ANALYSIS OF HOLD TIME FATIGUE TEST RESULTS OF AISI
304 STAINLESS STEEL BY FIVE EXISTING METHODS

by

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ABSTRACT

Selected high-temperature fatigue data for AISI 304 stainless steel are analysed using the linear creep-fatigue damage rules, the frequency modified parameter method, and the method given in ASME Code Case 1331-5. The capability of each method to predict fatigue lives obtained under known testing conditions is discussed.

The method of the ASME Code case which includes large safety factors, was found to be conservative. If, however, the method is used at 1050°F for cycles with long hold times, the safety factor of the resultant design may be significantly smaller than desired. The other four methods examined predicted the majority of the experimental fatigue lives within a factor of two. The linear creep-fatigue damage rule using a time ratio for creep damage appears to be superior to the others.

INTRODUCTION

Several methods of estimating the time dependency of fatigue at elevated temperatures have been proposed in the literature (Refs. 1-6). Each

investigator has demonstrated the capability of each particular method to predict the time dependent phenomenon of fatigue fracture. From the design-engineer's viewpoint, it is of practical importance to compare the accuracy of each predictive method for a particular material of interest.

In this report, the hold time fatigue life of Type 304 austenitic stainless steel at 1050°F, 1100°F and 1200°F was calculated using the method contained in ASME Code Case 1331-5, using three types of linear creep-fatigue damage rules, and using the frequency modified parameter method. The accuracy of each method in predicting the fatigue life is discussed by comparing the experimental and calculated lives of hold time fatigue tests.

METHODS OF ANALYSIS

For the readers' convenience, each predictive method is briefly described in the following three paragraphs.

In the linear creep-fatigue damage rules, fracture is assumed to occur when the sum of fatigue damage and creep damage reach a prescribed value (Refs. 2,3). The fatigue damage is always defined as the ratio of the number of cycles, n , at a given strain range, divided by the number of cycles that would cause failure at that strainrange, N_f . When cycling at several strain ranges, each portion of the damage is linearly added. At low temperatures, where there is little effect of creep (i.e., the effect of time), the linear damage rule using the cycle ratio as a measure of fatigue damage is known to successfully predict fatigue life (Refs. 7,8).

On the other hand, the creep damage accumulated during elevated temperature testing is usually defined by either a life exhaustion rule or a ductility exhaustion rule. In the life exhaustion method, the creep damage is defined as the ratio of time spent at a given stress level, Δt , to the time-to-rupture, t_r , under the same stress level. Here again the ratios are linearly added in the case of several stress levels. To obtain the creep rupture time experimentally, either static creep rupture tests or reversed creep rupture tests (cyclic creep) may be performed (Ref. 3). In the ductility exhaustion rule, the creep damage is defined as the ratio of the plastic strain accumulated under a given stress, $\Delta \epsilon$, to the creep-rupture-ductility, ϵ_f , under the same stress. In each rule, the sum of creep and fatigue damages is assumed to be one at fracture, and the fracture criteria may be expressed as follows:

- a) Life exhaustion rule:
(static creep rupture) $\sum \frac{n}{N_f} + \sum \frac{\Delta t}{t_{r,static}} = 1$
- b) Life exhaustion rule:
(cyclic creep rupture) $\sum \frac{n}{N_f} + \sum \frac{\Delta t}{t_{r,cyclic}} = 1$
- c) Ductility exhaustion rule: $\sum \frac{n}{N_f} + \sum \frac{\Delta \epsilon}{\epsilon_f} = 1$

The method proposed in ASME Code Case 1331-5 (Ref. 6) is a variation of the linear creep-fatigue damage rule. The rule uses "design" data for fatigue fracture and creep rupture instead of the actual fatigue and creep rupture data. The "design" data incorporate safety factors of either two on the strain range or twenty on the cycles to failure. The factors are meant to account for the many differences between the laboratory test conditions and actual component operating conditions. As intended,

the results of creep-fatigue life calculations based on the Code Case are conservative, especially when compared to laboratory fatigue test results.

In the frequency modified parameter method (Ref. 9), it is assumed that the time dependence of creep fatigue failures can be accounted for as follows:

$$N_f^* = (C/\Delta\epsilon_p)^{1/\beta} \nu^{1-K},$$

where N_f^* is the number of cycles to failure under creep-fatigue conditions, $\Delta\epsilon_p$ is the plastic strain range, ν is the cycling frequency, and the material constants, C , β and K are determined in the laboratory from the results of continuously-cycled fatigue-tests at various frequencies.

EXPERIMENTAL CONSTANTS FOR THE ANALYSIS

The material constants, which were necessary for the analysis, were obtained from references 10 and 11. They are listed in Table 1. The stress relaxation data from hold time tests were approximated by equations of the form

$$\ln \frac{\sigma_o}{\sigma} = \frac{A}{1+m} t^{1+m},$$

where σ_o , A and m were determined to best fit the relaxation data (Ref. 12).

RESULTS OF THE ANALYSES

Figure 1 shows a comparison of calculated fatigue lives with the actual experimental lives. The experimental results used include test data covering the temperature range from 1050°F to 1200°F. The range of fatigue life covered is from 100 to 10,000 cycles, and the length of the strain hold time per cycle is from one to 600 min.

