INFLUENCE OF ELEVATED TEMPERATURE ON FRACTURE BEHAVIOR OF STAINLESS STEEL

ABSTRACT

Fracture mechanics approaches have been employed to study the fracture behavior of the exchanger tubes made of austenitic stainless steel at elevated temperatures in fertiliser plant. Tests conditions range from ambient to elevated temperature, monotonic to cyclic loading, and creep. Experimental work was carried out for creep, creep-fatigue interaction and fatigue at ambient and high temperatures on notched specimens. The temperature test was grouped into the range of homologous temperature (77/4 in the range of 0.177 (RT), 0.3, 0.4 and 0.5 of melting point for AISI 316 stainless steel. Furthermore experimental work has been extended, by using another group of specimens made of AISI 304 stainless steel. Chemical composition analysis and tensile tests were initially performed to record the mechanical properties of both materials at room temperature.

Parametric representation of crack growth rate in terms of independent variables in Region II of crack growth has been proposed for creep, creep-fatigue interaction and fatigue of 316 stainless steel at ambient and high temperature rates. To demonstrate the validity of the present approach, the proposed equation has been used to

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determine the fatigue crack growth rate versus the change in the stress-intensity-factor relationship for AISI 304 stainless steel.

Based on this study, experimental results as well as analytical results obtained by using the proposed equation for AISI 316 and AISI 304 stainless steels were analyzed, and recommendations for applications were made. Thus in the present study it has been attempted to obtain a simple criterion for crack growth behavior in AISI 316 stainless steel under high temperature creep, fatigue and creep-fatigue interaction conditions.

**KEY WORDS**

Creep, fatigue; creep-fatigue interaction, crack growth rate; stress intensity factor; homologous temperatures, notched specimen, austenitic stainless steel.

**INTRODUCTION**

Austenitic stainless steels, used over a wide temperature range, are often employed in components, which are loaded under severe conditions [1-4]. Microcracks can occur where stress concentrations exist at notches and welds. Growth and linkage of these microcracks result in the formation of a large crack whose propagation is influenced by such effects as the load fluctuations, cyclic loading frequency, load waveform and thermal cycling value etc. [5-7]. This phenomenon involves the growth of small defects into macro- or micro-cracks that grow until fracture toughness of the components material is exceeded and catastrophic failure occurs [8-10]. In order to predict component lives, a complete understanding is needed of the behavior of material under creep, fatigue and creep-fatigue interaction [11-13].

The current study is concerned with crack growth of AISI 316 stainless steel subjected to cyclic loading conditions at high temperature since propagation is the dominant process of short life fatigue of structural component. It is also concerned with the use of an empirical expression to provide a simple criterion for crack growth behavior under high temperature.

**EMPIRICAL APPROACH**

In consideration of the controlled load, loading have been represented as shown in Fig 1(a), (b) and (c) for creep-fatigue interaction, creep and fatigue respectively. Parametric representation of crack growth in Region II of crack growth curve for cyclic loading conditions at ambient and high temperatures rate is proposed as given in the following.

1-Representation of crack growth rate in terms of independent variables is proposed for creep, creep-fatigue interaction and fatigue at ambient and high temperatures respectively. However, based on PARIS equation [16], the proposed equation is expressed by the following empirical relationship:

$$\frac{da}{dt} = A_m B_n \sigma^m \Delta K^m \exp \left( \frac{f_e}{f_r} \right)$$

$$\frac{da}{dN} = B_m \sigma^m \Delta K^m \exp \left( \frac{f_e}{f_r} \right)$$

where $A_m$ is the opening mode-stress intensity factor, $m$ is the applied stress, $n$, $m$, $A_m$ and $B_m$ all are constants.

