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# A New Model of High Temperature Low Cycle Fatigue Life Prediction - Applicability with Low Alloy Steels

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## ABSTRACT

Creep-fatigue data on low alloy steels were collected from National Research Institute for Metals (NRIM) Tokyo, Japan. These data were generated for 1Cr-Mo-V, 2.25Cr-Mo, and 9Cr-1Mo steels under a wide range of test conditions. A new creep-fatigue life prediction method was developed and data compiled were assessed to examine the applicability of the new method. A brief review of the empirically based, phenomenological life prediction methods was presented where no method was found to be applicable universally to all the creep-fatigue data.

The new model was developed within the viscosity concepts, in which the damage parameter was accounted for in terms of dynamic viscosity. The deformations, represented in terms of flow characteristics, generated every cycle, were proposed to culminate in the failure of the specimen when the specimen can no longer accommodate viscous flow or deformations.

This method was found to be conservative under all the test conditions employed by the NRIM. In lack of assessments of the same data with other life prediction models, comments on the comparison of the analyses by various methods cannot be established.

**Key Words**: low alloy steels, strain controlled tests, high temperature low cycle fatigue, total strain ranges, strain rate, cycles to failure.

## INTRODUCTION

The high temperature low cycle fatigue (HTLCF) is a failure mechanism of engineering components that operate at high temperatures and stresses. As a result, strain accumulation is compounded with plastic and creep strains depending upon the time of steady loading and temperatures. Therefore, failures occur in the low cycle regime which ranges typically from a few hundred cycles to ten thousand cycles. In such applications, not only creep and plastic strain accumulation processes produce failures, but also, several other potential processes such as oxidation, erosion, fretting, corrosion and other mechanisms aid in the cause of premature failures.

It also is recognized that present analytical capabilities to account for such complex interactions are limited where much of the data and the analysis remain classified. Therefore, newer methods are being developed for conservative life prediction. The life prediction therefore, is an analysis in which cyclic lives ($N_f$) of HTLCF test conditions are predicted from the use of other test parameters. A bank of experimental parameters such as strain rate, strain range, temperature, ramp rate, hold time and material parameters such as prior work, heat treatment, microstructure, density of second phases present and their sizes, influence the life. Therefore, effects of several test and material parameters are isolated in developing life prediction models.

Presently, two frameworks namely; initiation of crack growth to a "detectable" size and "crack growth" respectively exist in which life prediction models are developed. The former framework has been used extensively since 1950 (Manson, 1953 and Coffin, 1954). However, fewer models were developed within "crack growth" frameworks (Price and Elder, 1966, and Tomkins, 1966). The challenges are in the development of accurate "detection" techniques to monitor formation and growth of cracks in HTLCF. At lower total (or plastic) strain ranges, crack size data versus number of cycles can be analyzed, which is very difficult at higher strains as the number of cycles reduce drastically.

## Background

Halford (1987, 1991) summarized the methods of life prediction under isothermal conditions during the period 1953 to 1991. He reported over one hundred such methods of HTLCF life prediction. These and other studies (Miller et al, 1984, Lloyd and Wareing, 1981, Brinkman, 1985, and Anon 1989) provide the scope of this research area. A few of these empirically based, phenomenological methods and their references, are summarized in Table 1. A brief description, equations, test requirements together with the number of empirical parameters used in each method, is presented in Table 1. Applicability of some of these methods with one set of data generated in Bristol University (Priest and Ellison, 1982) and Society of Materials Science, Japan (Inoue et al, 1989) is reported in open literature these results are compared with other data in (Goswami, 1995 a).

Applicability of the methods summarized in Table 1 was assessed with data sparingly (Lloyd and Wareing, 1981, Brinkman, 1985, Priest and Ellison, 1982 and Inoue et al, 1989), where every method was found to have mixed success and limitations. Modifications of a few existing life prediction methods, shown in Table 1, were made with respect to specific data set, used by (Priest and Ellison, 1982 and Inoue et al, 1989), however, applicability of modified versions were not been determined for other data sets. Three methods became popular analytical tools in the area of high temperature low cycle fatigue life prediction. These are as follows:

1. ASME Nuclear Code Case N-47 (Anon, 1976)
2. Strain Range Partitioning Technique (Manson et al, 1971)
3. Continuum Damage Mechanics Approach (Lemaitre et al, 1973)

The first two methods are used extensively in the North America, whereas, the third approach was developed in France and used successfully there. No other method, shown in Table 1, has been used as a design procedure in HTLCF.

Table 1. Popular life prediction methods and their test requirements.

| Method of life prediction | Life prediction equation | No. of material parameters (n) | Details of the tests |
|---|---|---|---|
| Linear life fraction (Anon, 1976) | $1 = \sum N / Nf + \sum t / t_r$ | - strain -life data (4)<br>- creep-rupture (2 to 4) | 0/0 tests ( $\varepsilon_t$-$Nf$)<br>creep rupture<br>stress relaxation |
| Frequency modified (Coffin, 1969, 1976) Approach | $N_f = [F/\Delta\varepsilon_p]^{1/\beta'}$ $[v_t/2]^{1-k}[v_c/v\,t]^d$ | -strain-life data (4)<br>- frequency vs. life (2)<br>- stress-strain (2) | 0/0 tests.<br>hold time tests<br>frequency -life |
| Strain range partitioning (Manson et al, 1971). | $N_{ij}=A_{ij}\Delta\varepsilon_{ij}^{\theta jk}$<br>ij represent PP, PC, CP and CC loops. | four inelastic strain vs. life relations. (2x4) | Tests producing complex loops PP, PC, CP and CC. |
| Ductility Normalized SRP (Halford et al, 1977) | There are at least 23-24 versions of SRP applied to specific applications. | Plastic and creep ductility (2) and their exponents (2). | Tensile tests short time creep rupture tests. |
| Damage Rate Approach (Majumdar and Maiya, 1976). (no-creep) | $da/dN = a\,[T]\,[\varepsilon_p]^m\,[\dot{\varepsilon}_p]^k$<br>$da/dN = a[C]\,[\varepsilon_p]^m\,[\dot{\varepsilon}_p]^k$ | scaling factors (2)<br>strain -life (4)<br>strain rate -life (2)<br>assuming a crack size | 0/0 tests<br>metallographic evidence<br>hold time tests. |
| with creep | $1/c\ da/dt = G\,[\varepsilon_p]^m\,[\dot{\varepsilon}_p]^{k'}$ | scaling factor in creep cavity size (1)<br>strain-life and rate (6) | metallographic evidence, creep data, test time. |

| | | | |
|---|---|---|---|
| Damage function method (Osterg -ren, 1976) | $C = \sigma_T \Delta\varepsilon\, p\, N\, f^{\beta}$ $\nu^{\beta(K-1)}$ | strain-life (4) frequency-life (2) stress-strain (2) shape correction factor | 0/0 data. frequency -N*f* stress-life hold time. |
| Damage parameter approach (Chrz-anoswski 1976) | $d\omega/dt = [\, Co\ \{\sigma/(1-\omega)\}^{v0}\ d\sigma/dt\ \ H\,(d\sigma) + C\{\sigma/(1-\omega)^{v}]\ H\,(\sigma)$ | material parameter (3) fatigue -damage (2) creep-damage (2) | stress versus damage in creep and fatigue. |

The 0/0 in the above table denotes continuous fatigue behavior with no hold times and symbols have specific meaning (see original references).

