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CORRELATION OF HIGH CYCLE AND LOW CYCLE FATIGUE DATA FOR SOME HTGR STRUCTURAL METALS*

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ABSTRACT

An analytical procedure has been evaluated to determine whether low and high cycle fatigue testing techniques may be correlated in the 10^5 cycle region where the data overlap. The procedure, which is based on the use of cyclic stress-strain curves to convert high cycle fatigue stresses to equivalent strains, is shown to be acceptable for Incoloy 800H, Hastelloy X, Type 304 stainless steel and 2¼Cr-1Mo steel in the ranges of temperature for which data are available.

1. INTRODUCTION

Most fatigue work currently being carried out in the power industry is focused on the low cycle fatigue (LCF) regime where the cycles to failure (N_f) are typically less than 10^5. Such information is used to estimate the degree of fatigue damage accumulation in components which are subjected to large cyclic strain changes brought about by thermal transients. Relatively little attention has been paid to the high cycle fatigue (HCF) area for which N_f may be considerably greater than 10^5. Examples where this class of fatigue behavior occurs are in vibrating heat exchanger tubes, large rotating apparatus, and in tee joint locations where cyclic stressing may result from rapid thermal fluctuations caused by the mixing of fluids at different temperatures. To obtain meaningful HCF data the cycling rates should be in the 10-50 Hz range to simulate prototypic strain rates and attempts must be made to simulate the stress-strain history of components which are subjected to HCF deformation.

Since low cycle testing is usually carried out under strain control and slow cycling rates, and high cycle testing under load (stress) control at much faster rates of cycling, the question arises whether the two test procedures may be correlated in the 10^5 cycle range where they overlap. This is not a trivial question since differences in cycling rates could be important as could be the differences in early stress-strain history for strain controlled and load controlled tests. If, however, a correlation can be obtained then a single fatigue curve may be specified for the 10^2-10^8 cycle. Below is described an attempt to define a useful correlation technique for high and low cycle test procedures.

2. 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°C (4°F).

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

Below are given the materials examined together with the chemical compositions. In some cases two heats of the same material were used.

Table 1

Composition of High Cycle Fatigue Test Materials

Material	Heat	Concentration (Weight %) C	Ni	Mn	Cr	Mo	Others	Fe
2¼Cr-1Mo	Expcl.	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, 0.66 W	18.7

The 2¼Cr-1Mo steel was austenitized at 916°C (1700°F) for 1 hour, then held at 704°C (1300°F) for 2 hours and slow cooled; the Type 304 stainless steel, Incoloy 800H and Hastelloy X were solution treated at 1066°C (1950°F), 1149°C (2100°F) and 1177°C (2150°F), respectively, and all were then water quenched.

All specimens were surface ground to an hourglass configuration. The Hastelloy X specimens had a 0.64 cm (0.25 in.) minimum diameter whereas all others had a 0.32 cm (0.125 in.) diameter.

In a recent paper by Jaske[1] it was suggested that high cycle data be generated using one of the following procedures:

a) Performing the entire test under strain control while measuring the load.

b) Performing the initial portion of the test under strain control and switching to load control after steady state deformation has been achieved.

c) Performing the entire test under load control while monitoring the strain response to estimate the extent of initial transient deformation.

The current work was conducted using essentially the last procedure with slight modifications. Firstly, the unavailability of strain gauges to monitor deformation at the high cycling rates used precluded any measurements of the transient strain levels. Secondly, it was deemed unwise to begin the test under load control since the very large initial strains involved could lead to premature failure or specimen distortion. Instead, the load was increased from zero to the required value in about 10 seconds (400 cycles). It can be seen that this type of stress ramping is basically similar to that which would actually exist in cyclically stressed components during a reactor startup phase.

