

Full Length Research Paper

Statistical thermal fatigue-creep modeling of 316 stainless steel materials

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The main goal of this study is to investigate the creep fatigue behavior of 316 stainless steel materials. In the low cycle thermal fatigue life model, Manson's universal slopes equation was used as an empirical correlation which relates fatigue endurance to tensile properties. Fatigue test data were used in conjunction with different modes to establish the relationship between temperature and other parameters. Statistical creep models were created for 316 stainless steel materials. In order to correlate the results of short-time elevated temperature tests with long-term service performance at more moderate temperatures, different creep prediction models, namely Basquin model, Sherby-Dorn model and Manson-Haford model, were studied. Comparison between the different creep prediction models were carried out for a range of stresses and temperatures. A linear damage summation method was used to establish life prediction model of 316 stainless steels materials under fatigue creep interaction.

Key words: Stainless steel materials, low cycle thermal fatigue, statistical creep model.

INTRODUCTION

Stainless steel materials are widely used at elevated temperatures when carbon and low-alloy steel do not provide adequate corrosion resistance or sufficient strength. Consequently the thermal fatigue and creep behavior of the stainless steel materials has been the subject of a considerable amount of experimental and numerical studies. A series of equations have been proposed to correlate the low-cycle fatigue date (Collins, 1993). Manson et al. (1971) derived a strain range partitioning technique. A stress-strain cycle is separated into its components and then the damage caused by each cycle is determined. Based on creep-fatigue data of 304 stainless steel, Diercks and Rasks (1979) developed a multivariate best-fit equation for creep-fatigue life prediction. The creep-fatigue life is a function of parameters such as strain range, strain rate, temperature and hold time. Low cycle fatigue tests have been carried out by Nam et al. (1995) with three different materials

(1Cr-Mo-V steel, 12Cr-Mo-V steel and 304 stainless steel) for the investigation of the effect of surface roughness on the fatigue life.

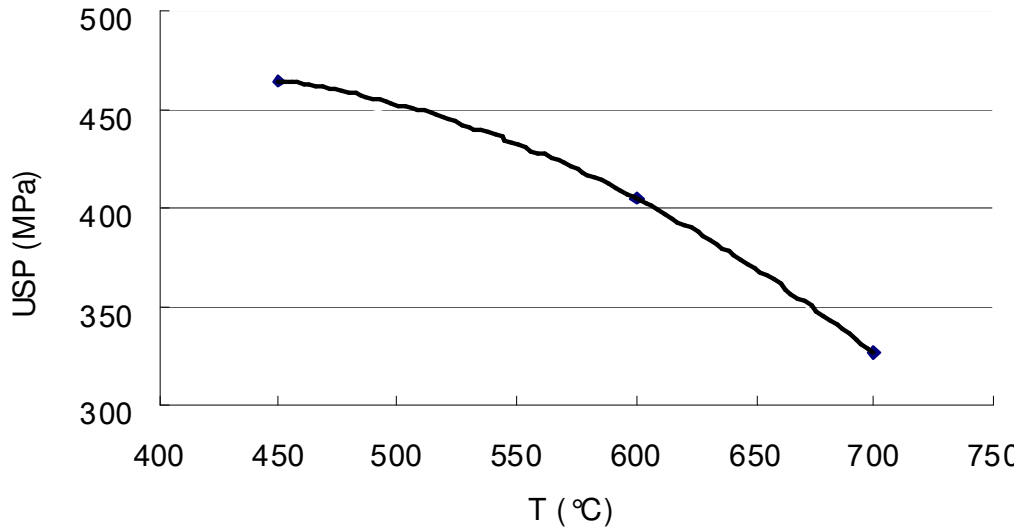
In the present paper, an analytical model has been established to predict fatigue-creep life for AISI 316 stainless steel. Manson's universal slopes equation has been used as an empirical correlation which relates fatigue endurance to tensile properties. Fatigue test data were used in conjunction with different modes to establish the relationship between temperature and other parameters. Then statistical creep models were created for AISI 316 stainless steel. To correlate the results of short-time elevated temperature tests with long-term service performance at more moderate temperatures, different creep prediction models have been studied. Comparison between the different creep prediction models and experimental results were carried out for a range of stresses and temperatures. A linear damage summation method was used to establish life prediction model of stainless steels materials under fatigue creep interaction.

The output from the model is an estimate of the cyclic endurance of AISI 316 stainless steels with respect to the onset of cracking, together with information on the nature

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Table 1. Relationship between temperature and other parameters.

