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DAMAGE IN HIGH TEMPERATURE COMPONENTS AND THE LIFE ASSESSMENT TECHNOLOGIES

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ABSTRACT

Damage modes of steam turbine and gas turbine components are summarized and life assessment methods based on damage measurement are presented. For steam turbine high temperature components, typical damage modes are creep, thermomechanical fatigue(TMF) and creep-fatigue, which are enhanced by material degradation. For gas turbine high temperature components, the same damage modes are observed, coupled with severe oxidation, corrosion, erosion, wear and microstructural change than steam turbine. The damage-based life assessment approaches are 1)Trend analysis, 2)Cumulative damage rule, and 3)Damage parameter and simulation analysis. Trend analysis correlates damage data with operation history to obtain damage trend curves. Cumulative damage rule is modified to reflect the effect of material degradation in the material life prediction. Damage parameters are selected to be consistent with physical quantities, and are correlated with imposed cycle/time as well as the stress/strain. Damage simulation analysis is used for validating the damage model and predicting the future trend. Those approaches will contribute to the condition-based life management or risk-based maintenance because the plant specific and probabilistic assessment can be accomplished.

KEYWORDS

Damage, Degradation, Steam turbine, Gas turbine, Creep, Fatigue, Life assessment

INTRODUCTION

As the number of fossil power plants in long-term use increases, demand for life extension and cost-effective maintenance is becoming greater. Accurate life assessment methods can provide a basis of realizing rational maintenance and life management. Thus, various kinds of life assessment methods have been proposed[1], which are divided into three categories, i.e. analytical methods, non-destructive methods and destructive methods. A comprehensive understanding of damage modes in actual components is indispensable for establishing an effective life assessment approach. Therefore, damage modes of steam turbines (including pipes) and gas turbines are summarized as the typical examples. Then, life assessment methods are presented in relation to a way of quantitative analysis of damage and degradation. They are, 1)Trend analysis, 2)Cumulative damage rule, 3)Damage parameter and simulation analysis. The importance of statistical analyses of actual damage data is demonstrated in regard to the on-conditioning life management and risk-based maintenance.

DAMAGE MODES IN STEAM TURBINE COMPONENTS

Figure 1 shows typical modes of damage and degradation in steam turbine components[2]. Steam turbine materials often show softening due to both creep/fatigue damage and thermal aging. Softening reduces material tensile, creep and fatigue strength. For high-pressure (HP) and intermediate-pressure (IP) turbine rotors, creep damage is accumulated in the bore and the dovetail hook. In the dovetail hook contacted area, creep softening reduces the fatigue strength, which leads to the high cycle or fretting fatigue under vibratory stress. Another degradation mode is embrittlement that enhances crack sensitivity. In the strain concentrations of casings and valves, cracks initiate due to TMF in the cyclic operation and then tend to grow due to creep under internal pressure. In this case, crack initiation and growth are assisted by softening and by embrittlement. For steam pipe weldments, creep damage is non-uniformly distributed depending on the microstructural inhomogeneity. In some cases, TMF cracking is experienced due to water induction from drain into the steam flow[3]. For low pressure turbine rotors, corrosion fatigue or SCC under centrifugal and vibratory stress are typical damage modes.

