LIFE ASSESSMENT FOR HIGH TEMPERATURE COMPONENTS - TECHNIQUES AND MODELS

A .N.KUMAR
Materials Department, Riso National Laboratory
P.O.Box 49, DK-4000 Roskilde, Denmark

(On leave from Indian Institute of Technology, New Delhi)

ABSTRACT

Extension of service lives of high temperature components based on health assessment and remaining life calculation data has been a major research and field activity over the past two decades. The concern has been focused on the development of appropriate methodologies and life prediction models that may be used with reasonable accuracy to maintain safety and integrity of plant components. A multitude of models and methodologies are proposed and used in industries for various component specific applications. A review is made here on the progress of development on the subject in general. High temperature component failure mechanisms are identified to be creep, creep fatigue and thermal fatigue. The currently available techniques are empirical in nature and have achieved varying degrees of success. The potential methods demand further in-depth research to be free from some uncertainties and ambiguities as outlined.

KEYWORDS

Life assessment, creep, fatigue, damage, techniques, temperature,models.

INTRODUCTION

High temperature components in power plants and other industries experience severe service conditions which lead to accelerated degradation in structures as well as properties and premature failures. The general concern about the safety and integrity of the components in fossil fired power plants began around 1970s when their design lives were exceeded or approached. Some of these components had shown a variety of ageing effects like cracking, leaking, bursting etc. The aged and damaged components had to be replaced involving huge expenditure and unscheduled plant outageing. A number of factors, however, led the plant owners to look for an alternative solution by extending operating lives beyond nominal design period. The concept was that based on the current health conditions of the high temperature components further extension of lives may be estimated (remaining life assessment or estimation 'RLA' or 'RLE').

Extensive research and field activities started immediately in many countries to develop the appropriate technology for assessing health condition and remaining life. By 1980s all the developed nations and other countries realized the significance of the problem and extended the activities by having many national and multinational projects. Rapid progress on the subject have been made by 1990s and a multitude of models and methodologies are developed for RLA of service components. A number of review articles have been documented over the past decade(Cane and Williams, 1987; Halford, 1991; Viswanathan and Gehl, 1992; Viswanathan and Wells, 1993). The approaches and methodologies for RLE have been continuously changing at a rapid pace as the technology is advancing and with the socio economic needs. An attempt is made here to review the progress over the past decades on the subject. The failure mechanisms, various methodologies and the associated models will be discussed in general for the thermal power plant components. These may, however, be applicable to other industries involved with high temperature with suitable modifications.

AIMS AND APPROACHES OF RLA

The primary objectives of life estimation technology may include;

(a) achieve financial incentive;
(b) extend useful life by avoiding catastrophic failures and unscheduled plant outages;
(c) set the inspection schedule and guide maintenance strategy;
(d) help develop improved alloys and optimize operating parameters;
(e) bypass stringent environmental and safety regulations with new equipments.

Essentially, two different approaches are followed for RLE (Fig. 1) namely

(i) post service approach in which field components are examined and tested during plant outageing to check the extent of damage and the data is used for RLA.
(ii) plant operating history approach which integrates the component operation history with material properties to give an approximated life prediction.

A more strategic way is to combine both the approaches where former one could be applied in critical locations as may be suggested through the later one.A third approach is the reappraisal of the original design based on the experience of past plant operation and the knowledge of future plant operating conditions. The number of life prediction models and techniques developed since 1953 is found to be well above hundred (Halford, 1991). Only the currently used and potential methods would be taken up for discussions in this review (Fig. 1).

