NASA Technical Memorandum 106684

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July 1994

APPLICATION OF AN ENERGY-BASED LIFE PREDICTION MODEL TO BITHERMAL AND THERMOMECHANICAL FATIGUE

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SUMMARY

The inelastic hysteresis energy supplied to the material in a cycle is used as the basis for predicting nonisothermal fatigue life of a wrought cobalt-base superalloy, Haynes 188, from isothermal fatigue data. Damage functions that account for hold-time effects and time-dependent environmental phenomena such as oxidation and hot corrosion are proposed in terms of the inelastic hysteresis energy per cycle. The proposed damage functions are used to predict the bithermal and thermomechanical fatigue lives of Haynes 188 between 316 and 760 °C from isothermal fatigue data. Predicted fatigue lives of all but two of the nonisothermal tests are within a factor of 1.5 of the experimentally observed lives.

NOMENCLATURE

$A_{k,m}$ coefficients in the damage functions $\delta D_{k,m}$; $k = P$ (plasticity; time-independent inelastic strain), C (creep; time-dependent inelastic strain) and $m = t$ (tension), c (compression)

C_{ij} coefficients of life relations in Generalized Strainrange Partitioning method; $i, j = P,C$

CP tensile creep reversed by compressive plasticity in a cycle

$CCOP$ bithermal compressive creep out-of-phase (PC)

F_{env} environmental factor

$G_{ij}(t_c)$ functions of t_c; $i, j = P,C$

$F(t_h)$ hold time function

$HRIP$ bithermal high rate in-phase (PP)

$HROP$ bithermal high rate out-of-phase (PP)

IP in-phase

N_f fatigue life

N_{ij}	generic Strainrange Partitioning cyclic lives; $i,j = P,C$
n'	cyclic strain hardening exponent
OP	out-of-phase
PC	tensile plasticity reversed by compressive creep in a cycle
PP	tensile plasticity reversed by compressive plasticity in a cycle
$TCIP$	bithermal tensile creep in-phase (CP)
$TMIP$	thermomechanical in-phase
$TMOP$	thermomechanical out-of-phase
t_c	average time required per cycle to introduce time-dependent inelastic strain range in creep-fatigue loading, t_e/N_{ij}
t_e	total exposure time
t_h	hold time in a cycle
t_o	time constant in the hold-time function, $F(t_h)$
α_{ij}	exponents of generic strain ranges in Generalized Strainrange Partitioning method; $i,j = P,C$
$\beta_{k,m}$	exponents in the damage functions $\delta D_{k,m}$; $k = P,C$ and $m = t,c$
γ_{ij}	exponents of exposure time in Generalized Strainrange Partitioning method; $i,j = P,C$
$\delta D_{k,m}$	damage in half-cycle; $k = P,C$ and $m = t,c$
δD_P	total damage in a rapid fatigue cycle
δD_T	total damage in a cycle
δW_P	time-independent inelastic strain energy density per cycle in isothermal fatigue
δW_T	total inelastic strain energy density per cycle in creep-fatigue
$\delta W_{k,m}$	inelastic strain energy density in half-cycle; $k = P,C$ and $m = t,c$
$\Delta\varepsilon_{ij}$	generic inelastic strain ranges in the Generalized Strainrange Partitioning method; $i,j = P,C$
$\Delta\varepsilon_{k,m}$	inelastic strain range in a half-cycle; $k = P,C$ and $m = t,c$
σ_t	stress at tensile peak strain in a cycle
σ_c	stress at compressive peak strain in a cycle

INTRODUCTION

Prediction of high-temperature, low-cycle fatigue life (HTLCF) under different types of loading conditions can be a complex process. Many attempts have been made in the last two decades to analyze the creep-fatigue interaction for life prediction (refs. 1 to 10). Notable among them are the Strainrange Partitioning (SRP) method (refs. 1 and 2), the Frequency Modified Life method (ref. 3), and the Inelastic Energy method (ref. 4). When these methods were proposed, the exposure time, t_e of the material to high temperature was recognized as one of the variables influencing creep-fatigue life. However, within a given creep-fatigue type of loading the effect of t_e was not considered explicitly as a possible source of enhanced damage accumulation. Prolonged exposure of the material to elevated temperature can introduce a number of metallurgical changes including oxidation, hot corrosion, and solid state transformations such as strain-ageing, which can enhance the damaging process and reduce the fatigue life. Further, the exact nature of damage from the same amount of exposure time can be different for different types of creep-fatigue loadings viz., tensile versus compressive dwell times.