These constants were estimated by the best fit through the data obtained from the experimental work performed using the test specimen made of type AISI 316 stainless steel. In addition, $A_m$ is a constant depending on the fatigue test number of cycle, and $B_m$ is a constant which has been suggested to be related to the obtained tensile mechanical properties ($\sigma_0$, the 0.2% proof stress, $\sigma_u$ the tensile strength and $E$ the material modulus of elasticity of the specimen material at room temperature). However, $B_m$ would be computed by using the following form:

$$B_m = \left( \sigma_0 + \sigma_u \right) / E$$

In the proposed equation (1), high temperature, holding time and stress rupture factors $f_r$, $f_s$ and $f_e$ have been suggested by a function of the form:

$$f_r = \left( f_s + f_e \right)$$
\[ f_r(T,T_w) = \left( \frac{T - T_w}{T - T_w} \right) \]
\[ f_m(T,T_w) = \frac{f_m}{(T/T_w)^{1/2t}} \]
\[ f_r(T,T_w) = \left( \frac{f_r}{(T/T_w)^{1/2t}} \right) \]

where \( a_i \) is the initial crack length, \( a_c \) is the crack length at fracture, \( \sigma_i \) is the true stress at the start of Region II, \( \sigma_c \) is the applied stress at fracture, \( t_o \) is holding time, \( t_c \) is fatigue frequency time per cycle and \( T/T_w \) is homologous temperature.

The interchanging factor \( m_x \) controls the relation between \( da/dN \) and \( da/dt \) as follows:
\[ \frac{da}{dN} = \frac{1}{da} \cdot \frac{da}{dt} \]
\[ m_x = \frac{N_s}{N_d} \]

where \( A_s = N_s/N_d \) is the frequency reduction ratio, \( N_s \) is the number of rotation per minute of driving motor shaft and \( N_d \) is the selected number of rotation per minute of each eccentric shaft.

The stress intensity factor \( K_c \) for round bar is expressed by (17) as follows:
\[ K_c = (a_e a_m)^{1/2} \cdot \sigma \cdot \int \left( \frac{2a}{d_e} \right)^{1/2} \left( 1 + \frac{a}{d_e} \right) + \frac{2a}{d_e} \right)^2 \left( \frac{2a}{d_e} \right)^2 \left( 1 + \frac{a}{d_e} \right)

Thus, in accordance with the proposed equation (1), high temperature crack growth rate under creep, fatigue and creep-fatigue interaction may be expressed by the following relationships:

A-For creep
\[ \frac{da}{dt} = m_x \cdot B_c \cdot \sigma_c a \cdot \exp \left( \left( \frac{f_a}{f_r} \right) - f_m \right) \]

B-For creep-fatigue interaction
\[ \frac{da}{dN} = m_x \cdot B_c \cdot \sigma_c a \cdot K_c a \cdot \exp \left( \left( \frac{f_a}{f_r} \right) - f_m \right) \]

C-For fatigue
\[ \frac{da}{dN} = B_f \cdot \Delta K_f \cdot \exp \left( \left( \frac{f_a}{f_r} \right) - f_m \right) \]

II-Representation of the propagation life (number of cycles to failure for crack propagation) in region II can be expressed as following:
\[ N_f = \frac{1}{A Y^* \Delta \sigma^*} \left( \frac{2}{m-2} \left( \frac{1}{a_0^2} - \frac{1}{a_f^2} \right) \right) \]

where \( N_f \) is the number of cycles to failure, \( a_0 \) is the stress range and \( Y \) is the geometrical correction factor.
EXPERIMENTAL WORK

Chemical composition inspection and tensile test was initially performed to record the material chemical composition and the mechanical properties of both AISI 316 as well as AISI 304 stainless steel at room temperature. The specimens employed in tensile test were the ASTM standard 25.4 mm gage length. Fatigue specimens were then machined into the shape and required dimension (AISI SS samples d=6.35 mm, dc=5.35 mm, and 2a=1 mm) according to ASTM code as shown in Fig. 2. Chemical composition and Mechanical properties at room temperature of the AISI 316 stainless steel is shown in Table 1 and Table 2 respectively.