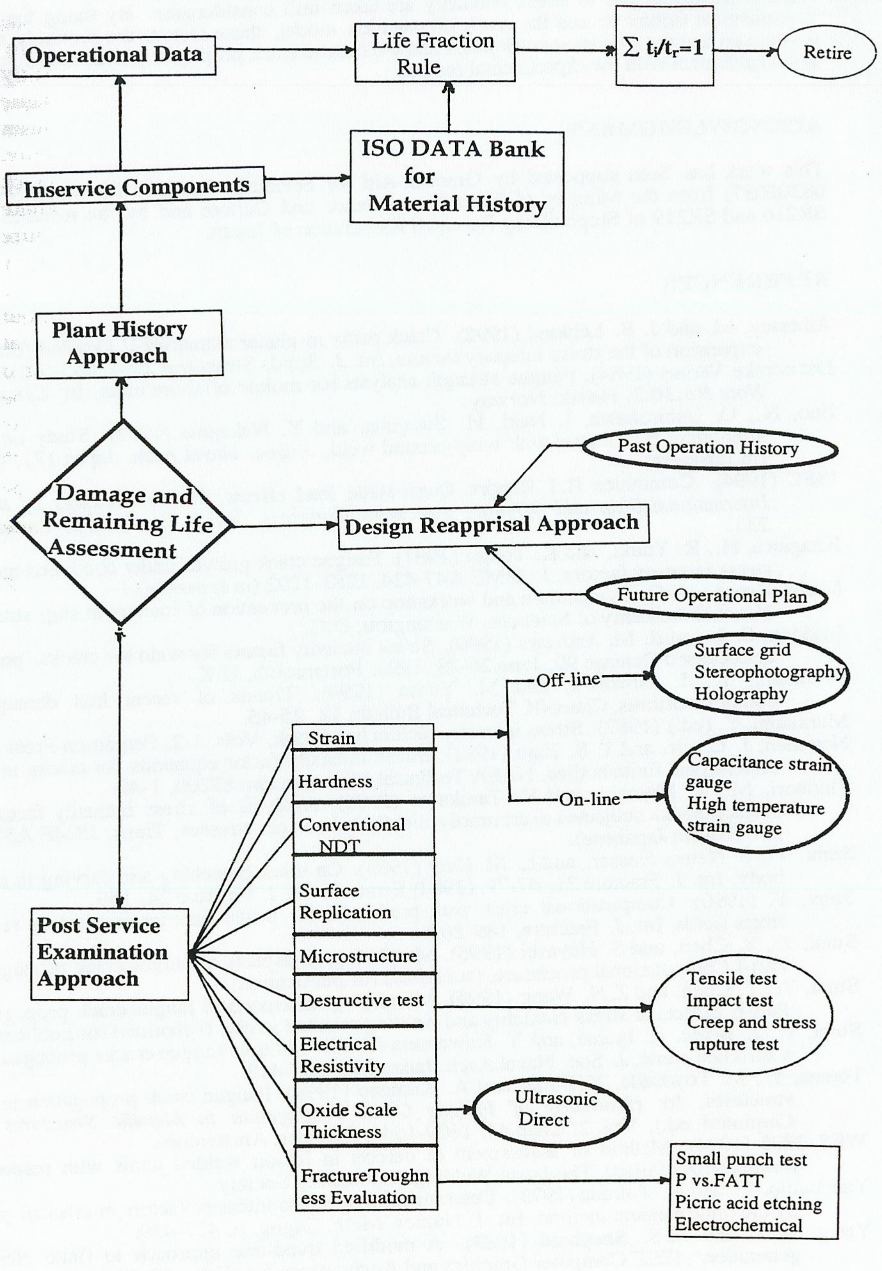

Fig.1 Illustration of Damage Assessment and Remaining Life Estimation Approaches and Various Techniques

FAILURE MECHANISM AND LIFE FRACTION RULE

The life limiting damage mechanisms under high temperature may be broadly categorised on the basis of operating conditions as (a) creep rupture (b) creep.-fatigue interaction and (c) thermal fatigue. The failure of components by any mechanism occurs by three stages, namely crack initiation, crack growth and final rapid fracture. The component life has essentially two components firstly, time period prior to crack initiation and secondly, time for the crack propagation up to the final size where rapid fracture ensues.. The final crack size can be estimated from the fracture toughness of the material concerned by using fracture mechanics methodology.

An approximate method for RLE applicable for high temperature components without any mechanistic basis is the use of Life Fraction Rule (LFR). If the service life at temperature (T) and stress (σ) is t_i and t_r represents the rupture life at same T and σ then life fraction consumed is t_i/t_r. Following LFR the component failure may be expected when $\Sigma t_i/t_r$ approaches unity for various sets of T and σ. A strain based (ε) modified form of LFR is given by $\Sigma\varepsilon_i/\varepsilon_r \rightarrow 1$ or a combined form using strain rate as $\Sigma f(\dot{\varepsilon}_i, t_i)/f(\dot{\varepsilon}_i, t_y) \rightarrow 1$ (Cane and Williams, 1987). LFR has been demonstrated to be valid only for variation in T and not σ. Ductile alloys tend to overestimate the life while the brittle alloys (castings, coarse grained HAZ, fusion lines) tend to underestimate life as shown in Fig. 2. The behaviour of the two groups is related with the underlying damage mechanism (Viswanathan and Gehl, 1992; Masuyama et al., 1990).

