N91-24313

FATIGUE BEHAVIOR OF A SINGLE-CRYSTAL SUPERALLOY

S6-26
19863

Sreeramesh Kalluri
Sverdrup Technology, Inc.
NASA Lewis Research Center Group

and

Michael A. McGaw
NASA Lewis Research Center

Single-crystal superalloys have been used extensively during the past decade in the manufacture of turbine blades of aircraft engines. At the present time, a single crystal superalloy, PWA 1480 is under consideration as a replacement material for the turbine blades of the high pressure fuel turbopump (HPFTP) of the space shuttle main engine (SSME). It is necessary to characterize the fatigue behavior of this material for the safe and reliable operation of the SSME. In order to achieve this goal, NASA Lewis Research Center purchased during the early 80's cast single crystal PWA 1480. The material was cast by TRW, Inc., both in the form of cylindrical bars (11/16 in. diam. and 6 in. long) and slabs (6.5 by 2.5 by 0.5 in.) along the ⟨001⟩ orientation. Even though each bar and slab was cast individually, all nominally had the same chemical composition (table I). The cast single crystal PWA 1480 material was observed to contain microporosity, especially between the dendrites (refs. 1 and 2).

Three separate experimental programs were conducted to characterize the fatigue behavior of this alloy at two laboratories (refs. 1 to 3). Fatigue tests were conducted at room temperature (in air) and at 1000 °F (in vacuum) on smooth specimens machined from both the cast bars and slabs. In this study the data from all of these programs are consolidated to provide a broader characterization of the fatigue behavior of the single crystal PWA 1480. The zero-mean-stress fatigue life relationships are expressed in terms of stress range versus cyclic life lines on log-log plots (figs. 1 and 2). At room temperature the slope of the life relationship of this single-crystal superalloy is larger than that observed typically in polycrystalline alloys. For a polycrystalline alloy, the slope of this line is usually between -0.07 and -0.14, whereas for PWA 1480 single crystal the slope is -0.17. A large amount of scatter was observed in the room temperature fatigue data generated at NASA Lewis Research Center. This scatter is attributable to the porosity observed both within the material and on the surface of the fatigue specimens (ref. 1). However, it is interesting to note that the data generated from both the cast bars and slabs are within the same scatter band (fig. 1). Also, the fact that two different laboratories and three separate test systems that were involved in generating the data does not appear to have affected the scatter in the data to a significant extent. Only two fatigue data points were available for the zero mean stress condition in vacuum at 1000 °F. The life relationship at this temperature was determined by using the slope of the room temperature zero-mean-stress fatigue data (fig. 2).

PRECEDING PAGE BLANK NOT FILMED

Characterization of the fatigue behavior of ⟨001⟩ oriented PWA 1480 single crystal under conditions of tensile mean stress was an objective of the work done at Argonne National Laboratory (ANL) (ref. 3). Fatigue data with tensile mean stresses were also generated by Rockwell International on this material (ref. 4). The material tested at ANL had the same chemical composition as the NASA Lewis material, while the Rockwell material had a chemical composition that was not significantly different from the material used at NASA Lewis (table I). In the current study an attempt was made to characterize the effect of tensile mean stress on the fatigue life of PWA 1480 single crystal by using the unified approach proposed by Heidmann (ref. 5). In this approach the fatigue life is modified by a mean stress parameter so that a single life relationship can be used to represent both zero and tensile mean stress data. A better correlation of the fatigue data was obtained by modifying the functional form proposed originally in reference 5. When tensile mean stresses are properly accounted for, the data with and without mean stress collapse to a single line (figs. 3 and 4). The implications of this type of treatment of mean stress effects, in terms of the conventional approach, are shown in figure 5 (room temperature in air) and Figure 6 (1000 °F in vacuum). These plots indicate that tensile mean stresses are likely to be more detrimental in low-cycle fatigue than in high-cycle fatigue for PWA 1480 single crystal. However, this type of behavior is exactly the opposite of the behavior exhibited by most polycrystalline alloys (ref. 6). The effect of tensile mean stress on the fatigue life appears to diminish at 1000 °F compared with room temperature. This result may be due to the differences in the deformation mechanisms at these two temperatures and environmental conditions. Additional experimental fatigue data on PWA 1480 single-crystal superalloy with different levels of mean stress and cyclic lives are necessary to confirm the trends of mean stress effects observed in this analysis.