The objectives of the present study are (a) to investigate whether a combination of time-dependent parameters and the mechanical hysteresis energy (inelastic strain energy density) supplied to the material in a cycle can be used as a damage parameter for high-temperature cyclic life prediction and (b) to determine whether such an approach can make use of isothermal data and corresponding life relationships for predicting the cyclic lives under bithermal and thermomechanical fatigue. The material considered is a wrought cobalt-base superalloy, Haynes 188 with ductility in the range of 60 to 70 percent.

EFFECT OF EXPOSURE TIME

Kalluri (ref. 11), recognized the importance of the exposure time within a given creep-fatigue type of loading. Working with type 316 stainless steel, he modified the Conventional SRP (CSRP) method by taking into account the exposure time, t_e in the basic equations. This analysis led to Generalized SRP (GSRP) method with exposure time modified life relations. The HTLCF data points of type 316 stainless steel, which could be predicted only to within factors of 2.3 when analyzed by the CSRP method, could be described by the GSRP method to within factors of 1.5. The baseline GSRP fatigue relations for the generic strain ranges containing creep are given in the form

$$N_{ij} = C_{ij}\left(\Delta\varepsilon_{ij}\right)^{\alpha_{ij}}\left(t_e\right)^{\gamma_{ij}} \tag{1}$$

For isothermal creep-fatigue, the CP and PC life relations for type 316 stainless steel at 816 °C are given by (ref. 11)

$$N_{CP} = 0.113\left(\Delta\varepsilon_{CP}\right)^{-1.63}\left(t_e\right)^{-0.332}$$

$$N_{PC} = 21.8\left(\Delta\varepsilon_{PC}\right)^{-0.696}\left(t_e\right)^{-0.223} \tag{2}$$

where t_e is the total time of exposure in hours. If t_c is defined as the average time taken in hours to introduce the inelastic strain range, $\Delta\varepsilon_{CP}$ in each cycle, then

$$t_c = \frac{t_e}{N_{CP}} \tag{3}$$

and the CP relation can be rewritten in terms of t_c as,

$$N_{CP} = 0.194\left(\Delta\varepsilon_{CP}\right)^{-1.22}\left(t_c\right)^{-0.25} \tag{4}$$

Similarly, the PC life relation for 316 stainless steel at 816 °C (ref. 11) can be reduced as follows.

$$N_{PC} = 12.4\left(\Delta\varepsilon_{PC}\right)^{-0.569}\left(t_c\right)^{-0.182} \tag{5}$$

The isothermal *CP* and *PC* fatigue data reported in Ref. 11 for type 316 stainless steel have been replotted and shown in figure 1. It is clear that the relation between the inelastic time-dependent strain range and the corresponding fatigue life is a function of time that is required to introduce the strain range in each cycle. With an increase in t_c, the fatigue life decreases as given by equations (4) and (5). Thus, in general, we find that the fatigue life is a function of the inelastic strain range and the corresponding time per cycle, which can be written in a form similar to equation (1),

$$N_{ij} = A_{ij}\left(\Delta\varepsilon_{ij}\right)^{\alpha_{ij}} G_{ij}\left(t_c\right) \tag{6}$$

where G_{ij} $(i, j = P, C)$ is a function of time, t_c, in each cycle under a particular type of creep-fatigue loading condition.

ENERGY BASED CONSIDERATIONS

The method presented in this paper is applicable to ductile materials subjected to cyclic inelastic deformation. Under such circumstances, the hysteresis loop associated with either rapid cycling fatigue (*PP*) or creep-fatigue with hold-time can be divided into two portions, namely tensile and compressive portions, and the inelastic strain energy density corresponding to these parts can be given for rapid fatigue by (ref. 12)

$$\delta W_{P,t} = \left(\frac{1-n'}{1+n'}\right)\sigma_t \,\Delta\varepsilon_{P,t} \tag{7}$$

and

$$\delta W_{P,c} = \left(\frac{1-n'}{1+n'}\right)|\sigma_c|\Delta\varepsilon_{P,c} \tag{8}$$

and for stress-hold, creep-fatigue loading conditions by

$$\delta W_{C,t} = \sigma_t \,\Delta\varepsilon_{C,t} \tag{9}$$

and

$$\delta W_{C,c} = |\sigma_c|\Delta\varepsilon_{C,c} \tag{10}$$

The damage in tension, $\delta D_{P,t}$, or in compression, $\delta D_{P,c}$, in the case of rapid fatigue, is taken as a function of the half cycle inelastic energy term (ref. 13). Using the energy relations (eqs. (7) and (8)) the damage functions can be given as

