Kinetics of Environmental Fatigue Crack Growth in Nickel-Copper Alloy: Part I. In Vacuum and Oxygen

S. PURUSHOTHAMAN, R. J. RICHARDS, J. K. TIEN, AND J. D. FRANDSEN

Fatigue crack growth rates have been determined in a nickel-copper alloy in the mild test environments of vacuum and oxygen. It is found that the fatigue crack growth mode in both vacuum and oxygen is ductile and the growth rate is sensibly independent of the maximum stress intensity levels and stress intensity ratio. The growth rate is found to be lower in vacuum than in oxygen, and the growth rate dependency on the cyclic stress intensity range is more pronounced in vacuum than in oxygen. These differences in behavior may be consistent with differences in crack closure behavior for the two environments.

It is a well documented observation that alloys exposed to an aggressive environment, such as hydrogen, usually suffer a ductility loss, often a drastic one, as in the case of certain steels. Although systematic results are scarce, there is sufficient information to show, also, that under fatigue loading conditions aggressive environments lead to higher crack growth rates (see for example Refs. 5 to 10).

In order to obtain an information base for the mechanistic understanding of the environmentally affected fatigue crack growth process, we have generated a matrix of fatigue crack growth rates and fracture toughness at ambient temperature in environments of increasing severity—vacuum, oxygen, and hydrogen—as functions of stress intensity range (ΔK), the maximum stress intensity (Kmax), the mean stress intensity (Kmean), and the stress intensity ratio R where R = Kmin/Kmax.

We chose Monel K-500* for this comprehensive study not only because it is a corrosion resistant heat exchanger structural material, but also because some environmentally affected crack growth information already exists for this alloy. It has been found, for example, that the effect of hydrogen on the fatigue crack growth rate is more pronounced in the peak hardness heat treated condition than in other heat treated conditions.

In Part I of this paper, we give the experimental details of the tests and describe the differences in fatigue crack growth behavior of Monel K-500 for an inert environment, vacuum, and a moderately aggressive environment, oxygen. A possible explanation for these differences based on crack closure considerations is offered. In Part II, the hydrogen affected crack growth rates, which are much different than oxygen and vacuum affected growth rates, will be presented and discussed.

EXPERIMENTAL PROCEDURE

The analyzed chemical composition and relevant mechanical properties of Monel K-500 are given in Table I. Monel K-500 is heat treatable and age hardened by the precipitation of submicroscopic (less than 5 nm) particles of γ' (Ni3(Ti,Al)) in the matrix. The microstructure after age hardening is shown in Fig. 1. The average grain size, as determined using a Hilliard circle, is 25 μm and the random inclusions in the microstructure are usually more than 25 grains apart.

The tapered double cantilever beam specimen (DCB), shown in Fig. 2, was used throughout these studies. The advantages of the DCB geometry are 1) it is possible to run a series of tests on one specimen because the stress intensity at the crack tip is independent of crack length for about 60 mm (Ref. 13), and 2) the macroscopic crack propagation direction stays roughly normal to the applied stress direction.

The tapered DCB specimens were machined from a 102 mm diam hot finished round bar with the expected crack growth direction parallel to the length of the bar. Prior to machining, the bar was solution annealed in argon for 10 min at 1255 K and water quenched. The machined DCB specimens were then heat treated to a peak hardness condition in argon at

Table I. Nominal Chemical Composition in Wt Pct of Peak-Aged Monel K-500

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Mn</th>
<th>Fe</th>
<th>S</th>
<th>Si</th>
<th>Cu</th>
<th>Ni</th>
<th>Al</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncharged</td>
<td>0.15</td>
<td>0.66</td>
<td>1.43</td>
<td>0.008</td>
<td>0.13</td>
<td>29.43</td>
<td>64.72</td>
<td>2.89</td>
<td>0.54</td>
</tr>
<tr>
<td>Charged</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A. Composition

B. Mechanical Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Uncharged</th>
<th>Charged</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA</td>
<td>45.4 pct</td>
<td>1.9 pct</td>
</tr>
<tr>
<td>Elongation</td>
<td>31.9 pct</td>
<td>2.5 pct</td>
</tr>
<tr>
<td>0.2 pct σy</td>
<td>633 MmN²</td>
<td>751 MmN²</td>
</tr>
</tbody>
</table>
LOADING DIRECTION

ROLLING DIRECTION

Fig. 1—Optical micrograph of peak-aged alloy. The grain size is 25 μm on an average. Notice also the few random but widely spaced titanium sulfide inclusions, randomly distributed in the microstructure.

Fig. 2—Tapered double cantilever beam specimens for the determination of fatigue crack propagation rates. This type of specimen insures that ΔK is constant over long crack extensions and that crack growth is in the machined groove and normal to the applied stress (after Ref. 13).

Fig. 3—Fatigue crack propagation rates plotted as a function of programmed stress intensity range, ΔK, for the alloy tested at the R value of 0.1 in vacuum and oxygen. The values of Paris law exponent m with the appropriate standard errors are also shown.

downs were always done between hydrogen and oxygen tests to minimize cross contamination of the test environments. Further, the preset external load was readjusted whenever a pressure change inside the chamber occurred (for example, pressure changes resulting from ambient temperature changes) in order to adjust for loads imposed on the sample from the pressure differential on the loading rod. Constant mean specimen load was thus maintained between similar tests. All testing was conducted at a frequency of 2 Hz.

Crack growth measurements over a distance of about 5 mm for each test, were taken optically with a traveling extensometer microscope with a resolution of ±10 μm. Crack growth rates were obtained by performing a linear regression fit of the crack length readings and the corresponding cycle numbers. The error of each fit was found by computing the standard error for each case.

In order to prevent unintentional crack retardation, the testing order was such that Kmax either remained constant or increased from one test for a given specimen. This served to keep the forward plastic zone size from decreasing and thus avoided the introduction of excessive compressive stresses at the crack tip.

After testing, fracture surfaces of the specimens were studied in an ETEC scanning electron microscope (SEM) to analyze the various modes of failure and to correlate them with the observed crack growth rates.

RESULTS

Two separate and distinct groups of tests were conducted in each of the three environments—vacuum, oxygen, and hydrogen. In the first group, R was set at 0.1 and the load was correspondingly controlled so that ΔK values of 24.8, 29.7, 34.7, 39.6 and 49.5 MN/m^{3/2} and corresponding K_{max} values of 27.5, 33, 38.5, 44 and 55 MN/m^{3/2} were applied for all three environments. The results of the first group of tests in vacuum and oxygen are shown in Fig. 3. Values of