T (°C)	450	600	700
UTS (MPa)	465	405	326
E (GPa)	168.5	151	142
RA (%)	70	70	68

**Figure 1.** Relationship between temperature T and ultimate tensile strength UTS.

of the dominant failure mechanism. These informations allow material selection or design improvements to proceed with minimum reliance on component testing.

LOW CYCLE THERMAL FATIGUE LIFE MODELS

The low cycle thermal fatigue life can be obtained from the total strain range vs. life. When the cyclic material data are unavailable or not enough, Manson's universal slopes equation (Manson, 1965) can be used as an empirical correlation which relates fatigue endurance to tensile properties:

$$\Delta\varepsilon = 3.5 \frac{UTS}{E} (N_f)^{-0.12} + \varepsilon_f^{0.6} (N_f)^{-0.6} \quad (1)$$

where $\Delta\varepsilon$ is the total strain range, UTS is the ultimate tensile strength, E is the Young's modulus, N_f is the number of cycles to failure and ε_f is the true ductility which can be obtained by following equation:

$$\varepsilon_f = \ln\left(\frac{100}{100 - RA}\right) - \varepsilon_H \quad (2)$$

Where RA is the percentage reduction in area at tensile failure and ε_H is the prestrain.

The parameters for estimating fatigue life of stainless steels are being collected by a number of researchers (Boller, 1987). Table 1 shows the elevated-temperature data for the AISI 316 stainless steel.

To find the relationship between temperature T and other parameters, data in Table 1 is used in conjunction with different modes. The results in Figure 1 show that the polynomial model provides the best fit ($R^2=1$) for the relationship between temperature T and ultimate tensile strength UTS and a model of the following type is expected:

$$UTS(T) = -0.0016T^2 + 1.238T + 223.8 \quad (3)$$

Figure 2 shows that the natural logarithmic model provides the relative better fit ($R^2=0.9999$) for the relationship between temperature T and Young's modulus E.

$$E(T) = -60.068 \ln(T) + 535.53 \quad (4)$$

It can be seen from Table 1 that for AISI 316 stainless steel, the percentage reduction in area RA only change

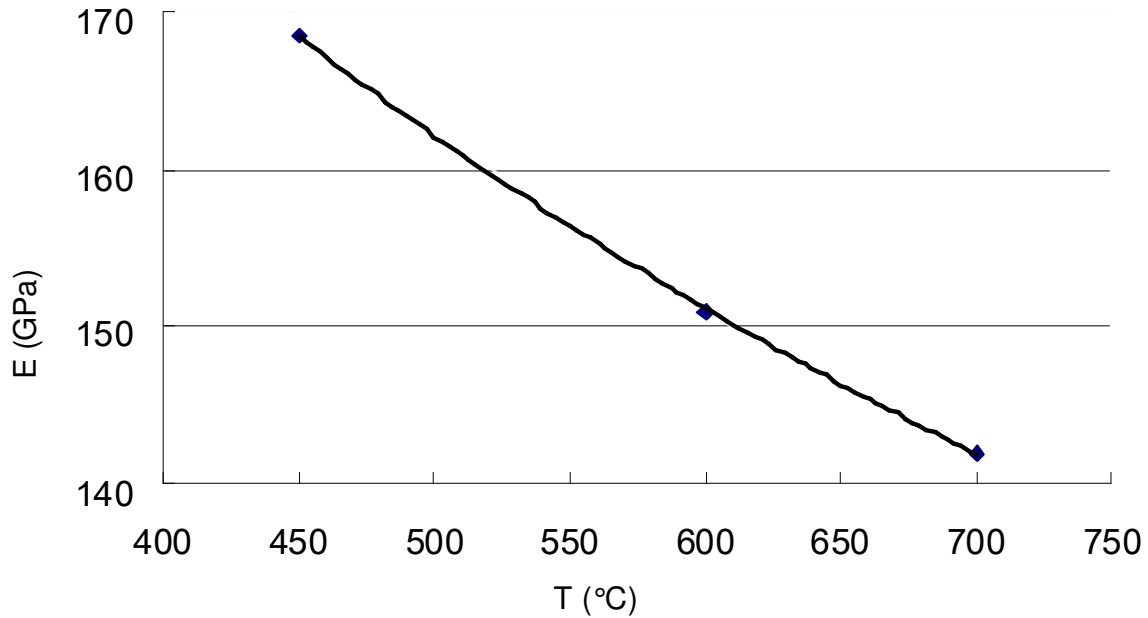


Figure 2. Relationship between temperature T and Young's modulus E.

Table 2. Summary of estimated creep properties for the AISI 316 stainless steel (MPa).

