Thoughts on Fatigue Certification of Metal Additive Manufacturing for Aircraft Structures

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4th joint EASA-FAA Additive Manufacturing Workshop

*Order of Australia Medal

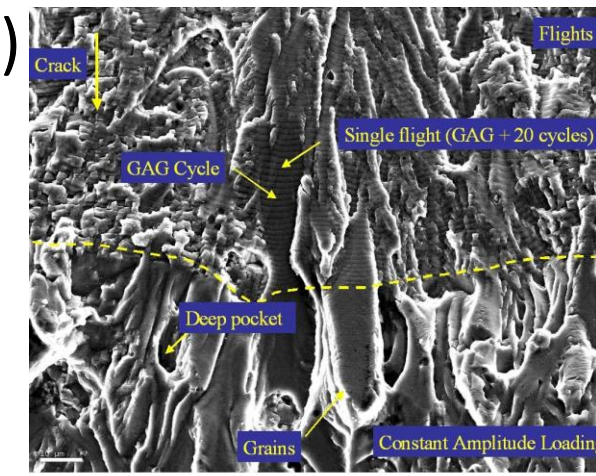
Outline

1. An Aussie AM (Supersonic Particle Deposition - SPD) example
2. General view of metal fatigue (weak link for AM)
3. Material/production near-surface discontinuities are the main source of scatter in life (all else being equal)
4. Examples of discontinuities from AM materials and conventional aircraft materials
5. Not all discontinuities are crack-like at first
6. Metrics to define discontinuities as cracks
7. Lincoln’s 5 for structural technology transition to new aircraft
8. Thoughts on fatigue certification (including the building block approach)
9. An equation that shows promise in predicting the life of AM parts
10. Wrap-up

About Molent AM

Caribou PNG 2009

- Aero Structures Consultant
- Aeronautical Engineer
- Principal Research Scientist
- Head, Aircraft Structural Integrity (retired) Aerospace Division Defence Science & Technology Group (DSTG)
- Aircraft Accident Investigation Committee - Airframe
- Experienced Accident Investigator
  - Assistance and Advice “Defence Aviation Safety Authority”



F111G Pulau Aur Malaysia 1999

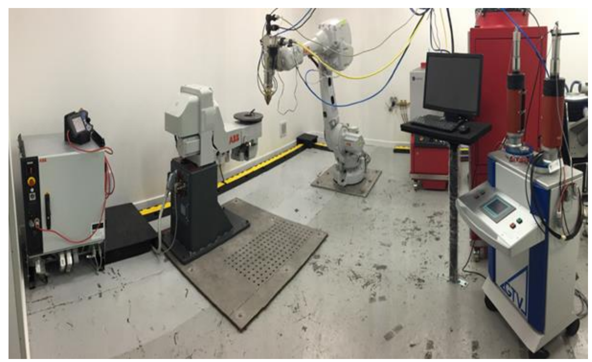
Acknowledgements

RUAG Australia AM Capability

SPD Fixed System

SPD Fixed System (with CB)

SPD Portable Unit (FPSPDU)

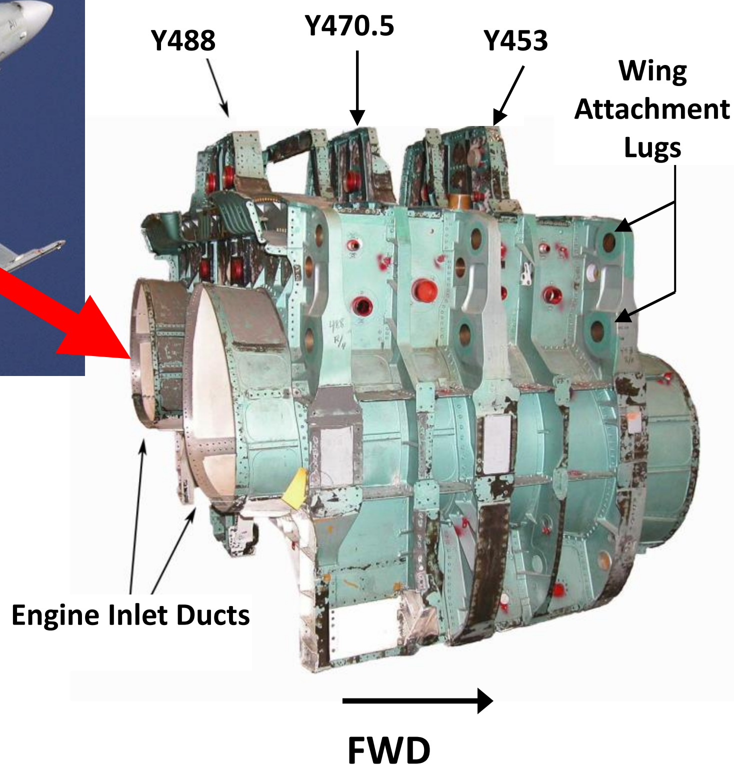


Laser Powder System

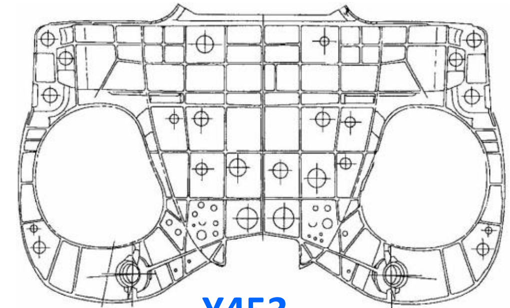
Laser Wire System

Together ahead. RUAG

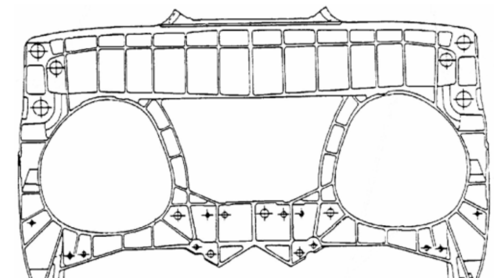
Anatomy of a Hornet Centre Barrel



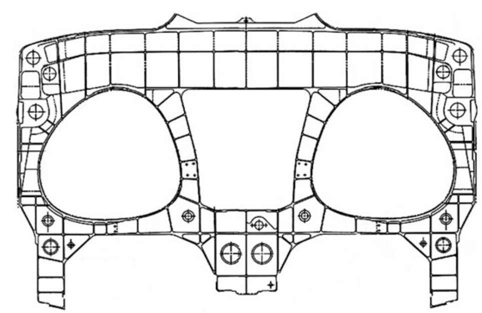
Material: 7050-T7451 Aluminium Alloy
Weight: ~ 500 kg (bare structure)



Y453



Y470.5

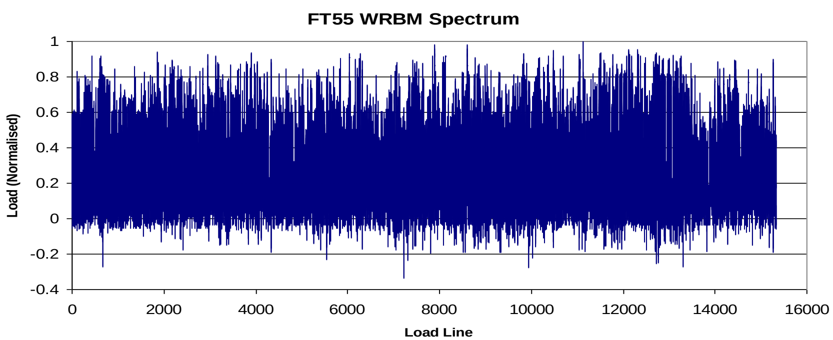


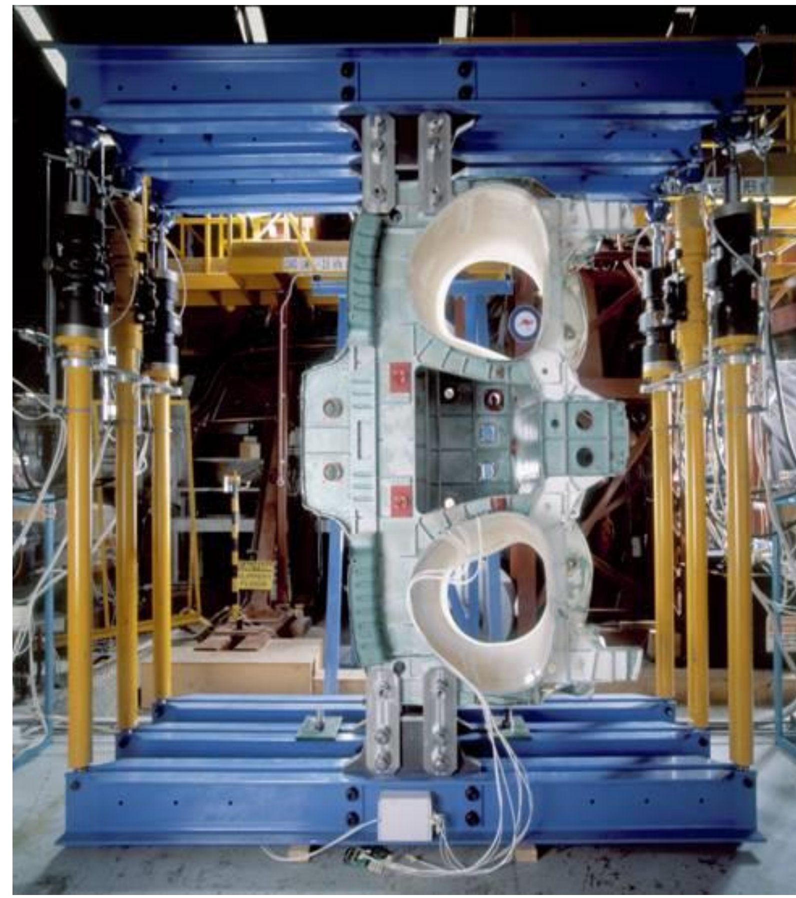
Y488

CB is fracture critical and loss of structural integrity in any of these members will cause the loss of the aircraft.

F/A-18 Centre Barrel Cycling (with AA7075 SPD repair/reinforcements) [1,2]

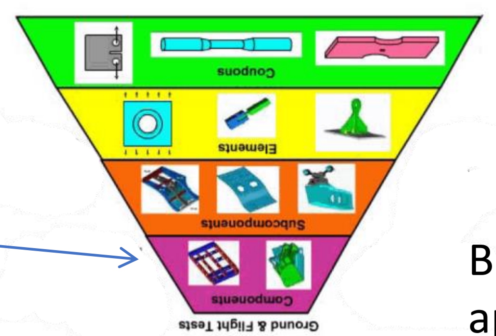
- 1 x FT55 block = 324.9 RAAF Hours (15,328 load lines)
- ~17 “real” hours to apply.
- Max load = 6464 in.kips = 730 kN.m ≈ 7.1g





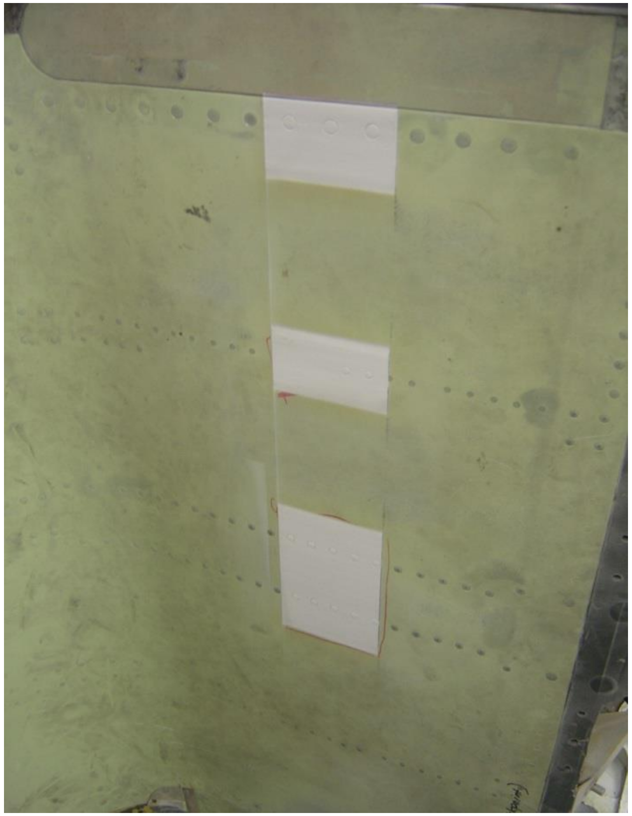
9 regions with SPD

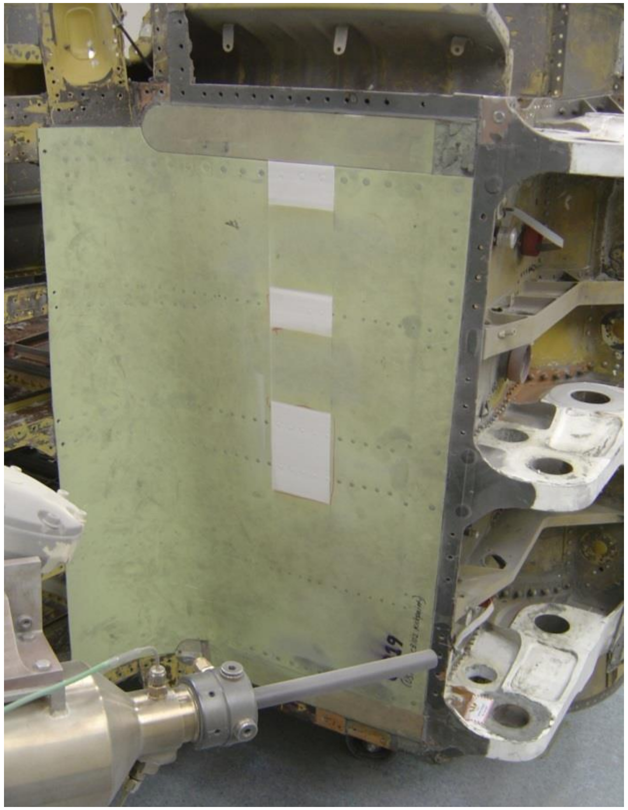
Flipped!