The crack growth concepts in HTLCF life prediction were first proposed by Price and Elder (1966). Tomkins (1966) modeled shear decohesion at the crack tip. Several such models (Solomon and Coffin, 1973, Dowling, 1977, Maiya, 1975, Solomon, 1973, Maiya and Busch, 1975, Wareing, 1975, Baudry and Pineau, 1977, Wareing, 1977, Skelton, 1978, Jaske and Begley, 1990 and Jaske, 1990) were developed to correlate crack growth and plastic strain range ($\Delta\varepsilon_p$) in empirical formulations. A common form of such representation is as follows:

$$da/dN = C\,(\Delta\varepsilon_p)^{\alpha}\ a^{Q} \qquad (1)$$

where a is crack length and C, $\alpha$ and Q are material parameters.

Several other parameters such as Mode I $\Delta K$ and other approaches within elastic-plastic parameters such as J-integral, $C^*$ and $T^*$ were developed. However, in summary, not a single approach can be applied universally under strain controlled, HTLCF, and high temperature crack growth processes.

Like most methods of HTLCF life prediction, summarized in Table 1, the new method also is an empirical model developed within the phenomenological framework.

Several correlating parameters, such as Coffin-Manson equation, stress-strain relationships, and viscosity expressions were used to develop the new model. An earlier version of the model presented in (Goswami, 1996, Goswami and Plumbridge, 1996) is discussed in this paper. Applicability of the proposed new method is assessed with a bank of creep-fatigue data on low alloy steels.

## The Model

The new model has been developed within the premise that deformation under creep-fatigue test conditions can be represented in terms of a viscous behavior, which is dissipative and irreversible. The dynamic viscosity therefore represented damage parameter. With the application of loads, which in the case of LCF is plastic strain dominated, or total strain range above elastic strain range, produce deformation with respect to time at a rate measured by strain rate. Every cycle, which is a time dependent term, produces a permanent strain and accumulates the damage. The damage parameter or the dynamic viscosity was described by equation (2).

$$\text{dynamic viscosity} = \Delta\sigma \times (\Delta\varepsilon_t / \dot{\varepsilon}) \qquad (2)$$

where $\Delta\sigma$ is the stress range, $\Delta \varepsilon_t$ is the total strain range and $\dot{\varepsilon}$ is the strain rate.

When the damage parameter reaches the toughness of a material the specimen fails. Toughness is a product of ductility and strength, where ductility is determined from the expression used by Edmund and White (1966) as follows:

$$N_f \, \Delta\varepsilon_p = D_p \qquad (3)$$

$N_f$ is the cycles to failure, $\Delta\varepsilon_p$ is plastic strain range and $D_p$ is the ductility.

The cyclic strength in a fatigue test was accounted in terms of saturated stress range at half life($\Delta\sigma_s$) represented in the following form:

$$\text{Toughness} = \Delta\varepsilon_p \, . \, Nf \, . \, \Delta\sigma_s \qquad (4)$$

The equations (2-4) presented above must be represented in terms of a mechanical equation of state for life prediction. Hart (1970) and Hart and Solomon (1973) presented such equations of state in creep. They accounted for the experimental fact that there is a scaling relationship. They constructed curves for stress and strain rate among the curves of different hardness; the constant hardness curves were brought in coincidence by translating along straight lines of slope m (Hart, 1970).

The new model presented in this paper, coincidence was used in terms of plots between the strain range to strain rate ratio, or cycle time, with number of cycles. The curves between the "cycle time" and cycles to failure had a slope in terms of m, as shown in Fig. 1 schematically, that was used in the equation of state as follows:

$$\sigma \times (\Delta\varepsilon_t / \dot{\varepsilon})^m = A \ \Delta\varepsilon_p \, . \, Nf \, . \, \Delta\sigma_s \quad (5)$$

Where A is a dimensional constant, which balances the units of the equation (5). Though the value of A varies with the test parameters, it was assumed unity for all the test conditions and the analyses performed.

Equation (5) was further modified by substituting stress-strain equation below.

$$K.(\Delta\varepsilon_p)^n \, . \, (\Delta\varepsilon_t / \dot{\varepsilon})^m = \Delta\varepsilon_p \, . \, Nf \, . \, \Delta\sigma_s \quad (6)$$

where, K and n are the parameters of stress-strain relation. Rearranging various terms of

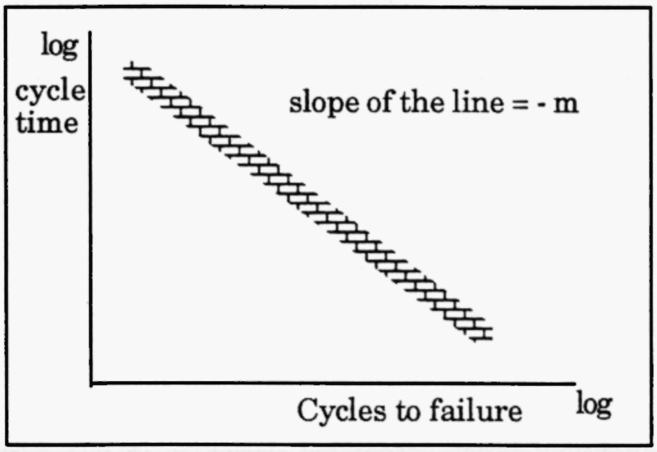



FIG. 1--Schematic determination of material parameter (m).

the equation (6) results in the following.

$$Nf = \{K.(\Delta\varepsilon_p)^{n-1} . (\Delta\varepsilon_t / \dot{\varepsilon})^m \} / \Delta\sigma_s \qquad (7)$$

Equation (7) was derived as a new life prediction equation. In the above equation only tensile strain rates were used and compressive strain rates were ignored, however, this may result in either conservative or over life prediction. Assessments with data will be performed to determine its' applicability for the continuous fatigue or symmetrical waveforms. However, for cycles containing hold times, an empirical adjustment was made in the above life prediction equation (7). A hold time correction was derived from data fitting as follows:

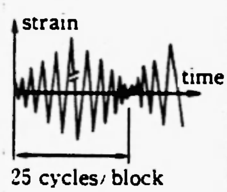
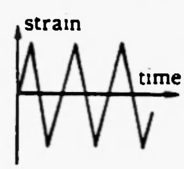
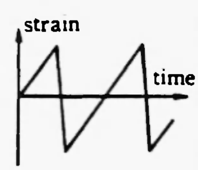
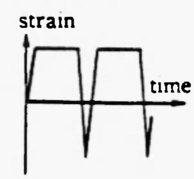
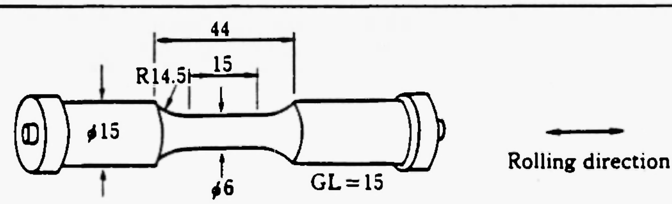
$$\text{Hold time correction} = \text{strain rate} / \{1+ \log(\text{time of hold in sec.})\} \qquad (8)$$

The above factor was used only for the cycles that contained hold times.

**Materials and Tests**

Three low alloy steels namely; 1Cr-Mo-V, 2.25Cr-Mo and 9Cr-1Mo were tested by NRIM (Anon, 1987, Anon, 1989 and Anon, 1993) under the test conditions summarized in Table 2. Tests were conducted from room temperature to 650°C with at least five strain rates, two hold time sequences of 6 and 60 minutes respectively in laboratory air. Tests with slow fast types of waveforms, in which the strain rates in tension and compression vary, were conducted at two temperature ranges. The specimen geometry and other details of the material, and test parameters, are available in (Anon, 1987, Anon, 1989 and Anon, 1993) for the three materials, summarized in Tables 2 and 3 respectively. The material parameters such as K, n and m used in the life prediction equation (7) are tabulated in Tables 4-6. It is pointed out that their values may vary with every test, however, those values tabulated in Tables 4-6 are assumed to remain constant for same temperatures and other associated variables in test parameters in order to simplify the analyses.

**Table 2. Details of the test matrix employed for different materials by NRIM**

| | | | | | | |
|---|---|---|---|---|---|---|
| Type of test | | Uniaxial | | | | |
| Type and capacity of testing machine | | Servohydraulic type, 50 kN | | | | |
| Loading condition | | Strain control under zero mean strain | | | | |
| | | Incremental step test[1)] | Constant amplitude test | | | |
| | | | Symmetrical | | Slow-fast | Tension hold |
| Waveform | |  |  | |  |  |
| Strain rate ($s^{-1}$) | Tension going | $10^{-3}$ | $10^{-3}$ | $5\times10^{-3}$, $10^{-4}$, $10^{-5}$ | $10^{-4}$, $10^{-5}$ | $5\times10^{-3}$ |
| | Compression going | | | | $5\times10^{-3}$ | |
| Hold time (h) | | 0 | 0 | 0 | 0 | 0.1, 1 |
| Temperature (°C) | | RT, 500, 550, 600, 650 | | 550, 600 | | |
| Environment | | Laboratory air | | | | |
| Specimen[2)] (dimensions in mm) | |  | | | | |

## Discussion on the Applicability of New Model

Assessment with data

In order to simplify the assessment, high temperature low cycle fatigue data were categorized as follows;

1. constant strain amplitude tests with symmetrical (triangular) waveform,

Table 3: Details of the material conditions and production histories of NRIM data.

| Material | Product form | Reduction ratio | Thermal history | Austenitic grain size |
|---|---|---|---|---|
| 1Cr-Mo-V | Forging | 3.2 | 1010°C/24h ac 700°C/38h ac 650/5h - 955°C/ 19h ac, 680°C/ 38h fc. | 7.5 following JIS G 0.551 (1977). |
| 1.25Cr-Mo | Plate, hot rolled | 39.1 | 925°C/50min.ac 690°C/60min.ac 655°C/60min.fc | 8.0 following JIS G 0.551 (1977). |
| 2.25Cr-Mo | Plate, hot rolled | 23 | 920°C/1.3h ac, 670°C/2.3h ac, 650°C/10.3h fc | 5.5 following JIS G 0.551 (1977). |
| 9Cr-1Mo | Plate, hot rolled | 8 | 1050°C/10min. ac, 770°C/1h ac 740°C/1h fc. | 11.6 following JIS G 0.551 (1977). |

(where ac for air cooling and fc for furnace cooling respectively)

Table 4: Material parameters used in the new model for 1Cr-Mo-V steel.

| Materials | K (MPa) | n | m | Temperature | Strain rate |
|---|---|---|---|---|---|
| 1Cr-Mo-V | 1082 | 0.128 | -0.32 | Room temp. | 0.1 %/sec. |
| 1Cr-Mo-V | 912 | 0.128 | -0.32 | 400°C | 0.1%/sec. |
| 1Cr-Mo-V | 815 | 0.143 | -0.30 | 500°C | 0.5%/sec. |
| 1Cr-Mo-V | 815 | 0.143 | -0.24 | 500°C | 0.1%/sec. |
| 1Cr-Mo-V | 815 | 0.143 | -0.40 | 500°C | 0.01%/sec. |
| 1Cr-Mo-V | 815 | 0.143 | -0.72 | 500°C | 0.001%/sec. |
| 1Cr-Mo-V | 693 | 0.133 | -0.36 | 550°C | 0.5%/sec. |
| 1Cr-Mo-V | 693 | 0.133 | -0.29 | 550°C | 0.1%/sec. |
| 1Cr-Mo-V | 693 | 0.133 | -0.4 | 550°C | 0.01%/sec. |
| 1Cr-Mo-V | 693 | 0.133 | -0.41 | 550°C | 0.001%/sec. |
| 1Cr-Mo-V | 693 | 0.133 | -0.24 | 600°C | 0.1%/sec. |

The parameters of cyclic stress-strain relations were determined by incremental step tests by linear regression analysis of log $\sigma$ to log $\varepsilon_p$ for plastic strains from 0.001 to 0.01 (Anon, 1987). The m was determined as follows, where cycle time = $\Delta\varepsilon_t / \dot{\varepsilon}$ tension.