REFERENCES

1. McGaw, M.A.: The Fatigue Damage Behavior of a Single Crystal Superalloy. M.S. Thesis, Case Western Reserve University, Cleveland, Ohio, 1987.
2. 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 submitted for the Fourth International Conference on Hydrogen Effects on Material Behavior, September 1989.
3. Majumdar, S.; and Kwasny, R.: Effects of a Mean Stress on the High-Cycle Fatigue Life of PWA 1480 and Correlation of Data by Linear Elastic Fracture Mechanics. Report prepared by Argonne National Laboratory for NASA Lewis Research Center, NASA CR-175057, 1985.
4. Fritzemeier, L.G.: Advanced Single Crystal for SSME Turbopumps. Report prepared by Rocketdyne Division of Rockwell International for NASA Lewis Research Center, NASA CR-182244, 1988.
5. Heidmann, K.R.: Technology for Predicting the Fatigue Life of Grey Cast Iron. Ph. D. Thesis, Case Western Reserve University, 1985.
6. Manson, S.S., and Heidmann, K.R.: A New Formulation of Mean Stress Effects in Fatigue. Proceedings of the Conference on Structural Integrity and Durability of Reusable Space Propulsion Systems, NASA CP-2471, May 1987.

CHEMICAL COMPOSITION OF CAST PWA 1480 SINGLE CRYSTAL

[WEIGHT PERCENT]

ELEMENT	NASA LEWIS BARS AND SLABS (REF. 1)	ROCKETDYNE MATERIAL (REF. 4)
CHROMIUM	10.40	10.16
COBALT	5.30	5.35
TUNGSTEN	4.10	4.13
TANTALUM	11.90	11.95
ALUMINUM	4.80	4.91
TITANIUM	1.30	1.35
NICKEL	BALANCE	BALANCE