**TABLE 1. Chemical Composition (wt %) of AISI 316 stainless steel.**

<table>
<thead>
<tr>
<th>Material</th>
<th>C</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>AISI 316</td>
<td>0.05</td>
<td>10.95</td>
<td>16.9</td>
<td>2.12</td>
<td>1.46</td>
<td>0.42</td>
<td>0.056</td>
<td>0.022</td>
</tr>
</tbody>
</table>

**TABLE 2. Mechanical Properties for AISI 316 stainless steel at RT.**

<table>
<thead>
<tr>
<th>Yield Stress MPa</th>
<th>Tensile Strength MPa</th>
<th>Elongation %</th>
<th>Reduction of Area %</th>
<th>Hardness Hv</th>
</tr>
</thead>
<tbody>
<tr>
<td>275</td>
<td>630</td>
<td>60</td>
<td>71</td>
<td>157</td>
</tr>
</tbody>
</table>

Tests of creep, creep-fatigue interaction and fatigue at different temperature levels, representing 0.177 (RT), 0.35, 0.40, 0.45 and 0.50 of melting point of the tested steel were performed under load control condition. Experimental work has been extended, by using another group of specimens made of AISI 304 stainless steel. The chemical composition and the mechanical properties at room temperature of AISI 304 stainless steel are given in Tables 3 and 4, respectively.

**TABLE 3. Chemical Composition (wt %) of AISI 304 stainless steel.**

<table>
<thead>
<tr>
<th>Material</th>
<th>C</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>AISI 304</td>
<td>0.06</td>
<td>8.85</td>
<td>18.12</td>
<td>0.11</td>
<td>1.12</td>
<td>0.58</td>
<td>0.028</td>
<td>0.006</td>
</tr>
</tbody>
</table>

**TABLE 4. Mechanical Properties for AISI 304 stainless steel at RT.**

<table>
<thead>
<tr>
<th>Yield Stress MPa</th>
<th>Tensile Strength MPa</th>
<th>Elongation %</th>
<th>Reduction of Area %</th>
<th>Hardness Hv</th>
</tr>
</thead>
<tbody>
<tr>
<td>330</td>
<td>650</td>
<td>47</td>
<td>56</td>
<td>159</td>
</tr>
</tbody>
</table>

Experiments were carried out using a specially designed mechanical apparatus equipped with a special cam system and load control mechanism. Schematic representation of the testing apparatus is shown in Fig. 3. Each end of the specimen is screwed into the specimen holders. The optical technique is adopted to measurements on the tested specimen, since the crack length can be estimated relative to the notch opening displacement. Crack detection and the measurement of notch opening displacement was made during running the tests by using a microscope through a peeping window with 100X magnification. A specially fabricated circular chamber provided with helical resistance heater was used to heat the specimen to the required temperature. Specimen temperatures were continuously monitored with thermocouples that was fixed to the specimen in vicinity of the specimen notch. The load waves were controlled for creep, fatigue and creep-fatigue interaction by adjusting the eccentric stroke. Thus, by changing the holding time $t_h$, the loading wave (Fig. 1a) which is the combination of the creep loading wave (Fig. 1b) and the fatigue loading wave (Fig. 1c) can be obtained. Cyclic load is applied by means of a lever and rotating cam system. The frequency of the fatigue-loading wave was 60 cpm, and the waveform was sinusoidal.

Crack initiation under loading conditions at $\sigma_{eq}=189$ MPa. The values of the applied stress $\sigma_{eq}$ corresponding to the maximum tensile stress were ranged between 120-210 MPa. The FCG rates ($\delta a/dN$) were determined by dividing each increment of crack extension by number of cycles producing that increment.

On all specimen, the circumferential notch was V-shaped with 30° angle. After notching the specimen with a file tool, the notch root radius obtained in the specimen was further reduced with a razor blade which were mounted on the tool post of the lathe through a specially fabricated fixture. The use of the razor blade produced a very sharp notch tip radius, $r = 0.05$ mm.
DISCUSSION

The most frequently used correlation between FCG rate and the stress intensity factor is the power law proposed by Paris (1963) [16]:

\[ da/dN = C (AK)^n \]

where \( C \) and \( n \) are material constants.

Paris equation predicts a linear relationship between \( \log(\text{da/dN}) \) and \( \log(\Delta K) \), but it holds only for intermediate FCG region under normal temperature conditions.

