FACTORS GOVERNING THE FATIGUE PERFORMANCE OF AM TI-6AL-4V COMPONENTS

Derek Warner*, Peipei Li, and Terrence Moran

Cornell Fracture Group, School of Civil and Environmental Engineering, Cornell University, Ithaca NY, USA
** Presenting Author email: derek.warner@cornell.edu*

Abstract
Before an additively manufactured component can be safely used in a load bearing application, its mechanical performance must be qualified. Traditional qualification approaches, involving the fabrication and testing of many identical components, negate one of the greatest benefits of additive manufacturing, i.e. the ability to quickly and cheaply fabricate one-off components. Thus, qualification methods that rely less on mechanical testing and more on predictive modeling are of value. This is most true for high cycle fatigue performance, where mechanical testing requires significant resources and produces stochastic results.

High cycle fatigue failure is difficult to predict because it can depend nonlinearly on many parameters, e.g. part geometry, residual stresses, surface characteristics, material defect characteristics, grain and dislocation structures, mechanical and environmental loading characteristics and their history. This has motivated a succession of fatigue models with ever increasing mechanistic fidelity, with some now diving down to the atomic scale. This raises the question of: what level of mechanistic detail is required to sufficiently predict the performance of AM Ti-6Al-4V components? In this talk, I will give my perspective on this question, building from a decade of AM Ti-6Al-4V fatigue modeling and experimentation across scales.

1. Introduction
Considering the challenges and resources required for component fatigue testing, material coupon testing is often relied upon as a surrogate probe of fatigue performance. However, this substitution is not without loss, as connecting component performance with coupon test data can be a substantial challenge for a multitude of reasons. First, the cyclic stress and strain histories experienced by components are rarely known, requiring interpolation and/or extrapolation from reference points and/or mechanical modeling. Second, the stress and strain histories in a component are often multiaxial and inhomogeneous in time and space, requiring additional interpolation, extrapolation, and assumption to connect component performance with coupon data. Third, controlling features such as residual stresses, surface roughness, microscopic defects, and crystalline microstructure, are not necessarily the same in test coupons and components. As such, the extent to which additively manufactured (AM) component performance can be predicted from coupon data is not obvious, particularly in the case of fatigue, where performance can be highly sensitive to variations in the above-mentioned features. Overall, the transferability of coupon fatigue data to components has been a long-standing challenge, even within traditional manufacturing.

2. Results
Here, we start by discussing our ability to predict defects (fatigue crack initiation sites) at the part scale from knowledge of the power and scanning schedule. The approach is simple, yet effective, involving a linear model and superposition. Predictive capabilities are examined using a build of powder bed fusion (PBF) of Ti64 fatigue coupons. The coupons had a similar geometry that varied in the surface area, but not volume. We show that the difference in defect populations between these two sets of coupons is not a function of their differing thermal history, but instead perhaps due to differing position on the build plate. Considering the symmetries of the arrangement, a difference in defect densities is hypothesized to be due to the powder spreading procedure.

Next, we show that the importance of the powder spreading process is not always a dominating feature. Examining two builds on two different machine architectures, we infer from symmetry of the build arrangement and X-ray CT analysis that gas flow in the build chamber can have a significant effect on the variability of defect population across the build plate. This finding is further examined with CFD modeling, which is found to be consistent with the laboratory observations.

The second part of the presented work examines the connection between defects and fatigue performance at both the coupon and component scale. Utilizing probabilistic weakest link modeling and laboratory test data, we show that the connection between the two scales depends on a multitude of factors. The connection between coupon and component fatigue performance depends not only on the difference in volume and surface area, but also on the density of crack initiation sites, gradient of the stress state, and the fatigue life distribution itself. The latter implies a dependence on post processing procedures.

The final part of the presentation focuses on the aspect of post processing for the case of Ti64, whereby HIP treatment followed by surface machining is a typical procedure for fatigue critical parts. In this context, examination of the literature data as a whole reveals an important message, i.e. the most commonly studied average attributes are insufficient to explain fatigue performance. For example, defect density and average microstructure size are incapable of describing fatigue performance (to within one order of magnitude) in this material. This emphasizes the potential importance of other microstructural features, such as sporadically occurring clusters of features or large phases, which are not necessarily apparent in standard microstructural analyses.

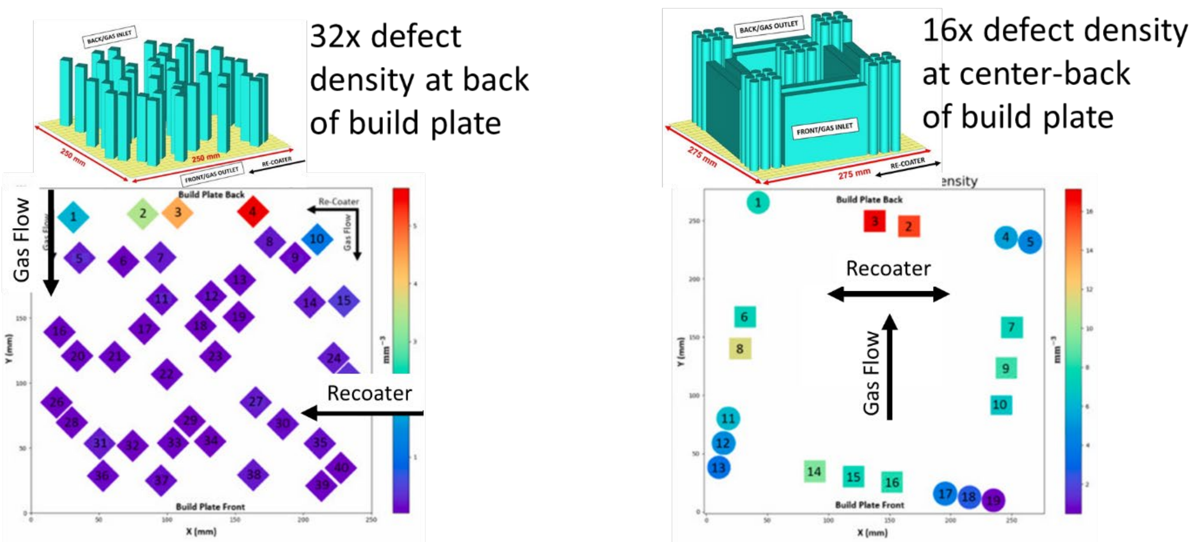

Figure 1: The above figure gives one example of a cause for fatigue performance at the component scale to differ from fatigue performance at the coupon scale. The upper images show the layout of two PBF Ti64 builds. The bottom images represent a top-down view of the build plate where specimens are colored to show the defect densities measured with X-ray CT. The images clearly show a heterogeneity in defect population across the build plate. The connection of this knowledge to fatigue performance of coupons and ultimately to components is dependent on multiple factors that will be discussed in the presentation.

Acknowledgements
This research was partially supported by the National Science Foundation Graduate Research Fellowship under Grant No. DGE-1650441 and the Office of Naval Research under contract #N0000142012484. Any opinion, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the NSF or ONR. Contributions by Nam Phan, Nima Shamsaei, Patricio Carrion, Seungjong Lee, and Johnathan Pegues, are gratefully acknowledged.