TIME-DEPENDENT CRACK GROWTH BEHAVIOR OF A NITROGEN STRENGTHENED Ni-Fe-Cr-Nb-N ALLOY 120

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ABSTRACT
Creep and creep crack growth behavior of alloy 120 (HR120™) were studied through the time-dependent fracture mechanics characterization at 871°C (1600°F). The material was tested under tensile, creep and creep crack propagation conditions to develop an understanding of time-dependent behavior under variable stresses at elevated temperature. The resulting properties were also compared with those of alloy 333 (RA333™) and alloy (HR160™) previously obtained using the same testing and data processing methods. Results show that at elevated temperature, alloy 120 and alloy 333 had little primary creep while alloy 160 demonstrated significant amount of primary creep. Comparison based on creep energy consumption rate indicates that creep crack growth resistance of alloy 120 is greater than that of alloy 333, but a little less than that of alloy 160.

INTRODUCTION
During long-term service of a high-temperature component creep damage usually occurs in areas of stress concentration and microcracks gradually initiate typically on grain boundaries. As time elapses, these microcracks may grow by a process of coalescence of creep cavities near crack tips. It has been realized that although cracks may pre-exist and initiate in a component during its service at elevated temperatures, a large portion of the component's life may be spent in crack propagation (Jani and Saxena, 1987). The recognition of the time a component spends in creep crack propagation as a portion of the service life obviously brings great economic benefits and is an important consideration in the assessment of “fitness for service” of high temperature components. With this concept, the life of an elevated-temperature-component is considered to depend on its crack growth rate (Liaw et al., 1989a, 1989b). Efforts have been made over years to develop a life prediction methodology to cope with this issue. The life prediction methodology, based on characterizing the stress field, strain-rate field and the stress-power dissipation rate at the tip of a creep crack with different fracture mechanics parameters, is expected to estimate the propagation rate of the crack, and thus, help establish the correct inspection intervals and predict the life of the component. The development of this methodology makes the data pertaining to time-dependent fracture mechanics important parameters for high-temperature life prediction analyses. The present research focuses on studying the time-dependent fracture mechanics properties of alloy 120 and comparing it with two other solid solution alloys: alloy 333 and alloy 160 (Ren et al., 1995) based on the same testing and data processing methods. The research results will benefit materials selection for elevated temperature applications and the development of the life prediction methodology.

EXPERIMENTAL PROCEDURES

The Material
Alloy 120 is a nitrogen strengthened Fe-Ni-Cr-Nb-N alloy with improved mechanical properties and hot workability through the addition of a carefully controlled amount of nitrogen and provision of nitrogen, niobium and
carbon within a defined relationship. Chromium is present at a level of 25% to provide superior oxidation resistance and nitrogen stability. The nominal composition of alloy 120 is given in Table 1. For comparison purpose, the compositions of alloy 333 and alloy 160 are also given in Table 2 and Table 3.

The alloy 120 material was provided by the Westinghouse Electric Company as solution treated plate 63 mm (2.48 in) thick. Metallographic analysis was conducted to determine its general microstructure. The results revealed that the material had mixed grain sizes, approximately 70% area with a grain size of 10 and 30% with a grain size of 6, average about 8.8, and the structure was uniform in all directions with no texture observed. The results from alloy 333 and alloy 160 used for comparison were also obtained in solution treated condition. The grain size of alloy 333 was 5.3 and that of alloy 160 was 3.0.

### TABLE 1 NOMINAL COMPOSITION (WT%) OF HR120™

<table>
<thead>
<tr>
<th></th>
<th>Ni</th>
<th>Fe</th>
<th>Cr</th>
<th>Co</th>
<th>Mo</th>
<th>W</th>
<th>Nb</th>
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<tbody>
<tr>
<td>Bal</td>
<td>33</td>
<td>25</td>
<td>3*</td>
<td>2.5*</td>
<td>2.5*</td>
<td>0.7</td>
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<tr>
<td>Mn</td>
<td>0.7</td>
<td>0.6</td>
<td>0.2</td>
<td>0.1</td>
<td>0.1</td>
<td>0.05</td>
<td>0.004</td>
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</tbody>
</table>