3. EXPERIMENTAL RESULTS AND ANALYSIS

Figures 1 through 4 show the basic high cycle data obtained for the load

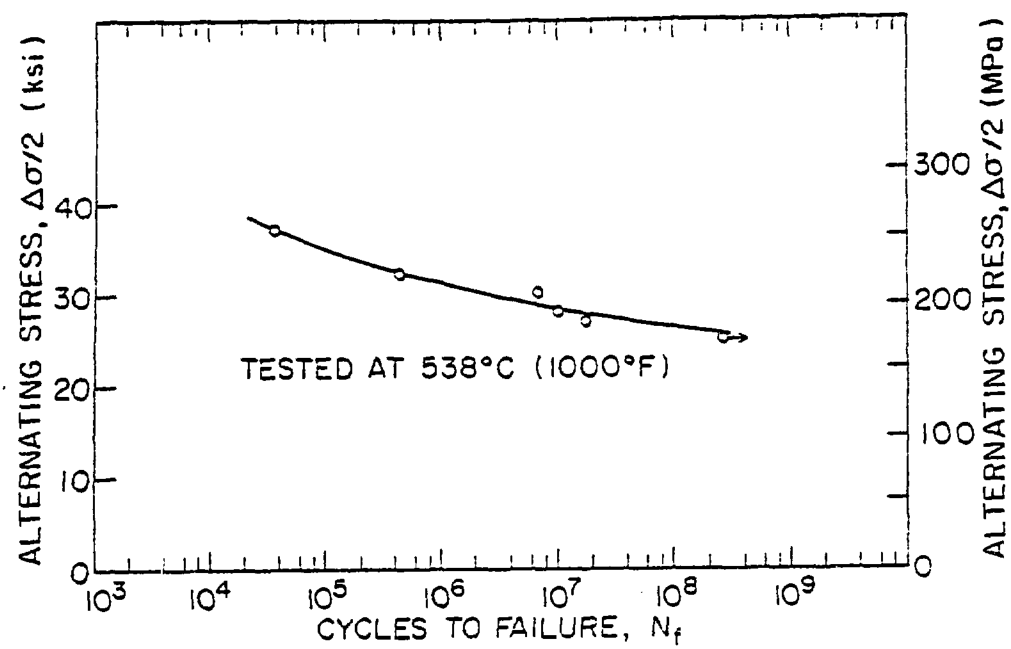

Figure 1. High cycle fatigue data for isothermally annealed 2¼Cr-1Mo steel.

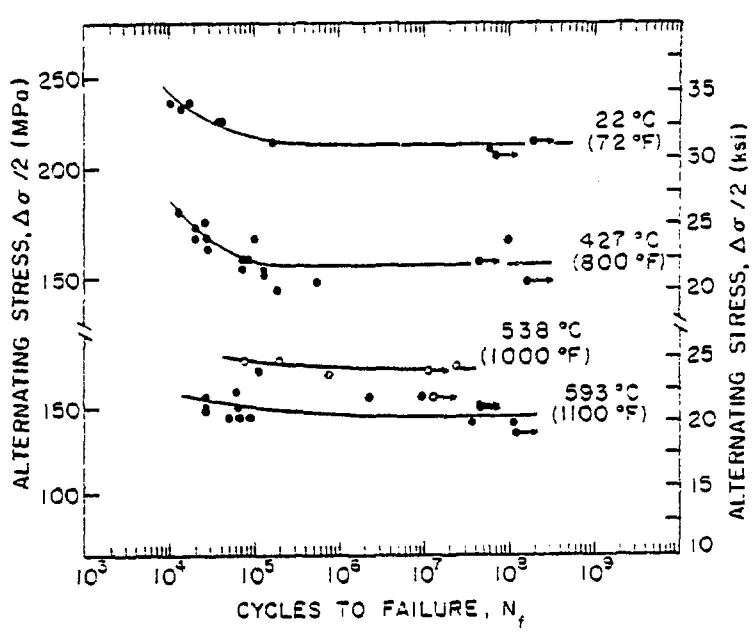

Figure 2. High cycle fatigue data for solution annealed Type 304 stainless steel.