Building block certification approach - flipped

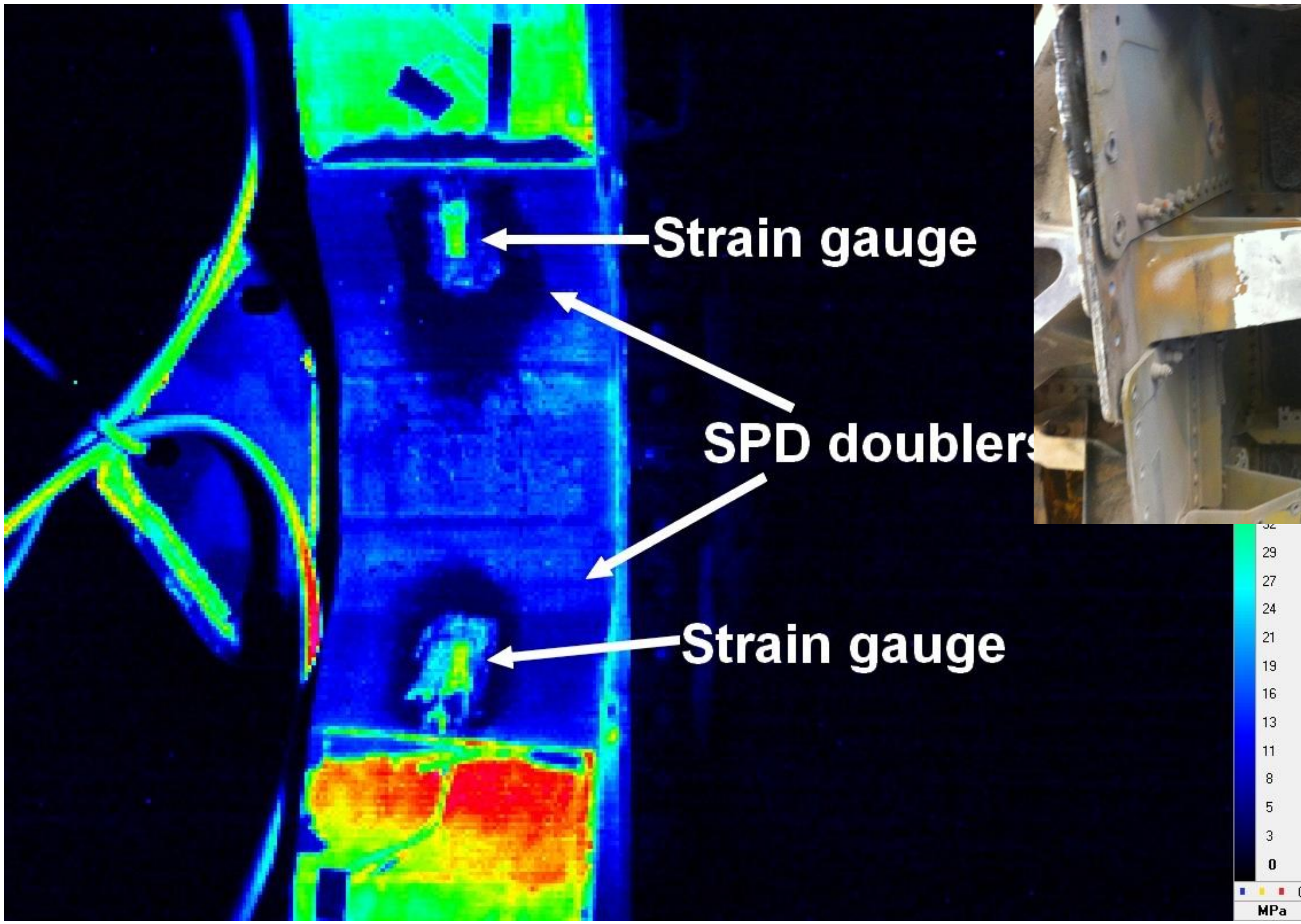
e.g. 1 Upper Skin Port - Along Fastener Line (Post SPD)





>Two Life-Times Achieved

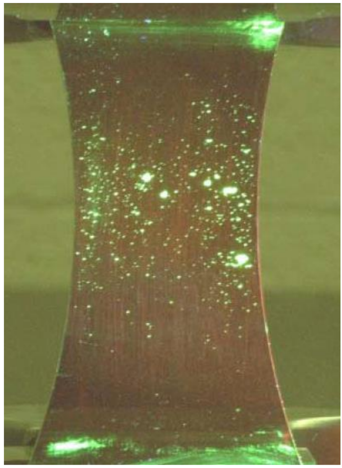
e.g. 2: Bulkhead (Y470) Crotch & TSA



Thermal Stress
Analyse image

> 2 lifetimes demonstrated

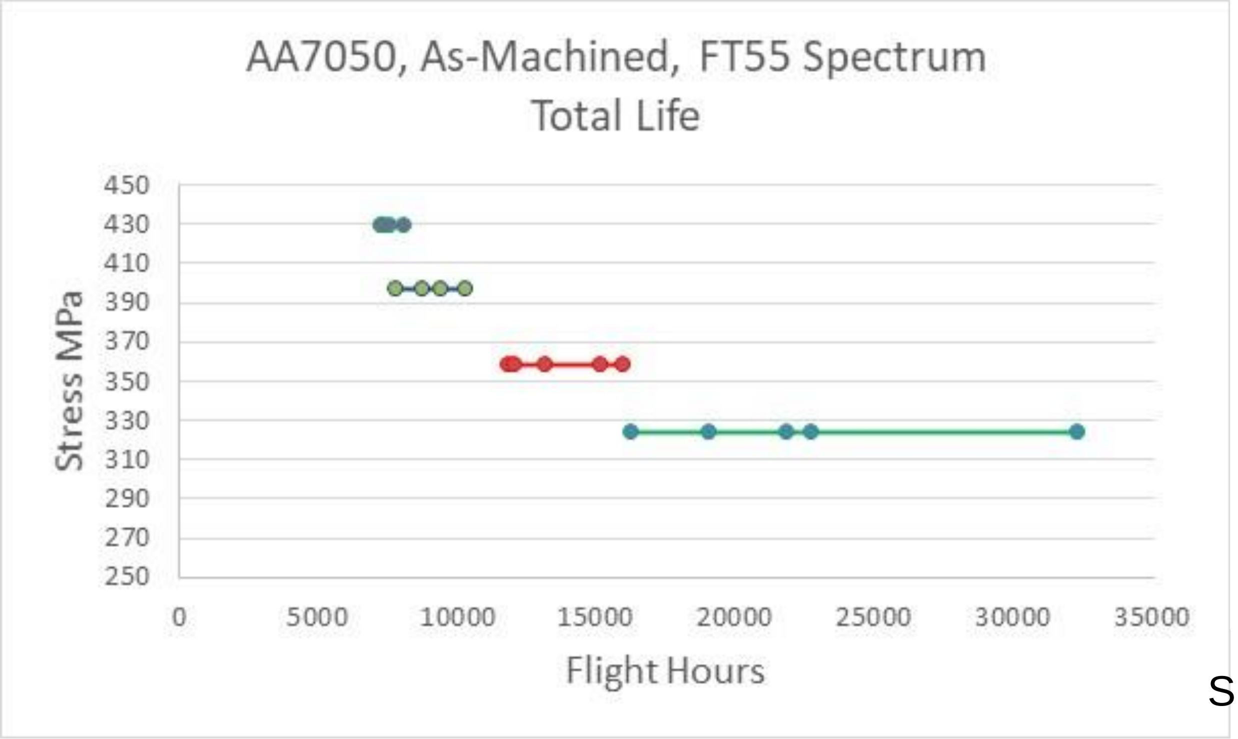
The metal aircraft fatigue problem space
LCF – Lead Cracks

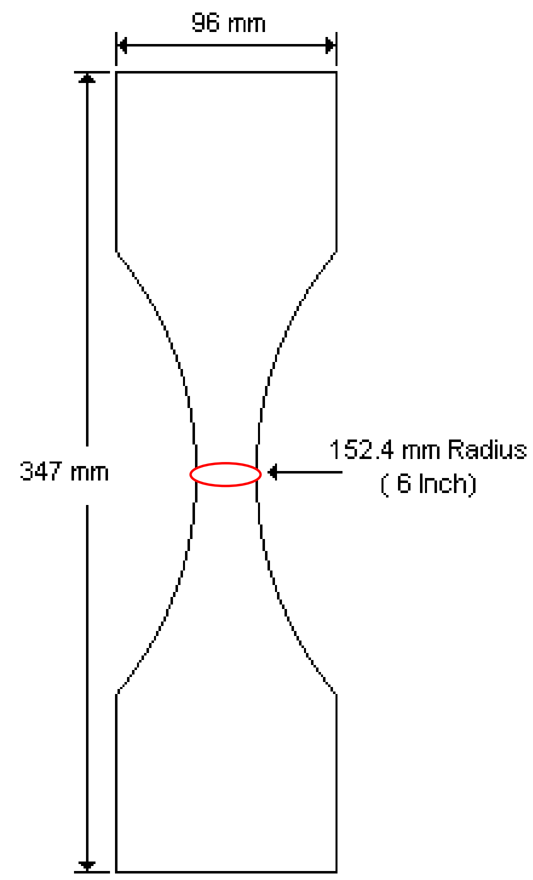


AA7050 specimen; fatigued then loaded to reveal cracks (dye penetrate)

1. The growth of cracks is the only measurable fatigue metric (and thus useful in assessing impact on structural integrity);
2. For production aircraft materials, cracks that will play a role in the fatigue life of a component nucleate from sub-mm surface or near-surface discontinuities at high stress regions (i.e. hotspots);
3. The majority of these cracks commence growing from near-day one of operations (but time dependent damage e.g. corrosion, fretting etc may also play a role);
4. Upwards of two-thirds of the total life spent in growing a detectable crack (» 1mm long). NDI limitations;
5. Thus the physically short-crack at the low ΔK regime is the area of most interest to fleet management & failure analyses; However,
6. Traditionally most data and analysis have been produced using long (> 1mm long) cracks (limitations acknowledged in ASTM E647).

