

Effect of Tensile Mean Stress on Fatigue Behavior of Single- Crystal and Directionally Solidified Superalloys

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Prepared for the
Symposium on Cyclic Deformation, Fracture, and Nondestructive
Evaluation of Advanced Materials
sponsored by the American Society for Testing and Materials
San Antonio, Texas, November 12-13, 1990



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AND DIRECTIONALLY SOLIDIFIED SUPERALLOYS

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SUMMARY

Two nickel-base superalloys, single-crystal PWA 1480 and directionally solidified MAR-M 246 + Hf, were studied in view of the potential usage of the former and usage of the latter, respectively, as blade materials in the turbo-machinery of the space shuttle main engine. The baseline zero-mean-stress fatigue life behavior of these superalloys was established, and then the effect of tensile mean stress on their fatigue life behavior was characterized. At room temperature these superalloys have lower ductilities and higher strengths than most polycrystalline engineering alloys. The cyclic stress-strain response was thus nominally elastic in most of the fatigue tests. Therefore, a stress-range-based fatigue life prediction approach was used to characterize both the zero- and tensile-mean-stress-fatigue data. In the past, several researchers, namely, Goodman, Gerber, Morrow, and Soderberg have developed methods to account for the detrimental effect of tensile mean stress on the fatigue life for polycrystalline engineering alloys. However, the applicability of these methods to single-crystal and directionally solidified superalloys has not been established. In this study these methods were applied to characterize the tensile-mean-stress fatigue data of single-crystal PWA 1480 and directionally solidified MAR-M 246 + Hf and were found to be unsatisfactory. Therefore, a method of accounting for the tensile-mean-stress effect on fatigue life that is based on a technique proposed by Heidmann and Manson was developed to characterize the tensile-mean-stress fatigue data of these superalloys. Details of this method and its relationship to the conventionally used mean stress methods in fatigue life prediction are discussed.

SYMBOLS

a_1, a_2	coefficients of quadratic function representing $G(N_{fm})$
B	coefficient of zero-mean-stress fatigue life relation
b	exponent of zero-mean-stress fatigue life relation
E	Young's modulus
$G(N_{fm})$	quadratic function of $\log(N_{fm})$

N_{f0}	fatigue life under zero mean stress
N_{fm}	fatigue life under tensile mean stress
RA	reduction in cross-sectional area, percent
S_a	alternating stress amplitude, $\Delta S/2$
S_m	tensile mean stress, $(S_{min} + S_{max})/2$
S_{max}	maximum stress in a cycle
S_{min}	minimum stress in a cycle
S_r	alternating stress amplitude that under fully reversed (zero mean stress) condition produces the same fatigue life as combination of S_a and S_m
S_u	ultimate tensile strength
S_y	yield strength
ΔS	stress range in a cycle, $(S_{max} - S_{min})$
σ_f	true fracture strength
σ'_f	fatigue strength coefficient

INTRODUCTION

Single-crystal (SC) and directionally solidified (DS) superalloys are extensively used as turbine blade materials in aircraft and are in use or being developed for use in rocket engine turbomachinery. These turbines operate at extremely high rotational speeds and subject the turbine blades to large centrifugal forces, vibratory loads, and thermal transients. The centrifugal loads produce a high tensile mean stress near the root of a turbine blade. For safe and reliable operation of the turbines, it is imperative that the tensile-mean-stress effects on the fatigue behavior of the turbine blade materials are well characterized. This enables designers to determine fatigue lives of engine components under different mean stress conditions.

Temperatures in rocket engine turbomachinery can range from extremely low (cryogenic) to extremely high (elevated) values. However, at the root of a turbine blade, where the highest mean stress exists, the temperature is not likely to be high owing to active cooling of the blade-disk attachment region. Therefore, as a first approximation the effect of tensile mean stress on the fatigue life of single-crystal PWA 1480 (hereafter called PWA 1480) was evaluated at room temperature by using the zero- and tensile-mean-stress fatigue data available in the literature. In the case of directionally solidified MAR-M 246 + Hf (hereafter called MAR-M 246) fully reversed (zero mean stress) fatigue life data were generated at room temperature in another program. Room-temperature fatigue data under different levels of tensile mean stress were

generated in this study on MAR-M 246. The effect of tensile mean stress on the fatigue life of MAR-M 246 was also characterized at room temperature.

In this paper the methods that are commonly used by designers to account for the detrimental effect of tensile mean stress for fatigue life were evaluated with the fatigue data of PWA 1480 and MAR-M 246. None of the commonly used methods were found to be satisfactory for these two materials. As a result, a method of accounting for the tensile-mean-stress effect on fatigue life that is based on a recently reported technique was developed to characterize the tensile-mean-stress fatigue data of PWA 1480 and MAR-M 246. Details of this mean stress effect method and its relationship to the commonly used methods are discussed.

