To be presented at the Symposium on Fatigue, ASME Winter Meeting, New York City, December 2-7, 1979.

LEVEL POINT OF A PROCEDURE FOR ESTIMATING THE HIGH
CYCLE FATIGUE STRENGTH OF SOME HIGH TEMPERATURE
STRUCTURAL ALLOYS*

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ABSTRACT

The generation of strain controlled fatigue data, for the standard strain rate of $4 \times 10^{-3} \text{ sec}^{-1}$, presents a problem when the cycles to failure exceed 10^5 because of the prohibitively long test times involved. In an attempt to circumvent this difficulty an evaluation has been made of a test procedure involving a fast cycling rate ($\sim 1 \text{ Hz}$) and load controlled conditions. The validity of this procedure for extending current fatigue curves from 10^5 to 10^8 cycles and beyond, hinges upon the selection of an appropriate effective strain value, since the strain usually changes rapidly during the early stages of fatigue. Results from annealed 2 1/4 Cr-1 Mo, Type 304 stainless steel, Inconel 800H and Hastelloy X, tested over a wide range of temperatures, show that the strain measured at $N_f/2$ is a reasonable estimate since it gives an excellent correlation between the strain and load controlled tests in the 10^5 cycle range where the data overlap. It seems clear that the differences in cycling rate and early stress-strain history for the two tests do not significantly affect the correlation. It may, therefore, be concluded that such load control test procedures may be used as a valid fast way for extending currently available fatigue curves from 10^5 to 10^8 cycles, and beyond.

*This work was performed under the auspices of the United States Nuclear Regulatory Commission.

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INTRODUCTION

Most fatigue work currently being carried out in the power industry is concerned with the low cycle fatigue (LCF) regime where the cycles to failure are typically less than 10^5 . Such information is used to estimate the amount of fatigue damage accumulation in components which are subjected to large cyclic strain ranges brought about by thermal transients.

Most experimental work is carried out at a recommended strain rate of 10^{-3} s⁻¹ in order to standardize the test procedures. Although this strain rate represents an accelerated straining condition compared to that which is normally experienced in test components [1], it is, nevertheless, insufficiently fast to obtain data, in the range 10^4 to 10^5 for practical, short testing times. For example, a test in the 10^4 - 10^5 cycle range could take approximately 1 year.

In order to circumvent this problem accelerated testing procedures are currently being developed to obtain meaningful high cycle fatigue (HCF) data which could be used to extend currently available fatigue curves from about 10^5 to the 10^8 - 10^9 cycle range. Jaske suggests that 3 accelerated test procedures may be used to obtain valid HCF data [1]:

- (a) Perform the entire test under strain control while measuring the load.
- (b) Perform the initial portion of the test, where large transient stress-strain responses often occur, in strain control. Once a stable response is achieved, switch to load control for the remainder of the test.

1. Numbers in brackets designate references at end of paper.

- c) Perform the entire test under load control while monitoring the strain response to assure that transient stress-strain effects are minimal.

A good motivation for adopting the 2 latter procedures is that load control is inherently more simple [1] and that faster rates of cycling may be used to reach high N_f values.

Over a period of years the authors have accumulated a large quantity of HCF data (10^4 - 10^8 cycle range) for a variety of power reactor materials [2-4]. An attempt is made here to evaluate their usefulness in extending current LCF curves up to the 10^8 - 10^9 cycle range. The data were produced primarily to evaluate the effects of fully reversible stresses on the fatigue life of vibrating heat exchanger components, large rotating apparatus and piping tee joint locations where the mixing of fluids at different temperatures may lead to cyclic stresses. In these situations the loading sequence involves a ramping of the applied stress (strain) from zero to some predetermined steady state value. The cycling rate employed was fast (40 Hz) in order to simulate anticipated frequencies. Although the test procedure does not exactly conform to any of Jaske's recommendations [1], because of the initial stress ramping sequence, the current work is intended to evaluate the effect of such ramping and to establish the usefulness of the current HCF test procedure as an optional alternative in estimating long term fatigue life.

EXPERIMENTAL PROCEDURES

All of the HCF results were obtained for an air environment on Materials Test Systems (MTS) closed loop electrohydraulic fatigue units operating in the push-pull mode with a sinusoidal load controlled waveform at a frequency of 40 Hz. Specimens were heated with a resistance type furnace controlled to $\pm 2^\circ \text{C}$ (4°F).