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$$\delta D_{P,t} = A_{P,t} \left(\delta W_{P,t} \right)^{\beta_{P,t}} \qquad . \tag{11}$$

$$\delta D_{P,c} = A_{P,c} \left(\delta W_{P,c} \right)^{\beta_{P,c}} \tag{12}$$

Under isothermal condition,

$$
\begin{aligned}
\delta D_{P,t} &\equiv \delta D_{P,c} = \frac{\delta D_P}{2} \\
A_{P,t} &\equiv A_{P,c} \\
\beta_{P,t} &\equiv \beta_{P,c} = \beta_P \\
\delta W_{P,t} &\equiv \delta W_{P,c} = \frac{\delta W_P}{2}
\end{aligned}
\tag{13}
$$

and the total damage, δD_P, in rapid fatigue is given by

$$\delta D_T = \delta D_P = A_P \left(\delta W_{P,t} + \delta W_{P,c} \right)^{\beta_P} \tag{14}$$

where it can easily be shown that

$$A_{P,t} = A_{P,c} = 2^{\left(\beta_P - 1 \right)} A_P \tag{15}$$

In the case of stress-hold cycles, damage is caused by time-dependent environmental effects such as oxidation and hot corrosion in addition to the damage caused by mechanical creep straining. For a given material, damage caused by oxidation depends upon temperature and the type of hold-stress imposed on the material. For example, hold time in tension induces void formation at the grain boundaries and triple point wedge cracking, which result in intergranular fracture. However, hold time in compression does not induce grain boundary voids and usually produces transgranular cracking, which can interact with oxidation in a different manner than intergranular cracking. In a tensile stress-hold bithermal fatigue test, Kalluri and Halford (ref. 14) observed oxide formation along the intergranular fracture surface and within the secondary cracks along the grain boundaries in Haynes 188. They had also observed that oxide formed primarily along the fatigue specimen's external surface and transgranular fracture surface in a compressive stress-hold bithermal fatigue test (ref. 14). These observations clearly indicate that the damage functions associated with tensile hold time should be different from those of the compressive hold time, as the nature and severity of damage associated with these two types of hold periods are differ-

ent. These creep and environmental damage factors, $F(t_h)$ and F_{env}, respectively, will have to be associated with the energy term in the case of hold period for obtaining the total damage caused by creep, oxidation, and mechanical straining. It is likely that $F(t_h)$ and F_{env} are not completely independent and each factor can have an influence on the other factor. However, as a first approximation, they are assumed to be separate and independent factors. The damage functions, $\delta D_{C,t}$ and $\delta D_{C,c}$, due to tensile and compressive stress-holds can be given as

$$\delta D_{C,t} = A_{C,t}\ \delta W_{C,t}^{\beta_{C,t}}\ F(t_h)F_{env} \qquad (16)$$

$$\delta D_{C,c} = A_{C,c}\ \delta W_{C,c}^{\beta_{C,c}}\ F(t_h)F_{env} \qquad (17)$$

The total damage due to a hysteresis loop, δD_T is defined as the algebraic sum of damages from the tensile and compressive halves of that hysteresis loop. With equations (11), (12), (16), and (17) the total damage, δD_T, associated with any hysteresis loop in either isothermal or bithermal fatigue in a ductile material can be obtained. The fatigue life is then given by

$$N_f = \frac{1}{\delta D_T} \qquad (18)$$

The above relation assumes that the critical damage at the time of failure is equal to unity and the damage in each cycle is the same, i.e., a linear damage rule for a given type of creep-fatigue cycle.

DATA ANALYSIS

Isothermal Fatigue Analysis

The isothermal, bithermal, and thermomechanical fatigue data of a wrought cobalt-base superalloy, Haynes 188, reported in Ref. 15 have been analyzed for the applicability of the inelastic energy-based damage model proposed in this paper. Hysteresis loops for the isothermal and nonisothermal fatigue tests are shown schematically in figure 2. Details of experimental equipment and testing procedures were described previously (ref. 15). The isothermal, bithermal, and thermomechanical fatigue data of Haynes 188 were previously analyzed on the basis of elastic and inelastic strain energy densities in a cycle (ref. 12). Figure 3 shows the inelastic strain energy density versus life in isothermal fatigue (PP) of Haynes 188 at 316 and 760 °C. The inelastic strain energy density in an isothermal cycle has been calculated using equations (7) and (8). The damage caused by the isothermal cycle is related to the life, N_f by equations (14) and (18).

The governing life relations, expressed in terms of δW_P and N_f, are given by (ref. 12),

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$$\delta W_P = 5000\left(N_f\right)^{-0.77} \text{ at 316 } ^{\circ}\text{C}$$

$$\delta W_P = 600\left(N_f\right)^{-0.77} \text{ at 760 } ^{\circ}\text{C}$$

(19)

where the energy is in N-mm/mm³. In obtaining these life relations a common exponent of -0.77 was used for fatigue life in Ref. 12. These inelastic energy-fatigue life relations are also shown in figure 3. The correlations between the inelastic strain energy density per cycle and the fatigue life for the isothermal data appear to be good and are used as the baseline relations (eq. (19)) for estimating the bithermal and thermomechanical fatigue lives.