* maximum

### TABLE 2 NOMINAL COMPOSITION (WT%) OF RA333™

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<tr>
<th></th>
<th>Fe</th>
<th>Ni</th>
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<tbody>
<tr>
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<td>25</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Co</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>0.1</td>
<td>0.01</td>
</tr>
</tbody>
</table>

### TABLE 3 NOMINAL COMPOSITION (WT%) OF HR160™

<table>
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<th></th>
<th>Ni</th>
<th>Co</th>
<th>Cr</th>
<th>Fe</th>
<th>Si</th>
<th>Mn</th>
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<td>Bal</td>
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<td>28</td>
<td>3.5</td>
<td>2.75</td>
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<tr>
<td>Ti</td>
<td>C</td>
<td>Mo</td>
<td>W</td>
<td>Nb</td>
<td></td>
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<tr>
<td></td>
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<td>0.05</td>
<td>1.0*</td>
<td>1.0*</td>
<td>1.0*</td>
<td></td>
</tr>
</tbody>
</table>

* maximum

### Test Matrix

The test matrix was designed to develop a sound database of alloy 120's time-dependent fracture mechanical properties for life prediction and elevated temperature applications. Meanwhile, these properties could be compared with the properties of alloy 333 and alloy 160 obtained in previous studies with the same testing and data processing methods. To characterize the creep crack propagation of a material using time-dependent fracture mechanics parameters, the testing program includes tensile, creep deformation, and creep crack growth tests.

The tensile tests were conducted to obtain the plasticity exponent (m) and the plasticity coefficient (D) of the Ramberg-Osgood stress-strain equation. These two parameters were used for the calculation of time-dependent fracture mechanics parameters. Meanwhile, conventional tensile property parameters such as the yield strength (s_y), Young's modulus (E) etc., were also developed. The tensile tests were conducted at temperature of 871°C (1600°F).

The creep deformation tests were performed to study the creep and creep-rupture behavior of alloy 120 at various temperatures and stress levels, and also to obtain the creep coefficient (A_2) and the creep exponent (n) for the calculation of time-dependent fracture mechanics parameters at 871°C (1600°F). In addition to the temperature of 871°C (1600°F) at which the time-dependent fracture mechanics characterization analysis was performed, the creep deformation tests were also conducted at another two temperatures of 816 and 927°C (1500 and 1700°F) at various stress levels ranging from 41 to 90 MPa (6 to 13 ksi) to provide a better understanding of the creep and creep-rupture behavior of the material. The test matrix is given in details in Table 4.

### TABLE 4 CREEP TEST MATRIX FOR HR120™

<table>
<thead>
<tr>
<th></th>
<th>816°C (1500°F)</th>
<th>871°C (1600°F)</th>
<th>927°C (1700°F)</th>
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<tr>
<td>S_y</td>
<td>41 MPa (6 ksi)</td>
<td>41 MPa (6 ksi)</td>
<td></td>
</tr>
<tr>
<td>S_2</td>
<td>-</td>
<td>48 MPa (7 ksi)</td>
<td>48 MPa (7 ksi)</td>
</tr>
<tr>
<td>S_3</td>
<td>62 MPa (9 ksi)</td>
<td>62 MPa (9 ksi)</td>
<td>62 MPa (9 ksi)</td>
</tr>
<tr>
<td>S_4</td>
<td>76 MPa (11 ksi)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>S_5</td>
<td>90 MPa (13 ksi)</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Creep crack growth tests were conducted to investigate the time-dependent fracture mechanics behavior of alloy 120. The tests were conducted at 871°C (1600°F) under load levels of 1179, 2669 and 3114 N (400, 600 and 700 lb).

### Testing Procedures

The tensile test sample had a gage length of 31.75 mm (1.25 in) and a diameter of 6.35 mm (0.25 in). The tests were conducted on a screw-driven tensile test machine. Load versus elongation curves were recorded from an extensometer attached to a 25.4 mm (1 in) gage length section of the specimen for small elongation and from the displacement of the crosshead for large elongation. The creep tests were performed in accordance with the ASTM standard E139-83 entitled "Standard Practice for
Conducting Creep, Creep Rupture, and Stress-Rupture Tests of Metallic Materials" (ASTM Committee, 1993a). Samples for creep deformation tests were identical to the tensile test samples. Lever-arm machines were employed to conduct the tests. The furnace temperatures were controlled within ±2°C (3.6°F) of the prescribed test temperatures. In each test, creep deformation was recorded across the shoulders of the sample using a dial gage and a linear variable differential transformer (LVDT) or a continuous chart recorder, depending on the duration of the test.