BACKGROUND

Several methods have been proposed by researchers to estimate the detrimental effect of tensile mean stress on the fatigue life for polycrystalline engineering alloys; methods that are commonly used in engineering design were summarized by Mitchell (ref. 1). These methods were proposed by Goodman, Gerber, Soderberg, and Morrow. All of these methods use fatigue life under the fully reversed (zero mean stress) condition as the reference for estimating the detrimental effect of tensile mean stress on fatigue life. The equations for the Goodman, Gerber, and Soderberg methods are as follows (ref. 1):

Goodman:

$$\frac{S_a}{S_r} + \frac{S_m}{S_u} = 1 \quad (1)$$

Gerber:

$$\frac{S_a}{S_r} + \left(\frac{S_m}{S_u}\right)^2 = 1 \quad (2)$$

Soderberg:

$$\frac{S_a}{S_r} + \frac{S_m}{S_y} = 1 \quad (3)$$

Equations (1) to (3) are valid for any arbitrary fatigue life, since S_a is normalized by S_r and S_m is normalized by either S_u or S_y . Morrow proposed a method of estimating fatigue lives under tensile and compressive mean stresses (ref. 2). The equation proposed by Morrow reduces to the following normalized form after some algebraic manipulation (ref. 3):

Morrow:

$$\frac{S_a}{S_r} + \frac{S_m}{\sigma_f'} = 1 \quad (4)$$

where σ'_f is obtained from fully reversed (zero mean stress) fatigue tests and is commonly used in strain-based fatigue life prediction methods (refs. 1 and 2). The methods of Soderberg and Morrow can be compared with those of Goodman and Gerber by rewriting equations 3 and 4 as follows:

$$\frac{S_a}{S_r} + \left(\frac{S_u}{S_y} \right) \left(\frac{S_m}{S_u} \right) = 1 \quad (5)$$

$$\frac{S_a}{S_r} + \left(\frac{S_u}{\sigma'_f} \right) \left(\frac{S_m}{S_u} \right) = 1 \quad (6)$$

The methods of Goodman, Gerber, Soderberg, and Morrow are schematically shown in figure 1. Soderberg's equation is conservative for most polycrystalline engineering alloys, Goodman's equation is good for brittle alloys but conservative for ductile alloys, and Gerber's equation is good for ductile alloys (ref. 1). Morrow's line is between Goodman's line and Gerber's parabola for low tensile mean stresses; however, it is above Gerber's parabola for high tensile mean stresses. Even though all of these methods were used extensively by designers to estimate the detrimental effect of tensile mean stress on the fatigue life for polycrystalline engineering alloys, they were not verified for their applicability to single-crystal and directionally solidified nickel-base superalloys. One of the objectives of this study was to establish the applicability of these methods to such superalloys.

MATERIALS AND PROPERTIES

Two nickel-base superalloys, single-crystal PWA 1480 and directionally solidified (columnar grained) MAR-M 246, both cast along the [001] crystallographic direction, were considered in this study. Substantial amount of room-temperature fatigue data was generated by several researchers on PWA 1480 (refs. 4 to 8). These fatigue data were generated both on unHIPed (as-received material that contained microporosity (refs. 4 and 5)) and HIPed (hot isostatic pressing process was used to reduce or eliminate microporosity in the as-received material (ref. 5)) PWA 1480 under zero- and tensile-mean-stress conditions. Unpublished room-temperature, zero-mean-stress fatigue data generated in 1988 on MAR-M 246 were obtained from S. Hailu and S.S. Manson, Department of Mechanical and Aerospace Engineering, Case Western Reserve University, Cleveland, Ohio. In this study additional room-temperature fatigue tests with different levels of tensile mean stress were conducted in load control on MAR-M 246.

The chemical compositions of PWA 1480 (unHIPed and HIPed) and MAR-M 246 are shown in table I. The PWA 1480 specimens tested by McGaw (ref. 4), Gayda et al. (ref. 5), and Kalluri and McGaw (ref. 8) at NASA Lewis Research Center and by Majumdar and Kwasny (ref. 6) at Argonne National Laboratory (ANL) were machined from the same heat of material. The PWA 1480 studied by all of these investigators was cast in the form of cylindrical bars, except that of Gayda et al., which was cast in the form of slabs. Fritzemeier (ref. 7) worked with two different heats of PWA 1480 at Rocketdyne. However, the chemical compositions of these two heats were not significantly different from the material tested at NASA and ANL. The tensile properties of all the

heats of PWA 1480 considered in this study were similar. Hence, the mechanical property data from all of these heats were combined to enlarge the data base for PWA 1480.

Tensile properties of PWA 1480 (for both the unHIPed and HIPed conditions) and MAR-M 246 are listed in table II. At room temperature both PWA 1480 and MAR-M 246 have higher values of S_u and lower values of RA than most polycrystalline engineering alloys. This resulted in a cyclic stress-strain response that was nominally elastic in most of the fatigue tests. Hence, the following stress-range-based life relation was used to characterize the zero-mean-stress (fully reversed) fatigue data for both of these alloys:

$$\Delta S = B(N_{f0})^b \quad (7)$$

Zero-mean-stress life relations of the type shown in equation (7) were fitted to the fatigue data of unHIPed and HIPed PWA 1480 by using the results reported in references 4 to 6 and references 5 and 8, respectively. The life relations for the unHIPed and HIPed PWA 1480 together with the fatigue data are shown in figure 2. It is worthwhile to note that scatter in the fatigue life increased beyond a fatigue life of 10^6 cycles for both unHIPed and HIPed PWA 1480. In computing the life relations runout test data were also included. This was done by considering the number of cycles at which a test was terminated as the fatigue life of that test. The slopes of the zero-mean-stress life relations of the unHIPed and HIPed PWA 1480 are almost identical (fig. 2). The fatigue lives of the HIPed material were only marginally better than those of the unHIPed material. Gayda et al. (ref. 5) reported that the HIPing process employed did not completely eliminate the microporosity of as-received (unHIPed) PWA 1480. This may be the reason for the marginal improvement in the cyclic lives of the HIPed PWA 1480. The zero-mean-stress life relation for MAR-M 246 was determined by using the Hailu and Manson unpublished data referred to earlier. The life relation together with the fatigue data for MAR-M 246 is shown in figure 3. The constants B and b (eq. (7)) for the zero-mean-stress life relations and the values of σ'_f for PWA 1480 (unHIPed and HIPed) and MAR-M 246 are listed in table III.