T(°K)	873.15	893.15	913.15	933.15	953.15
Time (h)					
10000	177.723	148.862	123.039	100.254	80.507
30000	153.419	124.558	100.254	80.507	62.279
100000	126.077	100.254	77.469	59.241	44.051

slightly as the temperature increases. Thus RA = 70 was used in this study. The true ductility ε_f then can be obtained by following equation:

$$\varepsilon_f = 1.20 - \varepsilon_H \quad (5)$$

Substituting Equations (3), (4) and (5) into Equation (1):

$$\Delta\varepsilon = 3.5 \frac{-0.001T^2 + 1.23T + 2238}{-60086 \ln(T) + 53553} (N_f)^{-0.12} + (1.20 - \varepsilon_H)^{0.6} (N_f)^{-0.6} \quad (6)$$

STATISTICAL CREEP MODELS

For providing accurate information upon which reliable design stresses may be based, the elevated-temperature tensile, creep and rupture test data on stainless steel are

being collected by a number of steelmakers (Truman, 1966; Lessells, 1966). Table 2 shows the summary of estimated creep properties for the AISI 316 stainless steel. To correlate the results of short-time elevated temperature tests with long-term service performance at more moderate temperatures, different creep prediction models have been studied.

Basquin model (Power law model)

In Basquin model the creep rupture time t_r is assumed to be governed by the imposed stress σ , as follows (Collins 1993):

$$t_r = B(\sigma)^{-m} \quad (7)$$

or in log transform

$$\ln t_r = \ln B - m \ln \sigma \quad (8)$$

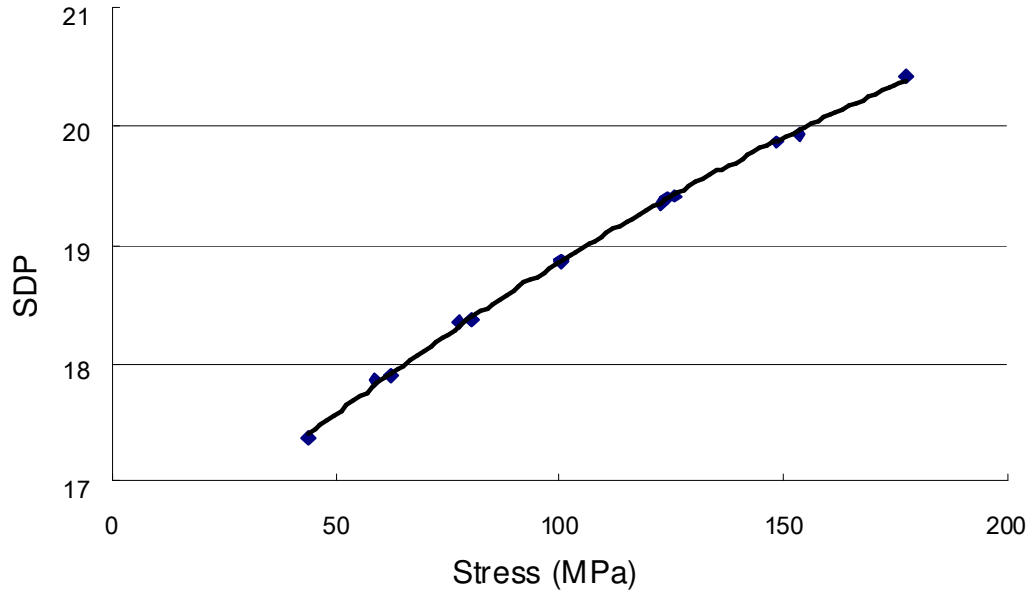


Figure 3. Relationship between the Sherby-Dorn parameter SDP and stress.

where B and m are empirical coefficients. To produce a model for creep an assumption was made that the empirical coefficient m is dependent on temperature T. It is generally believed that the polynomial model provides good fit. In other words, a model of the following type is expected:

$$t_r = B(\sigma)^{-(a+bT+cT^2)} \tag{9}$$

$$\text{or } \ln t_r = \ln B - (a + bT + cT^2) \ln \sigma \tag{10}$$

In order to estimate the best value of the parameters, multiple regression is employed with T and σ as main factors and t_r as response. The results of regression showed a model of the following type was fitted:

$$\ln t_r = C_1 + C_2T + (C_3 + C_4T + C_5T^2) \ln \sigma \tag{11}$$

$$\text{or } t_r = e^{(C_1+C_2T)} (\sigma)^{(C_3+C_4T+C_5T^2)} \tag{12}$$

For AISI 316 stainless steel, $C_1 = 227.64$, $C_2 = -0.21$, $C_3 = 15.16$, $C_4 = -0.078$, $C_5 = 0.000061$. Then:

$$t_r = e^{(227.64-0.21T)} (\sigma)^{(15.16-0.078T+0.000061T^2)} \tag{13}$$

Sherby-Dorn model

Sherby-Dorn theory can be expressed by the equation of

the form:

$$-SDP = \log t_r - \frac{B}{T} \tag{14}$$

Where SDP is the Sherby-Dorn parameter and B is constant for a given material. According to reference (Truman, 1966), the value of B is 21320. Thus Equation (14) can be rewritten as:

$$\log t_r = \frac{21320}{T} - SDP \tag{15}$$

The Sherby-Dorn parameter SDP is stress dependent, and a master curve for this relationship was found in reference (Truman, 1966). To find an empirical model for this relationship, the data is used in conjunction with different modes to find the best fit between stress and the SDP. As shown in Figure 3, the best relation between the SDP and stress is a polynomial model ($R^2=0.9993$) and it can be written as:

$$SDP = -0.00005\sigma^2 + 0.0325\sigma + 16.056 \tag{16}$$

Applying a in transform, after re-arranging the Equation (15) can be written as follows:

$$t_r(\sigma, T, B, a, b, c) = e^{2.3[\frac{B}{T} - (a\sigma^2 + b\sigma + c)]} \tag{17}$$

$$\text{or } t_r = e^{2.3\frac{21320}{T}} e^{-2.3(-0.00005\sigma^2 + 0.0325\sigma + 16.056)} \tag{18}$$

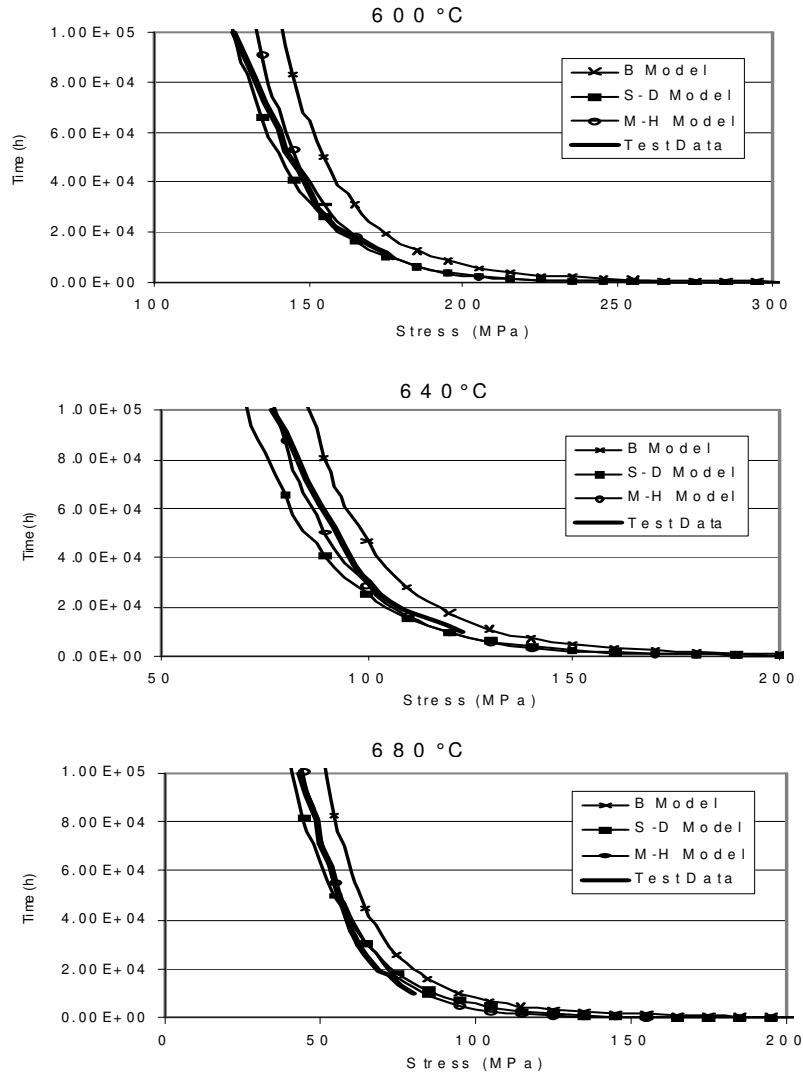


Figure 4. Comparison between creep prediction models and test results.

