THE $\Delta K_{th}$ BEHAVIOUR OF THREE STAINLESS STEELS IN DIFFERENT ENVIRONMENTS

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ABSTRACT

The fatigue threshold values, $\Delta K_{th}$, were measured for three stainless steels (KCR 171, CA 15 and 304) in different environments, generally at $R=0.1$. In white water, $\Delta K_{th}$ for KCR 171 and CA 15 was lower than in air, probably as a result of increased hydrogen embrittlement effects. In silicone oil, $\Delta K_{th}$ for KCR 171 and CA 15 was higher than in air, at least partially as a result of an increase in plastic zone size and in crack closure effects.

KEYWORDS

Fatigue thresholds; influence of environment; R-ratio; crack closure; corrosion-fatigue; hydrogen embrittlement; stainless steels.

INTRODUCTION

The influence of the environment on the threshold value of the cyclic stress intensity factor, $\Delta K_{th}$, is very variable. Depending on the material and environment, an aggressive environment can decrease (Voskovsky, 1976; Haugen- sen, 1977), not influence (Naultz and Weiss, 1976; Bailon and others, 1983) or increase (Stewart, 1980; Ritchie and others, 1980; Bailon and others, 1983) $\Delta K_{th}$. An inert environment generally (Beever, 1977; Bailon and others, 1983) but not always (Stewart, 1980; Ritchie and others, 1980) increases $\Delta K_{th}$. This seemingly confusing behaviour occurs since the environment can influence not only the fracture and plastic properties of the material at the crack tip but also the crack tip morphology (Radin, 1970) and crack closure. A change in the $(\Delta K_{th})_{th}/\Delta K_{th}$ ratio can thus result, where $(\Delta K_{th})_{th}$ represents the portion of $\Delta K_{th}$ effectively acting on the material immediately ahead of the crack tip. Accordingly, $\Delta K_{th}$ can be decomposed thus:

$$\Delta K_{th} = (\Delta K_{th})_{th} + \Delta K'_{th}$$

where $(\Delta K_{th})_{th}$ should be determined by the fracture and plastic properties
of the crack tip material. As such, it is a material property that can be influenced by the environment. The $\Delta K_{th}$ component represents the influence on the threshold of effects which cause the effective $\Delta K$ to differ from the applied $\Delta K$. Crack closure, changes in crack tip morphology (e.g., crack branching) and the presence of residual stresses ahead of the crack tip can relatively easily be measured. Assuming the other contributions to be negligible ($\Delta K_{x+r} + \Delta K_{th}$), equation (1) can be more conveniently written to include $K_{th}$, the stress intensity at which the crack tip becomes open:

$$\Delta K_{th} = (\Delta K_{x+r} + \Delta K_{th}) - (K_{th} - K_{ref})$$  

(2)

The usual method of measuring $K_{th}$ is by recording load-crack mouth opening displacement (CMOD) hysteresis loops and evaluating the change in compliance. The possibility of a change in crack tip morphology can be evaluated by detailed fractography. Residual stress effects can be kept to a minimum by correcting testing and sample preparation procedures.

The present paper considers, for three stainless steels, the influence of environment on $\Delta K_{th}$ and on the near-threshold fractography as well as the influence of environment, $\Delta K$ and $R$ on the near-threshold $K_{th}$.

**EXPERIMENTAL PROCEDURE**

The materials studied were KCR 171 a 24% Cr, 8% Ni, 1% Mo austenitic-ferritic stainless steel containing approximately 55% of austenite, CA 15, a 12% ferrite and metastable austenitic 304 stainless steel containing less than 10% of delta formed at room temperature, 20 Hz and generally at $R = 0.1$. Tests were carried out in air at 55% relative humidity, white water, and silicon oil. A servohydraulic machine interfaced for automatic test control and data acquisition was employed. The crack lengths were measured optically using a travelling microscope with resolution better than 0.01 mm. Hysteresis loops of load versus CMOD in the near-threshold region were recorded digitally at reduced line was first calculated for the portion of the K versus CMOD curve for which elastic behaviour was obtained for the fully opened crack. The deviation of the experimental points from this line were then plotted as $K_{ref}$ taken as the point at which the crack closure portion of the elastic portion of the fully opened crack. The low crack propagation rates and the $\Delta K_{th}$ values were measured by employing a load-shedding procedure, with decreasing shedding steps of 0.1%, 0.5% and 3%.