Table 5: Material parameters used in the new model for 2.25Cr-1Mo steel.

| Materials | K (MPa) | n | m | Temperature | Strain rate |
|---|---|---|---|---|---|
| 2.25Cr-1Mo | 796 | 0.100 | -0.3 | Room temp. | 0.1 %/sec. |
| 2.25Cr-1Mo | 741 | 0.109 | -0.26 | 300°C | 0.1%/sec. |
| 2.25Cr-1Mo | 730 | 0.096 | -0.35 | 400°C | 0.1%/sec. |
| 2.25Cr-1Mo | 652 | 0.105 | -0.4 | 500°C | 0.5%/sec. |
| 2.25Cr-1Mo | 652 | 0.105 | -0.5 | 500°C | 0.1%/sec. |
| 2.25Cr-1Mo | 652 | 0.105 | -0.32 | 500°C | 0.01%/sec. |
| 2.25Cr-1Mo | 652 | 0.105 | -0.55 | 500°C | 0.001%/sec. |
| 2.25Cr-1Mo | 428 | 0.082 | -0.3 | 600°C | 0.5/sec. |
| 2.25Cr-1Mo | 428 | 0.082 | -0.43 | 600°C | 0.1%/sec. |
| 2.25Cr-1Mo | 428 | 0.082 | -0.44 | 600°C | 0.01%/sec. |
| 2.25Cr-1Mo | 428 | 0.082 | -0.38 | 600°C | 0.001%/sec. |

The parameters of cyclic stress-strain relations were determined by incremental step tests by linear regression analysis of log $\sigma$ to log $\varepsilon_p$ for plastic strains from 0.001 to 0.01 (Anon, 1989).

Table 6: Material parameters used in the new model for 9Cr-1Mo steel.

| Materials | K (MPa) | n | m | Temperature | Strain rate |
|---|---|---|---|---|---|
| 9Cr-1Mo | 975 | 0.117 | -0.29 | Room temp. | 0.1 %/sec. |
| 9Cr-1Mo | 693 | 0.132 | -0.32 | 500°C | 0.1%/sec. |
| 9Cr-1Mo | 609 | 0.142 | -0.36 | 550°C | 0.5%/sec. |
| 9Cr-1Mo | 609 | 0.142 | -0.29 | 550°c | 0.1%/sec. |
| 9Cr-1Mo | 609 | 0.142 | -0.45 | 550°C | 0.01%/sec. |
| 9Cr-1Mo | 609 | 0.142 | -0.42 | 550°C | 0.001%/sec. |
| 9Cr-1Mo | 443 | 0.121 | -0.5 | 600°C | 0.5%/sec. |
| 9Cr-1Mo | 443 | 0.121 | -0.35 | 600°C | 0.1%/sec. |
| 9Cr-1Mo | 443 | 0.121 | -0.42 | 600°C | 0.01%/sec. |
| 9Cr-1Mo | 443 | 0.121 | -0.58 | 600°C | 0.001%/sec. |
| 9Cr-1Mo | 343 | 0.125 | -0.46 | 650°C | 0.1%/sec. |

The parameters of cyclic stress-strain relations were determined by incremental step tests by linear regression analysis of log $\sigma$ to log $\varepsilon_p$ for plastic strains from 0.0005-0.0091 (Anon, 1993).

2. constant strain amplitude tests with slow-fast waveform, and
3. constant strain amplitude tests with tensile hold.

The HTLCF data on three materials namely; 1Cr-Mo-V, 2.25Cr-Mo and 9Cr-1Mo steels were used and assessments with the new model performed below.

## 1Cr-Mo-V Steel

### Constant Strain Amplitude Tests under Symmetrical (Triangular) Waveform

The material parameters used in the assessments are summarized in Table 4 for this material. Several temperatures and strain rates were used with constant strain amplitude tests. The value of parameter m was determined from data fitting, shown schematically in Fig. 1, from continuous fatigue conditions, which were used in life prediction analysis with slow-fast and hold-time waveforms. The analysis was carried out with the use of various parameters from Table 4 and predicted versus experimental lives or observed cyclic lives were plotted in Fig. 2. Figure 2 shows that the life prediction is conservative

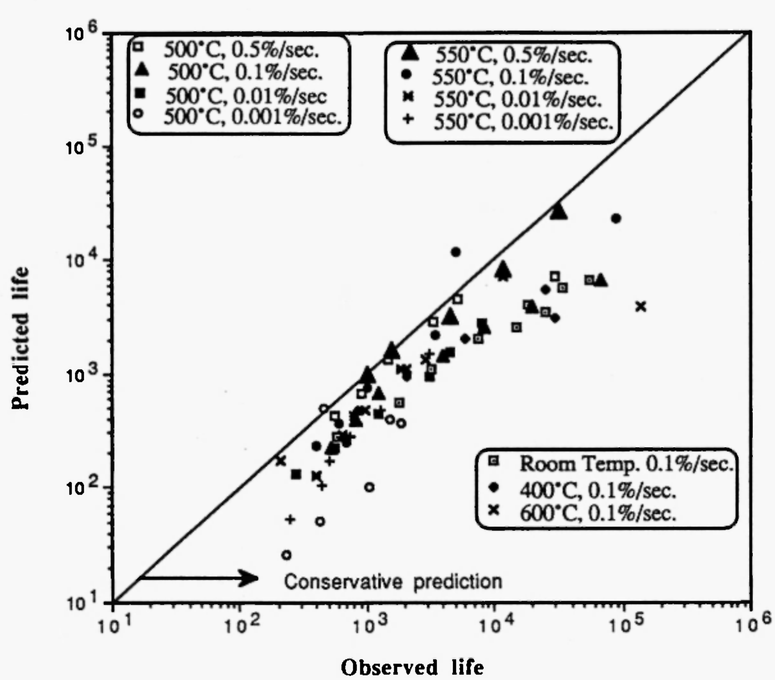



FIG. 2--Life prediction of 1Cr-Mo-V steel under continuous fatigue conditions.

for all the data used. It shows that as the range in the experimental lives increase, from $10^4$ cycles, the range in the predicted lives also increase. It is also observed that with a decrease in the strain rate the new model predicts lives more conservatively. A decreasing strain rate increases the cycle time, that contributes to the strain enhancement than that employed in a test. As a result prediction is very conservative.

Assessment of NRIM data with other life prediction methods has not been reported, therefore, comparison of the life prediction by the new and other methods is not possible. In a separate study (Goswami, 1995 a), it was observed that the prediction capability of methods, shown in Table 1, was found dependent upon the test parameters such as temperatures, strain ranges, strain rates, hold times and other factors. In that, strain range partitioning technique (SRP) was found applicable at high temperatures, higher strain ranges than the damage summation approach (DSA). The material in annealed condition was better represented by SRP and quenched and tempered condition was by DSA. Therefore, it is imperative that other methods may also exhibit the similar trends in life prediction of NRIM HTLCF data.

The new method was found to apply better in a range of temperatures, strain rates and strain ranges where the life prediction by the new model was very similar to the experimental lives. In the case of this material, under symmetrical test conditions, such combinations were 500°C, 0.5-0.1%/sec, total strain ranges above 0.25% and 550°C, 0.5-0.01%/sec, at all strain ranges. However, as the strain rate decreased to 0.001%/sec. the prediction was very conservative within a factor of 5.

