

## High cycle fatigue and fatigue crack growth rate in additive manufactured titanium alloys

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The Wire+Arc Additive Manufacture (WAAM) can produce large area metal parts in terms of metre-scale, with higher deposition rate compared to the powder bed fusion AM processes. The process also offers lead time reduction and much lower buy-to-fly ratio compared to forgings. Research is much needed in the fatigue and fracture properties for qualification of additive manufactured aircraft components.

WAAM Ti-6Al-4V alloy has been tested and modelled, focusing on two key areas of structural integrity: (1) high cycle fatigue and the effect of defects; (2) fatigue crack growth rates and effects of heterogeneous microstructure and process induced residual stresses. The key objectives are: (a) to develop predictive methods for defect tolerant fatigue assessment taking account of the defect size, location, distribution and current NDT capabilities; (b) to study fatigue crack propagation behaviour in two crack orientations with respect to the material build direction, to provide crack growth rate and fracture toughness properties for damage tolerance design considerations.

### (1) Effect of defects on high cycle fatigue performance

Interrupted fatigue-tomography experiments were performed on specimens with porosity defects embedded in the gauge section. Defects were embedded intentionally using contaminated wires. In practice, feedstock may get contaminated causing pores of considerable size in the material. Static strength was comparable to the reference group without porosity, but both ductility and fatigue strength were significantly reduced owing to the presence of defects. S-N data could not correlate the test results owing to different pore sizes and at different applied stresses (*Figure 1a*). Using the fracture mechanics and Murakami's equation for stress intensity factor of embedded pores [1], good correlation was found between the fatigue life and stress intensity factor of the crack initiating defects (*Figure 1b*). Critical pore diameter was found to be between 50-100 micrometers. Method from El-Haddad et al. [2] is used to establish the Kitagawa-Takahashi diagram for criticality analysis of porosity defects.

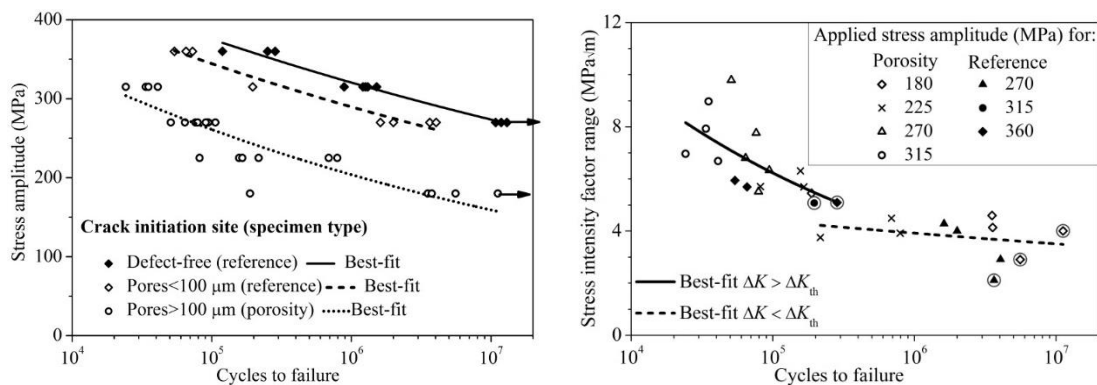


Figure 1. (a) S-N data of control and porosity specimens, divided by porosity size and location; (b) stress intensity factor range vs. fatigue life, showing good correlation with critical pore size

### (2) Fatigue crack growth rate

Compact tension specimens made by three different WAAM build strategies with two crack orientations, i.e. crack either across or parallel to the deposited layers. Residual stress in the large build wall and small laboratory coupons were determined by the neutro diffraction and contour methods. Microstructure and texture characteristics and their influence on the crack growth rates and path were investigated. A predictive model based on linear elastic fracture mechanics has been developed.

Key findings are: (a) residual stress in small C(T) specimen is very low (below 100 MPa), *Figure 2a*, despite being extracted from a much larger build wall that contained much higher residual stress (maximum tensile residual stress is around 600-800 MPa depending on the build size and location to the substrate palte). Fatigue crack growth rate measured by small samples is mainly affected by the microstructure morphologies (*Figure 2b*); residual stress effect is negligible. (b) Life prediction method for large parts: residual stress must be considered and can be accounted for by the effective *R* ratio term; fatigue crack

growth rate (FCGR) should be considered as material's intrinsic property, which is measured by small samples with negligible residual stress. (c) compared to traditional manufacturing methods, fatigue crack growth rates in as-built WAAM Ti-6Al-4V is lower than the mill annealed, similar to the beta annealed, and slightly greater than cast conditions, making the WAAM a viable additive manufacture process to produce aerospace titanium alloys for damage tolerant design.

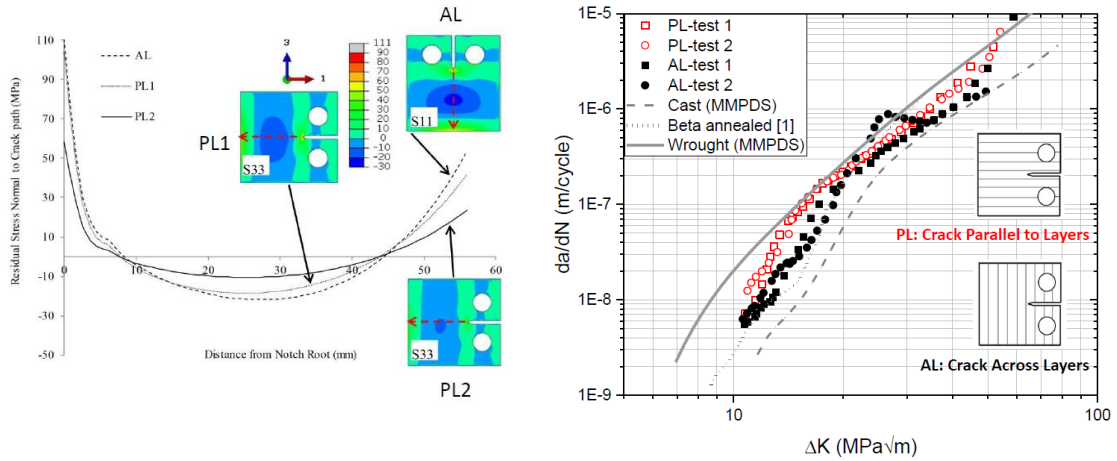


Figure 2. (a) residual stresses in compact tension specimens (maximum stress is about 100 MPa at notch root; AL: crack across additive layers; PL: crack parallel to layers); (b) fatigue crack growth rates in single bead built; difference in crack growth rate at lower stress intensity factor range is owing to the difference in microstructure morphology.

### References

- [1] Murakami Y. Metal fatigue: Effects of Small Defects and Nonmetallic Inclusions. 1st ed. Chapter 4. Elsevier; 2002
- [2] El Haddad MH, Topper TH, Smith KN. Prediction of non-propagating cracks. Eng Fract Mech 1979; 11: 573–84.

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