CUMULATIVE FATIGUE DAMAGE BEHAVIOR OF MAR M-247

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Cumulative Fatigue Damage Analysis is the term used to describe the assessment of fatigue lives of metallic materials under variable amplitude or block loading. A linear life-fraction rule, known as the Palmgren-Miner Linear Damage Rule (LDR) is the standard model currently used in engineering design for assessing cumulative fatigue-damage. In recent years, it has been discovered that engineering metals and alloys exhibit pronounced nonlinear cumulative fatigue damage behavior under certain conditions of loading. Conditions for which pronounced nonlinearity and subsequent fatigue life degradation might exist can now be identified readily using engineering models developed at the Lewis Research Center of NASA. The models reflect the accumulation of fatigue damage through the nonlinear sequence of microcrack initiation, microcrack growth, macrocrack initiation, macrocrack growth, and eventual fracture. Despite the extreme complexity of the physical mechanisms of fatigue, relatively simple engineering models have evolved. They are proving useful in guiding the evaluation of the cumulative fatigue damage behavior of materials tested in laboratory environments.

The simplest and most common laboratory test procedure for evaluating cumulative damage behavior is the two-level loading sequence in which low-cycle fatigue (LCF) is applied for a portion of the expected LCF life followed by high-cycle fatigue (HCF) loading until failure. Analysis of hundreds of two-level loading experimental results from the literature has led to the development of several simple engineering models, including: the Double Linear Damage Rule (DLDR), the Damage Curve Approach (DCA), and the Double Damage Curve Approach (DDCA). Each has its regime of utility, but all three give rise to essentially the same numerical results. Another common attribute in these models is the recognition that the degree of nonlinearity in damage accumulation depends solely upon relative life levels of the extreme cycles. In other words, LCF/HCF lives of $10^2/10^5$ or $10^4/10^7$ will exhibit equal degrees of nonlinearity and hence equal degrees of fatigue life degradation.

The object of this study was to examine the room temperature fatigue and nonlinear cumulative fatigue damage behavior of the cast nickel-base superalloy, MAR M-247. This is the bill-of-material for the turbine housings and inlet guide vanes of both the oxidizer and fuel turbopump designs from the Alternate Turbopump Development (ATD) program. Pratt & Whitney Corp. (West Palm Beach group) is performing this program under contract to NASA Marshall Space Flight Center. Through a small cooperative agreement with NASA Lewis Research Center, a casting of MAR M-247 was obtained from Pratt & Whitney Corp. The casting was

produced using the MICROCAST-X process of the Howmet Corp. and had been HIPed and heat treated according to engineering use specifications from the ATD program requirements. Axial fatigue specimens possessing a half-inch uniform gage section were machined from this casting.

The fatigue test matrix carried consisted of single-level, fully reversed (R = -1, either load or strain control) fatigue experiments (fig. 1). Duplicate tests were performed at each of three test conditions. The mechanical test parameters were chosen to establish two lower-life LCF levels (N_{1A} & N_{1B}) and one higher-life HCF level (N_2) for use in the two-level loading experiments. Two-level block loading experiments (in which higher amplitude strain or load cycling, corresponding to lower life levels, N_{1A} and N_{1B}) were conducted for various life fractions, followed by load cycling (corresponding to a higher fatigue life level, N_2) to failure (fig. 2). In these tests, LCF life fractions (n_{1A}/N_{1A} and n_{1B}/N_{1B}) of approximately 0.1, 0.2, and 0.3 were applied and the HCF life remaining in the second loading level was observed. Two series of tests were performed: one of the two baseline fatigue LCF life levels was used in the first loading block, and the HCF baseline loading level was used in the second block in each series. For each series, duplicate tests were performed at each applied LCF life fraction.

The results of the baseline fatigue characterization tests are shown in figure 3. The lowest life tests were performed under strain control at 10 cpm, $\Delta\epsilon_t$ = 1.0 percent. A small amount of inelastic strain range, on the order of 0.1 percent, was observed. The balance of the tests was performed under load control, at 100 Hz, and nominally elastic behavior was observed. These results agreed with results obtained by Pratt & Whitney (ref. 2).

