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LETTER

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Rapid extrapolation of high-temperature low-cycle fatigue curves for a nickel superalloy

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Abstract

In many industrial applications, ranging from the energy, the aviation to the microelectronics field, metallic alloys are subjected to fatigue load at elevated temperatures. The detrimental influence of temperature and creep deformation damage on the structural performance of such components has for several decades posed a serious challenge to the work of scientists and engineers, and the methods developed to account for creep fatigue interaction require extensive testing and work for being calibrated and implemented. In the present letter, the authors propose a quick iterative procedure to translate the fatigue curve of an alloy in order to consider the reduction of resistance caused by creep damage. The method is validated against high-temperature fatigue results for the Haynes 230 commercial nickel superalloy showing promising results.

KEYWORDS

creep-fatigue interaction, low-cycle fatigue, nickel superalloy, time ductility exhaustion

1 | TIME FRACTION CREEP DAMAGE INTEGRATION

Taken a specimen undergoing a variety of loads which generate creep deformation, this specimen has a limiting failure time t_R dependent on the applied load σ_i. If the damage generated by each loading condition, lasting a time t_i, is independent of the order, linear damage summation can be applied to determine the total damage of the sequence.[1]

$$D_c = \sum \frac{t_i}{it_R(\sigma_i)} \tag{1}$$

The results of creep testing in terms of time to failure t_R at different temperatures T and applied nominal stresses σ can be reassumed in a two-dimensional space recurring to the Larson Miller parameter (LMP).[2] The constant C is equal to 20 for most metals if time is expressed in hours.

$$LMP = T(\log t_R - C) \tag{2}$$

Plotting the nominal applied stress versus the LMP value for the creep tests, the results, typical of the alloy, can be expressed in the form

$$\sigma = A \cdot LMP^{a}. \tag{3}$$

Combining Equations 2 and 3, it is possible to obtain the stress causing failure at a given time and temperature:

$$\sigma = A \cdot T^{a} (\log t_R - C)^{a}. \tag{4}$$

Dealing with high-temperature low-cycle fatigue problems, it is necessary to fully characterize the cyclic stress-strain response of the alloy. The correlation between deformation range, temperature, frequency or strain range, and stress can be obtained by testing and modeled by the means of an opportune constitutive law.

$$\sigma = \sigma(T,\ f,\ \varepsilon) \tag{5}$$

In the hypothesis of high-temperature cyclic loading imposed by a triangular deformation wave of frequency f, amplitude ε_a, and loading ratio $R = \varepsilon_{max}/\varepsilon_{min} = -1$, combining Equation 4 with a constitutive law in the form of Equation 5 and with the concept of time fraction damage summation introduced by Equation 1, it is possible to obtain the quota of ideal damage introduced in the material by a single loading starting from the undeformed configuration and reaching ε_a linearly in a time corresponding to $t = 1/4f$, by integrating in the form:

$$d_{ci} = \int_0^{t=1/4f} \frac{dt}{10^{\left[(\sigma(T,f,\varepsilon(\varepsilon_a,f,t))/A)^{1/a}/T - C\right]}}. \tag{6}$$

The integral corresponds to the addition of the damage caused by the infinitesimal load application time dt divided by the instantaneous time to failure, from Equation 4, in which the instantaneous load is given by the stress-strain relationship calibrated on cyclic testing, thus dependent on temperature, strain rate, and strain range. It is necessary to experimentally determine the material response to a fatigue load at a reference temperature and frequency, which can be described by the known Smith Watson Topper (SWT) equation.[3]

$$\varepsilon_a\left(T_{ref}, f_{ref}, N\right) = \frac{\sigma_f'}{E}(N)^{b} + \varepsilon_f'(N)^{c} \tag{7}$$

The low-cycle fatigue response of the material for temperatures different from the reference temperature can be obtained by translating the reference curve proportionally to the logarithm of the creep damage introduced at the new temperature:

$$\varepsilon_a(T,\ f,\ N) = \varepsilon_a\left(T_{ref}, f_{ref}, N\right) \frac{\log d_{ci}(T,\ f,\ N)}{\log d_{ci}\left(T_{ref}, f_{ref}, N\right)}. \tag{8}$$

The creep damage computed by Equation 6 is dependent on the deformation amplitude to which the material is subjected for a given number of cycles. An iterative is then necessary. The application of the here presented approximation is summarized as follows:

1. Perform creep testing to failure in the range of temperatures of interest to obtain the constants A and a.
2. Characterize the cyclic response of the alloy for the necessary range of temperatures and frequencies to calibrate a correlation in the form of equation 5.
3. Perform fatigue testing at a certain reference temperature and strain rate to calibrate the SWM model.
4. Generate an array of number of cycles on which to compute the relative deformation amplitude for the temperature of choice.
5. Assume and initial strain amplitude equal to the strain amplitude of the reference fatigue curve and compute the integrated creep damage component both at the desired temperature and at the reference temperature.
6. Apply Equation 8 and repeat the computation of the integrated creep damage at the new temperature until convergence is reached.