Constant Strain Amplitude Tests with Slow-Fast Waveform

Slow-fast waveforms, in which the strain rates in tension and compression vary, are difficult to account in a model. Like other methods, tabulated in Table 1, the new model also is a material model, in them micro-mechanistic aspects that strain rates cause are

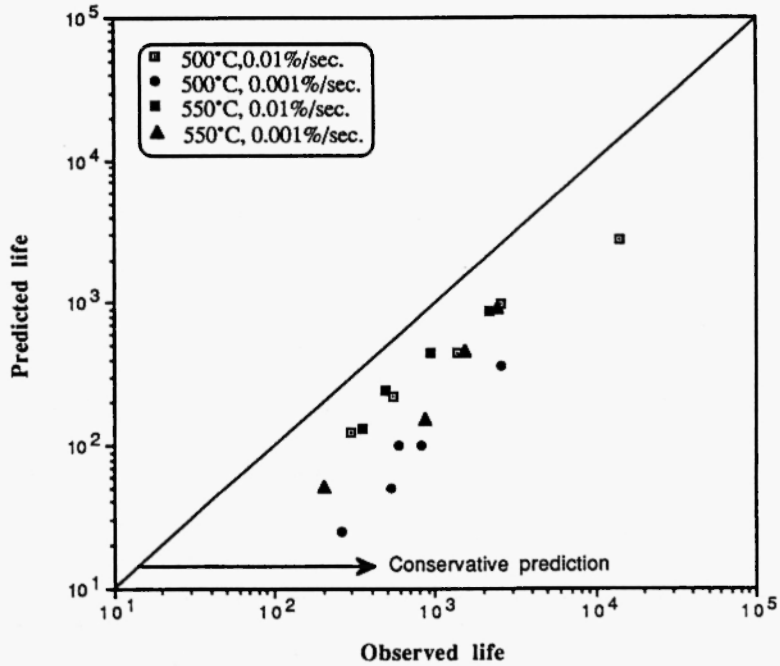



FIG. 3--Life prediction of 1Cr-Mo-V steel under slow-fast waveforms.

difficult to incorporate. Like most methods (see Table 1), this method also assumes strain rates in one direction. Therefore, the tensile strain rates which were lower (50 to 500 times) than compression strain rates, were used in the analysis. The predicted life by the new method under slow-fast conditions and observed life is shown in Fig. 3. It is apparent that a conservative prediction may result under such conditions, since variable strain rates cause either a healing or damaging effect, that cannot be separated by most methods. Higher strain rates (>0.01%/sec.), higher total strain range (>0.3%) and higher test temperatures (>550°C) predict the lives conservatively within a factor of 2-4, as was the case for SRP (Goswami, 1995 a).

Constant Strain Amplitude Tests with Tensile Hold

The equations (7-8) were combined and assessments performed for tensile hold cycles of 6 and 60 minutes. In these cases the predicted lives were very similar to that of experimental lives for the 6 min. hold cases above 0.3% total strain range at 500°C, as

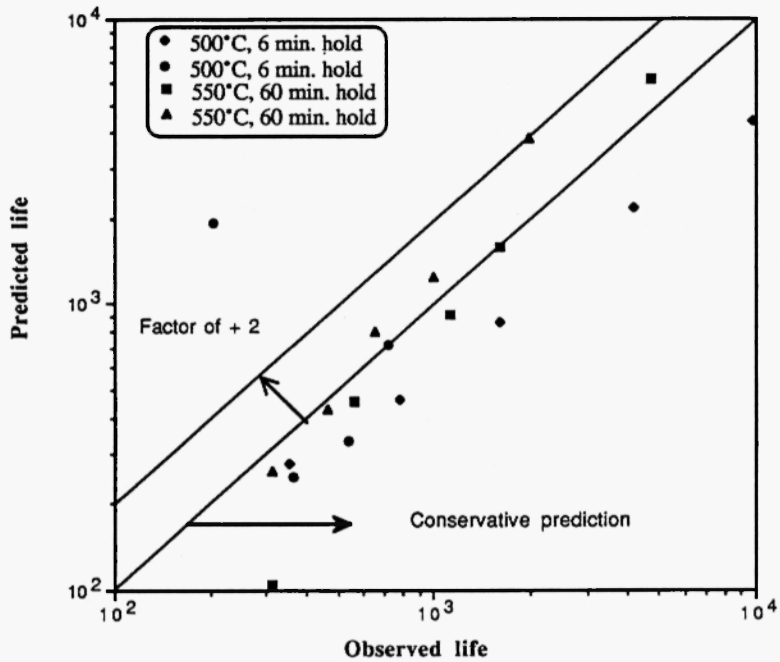



FIG. 4--Life prediction of 1Cr-Mo-V steel under tensile hold waveforms.

was the case with hold time of 60 min. and 550°C in Fig. 4. In all the cases, cyclic lives were predicted in a factor of $\pm$ 2. This factor is used extensively as a criterion in HTLCF life prediction. One point in Fig. 4 shows the associated experimental error.

## 2.25Cr-1Mo Steel

### Constant Strain Amplitude Tests with Symmetrical (Triangular) Waveform

The material parameters used in the analysis are tabulated in Table 5 and the life prediction results are shown in Fig. 5 respectively. At constant strain rates of 0.1%/sec, the predicted lives were very conservative below total strain range of 0.5% at room temperature. The experimental lives observed to improve at 300°C for this material, which may be due to dynamic strain aging that causes recrystallized Mo-C clusters (Wilson and Troman, 1970) and improve fatigue resistance during continuous fatigue as well as during holds (Challenger et al, 1981). Predicted lives were conservative at 300°C

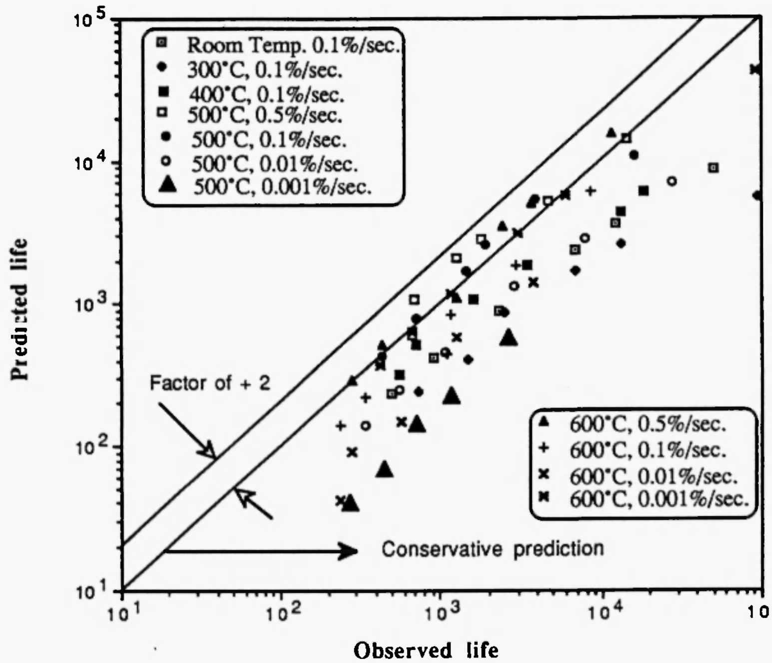



FIG. 5--Life prediction of 2.25Cr-Mo steel under continuous fatigue conditions.

