The State Of The Art In The Durability & Damage Tolerance (DADT) Assessment Of Limited Life Additively Manufactured Parts

https://www.researchgate.net/publication/389491535_The_State_Of_The_Art_In_The_Durability_Damage_Tolerant_DADT_Assessment_Of_Limited_Life_Additively_Manufactured_Parts

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DRMS2025, 2nd International Conference on Durability, Repair and Maintenance of Structures, Faculty of Engineering, University of Porto, 13th -14th March 2025.

OVERVIEW

- **The objective of this presentation is to delineate the State of The Art in the Durability Assessment of Additively manufactured (AM) and Cold Spray Additively Manufactured (CSAM) parts and Cold Spray Repairs to metallic airframes.**

- **It also highlights the unique potential of Boeing Space, Intelligence and Weapon Systems (BSI&WS) laser powder fusion (LPBF) built Scalmalloy® to build limited life aircraft parts and drones that are both durable and corrosion resistant.**

BACKGROUND: The 2019 memo by the Under Secretary, Acquisition and Sustainment [1] enunciated that:

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- As of March 21st 2019, **the DoD will use AM to "*enable the transformation of maintenance operations and supply chains, increase logistics resiliency, and improve self-sustainment and readiness for DoD forces*".**

- **This memo further stated that:**

- **"AM parts or AM repair processes can be used in both critical and non-critical applications. For all applications, the appropriate level of *qualification, certification, and risk/safety evaluation* must be completed by the appropriate engineering support activity".**

1. Under Secretary, Acquisition and Sustainment, Directive-type Memorandum (DTM)-19-006 – "Interim Policy and Guidance for the Use of Additive Manufacturing (AM) in Support of Materiel Sustainment", Pentagon, Washington DC, March 21st, 2019.

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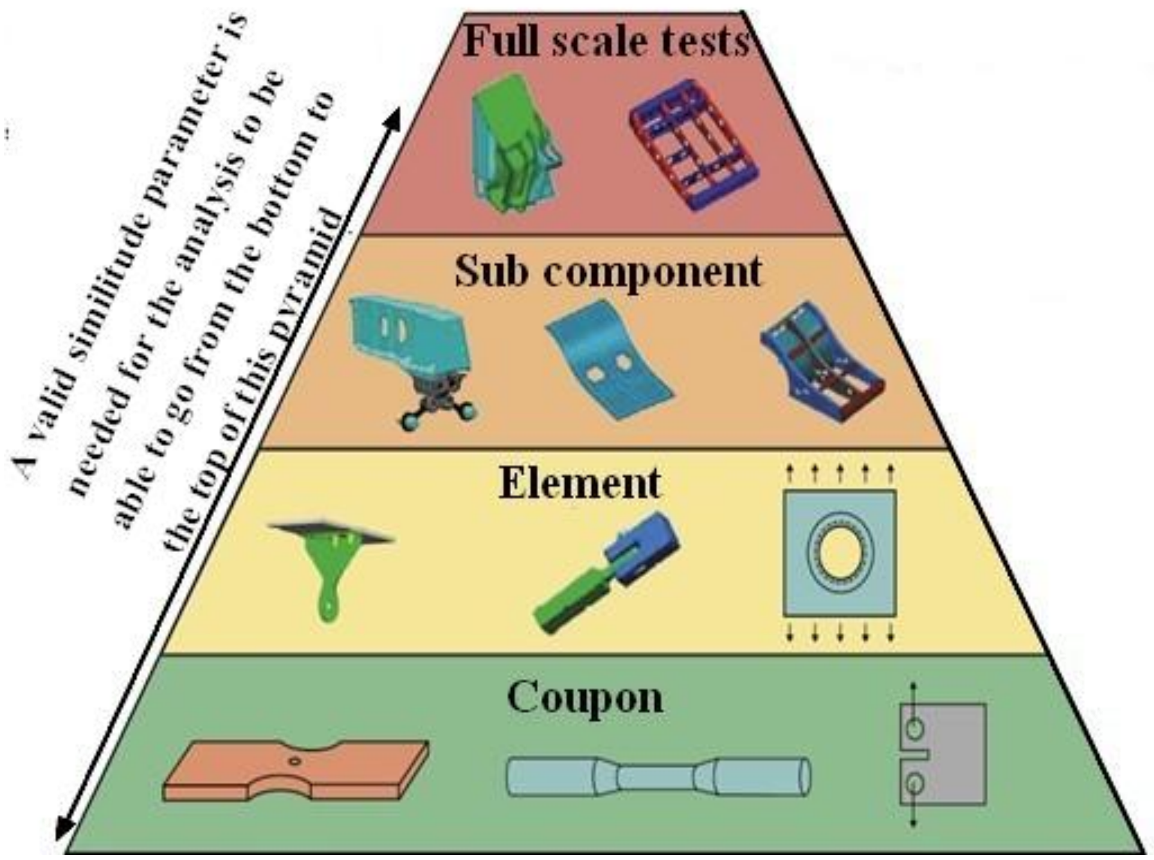
Durability & Damage Tolerance Assessment of AM Parts

- **Airworthiness Certification requires a Durability & Damage Tolerance (DADT) assessment of AM Parts.**
- **The certification requirements for Space applications (conventionally manufactured parts) are given in NASA-HDBK-5010 [2].** ***We will come back to this Standard later in this presentation.***
- **These requirements are similar to the Airworthiness Certification requirements for Military Aircraft (for conventionally manufactured airframes) that are delineated in US Joint Services Structural Guidelines JSSG2006 [3] and USAF MIL-STD-1530Dc [4] and in**
- **USAF Structures Bulletin EZ-SB-19-01 [5] addresses the Certification of AM and CSAM parts, and (by implication) Cold Spray repairs.**

2. NASA-HDBK-5010, Fracture Control Handbook For Payloads, Handbook For Payloads,, Experiments, And Similar Hardware, May 2005, Revalidated 2012. Available online at https://standards.nasa.gov/standard/nasa/nasa-hdbk-5010 (accessed on 024/09/2022).
3. Department of Defense. Joint Service Specification Guide; Aircraft Structures, JSSG-2006; October 1998. Available online: http://everyspec.com/USAF/USAF-General/JSSG-2006_10206/.
4. MIL-STD-1530D, Department Of Defense Standard Practice Aircraft Structural Integrity Program (ASIP), 13 October 2016. Available online: http://everyspec.com/MIL-STD/MIL-STD.../download.php?spec=MIL-STD-1530D, (accessed on 02/07/2020).
5. C. Babish, Structures Bulletin EZ-SB-19-01, Durability and Damage Tolerance Certification for Additive Manufacturing of Aircraft Structural Metallic Parts, Wright Patterson Air Force Base, OH, USA, 10 June 2019. Available online: https://daytonaero.com/usaf-structures-bulletins-library/ (accessed on 02/02/2020.

Durability and Damage Tolerance Analysis Requires A Building Block Approach ala MIL-STD-1530D & JSSG2006



The MIL-STD 1530D building block approach, slide courtesy of Russell Wanhill

Section 5.3 of USAF Mil Standard MIL-STD-1530Dc [4] explains that analysis is the key to both the damage tolerant design and the durability assessment of military aircraft.

***NASA-HDBK-5010 says pretty much the same thing for Space Structures/Vehicles*.**

Section 5.3 of USAF Mil Standard MIL-STD-1530D also states that the primary role of testing is "to validate or correct analysis methods and results and to demonstrate that requirements are achieved."

The Durability & Damage Tolerance (DADT) Challenge

Both **MIL-STD-1530D and USAF Structures Bulletin EZ-SB-19-01 [5] require that the DADT assessment shall consider Linear Elastic Fracture Mechanics (LEFM)**.

USAF Structures Bulletin EZ-SB-19-01 [5] states:

The most difficult challenge facing the implementation of AM is to establish an "accurate prediction of structural performance specific to DADT".

AM and CSAM Limited-Life Replacement Parts

As aptly illustrated in the joint paper with US Navy (Navair) and the US Naval Research Lab (NRL) [6], AM and CSAM have the potential to rapidly build (print) parts that, when subjected to representative operational flight load spectra, have a fatigue life that is sufficiently long that they would be attractive for use as limited-life replacement parts on operational aircraft.

***The operational life of a "limited-life" part can be less than the design life of the airframe* [5,6].**

Such limited-life parts can play a vital role in ensuring aircraft availability (fixed and rotary wing and drones) and thereby ensuring/maintaining critical force multipliers, and reduce maintenance costs.

The use of AM and CSAM to build limited-life parts also addresses logistics problems, viz: time to obtain parts and part availability. *Question: What would be the time in a conflict?*

6. Jones R., Raman RKS**.,** Iliopoulos AP., Michopoulos JG., Phan N., Peng D., (2019) Additively manufactured Ti-6Al-4V replacement parts for military aircraft, International Journal of Fatigue, pp. 124, pp. 227-235. (**US Navy, ONR funded**)

With This Background Let Us Next Examine AM Scalmalloy®: An additively Manufactured Aluminium Alloy

- Scalmalloy®, a high-strength aluminium/magnesium/scandium (Al-Mg-Sc) alloy, was initially developed by Airbus for the additive manufacturing of aluminium alloy aerospace parts [7].

- The **US Navy study** into additive manufactured (AM) aluminium alloys [8] found that, **of the various AM aluminium alloys assessed, Scalmalloy® had superior tensile strength, Young's modulus, yield strength, and elongation to failure**.