The results of the two-level loading experiments are shown as cumulative fatigue damage interaction plots (figs. 4 and 5). In figure 4, the LCF life level, N_{1A} corresponding to the first loading block was approximately 7000 cycles to failure. The second load level corresponded to approximately 10^7 cycles to failure (N_2). These life levels result from a consideration of the average of the fatigue lives obtained in the baseline fatigue characterization. Also shown in the figure are predicted results based on a linear damage approach, and two nonlinear cumulative damage approaches, the Double Linear Damage Rule (ref. 1) and the Damage Curve Approach (ref. 1). As can be observed, for the three duplicated test conditions employed in this series, MAR M-247 exhibits a very strong nonlinear cumulative interaction behavior. This behavior is predicted qualitatively based on the DCA and DLDR approaches. By contrast, predictions according to the LDR approach are in error by nearly a factor of 8 on the unconservative side with respect to the experimental results (the remaining HCF life is overpredicted by a factor of 33).

In figure 5, the LCF life level, N_{1B} corresponding to the first block of loading was approximately 340,000 cycles to failure. The second loading level was as before. The experimental results are again shown with predictions made according to both linear and nonlinear cumulative damage approaches. Nonlinear cumulative fatigue damage behavior is again exhibited. Predictions by the DCA and DLDR models again are qualitatively correct for all but two of the results shown in this figure. The cumulative fatigue damage results in this figure do show a bifurcation in behavior that has not previously been observed. The re-

maining HCF lives are either shorter than expected, or substantially greater, possibly indicating that the samples are from two separate populations of differing grain size, hardness, strength, etc. There is presently no physical evidence to explain the behavior. The specimens are to be thoroughly examined at MSFC using fractographic and metallographic techniques in anticipation of explaining the duality in behavior.

References

1. Manson, S.S.; Halford, G.R.: Practical Implementation of the Double Linear Damage Rule and Damage Curve Approach. Intern. J. Fracture, vol. 17, no. 2, Apr. 1981, pp. 169-192.

2. Heine, J.: Pratt & Whitney Aircraft, West Palm Beach group, private communication.

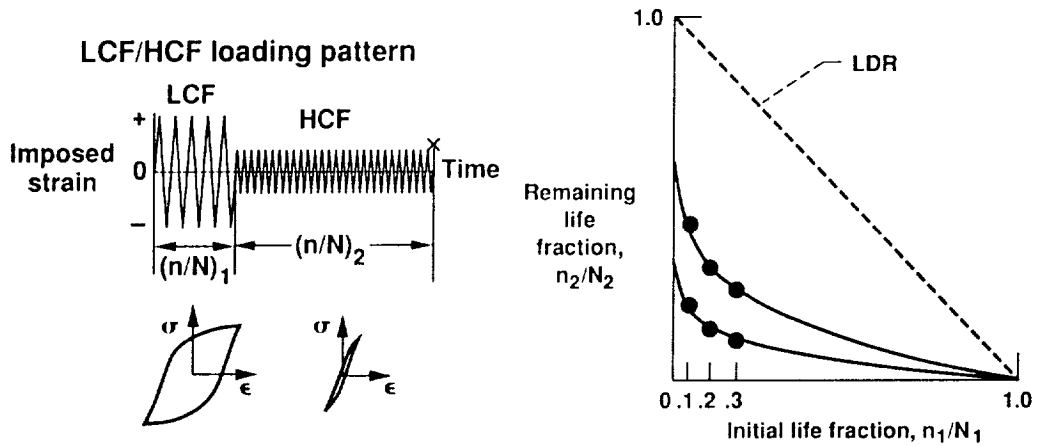# Approach: Baseline Fatigue Behavior
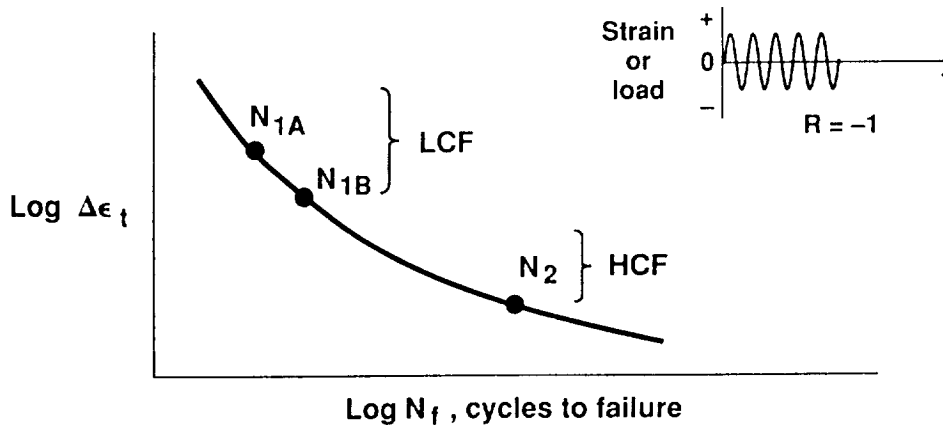
- Establish base life levels for HCF/LCF interaction study