TECHNIQUES AND MODELS FOR DAMAGE ASSESSMENT AND RLE

The available techniques for evaluation of damage state and the developed models that may be used for life prediction may be discussed under each failure mechanism.

Creep Damage

The processes leading to elevated temperature creep failures under service load condition essentially include creep strain accumulation, structural degradation and creep cavitation. A large number of models and techniques are available for creep failure ranging from empirical to generic mechanistic basis to some specific mechanisms based.

Strain Method. The technique is capable of detecting deformation and distortion arising out of creep damage at critical locations. A 'off line' surveillance system works on the replication principle using a scribed surface grid . A hard replica of the grid can be made during plant shutdown and examined by high resolution microscope. Two other methods include stereophotography and laser holography. A hologram taken on site is reconstructed in the laboratory for the measurement of the image. Radiography and ultrasonic methods also may be useful to indicate the distortion and wall thickness change respectively. The 'on line' systems include high temperature strain gauge and capacitance strain gauges. A number of uncertainties are associated with strain method in general, e.g. lack of analytical prediction model, poor repeatability in measurement, inference of through thickness data from surface strain values etc.

Hardness Method. Several attempts are made to link up remaining life and Larsen Miller parameter (LMP) with hardness data when creep damage involves thermal and strain induced softening. One correlation estimates the creep life and fatigue life for CrMoV steam turbine rotor has the form as (Kimura et al., 1988) LMP = $C(\sigma)\,H_v + P(\sigma)$ where $C(\sigma)$ and $P(\sigma)$ are functions of stress, H_v is the Vickers hardness. The LMP is also correlated with service stress to obtain the operating temperature and remaining life for 2.25 Cr - 1 Mo steel. Goto (1992) incorporated the stress effect on thermal softening by designing a new parameter (G) which may be represented by

$$G' + \Delta G = G = \log\left[T\,(20 + \log t)\right] \qquad (1)$$

While G represents the thermal softening behaviour including the effects of both T and σ, ΔG represents only the effect of σ. A normalized hardness data (H_v/H_{vo}) at stressed and unstressed locations can give a value of ΔG which in turn may be used for estimating the local stress. The model has been successfully applied at T root corner of a rotor for creep life prediction (Tanemura et al., 1988). However, any general relationship with hardness data is perhaps not possible because of poor repeatability in the measurement.data.

Surface Replication. The cavitation damage and microcracks in creep can be characterized quantitatively by surface replication technique which has been well established. A number of cavity parameters may be considered e.g. volume fraction of cavities, mean cavity size, fraction of cavitated grain boundaries. Four stages of cavity

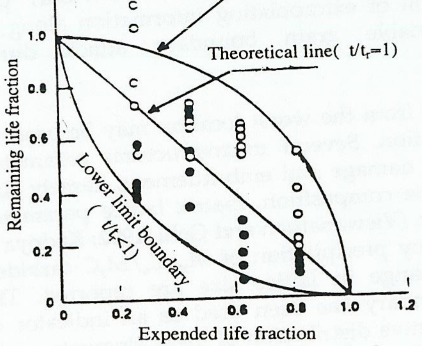

Fig.2 Application øf life fraction rule for two heats øf Cr-Mo steel illustrating the conserv ative estimation øf remaining life(Viswanathan and Gehl 1992)

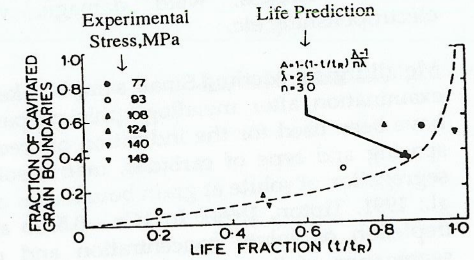

Fig 3.Computed and experimental data points illustrating the relation between fraction øf ca viated grain boundaries(A_f) and life fraction(t/t_r) in 2.25Cr-Mo steel(Cane and Williams 1987)

evolution in steels have been identified as a function of ageing process (Neubauer and Wedel, 1983) as shown in table 1.