ANALYSIS OF FATIGUE DATA WITH TENSILE MEAN STRESS

Room-temperature, tensile-mean-stress fatigue data for the unHIPed and HIPed PWA 1480 were obtained from references 6 to 8 and references 7 and 8, respectively. Tensile-mean-stress fatigue tests were conducted on MAR-M 246 under load control by using servohydraulic machines at 10 Hz. Failure was defined as separation of the specimen into two pieces. Since tensile properties and zero-mean-stress fatigue life relations are known for PWA 1480 and MAR-M 246, mean stress parameters that are commonly used in engineering design (eqs. (1) to (4)) can be determined for these materials.

The mean stress parameters of Goodman, Gerber, Soderberg, and Morrow are plotted in figure 4 together with the tensile-mean-stress fatigue data for unHIPed and HIPed PWA 1480 and for MAR-M 246. A mean stress parameter is considered to be unconservative if the tensile-mean-stress fatigue data of a material are below the line or curve of that parameter. However, if the tensile-mean-stress fatigue data are above the line or curve of a mean stress parameter, that parameter is considered to be conservative. It is clear from figure 4 that the mean stress parameters of Morrow and Gerber are

unconservative for most of the PWA 1480 and MAR-M 246 data at room temperature. Even the Goodman and Soderberg parameters are unconservative in many cases for these two materials. Since, Soderberg's parameter is conservative for most polycrystalline engineering alloys, this observation indicates one of the differences in the tensile-mean-stress fatigue behaviors of polycrystalline engineering alloys and directionally solidified nickel-base superalloys. Since the conventional methods of treating mean stress effects in fatigue are unconservative, it is necessary to explore the possibility of improving characterization of the tensile-mean-stress fatigue data of PWA 1480 and MAR-M 246.

Heidmann (ref. 3) proposed a unified method for treating mean stress effects in fatigue life prediction for polycrystalline engineering alloys. The unified method modifies N_{fm} by a parameter to obtain N_{f0} according to the following equation:

$$N_{f0} = N_{fm} \left[1 - \left(\frac{S_m}{\sigma_f'} \right)^{G(N_{fm})} \right]^{1/b} \quad (8)$$

where $G(N_{fm})$ is a function of the fatigue life N_{fm} and all the variables are defined in the symbol list. In the unified method it is assumed that the effect of mean stress on fatigue life depends both on the magnitude of mean stress and the life level. This is different from the approaches of Goodman, Gerber, Soderberg, and Morrow, which assume that the detrimental effect of tensile mean stress is the same at all fatigue life levels. The unified method was successfully applied in characterizing the mean stress fatigue behavior of several polycrystalline engineering alloys by Heidmann (ref. 3), Abdenour (ref. 9) and Manson and Heidmann (ref. 10). For a given value of N_{fm} the following relationship can be obtained from equations (7) and (8) after some algebraic manipulation:

$$\frac{S_a}{S_r} + \left(\frac{S_m}{\sigma_f'} \right)^{G(N_{fm})} = 1 \quad (9)$$

Note that equation (9) reduces to equation (4) (Morrow's mean stress parameter) when $G(N_{fm}) = 1$.

It has been shown earlier in this paper that Morrow's mean stress parameter is unconservative for PWA 1480 and MAR-M 246 (fig. 4). The reason is that, for these superalloys, the values of σ_f' are much larger than the respective values of S_u (table II). Normalization of S_m with S_u (instead of σ_f' as in eqs. (8) and (9)) enables a direct comparison of the unified method with the methods of Goodman and Gerber. Hence, S_u can be used to normalize S_m for these materials. This normalization changes equations (8) and (9) as follows:

$$N_{f0} = N_{fm} \left[1 - \left(\frac{S_m}{S_u} \right)^{G(N_{fm})} \right]^{1/b} \quad (10)$$

$$\frac{S_a}{S_r} + \left(\frac{S_m}{S_u} \right)^{G(N_{fm})} = 1 \quad (11)$$

Equation (11) is also known as the nonlinear Goodman equation. Doner et al. evaluated the nonlinear Goodman equation along with two other methods of treating mean stress effects in fatigue (ref. 11). Note that the value of $G(N_{fm})$ is equal to 1 and 2, respectively, for the Goodman and Gerber methods. The following functional form¹ of $G(N_{fm})$ was found to correlate the tensile-mean-stress data for PWA 1480 (ref. 8)²:

$$G(N_{fm}) = a_2 [\log(N_{fm})]^2 + a_1 \log(N_{fm}) + 2.0 \quad (12)$$

The value of $G(N_{fm})$ can be determined from tensile-mean-stress fatigue data by using equations (7) and (10). The constants a_1 and a_2 (eq. (12)) determined from regression analysis are listed in table III for the materials considered in this study. Plots of $G(N_{fm})$ versus $\log(N_{fm})$ data together with the correlations are shown in figures 5(a) and (b) for unHIPed and HIPed PWA 1480 and for MAR-M 246, respectively. These figures show that considerable scatter is present in the tensile-mean-stress fatigue data. Hence, the correlations in these figures are essentially depicting trends in the data. It is also evident from figure 5(a) that the tensile-mean-stress behaviors of unHIPed and HIPed PWA 1480 are quite similar. The behavior of MAR-M 246 (fig. 5(b)), however, is different from that of either type of PWA 1480. The value of $G(N_{fm})$ tends to increase with $\log(N_{fm})$ for both types of PWA 1480, but for MAR-M 246 it tends to decrease. This interesting observation is discussed in detail in subsequent sections of this report.

