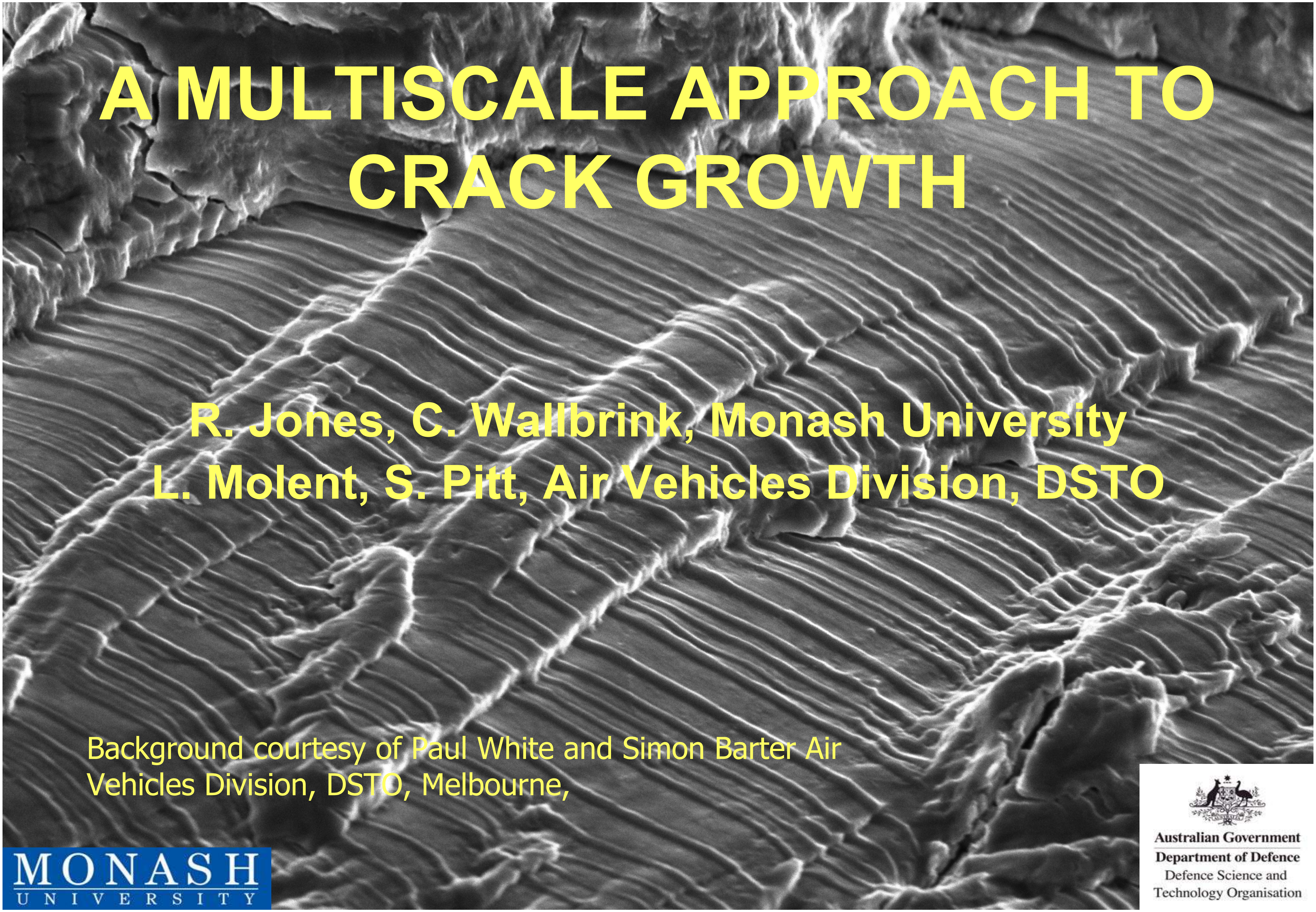

A MULTISCALE APPROACH TO CRACK GROWTH

R. Jones, C. Wallbrink, Monash University
L. Molent, S. Pitt, Air Vehicles Division, DSTO

Background courtesy of Paul White and Simon Barter Air Vehicles Division, DSTO, Melbourne,

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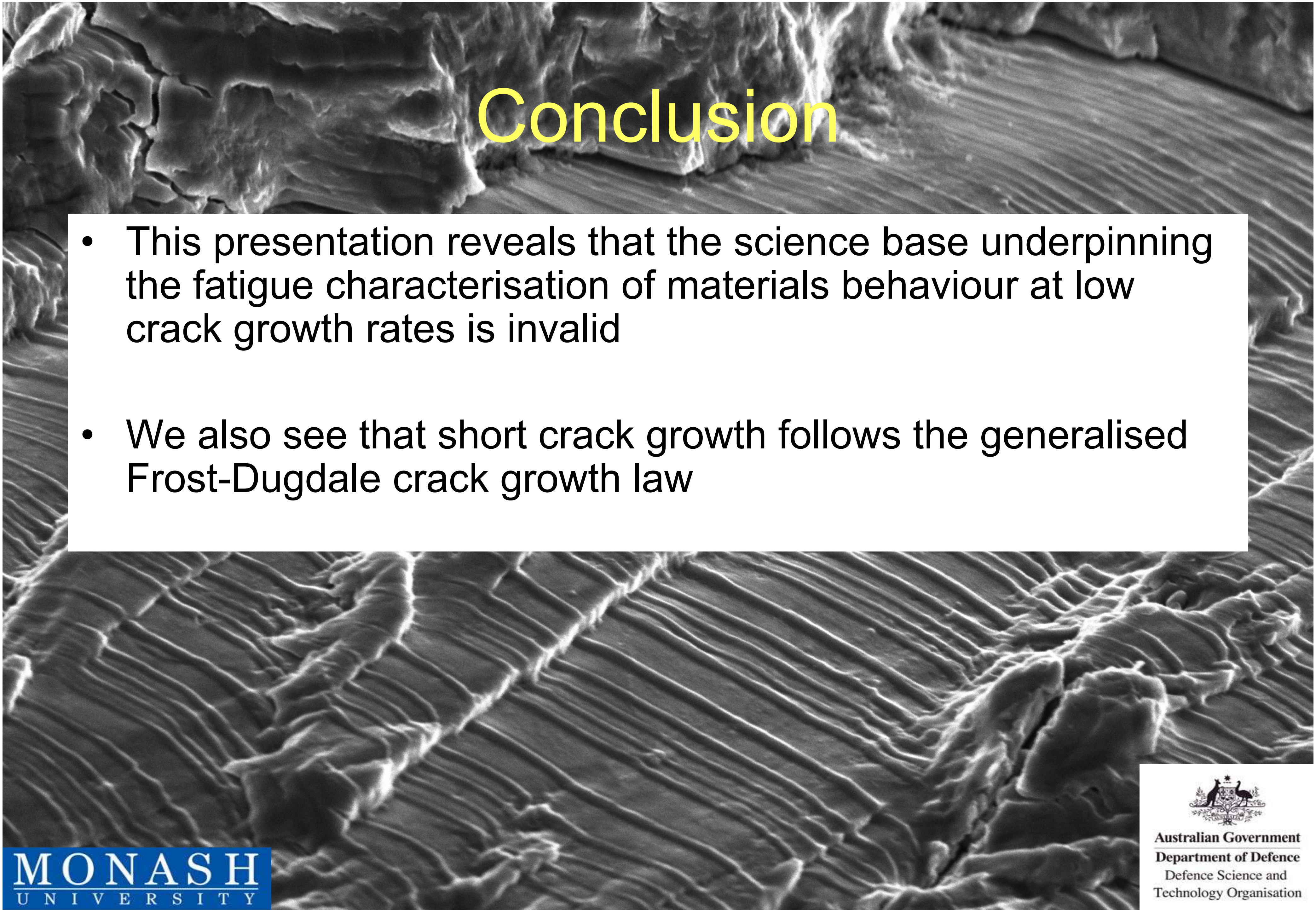
Conclusion



- This presentation reveals that the science base underpinning the fatigue characterisation of materials behaviour at low crack growth rates is invalid
- We also see that short crack growth follows the generalised Frost-Dugdale crack growth law

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Why is this important

- The scientific basis all of the current fatigue crack growth laws, AFGROW, FASTRAN, NASGRO, etc, is invalid in Region I.

- Region I is the region in which a crack will spend most of its life.

- The current similitude based methodology is non conservative for small sub mm cracks in highly stressed components, i.e. it is both incorrect and unconservative.

- Corrects the science base needed to predict delamination growth in composites.

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Early crack growth concepts:

- The USAF funded research in the late 50’s

  H. W. Liu, “Crack propagation in thin metal sheet under repeated loading”, WADC TN 59-383, *1959*.

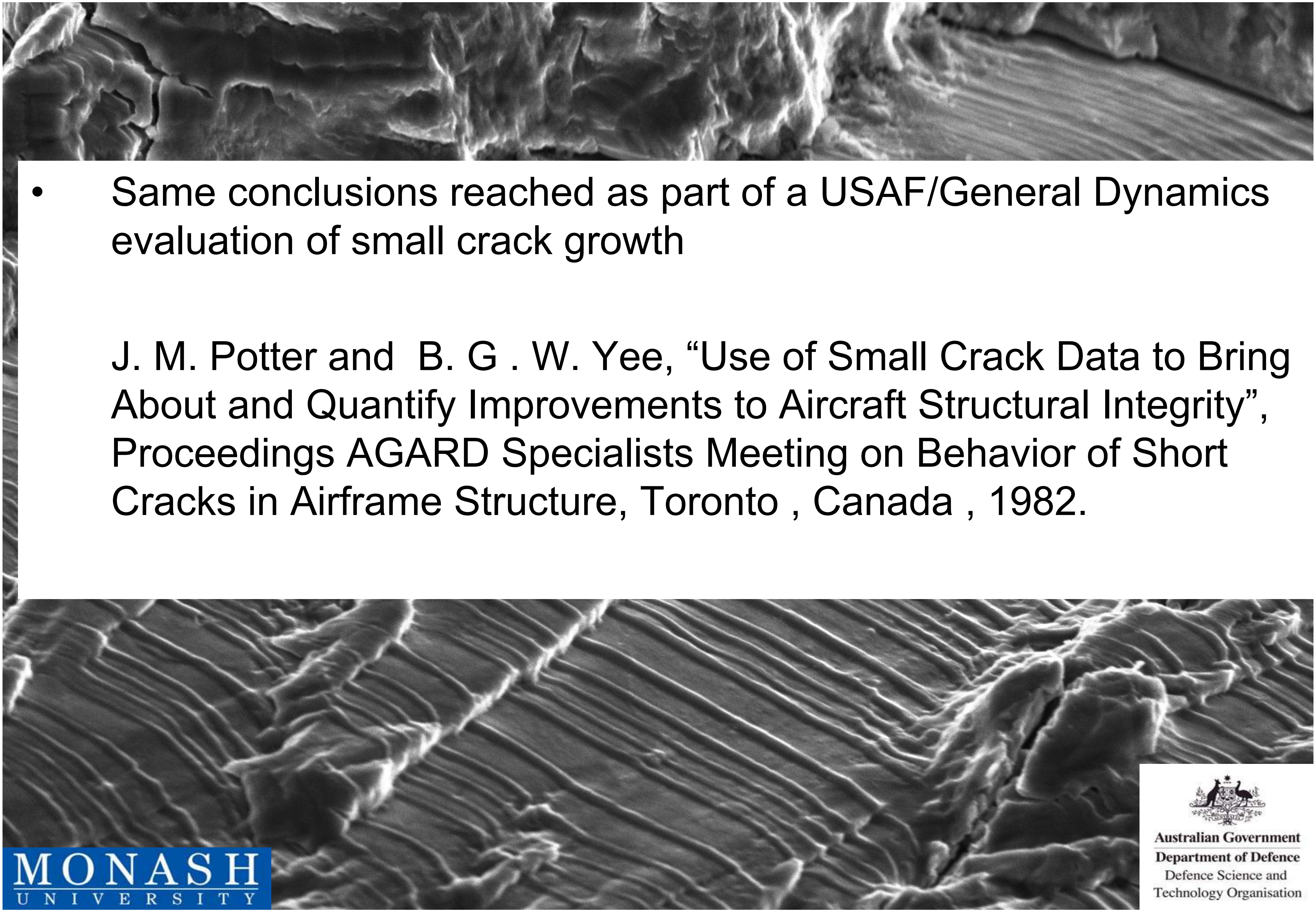
  An extensive test program using centre cracked panels revealed that for short cracks

$$da/dN \ \alpha \ a \qquad \Leftrightarrow \qquad N \ \alpha \ \ln(a) - \ln(a_{initial})$$

- Frost and Dugdale at Sheffield and the National Engineering Labs, in East Kilbride, Scotland.