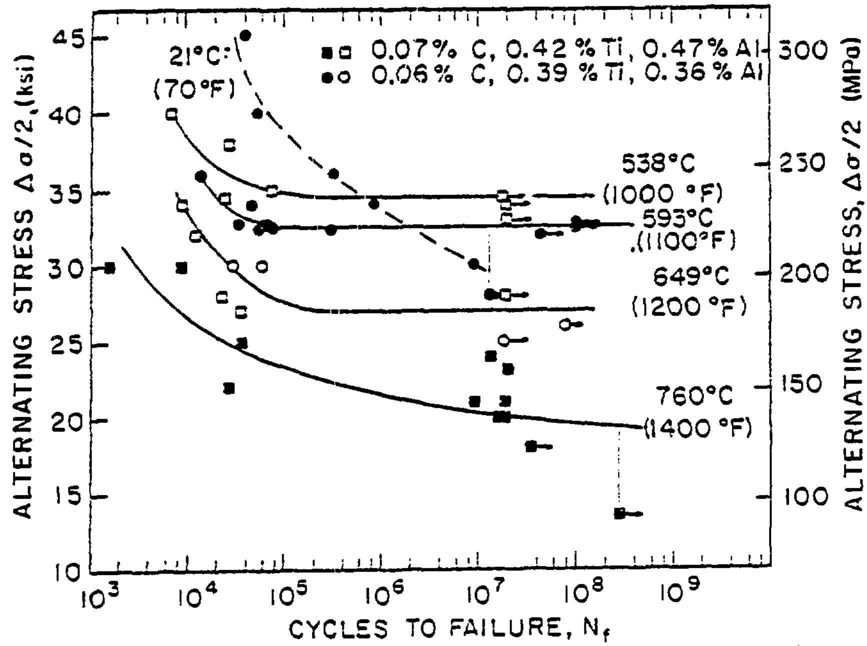

Figure 3. High cycle fatigue data for Incoloy 800H.

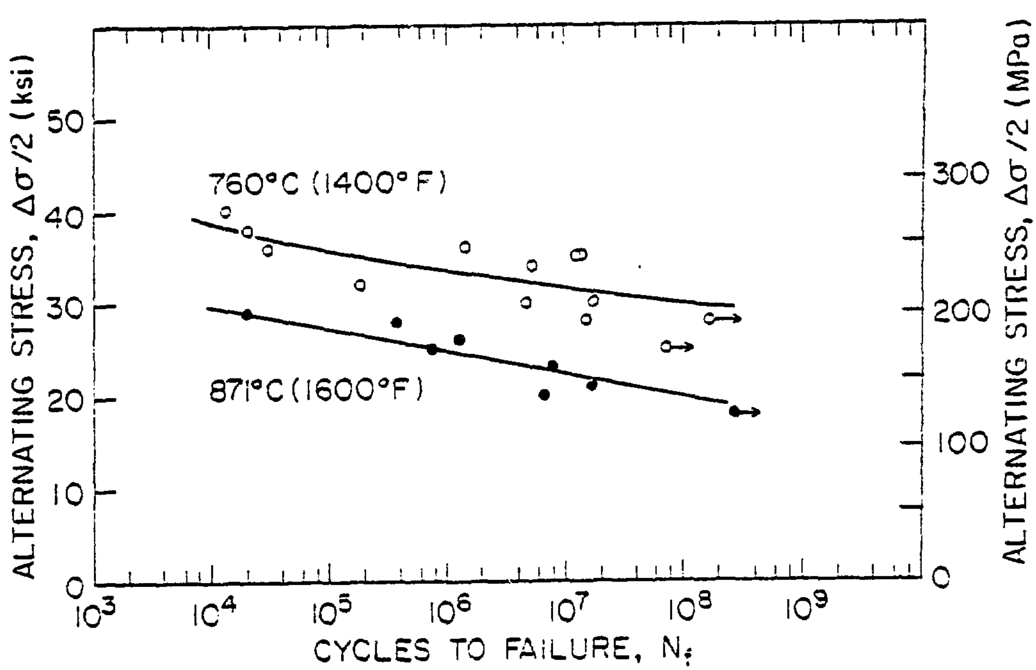

Figure 4. High cycle fatigue data for Hastelloy X.