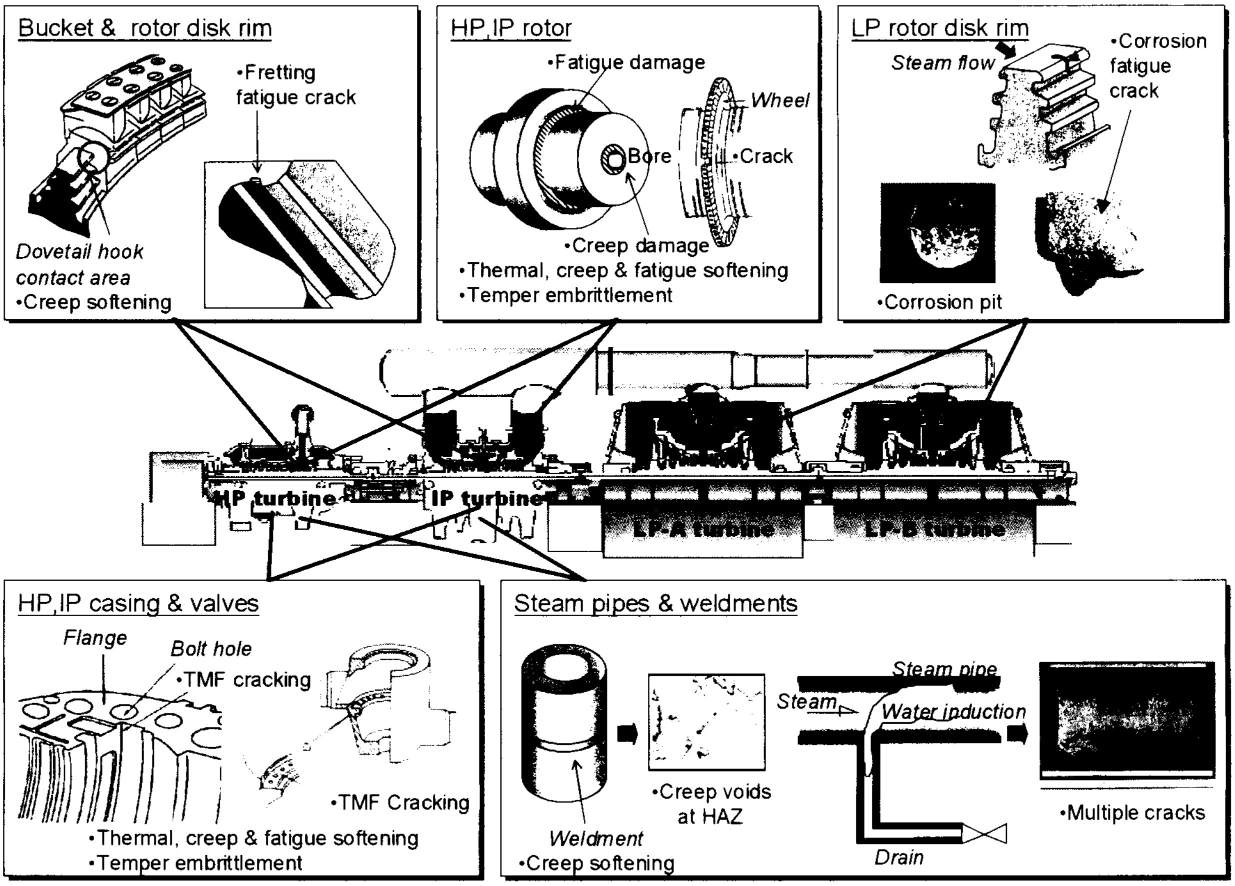

Figure 1: Damage modes of steam turbines and steam pipes

DAMAGE MODES IN GAS TURBINE COMPONENTS

Figure 2 shows the modes of damage and degradation in gas turbine components[4]. Hot gas flow may cause oxidation, corrosion and erosion depending on the gas composition and temperature. TMF is introduced during cyclic operation under severe thermal gradient due to internal cooling. Coating layer suffers from oxidation, hot corrosion, erosion, TMF cracking, spalling and degraded phase formation. If the oxides and cracks develop in the coating layer, they will grow into the substrate. For stage 1 nozzles, TMF cracking is the primary damage mode. Material degradation causes the reduction of ductility and toughness, but they can be refurbished by heat treatment. For stage 2 and 3 nozzles, creep deflection is significant. For combustion liners, TMF cracks are observed in the welded portion and sometimes grow by vibratory stress. Wear occurs in the support parts due to vibration. For transition pieces, creep deformation and TBC spalling also occur.