Fatigue Coupon S-N Results



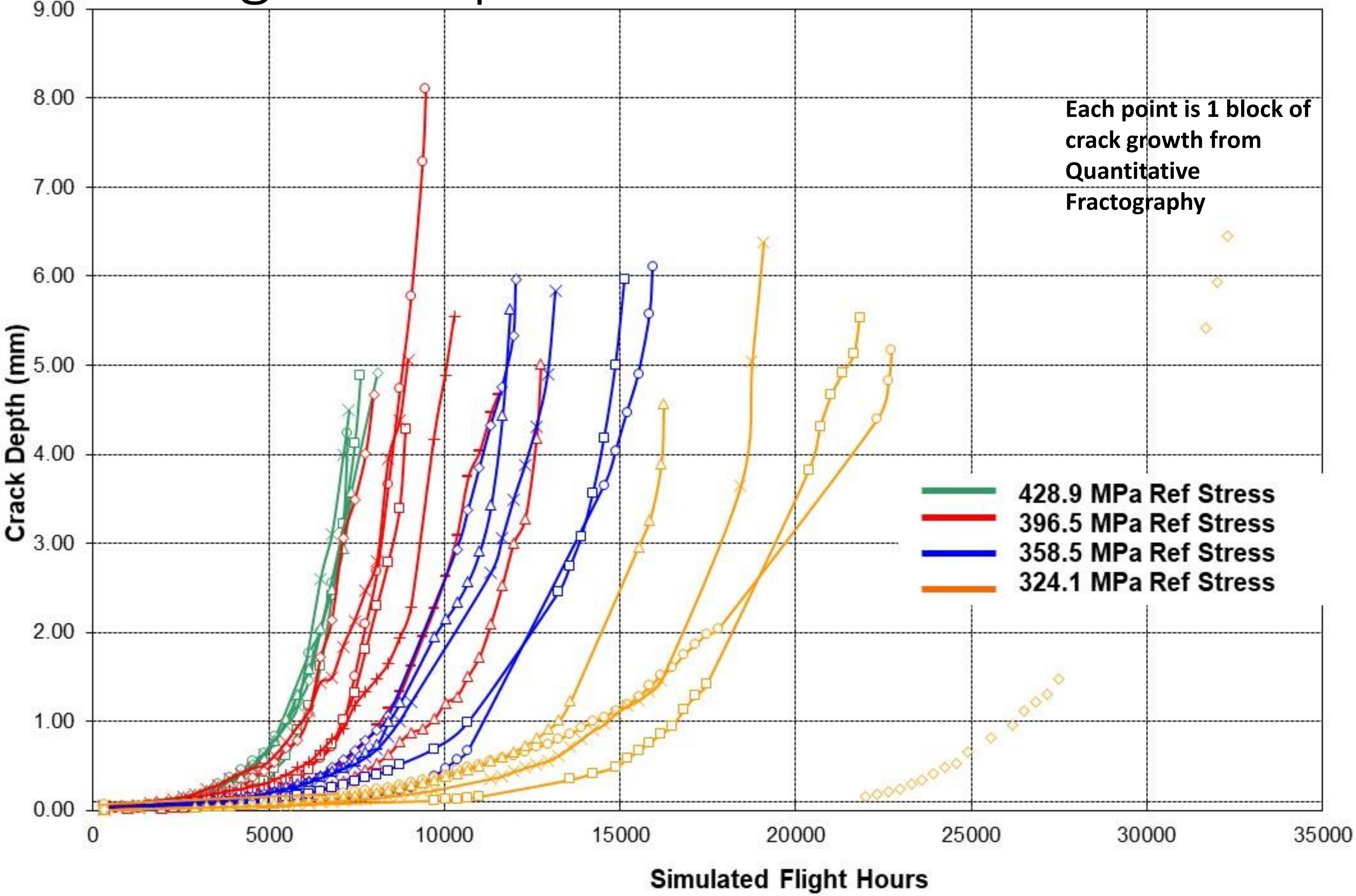


Specimen thickness: 6.25mm

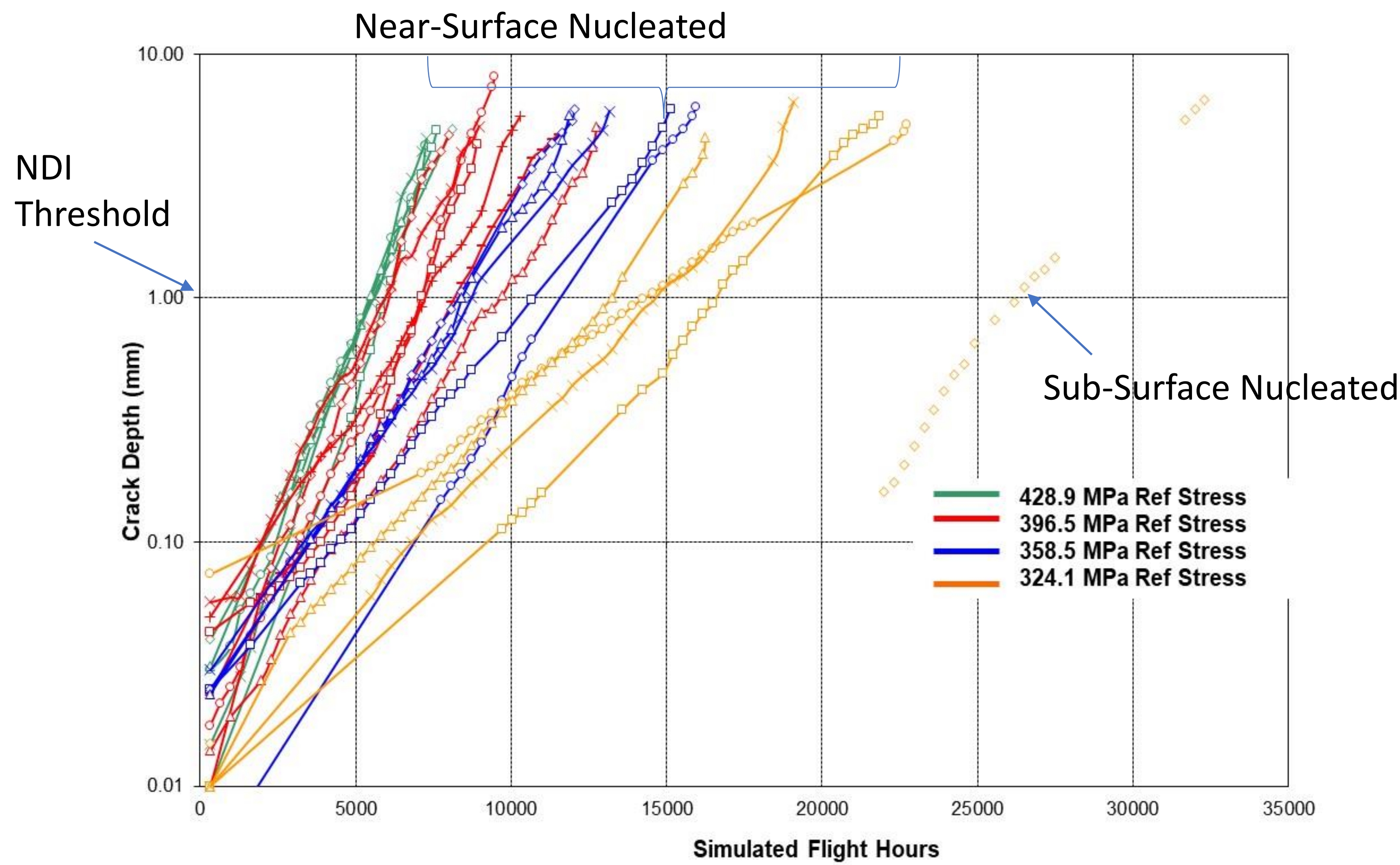
7050-T7451 Aluminum alloy

- Nominal test section is 28mm wide by 6.25mm thick
- Analytical K_t of 1.055
- Four or Five Coupons per Stress level

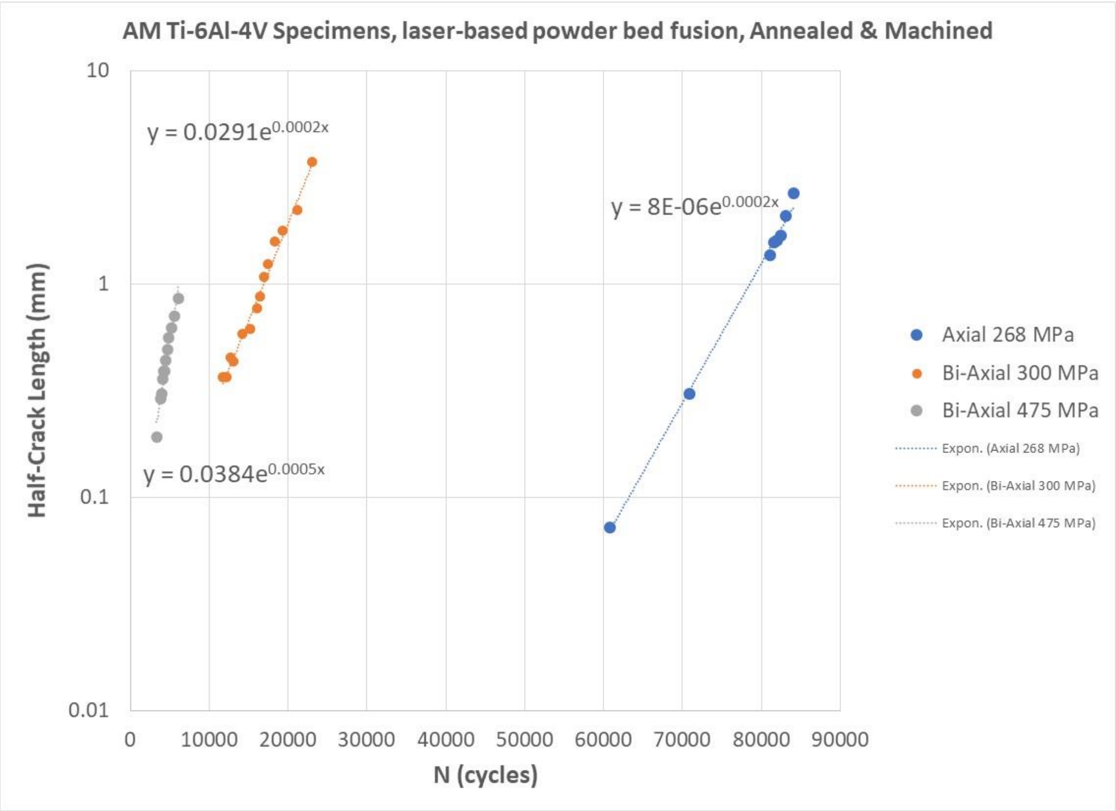
Fatigue Coupon Crack Growth Results

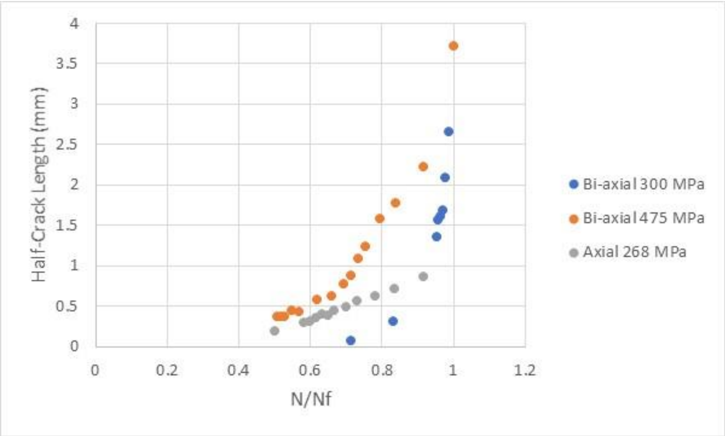


Fatigue Coupon Crack Growth Results - Exponential

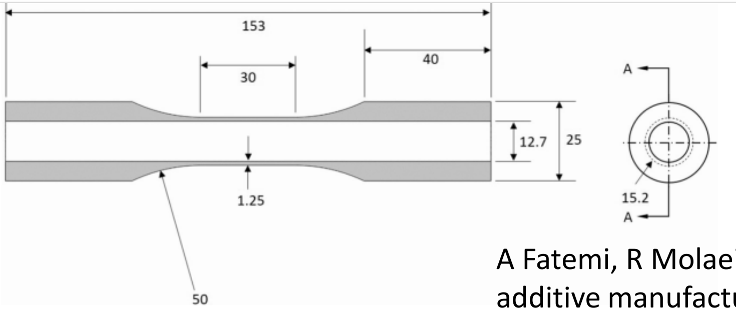


Lead Crack for AM Example





Max Principal Stress



A Fatemi, R Molaei, S Sharifimehr, N Phan, N Shamsaei, Multiaxial fatigue behavior of wrought and additive manufactured Ti-6Al-4V including surface finish effect, Fatigue 100 (2017) 347–366

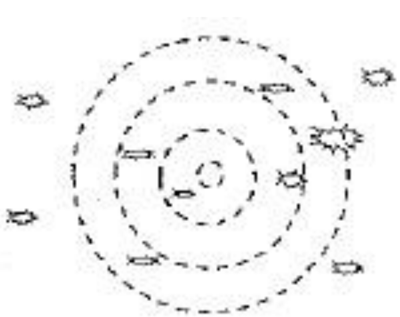
Metal Fatigue Scatter (in monolithic structure) LCF