  N. E. Frost and D. S. Dugdale, “The Propagation of Fatigue Cracks in Test Specimens”, Journal Mechanics and Physics of Solids, 6, pp 92-110, *1958*.

  Performed an extensive test program that revealed that for short cracks $da/dN \ \alpha \ a$



- Same conclusions reached as part of a USAF/General Dynamics evaluation of small crack growth

  J. M. Potter and B. G . W. Yee, “Use of Small Crack Data to Bring About and Quantify Improvements to Aircraft Structural Integrity”, Proceedings AGARD Specialists Meeting on Behavior of Short Cracks in Airframe Structure, Toronto , Canada , 1982.

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Subsequently confirmed by

L. Molent, R. Jones, S. Barter, and S. Pitt, “Recent Developments In Fatigue Crack Growth Assessment”, International Journal of Fatigue, In press.

Polak J., Zezulka P., “ Short crack growth and fatigue life in austenitic-ferritic duplex stainless steel”, Fatigue Fract Engng Mater Struct 28, 923–935, 2005.

S. A. Barter, L. Molent, N. Goldsmith and R. Jones, “An experimental evaluation of fatigue crack growth”, Journal Engineering Failure Analysis, Vol 12, 1, pp 99-128, 2005.

Harkegard G., Denk J., Stark K., “ Growth of naturally initiated fatigue cracks in ferritic gas turbine rotor steels”, International Journal of Fatigue, (2005), pp 1–12.

Murakamia Y., Miller K. J., “ What is fatigue damage? A view point from the observation of low cycle fatigue process”, International Journal of Fatigue, pp 1–15, 2005.

Kawagoishi, N. Chen Q. and Nisitani H., “ Significance of the small crack growth law and its practical application”, Metallurgical and Materials Transactions A, Volume 31A, pp 2005-2013, 2000.

R. Jones, S. Barter, L. Molent, and S. Pitt, “A multi-scale approach to crack growth”, Chapter in the Book, Multiscaling in molecular and continuum mechanics: biology, electronics and material science, Edited by G. C. Sih, Springer, March 31, 2006.

Caton M. J., Jones JW, Boileau J. M, and Allison J. E., “ The effect of solidification rate on the growth of small fatigue cracks in a cast 319-type aluminum alloy”, Metallurgical and Materials Transactions A, Volume 30A,pp 3055-3068, 1999.

Nisitani, H, Goto M. and Kawagoishi, N., “A small-crack growth law and its related phenomena”, Engineering Fracture Mechanics, Vol. 41, No. 4, pp. 499-513, 1992.

H. W. Liu, “A review of fatigue crack growth analyses”, Theoretical and Applied Fracture Mechanics 16 (1991), pp 91-108,

Tomkins, B.,“ Fatigue crack propagation—an analysis ”, *Phil. Magazine* , 18, 1041–1066, (1968).

The da/dN v ΔK concept (similitude) Paris et al, and Liu

- P.C. Paris, M.P. Gomez and W.E. Anderson, A rational analytic theory of fatigue, *Trend in Engineering, 13* (January 1961) 9 14.

First paper to link da/dN to K_{max}

- H.W. Liu, Fatigue crack propagation and applied stress range, *ASME Trans., Journal of. Basic Engineering, 85D* (1) (March 1963 pp 116-122.

Linked da/dN to (ΔK)

Built on Paris' concept of similitude so that the need to have a linear relationship between ln(a) and N forced Liu to set m =2. However, this gave an incorrect stress dependency.

- P.C. Paris and F. Erdogan, “A critical analysis of crack propagation laws”, *ASME Trans., J. Basic Engineering, 85D* (4) (December 1963) pp 528. Same general formulae as Liu (1963) but stated

  $$da/dN \; \alpha \; (\Delta K)^4 \quad \text{and} \quad da/dN \; \alpha \; a^2$$

  This infers that crack growth is merely a function of ΔK and K_{max}. Two different cracks with the same (effective) stress intensity factor range ΔK and K_{max} will grow at the same rate.

  This is termed similitude.

- Whilst this gave an improved stress dependency it was inconsistent with, and hence ignored, Liu’s and Fost and Dugdale’s earlier experimental results for the crack growth history of centre cracked panels that revealed:

  $$N \; \alpha \; \ln(a) - \ln(a_{initial})$$

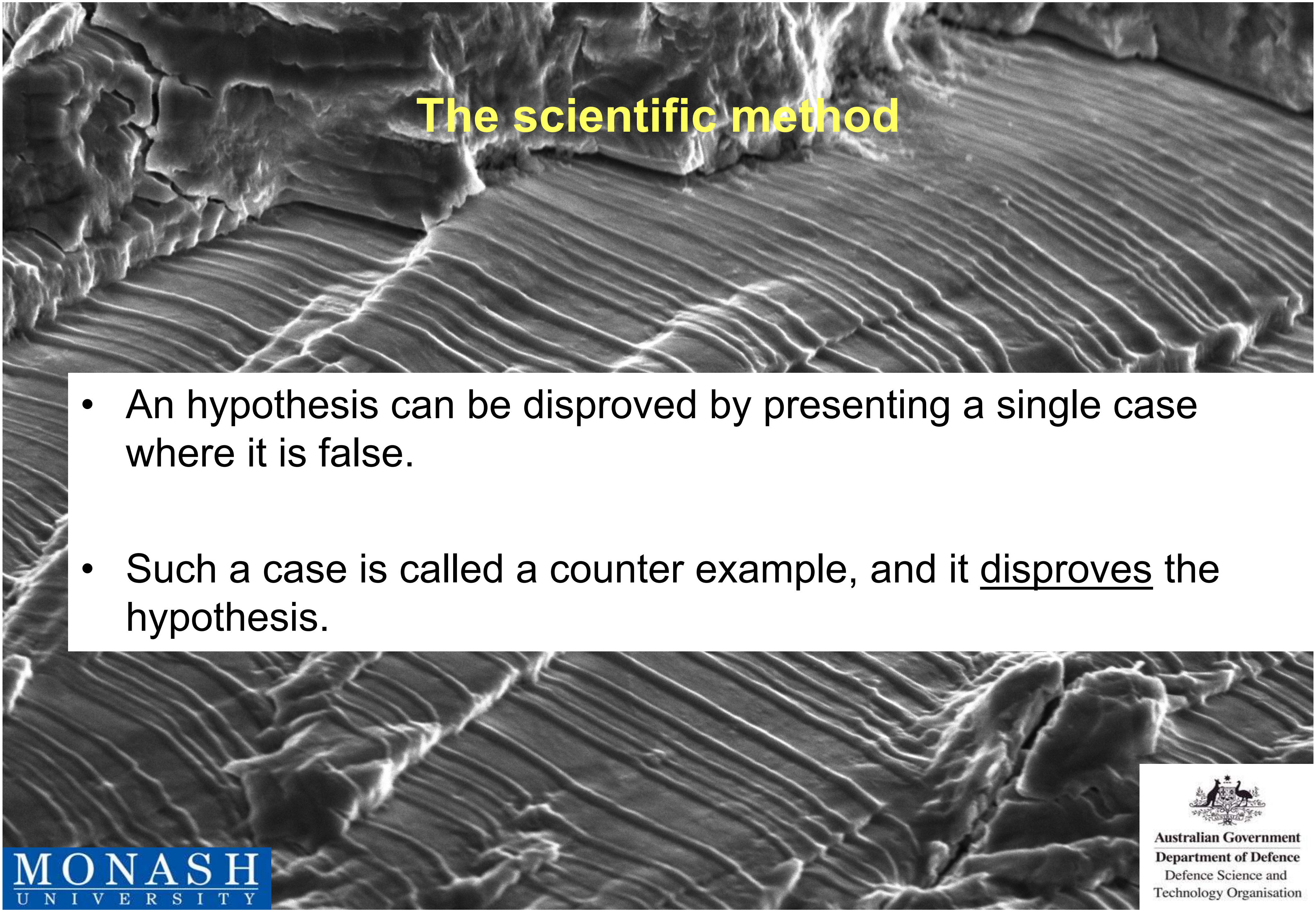
Current approaches are built on the generally accepted hypothesis for crack growth:

- Commonly accepted hypothesis: Crack growth is uniquely characterised by the stress intensity factor.

Two different cracks with the same (effective) stress intensity factor range ΔK and K_{max} will grow at the same rate.

- In the mid 1970’s Pearson, RAE Farnborough UK, showed that fatigue crack growth laws, determined for macroscopic crack growth data, could not be used to predict the growth of small sub-millimetre cracks, and that the constants in the crack growth law were a function of the size of the crack.

Pearson S., “Initiation of fatigue cracks in commercial aluminium alloys and the subsequent propagation of very short cracks”, Engineering Fracture Mechanics, 1975. Vol. 7, pp. 235-247.



The scientific method

- An hypothesis can be disproved by presenting a single case where it is false.

- Such a case is called a counter example, and it <u>disproves</u> the hypothesis.