7. Available online: https://www.apworks.de/scalmalloy (accessed on 20/08/2023).
8. Muhammad, M.; Nezhadfar, P.D.; Thompson, S.; Saharan, A.; Phan, N.; Shamsaei, N. A comparative investigation on the microstructure and mechanical properties of additively manufactured aluminum alloys. Int. J. Fatigue 2021, 146, 106165. https://doi.org/10.1016/j.ijfatigue.2021.106165

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With This Background Let Us Next Examine AM Scalmalloy®: An additively Manufactured Aluminium Alloy

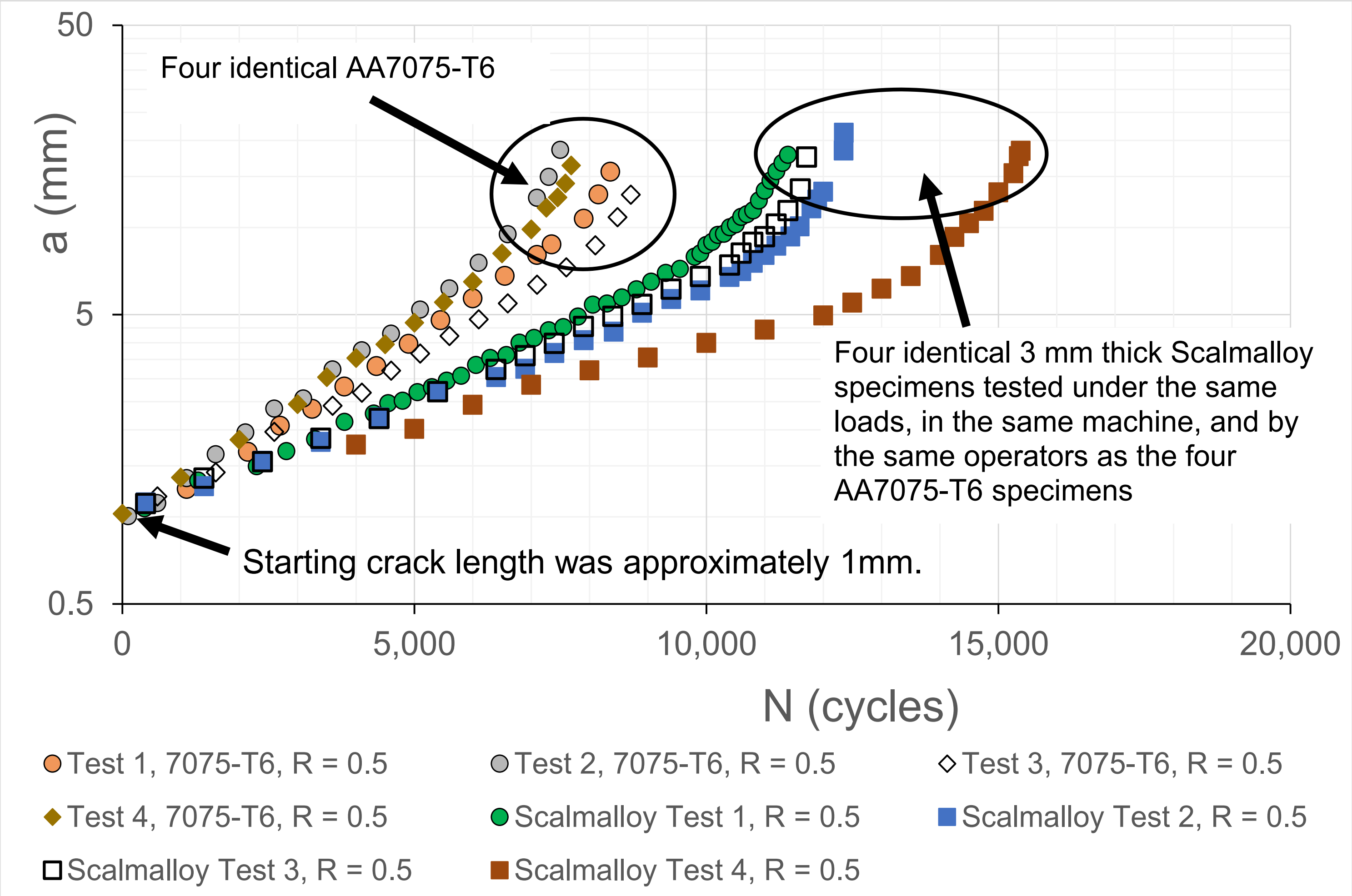
The **Boeing Space Intelligence and Weapon Systems (BSI&WS) funded study** [9] revealed that Scalmalloy® had a tensile strength, Young's modulus, yield strength, and an elongation to failure that were comparable to the commonly used aerospace-quality aluminium alloys, AA7050-T7451 and AA7075-T7351, superior to the AM aluminium alloys Al7Si0.6Mg and Al10SiMg, which are now increasingly being used in space applications, and also to the AM aluminium alloy 7A77, see the Table below.

	σ_y (MPa)	σ_{ult} (MPa)	Strain to Failure $\left(\frac{mm}{mm}\right)$
LPBF Scalmalloy®, heat treated at 325 °C for 4 h	508	530	0.16
A-l7Si-0.6Mg, heat treated	-	330	0.05
AA7050-T7451	432	521	0.11
AA7075-T6	503	575	0.11
AA7075-T7351	456	518	0.15
Al-7Si-0.6Mg, heat treated	-	330	0.05
AM 7A77	375	425	0.55
AA2024-T3	345	483	0.18

9. Jones R., Peng P., Ang ASM., Aston RW., Schoenborn ND., Phan ND., A comparison of the damage tolerance of AA7075-T6, AA2024-T3 and Boeing Space, Intelligence, and Weapons Systems AM built LPBF Scalmalloy, Aerospace, 10(8), 733; https://doi.org/10.3390/aerospace10080733

Boeing Space, Intelligence and Weapon Systems LPBF Scalmalloy®: Damage Tolerance

This study [9] also revealed that **Boeing Space, Intelligence and Weapon Systems (BSI&WS) LPBF built Scalmalloy® had a Damage Tolerance that was superior to that of conventionally manufactured 7075-T6,** **which is widely used in both fixed and rotary wing aircraft.**



Boeing Space, Intelligence and Weapon Systems LPBF Scalmalloy®: Durability & Environmental Resistance

It was subsequently shown [10, 11] that:

i) **BSI&WS LPBF built Scalmalloy® had a long crack *da/dN* versus Δ*K* curve (Damage Tolerance) that was equivalent to that of conventionally manufactured 2024-T3 [10].**

ii) **The durability of Boeing Space, Intelligence and Weapon Systems LPBF built Scalmalloy® could be predicted from 1st principles [10].**

iii) **Boeing Space, Intelligence and Weapon Systems LPBF built Scalmalloy had a durability that was superior to that of conventionally manufactured 7075-T6.**

iv) **Boeing Space, Intelligence and Weapon Systems LPBF built Scalmalloy was exceptionally resistant to environmental degradation [11].**

v) **The durability of Boeing Space, Intelligence and Weapon Systems LPBF built Scalmalloy® after 28 days prior exposure to an ASTM B117-19 5% NaCl at 35°C could be predicted from 1st principles [11].**

10. Jones, R.; Ang, A.; Aston, RW.; Schoenborn, ND.; Champagne, VK.; Peng, D.; Phan ND., On the Growth of Small Cracks in 2024- T3 and Boeing Space, Intelligence and Weapon Systems AM LPBF Scalmalloy®, Fatigue & Fracture of Engineering Materials & Structures, 48, 1, 31-43, 2025. https://doi.org/10.1111/ffe.14468
11. Andrew Ang, Richard Aston, Hannah King, Shareen S.L. Chan, Nicole D. Schoenborn, Daren Peng, and Rhys Jones, Corrosion And Fatigue Behaviour Of Boeing Space, Intelligence, And Weapons Systems Laser Powder Fusion Built Scalmalloy® In 5% NaCl, Fatigue & Fracture of Engineering Materials & Structures, 19th February, 2025. https://doi.org/10.1111/ffe.14601

To Perform The Necessary DADT Predictions It Is Best To Use The Hartman-Schijve (HS) Variant Of The NASGRO Crack Growth Equation

Fortunately, the growth of *both long and small cracks* in conventionally manufactured, AM, and CSAM materials, as well as in cold spray repairs, can often be expressed as per the Hartman-Schijve (HS) variant of the NASGRO equation [12], viz:

$$da/dN = D\,(\Delta\kappa)^p \qquad (1)$$

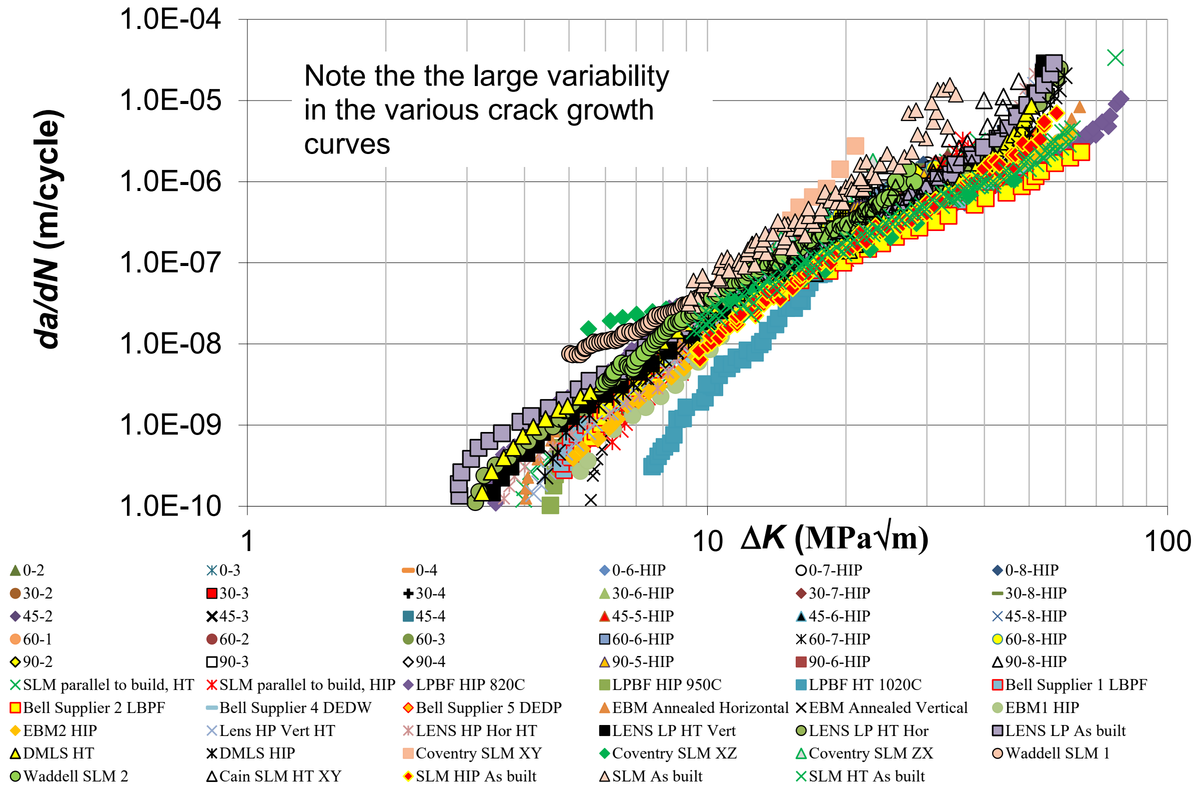
where $\Delta\kappa$ is the **crack tip (similitude) parameter** as defined by Schwalbe [13], viz:

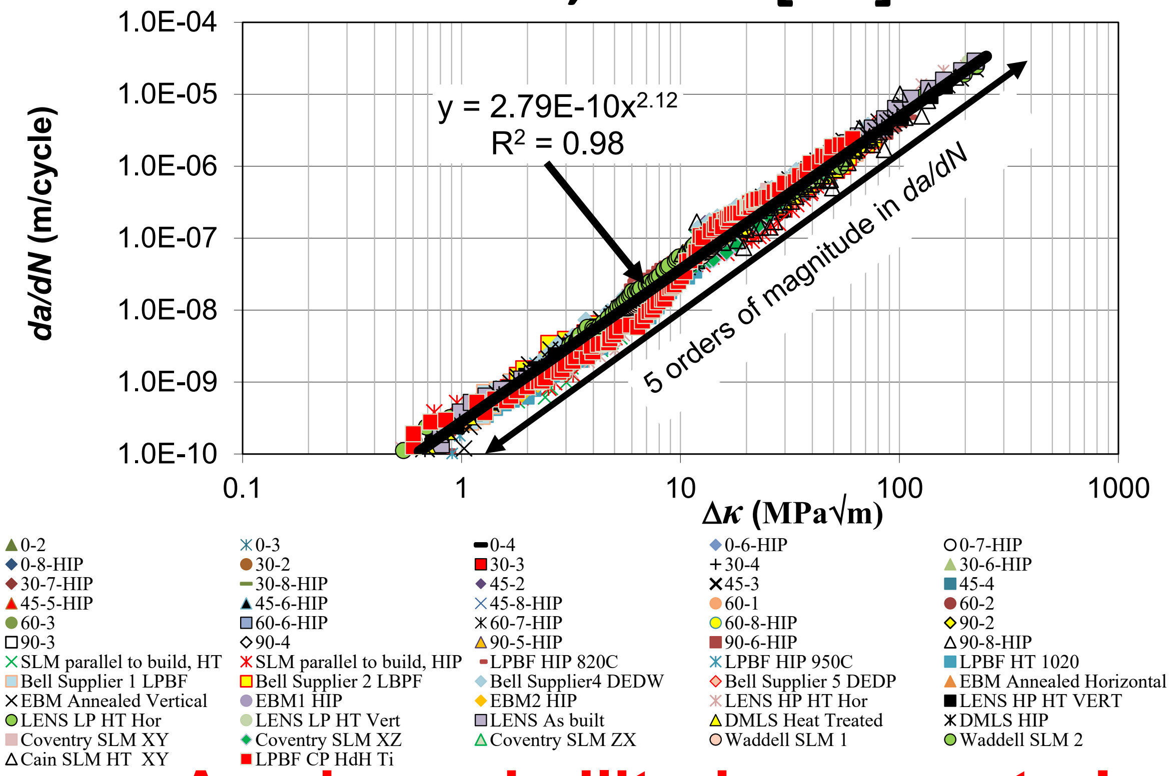
$$\Delta\kappa = (\Delta K - \Delta K_{thr})\,/(1-(K_{max}/A))^{1/2} \qquad (2)$$

There are a number of related equations that are related to the hypothesis that *da/dN* is a function of how much ΔK exceeds the fatigue threshold. A few selected examples of the application of Equations (1) and (2) to both conventionally manufactured and AM materials are given in [12,14-20].

12. Jones R., Fatigue Crack Growth and Damage Tolerance, Invited Review Paper, Fatigue and Fracture of Engineering Materials and Structures, (2014), 37, 5, pp. 463–483
13. Schwalbe K.H., (2010) On the Beauty of Analytical Models for Fatigue Crack Propagation and Fracture-A Personal Historical Review, J. ASTM Intl., 7, 3-73.
14. Jones, R.; Rans, C.; Iliopoulos, A.P.; Michopoulos, J.G.; Phan, N.; Peng, D. Modelling the Variability and the Anisotropic Behaviour of Crack Growth in SLM Ti-6Al-4V. Materials 2021, 14, 1400. https://doi.org/10.3390/ma14061400. **(ONR funded)**
15. Main B., Evans R., Walker K., Yu X., Molent L., Lessons from a fatigue prediction challenge for an aircraft wing shear tie post. International journal of fatigue. 2019;123:53-65.
16. Tan J.L., Chen B.K., Prediction of fatigue life in aluminum alloy (AA7050-T7451) structures in the presence of multiple artificial short cracks, Theoretical and Applied Frac. Mechanics, 2015, 78, 1-7.
17. Ye J., Syed AK., Zhang X., Eimer E., Williams S., Fatigue crack growth behaviour in an aluminium alloy Al-Mg-0.3Sc produced by wire based directed energy deposition process, Fatigue & Fracture of Engineering Materials and Structures, 2023, 1-2. https://onlinelibrary.wiley.com/doi/epdf/10.1111/ffe.141138
18. Jones; R., Peng; D., A Building Block Approach to Sustainment and Durability Assessment: Experiment and Analysis, In: Aliabadi, Ferri M H and Soboyejo, Winston (eds.), Comprehensive Structural Integrity, 2nd Edition, vol. 7, pp. 73–101, 2023. Oxford, UK. Elsevier, ISBN 978-0-12-822944-6 **(both ONR and US Army, ITC-IPCA, Tokyo funded)**
19. Markham, MJ.; Fatemi, A.; Nam Phan, Mixed-Mode Small Fatigue Crack Growth Rates and Modelling in Additively Manufactured Metals, International Journal of Fatigue, 2024. doi.org/10.1016/j.ijfatigue.2024.108258
20. Dastgerdi; JN., Jaberi; O., Remes; H., Lehto; P., Toudeshky; HH., Kuva; J., Fatigue damage process of additively manufactured 316L steel using X-ray computed tomography imaging, Additive Manufacturing, 2023, 70, 103559. https://doi.org/10.1016/j.addma.2023.103559

Example: The variability in 57 R = 0.1 *da/dN* versus Δ*K* curves for tests performed by a wide range of labs on AM Ti-6Al-4V, from [18]





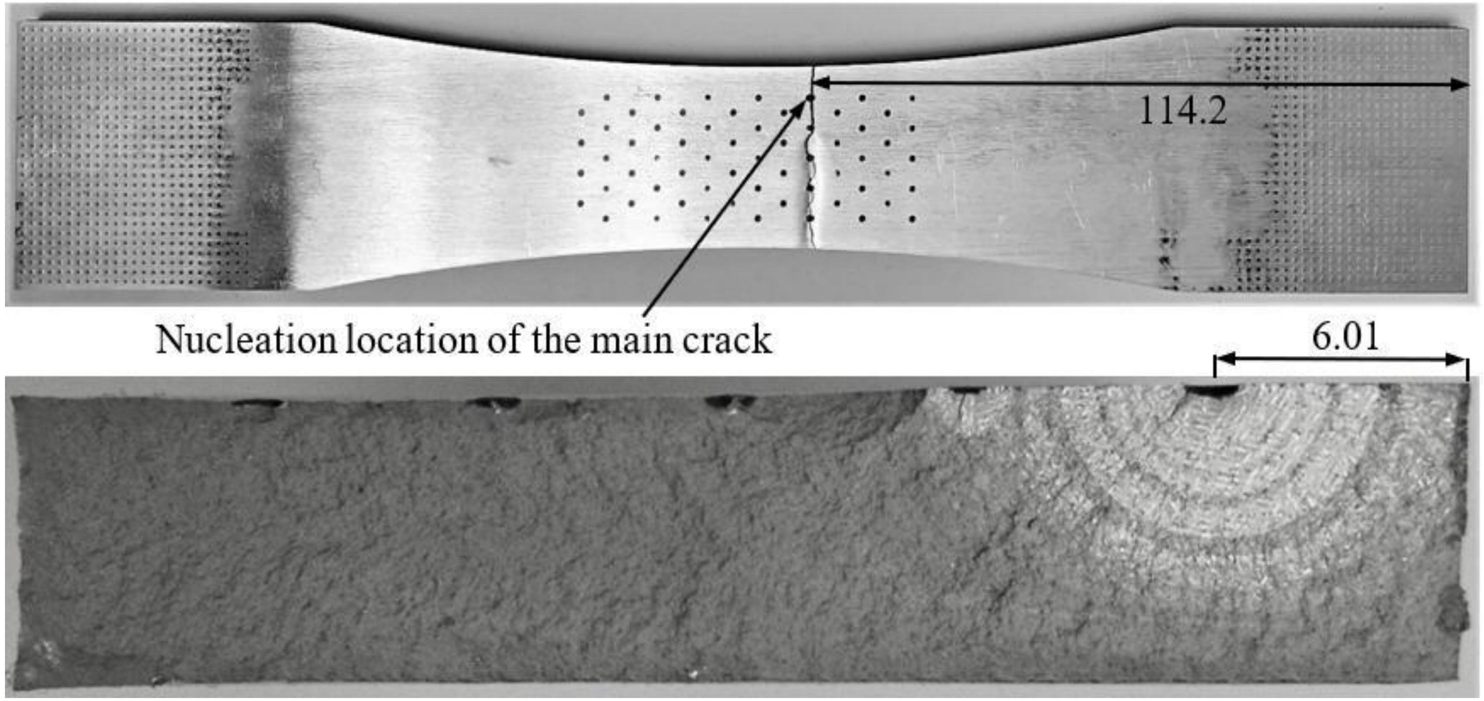
A unique similitude parameter!

When allowance is made for the effect of the different build processes on the variability in the two fracture mechanics *parameters* ΔK_{thr} and *A*, then (allowing for experimental error) each of these 57 curves collapse, over 5 orders of magnitude in *da/dN*, onto a single unique *da/dN* versus Δκ Master Curve [18].

The data covers a wide range of AM processes, see [20] for more details. LENS = Laser Engineered Net Surface, **EBM** = Electron Beam Melt, **SLM** = Selective Laser Melt, **LPBF** = Laser Powder Bed Fusion, **DED** = Directed Energy Deposition, **DMLS** = Directed Metal Laser Sintering, **WAAM** = Wire arc additively manufactured, **HIP** = Hot Isostatic Press.