shown in Fig. 5. As the temperature increases from 300°C, the region of dynamic strain aging gives rise to other mechanisms such as oxidation. Thereby, experimental lives decline with the increase in temperature noticed in (Goswami, 1995 a, b). The beneficial effects produced by Mo-C clusters at 300°C and detrimental effects of oxidation above 400°C are difficult to account in this material model. Other micro-mechanistic models must be developed to address this interactive phenomenon of deformation processes. At the outset, the prediction by the new model is within a factor of $\pm$ 2. It was also noticed that as the strain rate decreased and temperature increased, the prediction by the new model became very conservative in Fig. 5. A range of test temperatures, strain rates, and strain ranges was found to exist where predicted and observed lives were similar in Fig. 5.

<u>Constant Strain Amplitude Tests with Slow-Fast Waveform:</u>

The same criterion was used in the life prediction of slow-fast waveforms that used for

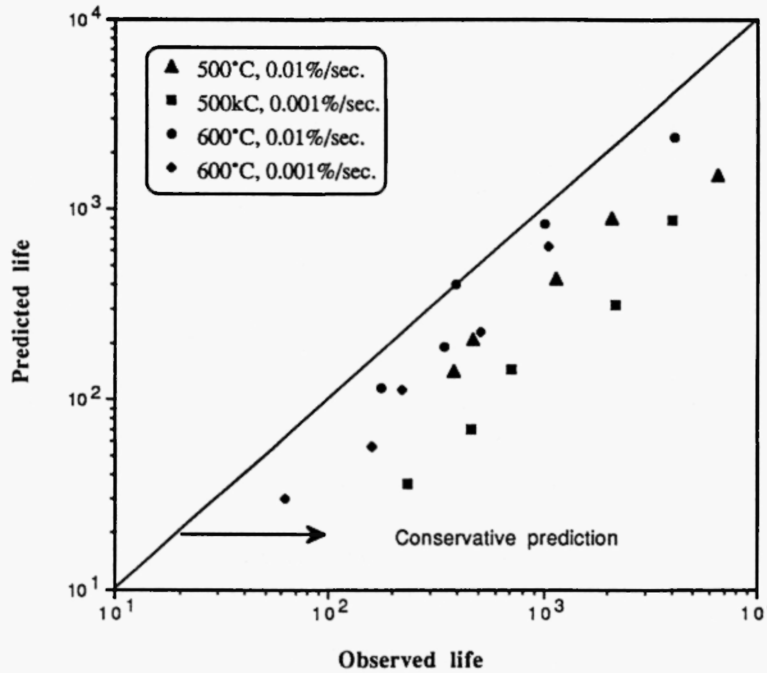



FIG. 6--Life prediction of 2.25Cr-Mo steel under slow-fast waveforms.

1Cr-Mo-V steel. At 500°C with tensile strain rates of 0.01 and 0.001%/sec the predicted lives were very conservative. However, as the temperature increased to 600°C, the predicted lives were in a factor of $\pm 2$, shown in Fig. 6. Behavior of the new method with higher temperatures was similar to SRP, however, why such a trend was observed is beyond the scope of this paper.

Constant Strain Amplitude Tests with Tensile Hold

The predicted and observed lives are plotted in Fig. 7. It was found that as the temperature increased from 500 to 600°C the predicted and experimental lives were quite similar at very low strain ranges (<0.25 %). However, as the hold times increased to 60 min. the new model was found to be very conservative, in Fig. 7.

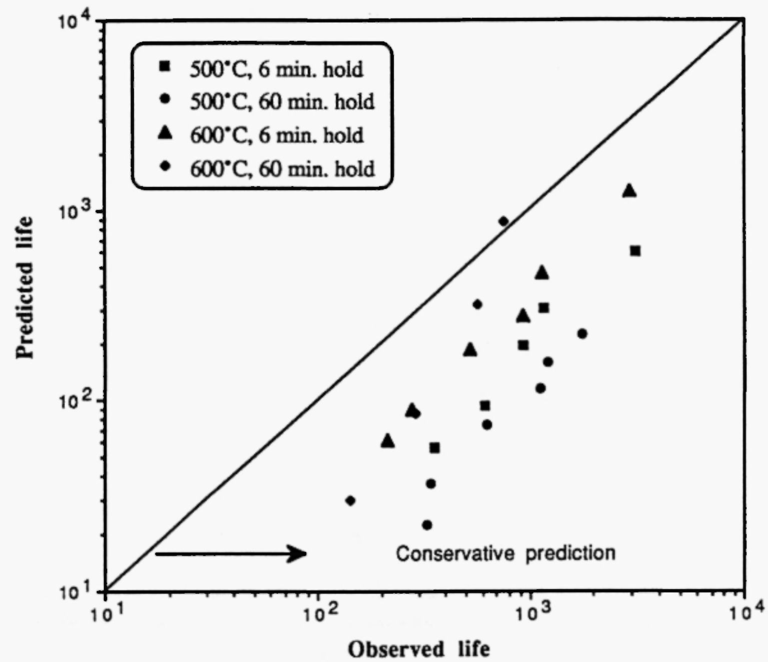



FIG. 7--Life prediction of 2.25Cr-Mo steel under tensile hold waveforms.

## 9Cr-1Mo Steel

<u>Constant Strain Amplitude Tests with Symmetrical (Triangular) Waveform:</u>

The material parameters used in the analysis for life prediction are shown in Table 6. Figure 8 shows that the predicted lives were very conservative at room temperature and with lower total strains (<0.7%). However, with an increase in temperature to 500°C predicted lives were in a factor of 2 above total strain range (>0.25%). At 550°C and 0.5%/sec strain rates, the predicted lives were very similar to experimental lives. With a decrease in strain rates the life prediction were very conservative. However, at 600°C under strain rates of 0.5 %/sec. and 0.1%/sec., the predicted and experimental lives were similar. Other methods examined in (Priest and Ellison, 1982, and Inoue et al, 1989) were also found to be conservative in a wide spectrum of test conditions.