**RESULTS**

$\Delta K_{th}$ and $K_{th}$ values

Figure 1 presents typical $da/dN$ versus $\Delta K$ results. The threshold values, $K_{th}$, for the various materials and environments are shown in Figure 1. For KCR 171, a series of measurements were performed in air at $R = 0.1$ for 40 MPa m/2, at $R = 0.1$, $K_{th}$ remained essentially constant at 6 MPa m/2 with a standard deviation of 0.02 MPa m/2, at $R = 0.2$, the constant $K_{th}$ was 7.9 MPa m/2 with a standard deviation of 0.15 MPa m/2. A series of $K_{th}$ measurements were also performed at $R = 0.5$ in air and following the introduction of white water, silicone oil and silicone oil contaminated with 2% of viscous paint stripper as to transform it into an aggressive environment of similar viscosity. These changes in environment were performed at a $K_{th}$ of 14 MPa m/2 for which $K_{th}$ in air was 7.8 MPa m/2. The introduction of white water or of contaminated silicone oil had no influence on the load-CMOD hysteresis loop shape at $K_{th}$ of 10 MPa m/2. The introduction of silicone oil resulted in a very rapid increase in $K_{th}$ over the first 20 cycles and then a more gradual increase. After 1000 cycles $K_{th}$ became constant at 8.5 MPa m/2. Gradually increasing $K_{th}$ to 30 MPa m/2 and, when necessary to detect crack closure, decreasing $K_{th}$ during the recording of a hysteresis loop resulted in essentially constant $K_{th}$ of 9.6 MPa m/2. On a second sample, silicone oil was introduced at $R = 0.5$ at a $K_{th}$ value of 17.9 MPa m/2 for which no crack closure effects were noticed in air. Silicone oil contamination again resulted in crack closure with $K_{th}$ becoming constant at 9.9 MPa m/2 after 3000 cycles.

**TABLE I: $\Delta K_{th}$ values in MPa m/2**

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>R</th>
<th>AIR</th>
<th>WHITE WATER</th>
<th>SILICONE OIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>KCR 171</td>
<td>0.1</td>
<td>7.2</td>
<td>6.1</td>
<td>9.2</td>
</tr>
<tr>
<td>KCR 171</td>
<td>0.5</td>
<td>5.0</td>
<td>-</td>
<td>6.5</td>
</tr>
<tr>
<td>CA 15</td>
<td>0.1</td>
<td>9.3</td>
<td>8.8</td>
<td>-</td>
</tr>
<tr>
<td>304</td>
<td>0.1</td>
<td>6.9</td>
<td>6.4</td>
<td>7.9</td>
</tr>
</tbody>
</table>

Values of $K_{th}$ were determined for tests at $R = 0.1$ to 0.4 for CA 15. The value of $K_{th}$ remained essentially constant at 6.3 MPa m/2 with a standard deviation of 0.15 MPa m/2 as $K_{th}$ was increased from 10.3 to 17.9 MPa m/2. For higher $K_{th}$ values up to 24.4 MPa m/2, $K_{th}$ decreased slightly to 5.8 MPa m/2. As well, $R$-ratios of 0.1-0.4 appeared to have no significant influence on $K_{th}$. Bignone and others (1982) have also observed little or no influence of $K_{th}$ or $R$ on $K_{th}$ near $\Delta K_{th}$ for a number of other materials.

![Fig. 1 Near-threshold crack growth rate curves for a) KCR 171 and b) 304 steels.](image)
Fractographic and plastic zone size observations

For all three materials and for both phases of KCR 171 and CA 15, the near-threshold fractography consisted of fine crystallographic facets (Fig. 2). Features observed included flat, rather smooth facets (Fig. 2a), parallel sheet-like facets separated by fine cracks (Fig. 2b), crystallographic steps (Fig. 2c) and river lines which often increased in number on crossing grain boundaries. These river lines often were crystallographically serrated (Fig. 2d) and at times formed fan-shaped patterns, very similar to those observed during transgranular stress corrosion cracking (tsc) (Hukai and others, 1978; Dickson and others, 1980). The other features mentioned can also be observed on tsc fracture surfaces. The near-threshold fractography of the 304 steel (Fig. 3) was observed to be particularly similar to that typical of tsc of the 300 series stainless steels. The crystallographic facets produced in silicone oil tended to suggest a less brittle fracture mode; however, closer examination indicated that the only difference was that edges and corners which acted as asperities had generally been rounded by crack closure (Fig. 4a). Etch-pit shapes (Alt Bassi and others, 1983) showed that the fracture planes in the KCR 171 ferrite were (100).

Silicone oil introduction after testing in air resulted in the occurrence, on the portion of the fracture surface previously produced and which was quite close to the crack front when this oil was introduced, of quasimacroscopic regions almost completely flattened (Fig. 4b) by crack closure. The crystallographic aspects were still discernible, however, in the more pronounced microscopic depressions. The introduction of this inert environment during a test in air resulted in a rapid increase in plastic zone size, similar to other observations (Davidson and Lankford, 1977; Baylon and others, 1983). This rapid increase was clearly observed with the traveling microscope employed for crack length measurements. A doubling in surface plastic zone size was estimated microscopically after the test.