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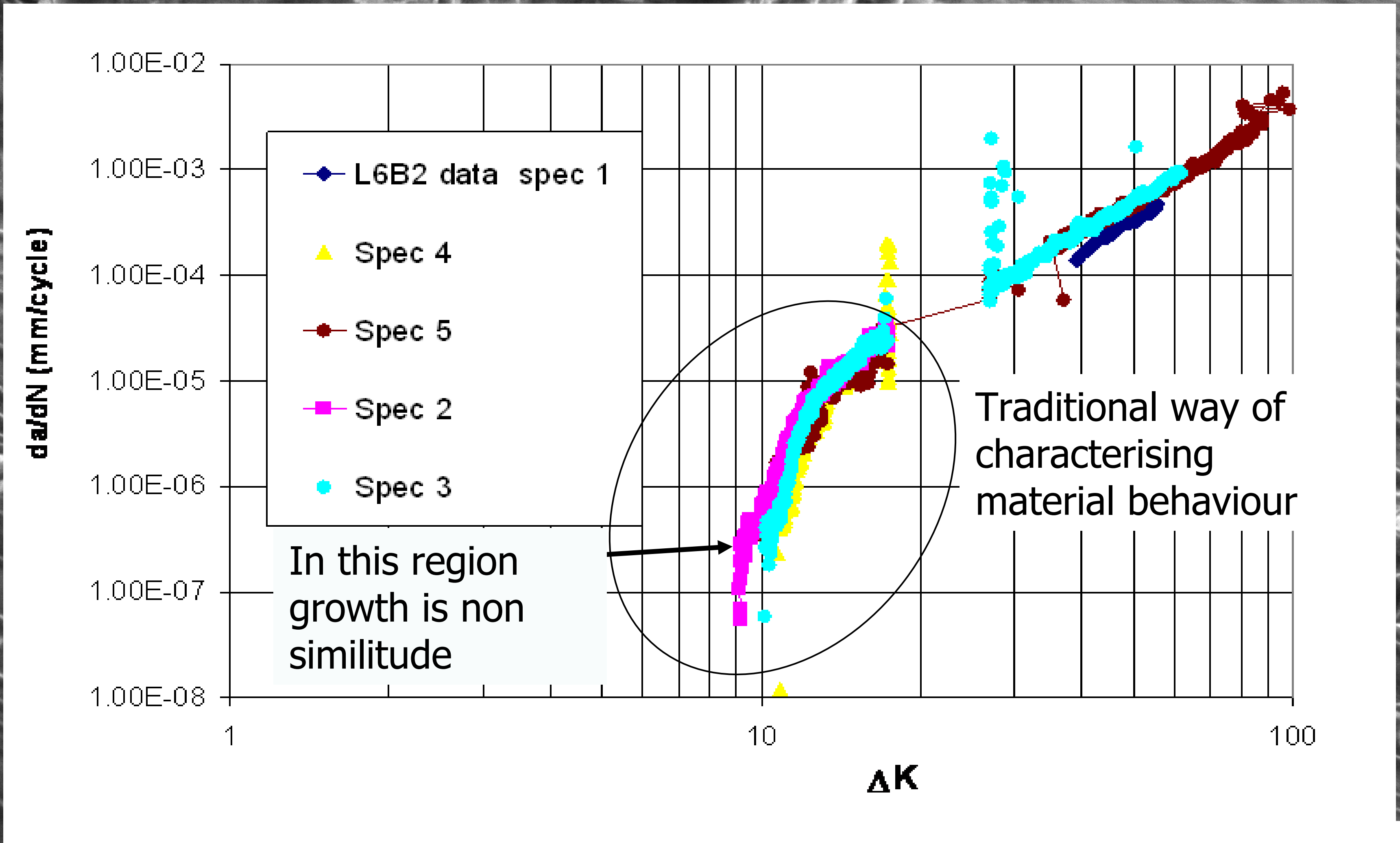
1st example: Crack growth v ΔK data for L6B-2 cast steel



Traditional way of characterising material behaviour

In this region growth is non similitude

Data courtesy of B. Chen, Rail CRC

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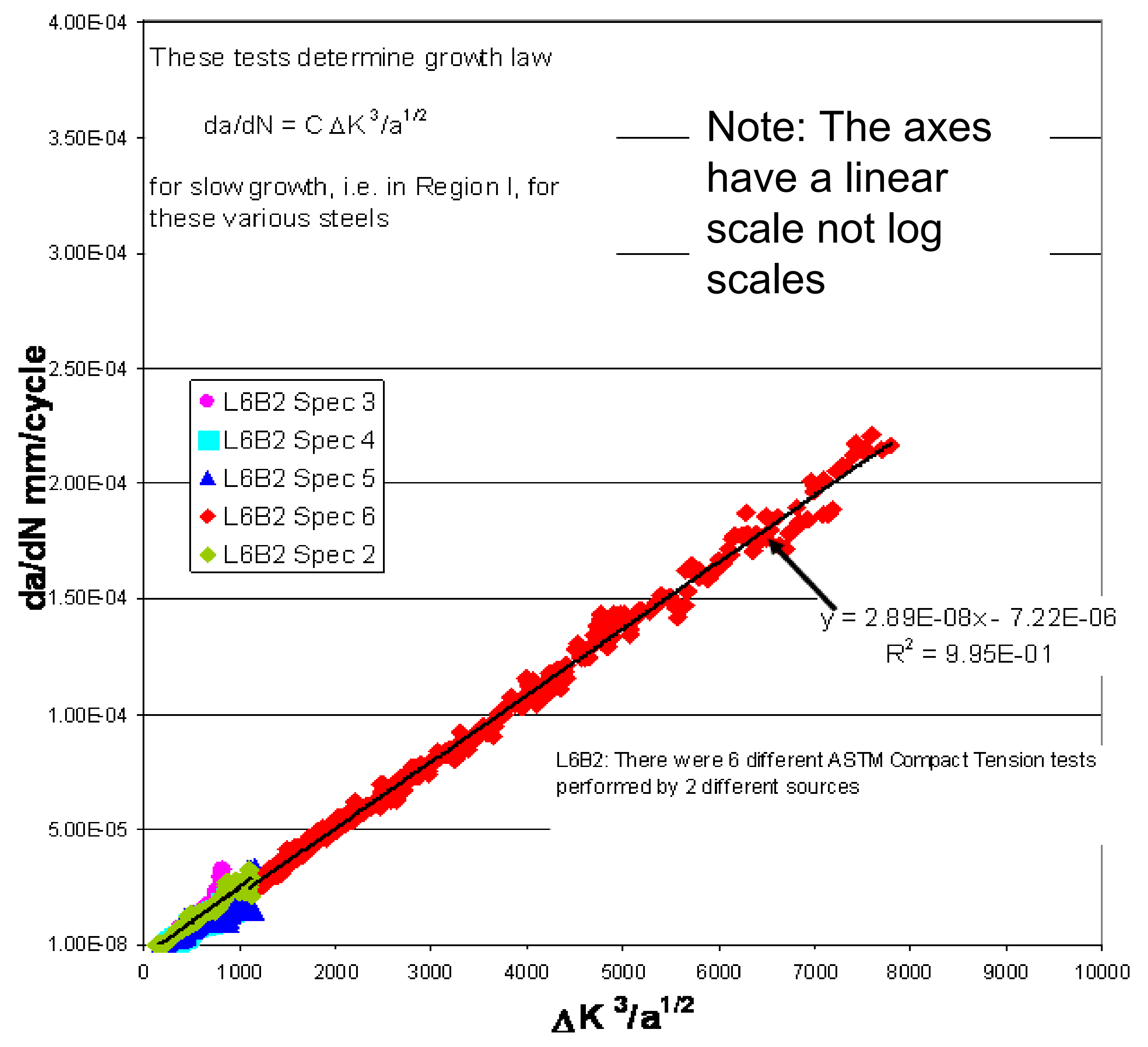
In this case analysis of the data shows that da/dN = C $(\Delta K)^3 / a^{1/2}$

Here we see a linear relationship between da/dN and $\Delta K^3/a^{1/2}$,

i.e. the crack growth rate is a function of both ΔK and the crack length a.

This expression for da/dN also yields the experimentally observed log-linear relationship