(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 endurance limit except at very high test temperatures where precipitation strengthening is much smaller.[2,3] Hastelloy X and $2\frac{1}{4}$Cr-1Mo are not thermally strengthened at the test temperatures used[2,4] and endurance limits are not achieved even after 10^8 accumulated cycles.

In order to correlate these data with low cycle results, low cycle information was obtained from the open literature.[5-10] 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., Martest Company, and Oak Ridge National Laboratory (ORNL). These organizations are referenced in the appropriate figures. For the low cycle results, only data obtained for a strain rate of 4×10^{-3} sec^{-1} were considered since this represented the predominant straining condition.

Figure 5 is a schematic of the stress-strain responses for low cycle and

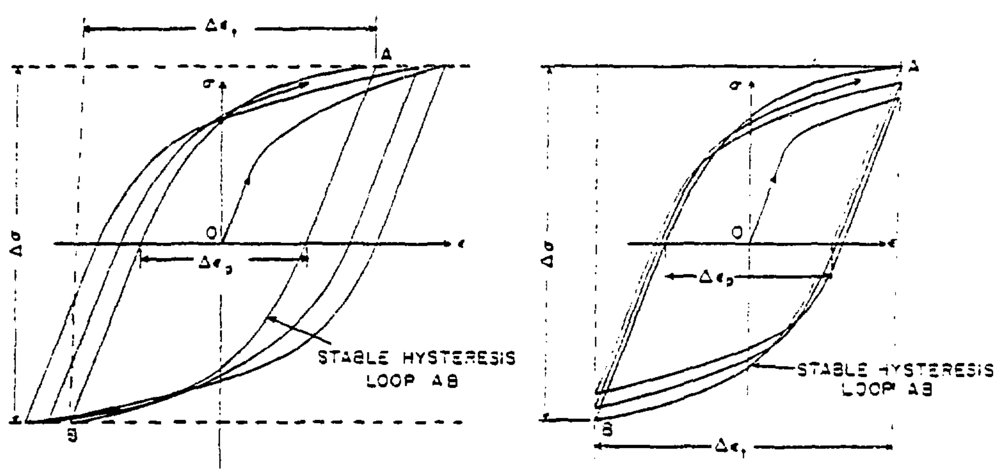

Figure 5. Schematic of high cycle and low cycle fatigue test conditions.

high cycle test procedures. 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.

Figures 6 through 9 show that a good correlation may be obtained for LCF and HCF data in which stress is the dependent variable, provided a suitable choice is made for an "average" stress for the strain controlled LCF tests. In this case the value is arbitrarily taken to be the measured stress level at half the fatigue life, i.e. at 0.5 N_f. This appears to be a logical choice since data for several austenitic materials show that after an initial period of cyclic work hardening the stress level approaches a relatively stable value which is maintained over a large proportion of the remaining fatigue life.[7] For all materials and test temperatures single curves may be drawn through the low and high cycle data. The implications of these good correlations are: (a) the difference in the strain rate for the two types of test, which could amount to 1-2 orders of magnitude, is relatively insignificant, (b) the differences in the stress-strain history prior to the establishment of stable hysteresis loop conditions also does not seem to be important. Strain rate differences, however, could become important for very slow LCF test conditions if time dependent (creep) deformation becomes pronounced.

In order to correlate the data using strain as the dependent variable a means must be devised to convert the HCF stresses to equivalent strains. Previous workers often assumed that the deformation in HCF is purely elastic so that a direct stress to strain conversion may be made using Young's modulus. This was found to be invalid for the four materials tested. Figure 10 illustrates this for Incoloy 800H. Clearly, the strains are greatly underestimated since significant plasticity is associated with the current HCF tests in the 10^4 cycle range. To circumvent this problem cyclic stress-strain curves were constructed from the data in references 5 through 10. 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 equivalent strains it may be shown that a good correlation is obtained as shown in Figures 6, 9, 12 and 13. The use of cyclic stress-strain curve data thus appears to be an acceptable procedure for correlating HCF and LCF data. In addition, the correlation obtained between the two test procedures indirectly validates one of the HCF test procedures recommended by Jaske.[1]