Constrained cavity growth model uses the fraction of cavitated grain boundaries for RLA as shown in Fig. 3 and the relationship considering the lower bound of scattered data for 1 Cr - 0.5 Mo steel may be represented as (Ellis et al, 1989)

$$A_f = 0\ 5717\ (t/t_r) - 0.816 \tag{2}$$

Accuracy of the model for RLA depends on the heat specific constants which are determined experimentally for each heat. For a rotor steel a recent work finds a correlation as where the left hand side is normalized by A_{fc} which is the grain size

$$A_f/A_{fc} = 0.903\ (t/t_r) - 0.064 \tag{3}$$

correlated value of A_f. A simpler approach for life evaluation suggested by Ellis et al. (1989) uses the lower bound values for life fraction as shown in table 1 for different cavitation stages. The reinspection interval is set from the model using a safety factor of 3 for each stage. With the change in cavitation morphology the inspection interval decreases for the same consumed life. Several factors cast doubt on the success of the model for reliable RLA and these may include, cavitation behaviour, poor reproducibility during replication, problem of extrapolating information along the section thickness, weld damage, variable grain boundary attack during electropolishing etc.

Table 1: Remaining life versus cavitation stage

Cavitation Stage	Life fraction consumed (t/t_r)	Remaining life	Reinspection interval
Undamaged (virgin)	0.27	2.7 t	0.9 t
Class A (isolated)	0.46	1.17 t	0.4 t
Class B (oriented)	0.65	0.54 t	0.18 t
Class C (linked)	0.84	0.19 t	0.06 t
Class D (macrocrack)	1.0	0	-

<u>Metallurgical Method</u>.Small sample taken from the worst location may be used for examination after metallographic preparation. Several microstructural parameters have been used for the indication of creep damage and embrittlement, namely size, spacing and type of carbides, matrix solute composition, matrix lattice parameter, segregation of solute at grain boundaries etc. (Viswanathan and Gehl, 1992; Kadoya et al.; 1991, Tipton, 1994). In 1Cr - 0.5Mo alloy precipitation of $M_{23}C_6/M_7C$ carbides, depletion of solute concentration and change in lattice size are reported. The segregation of P and Sb to the grain boundary has been used as an indicator of embrittlement in low alloy steel. A comparative distribution of these elements could be checked by Auger Analyzer at the grain boundary and matrix. Testing of subsize charpy specimen may be conducted to confirm the degree of embrittlement due to segregation. Interprecipitate distance (λ) has been used to quantify the damage state as $\lambda = \lambda_0^3(1. + kt)$ where $\lambda = \lambda_0$ at t = 0. However, quantitative modelling using metallurgical parameters with reasonable degree of success has been limited mainly because of excessive scattering in data.

<u>Oxide Scale Method</u>.A methodology is developed by EPRI to assess the health condition and life consumption of heater tubes based on steam side oxide scale thickness data (Viswanathan and Gehl, 1992). The kinetics of oxide scale growth could be studied by both direct and ultrasonic measurement. An improved method for the calculation of reference stress in boiler tubings has also been proposed by EPRI. Oxide scale method has proved to be of considerable potential for RLA.

<u>Other Methods</u>.Long term heating lowers the electrical resistivity of steels and so this parameter has been used to assess the creep damage. The resistivity change is accelerated with the application of stress and the resistivity change has been shown to be linear with life fraction (Fig. 4) up to t/t_r equals to 0.7 for rotor steel by Tanemura et al. (1988). Beyond 0.7 microstructural damage leads to cavitation making the plot non-linear. The other non-destructive test methods for RLE may include the use of Electron Microscopy, Positron Annihilation Measurement, Ultrasonic Velocity Measurement, X-ray Diffraction etc. In addition to the non-destructive techniques as discussed, several other methods of destructive nature are also used for creep life evaluation like tensile test, charpy energy test, creep rupture test etc. The tests are conducted on the specimens made from the material removed from the inservice component which limits the frequency of such destructive tests.

<u>Accelerated Creep and Rupture Tests.</u>The tests are conducted under accelerated conditions with increased stress (σ) or temperature (T) or both to provide direct knowledge about component health damage. Isostress rupture method uses several samples to test over a range of T above service T but close to service σ level. A linear plot between log t_r and T is generally obtained and the plot may be extrapolated to the service temperature to determine the remaining life as may be seen in Fig.5 (Strang et.