These tests determine growth law

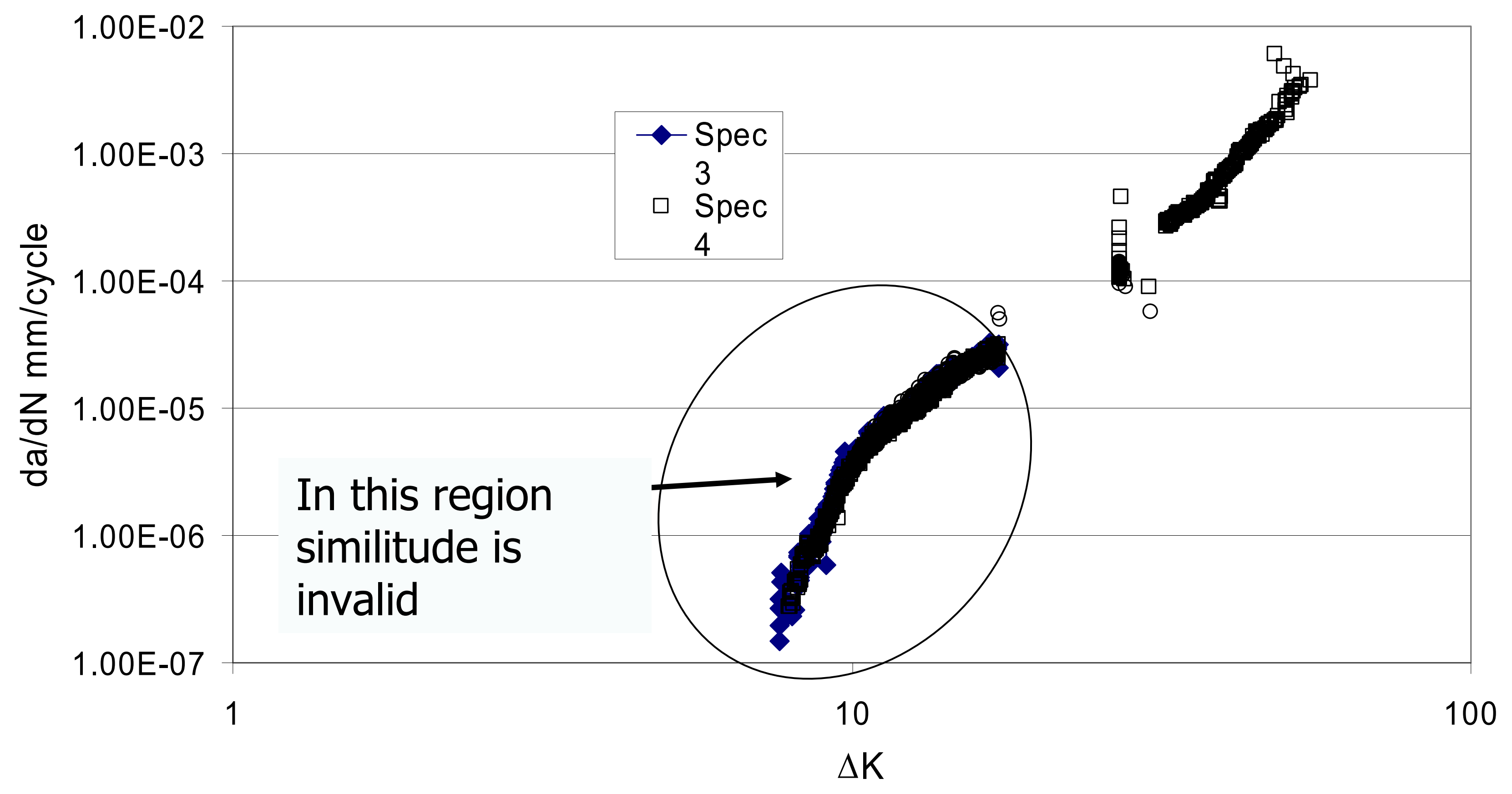
$$da/dN = C\,\Delta K^3/a^{1/2}$$

for slow growth, i.e. in Region I, for these various steels

Note: The axes have a linear scale not log scales

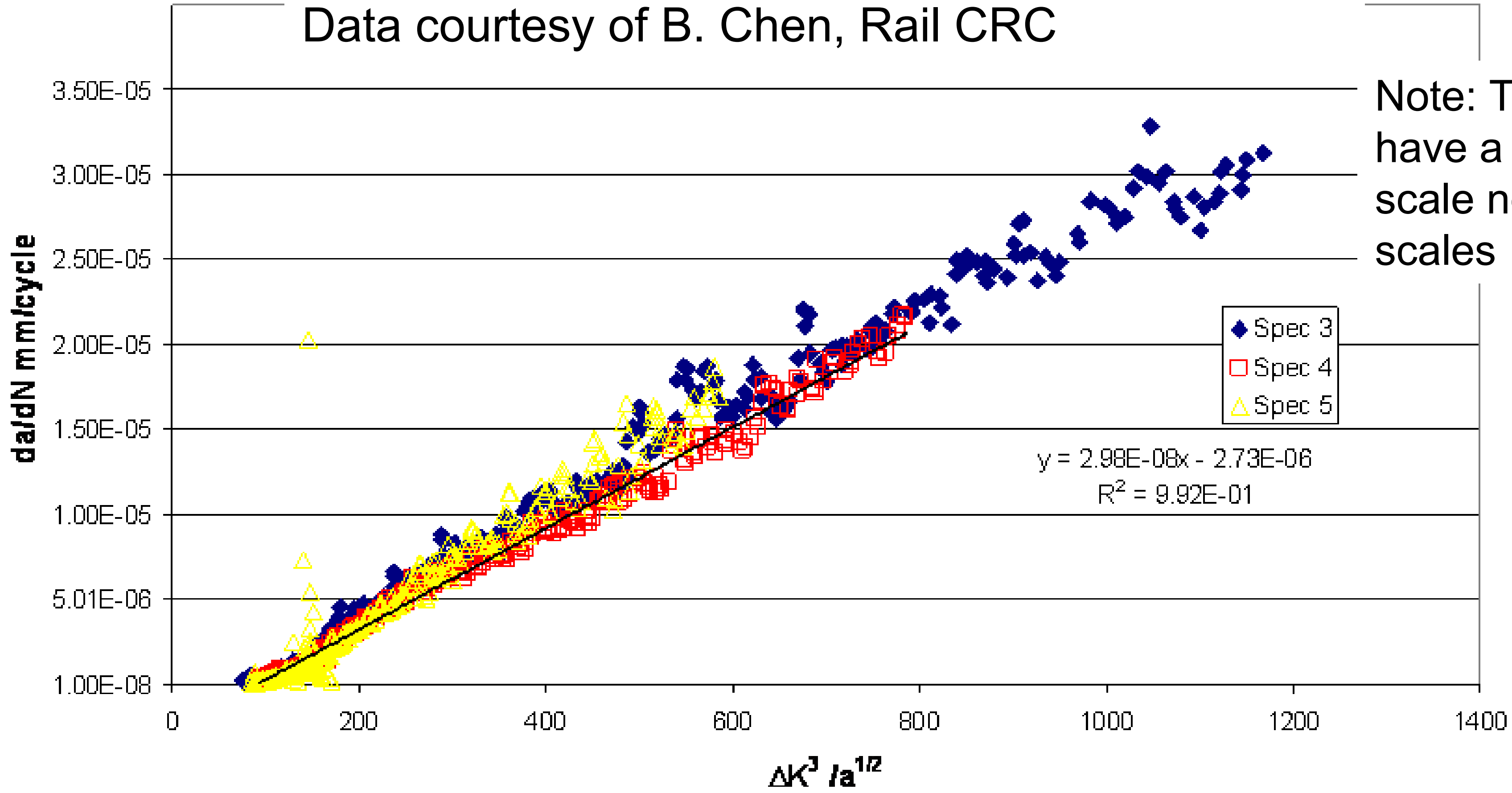
L6B2: There were 6 different ASTM Compact Tension tests performed by 2 different sources

2nd counter example: Grade 1 Austempered Ductile Iron



In this region similitude is invalid

2^{nd} counter example: Grade 1 Austempered Ductile Iron


Data courtesy of B. Chen, Rail CRC

Note: The axes have a linear scale not log scales

Here we again see that the crack growth rate is a function of both ΔK and the crack length a.

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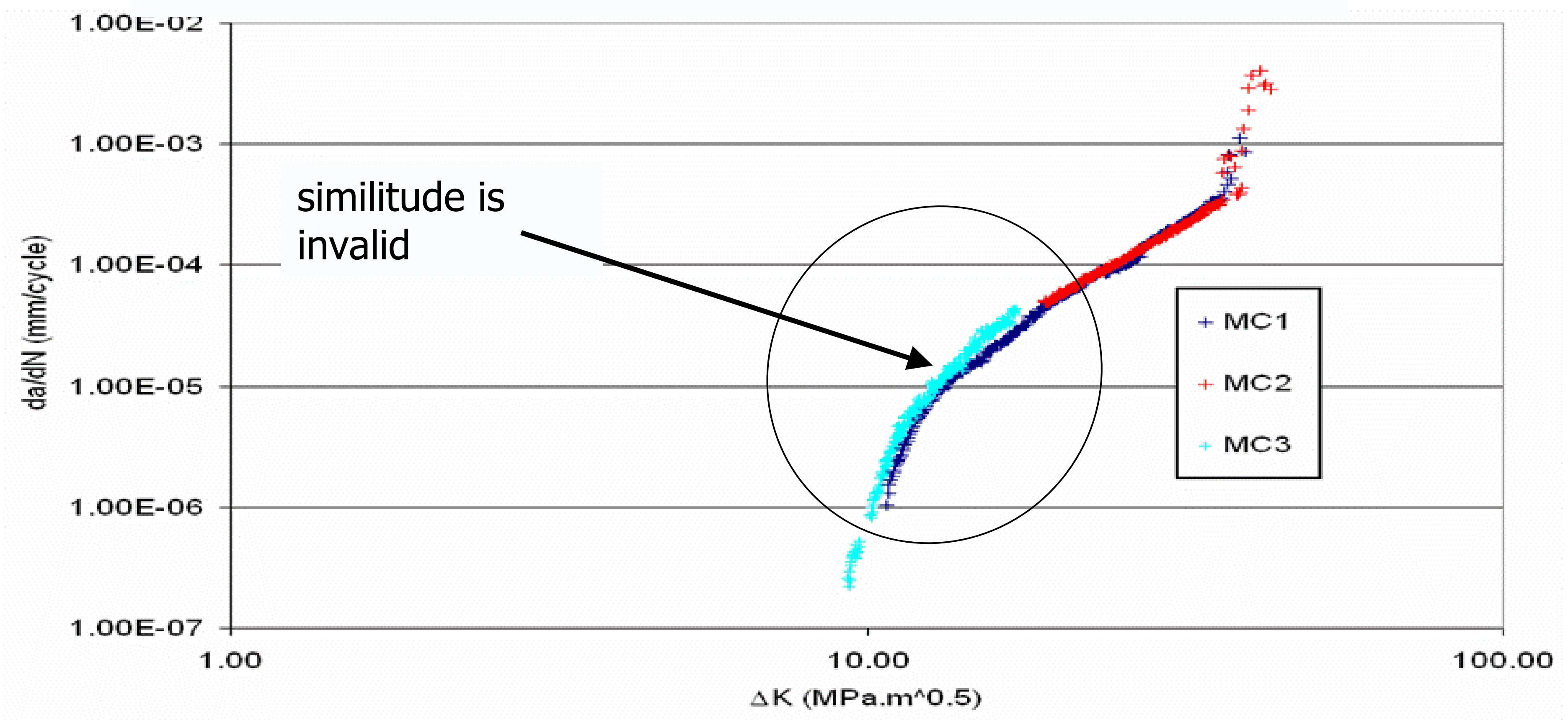
3rd and 4th Counter example: Wheel steels, Rail CRC data from B. Chen.

Table 1 Conventional wheel steels

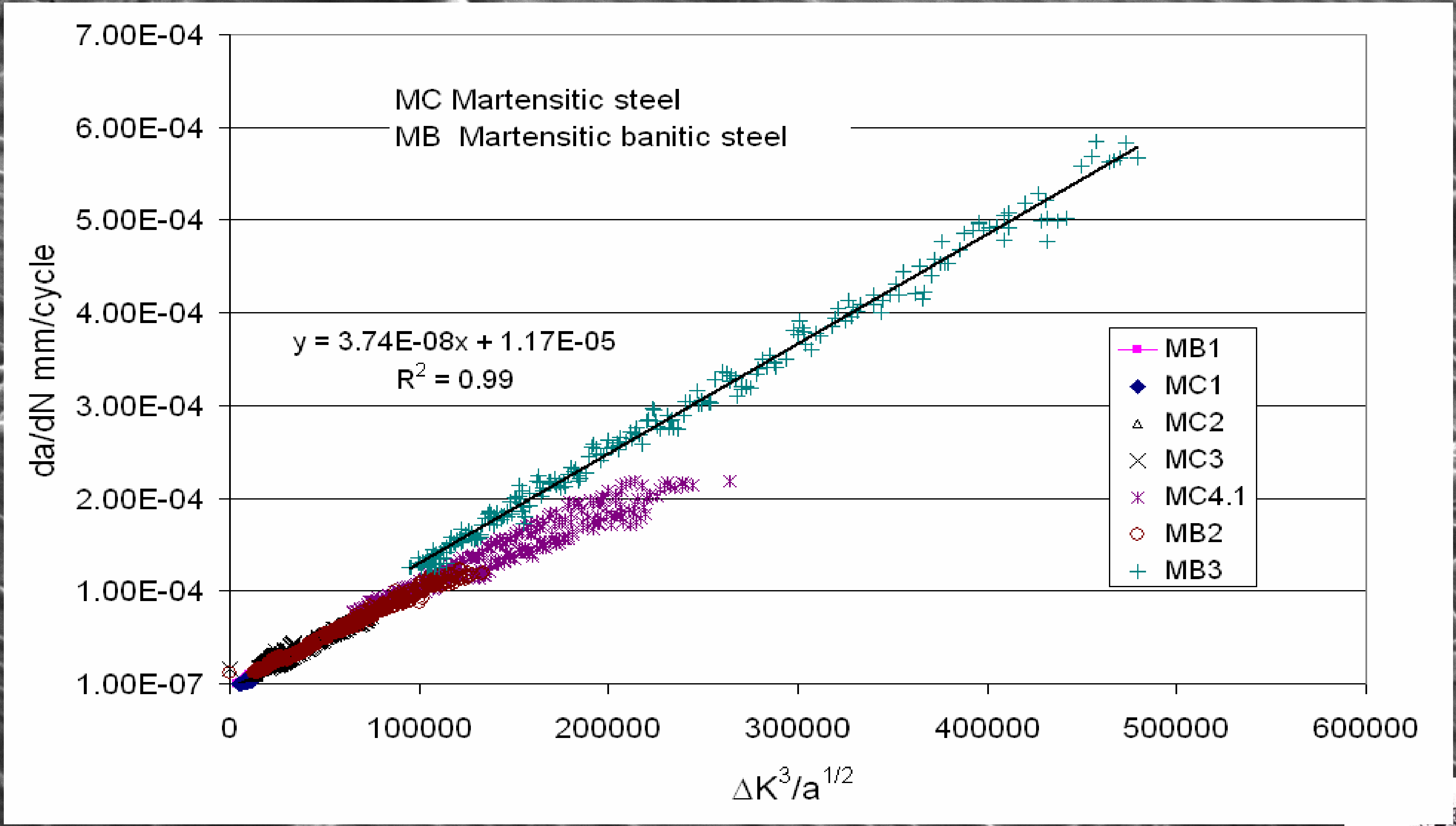
Class	C	Si	Mn	P	S	Ni	Cr	Mo	Al	Cu	Nb	Sn	Ti	V
B	0.64	0.25	0.75	0.009	0.019	0.1	0.11	0.02	0.009	0.23	0.003	0.012	0.005	0.002
C	0.74	0.27	0.79	0.008	0.027	0.08	0.08	0.02	0.006	0.22	0.003	0.02	0.005	0.002
MB	0.65	0.87	0.77	0.008	0.019	0.08	0.11	0.04	0.01	0.21	0.002	0.01	0.007	0.089
MC	0.74	0.81	0.84	0.007	0.019	0.06	0.07	0.02	0.007	0.12	0.002	0.006	0.006	0.082



similitude is invalid

Wheel steels

Note: The axes have a linear scale not log scales



Here we again see that the crack growth rate is a function of both ΔK and the crack length a.