The ASME Code Case method predicts lives approximately a factor of twenty smaller than the experimental values. This conservativeness is expected because as already noted, the creep and fatigue "design" data used in the analysis are significantly smaller than the actual lives. The three linear creep-fatigue cumulative damage rules and the frequency modified parameter method predict the majority of the experimental fatigue lives within a factor of two.

Actual loading conditions in a design application could differ significantly from those employed in the present hold-time fatigue-tests. Even under largely similar loading conditions, the length of the hold time and the number of cycles applied for instance, could be much larger than 600 min or 10,000 cycles, respectively. Figures 2 and 3 indicate how the accuracy of the predictions may change when these two particular test variables are extrapolated. In order to successfully apply any of these methods to actual loading conditions, the accuracy and the conservativeness of the calculated results should not change with an increase of these variables.

In Fig. 2, the ratio of the actual fatigue life to the calculated fatigue life, R , was plotted as a function of the length of strain hold time per cycle. For the ASME Code Case, the ratio appears to decrease with increasing hold times at 1050°F, implying that the conservativeness of the design based on the Code Case rules may decrease accordingly.

In Fig. 3, the ratio, R , is plotted as a function of the actual fatigue life. This ratio increases with an increase in actual life for the case of linear cumulative damage with the ductility exhaustion rule. No significant trend in this ratio can be seen in the results of the other four methods.

Besides the difference in range of hold times and number of cycles applied, the loading wave form for each cycle in an actual application may differ from those in the hold-time fatigue-tests. Whether the accuracy of the predictions holds for various loading wave forms is of practical interest. Fig. 4 compares the accuracy of predictions for the tensile hold-time tests (white area) and the tests with compressive or symmetrical hold-times (hatched area). In the frequency modified method and the ASME method, the fatigue lives with compressive or symmetrical hold-times are always predicted smaller than the actual fatigue life. This is because the material is sensitive to the loading pattern and the methods do not account for variations of the wave pattern within each cycle.

CONCLUSION

The results of the present comparison using hold-time creep-fatigue data for Type 304 stainless steel may be summarized as follows:

Linear creep-fatigue damage rules using the time ratio for the creep damage appear to be better than the other methods. If the application of the methods is limited to loading conditions very similar to those used in the present hold-time fatigue tests, all three linear creep-fatigue damage rules and the frequency modified parameter method can predict the creep-fatigue life within about a factor of two.

The method proposed in ASME Code Case 1331-5 is reasonably conservative. However, if the method is applied for situations involving very long hold-times, the conservativeness of the lifetime prediction could be significantly reduced.

The linear creep-fatigue damage rule incorporating the ductility exhaustion method tends to predict lifetimes with increasing conservativeness as the strain range is reduced. The frequency modified parameter method is insufficient when the damage accumulated by the material is different under tension cycling than under compression cycling.

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Table 1. Material Constants Used in the Analysis

•Static Creep Rupture Data (Ref. 10)

$$\sigma = 59 \times t_{r,static}^{-0.107} \quad \text{at } 1050^{\circ}\text{F}$$

$$\sigma = 51 \times t_{r,static}^{-0.117} \quad \text{at } 1100^{\circ}\text{F}$$

$$\sigma = 41 \times t_{r,static}^{-0.156} \quad \text{at } 1200^{\circ}\text{F}$$

where σ is the stress level, and t_r is the time to rupture.

•Reversed Creep Rupture Data

$$\sigma = 67 \times t_{r,cyclic}^{-0.175} \quad \text{at } 1100^{\circ}\text{F}$$

•Fatigue Fracture Data

$$\Delta\epsilon_p = 0.51 N_f^{-0.478} \quad \text{at } 1050^{\circ}\text{F}$$

$$\Delta\epsilon_p = 0.26 N_f^{-0.433} \quad \text{at } 1100^{\circ}\text{F}$$

$$\Delta\epsilon_p = 1.33 N_f^{-0.67} \quad \text{at } 1200^{\circ}\text{F}$$

•Creep Ductility Data (Ref. 10)

$$\epsilon_f = -0.312 + 0.0196\sigma \quad \text{at } 1100^{\circ}\text{F}$$

$$\epsilon_f = 0.125 + 0.010\sigma \quad \text{at } 1200^{\circ}\text{F}$$

•Constants for the Frequency Modified Parameter Method (Refs. 9,11)

$$C = 0.49, \beta = 0.56, K = 0.69 \quad \text{at } 1100^{\circ}\text{F}$$

$$C = 0.81, \beta = 0.75, K = 1.10 \quad \text{at } 1200^{\circ}\text{F}$$

Fig. 1. Relationship between Actual Fatigue Life and the Calculated Fatigue Lives.

Fig. 2. Ratios of Calculated Fatigue Lives to Actual Fatigue Lives as a Function of the Length of Hold Time.

Fig. 3. Ratios of Actual Fatigue Lives to the Calculated Fatigue Lives as a Function of the Actual Fatigue Life.

Fig. 4. The Distribution of the Ratios between Actual Fatigue Life and the Calculated Life for the Hold-Time Fatigue Test at 1100°F.