Fatigue Crack Tip Deformation Processes as Influenced by the Environment

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The shape of a fatigue crack tip as influenced by an air or a vacuum environment has been investigated in two stainless steels and an aluminum alloy. Under plane strain conditions and at crack growth rates in the Paris region, the crack tip opening displacement (CTOD) is much larger in vacuum than in air, a circumstance attributed to strain localization in air due to the presence of moisture and the absence of strain localization in vacuum. In type 304 stainless steel, a strain-induced transformation from austenite to martensite occurs at the crack tip, and the extent of this strain-induced transformation in type 304 stainless steel is consistent with the degree of blunting taking place at the crack tip as influenced by the environment. In air, the extent of transformation is a function of the $\Delta K$ level, and as a result, the crack opening level is found to differ in a $\Delta K$ decreasing test as compared to a $\Delta K$ increasing test. Fatigue striations are observed in air but are absent in vacuum. It is proposed that the greater extent of blunting in vacuum is responsible for the absence of striations in vacuum.

I. INTRODUCTION

When fatigue crack growth occurs in type 304 stainless steel, the plastically deformed material at the tip of the fatigue crack can undergo a strain-induced transformation from austenite to martensite ($\alpha'$. As shown in Figure 1, it has been found that the extent of this transformation is greater in vacuum than in air, and the present article is directed at providing an explanation for this difference. The environment, of course, has long been recognized to influence fatigue crack growth behavior, and it is well known that for metals and alloys, the rate of fatigue crack growth in air is higher than in vacuum. For example, Figure 2 shows the effect of an air vs vacuum environment on the fatigue crack growth rate of type 304 stainless steel at room temperature. For both steels and aluminum alloys, at room temperature, it has been shown that the moisture content of air, rather than oxidation, is primarily responsible for this effect. However, it is a difficult matter to be specific about the mechanistic processes by which moisture exerts this influence. Presumably, a reaction of water vapor with the exposed metal at a crack tip is involved with attendant release of hydrogen into the metal. There are several possible ways by which this hydrogen can influence fatigue crack growth, and among these, the process of hydrogen-induced softening and strain localization is of particular interest. Some evidence for strain localization in air during fatigue crack growth is provided by the fact that the slip process at a fatigue crack tip is less uniformly distributed in air than in vacuum. In the present investigation, consideration was given as to whether or not strain localization in air also influenced the extent of the strain-induced transformation by comparing crack tip deformation behavior in air with that in vacuum.

The research program to be described focused primarily on the behavior of type 304 stainless steel, with auxiliary tests of type 316 stainless steel and the aluminum alloy 2219 added for purposes of comparison. The strain-induced transformation in the 304 alloy is accompanied by a volume expansion of about 2 to 3 pct, and a number of authors have indicated that this transformation leads to a reduction in the rate of fatigue crack growth. This effect of the transformation on the growth rate has been ascribed to a perturbation of the stress field at the fatigue crack tip.

In the present investigation, we have directed attention to the shape of the crack tip in both the plane stress surface regions as well as the plane strain interior regions of a specimen under load. The results confirm the finding that the extent of transformation at a crack tip is greater in vacuum than in air and show that the nature of the crack tip blunting process as influenced by the environment is responsible for this difference. The greater rate of crack growth in air as compared to vacuum is attributed to strain localization induced by the environment. The results also indicate that fatigue striations, which are formed in tests carried out in air but not in vacuum, are absent in vacuum because of the greater degree of blunting at the crack tip.

II. MATERIALS AND EXPERIMENTS

A. Materials

The material primarily investigated was type 304 stainless steel. The extent of strain-induced transformation in this alloy depends upon the applied strain, and because of the associated 2 to 3 pct volume expansion, the transformation is more extensive under tensile rather than compressive loading, as shown in Figure 3. We consider that this strain-induced transformation is responsible for the observed high fatigue resistance of notched 304 stainless steel specimens. The smooth bar fatigue strength of this material is above its yield strength (YS) for $R = -1$ loading and will be even higher than its YS for $R = 0.05$ loading. (The term $R$ is the ratio of...
the minimum to the maximum load in a cycle). Therefore, in order to initiate a crack at a notch, plastic deformation accompanied by a volume expansion of the strain-induced product will occur. As a result, at the minimum load of a cycle, there will be a compressive stress field ahead of the notch whose magnitude is enhanced by the transformation. Since the volume of material that undergoes plastic deformation at a crack-initiating notch is larger than the volume that is plastically deformed at the tip of a newly formed fatigue crack as it grows into the plastic zone of the notch, there will be little additional transformation as the crack penetrates the plastically deformed and transformed zone. However, in the wake of this short fatigue crack, the residual compressive stresses at minimum load will be able to relax and create a strong closure effect, much as in the case of an overload. This closure will reduce the level of $\Delta K_{eff}$, the difference between $K_{max}$ and $K_{op}$, and thereby raise the stress required for propagation. As a consequence of this initial resistance to fatigue crack propagation, there will be a reduction in the notch sensitivity, $q$, defined as

$$q = \frac{K_f - 1}{K_T - 1}$$

where $K_f$ is the fatigue strength of an unnotched specimen divided by the fatigue strength of a notched specimen and $K_T$ is the theoretical stress concentration factor. The increased difficulty in growing a fatigue crack from a starter notch in 304 is evidenced in the present work by the fact that a much higher stress intensity factor, of the order of 20 MPa m$^{-1/2}$, is needed to start the propagation of a crack from a through-thickness starter notch with a tip radius of 50 $\mu$m than would be the case with other steels, where crack propagation is usually initiated at 10 MPa m$^{-1/2}$ from a chevron notch. Attempts to start a fatigue crack from a chevron notch in a 304 specimen proved to be even more difficult. However, for 304 stainless, once the crack had grown out of the initial, relatively large plastic zone at the notch, the crack could be grown in air at $\Delta K$ levels as low as 5 MPa m$^{-1/2}$ at an $R$ value of 0.05 (Figure 2).

It is also noted that for 304 stainless steel, if the mean stress is made more negative, the notch sensitivity will increase as there will be less transformation as the mean stress is lowered, in accord with Figure 3. The notch sensitivity also increases at temperatures above the range at which strain-induced transformation occurs.

Fig. 1 — The effect of an air vs a vacuum environment on the extent of strain-induced transformation during fatigue crack growth in 304 stainless steel.

Fig. 2 — The rate of fatigue crack growth in air and in vacuum as a function of $\Delta K$ for 304 stainless steel.

Fig. 3 — The extent of transformation from austenite to martensite in type 304 stainless steel as a function of either tensile or compressive true stress.