2 | HIGH-TEMPERATURE FATIGUE CURVE EXTRAPOLATION FOR A NICKEL SUPERALLOY

The procedure introduced in the previous paragraph was applied to compute the low-cycle fatigue curves at various temperatures for the commercial nickel superalloy Haynes 230. The experimental results chosen as framework for the verification of the model were not performed by the authors but are of public dominion. Barrett et al[4] and Ahmed et al[5] performed cyclic testing at the temperatures and frequencies required to obtain the stabilized hysteresis cycle in the same conditions of the fatigue data. Fatigue and creep testing results are instead reported by the manufacturer.[6] The creep results for samples realized from plates and tested at temperatures ranging from 649°C to 1149°C are reported in Figure 1A. The constants of Equation 3 are calibrated on the results of the tests performed up to 982°C, which corresponds to the highest fatigue testing temperature, obtaining $A = 7.94855E - 33$ and $a = -7.26155$. The fatigue tests as well were performed on specimens manufactured from plates, at a frequency $f = 0.33$ Hz and temperatures ranging from 427°C to 982°C. The fatigue results at the lowest temperature, 427°C, were chosen as reference, calibrating the SWT parameters as: $E = 190\,000$ MPa, $\sigma_f' = 1400$ MPa, $b = -0.1$, $\varepsilon_f' = 0.4$, $c = -0.58$, see Figure 1B. All the fatigue results are plotted in Figure 2A, where the solid lines represent the result of the extrapolation according to Equation 8. Figure 2B shows how the deformation amplitude imposed in the test versus the extrapolated amplitude for the corresponding number of cycles is included in a scatter band of ±20%, indicating a good accuracy.

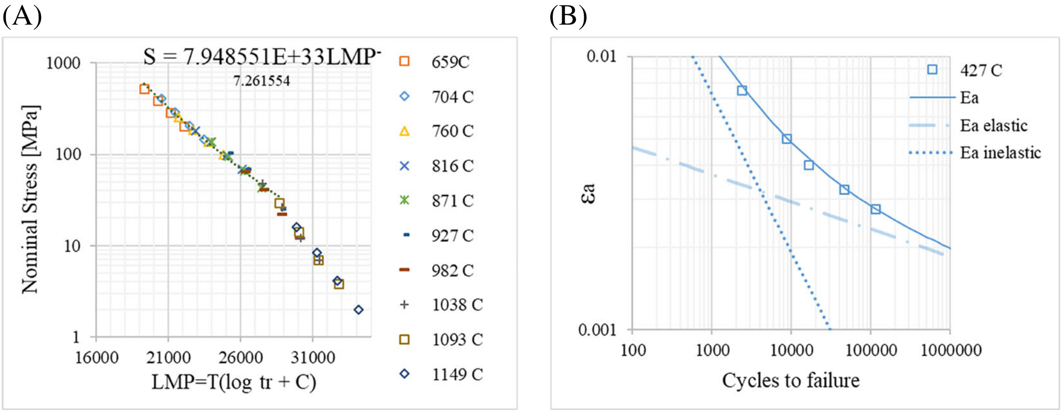

FIGURE 1 Creep failure results and trendline for the range of temperatures of interest for the fatigue testing A,. Reference fatigue curve at 427°C B,

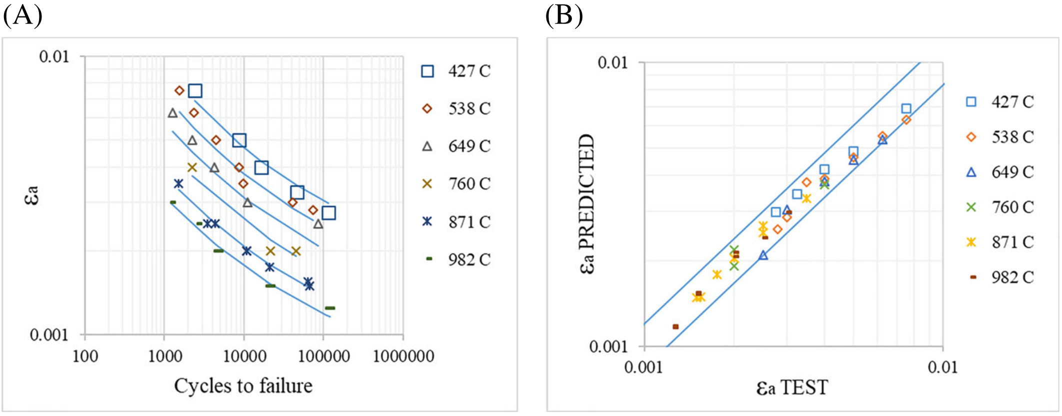

FIGURE 2 Fatigue testing results from 427°C to 982°C. The lines indicate the extrapolated fatigue curves A,. Predicted versus experimental fatigue strain amplitude, scatter ±20% B,

3 | CONCLUSIONS

A method for computing the influence of temperature on fatigue life through the basic concepts of creep damage is presented. Having obtained a full characterization of the mechanical response under cyclic loading, of the creep life time versus load and temperature and a fatigue curve obtained at a reference temperature and testing frequency, it has been possible to extrapolate the fatigue response for higher temperatures obtaining results in good agreement with the experimental data available at these temperatures. The method accounts for the influence of frequency on the creep damage, introduced indirectly through the material cyclic response and directly through the integration time for the integrated creep damage. The accuracy of the method to predict the fatigue response to different frequencies than the reference one has not been validated by experimental results. Should this ability be positively verified, the method would be a powerful tool for the extrapolation of high-temperature fatigue curves at low strain range, condition for which experimental testing could require unfeasible time.

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