Several investigations have been conducted to study the effect of stress ratio \( (R=K_{\text{min}}/K_{\text{max}}) \) for variable loading at normal temperature conditions on fatigue crack propagation rate. Barksom [18] has proposed the following form:

\[ da/dN = A (AK)^n / (1-R) \]

where the stress ratio \( R \geq 0 \).

Solomon and Coffin (1973) [19] pointed out that crack growth rate was seen to increase with decrease in frequency and they expressed the following empirical relationship for elevated temperature:

\[ da/dN = C (AK)^n \]

where \( a \) is the stress intensity factor range. \( n \) is the frequency. \( C \), \( a \), and \( \beta \) are material constants, and \( \gamma \) were temperature and material temperature.

This type of relationship has been used by Yokobori and Sato (1976) [20] at room temperature.

Based on Solomon equation, Plumtree and Schaefer (1987) [21] have developed the following expression:

\[ da/dN = C (AK)^n \theta \]

where \( \theta \) is the ratio of loading to unloading times.

Based on another line of considerations, the present work proposes a more general equation that takes into consideration the effects of high temperature rates, holding time and stress rupture factors \( f_x, f_y \), and \( f_z \). However, parametric representation of high temperature crack growth rate in terms of independent variables, such as \( K, \sigma_{\text{eq}} \), temperature effect and some material constants have been suggested as given in equation (1). The values of \( n, n_1, \) and \( B_\alpha \) were suggested in this work in accordance with creep, creep-fatigue interaction and fatigue loading conditions for type AISI 316 stainless steel.

The present results show that 3.1 for creep, \( n=1 \) and \( n=3.21 \) for creep-fatigue interaction and \( n=3.63 \) for fatigue loading conditions respectively to correlate for AISI 316 stainless steel at room temperature. A line fit regression was used to obtain the best fit through the experimental data resulted from the tests that performed at ambient and high temperature rates. The results given in Table 5. show the best-fit representation of the constants for equations 3, 4 and 5.

<table>
<thead>
<tr>
<th>Loading condition</th>
<th>( M )</th>
<th>( N )</th>
<th>( B_\alpha )</th>
<th>( t_{\text{fit}} )</th>
<th>( \sigma_{\text{eq}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Creep eqn. (3)</td>
<td>3.1</td>
<td>0</td>
<td>3.15x10^-3</td>
<td>( \infty )</td>
<td>130-210</td>
</tr>
<tr>
<td>Creep-fatigue interaction eqn. (4)</td>
<td>1</td>
<td>3.21</td>
<td>4.525x10^-4</td>
<td>60</td>
<td>189</td>
</tr>
<tr>
<td>Fatigue eqn. (5)</td>
<td>0</td>
<td>3.63</td>
<td>1.375x10^-5</td>
<td>0</td>
<td>189</td>
</tr>
</tbody>
</table>

To satisfy the physical reality that unstable crack growth occurs rapidly when the operating temperature approaches a high temperature rates, the effective empirical factor \( f_x, f_y \) and \( f_z \). For equations 3, 4 and 5, have been taken into account.

In consideration of the possibility of creep, creep-fatigue interaction and fatigue effect, on notched specimen at different temperature rate, tests were conducted and results are plotted as shown in Figures 4-12.
The crack tip radius upon the specimens or component performance can be indicated by the fatigue life for notched specimens as represented by the curves shown in Fig. 4. It's evident that the specimens having sharper crack tip is the shorter fatigue life. Thus, the presence of notch, crack decreases the material creep and fatigue resistance.

The curves shown in Fig. 5, indicate that, at normal as well as elevated temperature, the notched specimen will develop cracks. Further, when a crack has grown at high temperature, the stress intensity factor $K_i$ comes closer the critical value $K_c$ and the crack accelerates more rapidly until the critical stress intensity factor $K_c$ is exceeded and final catastrophic failure occurs.

To demonstrate the validity of equations 3.4 and 5, the values of the $m$ and $b_k$ as given in Table 5 for AISI 316 stainless steel have been used to determine the relationship of $da/dN$ versus $dK$ (see Appendix A).

The proposed equations 3.4 and 5 have been employed to develop a family of curves representing the relationship between $da/dN$ versus $dK$ as shown in Figures 1-10 for AISI 316 stainless steel under creep, creep-fatigue interaction and fatigue loading conditions ambient and high temperature rates.