Below are listed the materials examined together with their chemical compo-

sitions. In some cases two heats of the same material were used. No obvious systematic differences in fatigue life could be attributed to heat-to-heat variations and the heats were used interchangeably.

Table 1

Composition of High Cycle Fatigue Test Materials

Material	Heat	Concentration (Weight %)						Fe
		C	Ni	Mn	Cr	Mo	Others	
2 1/4Cr-1Mo	Exptl.	0.12	0.21	0.44	2.20	0.91	-	Bal.
T304 SS	55697	0.06	9.38	0.91	18.50	0.05	-	Bal.
T304 SS	BNL Heat	0.08	9.55	1.74	18.68	0.25	-	Bal.
I-800H	HH 3113A	0.06	32.11	0.90	20.35	-	0.39 Ti, 0.36 Al	45.2
I-800H	HH 7427A	0.05	32.17	0.67	19.83	-	0.43 Ti, 0.39 Al	45.4
Hastelloy X	4-2809	0.11	Bal.	0.50	20.67	8.86	2.1 Co, 0.65 W	18.7

The 2 1/4Cr-1Mo steel was austenitized at 916°C (1700°F) for 1 hour, then held at 704°C (1300°F) for 2 hours and slowly cooled; the Type 304 stainless steel, Incoloy 800H and Hastelloy X were solution treated at 1066°C (1950°F), 1159°C (2100°F) and 1177°C (2150°F), respectively, and all were then water quenched. After heat treatment the specimens were surface ground to an hourglass configuration. The Incoloy 800H heat HH 7427A and the Hastelloy X specimens had a 0.25 cm (0.25 in.) minimum diameter whereas all others had a 0.32 cm (0.125 in.) diameter.

At the initiation of each test the load was ramped from zero to the predetermined value in approximately 10 seconds (400 cycles). Testing continued at this load level until either failure occurred or it was decided that failure was highly unlikely and the test was aborted.

EXPERIMENTAL RESULTS AND ANALYSIS

Figures 1 through 4 show the basic high cycle data obtained for the load (stress) controlled condition. It seems that those materials which are known to exhibit thermally induced strengthening (Type 304 stainless steel and Incoloy 800H) show a well defined fatigue limit except at very high test temperatures where precipitation strengthening is much smaller or absent [5,6]. Hastelloy X and 2 1/4Cr-1Mo are not thermally strengthened at the test temperatures used [5,7] and fatigue limits are not achieved even after 10^8 accumulated cycles.

In order to correlate these data with LCF results, low cycle information was obtained from the open literature [8-13]. The data were from Argonne National Laboratory (ANL), Battelle Memorial Institute (BMI) now Battelle Columbus Laboratories, General Atomic Company (GA), General Electric Company (GE), Aerojet Nuclear Corporation (ANC) now EG&G Idaho, Inc., and Oak Ridge National Laboratory (ORNL). These organizations are referenced in the appropriate

Figure 1. High cycle fatigue data for isothermally annealed 2 1/4Cr-1 Mo steel.

Figure 2. High cycle fatigue data for Hastelloy X.

Figure 3. High cycle fatigue data for solution annealed Type 304 stainless steel.

Figure 4. High cycle fatigue data for Incoloy 800H.

Figure 5. Schematic of high cycle and low cycle fatigue stress-strain curves.

figures. For the low cycle results, only data obtained for a strain rate of $4 \times 10^{-3} \text{ sec}^{-1}$ were considered since this represented the predominant straining condition. Figure 5 is a schematic of the stress-strain responses for standard strain controlled LCF and load (stress) controlled HCF test procedures. Stress and total strain ranges are given by $\Delta\sigma$ and $\Delta\epsilon_t$, respectively, and the plastic strain range is given by $\Delta\epsilon_p$. In the low cycle case straining is sufficiently slow for the stress-strain curves to be continuously monitored. For the high cycle case, in which the cycling rate is extremely high and the strains are low, it is practical only to monitor the load (stress). Note that significant differences may occur in the initial stress-strain responses for the LCF and HCF testing depending on the stress (strain) levels selected. These differences disappear as soon as a steady state hysteresis loop is established at which point load and strain control occur simultaneously.

