FEM thermal-structural analysis and a fracture mechanics model as a damage estimation as shown in Fig. 1. Initial crack lengths are derived from crack-length records made at the latest scheduled inspection in the database. As shown in Fig. 4, the nozzle is divided into 16 portions, like airfoil portions, outer wall portions and inner wall portions. Crack growth records for each portion are summarized. The longest crack in each portion was chosen from the database as initial crack for the fracture mechanics analysis.

A stress range for the fracture mechanics model is derived from a 3D FEA (Finite Element Analysis) model which described a gas turbine operation cycle from startup to shutdown. A typical Mises equivalent stress distribution is shown in Fig. 5. High stresses appeared at the junction between an airfoil and the end walls shown as bright pattern. A typical temperature-versus-stress profile for the nozzle is also shown in Fig. 5. The stress range between steady state and shutdown is considered to propagate cracks.

The maximum stress range in each portion is applied to the fracture mechanics model. The crack is assumed to initiate at the point of maximum stress in each portion. A stress distribution in thickness is approximated using a following quadratic equation derived from an analytical thermal stress equation and the FEA results.

\[ \sigma = \frac{\sigma_0}{1+n} \left[ \left( 1 - \frac{x}{t} \right)^2 + n \right] \]  

\( \sigma \): Nozzle wall stress,
\( \sigma_0 \): Nozzle wall stress at outside surface,
\( x \): Distance from nozzle outside surface,
\( t \): Nozzle wall thickness,
\( n \): Shape factor

Fig.3 Thermal fatigue cracks in a nozzle

Fig.4 Display examples of system

Fig.5 Stress distribution and profile
The fracture mechanics model is described as a following equation. An acceleration factor due to the effect of creep during operations is taken into account as a factor $C_1$. Material degradation after a weld repair is also applied to a model as a factor $C_2$. Both factors are derived from the crack growth records in the database by using approximation with minimum residuals. The factors for the best-fit curves of the crack growth behavior are derived, using the crack-length records, from statistical regression analyses.

$$\frac{da}{dN} = (C_0 \cdot C_1 \cdot C_2) \cdot \Delta J^m$$  \hspace{1cm} (2)

$a$: Crack depth, $N$: Cycles, $\Delta J$: J-integral range, $C_0$, $m$: Material properties, $C_1$: Acceleration factor due to creep effect $C_2$: Acceleration factor due to material degradation

The model assumes semi-ellipse shaped cracks, and shape factors are derived from the Raju-Newman's equation. J-integral ranges are calculated using the following Buchanet and Bamford's equation. Crack propagation in the depth and on the surface is calculated.

$$\Delta J = \frac{(\Delta \Delta K)^2}{E}$$

$$K = \sigma_e \sqrt{\frac{K}{a}} \left[ A_0 F_0 + 6.37 A_1 F_1 + 0.05 A_2 F_2 \left( \frac{a}{t} \right)^\gamma \right]$$  \hspace{1cm} (3)

$\Delta K$: Stress Intensity factor range, $A_0, A_1, A_2$: Factors derived from stress distribution, $F_0, F_1, F_2$: Shape factors

A crack growth analysis result is shown in Fig. 6. The vertical axis shows crack depth and the horizontal axis shows life fraction $N / N_{fp}$. The $N_{fp}$ was the number of cycles of a crack penetration which was calculated using the model. The solid line is the calculated crack growth curve. Markers show the maximum crack depth in field inspection data. The crack depth was calculated from crack lengths in the inspection record and a relationship between crack depth and crack length on the surface that was derived from inspecting scrap nozzles. The analysis results agreed with field inspection data within a factor of 1.2. Thus a model that can predict the residual life of the nozzles was established.

Residual Life Assessment Based on Field Data

In the residual-life-assessment subsystem based on field data, the best-fit curves of the crack growth behavior are derived, using the crack-length records, from statistical regression analyses. The best fit regression curve can predict crack propagation with extrapolation. The variation in the maximum crack length and crack density of the nozzles, in relation to the number of startup and shutdown operations, is shown in Fig. 7. These results were obtained by the inspection of a 25-MW-class gas turbine. The maximum crack length and crack density increase exponentially, and the trends of both plots show certain strong similarities.

The subsystem can also apply some statistical distributions such as normal distribution, log normal distribution and Weibull distribution and predict crack growth curves with a confidence level. The subsystem can also predict maximum crack length from partial inspection records by using statistical extremes analysis.
Residual Life Assessment Based on Sample Test

In the residual-life-assessment subsystem based on sample tests, a critical crack length is calculated from material small-punch (SP) test results. To evaluate the degradation of the nozzle material, we conducted the SP tests. The test apparatus is illustrated in Fig. 8(a). A 10 × 10 × 0.5-mm test piece was extracted from the nozzle surface, placed in a die, and punched out with a puncher. The small-punch fracture energy is defined as the area between the load-displacement curve and the maximum load value.

The variation in the small-punch fracture energy and crack density, relative to the operation time, is shown in Fig. 8(b). A rapid increase in surface crack density occurs when the fracture energy saturates. This increase suggests that material degradation occurs at the surface of the nozzles. The variation in the fracture energy shows a good correlation with the crack density. Consequently, the small-punch test is appropriate for evaluating the material degradation of nozzles.

A decrease in the SP energy indicates embrittlement of the material. The relation between the decrease in SP energy and the fracture toughness was assumed to have following linear relationship.

\[
a_{cr} = a_{cr0} \cdot \frac{Esp}{Esp_0}
\]

\[
Esp = Esp_0 \cdot \exp(D \cdot t)
\]

\(a_{cr}\): Critical crack depth,
\(a_{cr0}\): Critical crack depth of unused material,
\(t\): Time, \(Esp\): SP energy,
\(Esp\): SP Energy of time, \(t\),
\(Esp_0\): SP Energy of unused material,
\(D\): Coefficient derived from regression

Integrated Residual Life Assessment

The integrated residual-life-assessment subsystem synthesizes the crack-growth curve by using the crack-growth curve of the fracture mechanics model and the field crack-growth records. The subsystem estimates the residual life of the nozzles by using the crack-growth curve and the critical crack length derived from the residual life assessment based on the sample test subsystem. The residual life is estimated as number of operations when the calculated crack depth reaches the critical crack depth. A example of results is shown in Fig. 9.

Fig. 9 Display of integrated residual life assessment.
**Life Management**

In the life management subsystem, the optimal maintenance and operation are investigated by varying such factors as operation conditions, the intervals of scheduled inspections, replacement, cooling, and so on. An example of results is shown in Fig. 10. The vertical axis shows residual life of the nozzle, which is described by a margin between the crack depth and the critical crack depth. The horizontal axis shows use time. The conventional maintenance replaces the component every scheduled maintenance. The recommended maintenance using the system can extend the life of the component. The system can support optimal maintenance scheduling.

![Fig.10 Display example of life management.](image)

**SUMMARY**

1. We have developed a life management system for hot-gas-path components. The system makes possible integrated residual life assessment by the use of numerical analyses, material destructive tests, nondestructive inspections, statistical analyses of field machine data, and a database.

2. We have applied the system to first-stage nozzles and to the investigation of maintenance optimization.

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**REFERENCES**