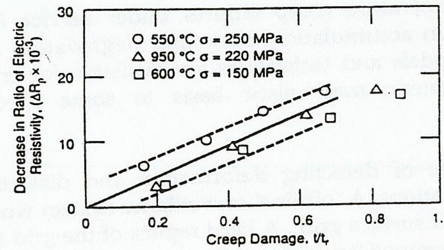

Fig 4 Linear decrease in resistivity ratio with creep life up to 0.7 for different sets øf stress and temperature(Tanemura et.al 1988)

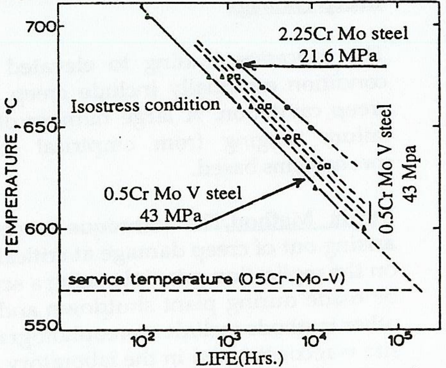

Fig.5 Remaining life estimation by extrapolation øf log t_r versus temperature plot in Cr-Mo -V steel (Cane and Williams 1987)

al., 1994). However, the predicted values of remaining life from extrapolation are reported to be in agreement with the actual lives within a factor of two in both brittle and ductile alloys. The linear plot as discussed may be analytically represented by log t_r = A+BT which has been successfully used for RLE of boiler heater. However, the method has been invalidated for 1 Cr Mo V rotor steels (Strang et al., 1994). Several modifications of the method have been recommended for improvements such as (Kadoya et al., 1990; Viswanathan and Wells, 1993; Strang et al., 1994).

(a) use of miniature test piece representing the bulk microstructure of the critical region;
(b) use of inert gas for miniature specimen testing to avoid oxidation effect (Fig. 6);
(c) consideration for oxidation effect when standard specimen is tested in air to avoid conservatism in life estimation.Oxidation effect reduces the life because of notching or oxide fingering at grain boundaries.

The isostress test has the merit that the prediction is not based on virgin material data and LFR. The drawbacks of the method is that it is time consuming and expensive involving plant outageing, sample cutting, machining etc.In isospecimen test the life fraction is given by the ratio of consumed life by a single specimen at accelerated test conditions to the rupture time for virgin sample under same test condition. The ISO data scatterband is used as reference as the virgin material data are rarely available.

A parametric equation of the form $P(\sigma) = H(T, t_r)$ is used for life evaluation by extrapolation of data in stress rupture tests which is conducted over ranges of stress and temperature. Various forms of functions of P and H are available in literature andthe most commonly used are Larsen-Miller, Manson-Hafered parameters.The lifefraction rule for rupture analysis may be modified as (Cane and William ,1987

$$\frac{t_s}{T_s}+\frac{t_t}{T_t}=1 \qquad (4)$$

where t_s is service time and t_t is rupture time under accelerated condition. T_s and T_t represent the rupture time under service condition and accelerated condition (virgin material) respectively. It has been confirmed that test results based on temperature acceleration agree well with LFR prediction in case of ductile alloys. The brittle alloys exhibit better match in results with LFR prediction when both the parameters (T and σ) are accelerated.Creep life estimation using strain based models has also been proposed and the general form of equation may be as $\varepsilon = f(\sigma, t, t_r, T)$. Knowing ε or $\dot{\varepsilon}$ under accelerated condition life estimation may be performed.

Creep Crack Growth Situation.The preceding sections dealt with life assessment based on damage evaluation up to the point of crack initiation. The cracks under creep condition propagate and thus consumes some life which may be predicted using appropriate fracture mechanics based crack growth models. The model essentially involves two components, firstly an appropriate equation involving crack growth driving force (K, C_t, C*), crack size, applied stress, component size and geometry and secondly, a functional relation between the crack growth rate ($\dot{a}$) and crack driving force parameter. C_t parameter represents a better correlation with $\dot{a}$ over a range of crack growth than K and C* and the general form of equation for C_t is expressed as (Saxena et al., 1984).

$$C_t = a\,\sigma\,\dot{\varepsilon}\,(A, n)\,H\,(\text{geometry}, n) \qquad (5)$$

where σ and $\dot{\varepsilon}$ are- far field stress and strain rate respectively, H - function of geometry and creep exponent n. The general form of relation between $\dot{a}$ and C_t may be expressed as $\dot{a}\ \alpha\ b\ c_t^m$ where b and m are constants. The equation can give the time increment (Δt) required for crack intention (Δa) and this may be repeated to obtain the crack growth life as initial size (a_0) approached final crack size (a_f). The output may be obtained as a plot between a and t which is easy to interpret, but the results are greatly influenced by the values of constants (A, n, b, m) which are often too scattered. A number of non-destructive techniques like magnetic particle inspection, dye penetrant inspection, ultrasonic examination, X-ray radiography and eddy current testing are used to monitor the crack growth during subcritical propagation. An unified model given by Ainsworth et.al suggests that the service life should have three components,namely time to rupture,time preceeding crack growth and time during crack growth.The components needs to be summed up after estimating using a reference stress which depends on component geometry.