4. CONCLUSIONS

The above results and analyses for isothermally annealed 2¼Cr-1Mo steel, Type 304 stainless steel, Incoloy 800H, and Hastelloy X strongly indicate that the cyclic stress-strain curves may be used as an acceptable means for correlating HCF and LCF data. For the data evaluated, the analyses show that differences in strain rate and early stress-strain history for the two types

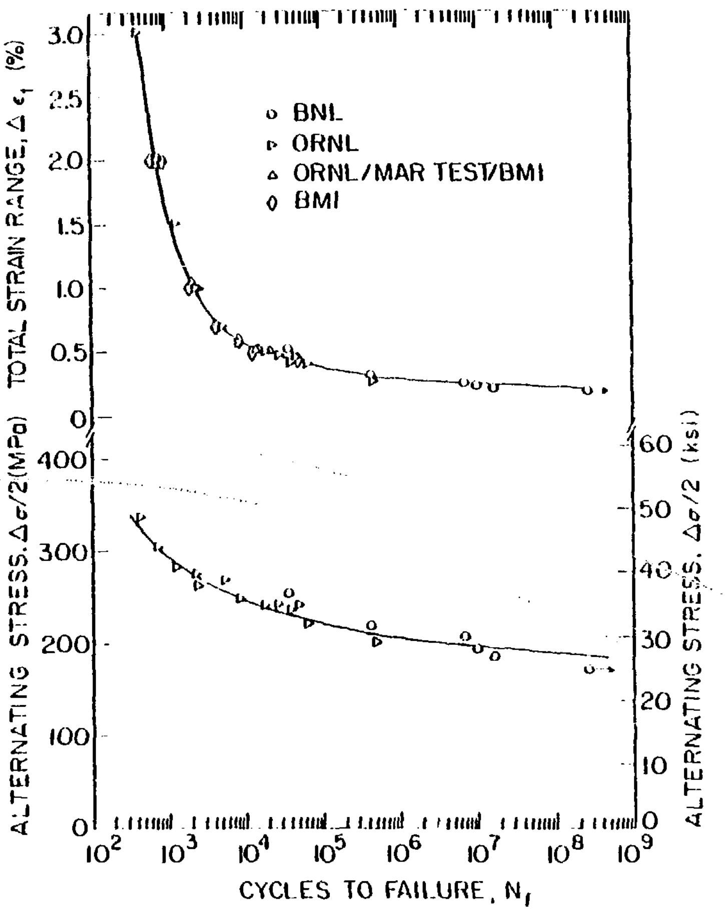

Figure 6. Correlation of high and low cycle fatigue data for isothermally annealed 2¼Cr-1Mo steel at 538°C (1000°F).