Bithermal Fatigue Analysis

The hysteresis energy associated with the tensile and compressive portions of a bithermal fatigue cycle is given by equations (7) to (10) depending on the type of loading. The total inelastic strain energy density in a bithermal cycle (fig. 2), δW_T is defined as the sum of the inelastic strain energy densities in the tensile and compressive halves of the cycle. The total inelastic strain energy density is plotted against the fatigue life for all the bithermal tests of Haynes 188 in figure 4. For comparison, the inelastic strain energy density versus isothermal fatigue life relations (eq. (19)) are also shown in figure 4. The thermomechanical fatigue data shown in the figure will be discussed later. As pointed out earlier, Haynes 188 is a ductile material and hence the damage functions given by equations (11), (12), (16), and (17) can be used.

The factors $F(t_h)$ and F_{env} are dependent on the creep and oxidation effects. The creep effect is a function of time which increases with increasing time. In the primary stage when the load is held constant, a power law with an exponent of one-third governs the creep strain accumulation. Hence, the damage effect is also assumed to be a one-third law, given in the form

$$F\left(t_h\right) = \left(\frac{t_h}{t_o}\right)^{1/3}$$

(20)

where both t_h and t_o are in minutes and t_o, which is a constant, and is taken as 1 min for calculation purposes.

The environmental effect (oxidation) is also time dependent, but may attain a saturation value at a given temperature. The exact nature of the function is dependent on the material. Further, during tensile loading the tensile stress will assist the oxide to penetrate inside the material, causing more damage. In compression the effect of oxidation will be restricted to the surface of the material. Hence the value of F_{env} in tension will be higher than that in compression. In addition, the type of environment can also influence damage accumulation. For example, damage accumulation in the form of crack propagation rate has been observed to be higher by a factor of 2 to 3 in the presence of hot corrosion than in air (ref. 16).

In bithermal fatigue, during in-phase loading, where the tensile stress assists oxidation at the higher temperature side the environmental effect is likely to be higher and F_{env} is taken as 2, whereas in

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the out-of-phase loading, where the higher temperature occurs under compression, the environmental effect is likely to be lower and F_{env} is taken as unity. In the absence of clear functional relationships the above assumptions have been made. The values of F_{env} for the different types of loading conditions are given in table I. It can be modified as more quantitative information is available on the exact nature of environmental effects on damage accumulation.

The constants used to calculate the total damage in bithermal fatigue and creep-fatigue are shown in table II. These constants are based on the isothermal fatigue life relations (eq. (19)) and are used in conjunction with equations (11), (12), (16), and (17) to calculate total damage. Thus, for a typical TCIP loading, equations (12) and (16) have been used to compute $\delta D_{C,t}$ and $\delta D_{P,c}$ with the following:

$$\beta_{C,t} = \beta_{P,t} = \beta_P$$
$$A_{C,t} = A_{P,t} \tag{21}$$
$$F_{env} = 2$$

The total damage in a TCIP cycle can be given by,

$$\delta D_T = \delta D_{C,t} + \delta D_{P,c} \tag{22}$$

The total damage for other types of bithermal loading cycles has been computed in a similar manner and the relation between the total damage per cycle, δD_T and the fatigue life, N_f for the bithermal fatigue tests of Haynes 188 is shown in figure 5.

Thermomechanical Fatigue

In the case of thermomechanical fatigue, TMIP and TMOP tests, the values of the cyclic strain hardening exponent n' are 0.11 and 0.23, respectively, for Haynes 188 (ref. 15). In a previous study on the analysis of isothermal and nonisothermal fatigue data of Haynes 188 by strain energy method (ref. 12), it was determined that a value of 0.16 for n' correlated the data satisfactorily in the temperature range of 316 to 760 °C. The energies associated with the tensile and compressive portions of the TMIP and TMOP hysteresis loops have been computed with an average n' value of 0.16 by using equations (8) and (9) and equations (7) and (10), respectively. The values of stresses corresponding to the peak tensile and compressive mechanical strains have been used for σ_t and σ_c. This approach gives only approximate values of the inelastic strain energy density. The actual values can be determined by measuring the areas of the hysteresis loop in the tensile and compressive regions. The computed total inelastic strain energy density per cycle is plotted against the fatigue life for the thermomechanical fatigue tests of Haynes 188 in figure 4. The damage associated with the tension and compression regions has been computed as explained in bithermal loading. As an approximation, the creep time function is taken as unity as no hold time is involved in the stress-strain cycling. The values of the total damage computed on the basis of the above procedure are shown in figure 5 for Haynes 188.