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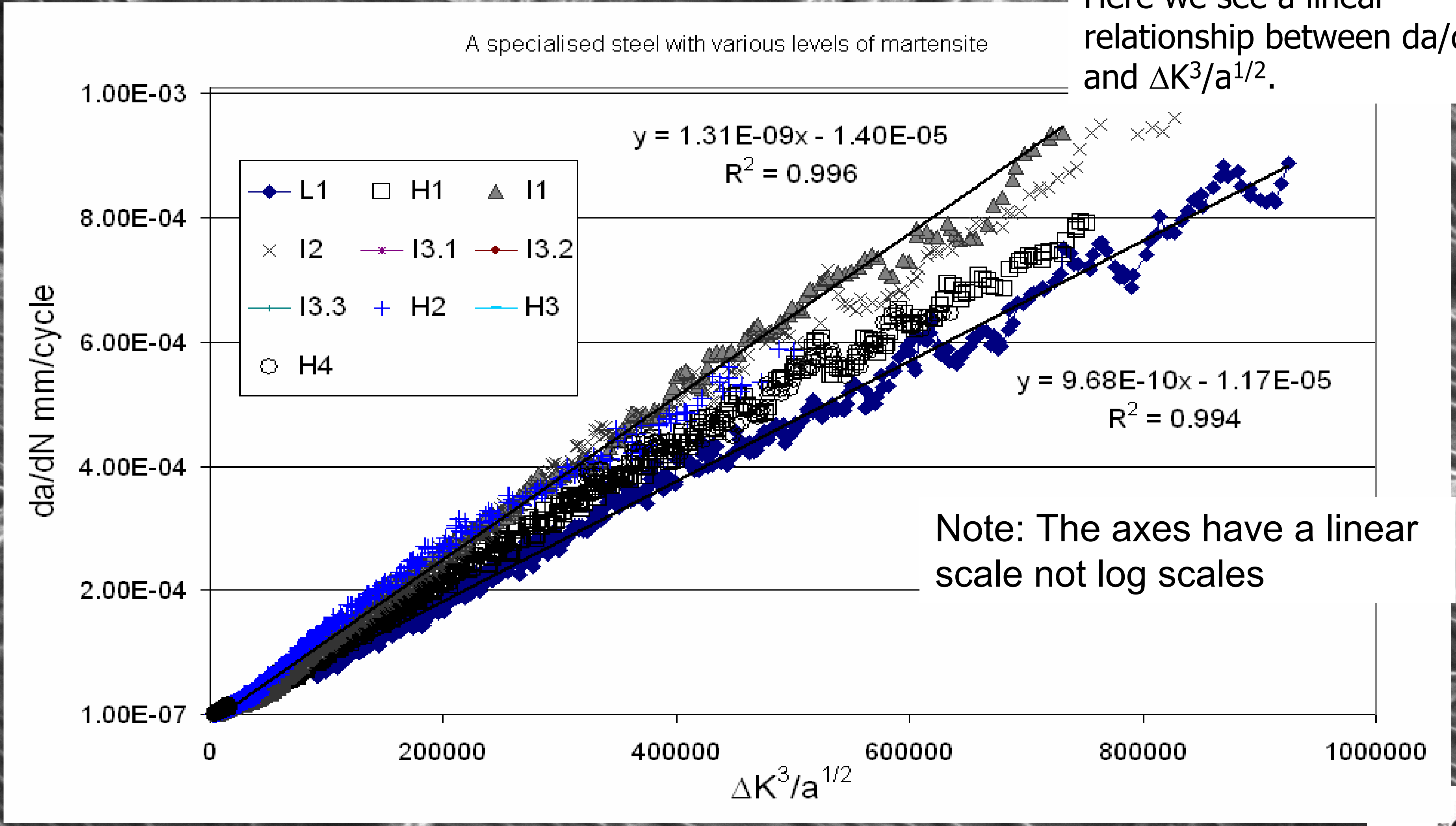
5th Counter example: Martensitic steels, with various amounts of matensite; H = high, = intermediate, L = low, Rail CRC data from B. Chen.



Here we see a linear relationship between da/dN and $\Delta K^3/a^{1/2}$.

Note: The axes have a linear scale not log scales

Here we again see that the crack growth rate is a function of both ΔK and the crack length a and that *growth is not governed by similitude.*

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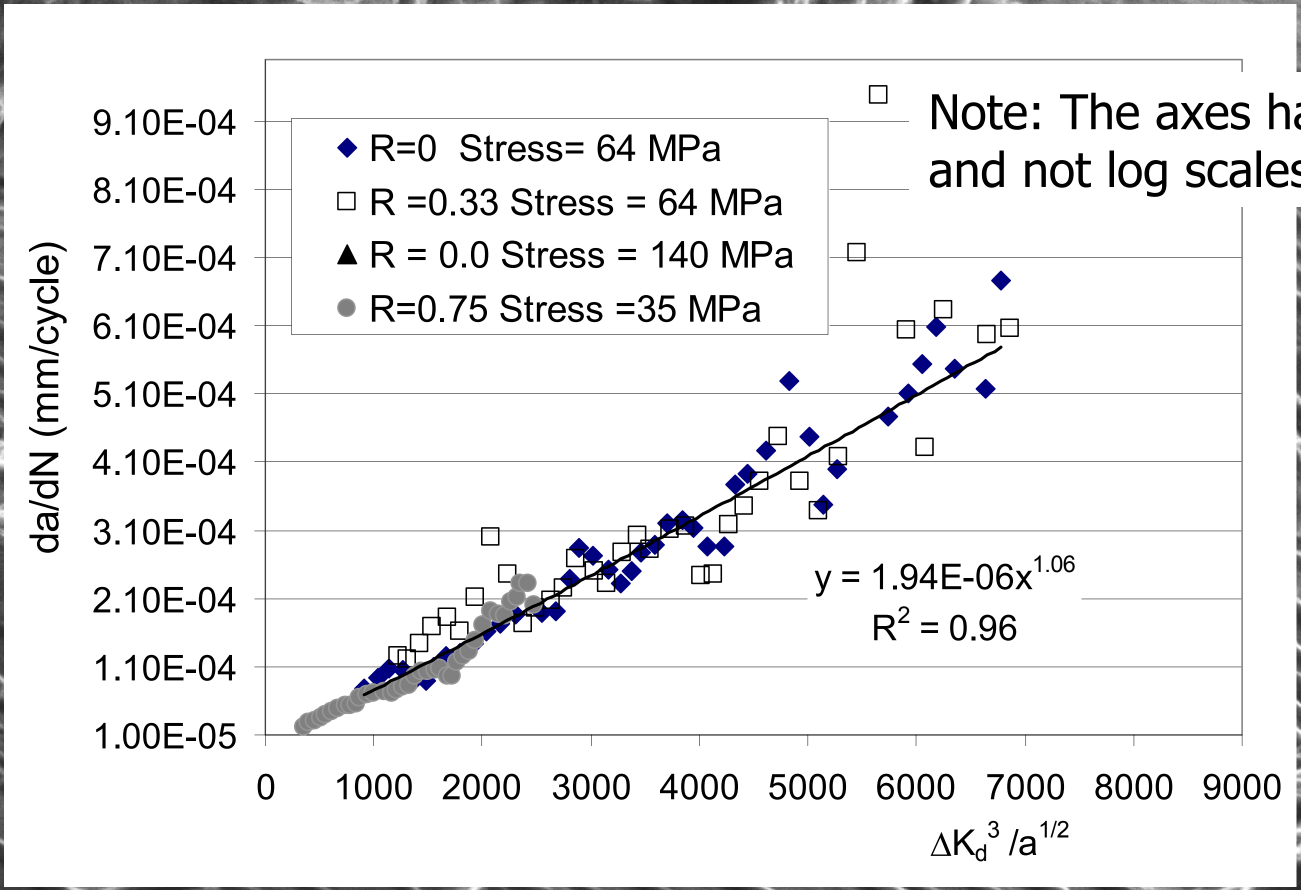
6th Counter example: Crack growth rate for D16 Aluminium under a range of stress amplitudes and R ratio’s



Note: The axes have a linear scale and not log scales

$\Delta K_d = \Delta K_{tot}^{(1-p)} K_{max,tot}^{p}$, where p =0.25, i.e. growth is governed by the Unigro formulation

J. Schijve, M. Skorupa, A. Skorupa, T. Machniewicz, P. Gruszczynski , “Fatigue crack growth in the aluminium alloy D16 under constant and variable amplitude loading”, International Journal of Fatigue 26, 1–15, 2004.

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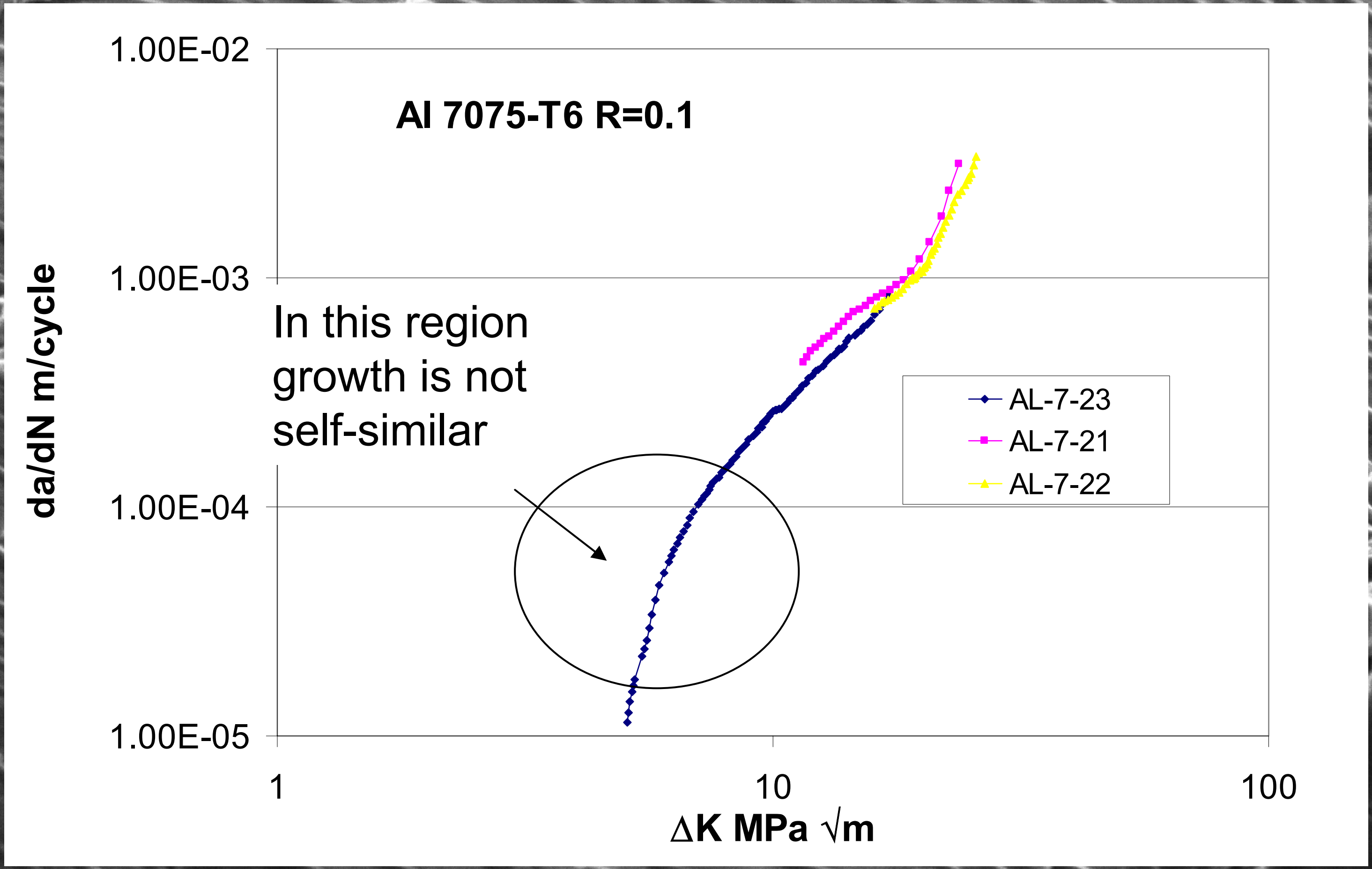
7th Counter examples: *Scott C. Forth, Christopher W. Wright, and William M. Johnston, Jr.*, "7075-T6 and 2024-T351 Aluminum Alloy Fatigue Crack Growth Rate Data", NASA/TM-2005-213907, August 2005