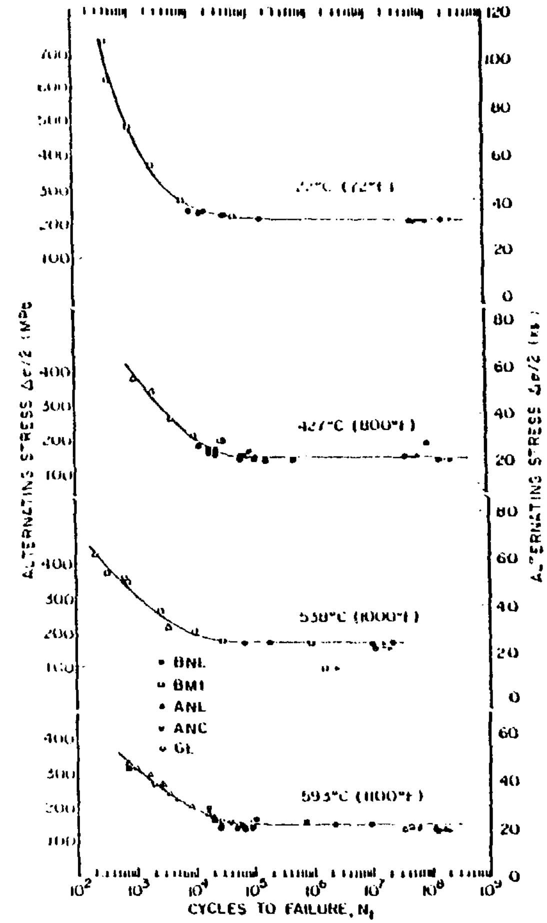

Figure 7. Correlation of high and low cycle fatigue data for solution treated Type 304 stainless steel using stress as the dependent variable.

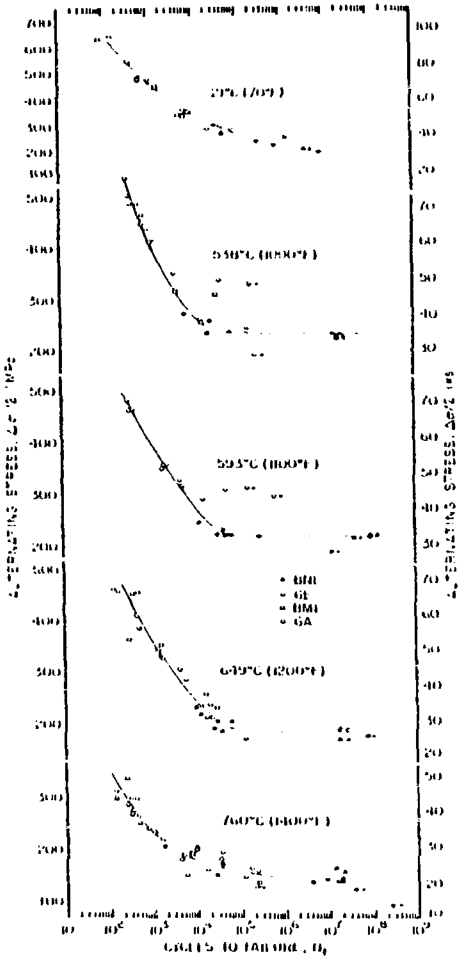

Figure 8. Correlation of high and low cycle fatigue data for Incoloy 800H using stress as the dependent variable.

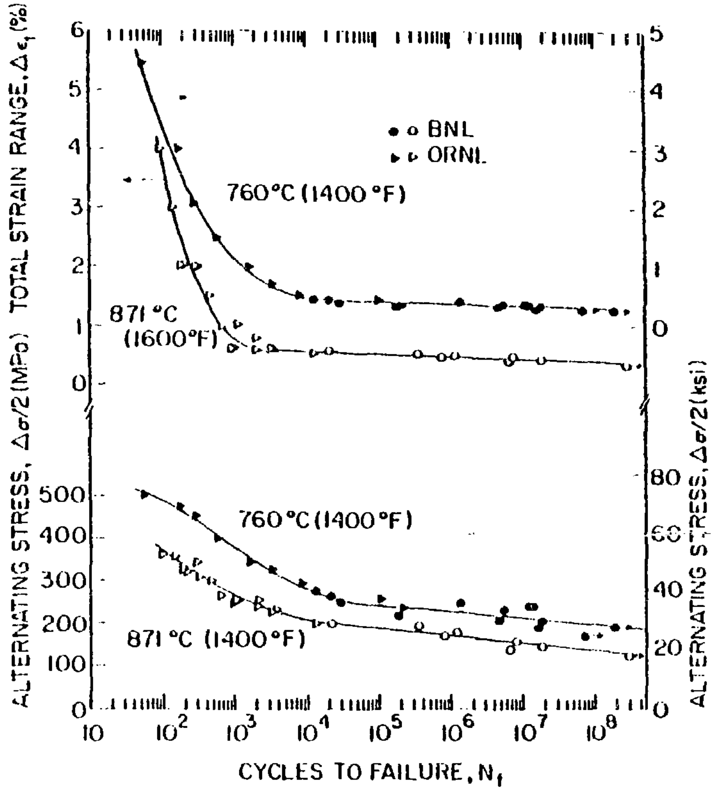

Figure 9. Correlation of high and low cycle fatigue data for Hastelloy X.

