CRACK-DEFECT INTERACTIONS IN ADDITIVELY MANUFACTURED Ti-6AL-4V: DUAL SCALE POROSITY MODELLING USING WARP3D

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Abstract
Localized microstructural defects that often lead to unpredictable fracture have limited the wider adoption of additively manufactured (AM) alloys in critical components. In addition to the background porosity responsible for ductile failure in conventional alloys, defects resulting from the AM process can include large pre-existing voids (~30 μm) resulting in a dual-scale porosity failure process in AM alloys. In the present work, we undertook a numerical approach to explore the dual-scale void and crack interaction processes in both two and three dimensions in AM Direct Metal Laser Melted (DMLM) Ti-6Al-4V. A small-scale yielding modified boundary layer model with monotonically increasing applied displacement was used. The Gurson ductile damage model was implemented to model typical background pores, while the larger AM defects were explicitly represented in a finite element mesh. Fracture resistance curves were numerically generated for random instantiations of AM void distributions with increasing levels of AM defects. Individual outliers of fracture resistance, both over and under perfroming, were analyzed in more detail. It was seen that AM defects may activate a larger fracture process zone ahead of the crack tip, promote crack tortuosity, and on occassion lead to increased local material toughness over the conventional alloy.

1. Introduction
The emergence of additive manufacturing (AM) has provided industry the freedom to pursue increasingly complex designs perhaps untenable or unprofitable through traditional manufacturing methods. The freeform fabrication possible through additive manufacturing provides engineers freedom to design for weight reduction, minimized material waste, reduction of the number of parts in assemblies, shorter lead times and improved supply chains for spare parts. For aerospace applications a common choice for AM build material is Ti-6Al-4V due to its high strength, low density, high fracture toughness, and exceptional corrosion resistance. Despite the benefits of AM, these processes are vulnerable to microstructural irregularities such as the formation of porosity (void defects), increased surface roughness, oxygen enrichment, and residual stresses that result in variability in mechanical, especially failure, properties. Although such uncertain failure properties of AM builds currently hinder their wider application, their process-structure-property linkage is an active area of research aiming to better understand the relationships between additive manufacturing process parameters, microstructures, and their final mechanical properties. Here we explore both the 2D and 3D modeling of AM defect-crack interactions to elucidate the relationship between dual-scale porosity and fracture response of AM Ti-6Al-4V.

2. Results
To accomplish our goal, a numerical approach in both 2D and 3D was implemented based on a small-scale yielding, modified boundary layer model with imposed monotonic K_I remote displacement loading. The intrinsic background porosity in the fracture process zone (FPZ) was modeled with multiple rows of void-containing cells governed by a modified Gurson yield function criterion, while the larger AM void defects were explicitly modeled as discrete voids randomly instantiated throughout the FPZ finite element mesh at various volume fractions (Fig. 1a-c).

Computations of the fracture resistance curves in relation to snapshots of the cross-sectional planes of void growth and material damage within the FPZ provide detailed insights into the common damage dissipation mechanisms associated with crack-defect interactions and their effects on the variability of the fracture response in AM Ti-6Al-4V. Figure 1d shows the crack growth resistance curves for 10 randomly generated distributions of AM voids within the 3D FPZ for three AM void fractions of $V_f = 0.001$, 0.005, and 0.01. Our 3D results show that the presence of AM voids can improve or lower the steady-state toughness, as shown by AM #3D-A1 and AM #3D-A2, respectively, while an increase in V_f generally increases the scatter in the fracture resistance.

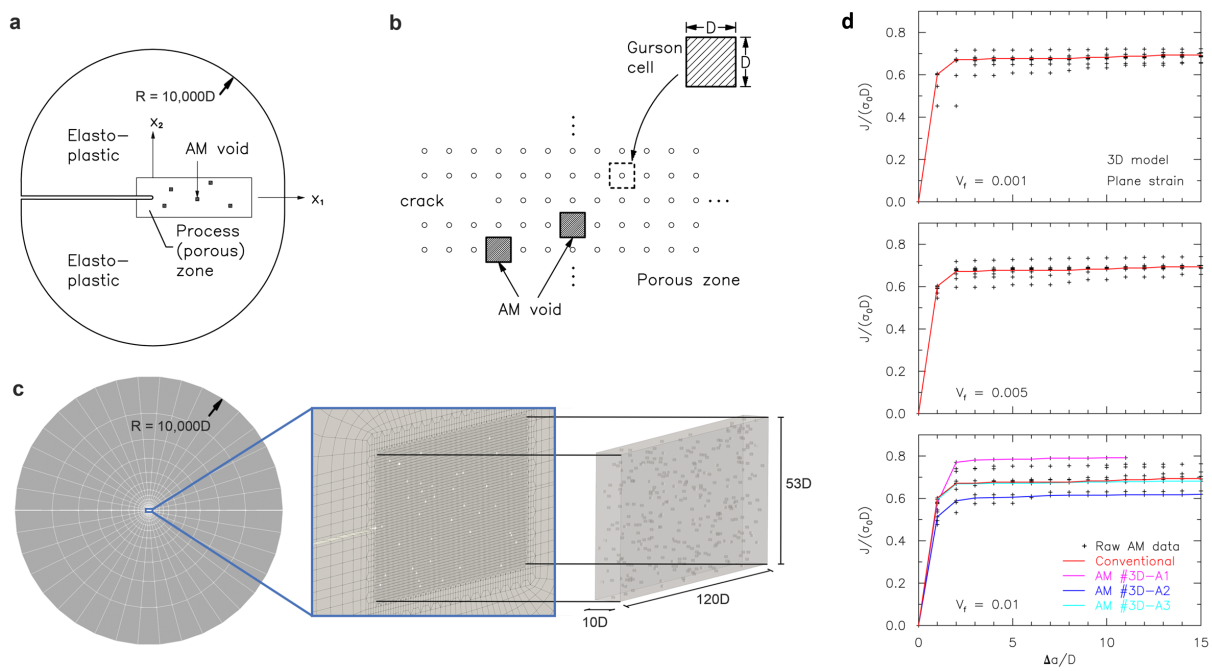

Fig.1 – (a) Boundary layer model with crack subjected to remote mode I loading. (b) Close-up view of the dual-porosity fracture process zone comprising of multiple rows of Gurson cell elements and randomly distributed discrete AM voids. (c) Finite element mesh with close up view of the 3D process zone. (d) Crack growth resistance curves for 3D plane strain models of AM Ti-6Al-4V with different AM void porosities V_f.

3. Conclusions

Results show that AM defects can contribute to an increased apparent toughness of the AM metal over its conventional counterpart by activating isolated and/or clustered damage zones surrounding the crack, which shields and blunts the crack-tip and promotes crack tortuosity. However, the presence of planar clusters of AM defects can also accelerate crack growth and cause premature failure by forming preferential crack paths.

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