After a function for $G(N_{fm})$ had been determined, the fatigue lives could be corrected for tensile mean stress by using equation (10). Fatigue data corrected for tensile mean stress are shown for unHIPed and HIPed PWA 1480 and for MAR-M 246 in figures 6(a), (b), and (c), respectively. These figures indicate the correlative capability of equations (10) and (12). The implied effect of tensile mean stress on the fatigue lives of unHIPed and HIPed PWA 1480 and of MAR-M 246 is shown in figures 7(a), (b), and (c), respectively. These plots indicate the life level dependency of mean stress effect for the materials. Note that tensile mean stress is actually more detrimental in the low-cycle-fatigue (LCF) regime than in the high-cycle-fatigue (HCF) regime for both the unHIPed and HIPed PWA 1480 but that for MAR-M 246 the tensile mean stress is more detrimental in the HCF regime than in the LCF regime.

DISCUSSION

The conventional methods that account for the detrimental effect of tensile mean stress (Goodman, Gerber, Soderberg, and Morrow) assume that the detrimental effect is independent of fatigue life level. The unified method of

¹In the unified method proposed originally by Heidmann (ref. 3), $G(N_{fm})$ was a linear equation in $\log(N_{fm})$.

²In ref. 8, S_m was normalized by true fracture strength σ_f instead of S_u .

Heidmann and Manson (refs. 3 and 9) is a more general method, since it allows the effect of tensile mean stress to vary with the fatigue life level. If for any material the mean stress effect is not dependent on the fatigue life level, $G(N_{fm})$ in Eqs. (8) to (12) becomes a constant. In the unified method, which was originally proposed and applied to the polycrystalline engineering alloys (refs. 3, 9, and 10), S_m was normalized by σ'_f . For PWA 1480 and MAR-M 246 the value of σ'_f is greater than S_u by a factor of 2.5 to 5. Hence, from a design point of view and from the observation that the Morrow method is unconservative in most of the cases for these materials (fig. 4), normalization of S_m by S_u is preferred. In addition, such a normalization reduces the unified method to the nonlinear Goodman method (ref. 11).

In this study considerable amount of scatter was present in the tensile-mean-stress fatigue data of PWA 1480 and MAR-M 246. Although scatter in fatigue life data is not uncommon, note that the correlations shown in figure 5 indicate mainly general trends in the data. In the case of PWA 1480, for example, no significant difference exists between the correlations of the unHIPed and HIPed materials. However, this may not always be the case, especially when the HIPing process employed eliminates all the microporosity of the unHIPed PWA 1480. Note also that almost all of the tensile-mean-stress fatigue data for PWA 1480 and MAR-M 246 are between 10^4 and 10^7 cycles. Extrapolations of the correlations on either side of these life levels should be done with caution in view of the observed scatter in the data. For engineering purposes, however, the following equations are recommended for $G(N_{fm})$:

Single-crystal PWA 1480 (unHIPed and HIPed):

$$G(N_{fm}) = \begin{cases} 0.66 & \text{for } 1 < N_{fm} < 10^4 \\ 0.118[\log(N_{fm})]^2 - 0.806 \log(N_{fm}) + 2.0 & \text{for } 10^4 < N_{fm} < 10^7 \\ 2.1 & \text{for } N_{fm} > 10^7 \end{cases} \quad (13)$$

Directionally Solidified MAR-M 246:

$$G(N_{fm}) = \begin{cases} 1.1 & \text{for } 1 < N_{fm} < 10^4 \\ 0.00437[\log(N_{fm})]^2 - 0.238 \log(N_{fm}) + 2.0 & \text{for } 10^4 < N_{fm} < 10^7 \\ 0.55 & \text{for } N_{fm} > 10^7 \end{cases} \quad (14)$$

A single correlation was determined for PWA 1480 by combining the tensile-mean-stress fatigue data of unHIPed and HIPed materials. The values of $G(N_{fm})$ obtained at $N_{fm} = 10^4$ and $N_{fm} = 10^7$ were used for extrapolating into the regions where no data were available. The recommended curves for $G(N_{fm})$ are also shown in figure 5 for PWA 1480 and MAR-M 246.

The effect of tensile mean stress on the fatigue life of single-crystal PWA 1480 is different from that on the fatigue life of directionally solidified (columnar-grained) MAR-M 246. For PWA 1480 (figs. 7(a) and (b)) the tensile mean stress is more detrimental in the LCF regime than in the HCF

regime. However, for MAR-M 246 tensile mean stress is more detrimental in the HCF regime than in the LCF regime (fig. 7(c)). The tensile-mean-stress fatigue behavior of single-crystal PWA 1480 is noteworthy because of the commonly accepted notion that tensile mean stress is more detrimental for a material in the HCF regime than in the LCF regime. The tensile-mean-stress fatigue behavior of MAR-M 246, however, is similar to the behavior of polycrystalline 9Ni-4Co-0.45C steel reported by Heidmann (ref. 3). It would be interesting to study the effect of tensile mean stress on the fatigue lives of other single-crystal and columnar-grained nickel-base superalloys to see whether they exhibit trends that are similar to the ones observed in this study.