In this region growth is not self-similar

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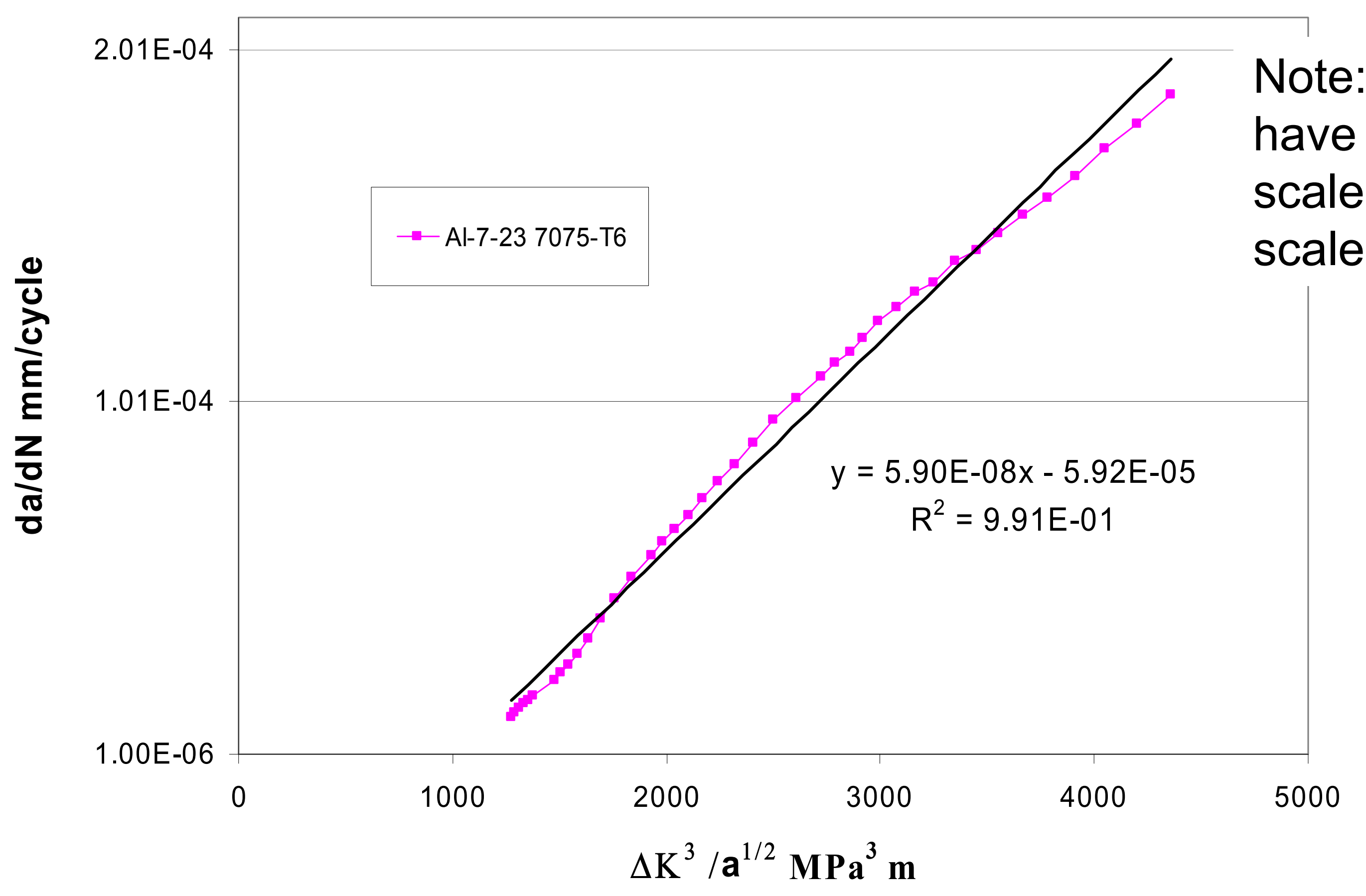
7th Counter example: *Scott C. Forth, Christopher W. Wright, and William M. Johnston, Jr.*, “7075-T6 and 2024-T351 Aluminum Alloy Fatigue Crack Growth Rate Data”, NASA/TM-2005-213907, August 2005



Note: The axes have a linear scale not log scales

In Region I there is a linear relationship between da/dN and $\Delta K^3/a^{1/2}$ i.e. non self similar growth

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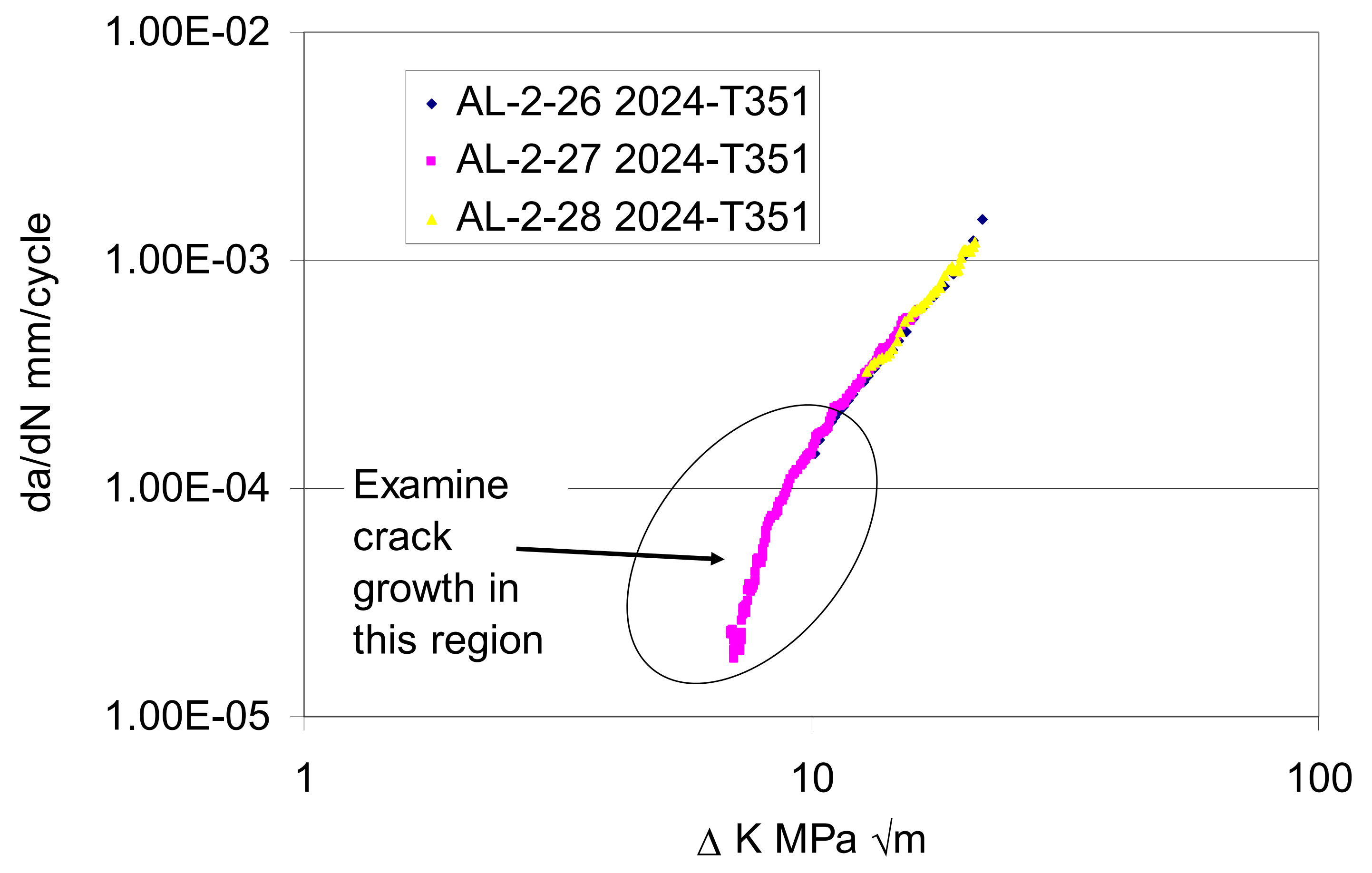
8th Counter example: *Scott C. Forth, Christopher W. Wright, and William M. Johnston, Jr.*, "7075-T6 and 2024-T351 Aluminum Alloy Fatigue Crack Growth Rate Data", NASA/TM-2005-213907, August 2005



Examine crack growth in this region

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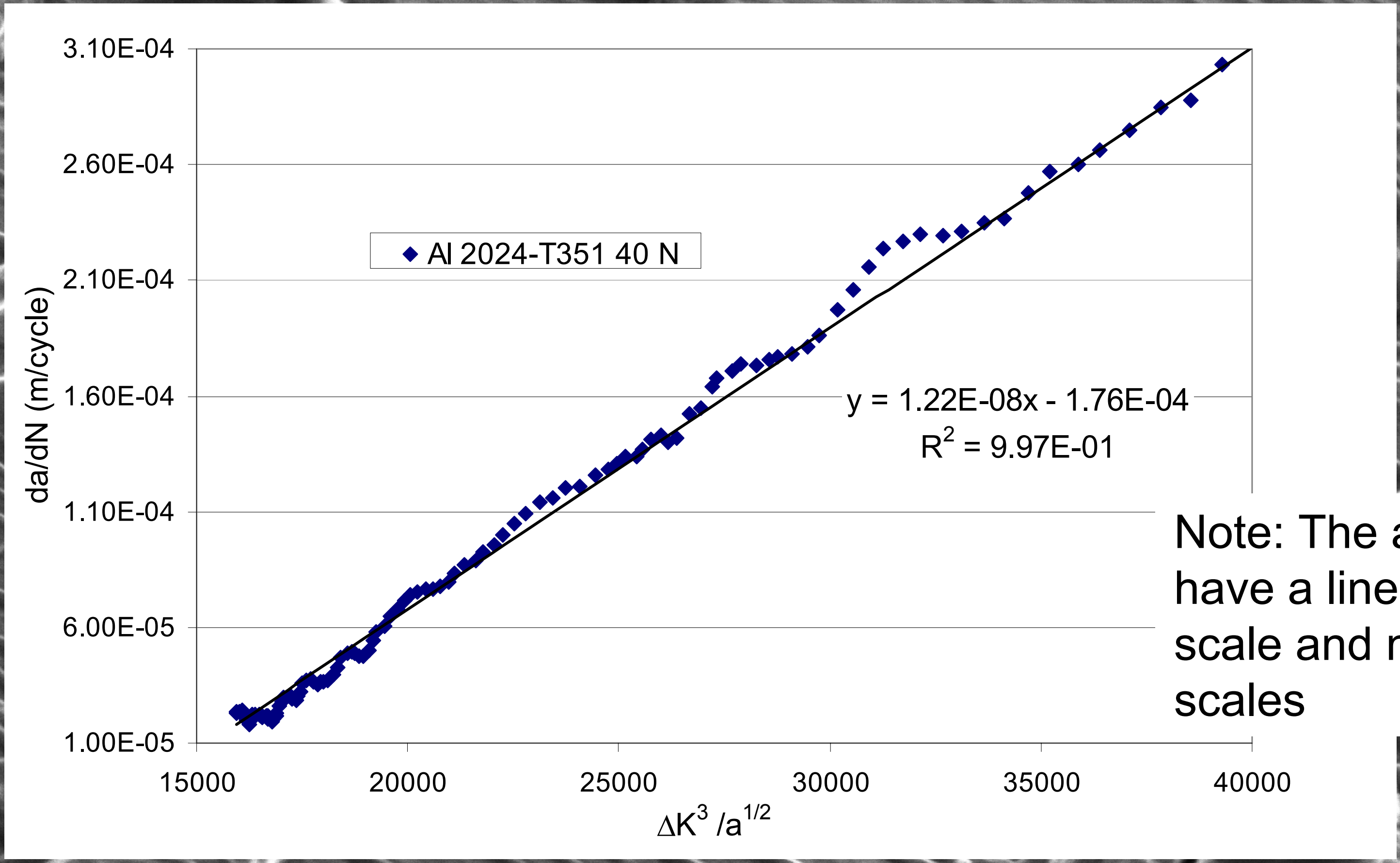
8th Counter example: *Scott C. Forth, Christopher W. Wright, and William M. Johnston, Jr.*, "7075-T6 and 2024-T351 Aluminum Alloy Fatigue Crack Growth Rate Data", NASA/TM-2005-213907, August 2005