In order to evaluate the usefulness of HCF test procedures in extending LCF fatigue curves to the 10^8 - 10^9 cycle range the strain levels for the LCF data must be converted to effective stress levels so that a direct comparison may be made with the load (stress) controlled HCF curves. Since the strain rate for LCF testing is slow ($4 \times 10^{-3} \text{ sec}^{-1}$) most workers are able to continuously monitor the changes in stress level during constant strain LCF testing [10]. For many austenitic alloys it is found that after a short initial period of transient deformation a reasonably constant hysteresis loop is maintained until fracture becomes imminent [10]. The measured stress at $0.5 N_f$ is, therefore, usually taken as the effective stress level in LCF testing. Using these effective stresses a comparison between LCF and HCF curves may be made and the results are given in Figures 6 through 9. In the 10^4 - 10^5 cycle range where the curves overlap a good correlation is obtained for the four materials at each

Figure 6. Correlation of high and low cycle fatigue data for isothermally annealed 2 1/4Cr-1 Mo steel as a function of alternating stress.

Figure 7. Correlation of high and low cycle fatigue data for Hastelloy X as a function of alternating stress.

Figure 8. Correlation of high and low cycle fatigue data for solution treated Type 304 stainless steel as a function of alternating stress.

Figure 9. Correlation of high and low cycle fatigue data for Incoloy 800H as a function of alternating stress.

of the given test temperatures.

The implications of these good correlations are:

(a) The differences in strain rate for the LCF and HCF test, which could be 1-2 orders of magnitude, are relatively insignificant. This will be discussed more fully below.

(b) The differences in the stress-strain history prior to the establishment of stable hysteresis loops is also unlikely to be important. It seems clear that possible effects of the transient deformation, which may exist for as little as one-thousandth of the total fatigue life [10], are readily erased by long term steady state cycling as discussed below.

To compare LCF and HCF strain controlled fatigue curves a means must be devised to convert the HCF stresses to effective strains. A simple conversion using Young's moduli has been used in the past and is based on the assumption that HCF stresses are purely elastic. The data given in Figure 10 for Incoloy 800 tested at room temperature show that this results in a very poor correlation with the LCF curve and indicates that in the 10^4 - 10^5 cycle range there is a considerable inelastic strain which is not accounted for in a simple Young's modulus conversion. The same result was obtained for other test temperatures and materials [3]. To overcome this problem "cyclic stress-strain curves" were constructed from the data in references 8 through 13. These curves, an example of which is given in Figure 11, relate the steady state stress and strain levels at $0.5 N_f$ and account for both elastic and plastic strain components. Using these curves to convert the HCF stresses to effective strains it may be shown that a good correlation is obtained (Figures 12 through 15). The use of cyclic stress-strain curve data thus appears to be an acceptable procedure for correlating HCF and LCF data.

Figure 10. Correlation of high and low cycle fatigue of Incoloy 800H at 22°C (72°F) as a function of strain; stress-to-strain conversions by Young's Modulus.

Figure 11. Cyclic stress-strain curves for solution treated Type 304 stainless steel.

Figure 12. Correlation of high and low cycle fatigue data for isothermally annealed 2 1/4Cr-1 Mo steel as a function of strain.

Figure 13. Correlation of high and low cycle fatigue data for Hastelloy X as a function of strain.

Figure 14. Correlation of high and low cycle fatigue data for solution treated Type 304 stainless steel as a function of strain.

Figure 15. Correlation of high and low cycle fatigue data for Incoloy 800H as a function of strain.