- Two LCF life levels, one HCF life level

- Replicate tests at each condition

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Figure 1

Approach: HCF/LCF Interaction Behavior

LCF/HCF loading pattern

- Two-level block loading tests run

- Three applied LCF life fractions designed to bracket maximum expected nonlinear interaction

- Duplicate tests at each condition

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Figure 2

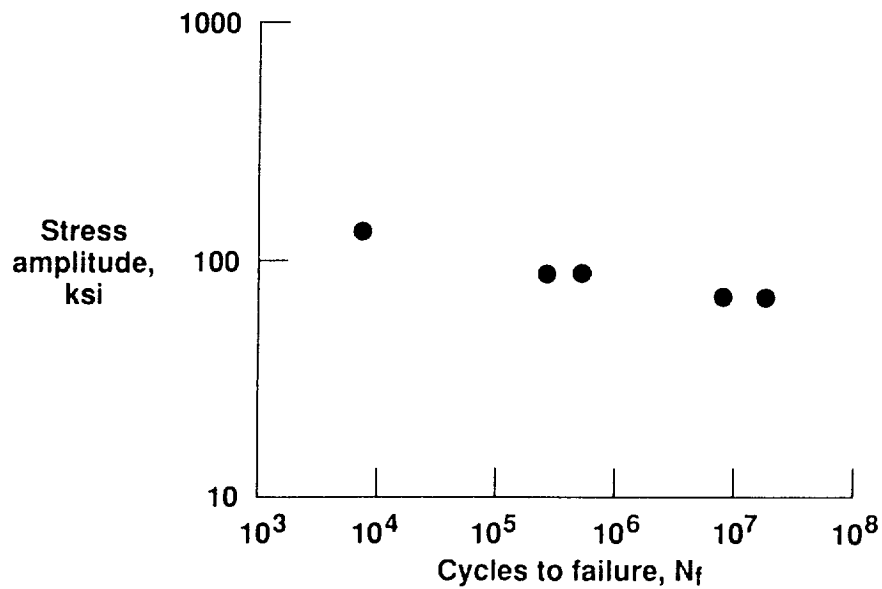# Results: Baseline Fatigue Behavior
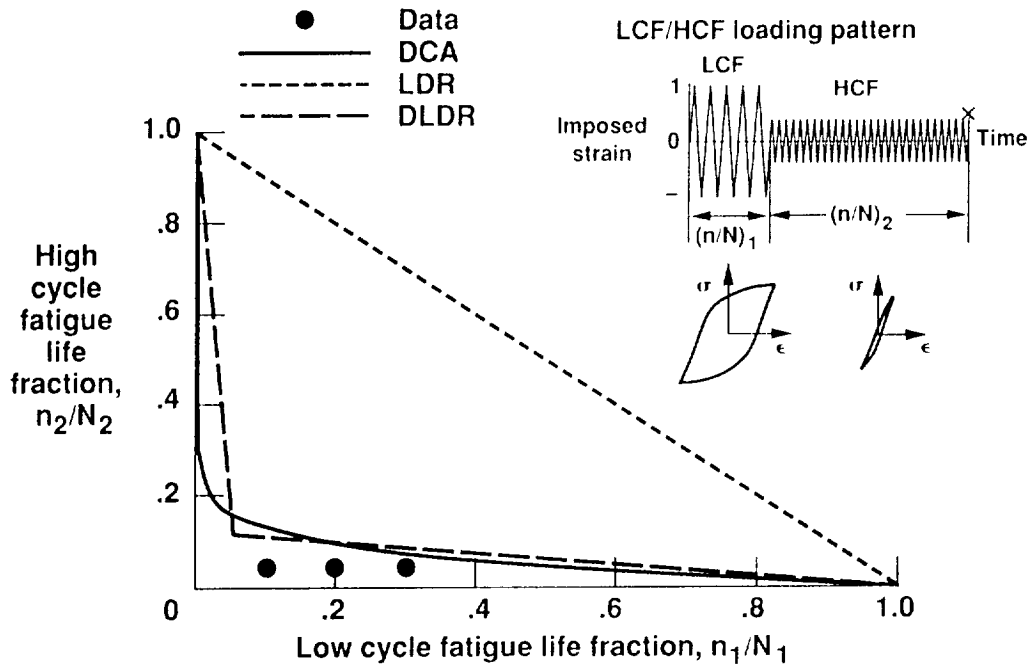## MAR M–247 in Air at Room Temperature

