Def Sci J, Vol 38, No. 4, October 1988, pp 467-476

Creep-Fatigue Interactions of Gas Turbine Materials

Tarun Goswami

Gas Turbine Research Establishment, Bangalore-560 093

ABSTRACT

The military aircraft gas turbine engines are often required to undergo a complex set of operating conditions where the load varies considerably with respect to time. The temperature range for performing such requirements also increases as the thrust increases. The modern design of gas turbine demands very high thrust-to-weight ratio. In order to achieve this, the design is limited in the low cycle regime. The low cycle regime necessarily has the plasticity effect because of fatigue and inelastic time dependent permanent deformation because of creep. Fatigue and creep interaction studies are very important for the safe life design of critical components such as turbine discs and blades.

1. INTRODUCTION

The inability to predict the crack initiation life of gas turbine components such as discs and blades is solely responsible for the premature replacement of such expensive components. The major difficulties encountered are the synergistic effects of creep-fatigue with the environment at high temperature. To understand the material behaviour at the creep range with interaction of fatigue and creep with environment led to the evolution of frequency modified approach and Strain Range Partitioning technique (SRP).

The committee on fatigue crack initiation at elevated temperature led by the American National Advisory Board[1] concluded that 'both the frequency modified fatigue life and the strain range partitioning method contained concepts that were attractive from the stand point of predicting time dependent damage in superalloys' and recommended that their extension to turbine disc analysis be undertaken

Received 16 May 1988

In this review an attempt has been made to understand the process of strain range partitioning and total strain version of SRP. The capability of a new model within the frame work of SRP is termed as Strain Energy Partitioning technique (SEP). How to model and establish the various combinations of the creep and fatigue and how best to accept these methods for the life prediction of gas turbine components have been highlighted.

2. LIFE PREDICTION MODELS

The life prediction of gas turbine materials operating at creep range can be dealt in two steps. The first separates the damage in time and the cycle fractions and later by a linear damage summation rule the time and cycle fractions are added together to give damage. This method is known as damage summation method.

2.1 Damage Summation Method

This method also known as linear life fraction damage rule. It was recommended[2] by the ASME boiler and pressure vessel code case 1592. This method was first proposed by Miner[3] and Robinson[4] later modified by Taira[5]. The cyclic and time fractions are added together to give the damage D=1 at failure.

$$\sum_{j=1}^{p}\left(\frac{n}{N_d}\right)_j + \sum_{k=1}^{q}\left(\frac{t}{T_d}\right)_k \leq D \tag{1}$$

where,

D is total fatigue-creep damage,

n is number of applied cycles of loading condition j which is specified by both strain and temperature,

N_d is number of design allowable cycles (or the actual fatigue life) at the cyclic loading condition,

t is accumulated hold time of the loading condition k,

T_d is time to rupture at the loading condition k.

The second approach considers the damage, cyclic and time fractions together These methods are the SRP and the SEP.

2.2 Strain Range Partitioning Technique

SRP was developed at NASA Lewis Research Centre introduced by Manson, Halford, and Hirschberg[6,7]. SRP is a tool to deal with high temperature low cycle fatigue and creep-fatigue interactions. This method, as suggested can be used successfully in the design of aeronautical gas turbines or other high temperature equipment. The life prediction by strain range partitioning technique addresses material behaviour under cyclic deformation called hysteresis, which is caused by inelastic strain time synergism.

The physics of creep-fatigue interaction, necessarily involves two types of strain accumulations namely the time dependent permanent inelastic strain because of creep and time independent plastic strain because of fatigue. Both these strains are known as inelastic strain. Since both these strains can be experienced in both the tensile and compressive directions, the possibilities of having various combinations of strains are :

i) Tensile plasticity reversed by compressive plasticity.

ii) Tensile plasticity reversed by compressive creep.

iii) Tensile creep reversed by compressive creep.

iv) Tensile creep reversed by compressive plasticity

They are represented by PP, PC, CC and CP hysteresis loops and are shown in Fig.