Analyzing the resulted curves shown in these figures indicate that, the reduction in fatigue life at elevated temperature was mainly due to the presence of cracks that grown at the tip of the notch rather than the creep-fatigue effects. In addition the time dependent deformation as well as deformation processes, is largely dependent upon the chemical composition as well as the mechanical properties of the material. Therefore, the development of alloys with a high resistance to creep-fatigue at elevated temperature involves producing a material in which movements of dislocations only take place with difficulty. However to verify this statement it has been intended to extend the experimental work by using another group of specimens made of AISI 304 stainless steel.

Comparison of the results shown in Figs. 1 and 12, indicate that, there is an improvement in the creep-fatigue metal resistance for the AISI 304 stainless steel at elevated temperature higher than that for AISI 316 stainless steel. However, it's evident that this improvement in the creep-fatigue resistance is attributed to the addition of elements whose atomic size and valences are largely different from basic materials such as chromium. In addition, it is recommended to increase the critical crack size at failure by using a material with a higher fracture toughness stress such as AISI 304 stainless steel ($K_{IC}$ value is 117 MPa√m for 304 and 98 MPa√m for 316 stainless steel).

Ultimately, it is clearly visible that material which is susceptible to creep-fatigue effects at elevated temperatures should only be subjected to stresses which keep it in the secondary region of straight-line through its service life.

**CONCLUSIONS**

Creep, fatigue and creep-fatigue interaction tests were performed at different temperature rates that are related to the material melting point on AISI 316 stainless steel specimens machined with V-notches. In addition, the experimental work has been extended by using some specimens made of AISI 304 stainless steel.

An empirical expression to provide a simple criterion for crack growth behaviour under high temperature from the practical point of view has been developed.

1. An extensive program of creep, creep-fatigue interaction and fatigue tests has been carried out on type AISI 316 stainless steel over the homologous temperature range 0.177-0.5.

2. A parametric representation formula of high temperature crack growth rate in terms of independent variables and some material constants taken into consideration the effects of high temperature rates, holding time and stress rupture factors has been proposed in this work.

3. A line fit regression was used to obtain the best fit through the experimental data, and evaluate the effective empirical factors.

4. The developed equation successfully modeled the crack propagation rate versus stress intensity factor range and a family of temperature dependent curves have been derived under creep, creep-fatigue interaction and fatigue loading conditions for type AISI 316 stainless steel over the homologous temperature range 0.177-0.5.

5. The derived curves are expected to be applicable to the AISI 316 stainless steel as well as AISI 304 stainless steel. Therefore, proposed approach is believed to be simpler than those currently published in the available literatures.
6-Comparison between the analyzed results on type AISI 316 stainless steel and type AISI 304 stainless indicated that the creep-fatigue resisting alloy is further strengthened by added alloying elements such as chromium, but this limits the amount that may be added. Thus, the use of alloying elements that raise the creep-fatigue metal resistance at elevated temperature will be beneficial.

ACKNOWLEDGMENT

The author extends his sincere thanks to Engineer T. Salama Head of Plant Sectors and Vice President of Delta Sarco Company, Talkha, Mansoora, EGYPT for conducting the cyclic tests.

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Appendix-A

Parametric representation of crack growth rate for AISI 316 stainless steel

Based on Paris equation [16], the proposed equation is expressed by the follows:

\[
\frac{da}{dt} = A_0 B_2 \sigma_s^n D K_1^n \exp\left(\frac{f_s}{f_r}\right) - f_m
\]

(1)

\[
\frac{da}{dN} = B_2 \sigma_s^n D K_1^n \exp\left(\frac{f_s}{f_r}\right) - f_m
\]

To demonstrate the validity of equations (1), thus the crack growth rate for AISI 316 stainless steel specimens \((\sigma_0, n) = 273\, \text{MPa}, \quad \Delta K = 530\, \text{MPa} \cdot \text{m}^{1/2}, \quad R = 0.2 \times 10^3\, \text{MPa}, \quad \text{and} \quad K_{\text{in}} = 69\, \text{MPa} \cdot \text{m}^{1/2}, \text{at room temperature}) under creep, creep-fatigue interaction and fatigue loading conditions at different temperature ratios would be determined as follows:

A-Creep:

\[B_2 = (\sigma_0/\beta) = 3.15 \times 10^9\]

\[A_0 = N_0 / N_a = 1500 (1/25) = 60 \, \text{cmm}\]

where \(f_m\) is corresponding to test frequency \(f\) (test number of cycles per minute).

\[\nu = 1/f = 4 \times 10^{-5} \quad \beta = 3.15 \times 10^9 \quad f_m = \beta (f/0.1) = 0\]

where the homologous temperature factor \(f_s\) is varying between 0.177 to 0.5 (298 to 842 K) in respect to AISI 316 austenitic stainless steel melting point of 1684 K.

Substituting the values of \(A_0, B_2, n, f_s, f_r\), and \(f_m\) into equation (3) gives

\[\frac{da}{dt} = (60/60) \times 3.15 \times 10^{-5} \sigma_s^{3.1} \exp\left(\frac{f_s}{f_r}\right) (\mu m/s)\]

(4)

where \(n=3.1\) and \(n=0\)

\[B_2 = 3.15 \times 10^9 , \quad f_r = (K_0 - K_{\text{in}}) / K_{\text{in}} \]

\[f_m = (1 - f_r) \beta (f/0.1)\]

B-Creep-Fatigue interaction:

\[B_2 = (\sigma_0 - \sigma_m) / E = 4.525 \times 10^4\]

\[\nu = 3.1 \times 10^{-5} \quad \beta = 1 \quad f_m = 7.14 \times 10^4\]

Substituting the values of \(B_2, f_s, f_r\), and \(f_m\) that correspond to the creep loading condition into equation (4) gives

\[\frac{da}{dN} = 4.525 \times 10^4 \sigma_s^{1.21} \exp\left(\frac{f_s}{f_r}\right) \text{micron/cycle}\]

(5)

where \(n=1\) and \(n=0.21\)

C-Fatigue:

\[B_2 = (\sigma_0 - \sigma_m) / E = 1.375 \times 10^5\]

\[\nu = 6 \text{ sec} \quad \beta = 1 \quad f_m = 1\]

Substituting the values of \(B_2, f_s, f_r\), and \(f_m\) that correspond to the creep loading condition into equation (5) gives

\[\frac{da}{dN} = 1.375 \times 10^5 \sigma_s^{1.21} \exp\left(\frac{f_s}{f_r}\right) \text{micron/cycle}\]

(6)

where \(n=0\) and \(n=3.61\).
Fig. 3. A schematic diagram for a typical creep-fatigue testing apparatus.

Fig. 4. Effect of high temperature rates on the fatigue crack growth as a function of number of cycles to failure, for 316 stainless steel.
Fig. 5. Effect of crack tip radius on the normalized stress-intensity factor at different temperature ratio, for 316 stainless steel.

Fig. 6. Creep crack growth rate as a function of stress-intensity factor at different temperature ratio, for 316 stainless steel (ρ = 0.05 mm).
Fig. 7. Creep-Fatigue interaction crack growth as a function of stress-intensity-factor at different temperature ratios, for 326 stainless steel ($\mu = 0.05\text{mm}$).

Fig. 8. Fatigue crack growth as a function of stress-intensity-factor at different temperature ratio for 316 stainless steel ($\mu = 0.05\text{mm}$).
Fig. 9. Effect of homologous temperature ratio (T/T_m) on crack growth ratio da/dN vs. stress intensity factor (AK) for 316 stainless steel using the proposed equation.

Fig. 10. Effects of T/T_m on the fatigue crack growth rates (da/dN) at different values of stress-intensity-factor (ΔK) for 316 stainless steel using the proposed equation (1).
Fig. 11. Comparison of experimental crack growth rate vs. stress-intensity-factor range for AISI 316 and AISI 304 (Experimental results).

Fig. 12. Comparison of analytical crack growth rate vs. stress-intensity-factor range for AISI 316 and AISI 304 using the proposed equation (1).