Note: The axes have a linear scale and not log scales

In Region I there is a linear relationship between da/dN and $\Delta K^3/a^{1/2}$ i.e. similitude is invalid

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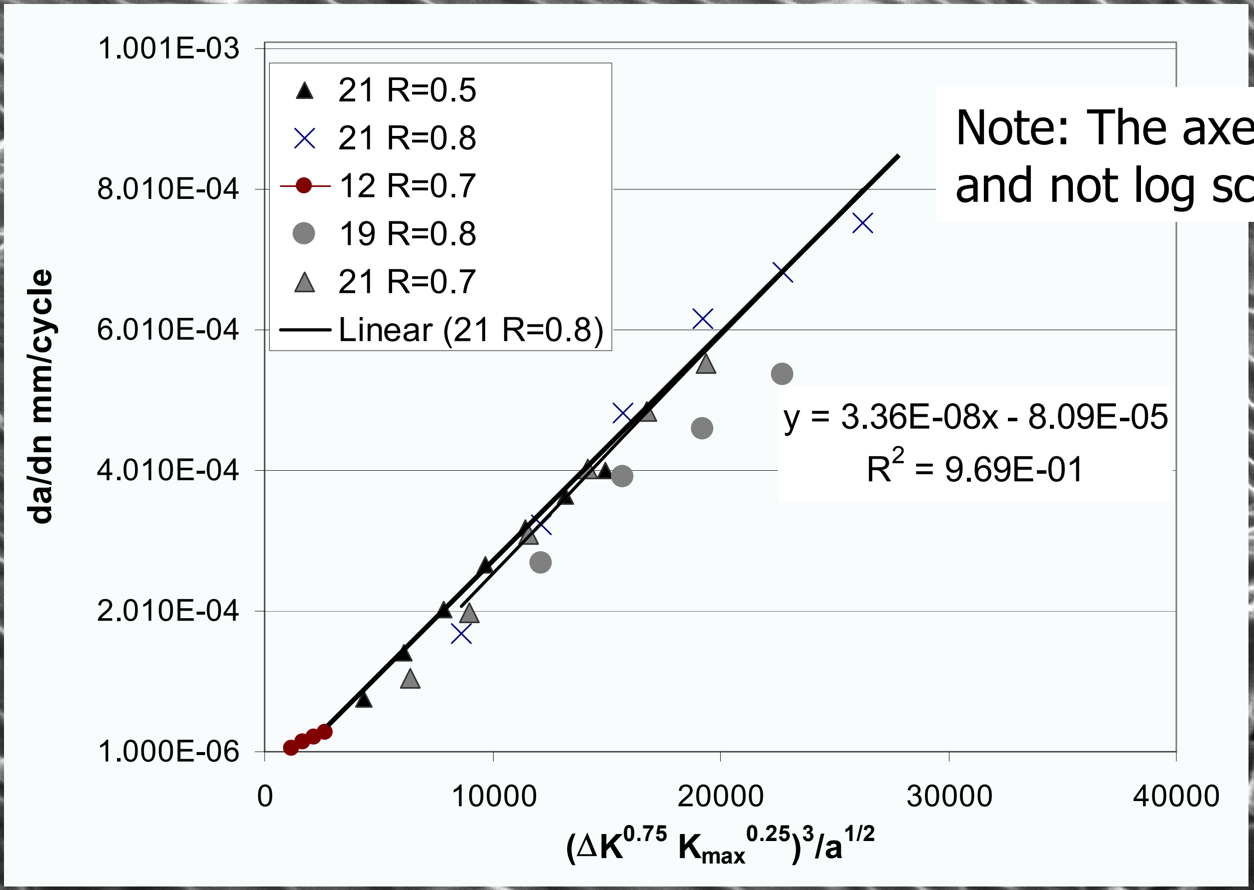
9th Counter example C.M. Hudson, “Effect of Stress Ratio on Fatigue-Crack Growth in Aluminum-Alloy 7075-T6 and 2024-T3 Specimens”, NASA Technical Note, NASA TN D-5390, August 1969.



Note: The axes have a linear scale and not log scales

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Conclusion

- The experimental data which covers three quite different materials viz:

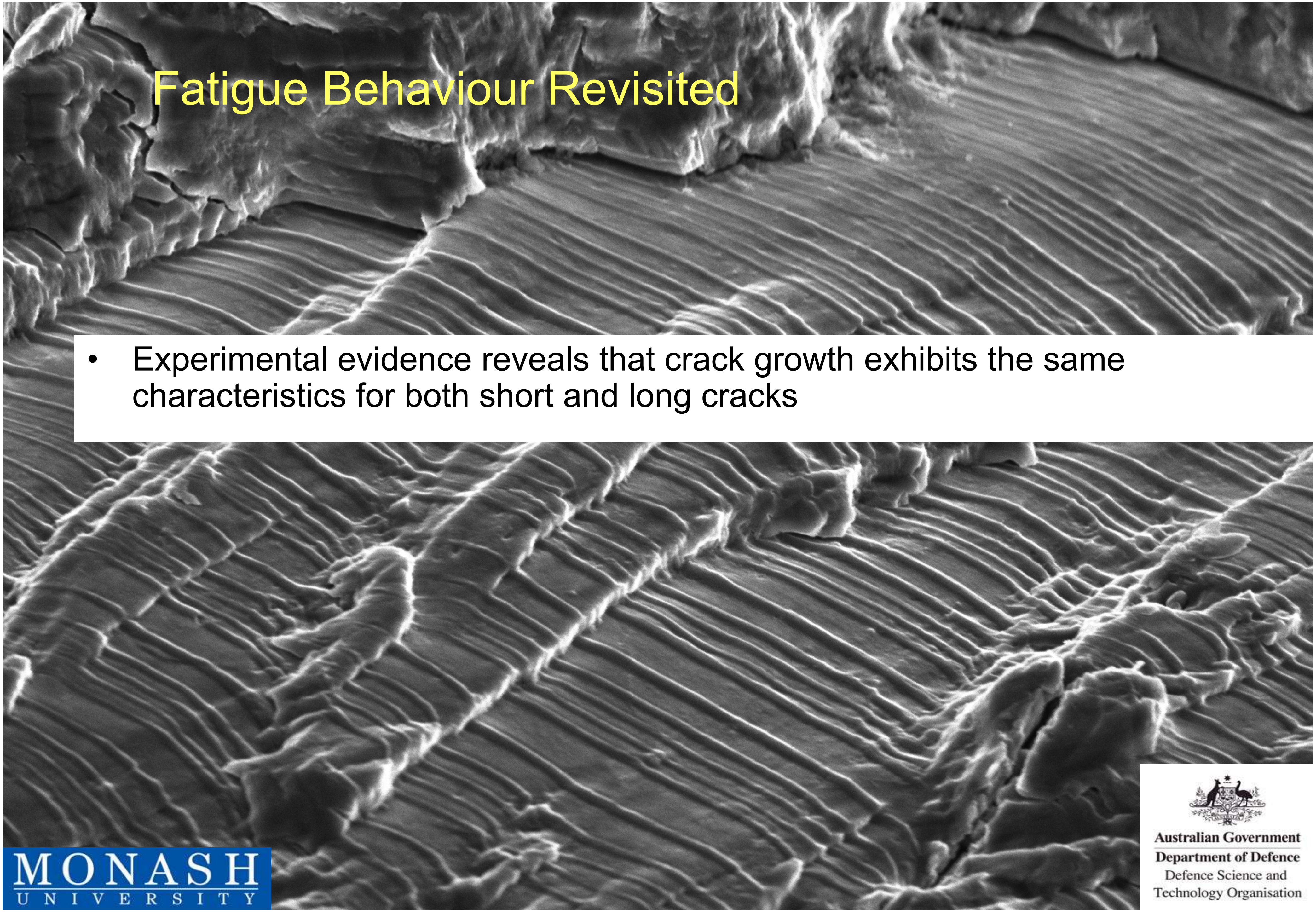
  i) six (rail) cast steels,
  ii) an austempered ductile iron,
  iii) 3 aircraft quality aluminium alloy’s with a range of R ratio’s.

  and was obtained by a variety of researchers, Rail CRC, NASA, DSTO, USAF, etc, using a variety of specimen configurations, i.e. ASTM compact tension, ASTM middle tension, etc, shows that the science base underpinning crack growth models AFGROW, FASRAN, NASGRO, etc in Region I is invalid.

- In these instances the hypothesis of similitude is incorrect.

- This is also true for delamination growth in composites.

Fatigue Behaviour Revisited



- Experimental evidence reveals that crack growth exhibits the same characteristics for both short and long cracks

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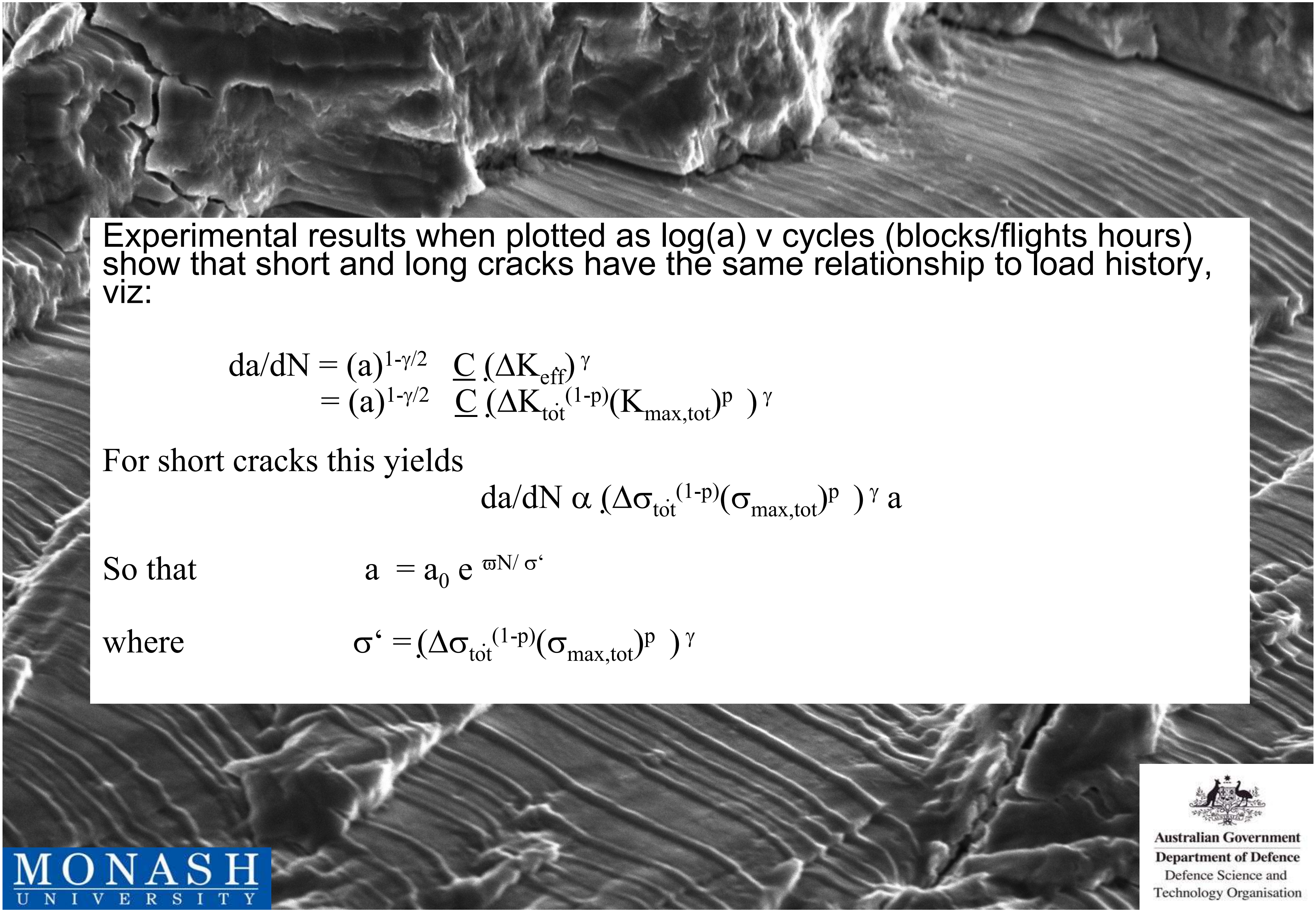


