MODELING OF MIXED-MODE CRACK GROWTH BEHAVIOR IN LB-PBF Ti-6Al-4V USING A CRITICAL PLANE FRAMEWORK

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Abstract
Many service loading conditions are multiaxial, and small cracks have been shown in many situations to grow in mode II or mixed-mode due to the orientation of defects and microstructural effects, particularly in additively manufactured metals. This paper uses fracture mechanics with a critical plane framework to predict crack growth rates using only mode I constants from the literature.

1. Introduction

Fatigue performance of additive manufactured (AM) metals is significantly affected by intrinsic defects to AM processes such as lack of fusion defects and gas porosities at the current state of the technology. Such defects often have complex morphologies and are oriented between the layers. A fracture mechanics-based fatigue analysis approach can consider the critical defect characteristics such as size, location, and shape, loading information, and crack growth properties as dictated by the microstructure. However, nearly all the existing studies in the literature only consider tensile dominated failure and mode-I crack growth under uniaxial loading. Hartman-Schijve (HS) equation has been shown to provide reasonable predictions of the mode I growth rates for a range of AM and wrought metals [1], [2]. This equation is shown below, where D and p are material constants, ΔK_{thr} is the cyclic threshold SIF, and A is the cyclic fracture toughness:

$$\frac{da}{dN} = D\left[\frac{\Delta K - \Delta K_{thr}}{\sqrt{1-\frac{K_{max}}{A}}}\right]^p = D\left[\frac{\Delta K - \Delta K_{thr}}{\sqrt{1-\frac{\Delta K}{(1-R)A}}}\right]^p \tag{1}$$

For multiaxial or mixed-mode small crack growth, it is necessary to employ a model which takes mode mixity into account. A critical plane-based Stress Intensity Factor (SIF) utilizing the Fatemi-Socie (FS) parameter given below has been shown to collapse mixed-mode small crack growth rates for a variety of loadings in wrought metals [3]:

$$\Delta K_{CPA} = 2G(FS)\sqrt{\pi a} = 2G\left(\frac{\Delta\gamma}{2}\left(1 + k\frac{\sigma_{n,max}}{\sigma_{YS}}\right)\right)\sqrt{\pi a} \tag{2}$$

where G is the elastic modulus, a is the half-crack length, $\Delta\gamma$ is the shear strain range, $\sigma_{n,max}$ is the maximum normal stress experienced on a given plane, σ_{YS} is the yield strength, and k is determined by fitting mode II crack growth rates to mode I crack growth rates on a da/dN-ΔK_{CPA} plot. A recent modification to the FS parameter was proposed which better accounts for axial mean stress and has been shown to accurately predict lives for materials exhibiting both shear and tensile failure modes [4] shown below:

$$FS_{modified} = \frac{\Delta\gamma}{2}\left(1 + k\frac{\sigma_{n,max}}{G\Delta\gamma}\right) \tag{3}$$

This paper shows that a critical plane-based SIF using the modified form of the FS parameter can collapse mixed-mode small crack growth rates for a variety of loadings. Then, after conversion of mode I HS equation constants from literature sources to their equivalent critical plane-based values, the HS equation can be used to accurately predict mixed-mode small crack growth rates without determination of additional constant values.

2. Results

Mode I constants for use with the HS equation were found in two different sources. Jones et. al found that for Ti-6Al-4V, D and p could be held constant at 2.79×10^{-10} and 2.12, respectively [2]. Sanaei and Fatemi determined that for LB-PBF Ti-6Al-4V in the machined annealed condition, ΔK_{thr} and A could be taken as 2.65 MPa√m and 53 MPa√m, respectively. The HS equation using these constants can accurately predict mode I small crack growth plotted as a function of the mode I SIF, as shown in Figure 1(a).

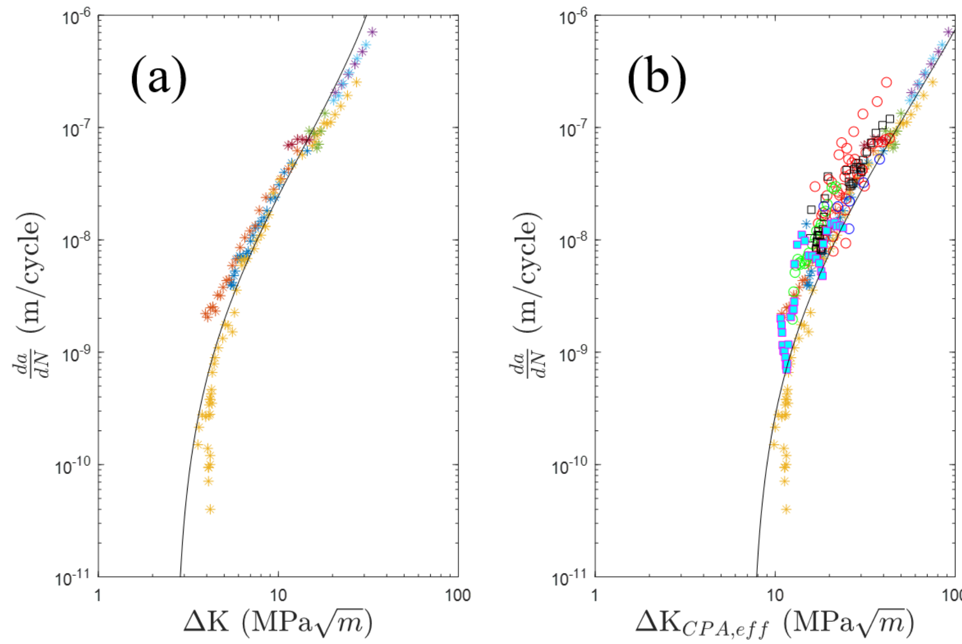

Fig. 1 – (a) Mode I crack growth rate data with HS prediction line, and (b) Critical-plane based mixed-mode crack growth data with critical plane-based HS prediction line.

These constants were then converted to their equivalent critical plane-based values, and the HS prediction line was plotted. Raw crack growth data from uniaxial (∗), pure torsion (○), and torsion with static axial compression (□) tests were then corrected for roughness-induced closure using the model proposed in [5] and plotted as a function of their critical plane-based SIF, shown in Figure 1(b).

3. Conclusions

Mixed-mode small crack growth rates in LB-PBF Ti-6Al-4V can be reasonably modeled using a critical plane-based framework using the HS equation with converted mode I constants from the literature.

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