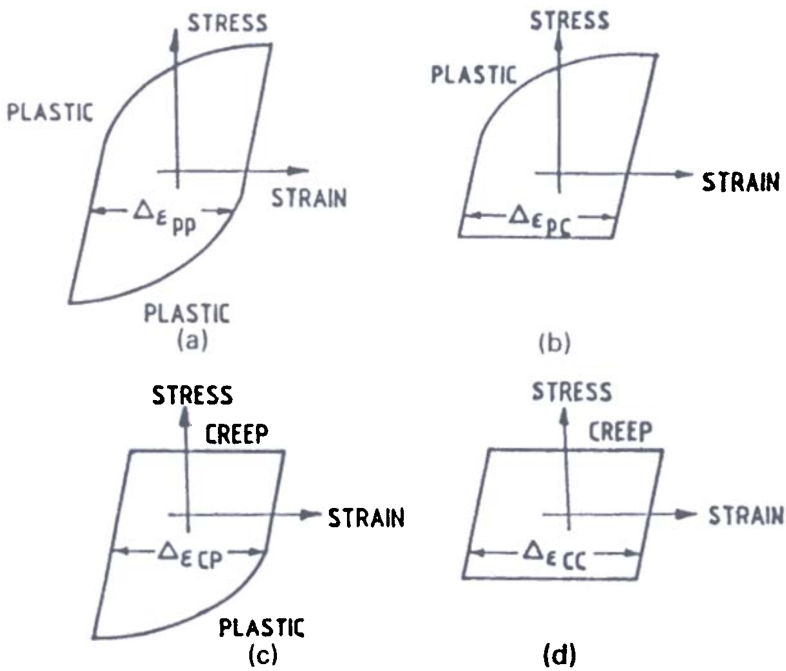

Figure 1. Partitioned hysteresis loops (a) PP, (b) PC, (c) CP, and (d) CC types.

The life prediction by SRP, can be done[8] in two steps,

i) To know the hysteresis loop for the cycle being analysed. To be able to partition the loop into inelastic strain components as shown in Fig. 2.

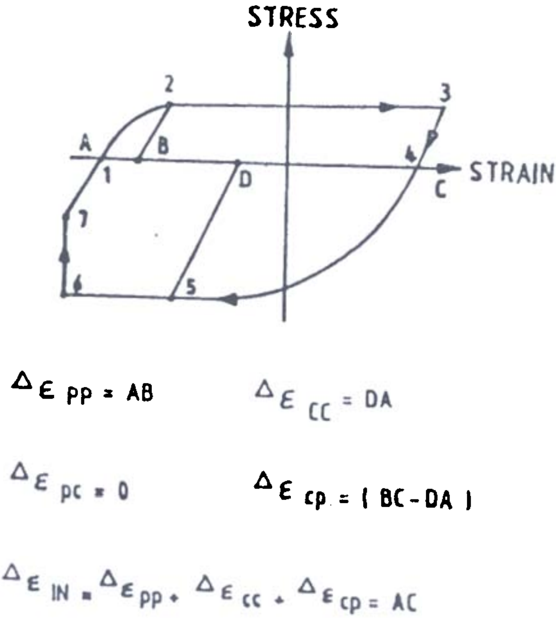

Figure 2. Partitioned of a complex hysteresis loop.

ii) A damage rule must be applied in order to predict the life associated with a combination of applied strain ranges.

Thus the loop can be studied and fractions could be established, if the single loop contains various combinations. The damage per cycle due to each of these components can be represented by $\frac{Fpp}{Npp}$, $\frac{Fcc}{Ncc}$ and $\frac{Fcp}{Ncp}$, and the total damage per cycle is equal to the sum of individual damage contribution hence,

$$\frac{}{N_{\text{pred}}} = \frac{Fpp}{Npp} + \frac{Fcc}{Ncc} + \frac{Fcp}{Ncp} \tag{2}$$

2.3 Modelling for Life

This method of strain range partitioning allows the life determination of the component operating at the creep range. The upper and lower bounds of life can be modelled for a particular kind of hysteresis loop. If inelastic strain range, $\Delta\varepsilon_{in}$, is entirely of PP type, the life is in PP type, i.e., *Npp*. Similarly if $\Delta\varepsilon_{in}$ is made up of most damaging type of strain range CP, the life will be of *Ncp* type. The lower and upper bounds on life for any given inelastic strain range can be obtained from the assumption that the actual life must lie between the most conservative and least conservative of the partitioned strain range-life relations. The bounds on life relationship is shown in Fig. 3.