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Equation (18) has been used for the computation of fatigue life in bithermal and thermomechanical loading conditions. Comparison of figures 4 and 5 indicates that the damage functions proposed in this paper, which modify the inelastic strain energy density by time-based functions, are able to provide an improved life prediction capability under bithermal and thermomechanical loading conditions for Haynes 188. The relation between the predicted and the experimental values of fatigue life is shown in figure 6 for Haynes 188. In all the cases except two thermomechanical tests, the predicted life values are within a factor of 1.5 of the corresponding experimental values.

DISCUSSION

In the damage analysis of bithermal and thermomechanical fatigue, it has been assumed that the equation constants (table II) associated with the baseline inelastic strain energy density-life relations in isothermal condition are valid. Secondly, oxidation and creep damages are more associated with hold time conditions than with rapid loading. Since quantitative information on the nature and extent of damage accumulation due to oxidation is not available for Haynes 188, the environmental damage factor is taken as two and one, respectively, for *IP* and *OP* loading conditions. However, F_{env} is likely to be different for other materials and loading conditions.

In high-strength, low-ductility materials, where the elastic strain is more dominant than the plastic strain, the tensile mean stress associated with CCOP and TMOP tests will enhance the damage advancement. While it is well known that tensile mean stress is detrimental to fatigue life its exact relationship with damage accumulation is not as clear under creep-fatigue conditions. The life prediction method proposed in this paper, when applied to high-strength, low-ductility materials, may have some limitations. In these materials both elastic and inelastic strain energy densities should be considered together with a model to represent the role of tensile mean stress and the elastic energy interaction in the enhancement of damage accumulation.

With the simple assumptions made in this study the inelastic energy approach appears to estimate the fatigue life within reasonable accuracy under bithermal and thermomechanical loading conditions.

CONCLUDING REMARKS

From the investigation carried out on the applicability of an energy based life prediction model to bithermal and thermomechanical fatigue data of Haynes 188, the following conclusions are drawn:

1. In high-temperature, low-cycle fatigue, where the effects of time-dependent damaging processes like creep and environmental effects such as hot corrosion or oxidation enhance the damage accumulation, the inelastic hysteresis energy per cycle, by itself, is not sufficient to describe the fatigue life.

2. Creep and environmental effect functions, when incorporated in cyclic damage accumulation functions, can be used in conjunction with isothermal energy-based fatigue life relations for life prediction of bithermal and thermomechanical fatigue.

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ACKNOWLEDGMENT

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TABLE I.—ENVIRONMENTAL FACTOR, F_{env} FOR HAYNES 188

Test type	Temperature,[a] °C	F_{env}
HRIP	760 <-> 316	2
HROP	316 <-> 760	1
TCIP	760 <-> 316	2
CCOP	316 <-> 760	1
TMIP	760 <-> 316	2
TMOP	316 <-> 760	1

[a]In bithermal and thermomechanical fatigue tests, the first value denotes the temperature in tension and at the tensile peak strain, respectively. Likewise, the second value denotes the temperature in compression and at compressive peak strain in bithermal and thermomechanical fatigue tests.

TABLE II.—CONSTANTS USED IN DAMAGE CALCULATIONS

Temperature, °C	$A_{P,t}\,(=A_{P,c})$	$\beta_{P,t}\,(=\beta_{P,c}=\beta_P)$
316	$1.933 \cdot 10^{-5}$	1.299
760	$3.034 \cdot 10^{-4}$	1.299

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(a) CP type of loading.
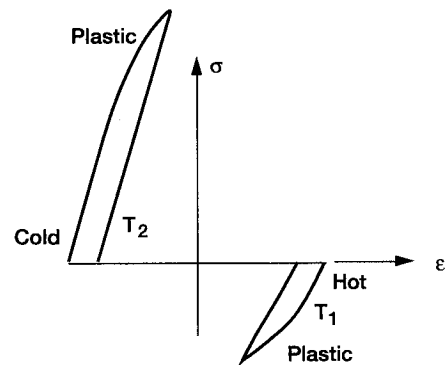

