Structural Integrity Performance of Additively Manufactured Titanium Alloys

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- Dr J Zhang (Beihang University, China)
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**Sponsors**
- Airbus
- WAAMMat programme
- LRF/NSIRC
Outline

- **Introduction**
  Additive manufacturing of titanium alloys
  Durability & damage tolerance requirements
  AM titanium projects at Coventry University

- **Fatigue & Fracture Responses**
  Challenges to AM structural integrity
  High cycle fatigue
  Fracture toughness
  Fatigue crack growth behaviour

- **Summary**
Metal AM Processes

- LASER
- SCANNER
- CHAMBER
- ROLLER / RAKE
- COMPONENT
- POWDER BED
- POWDER DELIVERY SYSTEM

- LASER
- Beam Guidance System
- Carrier Gas
- Lens
- DEPOSITION HEAD
- POWDER SUPPLY
- AM DEPOSIT

- EB Gun
- Electron Beam
- Wire Feed
- Deposition Layers
- Substrate
Aerospace Applications

Fig. 1  (a) Typical titanium aerospace bracket made by machining from wrought material and (b) optimized design based on the loading conditions leveraging the build capabilities of additive manufacturing. Drawings are not to scale.

Aerospace Applications

WAAM can build much larger parts and at faster deposition rate.

Ti-6Al-4V wing spar built for BAE Systems, top view (courtesy BAE Systems; PAWWAAM process)

Ti-6Al-4V external landing gear assembly (PAWWAAM process)

Durability & Damage Tolerance Requirements for Airframe

- Inspection
- Fatigue crack growth life
- Residual strength

“Three-legged stool” concept:
Need all three or safety falls over!

(Adapted from Grandt AF Jr.\(^1\), Eastin R & Swift S\(^2\))

1. Grandt, Alten F Jr, Damage tolerant design and nondestructive evaluation, John Wiley and Sons, New Jersey, USA, 2004
Core themes: Processes, Materials & Products

Research Groups
- Functional materials, Future manufacturing, Metrology
- Laser Engineering, Materials mechanics & measurement
- Structural Integrity, Welding & joining

Structural Integrity Key Research Themes
- Additive manufactured metallics (structural integrity focus)
- Advanced modelling & experimentation methods
- Non-destructive evaluation techniques
- Residual stress engineering (e.g. laser shock peening)
AM Ti-6Al-4V projects at Coventry University

Wire + Arc Additive Manufacture (WAAM)
- Fracture toughness (build strategy)
- Fatigue crack growth rate
  (effect of microstructure and residual stress)

Powder bed fusion (SLM, EBM)
- Heat-treatment/HIPing
- Defect tolerance

Powder feed (powder blown, cold spray)
Additive repairs, structural modifications
Challenges: bi-material system,
defects at material interface

To exploit:
Direction dependent properties for design innovation and safety

Five PhD students working on AM projects
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Challenge 1: Grain structure & texture

Microstructure: three main types, inhomogeneous, graded, with strong crystallographic texture
→ Anisotropic properties

Macro-graphic images of AM Ti-6Al-4V
(a) laser powder blown single bead
(b) laser powder blown three bead wide
(c) electron beam wire three bead wide
Challenge 2: Residual Stresses

WAAM Ti-6Al-4V
Produced by Cranfield University

1D stress plot
(average in mid thickness)

Distance from base plate (mm)

Substrate

WAAM build “Wall”

Cut & CMM measurement

Displacement profile
Input into FE model

2D stress map
(FEA)
Challenge 3: Defects (porosity, roughness)

Ti-6Al-4V

Crack initiation site

Optical micrographs (a)-(e) of the vertical planes of the 0.5\(P_0\), 0.7\(P_0\), \(P_0\), 1.3\(P_0\) and 1.5\(P_0\) samples

SLM SS 316L: Effect of laser power \(P_0\)
Challenge 4: Property dependency on Process methods and parameters

Properties depend on AM build methods, build strategies, process parameters, and post-AM treatments, such as:

- Heat treatment: for residual stress relief (necessary for SLM)
- Hot Isostatic Pressure (HIP): to close porosities
- Laser shock peening: to introduce compressive residual stress

Large variations in material performance, especially under fatigue loads

No “handbook” of AM metal mechanical properties
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- Summary
High Cycle Fatigue: SLM Ti-6Al-4V
Fatigue Strength of SLM Ti-6Al-4V

- Greater than reference cast alloys
- As-built SLM is significantly lower than wrought materials
- Sensitive to defects and surface polishing
- Heat treatment and HIP’ing both increase fatigue life
- Porosity is the primary cause for premature failure in un-HIP’ed conditions
- Variation with build orientation also observed
Fracture Toughness: AM vs. Wrought Ti-6-4