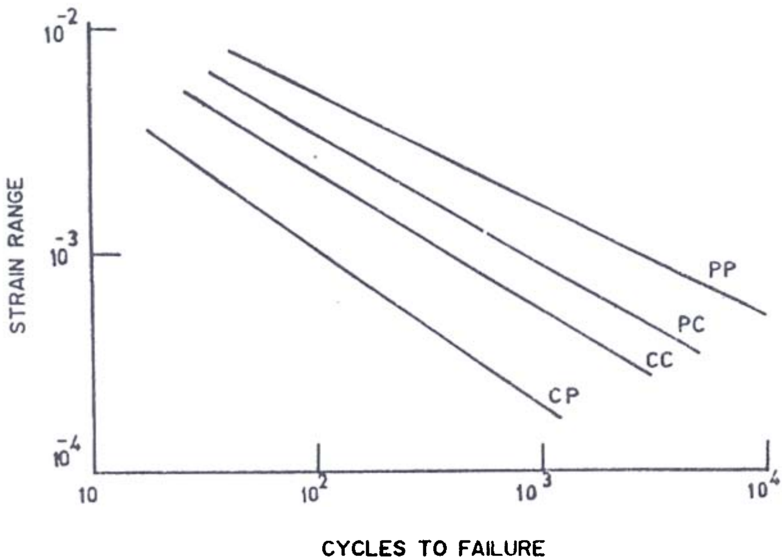

Figure 3. Bounds on life relationship.

Manson[9], assumed that a unique relation exists between the cyclic life N_{ij}, and strain range $\Delta\varepsilon_{ij}$, for each of these components

$$\Delta\varepsilon_{ij} = C_{ij} \quad N_{ij}^{\ S_{ij}} \tag{3}$$

where *ij* represents PP, PC, CP and CC strain ranges. This is the form of Manson-Coffin relation.

Manson[10], also proposed an interaction damage rule to substitute the linear damage rule in the life determination

$$\frac{Fpp}{Npp} + \frac{Fcp}{Ncp} + \frac{Fpc}{Npc} + \frac{Fcc}{Ncc} = \frac{1}{Np} \tag{4}$$

where F_{ij}, is the fraction of the total inelastic strain range that is due to $\Delta\varepsilon_{ij}$ and N_{ij}. This is the life obtained from the life relationship by considering the entire inelastic strain range to be $\Delta\varepsilon_{ij}$.

2.4 Total Strain Version of Strain Range Partitioning Technique

Manson and Zab[11] have taken the approach for treating the low strain and long hold times. They developed the basic Manson-Coffin plastic strain range power law of low cycle fatigue into a total strain range representation by the addition of the elastic and plastic strain range-life relations as

$$\Delta\varepsilon_t = \Delta\varepsilon_{pl} + \Delta\varepsilon_{el} \tag{5}$$

By considering the elastic and plastic fractions of strains, the method considers a broader range of strain range-cyclic life relations. This method is termed as total strain range SRP approach.

2.5 Approach to the Total Strain Range SRP

For formulating, first we have to determine the conventional inelastic strain range-life relation for the cycles involving plasticity and creep which are PP, CP, PC, and CC. Then the elastic strain range-life relations are determined for the same cycles. At elevated temperature, the elastic strain (stress) response is not only temperature dependent but also time dependent and hence wave-shape dependent. The slopes of these elastic lines as a first approximation, were found to be the same as the elastic line slope for pure fatigue cycling with no creep, that is PP type cycling. The principal influence of temperature and time is to shift the $Nf = 1$ intercepts of lines.

After the elastic and inelastic life relationships are obtained, they are then made available to display a family of total strain range-life relationships. The total strain versus life relationship necessarily involves the knowledge of the partitioning, i.e. relative creep and plastic strains. In other words, partitioning can be done by knowing the total strain range, total strain versus time history within the cycle and the temperature variations within the cycle. The total strain range-life relations to be used is the sum of the specific inelastic strain range-life relation. This is determined using the interaction damage rule in conjunction with the partitioned strain range fractions and the pertinent elastic strain range-life relations.

2.6 Calculating Life

The proposed total strain range SRP approach, is intended primarily for extrapolation into the low strain, long life creep-fatigue regime, where because of economic considerations creep-fatigue testing used to determine the constants in the life relations is nearly prohibitive. By adding the inelastic line to the elastic line, for the specific cycle of interest, the total strain range versus life curve is obtained.