CONCLUSIONS

The effect of tensile mean stress on the fatigue life of unHIPed and HIPed single-crystal PWA 1480 and directionally solidified MAR-M 246 was established by using the zero- and tensile-mean-stress fatigue data. The following conclusions were drawn from the analysis conducted on these two materials:

1. As expected, tensile mean stress was detrimental to the room-temperature fatigue lives of unHIPed and HIPed PWA 1480 and MAR-M 246. The mean stress parameters of Gerber and Morrow were unconservative for these superalloys. The parameters of Goodman and Soderberg were also unconservative in several cases.

2. The unified method of Heidmann for treating mean stress effects in fatigue life prediction was successfully applied to characterize the tensile-mean-stress fatigue data of PWA 1480 and MAR-M 246 with two modifications. The mean stress was normalized by the ultimate tensile strength instead of the fatigue strength coefficient, and a quadratic function was used for $G(N_{fm})$ instead of a linear function, as originally proposed.

3. The trends observed from the analysis indicated that tensile mean stress was more detrimental in the LCF regime than in the HCF regime for PWA 1480 (unHIPed as well as HIPed); the opposite was true for MAR-M 246.

4. No significant difference was observed in the tensile-mean-stress fatigue behaviors of unHIPed and HIPed PWA 1480 at room temperature.

5. Guidelines were proposed to determine at different life levels the detrimental effect of tensile mean stress on the fatigue lives of PWA 1480 and MAR-M 246.

REFERENCES

1. Mitchell, M.R.: Fundamentals of Modern Fatigue Analysis for Design. Fatigue and Microstructure, American Society for Metals, Metals Park, OH, 1978, pp. 385-437.
2. Morrow, J.: Fatigue Properties in Metals. Fatigue Design Handbook, SAE Advances in Engineering, Vol. 4, J.A. Graham, ed., SAE, 1968, pp. 21-28.
3. Heidmann, K.R.: Technology for Predicting the Fatigue Life of Gray Cast Iron. Ph.D. Thesis, Case Western Reserve University, Cleveland, OH, 1985.

4. McGaw, M.A.: The Fatigue Damage Behavior of a Single Crystal Superalloy. M.S. Thesis, Case Western Reserve University, Cleveland, OH, 1987.
5. Gayda, J.; Gabb, T.P.; and Dreshfield, R.L.: The Effect of Hydrogen on the Low Cycle Fatigue Behavior of a Single Crystal Superalloy. Paper presented at the Fourth International Conference on Hydrogen Effects on Material Behavior, Moran, Wyoming, 1989.
6. Majumdar, S.; and Kwasny, R.: Effects of a High Mean Stress on the High-Cycle Fatigue Life of PWA 1480 and Correlation of Data by Linear Elastic Fracture Mechanics, NASA CR-175057, ANL-85-74, Argonne National Laboratory, 1985, pp. 1-23.
7. Fritzemeier, L.G.: Advanced Single Crystal for SSME Turbopumps. (RI/RD-88-273, Rocketdyne; NASA Contract NAS3-24646), NASA CR-182244, 1989, pp. 1-44.
8. Kalluri, S.; and McGaw, M.A.: Fatigue Behavior of PWA 1480 Single Crystal in the Presence of Tensile Mean Stress, Paper presented at the 1990 Conference on Advanced Earth-to-Orbit Propulsion Technology, NASA Marshall Space Flight Center, Huntsville, Alabama, 1990.
9. Abdenour, K.: Technology for Predicting the Fatigue Life in the Presence of Mean Stress. M.S. Thesis, Case Western Reserve University, Cleveland, OH, 1986.
10. Manson, S.S.; and Heidmann, K.R.: A New Formulation of Mean Stress Effects in Fatigue. Structural Integrity and Durability of Reusable Space Propulsion Systems, NASA CP-2471, 1987, pp. 89-93.
11. Doner, M.; Bain, K.R.; and Adams, J.H.: Evaluation of Methods for the Treatment of Mean Stress Effects on Low-Cycle Fatigue. J. Eng. Power, vol. 104, no. 2, Apr. 1982, pp. 403-411.

TABLE I. - CHEMICAL COMPOSITIONS OF SUPERALLOYS

Element	PWA 1480			MAR-M 246
	NASA and ANL ^a	Rocketdyne ^b		
		UnHIPed	HIPed	
	Composition, wt %			
Cr	10.40	10.16	10.33	8.13
Co	5.30	5.35	5.36	10.15
W	4.10	4.13	4.05	9.35
Ta	11.90	11.95	11.98	1.52
Al	4.80	4.91	4.90	5.60
Ti	1.30	1.35	1.33	1.59
Mo	-----	-----	-----	2.42
Hf	-----	-----	-----	1.95
Ni	Bal.	Bal.	Bal.	Bal.

^aArgonne National Laboratory; data from ref. 4.^bData from ref. 7.TABLE II. - ROOM-TEMPERATURE TENSILE PROPERTIES
OF PWA 1480 AND MAR-M 246

Property	PWA 1480		MAR-M 246
	unHIPed ^a	HIPed ^b	
Elastic modulus, E, GPa	120	125	131
Yield strength, S _y , MPa	1021	987	924
Ultimate tensile strength, S _u , MPa	1109	1257	1080
Reduction in cross- sectional RA, percent	9.8	9.5	10.5

^aAverages of the values reported in refs. 4, 5, and 7.^bAverages of the values reported in refs. 5 and 7.