Compact-tension (CT) samples were used for creep crack growth tests. The samples were machined to a thickness of 12.7 mm (0.5 in) with a width of 50.8 mm (2 in). All the creep crack propagation tests were conducted in accordance with ASTM standard E1457 entitled "Standard Test Method for Measurement of Creep Crack Growth Rates in Metals" (ASTM Committee, 1993b). Prior to testing, each CT sample was fatigue-precracked at room temperature to produce a sharp crack tip and create a high stress concentration condition. The fatigue crack extended from the machined notch no less than 5% of the total crack length (a₀) and not less than 1.3 mm (0.005 in). All samples were side-grooved to a depth of 10% of the thickness on each side to minimize crack tunneling.

In order to measure the crack length as a function of time during testing using the DC potential drop technique recommended in ASTM standards (ASTM Committee, 1993), two heavy duty input wires were TIG (tungsten inert gas welding) welded on the top and the bottom of each sample on the mid-thickness line at the points 0.5W (W = width of the sample) from the non-notched side. Another two output leads were spot welded to the upper and lower edges of the machined notch opening. A schematic of the sample and the setup is given in Fig. 1.

In each test, a sample was mounted in a creep machine, heated to the desired temperature in a resistance-type furnace, and then loaded. All test temperatures were controlled within ±2°C (3.6°F) of the prescribed temperatures as they were in tensile and creep deformation tests. A constant 10 ampere DC current from a high-stability power supply was passed through the CT sample via the heavy duty input wires. The output voltage was monitored with a digital voltmeter capable of reading accurately in the one microvolt range. The no-current output voltage was also measured periodically to determine the thermal voltage so that the output voltage could be compensated accordingly. The loadline deflection (V) or the displacement of the extensometer was recorded as a function of time using a dial gage and/or a linear variable differential transformer (LVDT).

RESULTS AND DISCUSSION

The tensile test data were processed to obtain the values of plasticity exponent (m) and the plasticity coefficient (D) by fitting into the Ramberg-Osgood true stress-strain equation as follows:

$$\varepsilon = \frac{\sigma}{E} + D\sigma^m$$  \hspace{1cm} (1)

Data analysis reveals that with D = 1.4894 x 10⁻³⁰ MPa⁻¹ and m = 11.586, the model showed good agreement with the experimental data up to the ultimate tensile strength point as presented in Fig. 2.
Creep deformation curves of alloy 120 at 871°C (1600°F) under various stress levels are given in Fig. 3. It is apparent in Fig. 3 that almost no creep hardening occurs at this temperature. Further analysis on a more detailed ordinate scale revealed that the primary creep was less than 1%.

Figure 3. Creep curves of alloy 120 at 871°C (1600°F).

Figure 4. Alloy 120 demonstrates much longer creep-rupture life than alloy 333 and alloy 160, and presents little primary creep as well as alloy 333, while alloy 160 has a considerable amount of primary creep.

Figure 4 gives the typical comparison among the creep curves of alloy 120, alloy 333 and alloy 160. Obviously alloy 120 demonstrates much longer creep-rupture life than alloy 333 and alloy 160 in spite of its smallest grain size of the three as previously described. In Fig. 4, alloy 120 shows a creep-rupture life of 1513 hours at 871°C (1600°F) and 48 MPa (7 ksi). At the same temperature but a lower stress level of 41 MPa (6 ksi), alloy 333 has only 497 hours of creep-rupture life, and at the same stress level but a lower temperature level of 850°C (1562°F), alloy 160 has only 705 hours. It can also be observed in Fig. 4 that the alloy 120 presents little or no primary creep deformation as well as alloy 333, while alloy 160 has a considerable amount of primary creep.