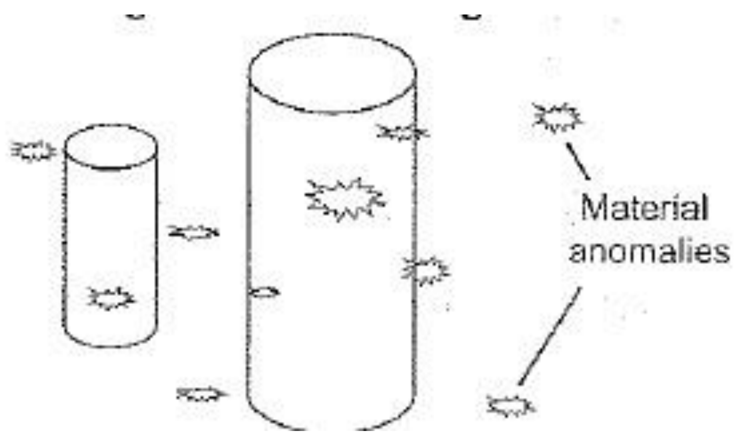
		Variable	Contribution to material scatter for lead cracks
1	**Build quality**	the initial discontinuities that lead to fatigue cracking	Most significant
2		stress concentrations leading to inter-aircraft variations in local stress	Any nominal variation in stress will lead to scatter. Build Quantity Dependent
3		fit-up or residual stresses	Any nominal variation in stress will lead to scatter. Build Quantity Dependent (significant and should be addressed)
4	**Material property**	crack nucleation and/or initiation period	Nucleation period insignificant
5		the fracture toughness of the material	Crack tear near end of life.
6		material cyclic stress intensity threshold	Threshold close to 0 for lead cracks.
7		the crack growth rate of fatigue cracks in the material being examined	Secondary

LCF = Low Cycle Fatigue

Size Effect (weakest link)

- All materials contain discontinuities
- A larger volume of material has a greater probability of containing a larger crack nucleating discontinuity or defect, leading to shorter lives.
- Bigger specimens have a greater probability of containing bigger crack nucleating discontinuities or defects, leading to shorter lives
- (Da Vinci found longer wires "weaker" than shorter wires)





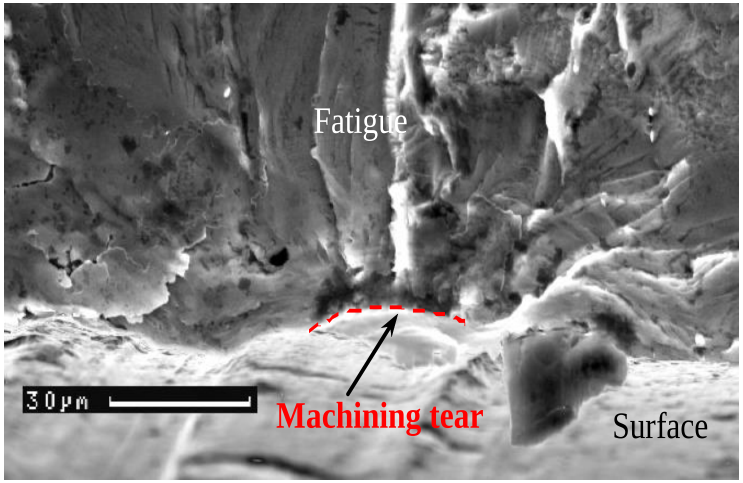
Types of Airframe Discontinuities

- Conventional production components have many sources of discontinuities that can cause fatigue cracking e.g.:

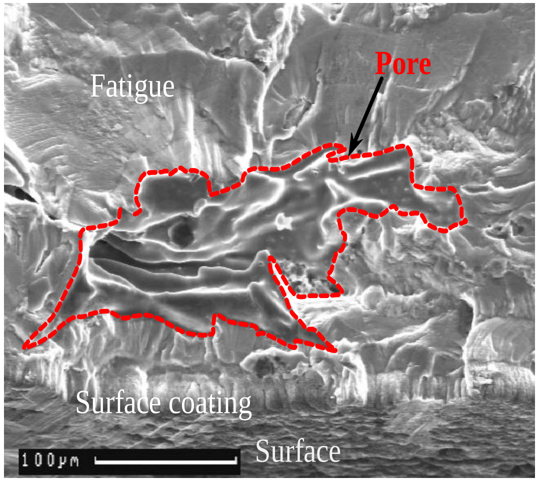
- **Machining damage**:
  - badly drilled holes
  - scratches, grooves, burrs, small tears, nicks
- **Surface treatments** (pickling, anodizing):
  - etch pits, sometimes intergranular attack
- **Constituent particles** (aluminium alloys and steels)
  - particles can be already cracked from production
- **Porosity** in thick aluminium alloy plate and castings

N.B: discontinuity depths mostly small, ≈ 0.01mm

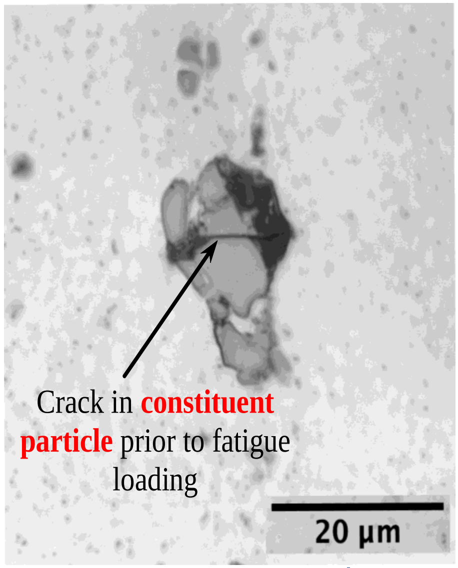
Types of Airframe Discontinuities: Examples



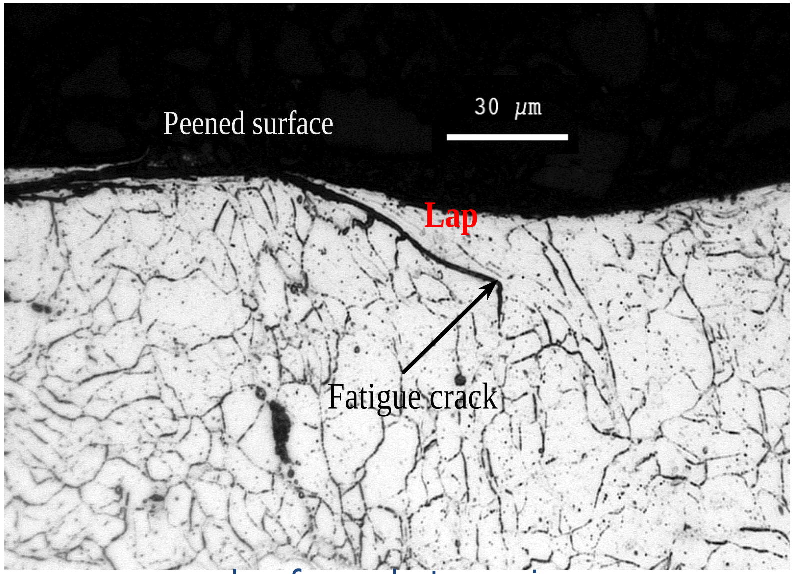
machining damage



porosity

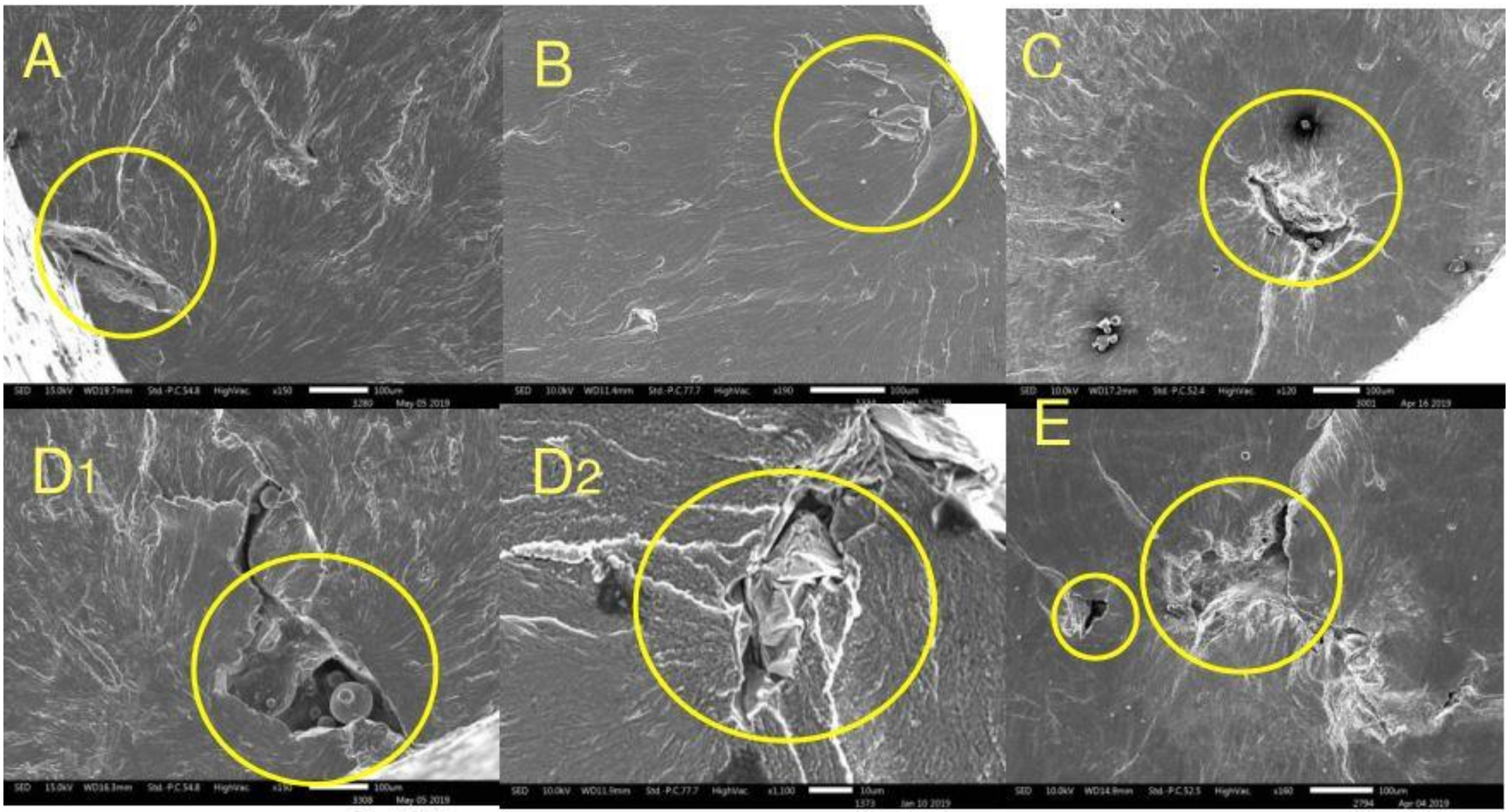


constituent particles



lap from shot peening

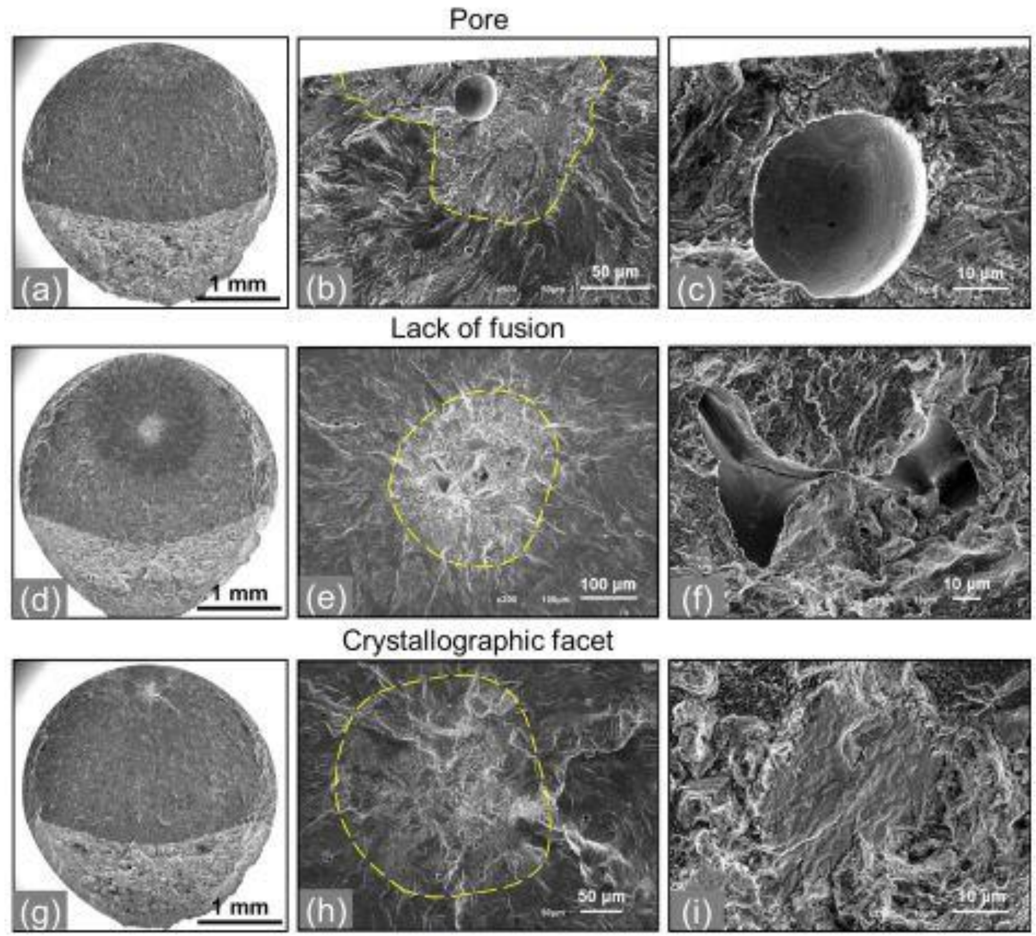
Types of AM Discontinuities (I):AlSi10Mg manufactured by selective laser melting (VHCF)