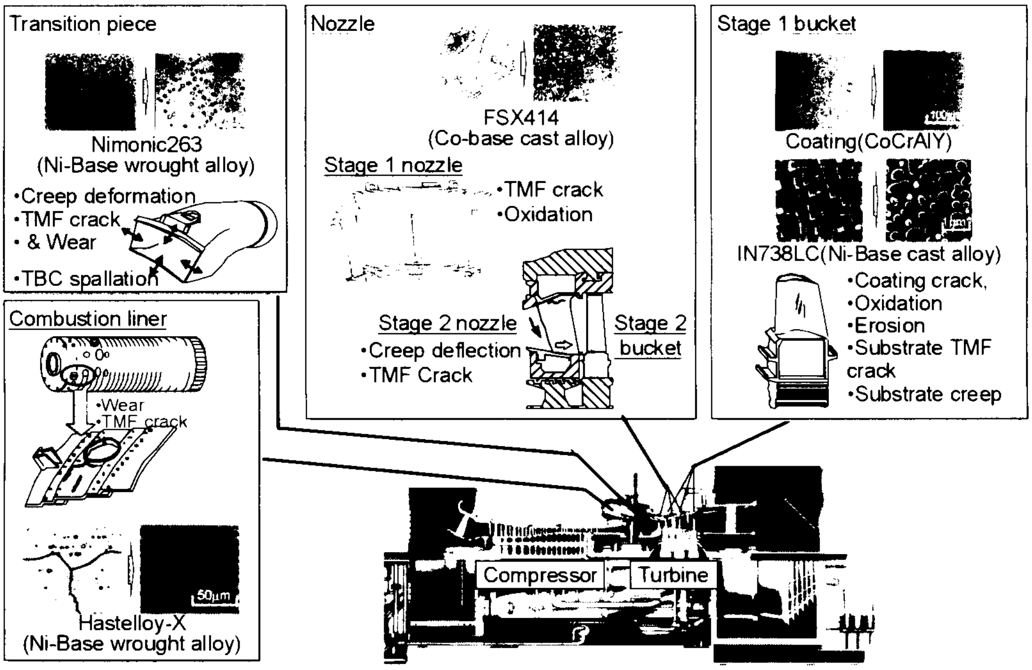

Figure 2: Damage modes in gas turbine components (1,100°C-class)

LIFE ASSESSMENT METHODS

To utilize the damage information of actual components for life assessment, trend analysis, cumulative damage rules, damage parameter and simulation analysis are implemented.

Trend Analysis

Trend analysis[4] correlates the measured damage quantities with operation history. Figure 3 shows the trend analysis flow for gas turbine nozzle vane cracks. These are the followed up data of individual cracks for periodic inspections. The maximum crack length a_{max} seems to obey the LCF crack growth law and the subsequent retardation is attributed to thermal stress relief by the cracks. On the other hand, the total crack length Σa increases monotonically with cycles. Another approach is the statistical trend analysis. As the crack length data of nozzles obey log-normal distribution, the statistics (mean, variance and number) are obtained and expressed as the functions of cycles. The maintenance management is conducted using a_{max} and Σa as the measure of structural integrity and repair amount, respectively.

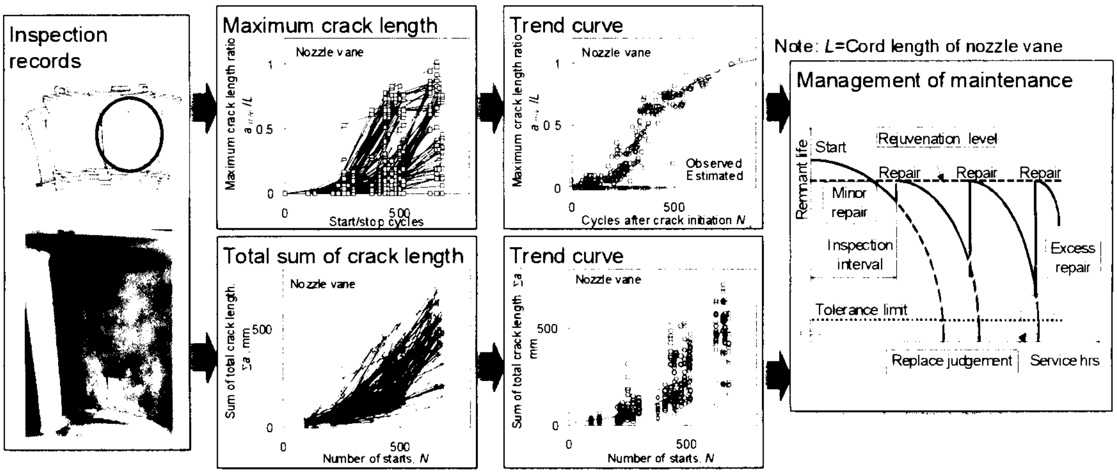

Figure 3: Trend analysis of TMF cracks for gas turbine nozzles

Cumulative Damage Rule

The conventional cumulative damage rule is described as follows.

$$\Phi_f = \sum_i \frac{n_i}{N_{fi}}, \quad \Phi_c = \int \frac{dt}{t_r}, \quad \Phi_f + \Phi_c = D_c \tag{1}$$

where, Φ_f: fatigue damage, Φ_c: creep damage, n_i: number of start-stop cycles of the operation mode i, N_{fi}: cycles to failure in the operation mode i, t_r: time to creep rupture, t: operation time, D_c: critical value of total damage. For long term operation, softening due to either thermal aging or damage may occur, which affects material life itself[2]. Figure 4 shows the modified cumulative damage rule based on hardness measurement. If the hardness HV_a is measured at the thermal aged portion, material creep life t_{ra} is estimated by HV_a. Therefore, creep damage is calculated as follows.

$$\Phi_c = \int \frac{dt}{t_{ra}(\sigma, T, HV_a(t,T))} \tag{2}$$

If the hardness HV_D is measured at creep damaged portion, HV_D represents creep damage effect and is correlated with the remnant creep life t_{rD}[5]. Therefore, the cumulative damage is calculated as follows.

$$\Phi_c = \frac{t}{t + t_{rD}(\sigma, T, HV_D(t,\sigma,T))} \tag{3}$$

Those definitions of damage should not be mixed up with one another.