Figure 3   CD-91-52292

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Results: LCF/HCF Interaction Behavior

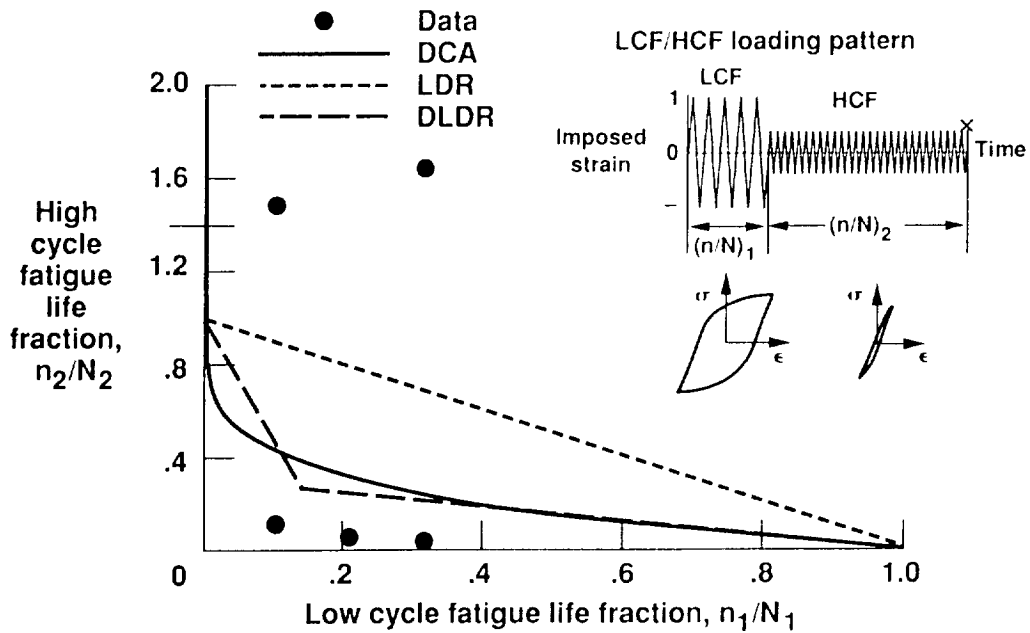## MAR M—247 Fatigue Interaction; $N_1 = 6764$; $N_2 = 11\,136\,861$

Figure 4

Results: LCF/HCF Interaction Behavior

MAR M–247 Fatigue Interaction; $N_1 = 342\,016$; $N_2 = 11\,136\,861$

Figure 5

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