2.7 Strain Energy Partitioning Technique

The SEP, developed by He Duan, Ning and coworkers[14] is assumed to be a modification over SRP. It has been designed to predict high temperature low cycle fatigue life of gas turbine components. The model for life prediction by this method, necessarily involves two variables, maximum tensile stress and partitioned inelastic strain range. The strain range component ($\Delta\varepsilon_{ij}$) in SRP are substituted by strain range energy component ($\sigma_T * \Delta\varepsilon_{ij}$) in SEP. The SEP is based upon the premise that it is the inelastic strain energy that determines the creep and fatigue damage. It implies that the work of the external forces is stored within the specimen in the form of strain energy (ΔU) under the action of deformation. The measure of this energy, that is the hysteretic energy, is $\int \sigma_T \varepsilon_{in}$.

The damage function method and SEP consider that low cycle fatigue life is mainly spent in growing cracks to a critical size. The tensile hysteretic energy, the tensile half of the hysteresis loop or the deformation occurred when the crack is open contributes to crack propagation and thus to fatigue damage. This energy is shown in Fig. 4.

$$U = \int_{ABCD} \sigma . d\varepsilon_{in} \tag{6}$$

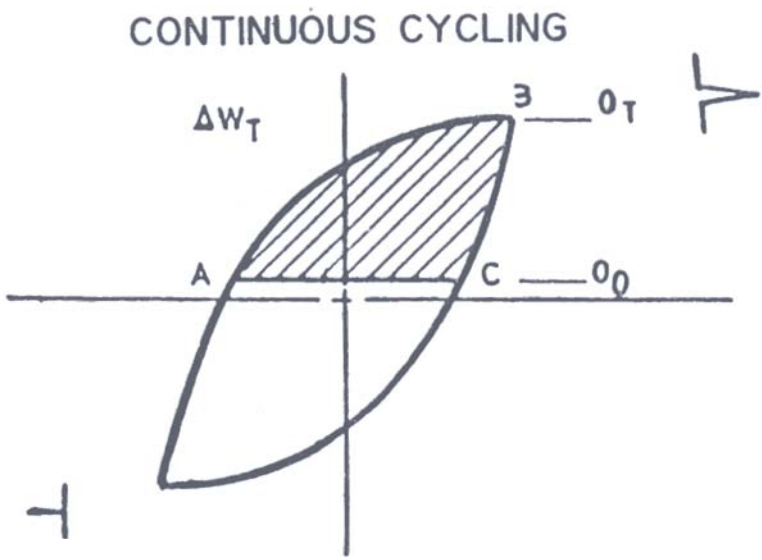

Figure 4. Schematic hysteritic loops defining net tensile hysteritic energy

Integrating, this can be represented as $a\sigma_T\Delta\varepsilon_{in}$ where a is shape factor which corrects the area approximated by $\sigma_T\Delta\varepsilon_{in}$ to make it equal to the true area. Unlike the SRP, the strain energy partitioning relationships are

$$N_{ii} = A_{ij} \, (\Delta U_{ij})_{ij}^{B} = A_{ij} \, (a_{ij} \, \sigma_T \, \Delta\varepsilon_{ij})_{ij}^{B}$$

$$\frac{1}{N_p} = \Sigma \, \frac{F_{ij}}{N_{ij}}; \qquad X = \frac{a_{ij}\sigma_T\Delta\varepsilon_{ij}}{a_{in}\sigma_T\Delta\varepsilon_{in}} \tag{7}$$

where A and B are material constants, where fraction of the strain energy component F_{ij}, is equal to X which can be obtained by measuring separately the actual area of tensile half of a stable hysteresis loop.

The four partitioned SRP and SEP relationships are plotted between the partitioned strain energy versus life relationships $N_{ij} - (a_{ij} \, \sigma_T \, \Delta\varepsilon_{ij})$. The ability of the model to correlate the base line data was found satisfactory as the scatter band obtained was within the range of 2 per cent.

3. DISCUSSIONS

Damage summation approach assumes the damage fraction in creep and in fatigue are same and that the life is used up when the damage summation equals the factor D. It ignores the interaction effect of creep and fatigue. A deviation from unity may indicate the interaction of fatigue and creep. During hold time the stress relaxation takes place followed by stress redistribution at a localised region. This is because of temperature and time dependent deformation. This method, hence may give over or underestimated design guidelines thus needs further modification.