A: Surface Origin; B: Sub-surface; C: Internal; D: Near-surface; E: Melt pool type

Ref: Guian Qian, Zhimo Jian, Yujia Qian, Xiangnan Pan, Xianfeng Ma, Youshi Hong, Very-high-cycle fatigue behavior of AlSi10Mg manufactured by selective laser melting: Effect of build orientation and mean stress, Fatigue Volume 138, September 2020, 105696

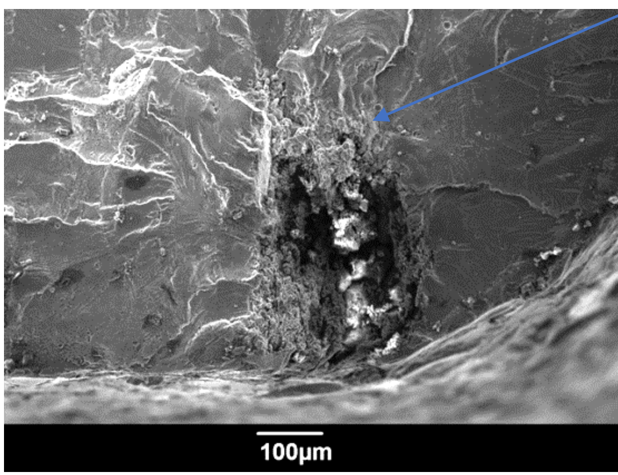
Types of AM Discontinuities (II):Nickel Alloy IN718 manufactured by selective laser melting (VHCF)



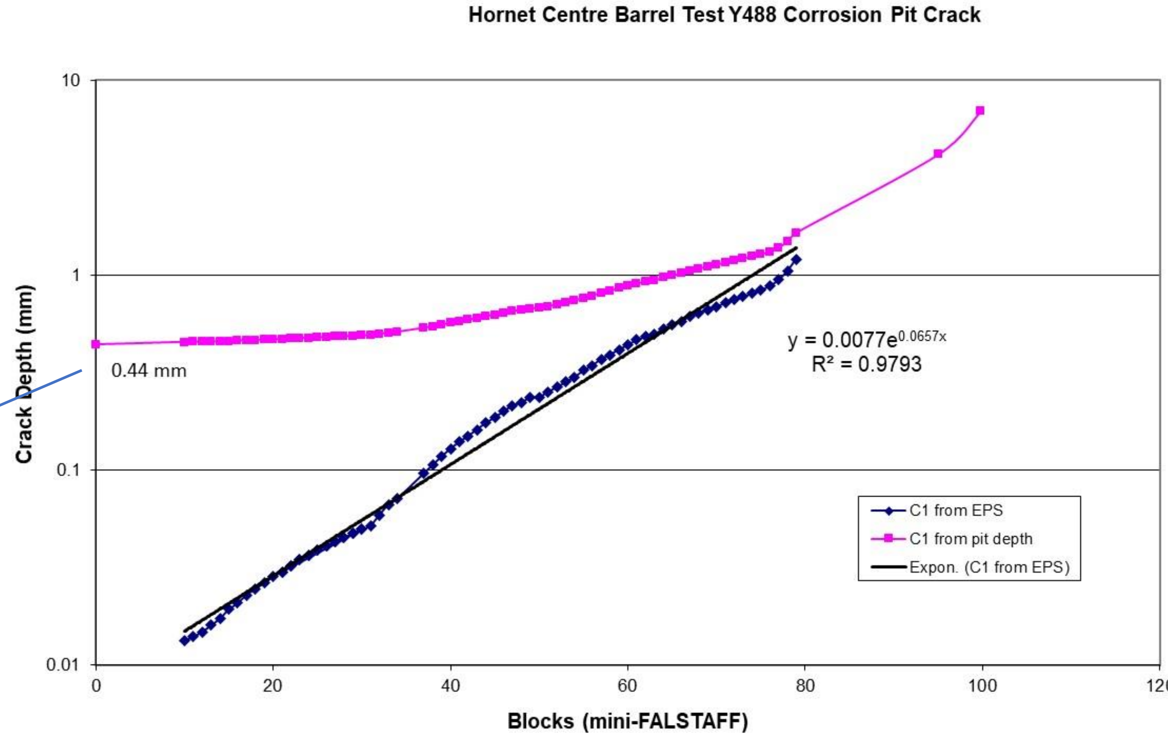
Ref: Kun Yang, Qi Huang, Qingyuan Wang and Qiang Chen, Competing crack initiation behaviors of a laser additively manufactured nickel-based superalloy in high and very high cycle fatigue regimes, Fatigue [Volume 136](), July 2020, 105580

Not all Defects are totally Crack-like

e.g. Corrosion Pit in Bulkhead

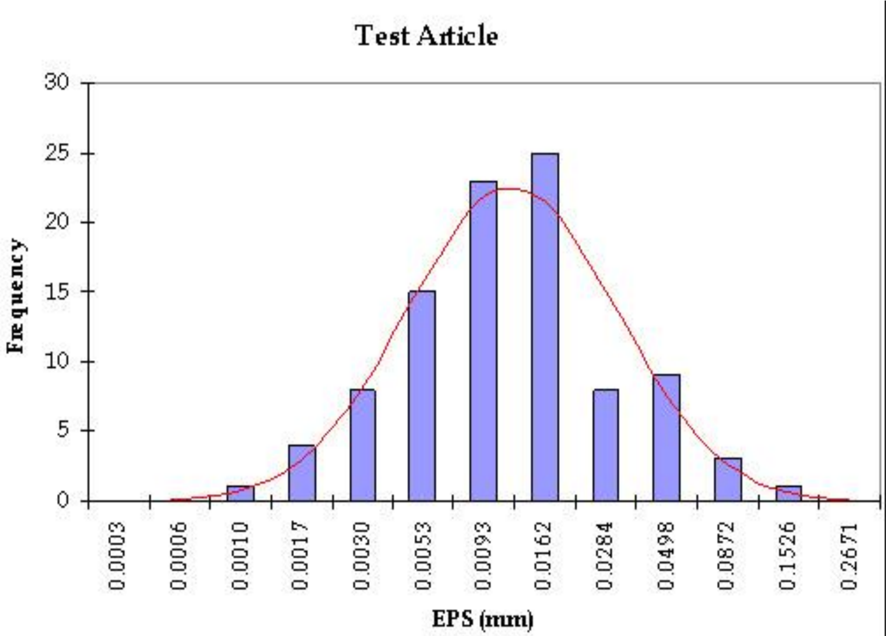


A SEM view of AA7050-T7451 fracture surface showing the corrosion pit at its origin of C1

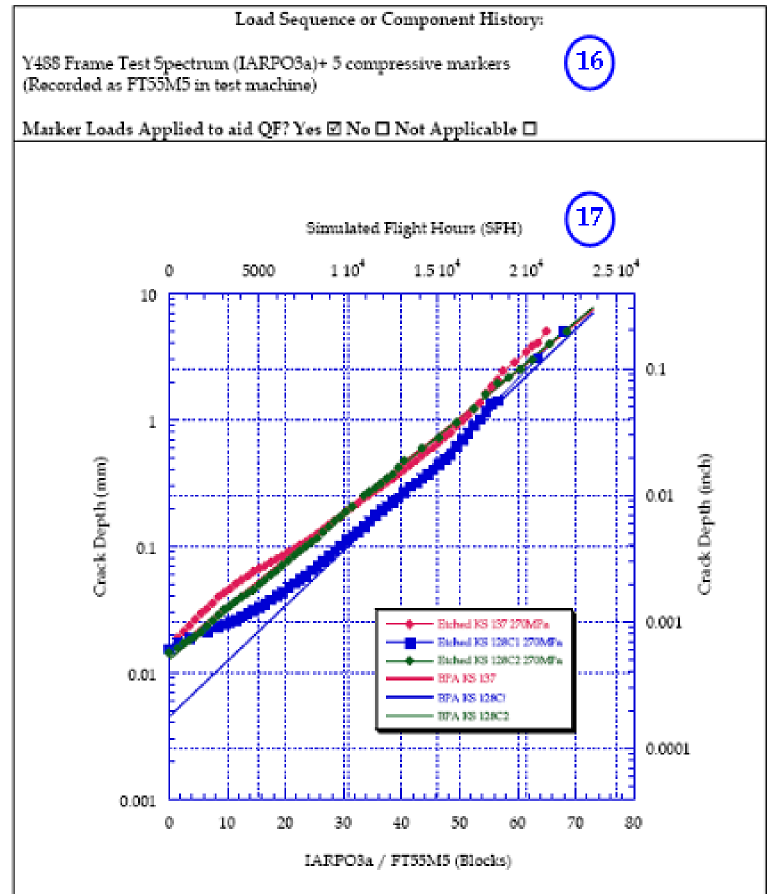


Highly 3D
Multiple origins
Significant period to transition to stable 2D crack

Equivalent Pre-crack Size (example) [8,10,11]



EPS distribution from cracks in AA7050 test article nucleating from etch pits (mean ≈ 0.01mm deep). Approx 200 samples.



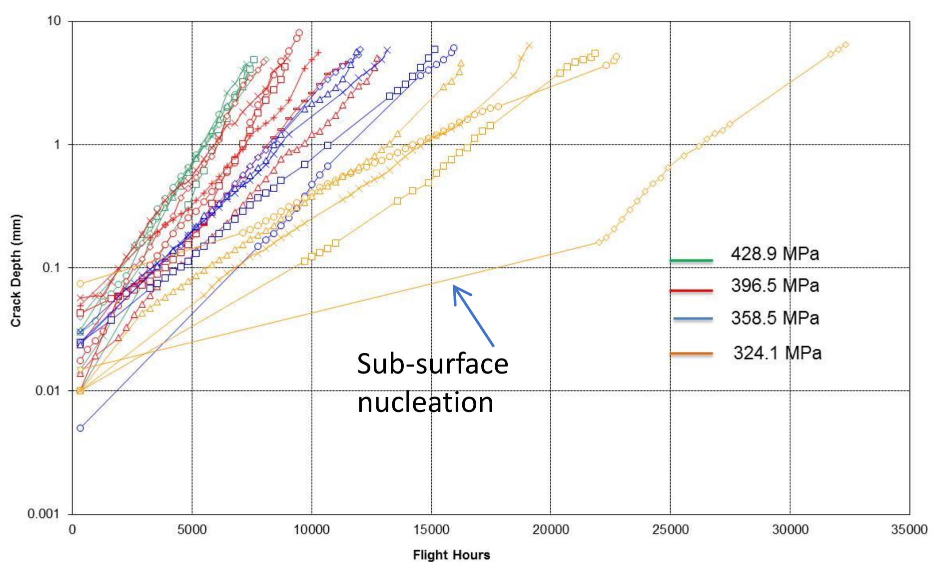
graphical representation of the QF data and back projected EPS curves

EPS Distribution

- For analyses need mean (μ) and std deviation (σ)
- Values extremely sensitive to choice of distribution e.g. log-normal vs Weibull etc
- Prob of failure dependant on $+X\sigma$
- $1 \leq X \geq 3$
- Surrogate AM EPS (EIFS)? (Material/process dependant)