Manson-Haferd model

The Manson-Haferd model can be written as follows:

$$\ln t_r = a_0 + a_1 \cdot T \tag{19}$$

$$\text{or } t_r = C \cdot e^{a_1 \cdot T}; (C = e^{a_0}) \tag{20}$$

It is clear that the Manson-Haferd model is a straight line in the $\ln t_r$ - T coordinates. The parameter a_1 is a function of stress, $a_1 = a_1(\sigma)$. A master curve for the slope of the line as a function of stress is given in reference (Lessells, 1966), and it shows a similar curvature as the S-D master curve. Therefore, a quadratic model appears as a reasonable choice for $a_1(\sigma)$, that is:

$$\ln t_r = a_0 + (b_0 + b_1 \cdot \sigma + b_2 \cdot \sigma^2) \cdot T \tag{21}$$

Based on creep data in Table 2, multiple regressions was used to estimate coefficients in Equation (21). The regression shows a very good fit with the quadratic model and the Manson-Haferd model can be written as follows:

$$t_r = e^{62.99} \cdot e^{(-0.051 - 0.000077\sigma - 0.000000098\sigma^2)T} \tag{22}$$

Comparison of the statistical creep models

Comparison between three different creep prediction models and experimental results for a range of stresses and temperatures are shown in Figure 4. It can be seen that the three prediction models are reasonably similar over the stress range 0 to 350 MPa and temperature range 600 to 680°C. It is also clear that the Manson-Haferd model predictions are consistent with

experimental results throughout all range of considered stresses and temperatures. Thus the Manson-Hafner model is expected to be the reasonable one of the three statistical creep models.

COMBINED FATIGUE AND CREEP

For comprising both fatigue and creep damage, different damage summation method was considered by researchers (Chen, 1998; Yaguchi, 1996). The D_f was defined as fatigue damage and D_c was defined as creep damage. The fatigue damage D_f can be described by Miner's law:

$$D_f = \sum_{i=1}^m \frac{n_i}{N_i} \quad (23)$$

where n_i is the number of applied cycles at i th stress range, N_i is the number of cycles to fatigue failure for the i th stress range only, m is the number of different stress ranges. Similarly for creep damage evaluation, if the stress is assumed to be piecewise constant, the creep damage D_c can be simply described by Robinson's rule:

$$D_c = \sum_{j=1}^n \frac{t_j}{T_j} \quad (24)$$

where t_j is the hold time at the j th stress level. T_j is the creep rupture time for the j th stress level alone, and n is the number of different stress levels. Creep-fatigue failure can be defined as:

$$D_f + D_c \geq D_{cf} \quad (25)$$

Where D_{cf} is the critical damage that is determined according the test results.

However, this criterion ignores the interaction between creep and fatigue. When take account of the interaction between creep and fatigue, the critical damage is a non-linear function of creep damage and fatigue damage. Chen et al. (1998) shown that the experimentally measured creep-fatigue life time is slightly lower than that predicted by the linear damage summation rule. The experimental results by Yaguchi, (1996) shown that different loading sequences (fatigue followed by creep, or creep followed by fatigue) can affect the lifetime of the material. However, often the experimental data on rupture life under the actual operating stress and temperature may not be available as the generation of such data is highly time consuming and expensive.

Therefore the linear damage summation rule is still widely used for its simplicity. Because there is only one level of fatigue loading and creep loading in the linear damage summation rule, the fatigue damage D_f and

creep damage D_c can be defined as follows:

$$D_f = \frac{N}{N_f} \quad (26)$$

$$D_c = \frac{Nt_h}{t_r} \quad (27)$$

Where N_f represents the number of cycles to failure in continuous fatigue tests, N is the number of cycles to failure in creep-fatigue test, t_r is the rupture time for a pure creep test and t_h is the hold time. As mentioned above, a linear damage summation method, comprising both fatigue and creep damage, is considered to provide a good correlation of measured life with predicted life. When $D_f + D_c \geq 1$ failure is predicted. Then the linear damage summation method can be described as follow:

$$\frac{N}{N_f} + \frac{Nt_h}{t_r} \geq 1 \quad (28)$$

$$\text{or } N \geq \frac{N_f t_r}{t_r + N_f t_h} \quad (29)$$

CONCLUSIONS

An analytical model has been established to predict fatigue-creep life for AISI 316 stainless steel. The low cycle thermal fatigue life model and the statistical creep model have been created separately and a linear damage summation method has been used to combined fatigue and creep. This fatigue-creep life prediction model offers the possibility to correlate different tests. However, there still remains a number of issues, such as crack wedging or crack blunting, which need to be examined for improving the confidence of the model. Therefore further experimental work is necessary to obtain data from bigger range of cycle frequencies in order to validate the life prediction model of AISI 316 stainless steel under creep-fatigue.

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