The minimum creep rate values (\( \dot{\epsilon} \)) were developed from the engineering creep strain versus time curves of the recorded test data. The minimum creep rate (\( \dot{\epsilon} \)) and the initial engineering stress (\( \sigma \)) were fitted to Equation 2 as follows to obtain the values of creep coefficient (\( A_2 \)) and creep exponent (\( n \)):

\[
\dot{\epsilon} = A_2 \sigma^n
\]  

At 871°C (1600°F), \( n \) equals to 9.85, and \( A_2 \) has a value of \( 5.591 \times 10^{-22} \text{ MPa}^{-n/2} \text{ h} \). The minimum creep rate versus stress relationship of alloy 120 developed in present investigation are presented in Fig. 5. Apparently at a given stress, creep rate increases with the temperature, but the rate at which creep rate changes with stress is not significantly affected by temperature. This is shown in Fig. 5 where the slopes of the fit lines and the values of the creep exponent are relatively constant at various temperatures.
The minimum creep rate versus stress relationship of alloy 120 is compared with those of alloy 333 and alloy 160 in Fig. 6. The intent of Fig. 6 is to compare the minimum creep rate and stress relationship at 871°C (1600°F). Since no data at this temperature are available for alloy 160. The data of alloy 160 at 850°C (1562°F) and 900°C (1652°F), lower and higher than 871°C (1600°F) respectively, are plotted in the Fig. 6. Obviously, alloy 120 has the lowest creep strain rate of the three alloys. The dashed line in Fig. 6 represents the estimated minimum creep rate versus stress relationship of alloy 160 at 871°C (1600°F), obtained by linear interpolation using its 850°C (1562°F) and 900°C (1652°F) data. It clearly shows that at 871°C (1600°F), alloy 160 is comparable with alloy 333, and both have greater creep rate and therefore are weaker than alloy 120 in terms of creep deformation resistance.

![Figure 6](image)

Figure 6. At 871°C (1600°F), alloy 120 has the lowest creep strain rate compared to alloy 333 and alloy 160.

The data obtained from creep crack growth tests consisted of potential drop and load-line deflection as a function of time. The crack length was determined from the potential drop data using Johnson's formula (Johnson, 1956). A typical curve of creep crack length as a function of time is given in Fig. 7. The general trend in Fig. 7. shows that the crack is relatively stable during the initial period of time but grows faster and faster as time elapses. It can also be observed in Fig. 7 that for a very short period of time, high crack growth rate occurs upon increasing the load, first from 0 N to 1179 N (400 lb) at the beginning of the test and then from 1179 N (400 lb) to 2669 N (600 lb) during the test. Many mechanisms can be responsible for such observation depending on the specific circumstances. In the present case, the short time high growth rate upon loading might be caused by crack propagation in the weakened crack tip material developed during the fatigue precracking process, while that observed when the load was increased during the test might be attributed to the creep zone transition. As it will be discussed later through calculation results, the creep crack propagated under 1179 N (400 lb) in a small-scale creep condition. When the load was increased to 2669 N (600 lb), the creep zone in the specimen transited into an extensive creep condition, and this might cause the creep crack growth rate to increase a little before it became relatively stabilized.

![Figure 7](image)

Figure 7. A typical curve of creep crack length as a function of time.

The data of crack length (a) and loadline deflection (V) were further processed numerically to obtain their respective rates [da/dt (a) and dV/dt (V)] with a seven-point incremental polynomial technique, and then used to calculate the time-dependent fracture mechanics parameters for characterizing the creep crack propagation rates. The time-dependent fracture mechanics parameters C*(t) and C, for extensive and small-scale/transition creep conditions respectively, were calculated using the following equations:

$$C^*(t) = \frac{P \dot{V}_c}{B_N (W-a)} n + 1 \left(2 + 0.522 \frac{W-a}{W}\right)$$  \hspace{1cm} (3)

$$C_t = \frac{P \dot{V}_c}{\sqrt{BB_N W}} F/F$$  \hspace{1cm} (4)

where, $P =$ applied load (N)
Vc = the load-line creep deflection rate determined from the total deflection rate (dV/dt) (mm/hr)

BN = net thickness (distance between the roots of the side grooves in side-grooved specimens) (mm)

B = specimen thickness (mm)

n = creep exponent

\[ f' = f + \frac{3}{2 + a/W} \frac{f'}{f} \]

\[ f = 0.886 + 4.64(a/W) - 13.32(a/W)^2 + 14.72(a/W)^3 - 5.6(a/W)^4 \]

\[ f' = \text{derivative of } f \text{ with respect to } a/W \]

where:

- E = Young's Modulus (MPa)
- K = stress intensity factor (MPa·m\(^{1/2}\))
- v = Poisson's ratio

Figure 8. The creep crack growth rate characterized using the time-dependent fracture mechanics parameter \( C^*(t) \) at 871°C (1600°F).