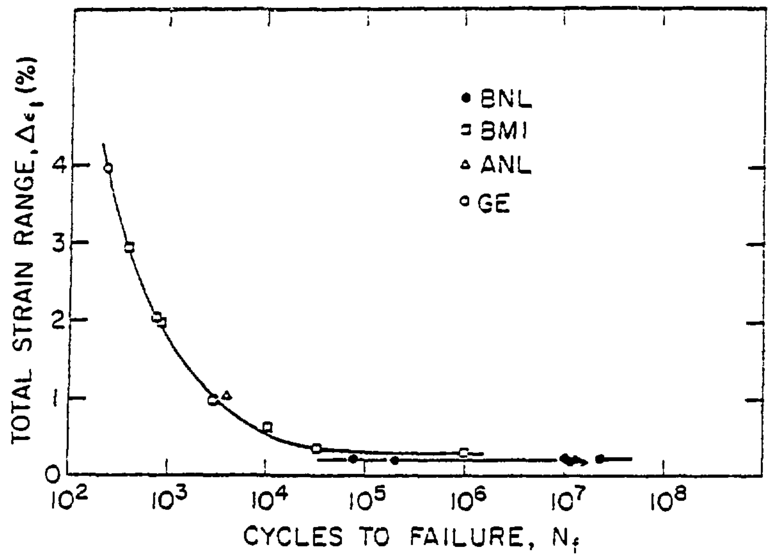

Figure 10. Correlation of low and high cycle fatigue data for solution treated Type 304 stainless steel at 538°C (1000°F); stress to strain conversions for BNL data obtained by use of Young's modulus.

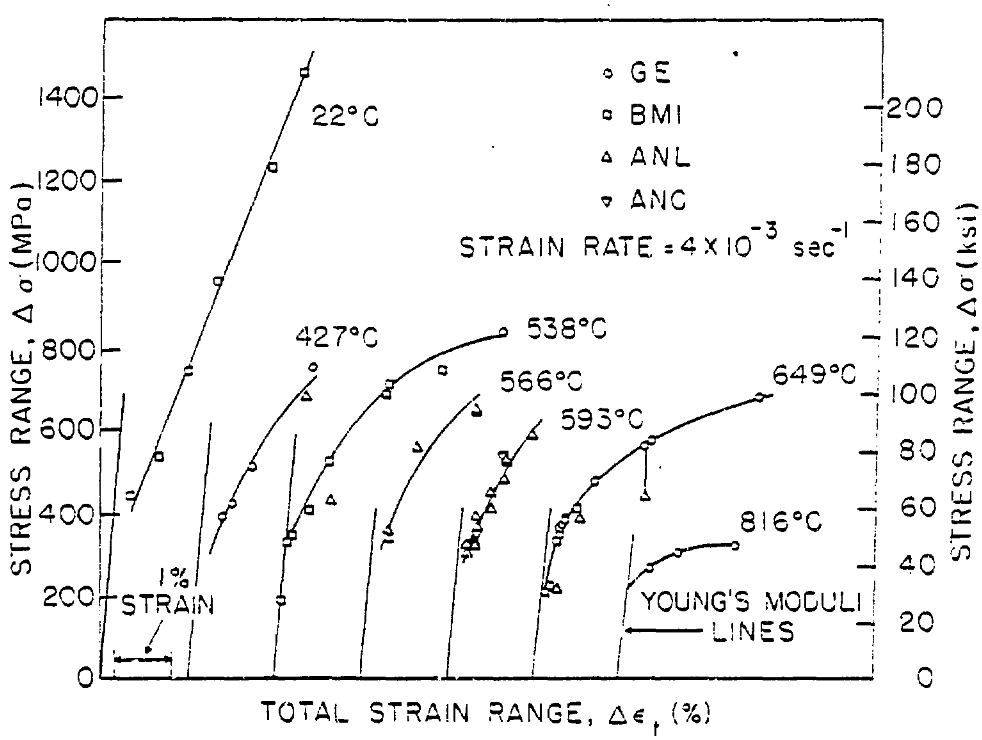

Figure 11. Cyclic stress-strain curves for solution treated Type 304 stainless steel.