Boeing Space, Intelligence and Weapon Systems LPBF Scalmalloy®: Durability

Reference [10] was the 1st to illustrate how the durability of Boeing Space, Intelligence and Weapon Systems (BSI&WS) LPBF built Scalmalloy®, could be PREDICTED from 1st principles using the Hartman-Schijve crack growth equation with NO ADJUSTABLE PARAMETERS.



A typical durability test specimen.

Boeing Service Contract No. 2399071 **Boeing Service Contract No. 2399071**

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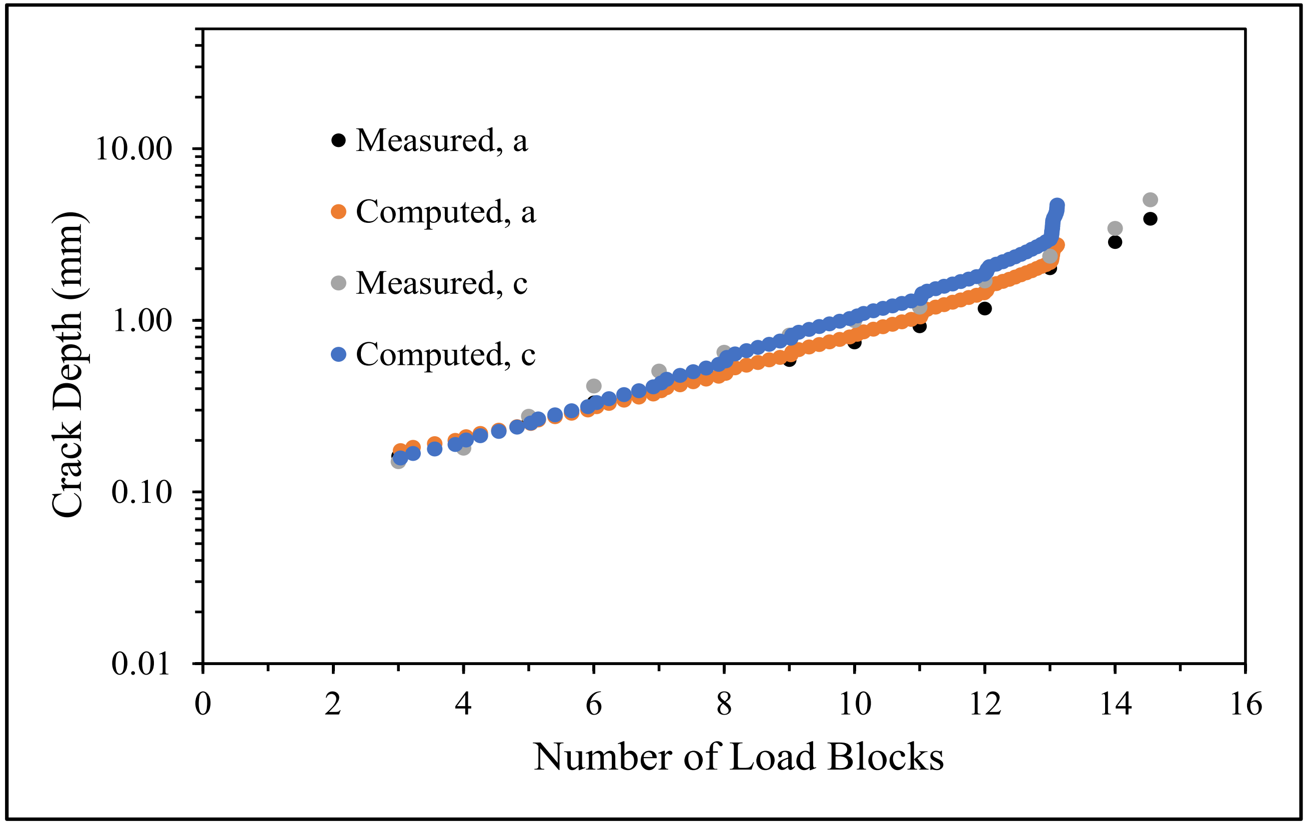
Boeing Space, Intelligence and Weapon Systems LPBF Scalmalloy: Durability

An example given in [10] for the growth of small naturally occurring cracks in Boeing Space, Intelligence and Weapon Systems LPBF built Scalmalloy®.



Measured and predicted crack growth histories for the specimen, from [11].

Boeing Service Contract No. 2399071 Boeing Service Contract No. 2399071

Boeing Space, Intelligence and Weapon Systems LPBF Scalmalloy®: Effect Of Environment On Durability

It was subsequently shown [11] that **Boeing Space, Intelligence and Weapon Systems LPBF built Scalmalloy® is exceptionally highly resistant to environmental degradation**, **and that prior exposure in an ASTM B117-19 5% NaCl at 35°C environment for 28 days had no significantly measurable effect on its durability.**

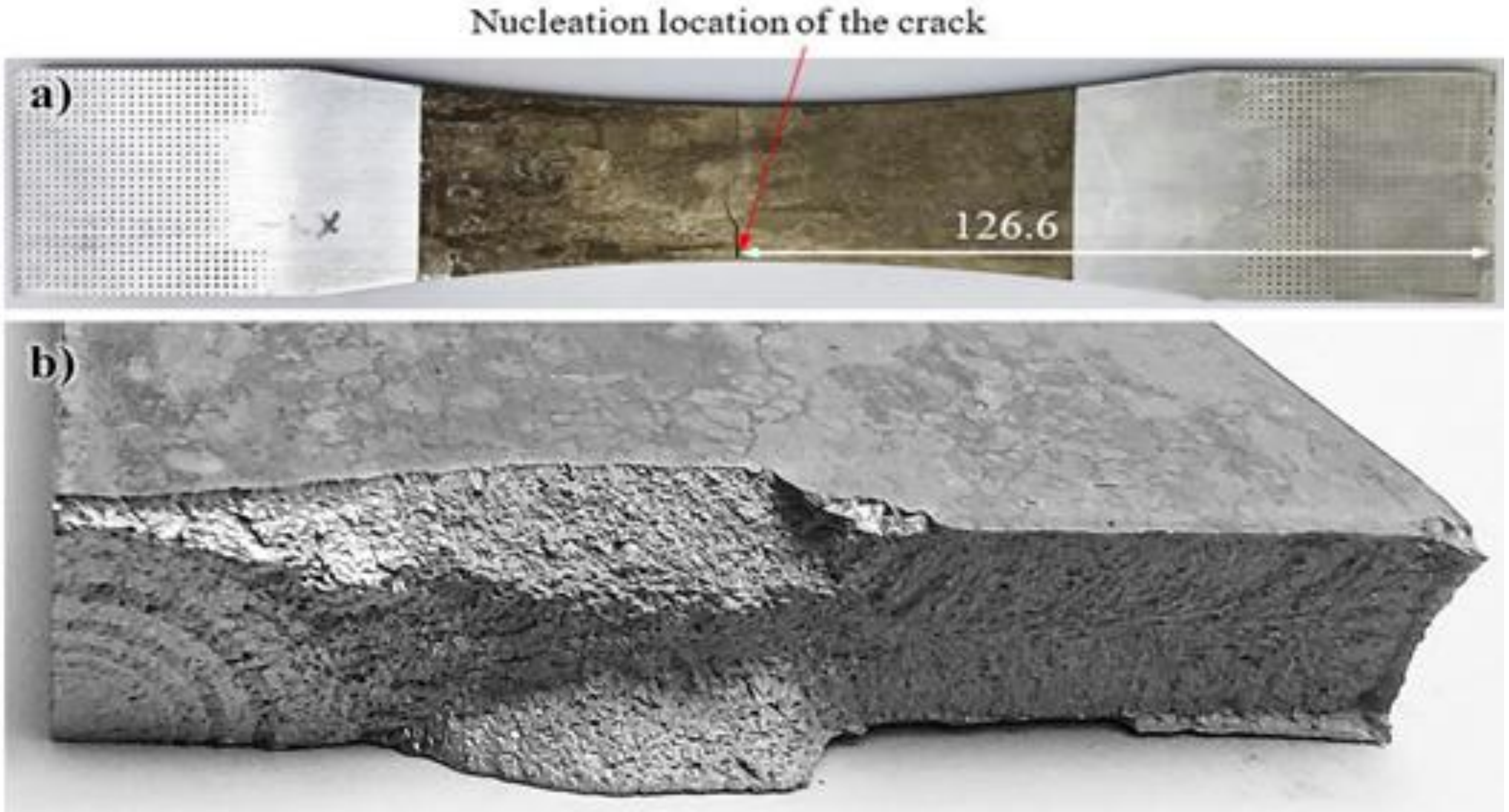
Contrast this with the extensive corrosion that can arise in conventionally built 7000 series aluminium alloys in operational military aircraft, from [21].

11. Andrew Ang, Richard Aston, Hannah King, Shareen S.L. Chan, Nicole D. Schoenborn, Daren Peng, and Rhys Jones, Corrosion And Fatigue Behaviour Of Boeing Space, Intelligence, And Weapons Systems Laser Powder Fusion Built Scalmalloy® In 5% NaCl, Fatigue & Fracture of Engineering Materials & Structures, 2025. https://doi.org/10.1111/ffe.14601

21. Mendoza R., In-service corrosion issues in Sustaiment of Naval Aircraft, AFRL-2022-5607, ASETSDefense 2012: Workshop on Sustainable Surface Engineering for Aerospace and Defense, August 27-30, 2012, San Diego, CA. https://apps.dtic.mil/sti/tr/pdf/ADA580875.pdf

Boeing Space, Intelligence and Weapon Systems LPBF Scalmalloy®: Effect Of Environment On Durability

A Boeing Space, Intelligence and Weapon Systems Scalmalloy® specimen after 28 days in an ASTM B117-19 5% NaCl environment at 35°C and subsequently fatigue tested under repeated marker block loading, see [11] for details.