Fracture Toughness: Summary

- Fracture toughness is comparable to or greater than reference wrought alloy (based on EBM, WAAM Ti-6-4)
- SLM Ti-6-4 fracture toughness is 20-25% lower than wrought, because of reduced ductility
- Direction dependent: toughness is slightly higher (10%) when crack is across the additive layers than crack along the layers. Reason: $\alpha$ grain size varies within a layer band, causing more resistance to crack growth (WAAM, LENS Ti-6-4)
- Lower oxygen Grade23 Ti-6-4 has greater toughness (by 32%); but much lower tensile strength, comparing to commonly used Grade5 Ti-6-4 (based on WAAM study)
FCGR: WAAM Ti-6Al-4V

Fatigue crack growth rate is between two ref. alloys of conventional process isotropic when $\Delta K > 20$
direction dependent $\Delta K < 20$
slower for crack across layers owing to microstructure effect when crack is smaller (next slide)

Microstructure effect:
Size of $\alpha$ grains varies within a layer band, causing more resistance to crack growth.

Coarse $\alpha$ grains (top of a layer band)

Finer $\alpha$ grains (bottom of a band)
FCGR: SLM Ti-6Al-4V

FCGR: SLM Ti-6Al-4V

Tested at $R = 0.1$. Source: Riemer et al. Procedia Structural Integrity 2(2016) 1229-36
FCGR: Ti-6Al-4V via LENS or EBM process ("hot build", no need for HT)

$R = 0.1$, from Zhai et al. IJ Fatigue, 93(2016) 51-63

$R = 0.1$, from Edwards et al. J Manu Sci & Eng, 2014
Summary: Ti-6-4 fatigue crack growth rate

- Four AM processes are reviewed: EBM, LENS, SLM, WAAM
- Comparing to reference materials (wrought, upper band): AM Ti-6-4 has considerably slower crack growth rates (all four processes, but SLM Ti64 must be heat treated or HIP’ed)
- Microstructure effect causes direction dependent properties; FCGR is slower when crack propagates across the build layers comparing to crack growing along the layers (WAAM, EBM, LENS, SLM)
- Residual stress effect is small on small C(T) samples (WAAM, EBM, LENS, SLM)
- Defects have no significant effect on long crack growth rates (SLM, EBM, LENS; WAAM Ti-6-4 had no defects in test samples)
Conclusions

For additively manufactured Ti-6Al-4V (via EBM, LENS, WAAM, and SLM + heat treatment),

- **Fracture toughness** is comparable to or greater than wrought materials.
- **Fatigue crack growth rate** is slower than wrought alloys.
- **High Cycle Fatigue** strength is highly sensitive to defects.
- For **damage tolerant design** (based on fatigue crack growth life), current AM processes are viable manufacturing processes.
- For **durability design** (safe life principle), control of defects is a key challenge.
- Build speed is a challenge for AM to be adopted for larger parts.
Thank you!

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Life Prediction Methods (current)

Fatigue crack growth rate “law”

\[
\frac{da}{dN} = C(\Delta K, R_{eff})^n
\]

- \(\Delta K\): Applied load, geometry (FEA)
- \(R_{eff}\): Residual stress contribution (FEA)
- \(C, n\): Material property (obtained by coupon tests)

Microstructure effect reflected?
Micro-mechanical models (under development)

- Microstructural effect on crack growth rate (upper left)\textsuperscript{1}
- Microstructure models, e.g.
  - Crystal plasticity
  - Peri-dynamics (lower left)\textsuperscript{2}
- In-situ XCT, DIC, etc.
- Defects behaviour in fatigue


[2] S Silling, A Askari, Peridynamics models, SES 51st Annual Technical Meeting, Purdue University, 2014
### Overview: Additive Manufacture Projects (Aerospace)

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Fatigue & fracture properties

- Crack along layers
- Crack across layers

Exploit direction dependent properties (unique of AM)

Road map: Test/Modelling → Characterisation → Design innovation

AM build on convention part: effect of material mismatch, interface defects, and residual stress

Vertical stabilizer and fuselage attachment lugs

Aim: crack propagates across AM layers

Vertical stabilizer and fuselage attachment lugs

Lugs: build direction depends on load condition. Aim: crack propagates across AM layers

Repairing aero engine parts → hybrid material parts

Laser metal deposition

Damaged blisk (damaged site in red lines)

AM build on convention part: effect of material mismatch, interface defects, and residual stress

Substrate

Substrate
Problem
- AM material build on a substrate
- Scenario of structure repair (picture)

What to study?
- Crack orientation & path
- Residual stress effect
2. Residual stress engineering/control/mitigation

In-house robot-arm X-ray diffractometer (XRD)
Heavy users of neutron/XRD world-wide

Incremental hole drilling & Contour methods are complementary to the diffraction methods, as AM metals have inhomogeneous microstructure and potentially strong, varying crystallographic texture.