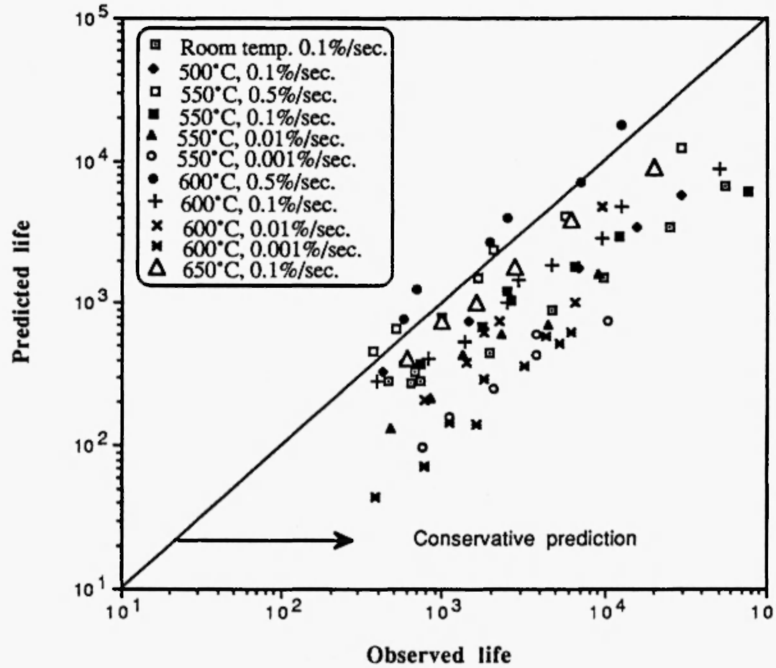



FIG. 8--Life prediction of 9Cr-1Mo steel under continuous fatigue conditions.

<u>Constant Strain Amplitude Tests with Slow-Fast Waveform:</u>

Figure 9 shows the predicted and experimental lives under slow-fast waveforms. At 600°C the predicted lives were higher than 550°C at both strain rates. The prediction was very conservative.

<u>Constant Strain Amplitude Tests with Tensile Hold</u>

With 6 min. hold times the predicted lives were in a factor of 2 for both temperatures. However, as the hold time increased to 60 minutes, more conservative life prediction resulted for 550°C which was in a factor of 2 for 600°C test conditions.

In lack of analysis of these NRIM, HTLCF, data with other methods of life prediction, summarized in Table 1, comparison of new and other methods was not possible. However, prediction capability of other methods as observed in (Goswami, 1995 a) was

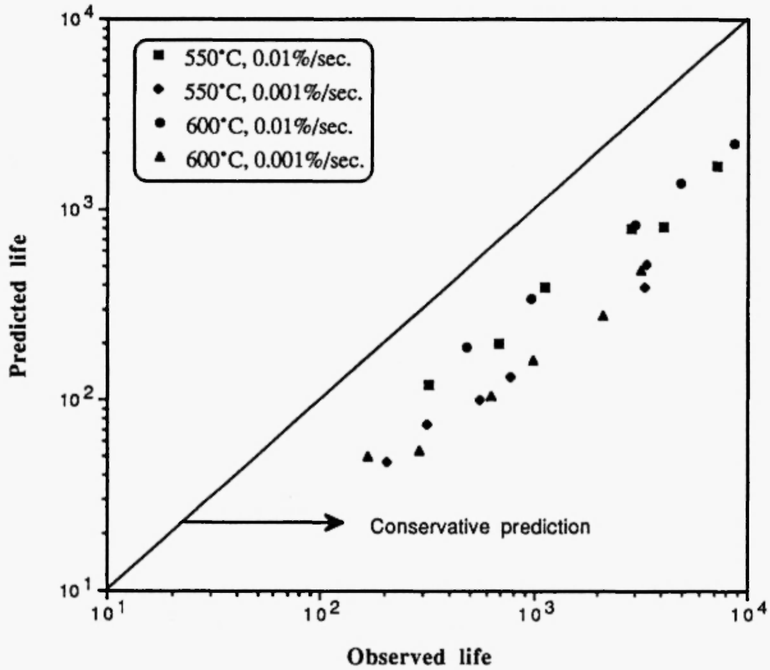



FIG. 9--Life prediction of 9Cr-1Mo steel under slow-fast waveforms.

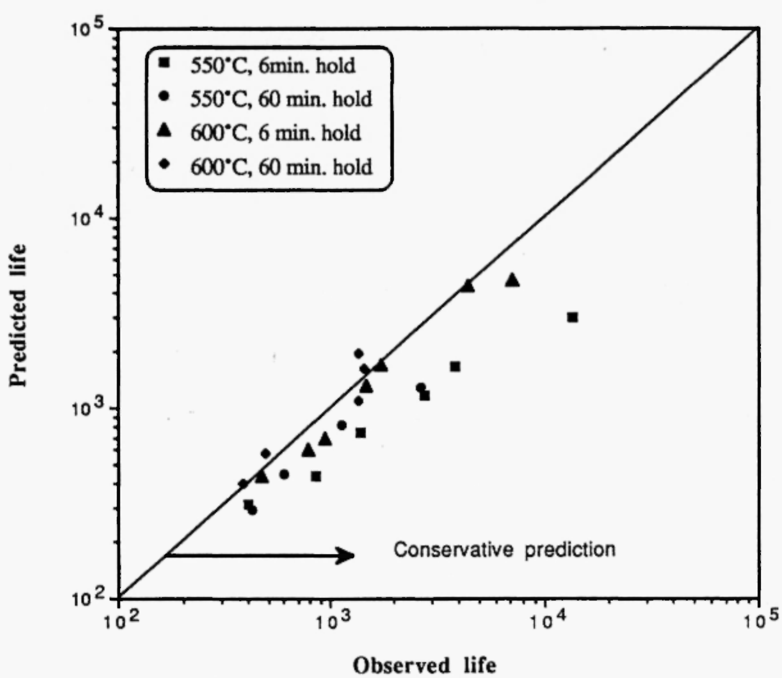



FIG. 10--Life prediction of 9Cr-1Mo steel under tensile hold waveforms.

dependent upon test and material parameters utilized. The DSA approach was found to predict 0 to 100% of test data in a factor of 2 depending upon test temperatures, material conditions, hold times and other unspecified parameters. With an increase in temperature from 485°C, the prediction capability declined. However, the SRP approach was found to be better applicable with higher temperatures and strain ranges in annealed conditions. It may be noted that both the approaches are very extensively used which do not use strain rates in the modeling. Therefore, applicability of these methods with different strain rate combinations is limited. The Frequency modified or separation approach uses the strain rates in different directions, however, a limited use of this method was found in the literature.

The methods described in Table 1 use a number of material parameters in each method, which were unspecified in the NRIM data sets. Use of material parameters determined from one set of data to other data sets is questionable, therefore, such analyses were not carried out to compare life assessments of new model with other models. However, this may become the topic of a future note should such analyses become available in the literature.