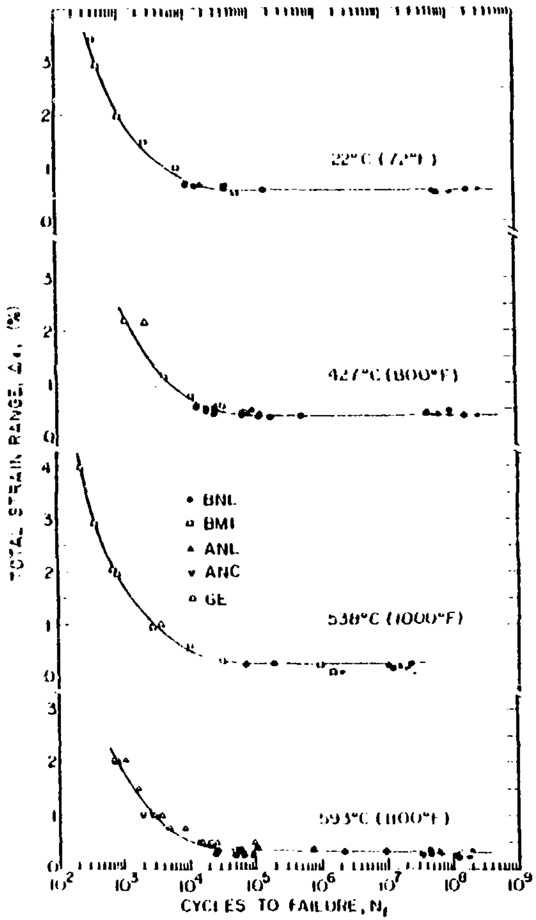

Figure 12. Correlation of high and low cycle fatigue data for solution-treated Type 304 stainless steel using strain range as the dependent variable.

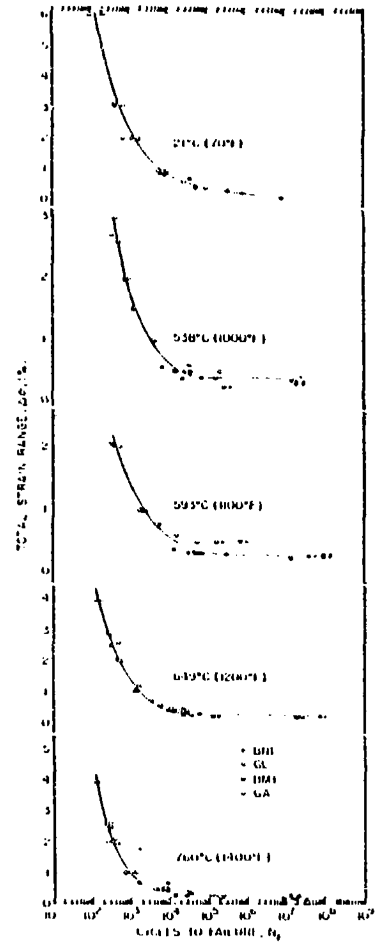

Figure 13. Correlation of high and low cycle fatigue data for Incoloy 800H using strain range as the dependent variable.

of test are not significant. Because of this the HCF procedure, which is usually used to obtain data for the analysis of rapidly stressed components, may also be used as a time saving procedure for extending the LCF curve from about 10^5 to 10^8 and beyond. However, additional work along the lines suggested by Jaske[1] should be conducted to compare other test procedures.

The above results are more comprehensively described in references 11 through 14.

ACKNOWLEDGEMENTS

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