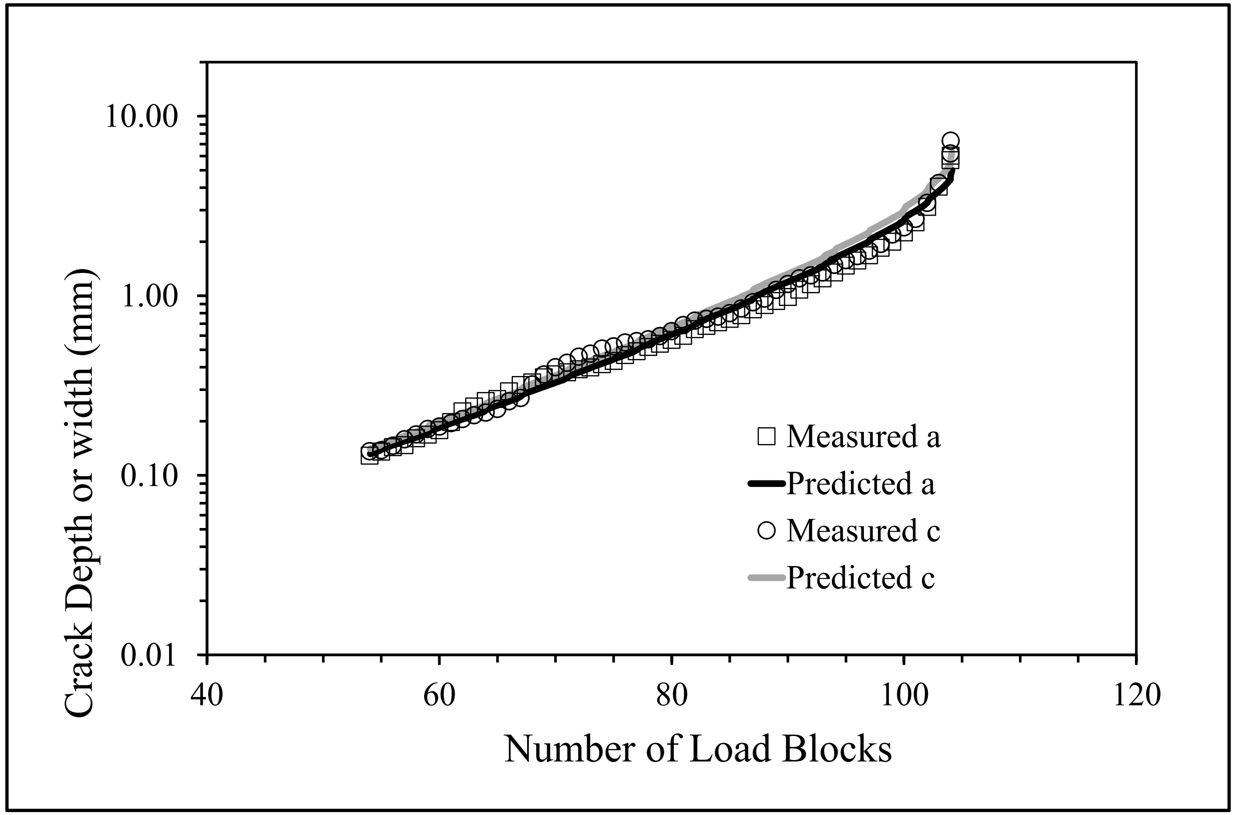
Boeing Service Contract No. 2399071

Boeing Space, Intelligence and Weapon Systems LPBF Scalmalloy®: Effect Of Environment On Durability

Reference [11] also revealed that its **durability could also predicted from first principles**. This **prediction used exactly the same Hartman-Schijve equation as that used in the predictions given in [10]**, **which were for specimens that were not subjected to 28 days in ASTM B117-19 environment**.

NO ADJUSTABLE PARAMETERS.

Boeing Service Contract No. 2399071



Measured and predicted crack growth histories, from [11].

SUMMARY

The durability and damage tolerance (DADT) of AM and Cold Spray Repairs is determined by just two fracture mechanics parameters, viz: the fatigue threshold and the fracture toughness. This makes it relatively easy to:

i. Determine the worst case (mean -3σ) crack growth curve mandated in NASA-HDBK-5010.

ii. Assess the quality of the build/part, the effect of different built processes and material anisotropy, *changes in microstructure* *and* its suitability for its use as a limited-life replacement part.

iii. Assess the effect of the environment on operational performance.

iv. Assess the ability of a Cold Spray Repair to maintain operational capability/availability.

These two (2) fracture mechanics parameters, together with the surface roughness and the level of the near-surface porosity/lack of fusion, determine the structural performance of AM and CSAM parts and Cold Spray Repairs.

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CONCLUSION

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We have also shown that:

i. Even after 28 days in an ASTM B117-19, 5% salt spray fog at 35°C BSI&WS LPBF Scalmalloy® does not experience significant environmental degradation.

ii. Furthermore, its durability can be predicted from first (1st) principles using the Hartman-Schijve crack growth equation.

iii. This argues well for the use of BSI&WS LPBF Scalmalloy® to print limited-life replacement parts for both fixed and rotary-wing aircraft as well as for attritable aircraft/drones.

The same formulation has also been shown to be able to predict the durability of a wide range of other AM and CSAM metals, cold spray repairs to corrosion damage and EAC cracking (IGC).

This durability analysis capability is now commercially available in the Zencrack Software Code with interfaces to the ABAQUS, Simcenter NASTRAN & ANSYS FE Codes, see: https://www.zentech.co.uk/zencrack_publications.

SLIDES IN RESERVE

A Proven Ability to Predict Crack Growth In Specimens with Environmentally Assisted Intergrannular Cracking (EAC)

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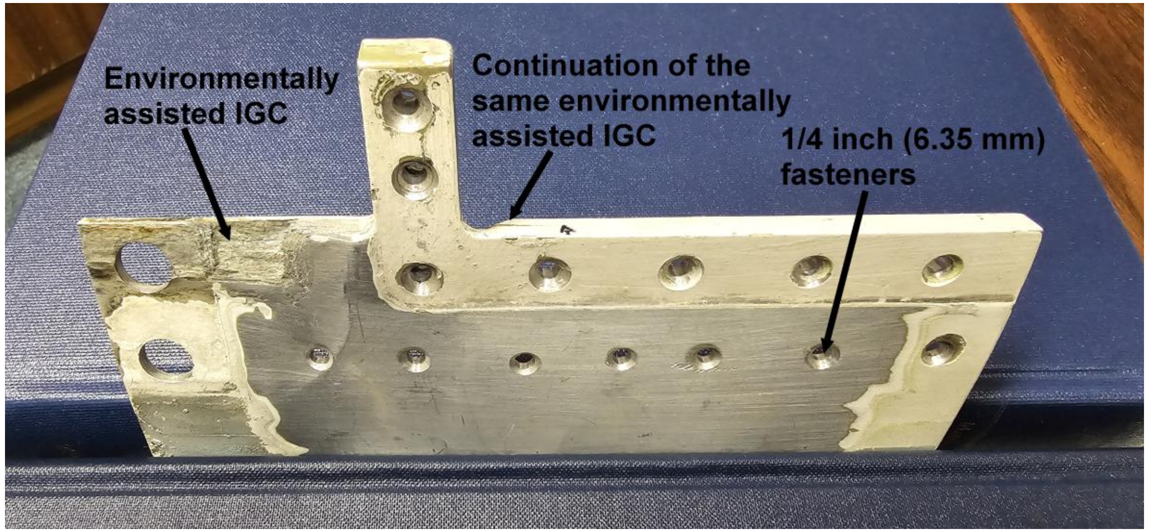
EASA Safety Information Bulletin [22] highlighted potential problems that can arise with Environmentally Assisted Cracking in aluminium alloys. Reference [23] had previously illustrated this phenomenon, albeit for 7075-T6, and how it can result in a new class of multi-site damage issues where we see both environmentally assisted intergrannular cracks and collocated cracking, with cracks nucleating from corrosion pits.

A key feature of [23,24] was that they highlight how the Hartman-Schijve equation is able to PREDICT the fatigue life of specimens under both operational flight loads and constant amplitude loading.



An example of EAC Intergrannular cracking seen in an operational aircraft.

The material is a 7075 aluminium alloy.

23. EASA Safety Information Bulletin, Environmentally Assisted Cracking in certain Aluminium Alloys, EASA 2018-04R2, 2021.
24. Lo M., Jones R., Bowler A., Dorman M., and Edwards D., Crack growth at fastener holes containing intergranular cracking, Fatigue and Fracture of Engineering Materials and Structures, (2017) 40, 10, pp. 1664–1675. (RAAF and US Navy funded)
25. Kundu S., Jones R., Peng D, et al, Review of Requirements for the Durability and Damage Tolerance Certification of Additively Manufactured Aircraft Structural Parts and AM Repairs, Materials 2020, 13, 1341; doi:10.3390/ma13061341

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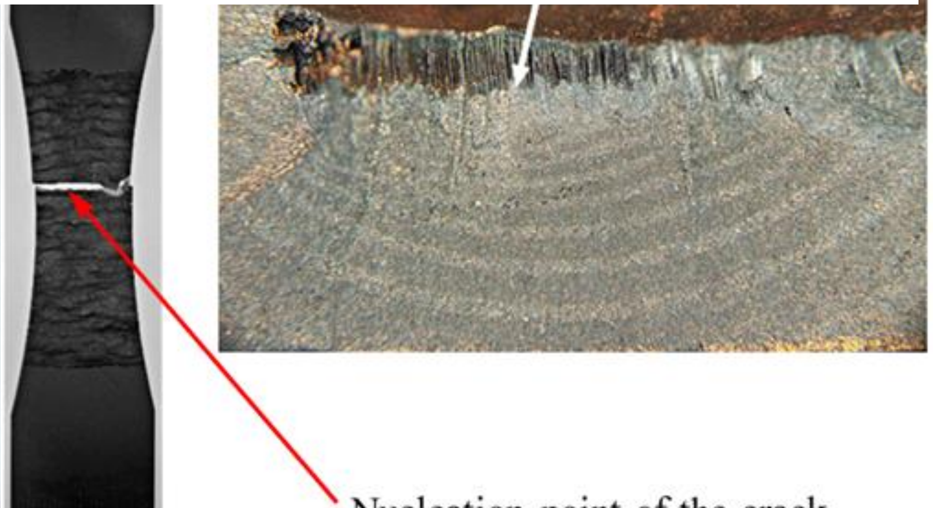
<u>Predicting</u> Crack Growth In A WAAM Part With An As-Built Surface

Since the effect of the manufacturing & build process and their resultant different material microstructures, on crack growth and the durability of AM and CSAM metals is controlled by just two fracture mechanics parameters, it is now possible to PREDICT the durability of AM parts. Examples that illustrate this for WAAM 18Ni 250 Maraging steel and also for WAAM CP-Ti are given in [26, 267].