## Conclusion

A new creep-fatigue life prediction model was developed in this paper. The model assumes that the damage is caused by plastic deformation which was represented by dynamic viscosity. When the damage or the dynamic viscosity reaches the material toughness the failure occurs. The material toughness uses mechanical properties of materials in terms of plastic strain range, ductility and the saturated stress range at half life. The equations were rearranged to produce an equation of state. The applicability of the proposed model was examined with creep-fatigue data on low alloy steels provided by NRIM where the prediction was found to be conservative. More assessments with data are recommended in order to use this model in design. From the assessments performed the new model was found to correlate and predict HTLCF lives conservatively.

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**References**

Anon, Code Case N-47, ASME Boiler and pressure vessel code, Criteria for design of elevated temperature, Class 1 components in Section III, Division 1, 1976, American Society of Mechanical Engineers.

Anon, Nonlinear Fracture Mechanics: Vol.1, Time dependent fracture, ASTM STP 995, A. Saxena, J. D. Landes and J. L. Bassani, eds. ASTM, 1989.

Anon, National Research Institute for Metals, Fatigue data sheet No. 58, 1987.

Anon, National Research Institute for Metals, Fatigue data sheet No. 62, 1989.

Anon, National Research Institute for Metals, Fatigue data sheet No. 78, 1993.

Baudry, G. and Pineau, A., Mat. Sci. & Eng.Vol. 28, 1977, pp. 229-242.

Brinkman, C. R. International Metals Reviews, Vol. 30, 1985, pp.235-258.

Challenger, K. D., Miller, A. K. and Brinkman, C. R., ASME Trans. J. Eng. Mat. and Tech. Vol. 103, 1981, pp. 7-14.

Chrzanowski, M. Int. J. Mech. Sci. Vol. 18, 1976, pp. 69-73.

Coffin, L. F. Jr. Trans. ASME vol. 76, 1954, pp. 931-950.

Coffin, L. F. Jr. in Proc. 2nd Int. Conf. on Fracture, 1969, pp.643-654.

Coffin, L. F. Jr. in Symposium on. Creep-fatigue interaction, MPC-3, ed. R. M. Curran, ASME, 1976, pp. 349-363.

Dowling, N. E. in Cyclic stress-strain and plastic deformation aspects of fatigue crack growth, ASTM STP 637, 1977, pp. 97-121.

Edmund, H. G. and White, D. J., J. Mech. Eng. Sci. Vol. 8, 1966, pp. 310-321.

Goswami, T. (a), High Temperature Materials and Processes, 14, 1995, pp. 21-33.

Goswami, T (b), High Temperature Materials and Processes, 14, 1995, pp. 1-20.

Goswami, T., ISIJ International, 36, 3, 1996 pp. 354-360.

Goswami, T. and Plumbridge, W. J., I. Mech. E. 1996, Paper No. L14/C494-95.

Halford, G. R. Chapter 6, Thermal Stresses II edited by R. B. Hetnarski, Elsevier Science Publication, 1987 pp. 330-428.

Halford, G. R. "Evolution of creep-fatigue life prediction models" ASME Winter Annual Meeting on Creep-fatigue interaction at high temperature, ed. G. K. Haritos and O. O. Ochoa. AD-Vol. 21, 1991.

Halford, G. R., Saltsman, J. F. and Hirschberg, M. H. in Proc. of Conference on environmental degradation of engineering materials, Virginia Tech. Printing Dept. 1977, pp. 599-612.

Hart, E. W., Acta. Metall. Vol. 18, 1970, pp. 599-610.

Hart, E. W. and Solomon, H. D., Acta. Metall. Vol. 21, 1973, pp. 295-307.

Inoue, T., Igari, T., Okazaki, M. and Tokimasa, K. Nucl. Engeg. Des. Vol. 114, 1989, pp. 311-321.

Jaske, C. E. and Begley, J. A., in Proc. of Symposium on ductility and toughness considerations in elevated temperature service, MPC-8, ASME, 1978, pp. 391-09.

Jaske, C. E., ASME J. of Pressure Vessel Tech. Vol. 112, 1990, pp.20-27.

Leis, B. N. J. Pressure Vessel Technol. ASME Vol. 99, 1977, pp. 524-533.

Lemaitre, J., Chaboche, J. L. and Munakata, Y. Proc. Symposium on Mechanical behavior of materials, Kyoto, Japan, 1973, pp. 239-249.

Lloyd, G.J. and Wareing, J. Metals Technology , 809, 1981, pp. 297.

Manson , S. S. "Behavior of materials under conditions of thermal stress; Heat Transfer Symposium" University of Michigan Engineering Research Institute, 1953, pp. 9-75.

Manson, S. S., Halford, G. R. and Hirschberg, M. H. in Proc. of Symposium on Design for elevated temperature environment, ASME, 1971, pp. 12-28.

Maiya, P. S., Scripta Metallurgica, Vol. 9, 1975, pp. 1277-1282.

Maiya, P. S. and Busch, D. E., Met. Trans. A, Vol 6, 1975, pp. 1761-1766.

Majumdar. S. and Maiya, P. S. in Symposium creep-fatigue interactions, MPC-3 ASME, 1976, pp. 323-336.

McLean, D. and Pineau, A. Met. Sci, Vol. 12, 1978, pp. 313-316.

Miller, D. A., Priest, R. H. and Ellison, E. G., High Temperature Materials and Processes, Vol. 6, 1984, pp. 155-194.

Ostergren, W. J. J. Test. and Eval. Vol. 4, 1976, pp. 327-339.

Priest, R. H. and Ellison, E. G., Res. Mech. Vol. 4, 1982, pp. 127-150.

Price, A. T. and Elder, W. J. J. of the Iron and Steel Institute, Vol. 204, 1966, pp. 594-98.

Radhakrishnan, V. M. in ASTM STP 770 D. Amzallag, B. N. Leis and P. Rabbe eds. ASTM 1982, pp. 135-151.

Skelton, R. P., Mat. Sci. & Eng. Vol. 35, 1978, pp. 287-298.

Solomon, H. D. and Coffin, L. F. Jr. Fatigue at elevated temperature, ASTM STP 520, 1973, pp. 112-122.

Solomon, H. D., Met. Trans. A, Vol. 4, 1973, pp. 341-347.

Tomkins, B. Phil. Mag., Vol. 18, 1966, pp. 1041-1066.

Wareing, J. Met. Trans. A, Vol. 6, 1975, pp. 1367-1377.

Wareing, J., Met. Trans. A, Vol. 8A, 1977, pp. 163.

Wilson, D. V., and Troman, J. K., Acta. Metall., Vol. 18, 1970, pp. 1197-1208.