Creep Fatigue Interaction

High temperature components undergo transient temperature gradient during start up, shut down or even during long steady operation. Differential thermal expansion during each transient causes a thermally induced cyclic stress on the components. A reliable life estimation for such situation demands the consideration of both creep and fatigue effects.A few examples where creep-fatigue effects may be present include,gas turbine blades and disks,high pressure rotors,steam turbine pipeworks,heavy section pressure vessels in nuclear and petrochemical industries. Major advances are made in recent time to understand the damage mechanisms and model creep fatigue interaction for high temperature components. However, studies on a large variety of

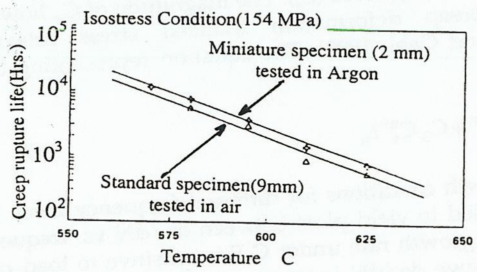

Fig.6 Creep rupture data for miniature and standard specimen. Miniature specimen shows 20 percent higher life (Strang et.al.1994)

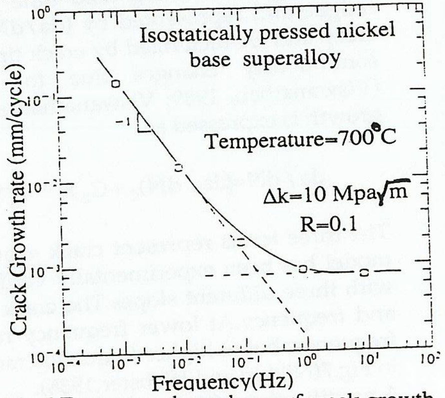

Fig.7 Frequency dependence øf crack growth rate indicating two slopes(Nikbin and Webster 1988)

alloy systems have revealed that each model is empirical in nature and can predict life within a factor of two in respect of actual life. The major variables affecting the models include frequency, temperature, strain range, waveform, ductility and damage characteristics of materials.

Crack Initiation Life.The basic approach considers the linear damage summation rule ($\varphi_f + \varphi_c = 1$) where φ_f quantifies the fatigue damage ($\Sigma N/N_f$) and φ_c represents the creep damage ($\Sigma t/t_r$). N_f and t_r are pure fatigue and rupture lives respectively. The summation rule is widely used in design after the rule was accepted in ASME Boiler and Pressure Vessel Code, Section III, Case N47. Kitagawa et al. (1988, 1989) suggested modifications to the rule, namely loading wavefront effect, ratcheting strain effect and weld joint effect. A modification has the general from as

$$\frac{N}{N_f}+\frac{t}{t_{r\,cyclic}}+a\left(\frac{\varepsilon}{\varepsilon_r}\right)=1 \quad \text{where} \tag{6}$$

$t_{r\,cyclic}$ - cyclic creep rupture time, ε_r - creep rupture ductility and a - material constant. The frequency modified Coffin-Manson relation has been shown to predict C-F life fairly accurately in 316 stainless steel (Viswanathan, 1989). The model involves a large number of material constants which vary with materials and test conditions. A damage rate accumulation method separates total damage into two, namely fatigue crack damage and creep cavitation damage. The components may be either additive or interactive and the agreement lies within a factor of two. Several other methods are proposed in literature on C-F interaction, namely, Strain range partitioning, Universal slope method, Ductility exhaustion, continuum damage etc.The continuum damage approach uses an incremental damage parameter as a function øf stress and stress increments. etc.