Metal AM Fatigue Certification – A view

- A *metal is a metal* and comes with a range of discontinuities* [3]. Welding is one extreme
- Variations in discontinuity sizes is the main contributor to scatter in lives (for nominally same everything else)
- We can deal with discontinuities (think probabilistics)



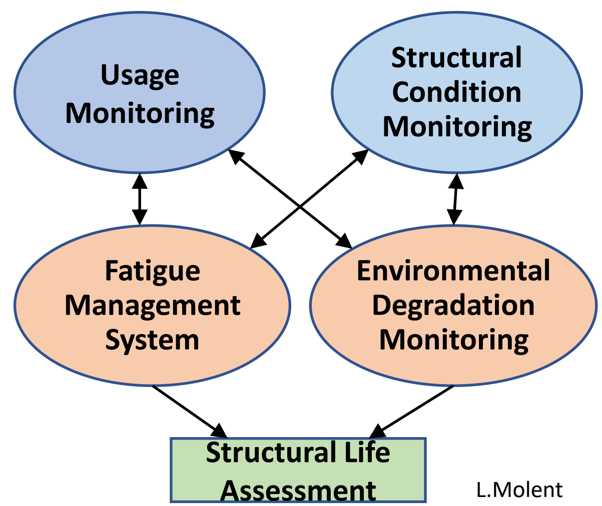
AA7050 coupons
Hornet Spectrum
Kt ≈ 1.04

Each point is 1 block of crack growth from QF

* +Residual stresses etc, etc

Metal AM Certification – Considerations

- Performance-Based Regulation (PBR): A regulatory approach that focuses on desired, measurable outcome: Still need methods
- Some guidance reflect the view that certification of any metal has a true and tested path
- No special considerations for AM? One example:
  - ***Structures Bulletin*** EZ-SB-19-01 Durability and Damage Tolerance Certification for Additive Manufacturing of Aircraft Structural Metallic Parts, AFLCMC/EZ, APAFB, Jun 2019.
    - 0.05” (1.27mm) damage tolerance
    - 0.01” (0.254mm) durability
  - Non-flight critical (NC) first
  - FAA/EASA AC 25.571 similar
  - Building block approach



RAAF in-service Airframe Management Process

L.Molent

C. Babish USAF Challenge Summary

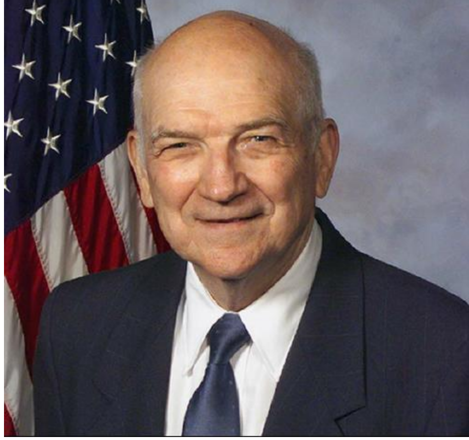
U.S. AIR FORCE

Summary

- DADT certification of structural parts requires significant test data to characterize the variability in DADT properties and to establish the initial damage type and size assumptions used in the DADTA
- The pursuit of AM for structural parts should begin with NC parts only
- If the test data and experience from building hundreds of various NC parts supports it, the pursuit of DC parts can begin
- Only when the test data and experience from building many hundreds of various NC and DC parts exists and is favorable, should the pursuit of FC parts begin
- This approach is expected to be more efficient in the long run than performing significant testing for part-specific AM applications only

Non-Critical = NC; Damage Critical = DC; Fracture Critical = FC; Damage Assessment Damage Tolerance (Analyses) = DADT(A)

Lincoln's 5



- Stabilised material and/or material processes – Material & processing specification, acceptance standards & manufacturing instructions
- Producibility – Material supply requirements (e.g. feedstock material), Part classification, Fabrication requirements (heat treatments, surface treatments etc), Inspections of the part/repair & environmental consideration of the repair/manufacturing venue - inspectability
- Characterise Material Properties – Establishing necessary material properties or generation of material allowables: e.g. strength, Fracture Toughness, Stress corrosion cracking data etc
- Predictability of Structural Performance – required static strength and fatigue tests
- Supportability – any in-service considerations (inspections etc)

Lincoln JW. Structural technology transition to new aircraft, proc. ICAF Symposium, Ottawa, Canada; 1987

THE HARTMAN & SCHIJVE (H&S) VARIANT*

$$da/dN = D\,(\Delta K - \Delta K_{thr})^{p}/(1 - K_{max}/A)^{p/2}$$ [4,5,6]

Here D and p are material constants, A is the cyclic fracture toughness, ΔK is the range of the stress intensity factor seen in a cycle, and ΔK_{thr} is the associated cyclic fatigue threshold (**long OR short crack**).

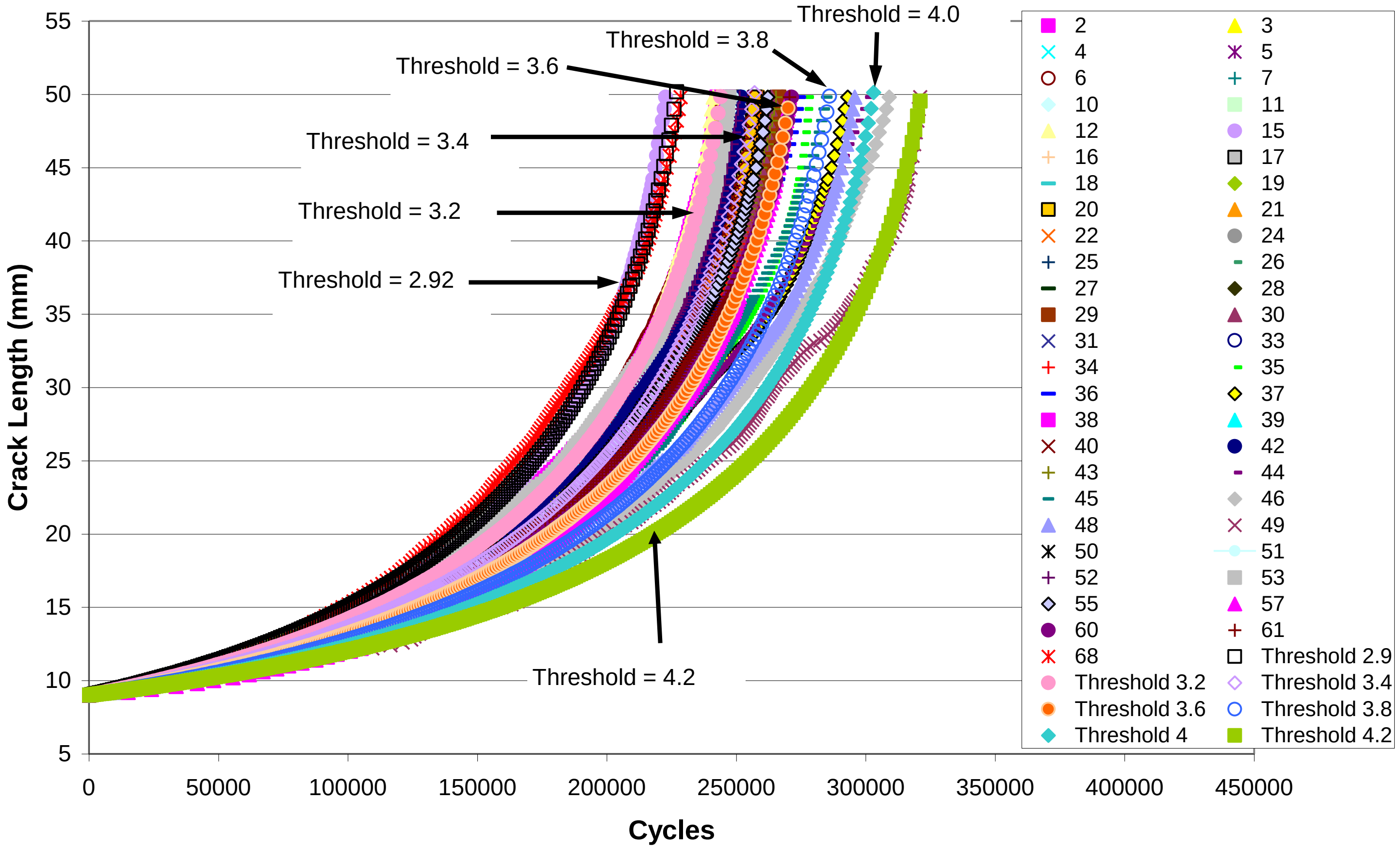
Only one da/dN vs ΔK at one *R* is required

For Ti-6Al-4V p = 2.13, D = 2.79 10^{-10} and

$$\Delta K_{th} \sim \Delta K_{thr} + 0.62$$ [5,6]

* Special form of NASGRO eqt. (recently (re)discovered by Art McEvily etc)

H&S Example 1: AA2024-T3 by Virkler et al. [4, 15]



Variability in Crack growth data from Virkler et al. 2024-T3 captured with various ΔK_{thr}. Half-crack length plotted.

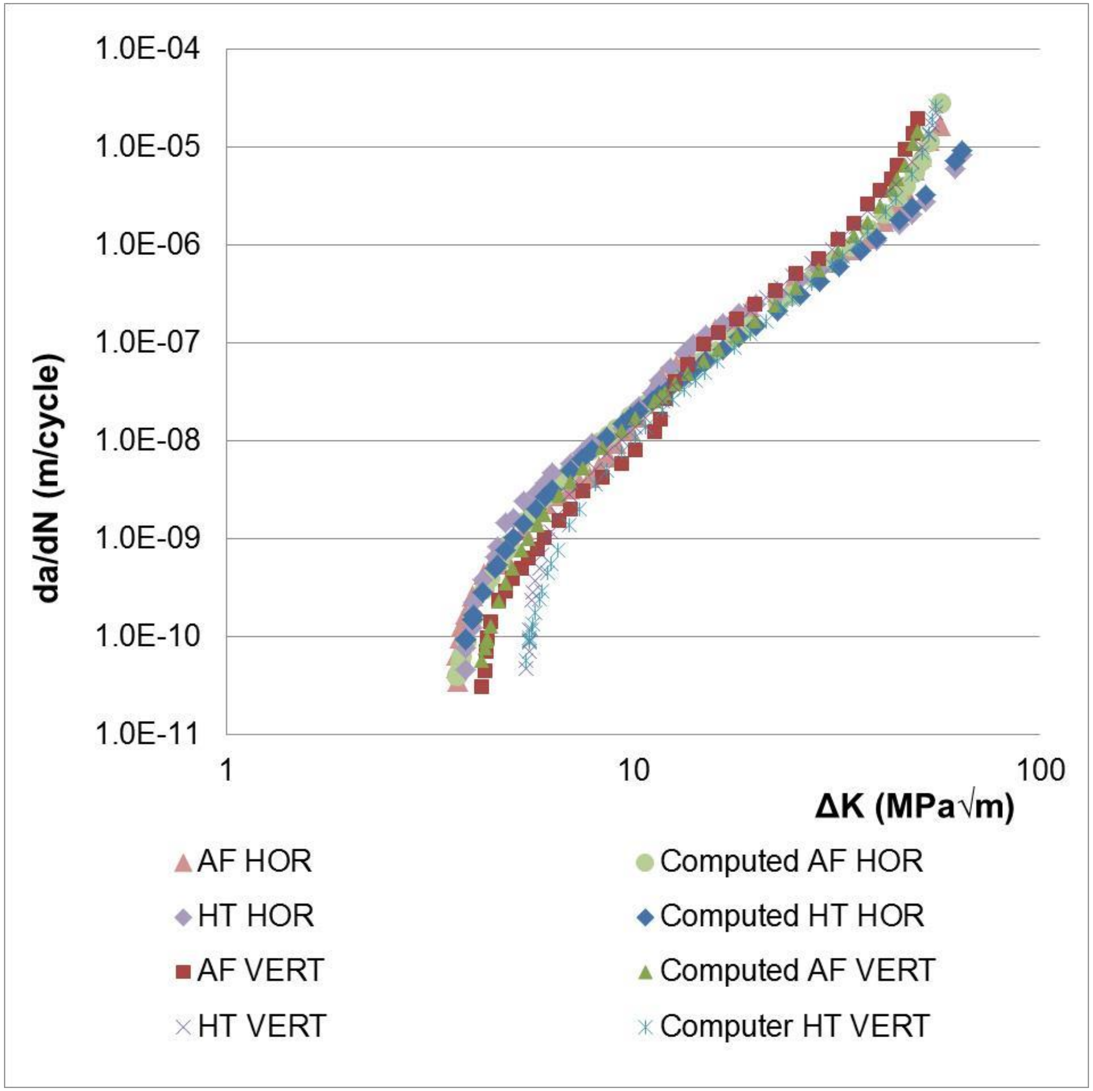
H&S VARIANT AM example [5]

Comparison of measured and computed crack growth for EBM Ti64 specimens with different build directions.