When the test time exceeded the transition time, i.e. \( t > t_T \), the creep zone was considered to be extensive and the creep crack propagation rates were correlated with Equation (3). Otherwise the creep crack growth rates were correlated with Equation (4) (ASTM Committee, 1993b). The transition time \( t_T \) was given as:

\[ t_T = \frac{K^2 (1 - v^2)}{E(n + 1) C^* (t_T)} \]

The calculation of Equation (5) has shown that under 1179 N (400 lb) the entire testing time was less than the transition time \( t_T \), i.e., the crack propagated in a small-scale creep condition, while under the other load levels, the creep zone transited into extensive creep condition in a short period of time. In order to compare the results with the other materials whose crack propagated mainly under extensive creep conditions, only the data under 2669 and 3114 N (600 and 700 lb) were processed with \( C^*(t) \) in Equation 3. The results developed from the test data for alloy 120 are plotted in Fig. 8. It shows that data from both tests with different load levels fall into the same trend and can be presented by following equation:

\[ \frac{da}{dt} = A [C^*(t)]^q \]

where, \[ A = 2.7459 \times 10^{-2} \text{ (mm/h)} \times (\text{m}^2 \text{ h/kg joule})^q \]

\[ q = 0.97243 \]

To compare with the other materials, the relationship in Fig. 8 is plotted with those of alloy 333 and alloy 160 in Fig. 9. It is obvious in Fig. 9 that at the same \( C^*(t) \) value, alloy 120 has a creep crack growth rate lower than alloy 333 but a little higher than alloy 160. Since the \( C^*(t) \) value represents the creep energy dissipation rate, therefore, in
other words, alloy 120 has higher creep crack growth resistance than alloy 333 but a little lower creep crack growth resistance than alloy 160 when the three materials consume creep energy at the same rate. It is should be pointed out that alloy 120 has the smallest grain size among the three alloys, which suggests the most vulnerable condition to creep damage from grain size point of view.

It is also worth pointing out that in Fig. 9, the curves for alloy 120 and alloy 333 were obtained at the same temperature of 871°C (1600), but the curve for alloy 160 was obtained at 3 various temperatures of 850, 900 and 950°C (1562, 1652 and 1742°F). For some materials, temperature has been found to affect the creep crack growth rate versus the time-dependent fracture mechanics parameter C*(t) relationship. Slight effect of temperature has been reported in type 316 stainless steel by Jaske et al. (1988). However, it was shown in a previous study by experimental results (Ren et al., 1995) that temperature variation had no effect on this relationship for alloy 160.

CONCLUSIONS

The following conclusions can be drawn from this investigation:
1) At 871°C (1600°F), alloy 120 demonstrates much longer creep-rupture life than alloy 333 and alloy 160 in spite of its smallest grain size among the three alloys tested.
2) For the conditions examined, alloy 120 presents little or no primary creep deformation as well as alloy 333, while alloy 160 has a considerable amount of primary creep.
3) At 871°C (1600°F), the creep coefficient A2 has a value of 5.591 x 10^2 MPa”/h, and the creep exponent n of 9.85 for alloy 120.
4) For a given stress, alloy 120 has the lowest creep strain rate compared to alloy 333 and alloy 160 at 871°C (1600°F).
5) The creep crack growth rate of alloy 120 can be uniquely correlated by the time-dependent fracture mechanics parameter C*(t) in the form of da/dt = A[C*(t)]^q where A has the value of 2.7459 x 10^-2 (mm/h)-(m^2/h/kilojoule)^q and q of 0.97243.
6) At a given C*(t) value, alloy 120 has a creep crack growth rate lower than that of alloy 333 but only a little higher than that of alloy 160 in spite of its smallest grain size among the three alloys tested.

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