Fatigue Performance and Cyclic Deformation Behaviour of Titanium Ti-6Al-4V Additively Manufactured by w-DED

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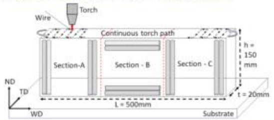
Background

New Wire Additive Manufacturing (NEWAM) is a research programme funded by the UK EPSRC Research Council. This is a six year research programme (2018 to 2024) comprising UK universities (Cranfield, Coventry, Manchester and Strathclyde) and industrial partners. This NEWAM research programme is focused on the process, material and structural integrity of structures additively manufactured by wire based directed energy deposition w-DED, and particularly by the Wire + Arc Additive Manufacturing (WAAM) process.

Coventry University are leading NEWAM material performance and structural integrity research areas to investigate material behaviour for fatigue initiation, fatigue fracture and residual stress. Hottinger Bruel & Kjaer (HBK) are providing tensile and strain controlled fatigue tests, and characterisation services to support this material fatigue behaviour research.

Materials Manufacturing

Titanium alloy material was deposited on a substrate by wire-arc additive manufacturing (WAAM) using a plasma arc energy source in an inert argon atmosphere using 1.2 mm diameter high quality Ti-6Al-4V wire. The material was deposited using a continuous torch path in a parallel square oscillation pattern across the wall thickness direction (TD), and back-and-forth along the wall longitudinal direction (WD). Two walls were deposited.

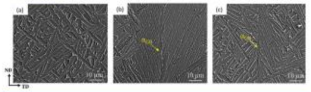


Microstructure Heterogeneity (SEM)

WAAM layer deposition gives rise to macroscopic heterogeneity of the microstructure in the form of columnar primary β grains aligning in parallel to the build direction. This is a result of the complex cyclic thermal history associated with solidification of sequentially deposited layers, leading to a systematic variation in the α+β transformation microstructure. WAAM generally produces wider columnar primary β grains compared to other AM processes.

SEM images in ND-TD plane show microstructure heterogeneity.

- Typical transformation bulk microstructure (a), shows classical lamellar α+β microstructures, with both Widmanstätten multi-variant (basketweave) and single variant colony.
- Transformation microstructure along a β grain boundary shows (b) continuous grain boundary α colonies, and (c) discontinuous α colonies.

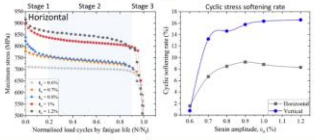


Cyclic Deformation Behaviour

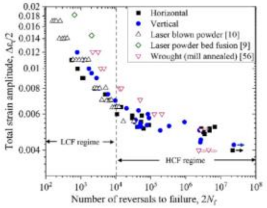
During strain controlled fatigue tests, three stages are observed, in the progression of maximum cyclic stress versus normalized load cycles, N/N_f, the ratio of cycle number (N) to separation failure (N_f):

- Stage 1: rapid cyclic softening, steep decrease in applied stress
- Stage 2: progressive cyclic softening, gradual decrease in stress
- Stage 3: rapid fatigue crack growth and failure

At higher strain amplitudes (>0.7% strain), where plasticity dominates, vertical orientation samples have ~2x higher cyclic stress softening rate due to their higher ductility.



Fatigue Test Results Comparison



Sample Preparation

Samples were prepared for:

- scanning electron microscope (SEM) microstructure analysis
- electron back scatter diffraction (EBSD) texture analysis
- micro X-ray computed tomography (micro-XCT) analysis
- tensile test to ASTM E8 (gauge 5.75mm Ø, 31.0mm length)
- fatigue test to ASTM E606 (gauge 5.0mm Ø, 10.0mm length) and polished to Ra≤0.2

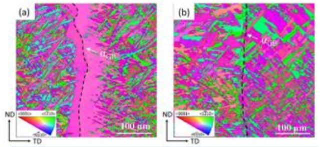
Tensile and fatigue samples prepared in horizontal and vertical orientations:

- **Horizontal orientation** parallel to the deposition plane.
  Loading axis parallel to the deposited layers.
  Loading axis perpendicular across columnar β grains and α_{GB}.
- **Vertical orientation** normal to the deposition plane.
  Loading axis perpendicular to the deposited layers.
  Loading axis parallel along the columnar β grains and α_{GB}.

Microstructure Heterogeneity (EBSD)

EBSD maps in ND-TD plane, along the columnar β grains show:

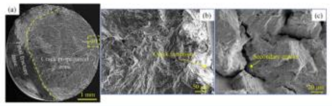
- (a) α phase with continuous α_{GB} colonies (the thick 'pink' region), indicating a strong crystallographic texture with similar orientation either side of the grain boundary.
- (b) α phase without continuous α_{GB} colonies (aka. multi-variant α_{GB} colonies) indicating a random or weak crystallographic texture. β grain boundaries without continuous α_{GB} colonies can be seen to have nucleated numerous α orientations, none of which cross the primary columnar β grain boundaries into the neighbouring grains.