The concept of the life bounds simplifies the complexity of the analysis and provides a conservative estimate of failure life. However SRP has a few limitations, in view of its final acceptance in the design of gas turbine components which operate at creep range. When the inelastic strain range is small, difficulties arise to model and predict the life. Moreover SRP is only applicable when the loop is stabilised. The fracture mechanics aspects of crack healing or relaxation by overloading and sequence effects cannot be predicted by SRP. The inelastic strain magnitude cannot be calculated correctly from non-linear structural analysis methods. Problems are encountered while computing for inelastic strain which is not accurate because of small strain, inadequate material properties, temperature distribution and loading history.

To date nickel-based superalloys are used as the materials in most of the gas turbine components. In reference, AGARD CP-243 it has been shown that PC life relationship in conventional nickel-based alloys is at the lower bound. This means that the PC line is the most damaging one of the four basic types of the strain range components (or strain energy component). Thus the PC line is the most important in the life evaluation of structural parts. From the tests of Rene 95, the compressive strain hold test consistently have shorter fatigue life than the tensile hold cycles for the same inelastic strain range. The compressive hold cycles develop a larger peak tensile stress than tensile hold cycles do. The larger peak tensile stress influences the cyclic life to a greater extent than the creep effects. The effect of stress to cyclic life in high strength, low ductility alloys is more important than the low strength, high ductility alloys. Thus the predictive life cycles of Rene 95, and Rene 80, PC lines by SEP are more accurate than by SRP, because the SEP includes the stress but the SRP does not. Halford and Nachtigal[15] modified SRP with a ratio of mean stress to amplitude of stress (σ_m/σ_a). It is physically reasonable for SEP that both stress and strain effects on cyclic life are considered. The maximum tensile stress is the summation of mean stress and stress range. In general, the mean stress is positive in PC cycles and negative in CP cycles and this may thus explain the damaging effects of the PC cycle in nickel-based superalloys.

REFERENCES

U.S. National Material Advisory Board (NRC), Analysis of Life Prediction Methods for Time Dependent Fatigue-Crack Initiation in Nickel-Based Superalloys, PB – 80, 158116, 1980.

2 Code case 1592, Nuclear vessels in high temperature service, Section III, ASME boiler pressure vessels code, (ASME, New York), 1974.

3 Miner, M.A., *Trans. of ASME,* **67** (1945), 159.

4 Robinson, E.L., *Trans. of ASME,* **74** (1952).

Taira, S., Life time of structures subjected to varying load and temperature, *In* Creep in Structures, (Academic Press, New York), 1962.

6. Manson, S.S., Halford, G.R. & Hirschberg, M.H., Creep-Fatigue Analysis by Strain Range Partitioning, NASA TMX–68171, 1972.

7. Halford, G.R. & Saltsman, J.F., Strain Range Partitioning – A Total Strain Range Version, NASA Technical Memorandum-83023, 1983.

8. Hirschberg, M.H. & Halford, G.R., Strain Range Partitioning – A Tool for Characterizing High Temperature Low Cycle Fatigue, NASA TMX - 71691, 1975.

9 Manson, S.S., Halford, G.R. & Hirschberg, M.H., Creep fatigue analysis by strain range partitioning, Symposium on Design for Elevated Temperature Environment, (ASME, New York), 1971.

10. Manson, S.S., The challenge to unify treatment of high temperature fatigue – A partition proposal based on strain range partitioning, *In* Fatigue at Elevated Temperature, ASTM-STP 520, 1973, pp 744–782.

Manson, S.S. & Zab, R., Treatment of Low Strains and Long Hold Times in High Temperature Metal Fatigue by Strain Range Partitioning, ONRL/sub - 3988/1 (Case Western Reserve University, Cleveland, Ohio), 1977.

12 Halford, G.R. & Nachtigall, A.J., *Journal of Aircraft,* **17** (1980).

13 Walker, K.P., Research and Development Program for Non Linear Structural Modelling with Advanced Time Temperature Dependent Constitutive Relationships, PWA 5700-50 (United Technologies Research Centre, East Hartfort, Connecticut), NASA CR-165533, 1981.

14 Hu Head, J., Duan, Z., Ning, Y. & Zhao, D., Strain energy partitioning and its application to GH 33 – A nickel-based superalloy and 1 Cr, 18Ni, 9Ti stainless steel, Life Prediction Methodology, Albany Conference, 1983, pp. 27.

15 Halford G.R. & Nachtigall, A.J., The Strain Range Partitioning Behaviour of an Advanced Gas Turbine Disc Alloy, AF 2-1 DA, NASA TM-79179, 1979.