(b) PC type of loading.
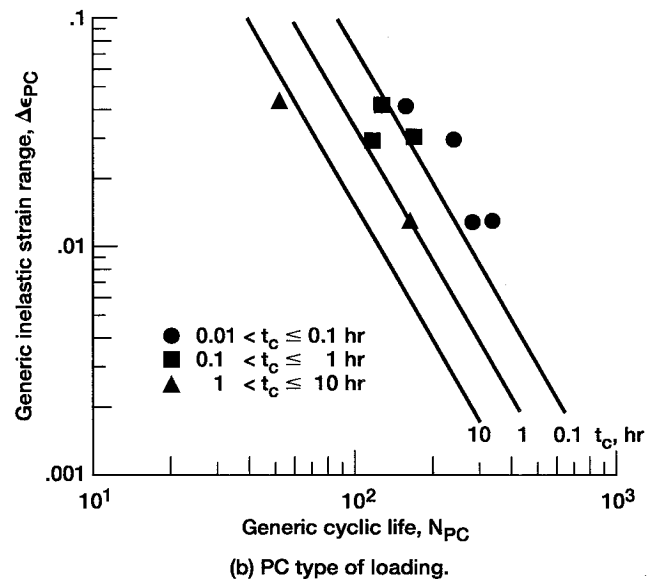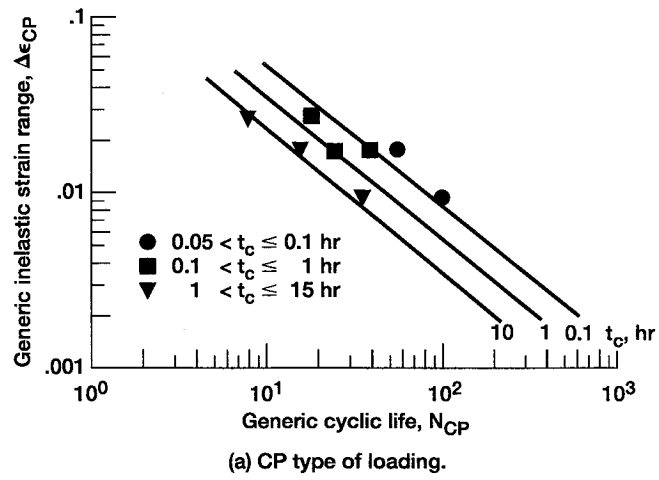
Figure 1.—Effect of hold time on the isothermal GSRP fatigue life relations of 316 stainless steel at 816 °C. Data from ref. [11].
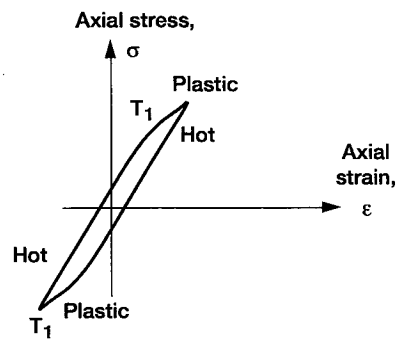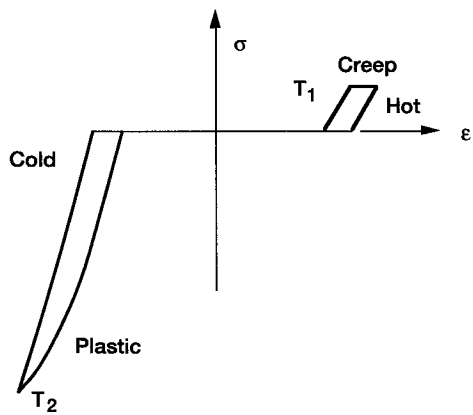
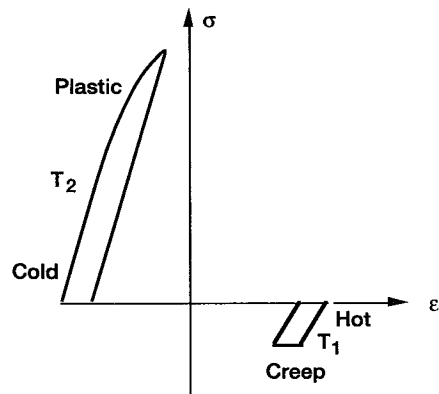(a) Isothermal rapid fatigue test.
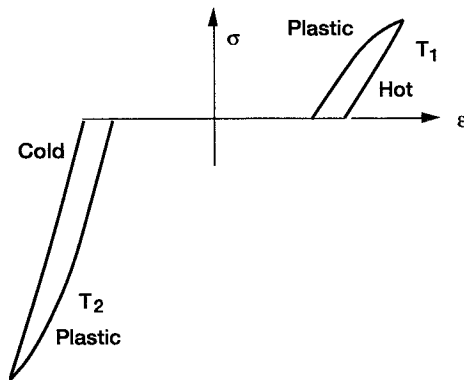
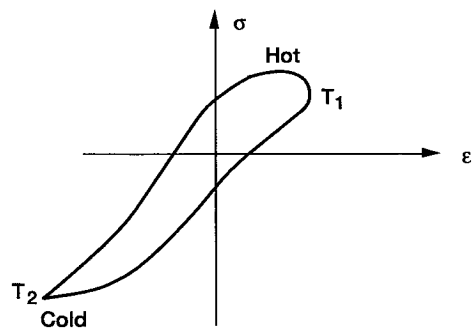(b) Bithermal HRIP test.