**DISCUSSION**

**Threshold values**

The $R = 0.1\Delta K_{th}$ values in white water for KCR 171, CA 15 and 304 steels are approximately 15%, 5% and 7% lower, respectively, than those in air. For KCR 171, no change in $K_{th}$ was detected for a change from air to white water; however, the measurements in white water were carried out only for a few thousand cycles, which was probably insufficient for an increased effect of corrosion-product induced crack closure to occur. As well, the increase in $K_{th}$ due to fretting oxide crack closure can be more pronounced at than near $\Delta K_{th}$ (Bigmonnet and others, 1983). The indication clearly is that the decrease in $\Delta K_{th}$ in white water is associated with a decrease in $(\Delta K_{th})_{th}$ probably as a result of an (or a more severe) embrittlement compared to testing in air. If increased corrosion-product induced crack closure occurs in white water, for which environment the fracture surfaces were, prior to cleaning in inhibited HCl solution, more strongly covered with corrosion product, the true decrease in $(\Delta K_{th})_{th}$ may actually be greater than suggested by the decrease in $\Delta K_{th}$. The corrosion-fatigue effects at higher $\Delta K$ values obtained during tests in white water on KCR 171 and CA 15 have been explained (Alt Bassi and others, 1983, 1984) by hydrogen embrittlement of the ferritic phase and hydrogen embrittlement is also the likely explanation for the observed decrease of $\Delta K_{th}$ and $(\Delta K_{th})_{th}$ in white water. In this respect, it is interesting to note that a similar decrease of $\Delta K_{th}$ in white water occurred for the metastable austenitic 304 steel.
For KCR 171, $\Delta K_{\text{th}}$ was $\approx 30\%$ higher in silicone oil than in air for both $R = 0.1$ and 0.5. For 304 stainless steel at $R = 0.1$, $\Delta K_{\text{th}}$ was $\approx 15\%$ higher in silicone oil than in air. For KCR 171, the value of $K_{\text{th}}$ increased initially rapidly and then gradually after a change from air to silicone oil near $\Delta K_{\text{th}}$ and stabilized after approximately 3000 cycles. The initial increase appeared to correspond well to the rapid increase in plastic zone. A subsequent gradual increase of this zone would have been very difficult to detect optically. Taking $K_{\text{th}}$ for KCR 171 as 7.8 MPa m$^{0.5}$ in air and 2.6 MPa m$^{0.5}$ in silicone oil, the increase in $K_{\text{th}}$ explains 80% and 20% of the increase in $\Delta K_{\text{th}}$ for testing in silicone oil at $R = 0.1$ and 0.5, respectively. Testing in silicone oil also produced fractographic evidence at both $R$-ratios for more crack closure than in air. An important portion of the increase in $\Delta K_{\text{th}}$ in silicone oil thus results from the increase in plasticity-induced crack closure effects, although as noted by Baillon and others (1983) toughness-induced crack closure generally occurs in combination with plasticity-induced or with oxide-induced crack closure. The portion of the increased $\Delta K_{\text{th}}$ in silicone oil not explained by the increased closure may be associated with the occurrence of some hydrogen embrittlement in air, as suggested by occasional observations of brittle striations above the $\Delta K_{\text{th}}$ region (Ait Bassidi and others, 1983, 1984). For the 304 steel, no measurements were performed of $\Delta K_{\text{th}}$ in white water or of the change in $K_{\text{th}}$ associated with a change in environment. For this austenitic steel, the effect of hydrogen embrittlement at $\Delta K_{\text{th}}$ in air may be small and the smaller increase in $\Delta K_{\text{th}}$ in silicone oil may be essentially associated with increased crack closure.

**Fractographic aspects**

The fractographic aspects of flattened or rounded asperities (Fig. 4a), obtained principally in silicone oil, indicate a combination of plasticity-induced and toughness-induced crack closure, in agreement with the increase in plastic zone size and associated with a change in this inert environment. No other fractographic differences were detected for the different environments, suggesting similar crack tip morphologies. Strong hydrodynamic wedging effects in silicone oil also were not indicated since the surface flattening was not uniform.

As noted by Dickson and others (1981), the crystallographic facets obtained near $\Delta K_{\text{th}}$ are very similar to those obtained during T SCC. These characteristic cleavage-type facets are produced near $\Delta K_{\text{th}}$ even in such inert environments as silicone oil and vacuum. The explanation proposed is that both types of cracking are produced by small, discontinuous, cleavage-type crack bursts, as experimentally observed for T SCC of Admiralty metal (Pugh, 1981), although near $\Delta K_{\text{th}}$ this cleavage is not necessarily environmentally-assisted.

**CONCLUSIONS**

It can therefore be concluded that testing in white water at $R = 0.1$ results in an increase of $\Delta K_{\text{th}}$ and $K_{\text{th}}$, compared to testing in air for KCR 171, CA 15 and 304 stainless steels. Testing in silicone oil results in an increase in $\Delta K_{\text{th}}$, which is at least partially associated with an increase in plastic zone size, in plasticity-induced crack closure and in $K_{\text{th}}$.

**ACKNOWLEDGMENTS**

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