Table I

CD-89-39510

PWA 1480 SINGLE CRYSTAL ZERO-MEAN-STRESS (R = −1) FATIGUE DATA

ROOM TEMPERATURE IN AIR

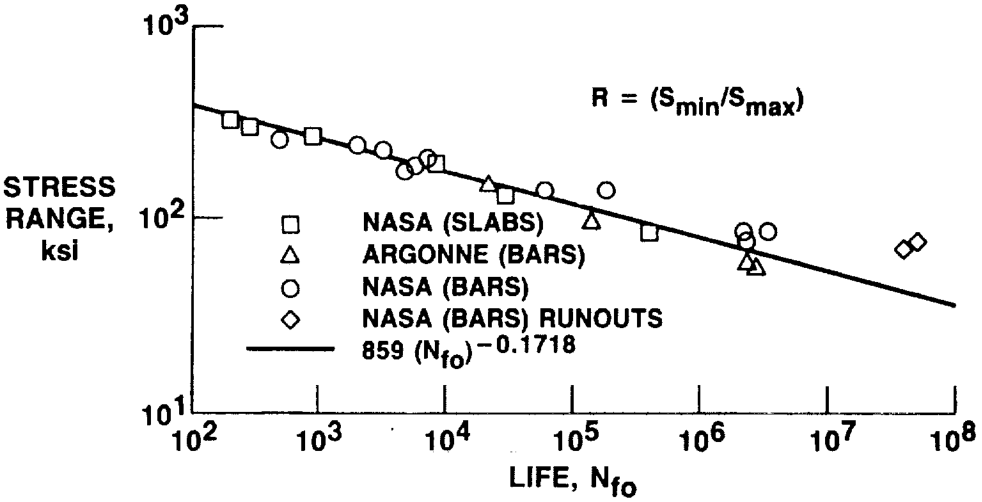


Figure 1

CD-89-39284

PWA 1480 SINGLE CRYSTAL ZERO-MEAN-STRESS (R = −1) FATIGUE DATA

1000 °F IN VACUUM

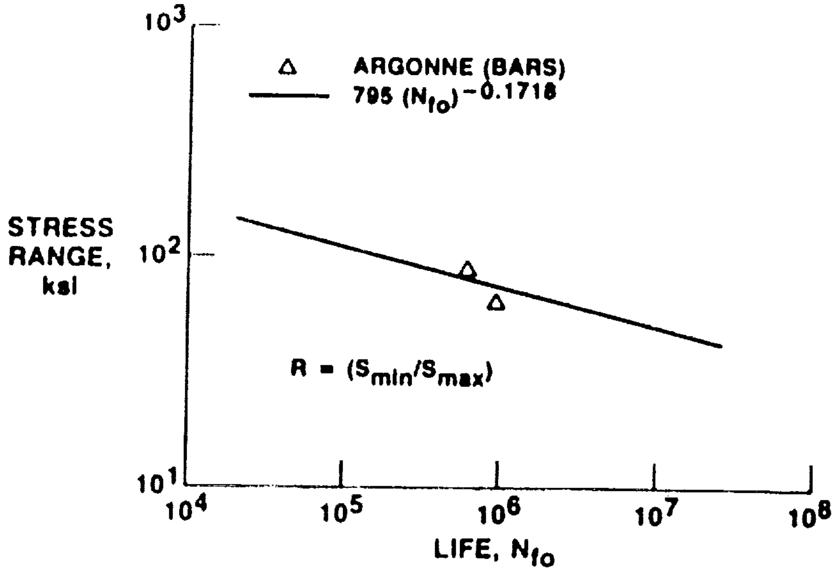
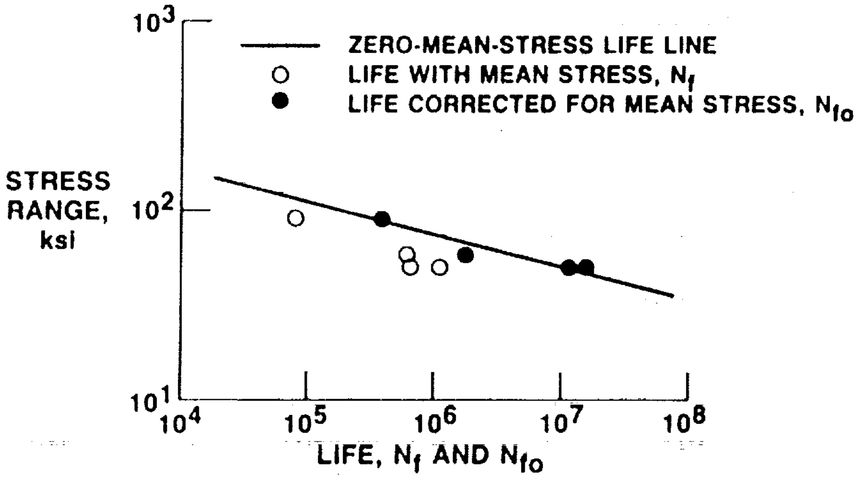


Figure 2

CD-89-39285

PWA 1480 SINGLE CRYSTAL TENSILE-MEAN-STRESS FATIGUE DATA

1000 °F, IN VACUUM; ARGONNE



$$N_{fo} = N_f \left[1 - \left(\frac{S_m}{S_f} \right)^{G(N_f)} \right]^{1/b}$$

$$G(N_f) = 0.087\,(\log N_f)^2 - 0.583\,(\log N_f) + 2.0$$

WHERE

S_m TENSILE MEAN STRESS

S_f TRUE FRACTURE STRENGTH

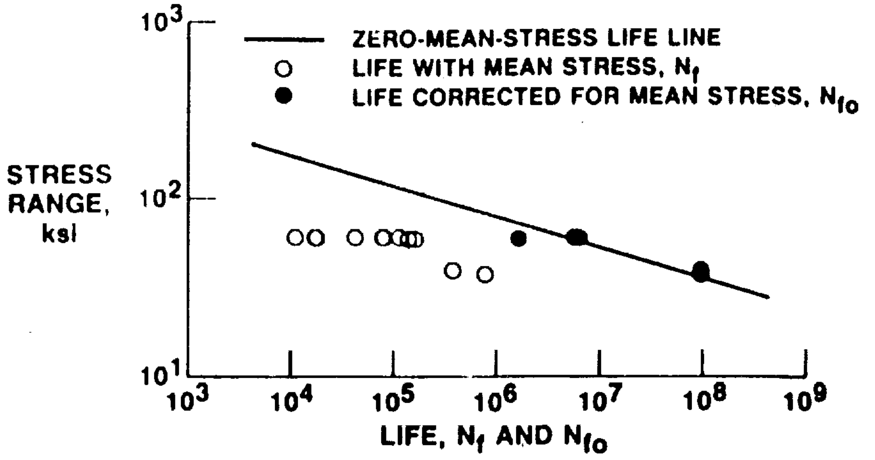
b FATIGUE STRENGTH EXPONENT

CD-89-39287

Figure 3

PWA 1480 SINGLE CRYSTAL TENSILE-MEAN-STRESS FATIGUE DATA

ROOM TEMPERATURE, IN AIR; ARGONNE AND ROCKETDYNE



$$N_{fo} = N_f \left[1 - \left(\frac{S_m}{S_f} \right)^{G\,(N_f)} \right]^{1/b}$$