TABLE III. - ZERO- AND TENSILE-MEAN-STRESS FATIGUE
CONSTANTS FOR PWA 1480 AND MAR-M 246

Constant	PWA 1480		MAR-M 246
	unHIPed	HIPed	
Coefficient of zero-mean-stress fatigue life relation, B, MPa	5200	5600	10 160
Exponent of zero-mean-stress fatigue life relation, b	-0.156	-0.155	-0.210
Fatigue strength coefficient, σ'_f , MPa	2895	3036	5875
Coefficients of quadratic function representing $G(N_{fm})$:			
a_1	-0.772	-0.823	-0.238
a_2	0.112	0.121	0.00437

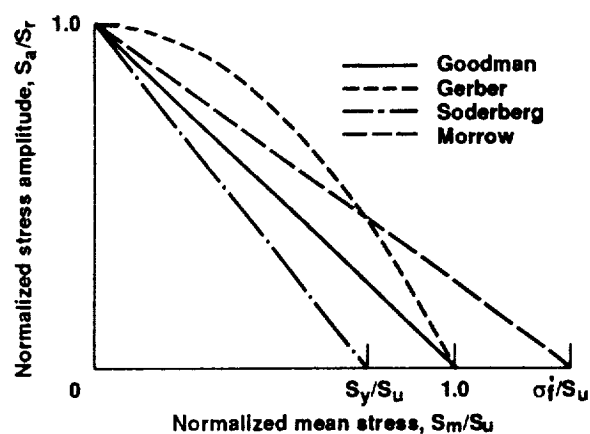


Figure 1.—Schematic illustration of nondimensional mean stress parameters.

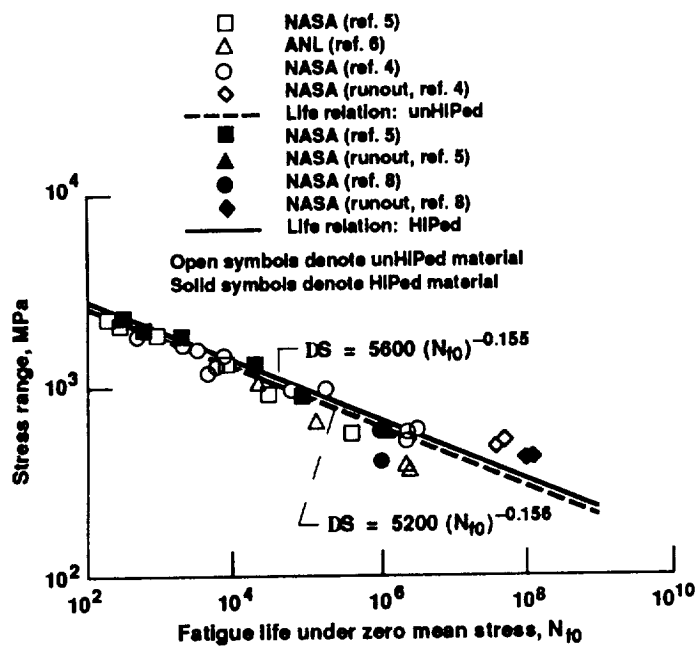


Figure 2.—Zero-mean-stress fatigue life relations of unHIPed and HIPed PWA 1480.

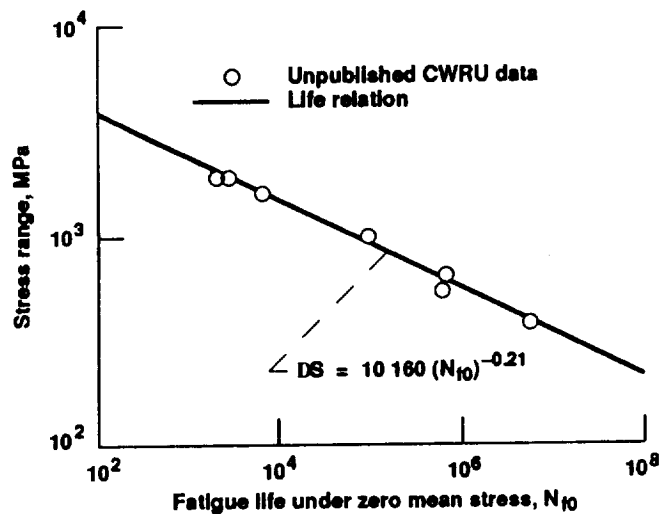


Figure 3.—Zero-mean-stress fatigue life relation of MAR-M 246.