Crack Growth Life.Crack growth occurs in creep fatigue situation during loading - unloading and during hold time period (t_h). The first component is controlled by fatigue and represented by $(da/dN)_0$ while the second contribution is controlled by creep and characterized by crack tip driving force (C_t). The magnitude of C_t, however, continuously changes due to creep deformation induced stress relaxation (Viswanathan, 1989; Viswanathan and Gehl, 1992). The equation representing crack growth is expressed as

$$da/dN=(da/dN)_0+C_2 K^{2m} t_h^{1-m}+C_3 C_t^m t_h \tag{7}$$

The three terms represent crack growth conditions for different frequency level. The model has been experimentally verified to yield plots between da/dN vs. frequency with three different slopes.The crack growth rate under C F is sensitive to load ratio and frequency.At lower frequency range da/dN increases sharply with decrease in frequency; but at higher frequency range da/dN becomes independent as may be seen in Fig.7(Nikbin and Webster,1988).

A modification of the model includes average C_t and replaces second and third term of the above equation. An average crack growth rate ($a_{av.}$) during hold period may be given by (Saxena and Gieseke, 1987; Gieseke and Saxena, 1989)

$$\dot{a}_{av}=t_h^{-1}(\dot{a}-\dot{a}_0)\,\text{and}\,C_{tav}=t_a^{-1}\int_0^{t_h} C_t\,dt \tag{8}$$

The crack growth rate equation may be rewritten as

$$da/dN=C\Delta K^n+b_1 C_{tav}^m t_n \tag{9}$$

Integrating the above equation between the limits of initial crack and final crack, the remaining life may be obtained.

Thermal Fatigue

Components operating under high temperature are subjected to simultaneous cycles both in temperature and mechanical stress. Gradual deterioration and eventual cracking occurs in the component due to constraint in free thermal expansion. Attempts to quantify the thermal fatigue situation by isothermal LCF models have proved to be wrong as the LCF damages are far less in comparison to the damages found in thermal fatigue.

Damage Initiation.Thermal fatigue behaviour may be grouped into two categories namely, thermomechanical fatigue (TMF) and thermal stress fatigue (TSF). TSF damage can be characterized experimentally by using thermal cycling test under simulated stress strain conditions. TMF damage can be studied in a servohydraulic fatigue machine where strain and temperature cycles on a uniaxial specimen can be measured and controlled independently.

A variety of alloys reveal several interesting behaviour with regard to the damage mechanism depending upon the load cycles and temperature. High strain at high temperature promotes creep damage, while high strain at low temperature would promote environmentally induced damage. Nitta and Kuwabara (1988) proposed a new approach based on extensive investigation on thermal fatigue prediction life which may be correlated with strain energy parameters of macrocrack propagation. TMF life could be well predicted from the characteristics of isothermal fatigue failure and crack propagation for all alloys including superalloys. The universal slope method with 10 per cent rule may conservatively predict life of wrought alloys but the method does not work for cast alloys. The strain range partitioning method has proved to be a success in many cases which may be represented as

$$\frac{1}{N_f}=\frac{1}{N_{pp}}+\frac{1}{N_{cc}}+\frac{1}{N_{pc}}\left(\text{or}\,\frac{1}{N_{cp}}\right) \tag{10}$$

where N_{pp}, N_{cc}, N_{pc}, N_{cp} - fatigue lives under $\Delta\varepsilon_{pp}$, $\Delta\varepsilon_{cc}$, $\Delta\varepsilon_{pc}$, $\Delta\varepsilon_{cp}$ respectively and N_f - fatigue life. The various strain ranges are dependent on direction of straining. Coffin-Manson relation can be applied for each type of straining. The base data i.e. $\Delta\varepsilon_{ij}$ - N_{fij} relation may be obtained from tensile and creep ductility. The model predicts the thermal fatigue life of wrought alloys with reasonable accuracy (Nitta and Kuwabara, 1988; Kitagawa, 1989).TMF life can be predicted somewhat conservatively by using total strain range which may be obtained from various mechanical properties.Isothermal fatigue at maximum temperature yields relationship between total strain range and life consumed.

Fracture Toughness Evaluation

The life of components under various damage mechanisms will finally depend on the fracture toughness of the material which controls the final rapid fracture.The fracture toughness data provides the final crack size that a material should be able to withstand.A number of nondestructive methods are available for the evaluation of fracture toughness data (Viswanathan and Gehl,1992; Kadoya et al,1991). An indirect approach uses the correlation between phosphorus content of the alloy and FATT.Small punch test,chemical etching using picric acid and electrochemical tests are the other promising methods.The electrochemical method depends on the polarization and repassivation characteristics of the material.The small punch tests use small specimens to determine the absorbed energy versus temperature plot which is of similar nature as the conventional charpy energy versus temperature plots.