$$G\,(N_f) = 0.142\,(\log N_f)^2 - 0.928\,(\log N_f) + 2.0$$

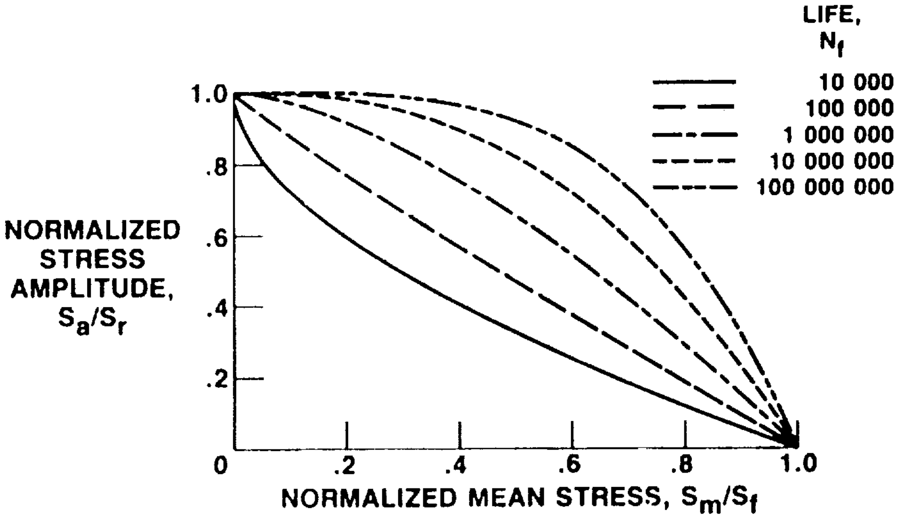
WHERE
S_m TENSILE MEAN STRESS
S_f TRUE FRACTURE STRENGTH
b FATIGUE STRENGTH EXPONENT

CD-87-39784

Figure 4

EFFECT OF TENSILE MEAN STRESS ON FATIGUE LIFE OF PWA 1480 SINGLE CRYSTAL

ROOM TEMPERATURE, IN AIR



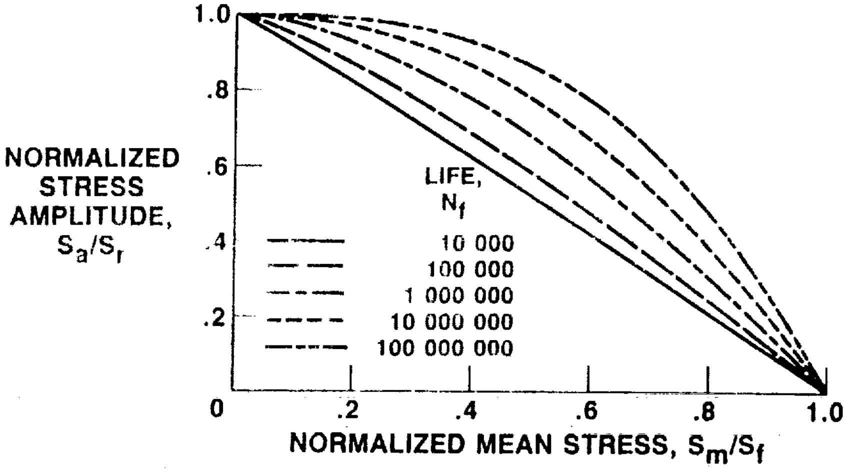
S_m TENSILE MEAN STRESS
S_f TRUE FRACTURE STRENGTH
S_a ALTERNATING STRESS AMPLITUDE
S_r FULLY REVERSED STRESS AMPLITUDE WHICH PRODUCES THE SAME FATIGUE LIFE AS A COMBINED MEAN AND ALTERNATING STRESS

CD-87-39788

Figure 5

EFFECT OF TENSILE MEAN STRESS ON FATIGUE LIFE OF PWA 1480 SINGLE CRYSTAL

1000 °F, IN VACUUM



S_m TENSILE MEAN STRESS

S_f TRUE FRACTURE STRENGTH

S_a ALTERNATING STRESS AMPLITUDE

S_r FULLY REVERSED STRESS AMPLITUDE WHICH PRODUCES THE SAME FATIGUE LIFE AS A COMBINED MEAN AND ALTERNATING STRESS

CD-89-39289

Figure 6