The Effect of Liquid Lithium on Fatigue Crack Propagation in 304L Stainless Steel at Elevated Temperatures

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Liquid lithium was observed to enhance fatigue crack propagation in 304L stainless steel at 973 K. The enhanced crack growth rates are shown to be associated with preferential grain boundary penetration in the vicinity of the tip of a propagating fatigue crack exposed to liquid lithium. The enhanced crack growth rates are correlated with the predictions of a model based on the summation of grain boundary penetration by liquid lithium and the growth rates in an argon environment.

INTRODUCTION

The effect of liquid lithium on the fatigue crack propagation characteristics of 304L stainless steel at 973 K has been investigated. Enhanced crack propagation rates in lithium at loading frequencies from 0.067 to 20 Hz accompanied by a transition from transgranular to intergranular propagation at high frequencies, were observed. The purpose of this paper is to present an interpretation of the observed behavior.

Grain Boundary Penetration

A brief review of the grain boundary penetration behavior of materials in liquid lithium provides the starting point for this discussion. Grain boundary penetration in several steels without an applied stress has been investigated. An important result of these studies is the set of equations developed by Olson et al which relates the extent of grain boundary penetration in 304L stainless steel to the time, temperature, and dissolved nitrogen concentration in the lithium. The equations can be written as:

\[ P = (k_p t)^{1/2} \]  \hspace{1cm} [1a]

above 1000 K: \[ k_p = 2.8 [N]^2 \exp(-17000/RT) \]  \hspace{1cm} [1b]

below 1000 K: \[ k_p = 4000 [N] \exp(-31000/RT) \]  \hspace{1cm} [1c]

where \( P \) is the depth of penetration in mm, \( t \) is the time in h, \( T \) is the temperature, and \([N]\) is the concentration of dissolved nitrogen in the lithium in wt pct. The role of nitrogen in the corrosion process is not fully understood but its importance is apparent. Comparing Eqs. [1a] and [1b] shows a change in both the activation energy and nitrogen exponent at 1000 K suggesting a change in corrosion mechanism.

Effect of Stress on Grain Boundary Penetration

The effect of stress on lithium corrosion has been studied by several investigators. Jordan et al performed constant load creep tests on Armco iron submerged in
molten lithium to determine the effect of an applied stress on lithium attack. Enhanced grain boundary penetration was observed in this material which experienced very little attack when exposed to lithium in the absence of a stress. Whipple extended this study by comparing the effect of compressive and tensile stresses on grain boundary penetration during steady state creep of Armco iron submerged in lithium. It was shown that the application of either a tensile or a compressive stress greatly increases the penetration. Furthermore, Whipple found the penetration rate coefficient to be proportional to the creep rate.

On the basis of these results, a strain-enhanced corrosion model was proposed. It was suggested that slip along planes intersecting grain boundaries fractured a corrosion product layer exposing new material which corrodes very rapidly.

The effect of nitrogen on the stress/corrosion behavior observed in the aforementioned studies has not been investigated. Eqs. [1a] and [1b] show the nitrogen level to be very important in the static corrosion of 304L stainless steel, but this may not be the case for strain-enhanced grain boundary penetration.

**FATIGUE IN LIQUID LITHIUM**

The effect of liquid lithium with a high dissolved nitrogen content (approximately 2000 ppm) on fatigue crack propagation in 304L stainless steel at 973 K has been investigated. A modified compliance technique was used to monitor the growth of fatigue cracks in standard ASTM compact tension (CT) specimens as described in another publication. Specimens were tested while submerged in a heated crucible filled with liquid lithium. Crack growth was related to variations in the system compliance which was obtained from measurements of the displacement between the crucible (lower grip) and upper pull rod (upper grip). Results reported previously will be reviewed here along with an evaluation of the mechanisms which contribute to enhanced growth rates.

**Effect of Lithium on the Rate of Fatigue Crack Propagation**

Several observations were made with respect to the effect of liquid lithium on the rate of fatigue crack propagation. First, the crack growth rate for a given imposed stress-intensity range, $\Delta K$, is higher when propagation occurs in a liquid-lithium environment than when it occurs in an argon environment.

Another important observation with respect to the influence of lithium is that for each frequency, the effect of the applied stress-intensity range is greater for the lithium environment than for the argon environment. This is reflected by an increase in the stress-intensity-range exponent in the Paris equation for fatigue crack growth rate, $da/dN$, as a function of $\Delta K$:

$$da/dN = A(\Delta K)^n$$

Values of $n$, the stress-intensity exponent, and $A$, an empirical parameter, are tabulated in Table I for each of the test conditions.

The final observation made with respect to crack growth rates is that for both the argon and lithium environments, the fatigue-crack-propagation rate, $da/dN$, increases with a decrease in frequency. The effect of frequency and environment on $da/dN$ is summarized in Fig. 1 which plots $da/dN$ as a function of frequency at a constant stress-intensity range for both environments. Figure 1 emphasizes two previous observations: 1) The

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Lithium</th>
<th>Argon</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.067</td>
<td>$9.5 \times 10^{-11}$</td>
<td>3.4</td>
</tr>
<tr>
<td>1.7</td>
<td>$6.0 \times 10^{-9}$</td>
<td>1.4</td>
</tr>
<tr>
<td>20</td>
<td>$2.9 \times 10^{-10}$</td>
<td>2.3</td>
</tr>
</tbody>
</table>

where: $da/dN = A(\Delta K)^n$, for $da/dN$ in $m$ and $\Delta K$ in MPa$\sqrt{m}$.

12 $\leq \Delta K \leq 18$. 

![Fatigue Crack Propagation Graph](image-url)