(c) Bithermal HROP test.

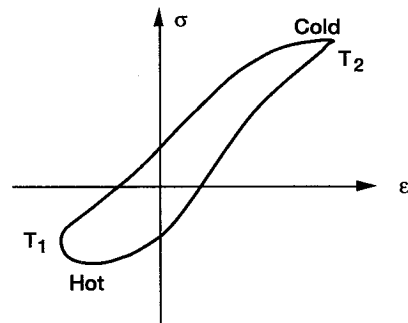Figure 2.—Hysteresis loops in isothermal, bithermal, and thermomechanical fatigue, $T_1 > T_2$.

(d) Bithermal TCIP test.

(e) Bithermal CCOP test.

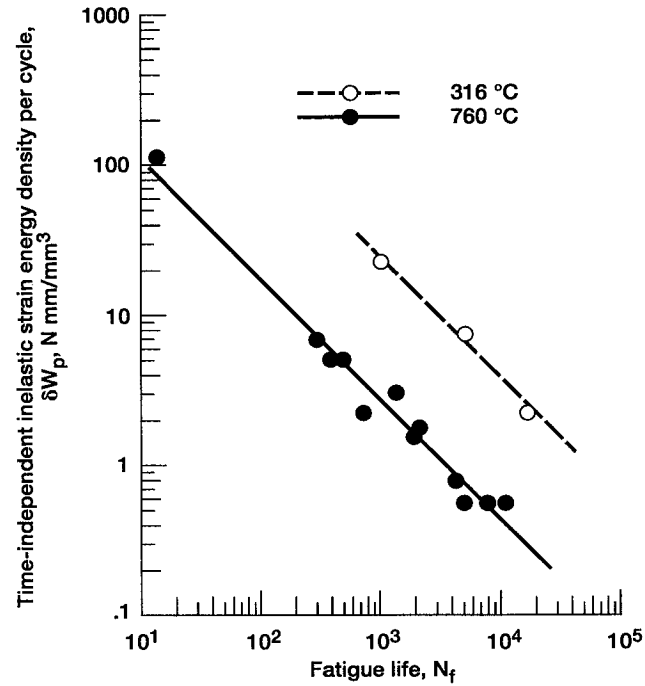(f) TMIP test.

(g) TMOP test.

Figure 2.—Concluded.

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Figure 3.—Relations between inelastic strain energy density per cycle and fatigue life of Haynes 188 in isothermal fatigue.
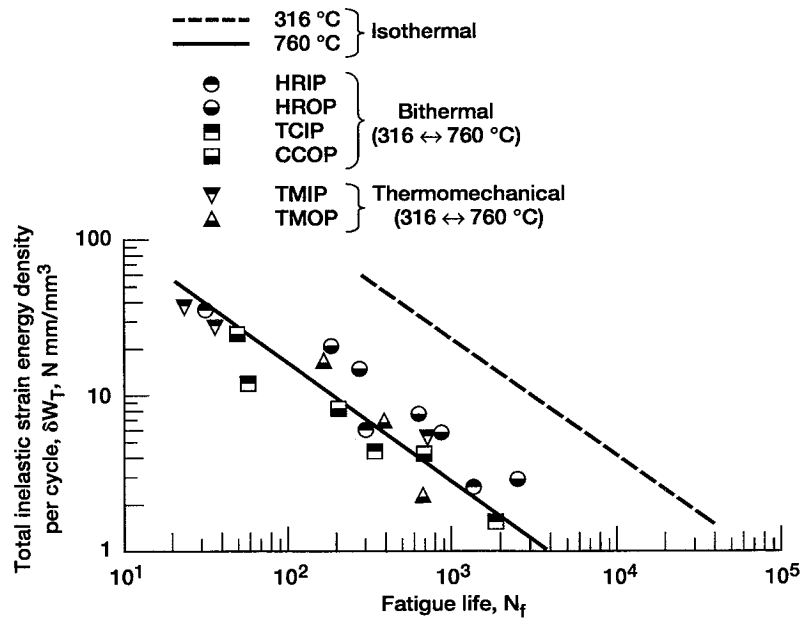

