ON OVERLOADS AND THE RATE OF FATIGUE-CRACK GROWTH
IN TYPE 304 STAINLESS STEEL

P. Lewinsky, H. Bao, and A. J. McEvily

The effect of an overload on the subsequent rate of fatigue-crack growth has been investigated in type 304 stainless steel. This material was selected because of its low yield strength and its tendency to form strain-induced martensite at the fatigue-crack tip. At a $\Delta K$ level of 12.5 MPa$\sqrt{m}$, two crack opening events were observed, one related to crack opening in the wake of the crack, and the other to crack opening at a higher level at the crack tip in the surface plane-stress region. At a $\Delta K$ of 22 MPa$\sqrt{m}$, the extent of crack tip blunting was so large that the first opening level was completely suppressed. At both $\Delta K$ levels, the extent of retardation was in accord with predictions. In this study, the low yield stress appeared to exert a greater influence on fatigue-crack growth behavior than did strain-induced martensite.

Introduction

In recent studies [1, 2], it has been shown that, in 9Cr–1Mo steel and 6061-T6 aluminum alloy, the retardation in the rate of fatigue-crack growth that occurs following an overload results from increased plasticity-induced closure in the wake of the crack tip in the surface plane-stress regions as the result of an overload. In the present investigation, we have selected type 304 stainless steel for investigation for two reasons. The first is that this alloy has a lower yield strength than the previous materials studied and, hence, would be expected to exhibit more retardation because of a larger overload plastic zone size and, as a result, more crack closure. The second reason is that, at the fatigue-crack tip of this alloy, a strain-induced transformation from austenite to martensite occurs, and we were curious to know what effect, if any, on fatigue-crack growth behavior is caused by this transformation. It is pointed out that this topic has also been recently investigated by Che and Schaper [3], and it is of interest to compare our results with theirs.

Materials and Tests

The nominal composition of type 304 stainless steel is given in Table 1, and the mechanical properties are given in Table 2. It is noted that the grain size of this material was relatively large, 76 $\mu$m. Compact specimens of 6.3 mm thickness were used for the fatigue-crack growth tests.

| Table 1. Nominal Chemical Composition (wt. %) of 304 SS |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Fe              | Cr              | Ni              | Mn              | Si              | Mo              | P               | S               | C               |
| bal.            | 18              | 8               | 1.7             | 0.4             | 0.3             | 0.31            | 0.25            | 0.08            |

The fatigue tests were generally carried out in air at room temperature. The one exception was a test carried out in vacuum (mPa). The test frequency was 10–30 Hz, and the ratio of minimum to maximum stress in a loading cycle, $R$, was 0.05. The % overload was defined as $100 \times (K_{\text{max,ol}} - K_{\text{max,b}}) / \Delta K$, and, in these tests, only single, 100% overloads were used. Here, $K_{\text{max,ol}}$ is the maximum value of $K$ in the overload, and $K_{\text{max,b}}$ is the maxi-
minimum $K$ level under a constant amplitude (baseline) testing. The test procedure was to establish a constant rate of crack growth at a $\Delta K$ level of either 12.5 MPa $\sqrt{m}$ or 22 MPa $\sqrt{m}$ and then to apply the overload, and then to continue cycling at the original $\Delta K$ level. At each stage of the test, the rate of fatigue-crack growth was determined, as were the crack opening levels. Crack opening levels were determined by using subtraction circuitry. Crack lengths were determined with a long-range telescope (Questar) with a resolution of better than 10 $\mu m$. In addition, the shapes of the crack tips were examined after an overload, and the fracture surfaces were also examined for information of interest.

**Table 2. Mechanical Properties of 304 SS**

<table>
<thead>
<tr>
<th></th>
<th>$\sigma_{0.2}$, MPa</th>
<th>$\sigma_u$, MPa</th>
<th>Elongation, %</th>
<th>$E$, GPa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>205</td>
<td>515</td>
<td>40</td>
<td>193</td>
</tr>
</tbody>
</table>

**Results and Discussion**

*Tests in Air.* Figure 1 shows the fatigue-crack growth rate before and after an overload. It is noted that there is an immediate short period of acceleration in the crack growth rate, which is followed by a longer period of retardation. In this case, the computed plastic zone size, $r_p$, was 2.6 mm ($r_p = K_{max,ol}^2 / 2\pi\sigma_y^2$), and it is seen that the crack growth rate returns to a constant level at about the computed distance. Figure 2 shows how the crack opening levels varied as the fatigue crack grew through the overload-affected zone. Immediately following the overload, there is a drop in the opening level associated with the wake of the crack. This drop persists throughout the overload-affected zone and comes about because of the lateral contraction of material in the overload plastic zone which serves to prop open and thereby lessen crack closure in the wake of the crack in both plane strain and plane stress regions. We also note in Fig. 2 that the second opening event, $K_{op,up}$, can be detected following an overload. This second event has been observed in aluminum and steel specimens [1, 2] and is associated with crack opening in the overload plastic zone at the surface of the specimen, i.e., it is a plane stress event. Previous work has shown that this upper opening level is responsible for the delay in crack growth following an overload. We have found that the rate of fatigue-crack growth can be expressed as

$$\frac{da}{dN} = A(\Delta K_{eff} - \Delta K_{eff,th})^2,$$

(1)

where $a$ is the crack length, $N$ is the number of cycles, $A$ is a material constant, $\Delta K_{eff}$ is the range of the effective stress intensity factor given by

$$\Delta K_{eff} = K_{max} - K_{op},$$

(2)

and $K_{eff,th}$ is the value of $\Delta K_{eff}$ at the threshold level for fatigue-crack growth. The large values of $K_{op,up}$ following an overload result in low values of $\Delta K_{eff}$ and, hence, low crack growth rates. In Fig. 2, $K_{start,op,up}$ is the level at which the opening of the crack wake in the overload affected zone at the surface begins. Figure 3 provides examples of the offset displacement plots used to determine the opening levels.

It is proposed that the initial acceleration that occurs following the overload is due to crack tip blunting which reduces the overload level below its steady-state value. As the fatigue crack begins to grow immediately following the overload, it has a low level of closure in its wake and can grow rapidly. However, as it grows further into the overload zone, closure starts to develop in the wake as a result of the relaxation of residual compressive stress within