The Role of Frequency and Environment in High Temperature Fatigue

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Recent investigations by the author and earlier work largely by Achter have indicated that the high temperature fatigue behavior of metals is significantly influenced by changing the surrounding environment from air to high vacuum. For example, the Coffin-Manson equation for A286, an iron-base superalloy, shows a strong frequency effect at 593°C and an exponent close to unity. On the other hand for this material and several others tested under high vacuum conditions ($\sim 10^{-8}$torr) at elevated temperature, at frequencies greater than 0.1 cpm, the plastic-strain range-fatigue life results all fit into a narrow scatter-band such that the exponent of the Coffin-Manson relationship was 0.5. These other material included NiA, 304 stainless steel, In 718 and mild steel. Additionally for these materials there was very little influence of temperature on the plastic strain fatigue resistance, the room temperature results coinciding with those at elevated temperature, provided the environment was a high vacuum.

The above described results are obtained from strain-limited smooth bar test specimens. Here failure can be thought of as a consequence of a two-stage process involving first the nucleation of cracks at the surface and secondly the propagation of one or more of these cracks through the specimen to failure. Since these two stages may involve different physical processes, the environment can enter into each stage in a different manner.

Insofar as crack nucleation is concerned, our work has indicated that in high temperature air the environment can significantly modify or alter completely the crack nucleation process. While the room temperature nucleation processes are largely considered to be crystallographic in nature, at high temperatures this becomes the exception rather than the rule. More commonly, oxidation processes control nucleation. For example, the cast nickel-base superalloys develop a surface "ridging" at specific grain boundaries associated with stress and identified as localized oxidation of grain boundary precipitates, mostly carbides. For mild steel at 500°C stress-induced cracking of the surface oxides leads to oxide-grooving, and strain localization. In In-718 at 650°C MC carbides exposed to the surface oxidize and microcracks grow from these oxidized carbides. For nickel A fatigue cracks also nucleate intergranularly at 550°C.

In cases where the environment does not change the mode of nucleation occurring at low temperature, it can perturb it. For example, Henry and Johnson have shown that in A286 at room temperature cracks nucleate by extrusions from growth twins and slip bands. At 593°C

these extrusions still control nucleation but, depending on the frequency, oxidation of the extrusion occurs, causing a localized grooving and intensifying strain concentration.

Although no systematic study of the effect of frequency of cycling on high temperature nucleation has been made, decreasing frequency enhances the role of oxidation in A286 and cast U500 . It would be anticipated that, at very high frequencies and short exposures nucleation processes would revert to their low temperature form.

Experiments performed in high vacuum (10^{-8} torr) at high temperature indicate that the nucleation processes for the above materials also revert to their low temperature form. For frequencies of 0.1 cpm and greater there was no evidence of intergranular crack nucleation for any of the metals studied. Rather slip band extrusion was commonly observed for A286 and In 718 at high temperature. For the very ductile metals, grown-boundary notching arising from excessive surface roughening was found. This mode of nucleation is common to this class of metals at room temperature and high strain as shown by Laird.

With respect to crack propagation the pronounced degradation in fatigue life found to occur in high temperature fatigue is largely associated with the changing mode of cracking from transgranular to intergranular, particularly for decreasing frequencies, or under conditions of long hold times. In our studies involving frequencies as low as 0.1 cpm, for all the materials studied, it was observed that crack propagation was mostly intergranular in air, (invariably so at low frequencies) while in high vacuum it was invariably transgranular. Since lower frequency low-cycle fatigue tests are very time-consuming, high strain crack propagation tests were conducted by Solomon and the author on A286 at 593°C in air and vacuum. These results showed that at frequencies less than 0.1 cpm the crack propagation mode was intergranular even in high vacuum, although the crack propagation rate was estimated to be about two orders of magnitude less than the corresponding test conducted in air.

From these several sets of experiments involving nucleation and crack growth, it is concluded that in air, three distinct regimes exist. Above frequencies of the order of 10^3 cpm, fatigue failure at high temperature is purely cycle dependent, and the time dependent aspects of nucleation and growth including creep and environment are completely supressed. Supporting evidence for this comes from experiments at ultrasonic frequencies by Tien. At frequencies typical for mechanical testing, failure is a frequency and time dependent process, the time dependency arising from environmental factors. It is in this regime that the time dependent effects can be completely suppressed by an environment of high vacuum. At still lower frequencies in air, fatigue failure is

largely time dependent and frequency independent. Here the time dependency is very strong and is the result of a combination of environmental and creep effects. In vacuum in this regime time dependency is a result of creep effects only.

It is commonly assumed that high temperature fatigue life can be predicted by the linear interaction of creep and fatigue, that is, by the linear addition of a time dependent and a frequency dependent process. The present work shows rather that two separate time dependent processes must be considered in addition to frequency effects. Of great interest in any specific metal is the identification of the specific frequencies associated with these regimes. Work is underway to identify these regimes and there is some indication that, in many metals, environment and fatigue alone interact at very low frequencies.