26. D. Peng, R. Jones, A.S.M. Ang, A. Michelson, V. Champagne, A. Birt, S. Pinches, S. Kundu, A. Alankar, Singh Raman RK, Computing the durability of WAAM 18Ni 250 Maraging steel specimens, Fatigue and Fracture of Engineering Materials and Structures, 45, 12, 2022, 3535-3545. DOI: 10.1111/ffe.13828 (**US Army, ITC-IPAC, Tokyo funded**)

27. Peng D., Ang ASM., Nicholas MB., Champagne VK., Birt A., Michelson A., Langan S., Jones R., Predicting the growth of small cracks in wire arc additively manufactured (WAAM) CP-Ti, Proceedings 21st Australian International Aerospace Conference (AIAC21), Melbourne, Australia, 24 – 26th March 2025. (**KRI, US Army funded**.)

Example: Predicting the durability of as-built wire arc additively manufactured (WAAM) 18Ni 250 Maraging steel, from [26].



Nucleation point of the crack

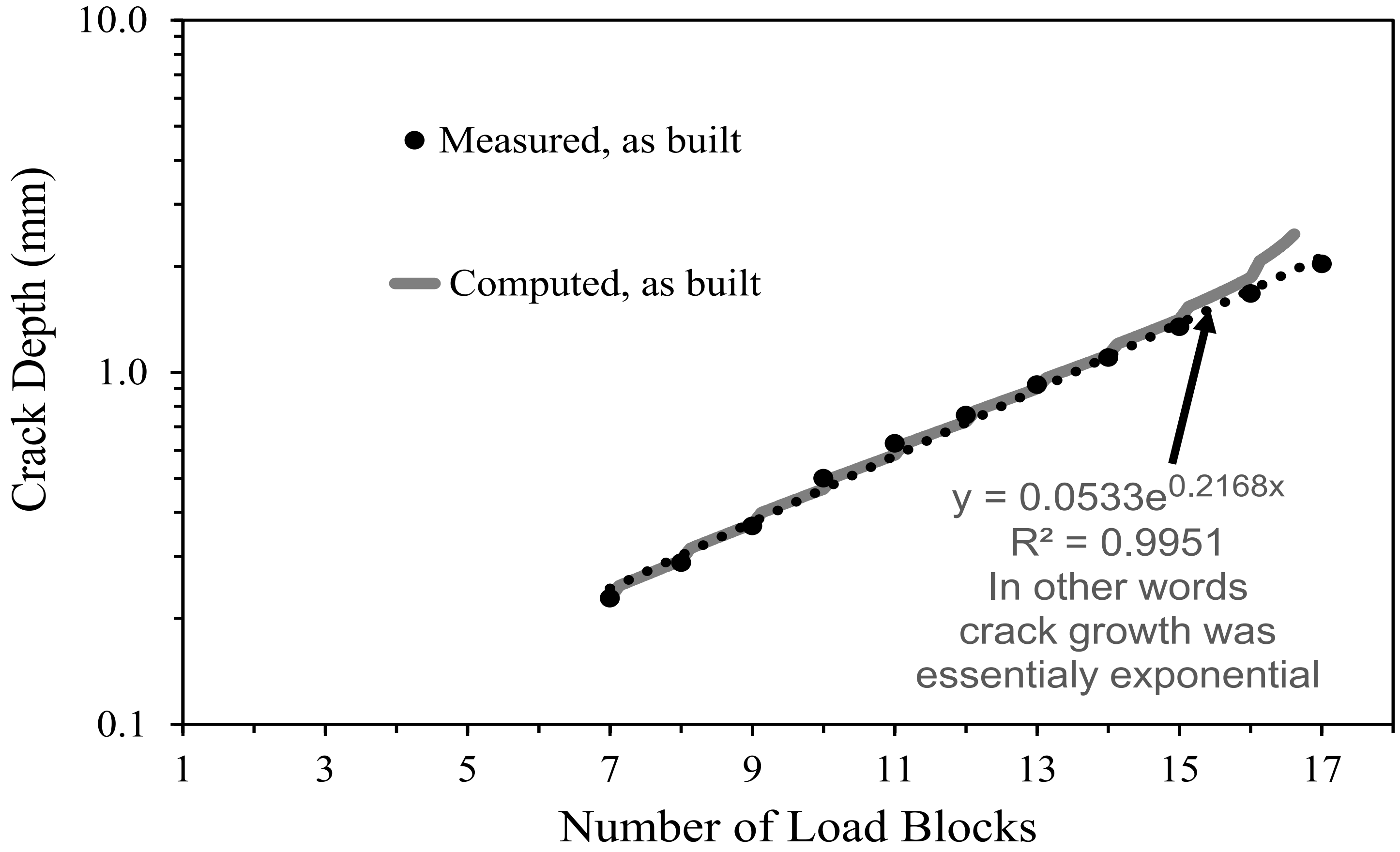
Predicting Crack Growth In A WAAM Part With An As-Built Surface

The measured and PREDICTED crack growth history, from [25].

Note: NAVAIR and Fatemi [19] have extended this finding to complex multi-axial (mixed mode) failures.

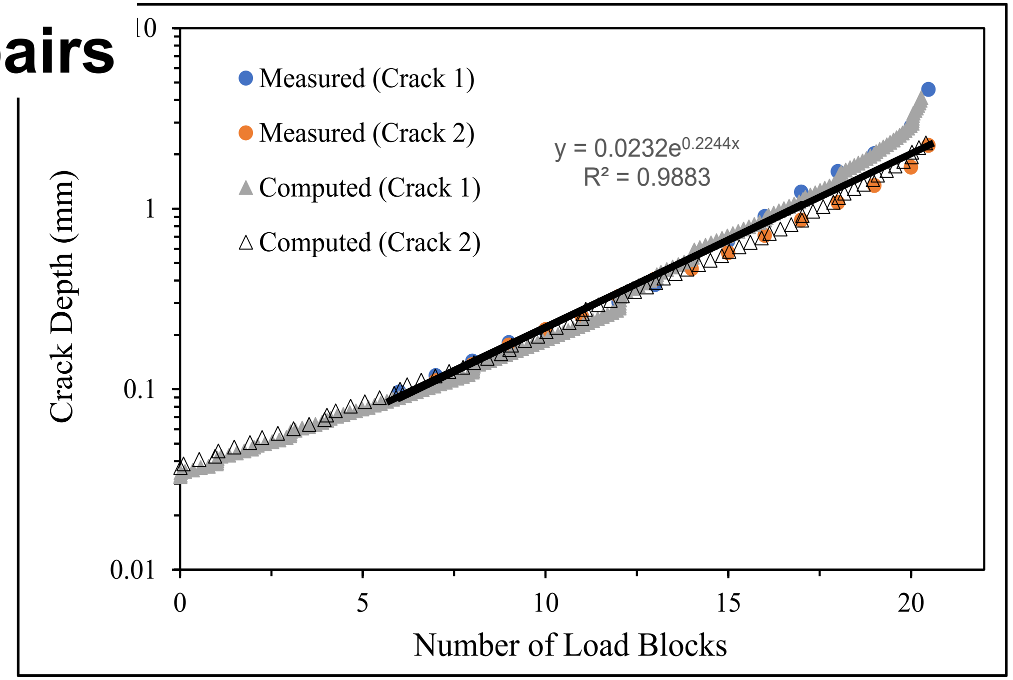
Since the initial crack size in this analysis was 0.01 inch (0.254 mm) **this analysis could also be used to assess the durability of the part.**

This observation is further substantiated in [28] for WAAM 18Ni 250 steels with both machined and as-built surfaces.



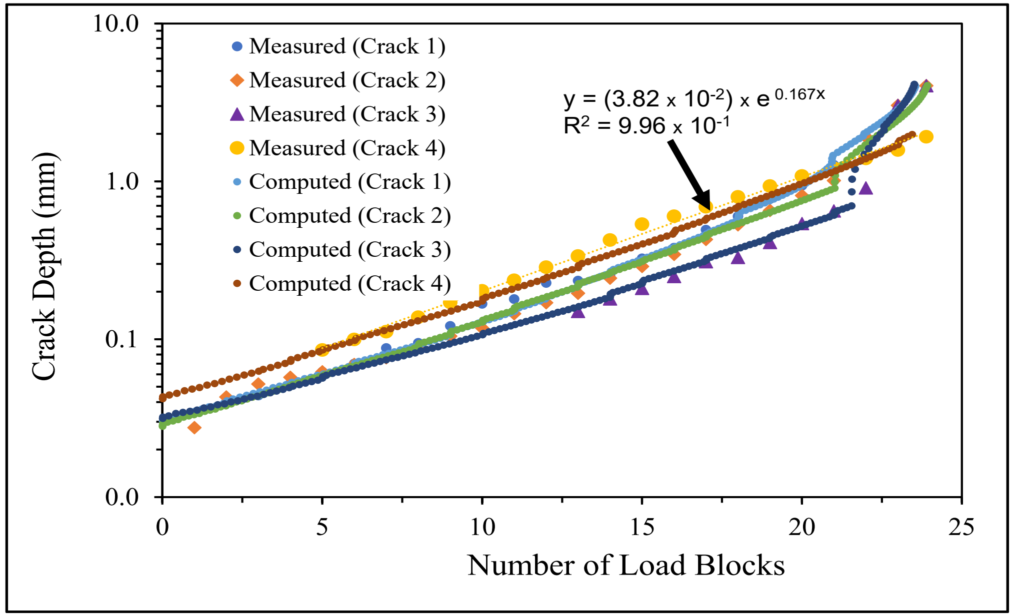
28. Peng D, Champagne VK, Ang ASM, Birt A, Michelson A, Pinches S, Jones R. Computing the Durability of WAAM 18Ni-250 Maraging Steel Specimens with Surface Breaking Porosity, Crystals, 2023; 13(3), 443. https://doi.org/10.3390/cryst13030443 (**US Army, ITC-IPAC, Tokyo funded**)

Predicting Small Crack Growth In Cold Spray Repairs



The Hartman-Schijve formulation has also been shown [29] to able to predict the durability of Cold Spray repairs to corrosion damage.

This is aptly illustrated in the two examples shown, which are both from [29].