EBM = Electron Beam Melt

Zhai Y., Galarraga H., Lados DA., (2016) Microstructure, static properties, and fatigue crack growth mechanisms in Ti-6Al-4V fabricated by additive manufacturing: LENS and EBM, Engineering Failure Analysis, Vol. 69, pp. 3-14

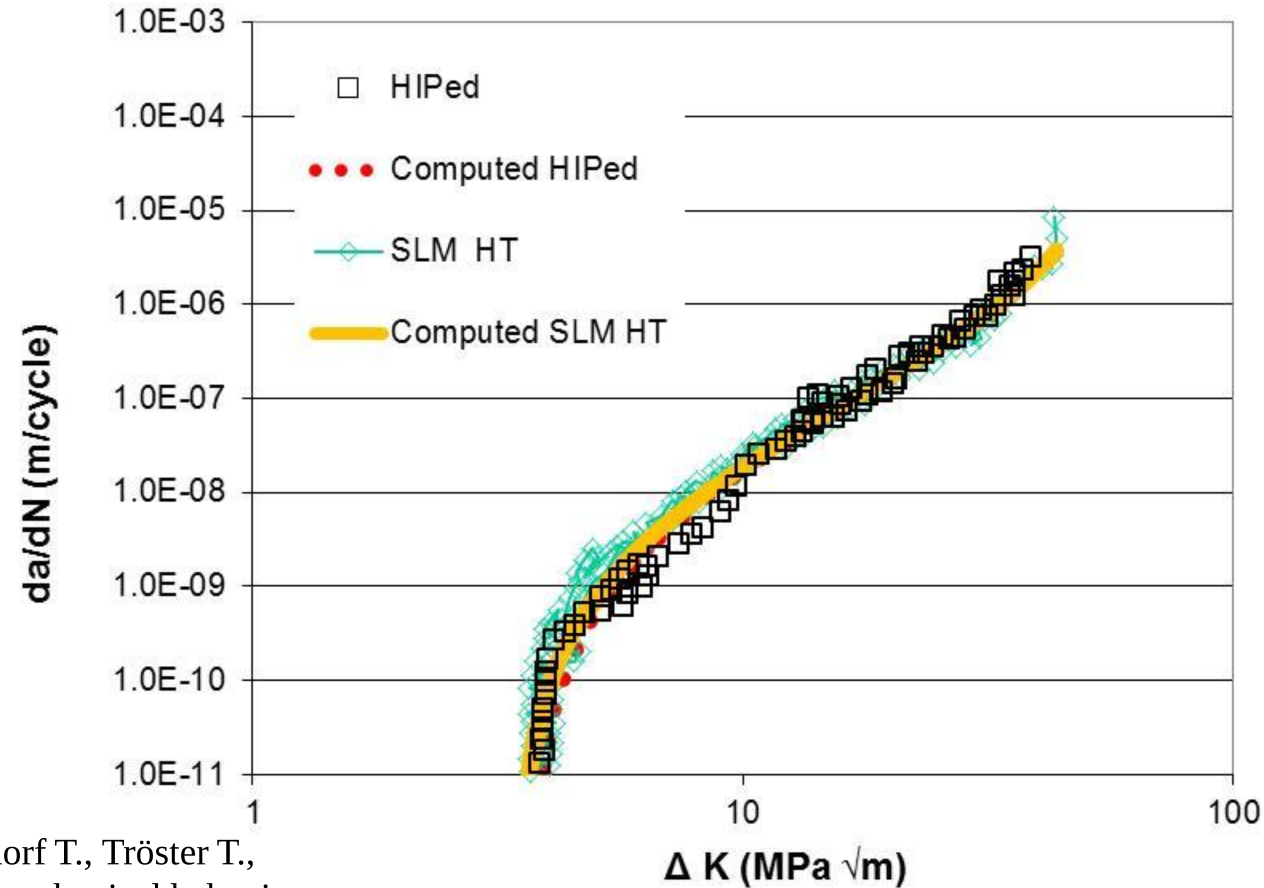
Courtesy Prof R. Jones
Monash Uni, Aust.



H&S VARIANT AM example 2 [5]

Measured and computed long crack da/dN versus ΔK curves for crack growth perpendicular to the build for **SLM Ti-6Al-4V and HIPed SLM Ti-6Al-4V**

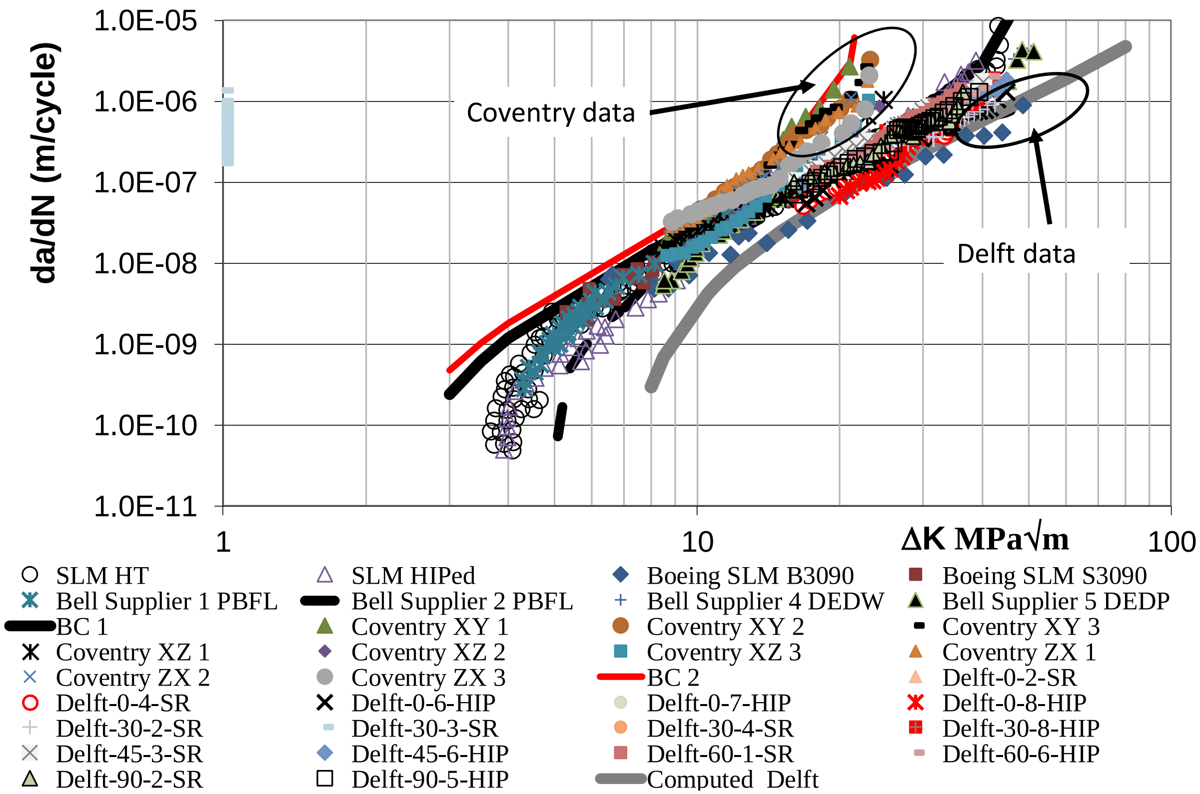
SLM = Selective Laser Melt
HT= Heat treated



Leuders S., Thöne M., Riemer A., Niendorf T., Tröster T., Richard HA., Maier HJ., (2013) On the mechanical behaviour of titanium alloy TiAl6V4 manufactured by selective laser melting: Fatigue resistance and crack growth performance, International Journal of Fatigue, 48, pp. 300–307

Courtesy Prof R. Jones
Monash Uni, Aust.

H&S VARIANT example 3 [7]



Variability in crack growth in Selected Laser Melt (SLM) specimens that have been either Hipped or heat treated (HT)

Courtesy Prof R. Jones
Monash Uni, Aust.

Accounting for variability

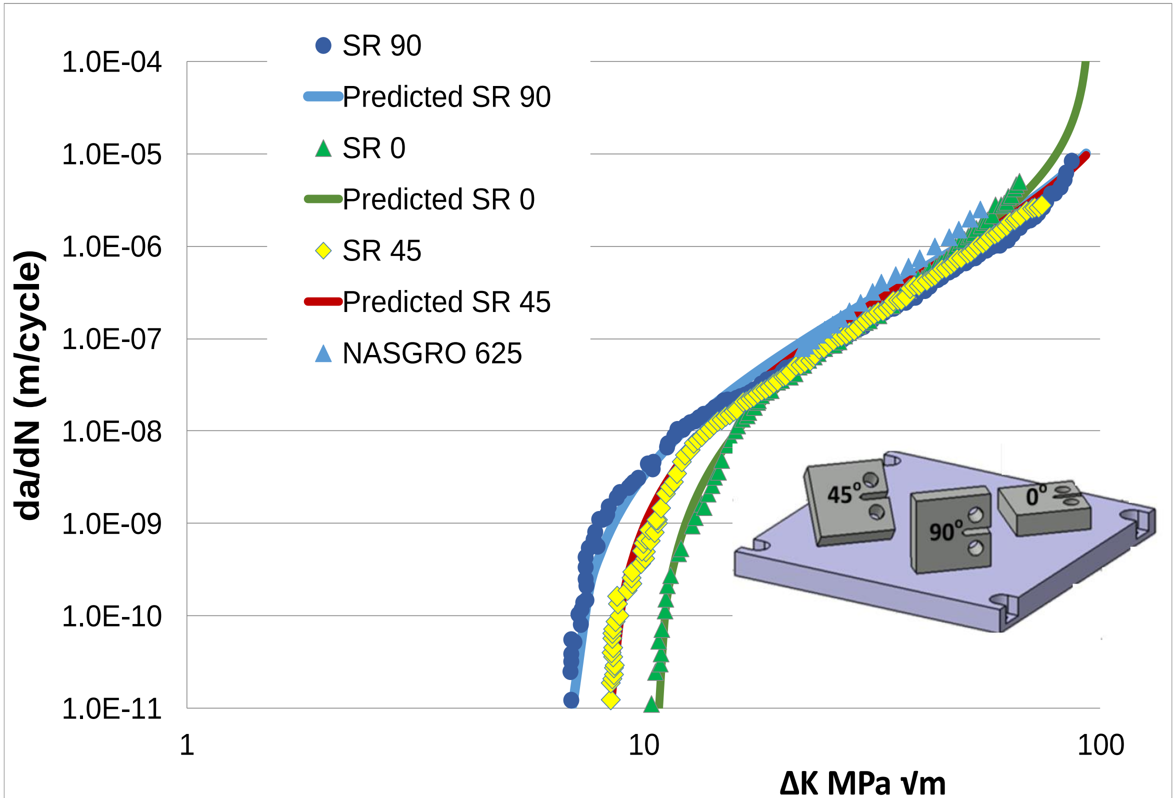
The variability in the crack growth histories are largely captured by allowing for variations in EPS and the threshold (ΔK_{thr}) and the toughness (A).

The variability in A is far greater than that in **(ΔK_{thr}) [6]**

The variability in A is a weak function of the variability in **(ΔK_{thr}) [6]**

Unlike conventionally manufactured parts the operational life of an AM replacement part is a strong function of the value of A associated with the particular A process (SLM, EDM, DMLS, LENS, etc). **[7]**

Example



Note how although there is variability in the threshold Region, there is little if any variation as K approaches Kc.

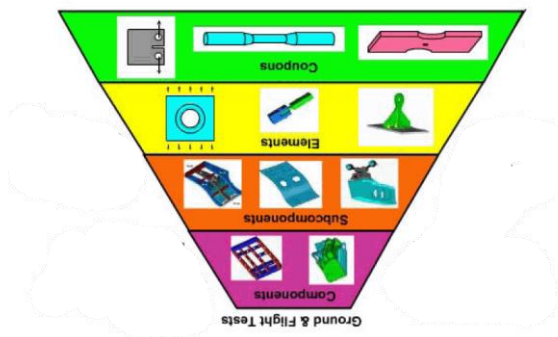
i.e. The variability in A is a weak function of the variability in (ΔK_{thr})

Comparison of measured and computed crack growth for stress relieved (SR) laser powder bed fusion (LPBF) Inconel 625 specimens cut from the 0, 45 and 90 directions.