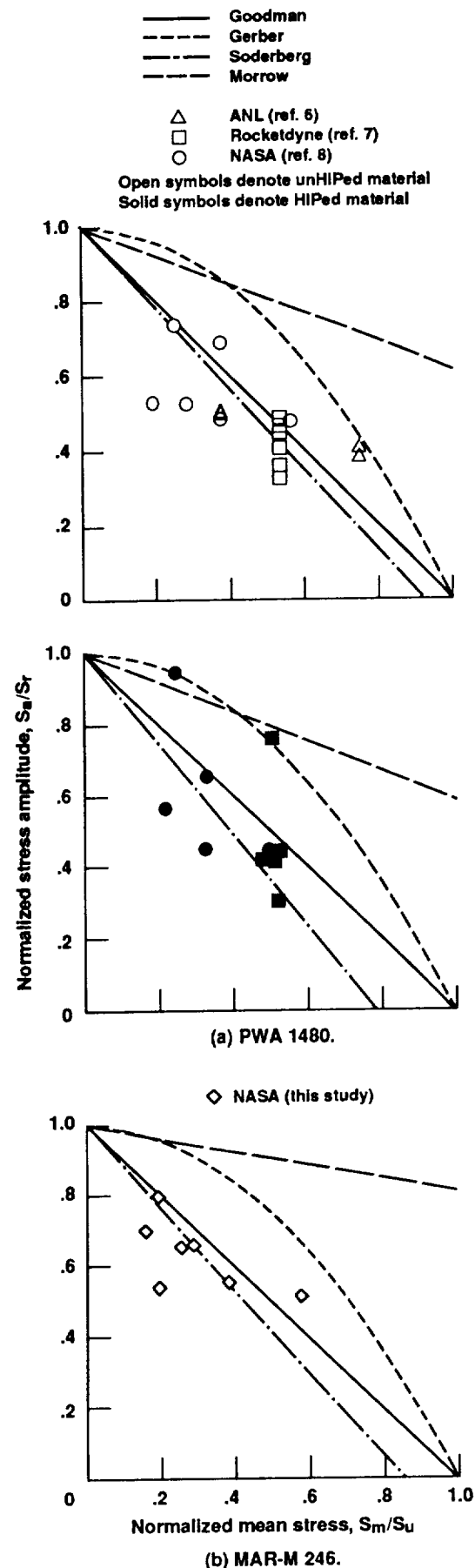
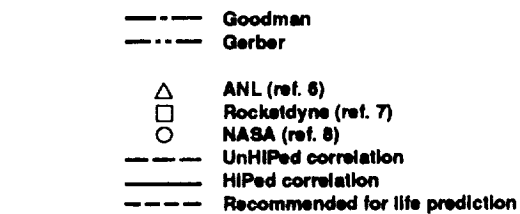
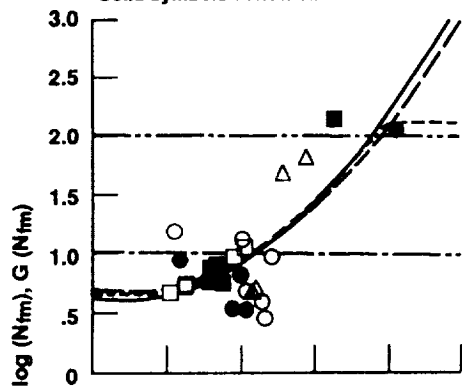


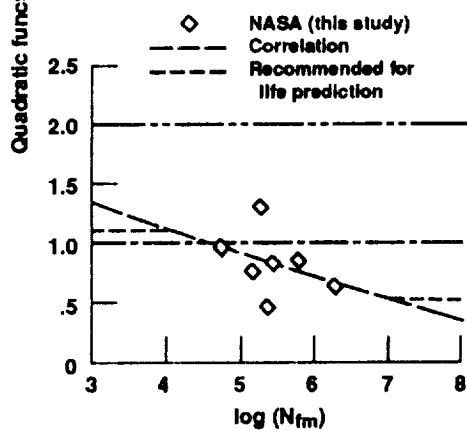
Figure 4.—Tensile-mean-stress fatigue data.



Open symbols denote unHIPed material
Solid symbols denote HIPed material

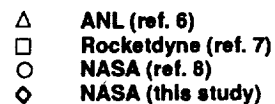


(a) PWA 1480.



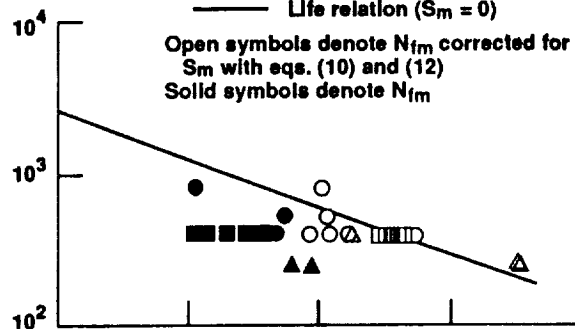
(b) MAR-M 246.

Figure 5.—Correlations of tensile-mean-stress fatigue parameter.

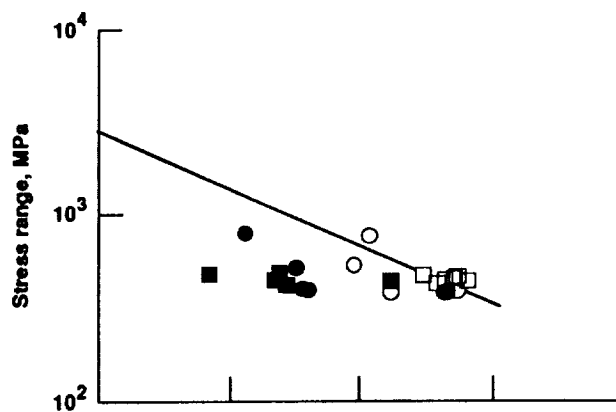


— Life relation ($S_m = 0$)

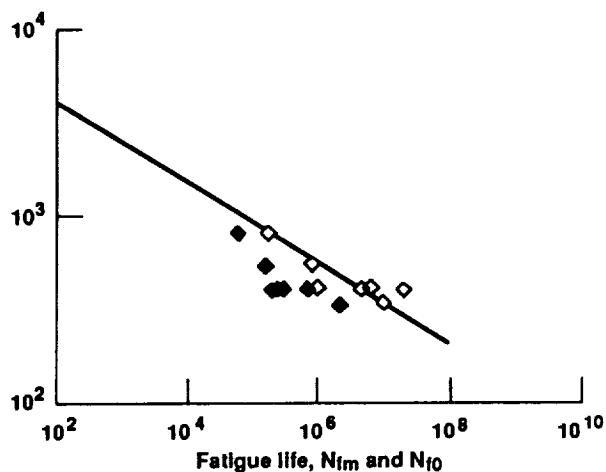
Open symbols denote N_{fm} corrected for S_m with eqs. (10) and (12)
Solid symbols denote N_{fm}



(a) UnHIPed PWA 1480.