29. Peng D., Tang C., Watts J., Ang ASM., Singh Raman RK., Nicholas MB., Phan ND., Jones R., Durability analysis of cold spray repairs: Phase I – Effect of surface grit blasting, Metals, 2024, 17, 2656. https://doi.org/10.3390/ma17112656 (**US Army, ITC-IPAC & LIFT funded**)

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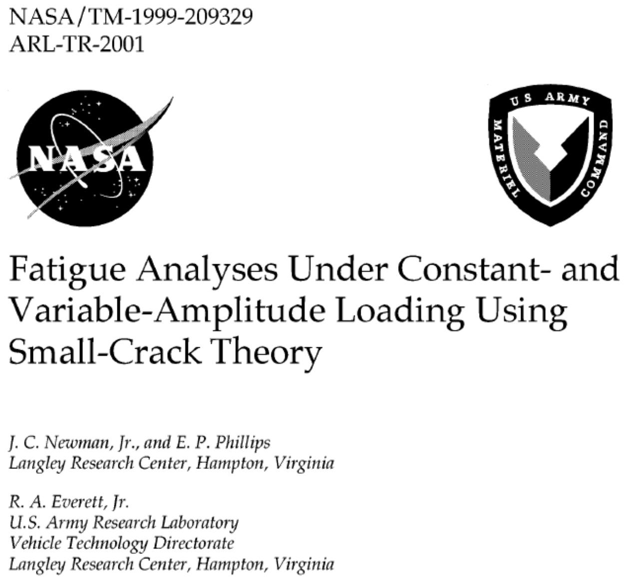
Why not use crack closure based equations


NASA/TM-1999-209329
ARL-TR-2001

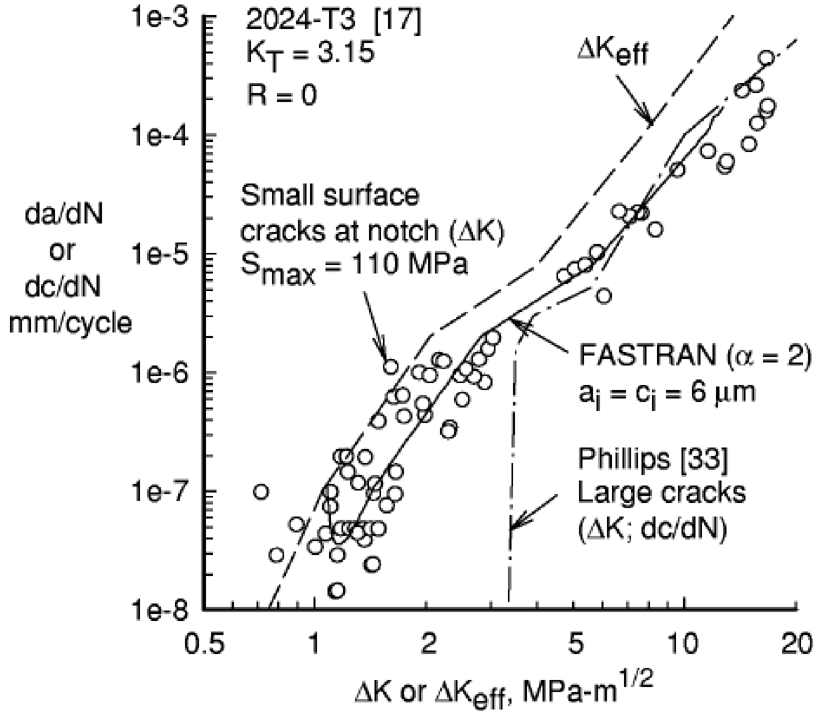
Fatigue Analyses Under Constant- and Variable-Amplitude Loading Using Small-Crack Theory

J. C. Newman, Jr., and E. P. Phillips
Langley Research Center, Hampton, Virginia

R. A. Everett, Jr.
U.S. Army Research Laboratory
Vehicle Technology Directorate
Langley Research Center, Hampton, Virginia

The AGARD (NATO) Round Robin Study [30], on the growth of small cracks in the aluminium alloy 2024-T3, is widely acknowledged as being the Seminal study into the growth of naturally occurring small cracks.

The subsequent 1999 NASA report, by Newman et al [31], led to the widespread belief that the closure corrected crack growth curve could represent the small crack growth curves seen in these tests, see the Figure shown in this slide.



30. Newman Jr. J.C.., Edwards P.R., Short-Crack Growth Behaviour in an Aluminium Alloy - an AGARD Cooperative Test Programme, AGARD-R-732, December 1988. https://ntrs.nasa.gov/citations/19890007916

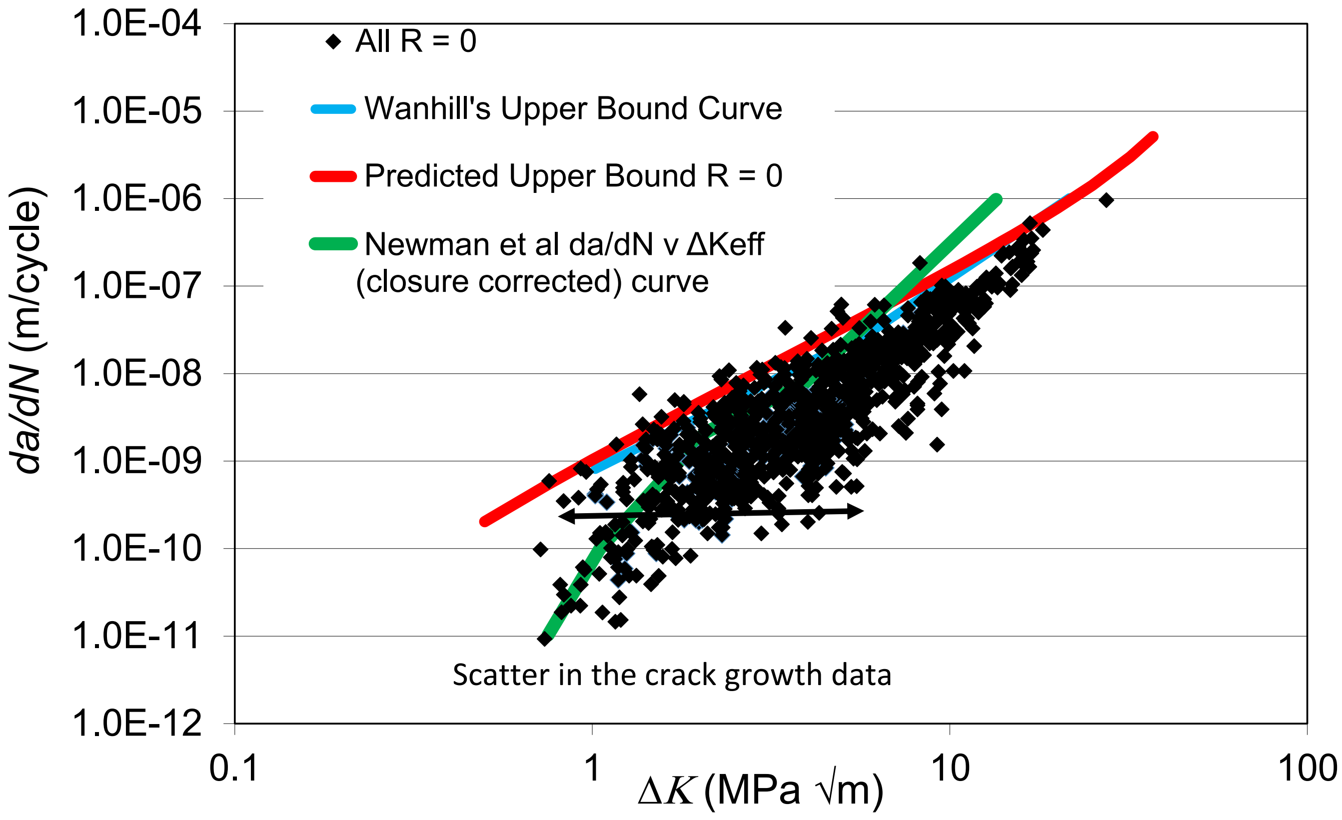
31. Newman JC., Phillips EP., Everett RA., Fatigue Analyses under constant and variable-amplitude loading using Small-Crack Theory, NASA/TM-1999-209329, 1999. https://ntrs.nasa.gov/citations/19990046065

So what is wrong?

Unfortunately, the report by Newman et al [31] is misleading in that it omitted numerous data sets that were obtained as part of the AGARD (NATO) Round Robin Study [30], see the figure in this slide.

The missing data sets include the upper bound curve obtained by Wanhill at the NLR in the Netherlands [32].

32. Wanhill RJH., Durability Analysis Using Short and Long Fatigue Crack Growth Data, Proceedings International Conference on Aircraft Damage Assessment and Repair, Ed-ited by Jones R. and N. J. Miller, Published by The Institution of Engineers Australia, ISBN (BOOK) 85825 537 5, July 1991. https://www.researchgate.net/publication/325102704_Durability_Analysis_Using_Short_and_Long_Fatigue_Crack_Growth_Data



The complete *R* = 0 data sets, including the upper bound curve obtained by Wanhill at the NLR in the Netherlands [32].

When was this mistake discovered? Answer: In 2025.

This unfortunate (and misleading) *error* was only discovered in 2025, see [33].

Here, i.e. in [33], it was shown how the worst-case (upper bound) curve required by NASA HDB-1510 could be PREDICTED from first principles using the Hartman-Schijve crack growth equation.

It was also shown that this PREDICTED upper-bound curve essentially coincided with that given by Wanhill [32].