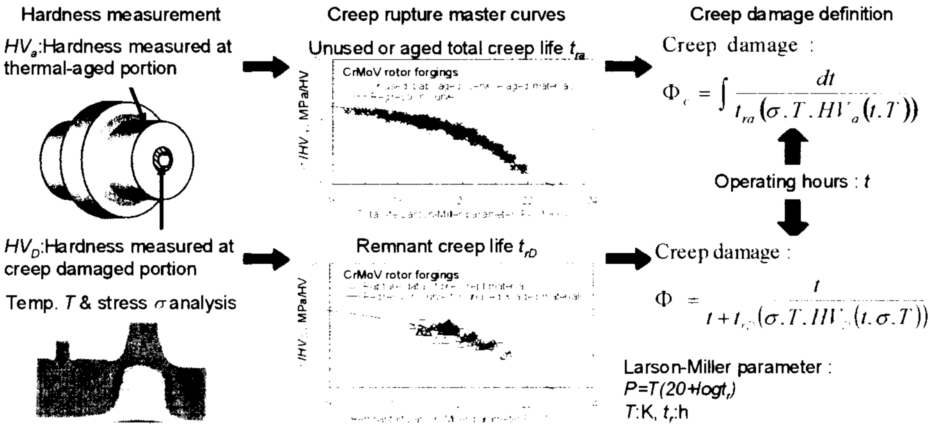

Figure 4: Cumulative damage evaluation procedures based on two cases of hardness measurement

Damage Parameter and Simulation Analysis

Parameters converted from measured physical damage are correlated with stress, strain, temperature, imposed cycles and time. The simulation analysis is used to verify or predict the damage evolution process obtained by damage parameter equations and trend analysis based on the stochastic damage model.

Fatigue damage

Figure 5 shows damage parameter evaluation for TMF cracks of gas turbine nozzle vane[4] and that of stem pipe with water injection[3], as well as the related damage simulation analysis[4]. The damage parameters selected are the maximum crack length a_{max} and the crack length density l. The damage equation for a_{max} is expressed by the following equation.

$$a_{\max} = E\exp(F\frac{N}{N_f}) \tag{4}$$

where, N is imposed cycles, N_f is cycles to failure (usually defined for 25% peak stress drop from steady-state value for LCF or TMF testing) and E,F are constants.
As l is closely related to the cumulative probability of multiple crack initiation, the damage equation is expressed by the following equation using the form of standard normal distribution function $\Phi()$.

$$\frac{l}{l_c} = \Phi\left[\left\{\ln\left(\frac{N}{N_f}\right) - \mu_{Lc}\right\}\Big/\sigma_{lc}\right], \qquad \Phi(u) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{u}\exp\left(-\frac{u^2}{2}\right)du \tag{5}$$

where, l_c, μ_{Lc}, σ_{Lc} are constants determined through the regression of experimental data. From Eqn. 4 and Eqn. 5, If we know a_{max} and l, N and N_f can be determined. The plastic strainrange $\Delta\varepsilon_p$ can be calculated from N_f by the Coffin-Manson law[1]. Simulation analysis is applied to nozzle vane cracks. Discrete mesostructure model is used for assigning material resistance distribution for the superalloy. Crack initiation, growth and coalescence process is calculated by Monte-Carlo simulation, using stochastic damage model derived from experimental observation. The maximum crack growth trend is stepwise due to crack coalescence, but is similar to trend analysis and the damage parameter approach.