Fatigue Testing

Strain controlled fatigue tests conducted to ASTM E606 at room temperature with fully reversed (R = -1) constant amplitude sinusoidal waveforms for cyclic strain amplitude ε_a between 0.4% and 1.2% strain (4000 and 12000 microstrain "µε"). Cyclic strain amplitudes were chosen to achieve equally distributed fatigue lives through the cycle range to capture the whole fatigue curve.

All of the fractured samples were analysed using SEM to identify the fatigue crack initiation sites; 96% had crack initiation from the α phase, of which 66% were at the surface and 30% near the surface. No defects were found in the fracture faces of any of the samples. Crack initiation sites in the fracture faces were either from α or α/β lamellar interface.



Conclusions

- Large single variant α colonies with strong crystallographic texture along the primary columnar β grain boundaries.
- Tensile and yield strengths are 5% higher normal to the material build direction (horizontal samples) owing to the columnar primary β grains with strong crystallographic texture along the α_{GB}.
- Elongation is 50% higher in the material build direction (vertical samples) owing to the combined effect of the bulk microstructure (α lath size) and α_{GB} parallel to the loading axis increasing ductility.
- This increased ductility causes ~2x higher cyclic stress softening rate in the material build direction (vertical samples) at higher cyclic strain amplitudes (>0.7% strain) where plasticity dominates.
- SEM fractography shows no porosity defects in the material as per the micro-XCT result and reveals fatigue crack initiation sources being either the α laths or α/β interface due to cyclic slip.
- In LCF regime, the vertical orientation average fatigue life is ~2.5x longer than horizontal due to the higher ductility in the former.
- In HCF regime, fatigue life performance is almost isotropic.

Tensile Properties

Tensile properties are compared with conventionally manufactured Ti-6Al-4V (wrought and cast), and minimum tensile properties recommended for PBF AM Ti-6Al-4V (ASTM F2924):

- WAAM tensile strengths are comparable with their wrought counterpart and higher than cast. In horizontal orientation they exceed PBF minimum, whilst vertical are equal to or just below.
- WAAM horizontal orientation have higher strengths than vertical.
- WAAM vertical orientation have 50% higher elongation than all others. This anisotropy in ductility is observed in AM built Ti-6Al-4V and is linked to the epitaxially grown primary β grains.

Table 1: Tensile properties of Ti-6Al-4V obtained from the engineering stress–strain data.

Material property	WAAM Horizontal	WAAM Vertical	Wrought (AMS 4928)	Cast (AMS 4992)	ASTM F2924
Yield strength ($YS_{0.2}$), MPa	842 ± 14	800 ± 23	861	765	825
Ultimate tensile strength (UTS), MPa	951 ± 12	898 ± 24	930	861	895
Elongation (%)	11 ± 2	17 ± 5	10 *	5	10

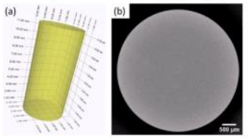
** AMS 4928 Elongation = 10% from MMPDS-11 [9], is stated as 25% in [3] from MMPDS-04.*

Micro-XCT Analysis

Micro-XCT analysis results show no porosity in the gauge length of a fatigue test sample:

- (a) by 3D rendering of a helix scan with 60% transparency
- (b) by cone beam orthogonal slice.

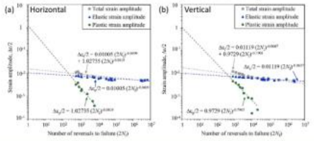
The sample was very homogeneous showing no sign of defects or porosity down to the ~ 7.4 µm resolution limit. This homogeneity is illustrated by the absence of any features in the 3D rendering of the helix scan and similar absence of any features in the 'grey' cone beam orthogonal slice. (One slice from a video sequence of continuous orthogonal slices through the gauge length.)



Strain-Life Fatigue Properties

Fatigue test results for horizontal and vertical orientation samples are compared (*top centre plot*) with mill annealed wrought hot rolled bar, laser beam PBF and laser blown powder DED. Failure is defined as the number of cycles to 20% load drop from the maximum tensile stress magnitude of the half-life hysteresis loop.

Strain-life fatigue properties are derived by separating the total strain amplitude of the half-life hysteresis loops into their elastic strain (Basquin equation) and plastic strain (Coffin-Manson equation) constituents, and their subsequent curve fitting.



References

This ICAF paper is a summary of the authors' journal paper (below), see these papers for references.
Syed, A. K., Plaskitt, R., Hill, M., Pinter, Z., Ding, J., Zboray, R., Williams, S., Zhang, X. (2023),
Strain controlled fatigue behaviour of a wire + arc additive manufactured Ti-6Al-4V,
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