33. Jones, R.; Ang, A.; Aston, RW.; Schoenborn, ND.; Champagne, VK.; Peng, D.; Phan ND., On the Growth of Small Cracks in 2024- T3 and Boeing Space, Intelligence and Weapon Systems AM LPBF Scalmalloy®, Fatigue & Fracture of Engineering Materials & Structures, 48, 1, 31-43, 2025. https://doi.org/10.1111/ffe.14468

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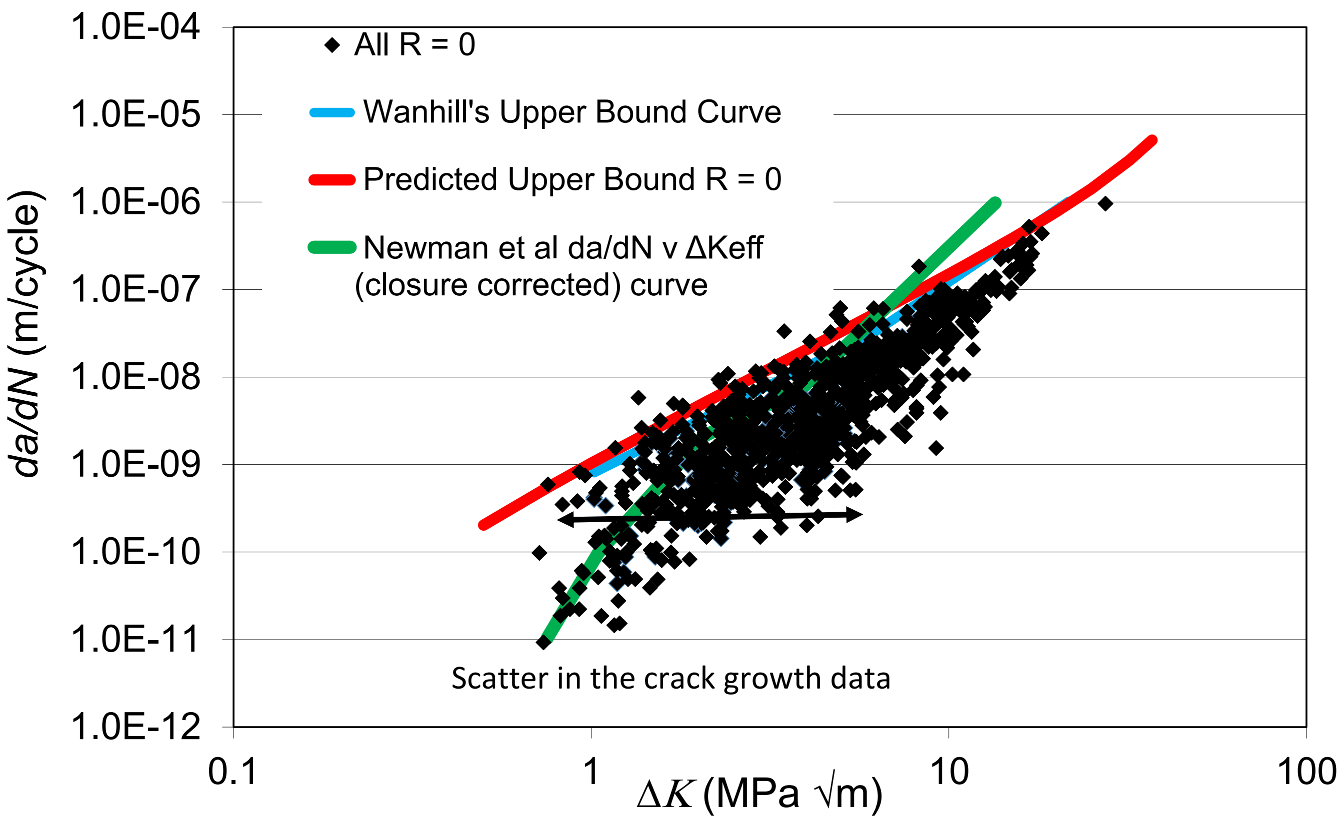
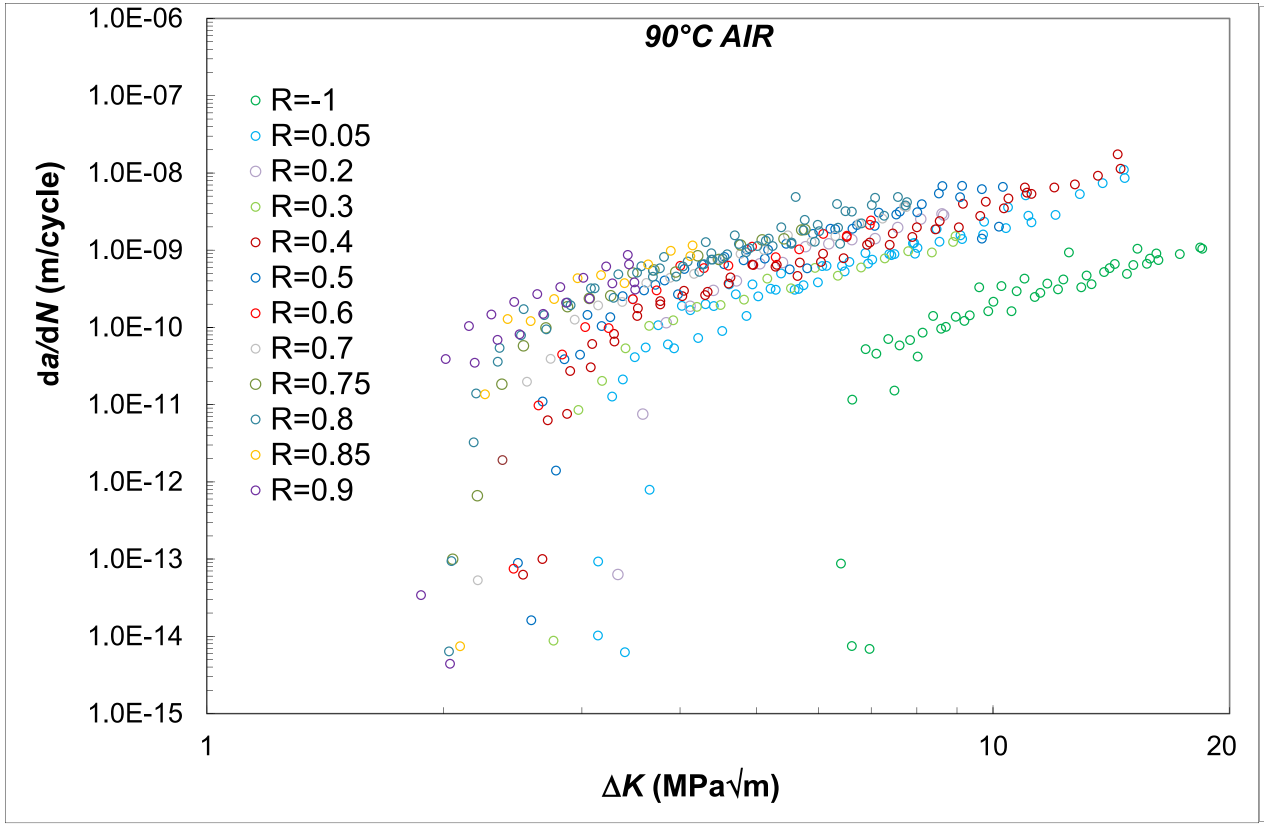
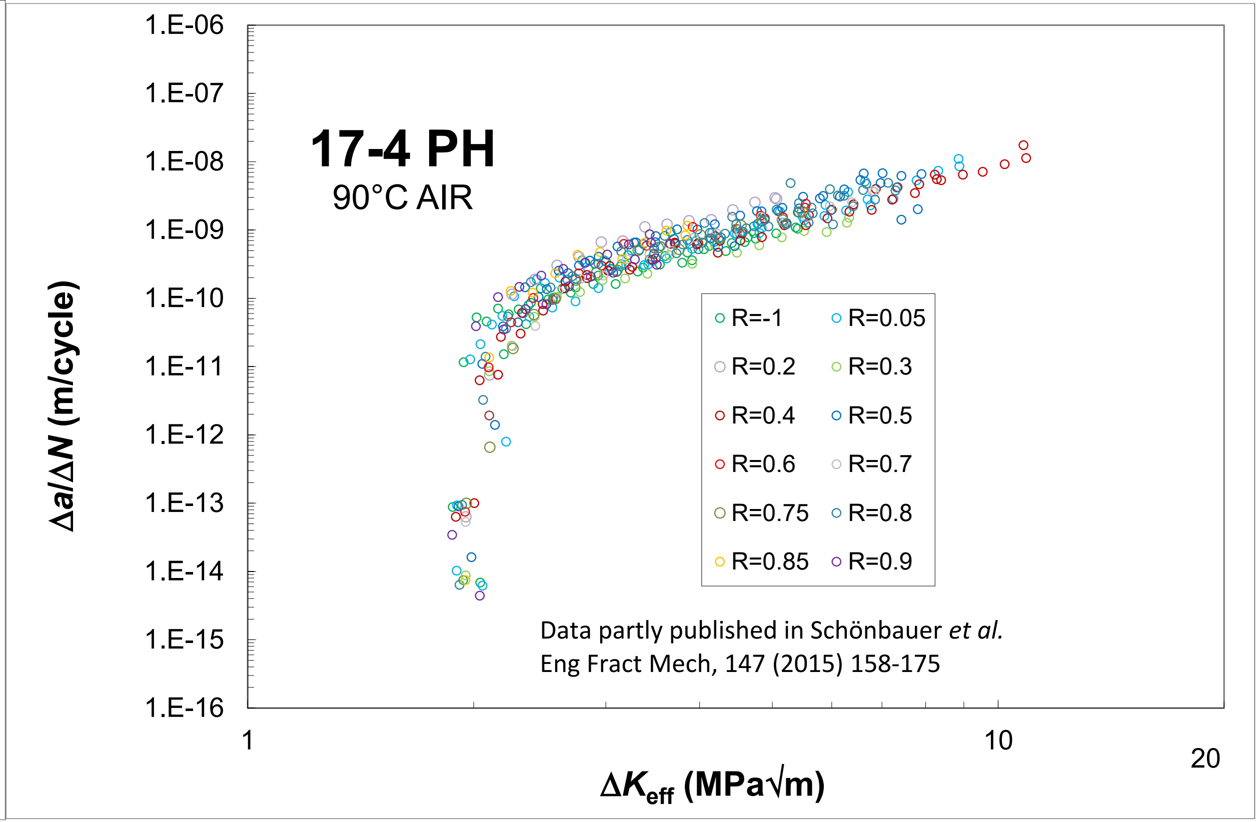


The complete *R* = 0 data sets, including the upper bound curve obtained by Wanhill at the NLR in the Netherlands [32] and the predicted upper-bound curve given in [33]. The closure-free curve does not represent an acceptable upper bound.

Problem with Newman's crack opening formulae, see [34]

The formulae developed by Newman et al differs from Elber's crack closure formulation. The Correct Mathematical Formulae is given in [34]. *This formulae often holds for both long and small cracks.* Example: Long cracks in 17-4PH steel at 90C. Other examples are given in [34].





34. Jones,R.; Ang, A.S.M.; Peng,D, Simple Scaling as a Tool to Help Assess the Closure-Free da/dN Versus ΔKeff curve in a Range of Materials, Materials, 2024,17,5423. https://doi.org/10.3390/ma17225423