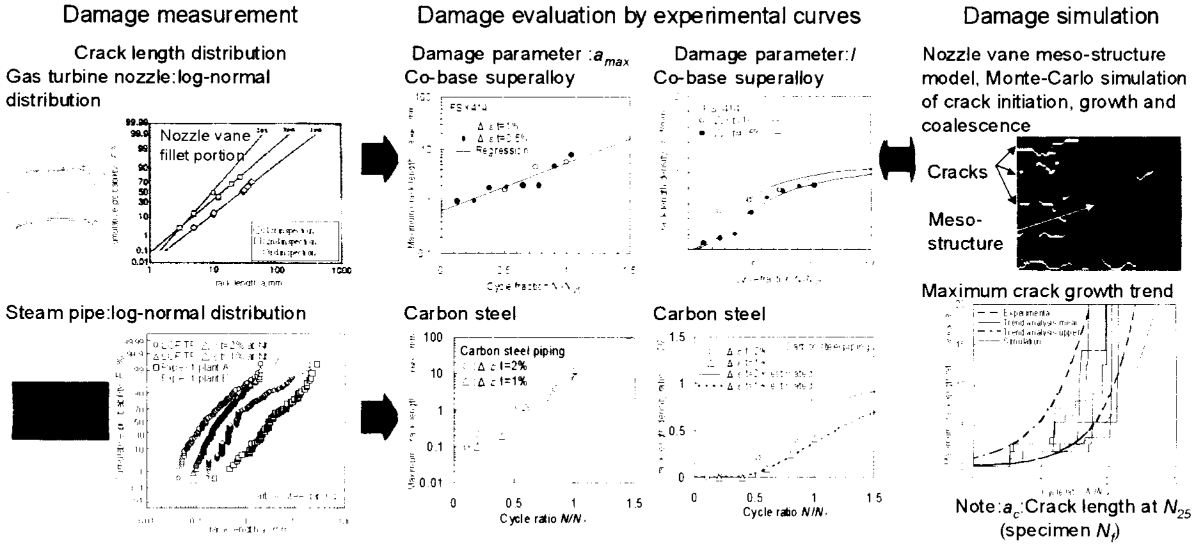

Figure 5: Damage evaluation by experimental curves and simulation analysis

Creep damage

For low alloy steels, creep damage is characterized by creep cavity formation and hardness change. Figure 6 shows the damage assessment methods for the weldment of low alloy steel piping[5]. The creep cavity A-parameter method[1] and the hardness method are applied. Softening curves have been provided for the weld portion from laboratory creep interruption testing data based on the carbide coarsening mechanism or the dislocation substructure recovery mechanism. The hardness method can be applied to the entire portion of weldments. Creep cavities are observed by scanning electron microscope for the replicas taken from actual components. Creep cavity formation depends on the material microstructure, the chemical composition (carbon contents) and the stress redistribution. These two approaches compensate each other for the creep life assessment of long term used components.

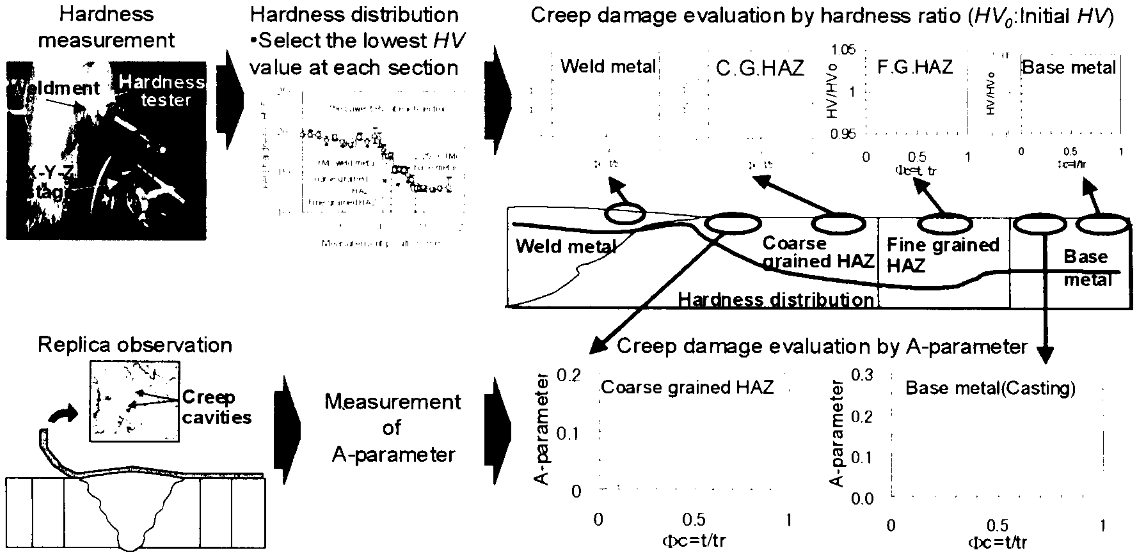

Figure 6: Creep damage assessment of weld portion of steam pipes

CONCLUDING REMARKS

It is demonstrated that the comprehensive knowledge of damage modes in actual components is effective for establishing practical life assessment methods. As the life assessment approaches presented here are based on the statistical treatment of damage data, they can be applied to probabilistic life prediction. The damage simulation analysis is a useful tool for investigating and modeling the stochastic nature of damage. Those approaches can contribute to life management and risk-based maintenance.

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