(b) HIPed PWA 1480.



(c) MAR-M 246.

Figure 6.—Fatigue data corrected for tensile mean stress.

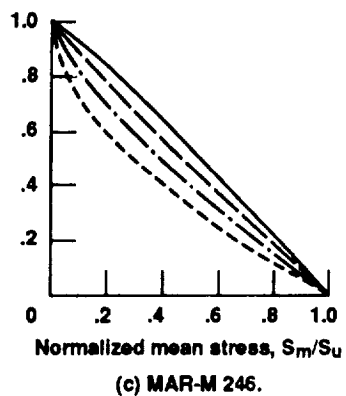
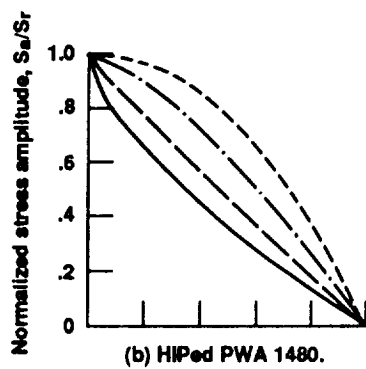
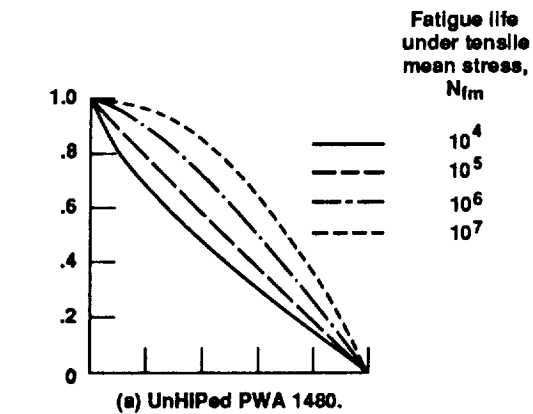


Figure 7.—Effect of tensile mean stress on fatigue life.

Report Documentation Page

1. Report No. NASA TM-103644		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle Effect of Tensile Mean Stress on Fatigue Behavior of Single-Crystal and Directionally Solidified Superalloys				5. Report Date	
				6. Performing Organization Code	
7. Author(s) Sreeramesh Kalluri and Michael A. McGaw				8. Performing Organization Report No. E-5827	
				10. Work Unit No. 553-13-00	
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191				11. Contract or Grant No.	
				13. Type of Report and Period Covered Technical Memorandum	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546-0001				14. Sponsoring Agency Code	
15. Supplementary Notes Prepared for the Symposium on Cyclic Deformation, Fracture, and Nondestructive Evaluation of Advanced Materials sponsored by the American Society for Testing and Materials, San Antonio, Texas, November 12-13, 1990. Sreeramesh Kalluri, Sverdrup Technology, Inc., Lewis Research Center Group, 2001 Aerospace Parkway, Brook Park, Ohio 44142. Michael A. McGaw, NASA Lewis Research Center.					
16. Abstract Two nickel-base superalloys, single-crystal PWA 1480 and directionally solidified MAR-M 246 + Hf, were studied in view of the potential usage of the former and usage of the latter, respectively, as blade materials for the turbo-machinery of the space shuttle main engine. The baseline zero-mean-stress fatigue life behavior of these superalloys was established, and then the effect of tensile mean stress on their fatigue life behavior was characterized. At room temperature these superalloys have lower ductilities and higher strengths than most polycrystalline engineering alloys. The cyclic stress-strain response was thus nominally elastic in most of the fatigue tests. Therefore, a stress-range-based fatigue life prediction approach was used to characterize both the zero- and tensile-mean-stress-fatigue data. In the past, several researchers, namely, Goodman, Gerber, Morrow, and Soderberg have developed methods to account for the detrimental effect of tensile mean stress on the fatigue life for polycrystalline engineering alloys. However, the applicability of these methods to single-crystal and directionally solidified superalloys has not been established. In this study, these methods were applied to characterize the tensile-mean-stress fatigue data of single-crystal PWA 1480 and directionally solidified MAR-M 246 + Hf and were found to be unsatisfactory. Therefore, a method of accounting for the tensile-mean-stress effect on fatigue life, that is based on a technique proposed by Heidmann and Manson was developed to characterize the tensile-mean-stress fatigue data of these superalloys. Details of this method and its relationship to the conventionally used mean stress methods in fatigue life prediction are discussed.					
17. Key Words (Suggested by Author(s)) Fatigue; Tensile mean stress; Life prediction; Polycrystalline alloys; Single-crystal superalloys; Directionally solidified superalloys			18. Distribution Statement Unclassified—Unlimited Subject Category 39		
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of pages 16	
				22. Price* A03	

National Aeronautics and
Space Administration

Lewis Research Center
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