Figure 4.—Total inelastic strain energy density per cycle versus fatigue life of Haynes 188 in bithermal and thermomechanical fatigue.
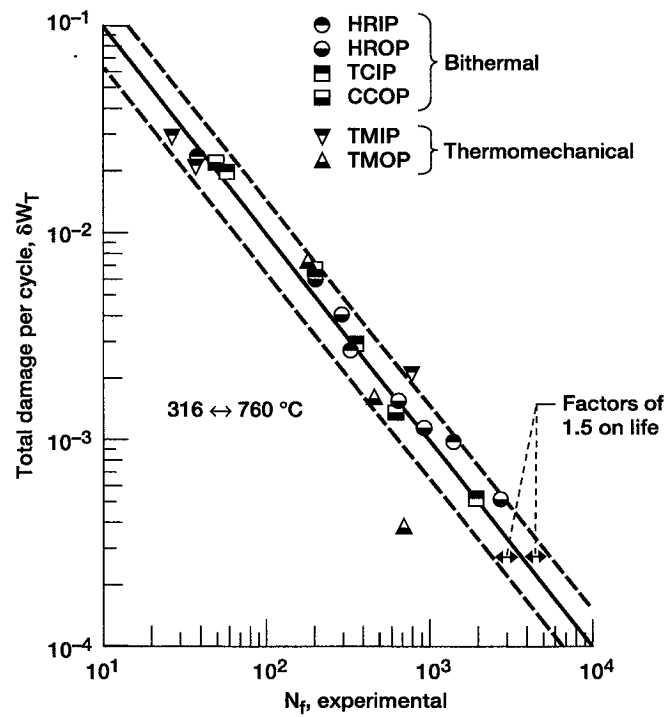
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Figure 5.—Relation between total damage per cycle and the fatigue life of Haynes 188 in bithermal and thermomechanical fatigue.
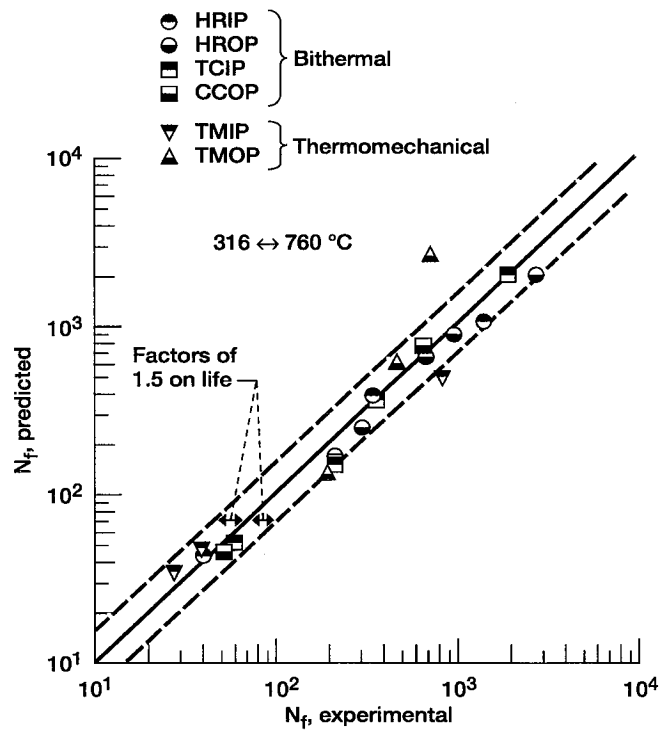

Figure 6.—Comparison of predicted and experimental bithermal and thermomechanical fatigue lives of Haynes 188.

REPORT DOCUMENTATION PAGE

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1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	July 1994	Technical Memorandum

4. TITLE AND SUBTITLE

Application of an Energy-Based Life Prediction Model to Bithermal and Thermomechanical Fatigue

5. FUNDING NUMBERS

WU–505–63–5B

6. AUTHOR(S)

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8. PERFORMING ORGANIZATION REPORT NUMBER

E–9038

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, D.C. 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM–106684

11. SUPPLEMENTARY NOTES

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12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Category 39

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

The inelastic hysteresis energy supplied to the material in a cycle is used as the basis for predicting nonisothermal fatigue life of a wrought cobalt-base superalloy, Haynes 188, from isothermal fatigue data. Damage functions that account for hold-time effects and time-dependent environmental phenomena such as oxidation and hot corrosion are proposed in terms of the inelastic hysteresis energy per cycle. The proposed damage functions are used to predict the bithermal and thermomechanical fatigue lives of Haynes 188 between 316 and 760°C from isothermal fatigue data. Predicted fatigue lives of all but two of the nonisothermal tests are within a factor of 1.5 of the experimentally observed lives.

14. SUBJECT TERMS

Fatigue (metal); Isothermal fatigue; Bithermal fatigue; Thermomechanical fatigue; Creep-fatigue; Hysteresis loop; Inelastic strain energy density; Exposure time; Damage; Life prediction

15. NUMBER OF PAGES

18

16. PRICE CODE

A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	