Jones (Monash) and Michopoulos (NRL) – Unpublished data

Conclusions

FLIP



The path to certification is fixed
The path may be demanding for FC components
Look for low hanging fruit
All sources of scatter need to be defined
The H&S offers one way of bounding the scatter
Let's fly!

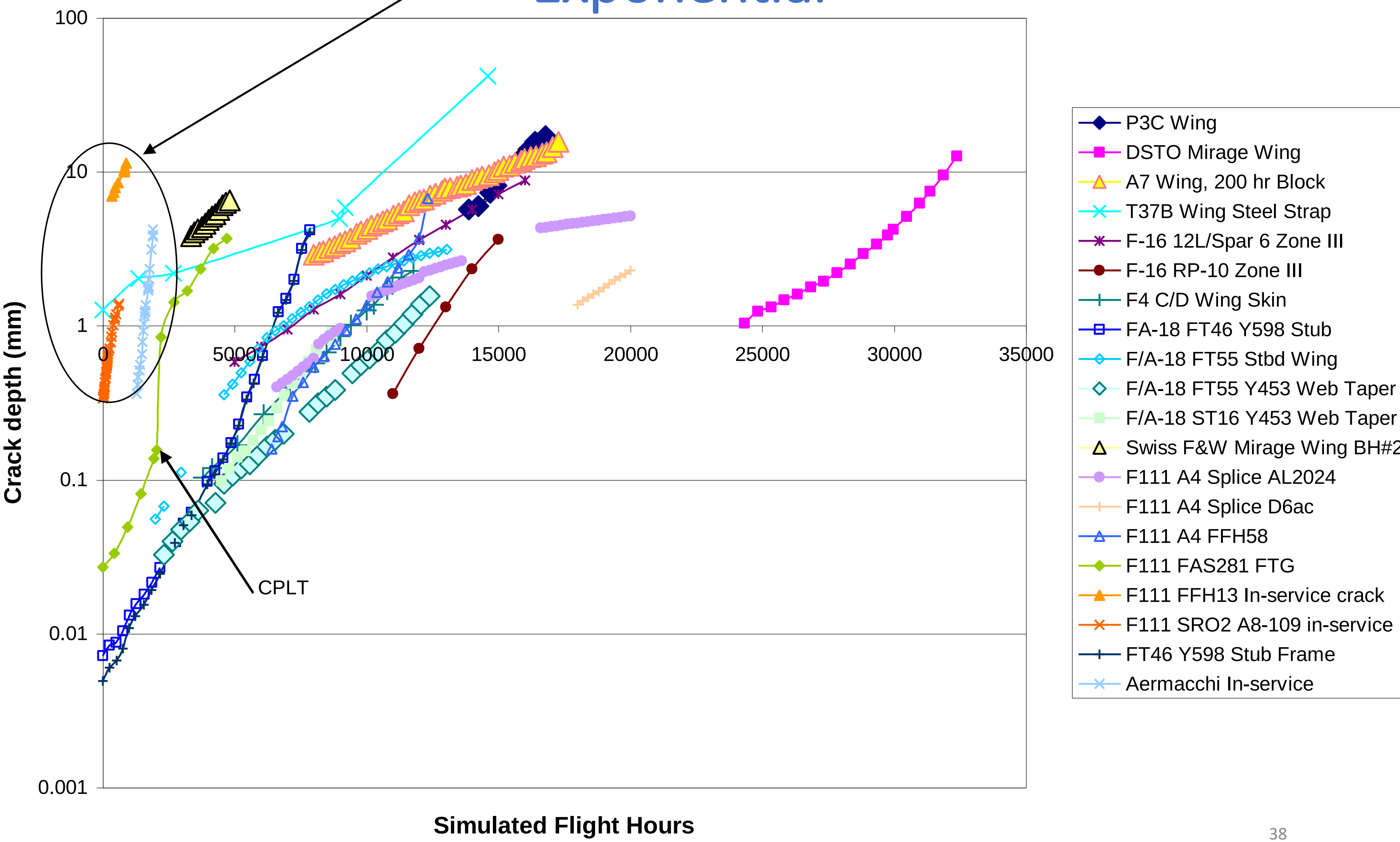
Questions?

Bibliography

1. Gorelik M. Structural Integrity Considerations for New Materials – Additive Manufacturing, IMECE 2016 Conference, Phoenix, AZ, Nov 2016
2. Molent L, Dixon B, Barter SA and Swanton G. Outcomes from the fatigue testing of seventeen centre fuselage structures, Fatigue 111C (2018) pp. 220-232
3. Jones R., Molent L., Barter S., Matthews N., Tamboli D. Supersonic particle deposition as a means for enhancing the structural integrity of aircraft structures. J. Fatigue 2014; 68:260-268.
4. Molent L and Dixon B. (Review Paper) Airframe metal fatigue revisited, J Fatigue 2020;131
5. Molent L. and Jones R. The influence of cyclic stress intensity threshold on fatigue life scatter, Int J Fatigue, 2015; 82: 748-756
6. Jones R., Michopoulos JG., Iliopoulos AP., Singh Raman RK., Phan N. and Nguyen T., Representing Crack Growth In Additively Manufactured Ti-6Al-4V, (2018) International Journal of Fatigue, 2018, 111, pp. 610-622.
7. Iliopoulos AP., R. Jones R., Michopoulos JG., Phan N., Singh Raman RK., Crack growth in a range of additively manufactured aerospace structural materials, Special Issue, Civil and Military Airworthiness: Recent Developments and Challenges, Aerospace, Aerospace, 5, 4, pp. 118-136, 2018, doi:10.3390/aerospace5040118
8. Jones R., Matthews N., Peng D., Phan N., Nguyen TT., Damage Tolerant Assessment Of Additively Manufactured Replacement Parts, Proceedings 13th International Conference on the Mechanical Behaviour of Materials (ICM13), 11th -14th June 2019, Melbourne, Australia
9. Molent L, Barter SA and Wanhill RJH. The Lead Crack Fatigue Lifing Framework, J Fatigue; 33 (2011) 323–331
10. Gallagher JP and Molent L. The equivalence of EPS and EIFS based on the same crack growth life data, Fatigue 2015; 80:162-170
11. Molent L., A review of equivalent pre-crack sizes in aluminium alloy 7050-T7451, Fat Fract Eng Mat Struct 2014;37: 1055-74
12. Barter SA, Molent L, Wanhill RJH. Typical fatigue-initiating discontinuities in metallic aircraft structures, J Fatigue 2012 ; 41:11-22
13. Jones R., Singh Raman RK., Iliopoulos AP., Michopoulos JG., Phan N. and Peng D., Additively manufactured Ti-6Al-4V replacement parts for military aircraft, Int. Journal of Fatigue, 2019; pp. 227-235. https://doi.org/10.1016/j.ijfatigue.2019.02.041
14. Alison J. McMillan, Daren Peng, Rhys Jones, Nam Phan, John G. Michopoulos, Additive manufacturing: Implications of surface finish on component life, Proceedings, SAMPE Europe Conference 2018, Southampton, 11-13th September, 2018.
15. Jones R., Matthews N., Baker A., Champagne V, Aircraft Sustainment and Repair, Butterworth-Heinemann Press, 2018, ISBN 9780081005408. (Book).
16. Virkler DA, Hillberry BM, Goel PK. The statistical nature of fatigue crackpropagation. Technical report AFFDL-TR-78-43, 1978. Ohio, USA: Air Force Wright Aeronautical Laboratory
17. Molent L. General fatigue lifing of metallic aircraft structures, DSTG-RR-0467, 2020
18. Molent, L. and Wanhill, R. Management of Airframe In-Service Pitting Corrosion by Decoupling Fatigue and Environment. Corros. Mater. Degrad. 2021, 2, 493–511

Additional Slides

A few In-Service and FSFT results ≈ Exponential



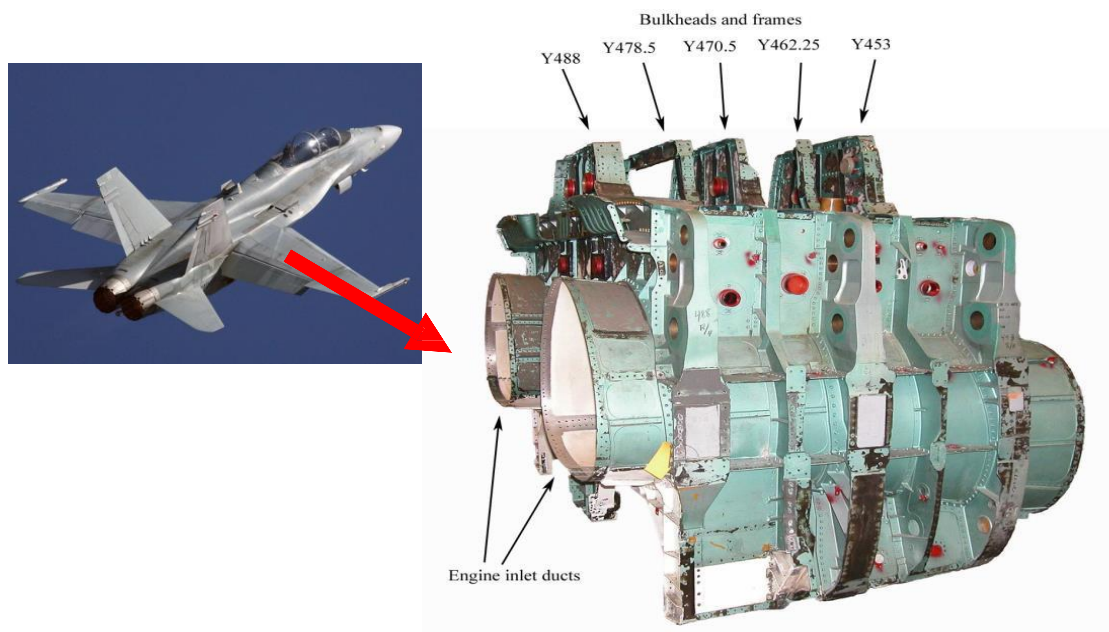
AM REPLACEMENT PARTS – Logistics Considerations

Logistics driven – a part may take between 9 – 24 months to arrive.

Question to be answered if AM replacement parts to be considered:

Will an AM replacement part last the required number of flight hours? (This is a Durability/Economic Life Certification Requirement.)

The certification of AM replacement parts requires a DURABILITY analysis/assessment of its economic life.

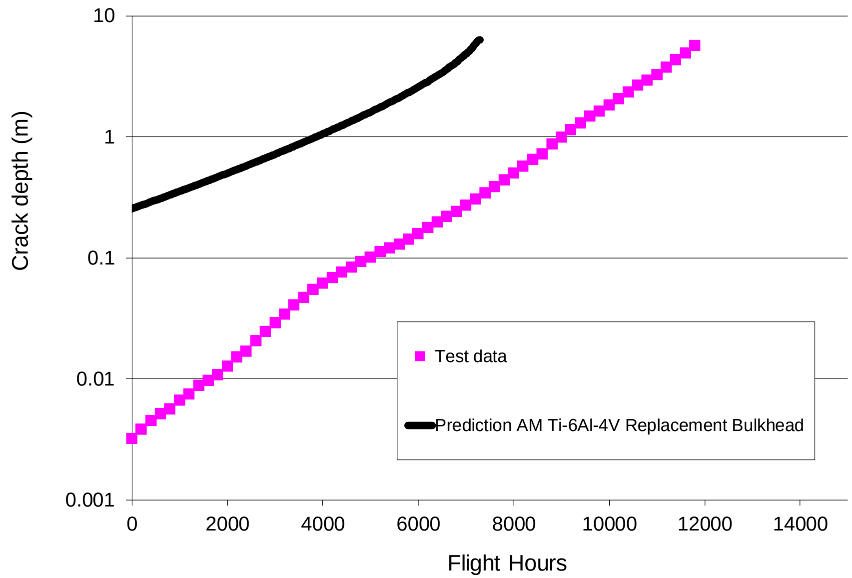


The Durability (Economic Life) Analysis Is Needed For Certification

Used the crack growth equation for small naturally occurring cracks in AM TI-6Al-4V, given above:

$$da/dN = 2.79 \times 10^{-10} \left[(\Delta K - 0.1) / (1-K_{max}/A)^{1/2}\right]^{2.13}$$

An EPS of 0.01 in (0.254). i.e. Material porosity/discontinuities/lack of fusion etc may be equivalent ot a 0.01 inch surface breaking crack.



The Design Life is 6,000 flight hrs

For less highly loaded parts the life of an AM Ti-6Al-4V replacement part would be even more attractive!!

L.Molent