REFERENCES

Cane, B.J. and J.A Williams (1987). Remaining life prediction of high temperature materials, *Intl. Matls. Reviews*, 32, 241-262.

Ellis, F.B. et al. (1989). *Remaining life prediction of boiler pressure parts*, EPRI report, Vol. 1, CS 5588.

Gieseke, B. and A.Saxena (1989). Correlation of creep fatigue crack growth rates using crack tip parameters, *Advances in Fracture Research* (K. Salama et al.,ed.) 189-196.Pergamon Press, NY,

Goto, T. (1992). Microstructure and mechanical properties of ageing materials. In: *Intl. Conf.Proceeding*,75-82,Chicago.

Halford, G.R. (1991). Evaluation of creep fatigue life prediction models. In: *ASME meeting on Creep-Fatigue Interaction at High Temperature* (G.K. Hasitos and O.O. Ochoa,ed.) 21.

Kadoya, Y. et al. (1991). Non-destructive evaluation of temp. embrittlement in Cr Mo V steel. In: *Proc. Joint power generation Conf. PWR-13* (A.S. Warmocu,ed.) ASME, New York.

Kadoya, Y. et al. (1990). Assessment of remaining life of fossil power plants by means of miniature creep rupture test, The ISIJ Japan, 30, 854-861.

Kimura, K.,K Fujiyama.and M.Muramatsu(1988). High temperature creep fatigue. In: *Current Japanese materials research* (R. Ohtani et al.,ed.) 247-270.

Kitagawa, M.,I. Nonaka, H. Hatton, and A.Ohtome(1988). Modifications to the creep-fatigue life criterion for high temperature nuclear components. In: *High temperature creep fatigue* (R. Ohtomi et al.,ed.) Current Japanese Materials Research, vol. 3, 233-245. Elsevier Applied Science,

Kitagawa, M. (1989). Life prediction and fatigue. In: *Superalloys, supercomposite and superceramics*, Academic Press, 413-423.

Masuyama, F.,N. Nishimura and T.Igori, T.(1990). *Creep damage simulation test and creep life assessment for elevated temperature plant components*, 30, 885-895.

Neubauer, B. and V. Wedel, V.(1983). Advances in life prediction method. In: *ASME meeting* (D.A. Woodford and J.R. Whitehead,ed.) 307-314.

Nitta, A. and K.Kuwabara(1988). Thermal mechanical fatigue failure and life prediction. In: *High temperature creep fatigue* (R. Ohtani et al.,ed.) Current Japanese Materials Research, Vol. 3, 203-222, Elsevier Applied Science, NY,.

Nikbin,K.M.and G.A.webster (1988) .Prediction of crack growth under creep-fatigue loading condition.In:*Low cycle fatigue*(H.D.Solomon et.al.,ed.)ASTM STP 942, 281-292.

Strang, A., S.M Beech and D.J. Gooch(1994). Remaining life evaluation of 1 Cr Mo V steam turbine rotors. In: *Materials for advanced power engineering*, part I, 549-560. Kluwer Academic Publishers, Netherlands,

Saxena, A. and B.Gieseke (1987). Transients in elevated temperature crack growth. In: *Proc. high temperature fracture mechanism and mechanics*, 3, 19-36.

Tanemura et al. (1988). Material degradation of long term service rotor. In: *Conf. Proc. on life assessment and extension*, Vol. I, 172-178., Netherlands,

Tipton, A.A. (1994). Method for estimating remaining life of steam turbine casings from a creep rupture standpoint. In: *Materials for advanced power engineering*, part I, 529-537.,Kluwer Academic Publisher, Netherlands,

Viswanathan, R. and S.M.Gehl (1992). Life Assessment Technology for Power Plant Components,*Journal of Metals*, 34-42.

Viswanathan, R. and C.H. Wells (1993). Life prediction of turbine generator rotors. In: *Technology for the nineties* ASME, 1-56.

Saxena, A., Shih, T.T. and Ernst, H.A. (1984). Wide range creep crack growth rate behaviour of A470 class 8 (Cr Mo V) steel. In: *Fracture Mechanics Symposium* (ed. R.J. Sanford) ASTM STP833, 516-531.

Viswanathan, R. (1989). Damage mechanisms and life assessment of high temperature components, ASM International, Ohio.