DISCUSSION

The analysis above clearly indicates the usefulness of load controlled HCF tests in extending LCF curves to the 10^8 - 10^9 range. An extremely important factor which has to be addressed, however, is the effect of strain rate since HCF cycling rates are typically 1-2 orders of magnitude higher than LCF rates in the 10^4 - 10^5 cycle regime where the low and high cycle curves overlap. Although the good correlations obtained between low cycle and high cycle data are only an indication that cycling rates are not of primary importance in this range, data to support this are available in the open literature [9]. For example, Figures 16 and 17 show how the fatigue life, N_f , varies as a function of the strain rate. The results are extremely limited and the most comprehensive are for Type 304 stainless steel which was solution treated and given a subsequent aging treatment at 593°C (1100°F) for 1000 hours. For both constant strain and constant stress tests the effects of strain rate are most pronounced in the 10^{-5} - 10^{-2} sec⁻¹ range. At the highest strain rates there is a tendency for the fatigue life to become independent of deformation rate. Manson [14] has shown that the total inelastic strain in fatigue may be considered to be the sum of a plastic component and a time dependent (creep) component. For the slowest strain rates the deformation is essentially creep controlled and N_f is independent of cycling rate. As the strain rate is increased the fatigue life also increases until a second frequency independent plateau is reached. This corresponds to plastic (creep free) deformation. Since the strain rate for the current HCF tests lie in the range 0.2-0.5 sec⁻¹ this would explain the lack of a frequency effect when the LCF and HCF data were correlated in the previous section. The available data, therefore, give a clear indication of the validity of using higher cycling rates to accumulate large numbers of

Figure 16. Effect of strain rate on the fatigue life of Type 304 stainless steel; specimens maintained at constant strain ranges.

Figure 17. Effect of strain rate on the fatigue life of of solution treated and aged Type 304 stainless steel; stress ranges are those measured at $N_f/2$.

of cycles in relatively short test times.

Although strain rate itself is unlikely to significantly affect N_f in the high cycle range there is a related effect which could be important for certain materials which are susceptible to thermally induced strength changes. Consider the measurement of the 10^5 cycle endurance limit in an age hardenable alloy using both LCF and HCF test procedures. At the standard low cycle strain rate of $4 \times 10^{-3} \text{ sec}^{-1}$ the test duration would be about 5 days for Type 304 stainless steel [10]. On the other hand, at a HCF deformation rate of 40 Hz it would take only 0.7 hour. In the case of Type 304 stainless steel age hardening is small at elevated temperatures [5] indicating that major thermally induced changes in the metallurgical structure do not occur during test. Hence, the correlation of LCF and HCF curves for such materials will probably not be influenced by this effect.

In the case of materials such as Inconel 718, which undergo rapid strengthening at elevated temperatures [15], considerable in-test strengthening would result during long term LCF testing. One would, therefore, expect that for a given endurance limit (say at 10^5 cycles) the fatigue strength measured by LCF techniques would be much greater than that obtained by HCF testing. This has been confirmed by Korth and Smolik [16]. For age softening materials the reverse behavior would be anticipated and fatigue strength measured by LCF procedures would give lower values. A possible procedure for minimizing such aging effects would be to thermally age materials prior to test so that the material is in a sufficiently stable metallurgical condition such that the length of the test time does not lead to difficulties with respect to the validity of the test.

Another important problem which needs to be considered is how differences in

the initial stress-strain response could influence subsequent steady state deformation and the fatigue life. Figure 5 shows that the attainment of stable hysteresis loops is different in strain controlled and load controlled tests. For load control there could be large strains associated with early deformation when the material is relatively soft, whereas for strain controlled procedures the stress amplitude continuously increases until stable conditions are reached. In the HCF tests used in the current study the ramping of the load permits significant work hardening to occur before the predetermined load level is attained. Hence, there is no tendency for the specimen to be subjected to large transient strains which could cause buckling or premature failure.

Results from the literature are not definitive in assessing the effects of transient deformation on fatigue life. However, there is strong evidence to show that for some face-centered cubic metals and alloys early deformation history is erased by subsequent long term steady state cycling. Coffin, for example, has demonstrated that for aluminum alloy 1100 and Type 347 stainless steel the cyclic stress-strain behavior is initially quite different for the annealed and cold worked states. However, deformation for each state rapidly proceeds towards a unique hysteresis loop as cycling continues at a given strain amplitude [17]. A similar result was obtained recently for Type 304 stainless steel [18]. It, therefore, appears that fatigue life is principally controlled by the magnitude of the steady state stress (strain); transient deformation behavior, for low stress (strain) conditions, only exists for a very small fraction of the overall fatigue life [10] and is quickly attenuated. There is no firm evidence that it can exert any noticeable influence on fatigue behavior. On this basis it may be concluded that the current HCF test procedure may be used as an optional alternative to those recommended by Jaske [1].

ACKNOWLEDGEMENTS

J. R. Hare carried out the fatigue tests and G. R. Searles prepared the manuscript.

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