Experimental results when plotted as log(a) v cycles (blocks/flights hours) show that short and long cracks have the same relationship to load history, viz:

$$\begin{aligned} da/dN &= (a)^{1-\gamma/2}\ \underline{C}\ (\Delta K_{eff})^{\gamma} \\ &= (a)^{1-\gamma/2}\ \underline{C}\ (\Delta K_{tot}^{(1-p)}(K_{max,tot})^{p}\ )^{\gamma} \end{aligned}$$

For short cracks this yields

$$da/dN\ \alpha\ (\Delta\sigma_{tot}^{(1-p)}(\sigma_{max,tot})^{p}\ )^{\gamma}\ a$$

So that $a\ = a_0\ e^{\varpi N/\ \sigma'}$

where $\sigma' = (\Delta\sigma_{tot}^{(1-p)}(\sigma_{max,tot})^{p}\ )^{\gamma}$

Simple Master Curve For Fatigue Crack Growth From Small (microns) to Macro Sized Cracks (4-10 mm’s)

For small cracks this yields the following relationship, viz:

$$\mathrm{In}(a) - \mathrm{In}(a_i)\ \alpha\ B; \qquad da/dB\ \alpha\ a$$

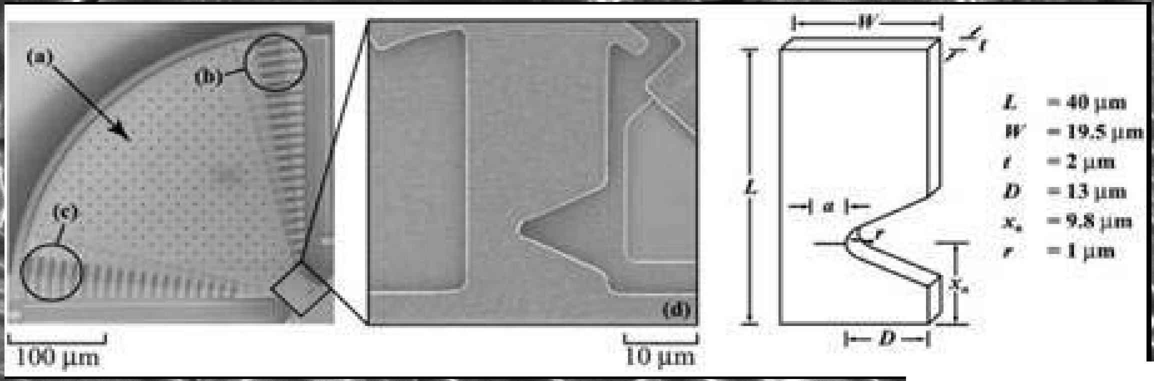
Then

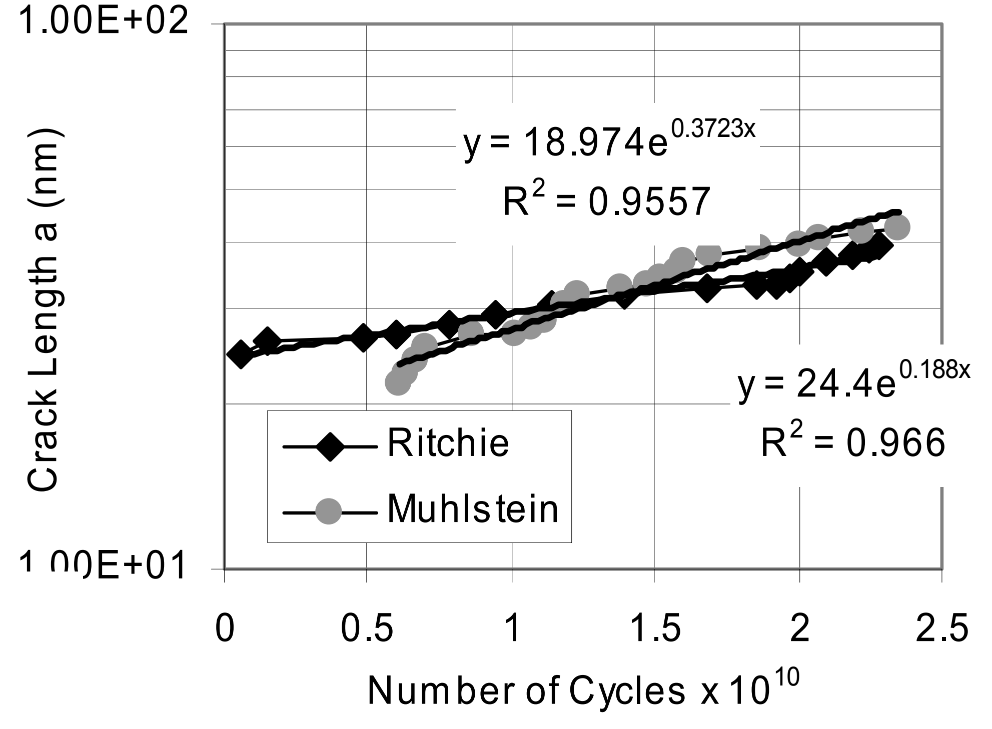
$$\mathrm{In}(a/a_f) - \mathrm{In}(a_i/a_f)\ \alpha\ B/B_f$$

$$\{da/dB/(da/dB)_f\}\ \alpha\ a/a_f$$

Here B_f is the life corresponding to a_f which is a macro crack size, not necessarily the crack size at failure.

Growth of near nano scale cracks: Ritchie, et al





Crack growth at the nano-scale in 2 µm thick polysilicon, adapted from Ritchie et al

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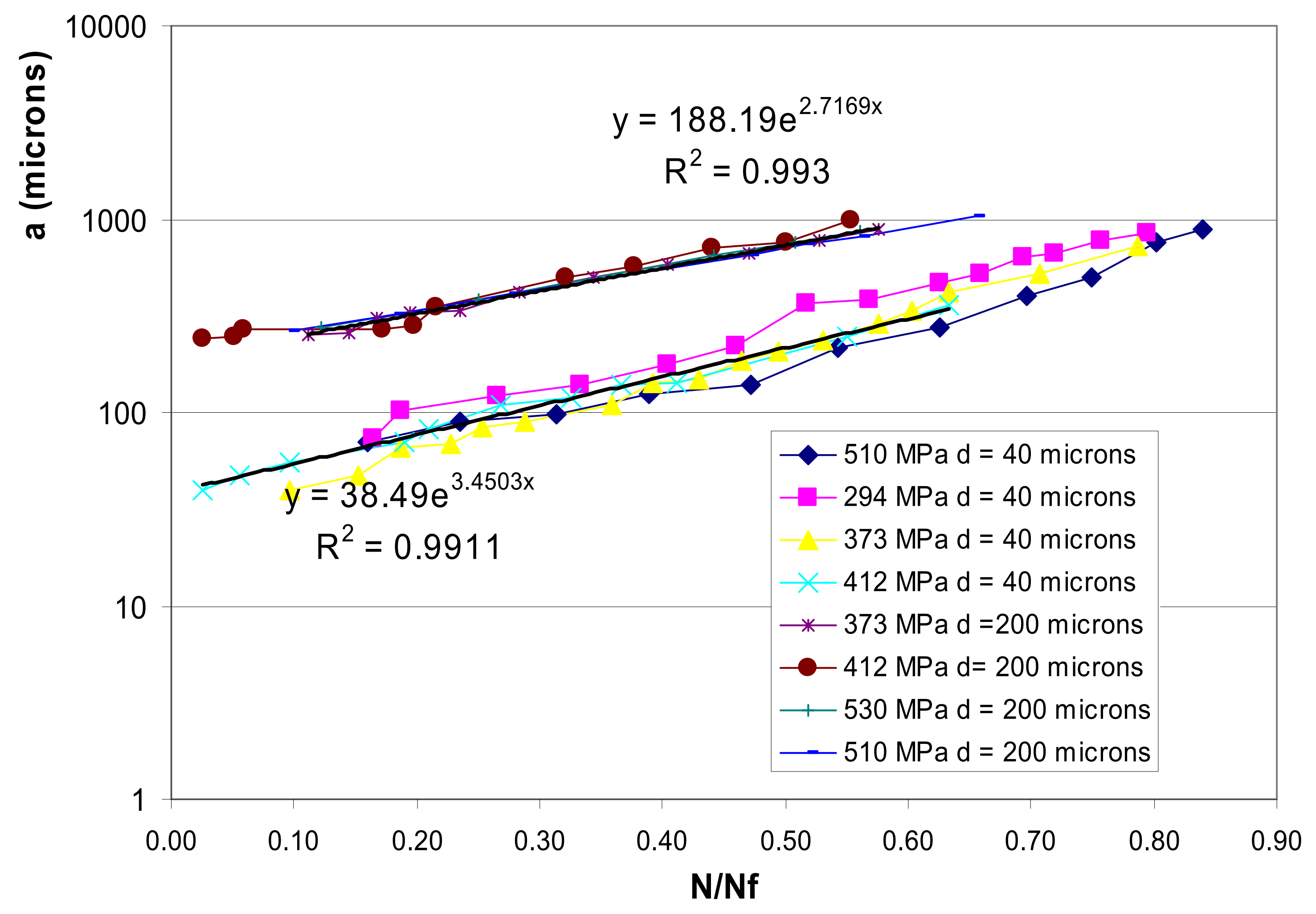
Y. Murakamia K. J. Miller, What is fatigue damage? A view point from the observation of low cycle fatigue process Int. Journal of Fatigue, (2005) 1–15.



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Simple Master Curve For Fatigue Crack Growth From Small (microns) to Macro Sized Cracks (4-10 mm's)

For small cracks this yields the following relationship, viz:

$$\ln(a) - \ln(a_i) \; \alpha \; B; \qquad da/dB \; \alpha \; a$$

Then

$$\ln(a/a_f) - \ln(a_i/a_f) \; \alpha \; B/B_f$$

$$\{da/dB/(da/dB)_f\} \; \alpha \; a/a_f$$

Here B_f is the life corresponding to a_f which is a macro crack size, not necessarily the crack size at failure.

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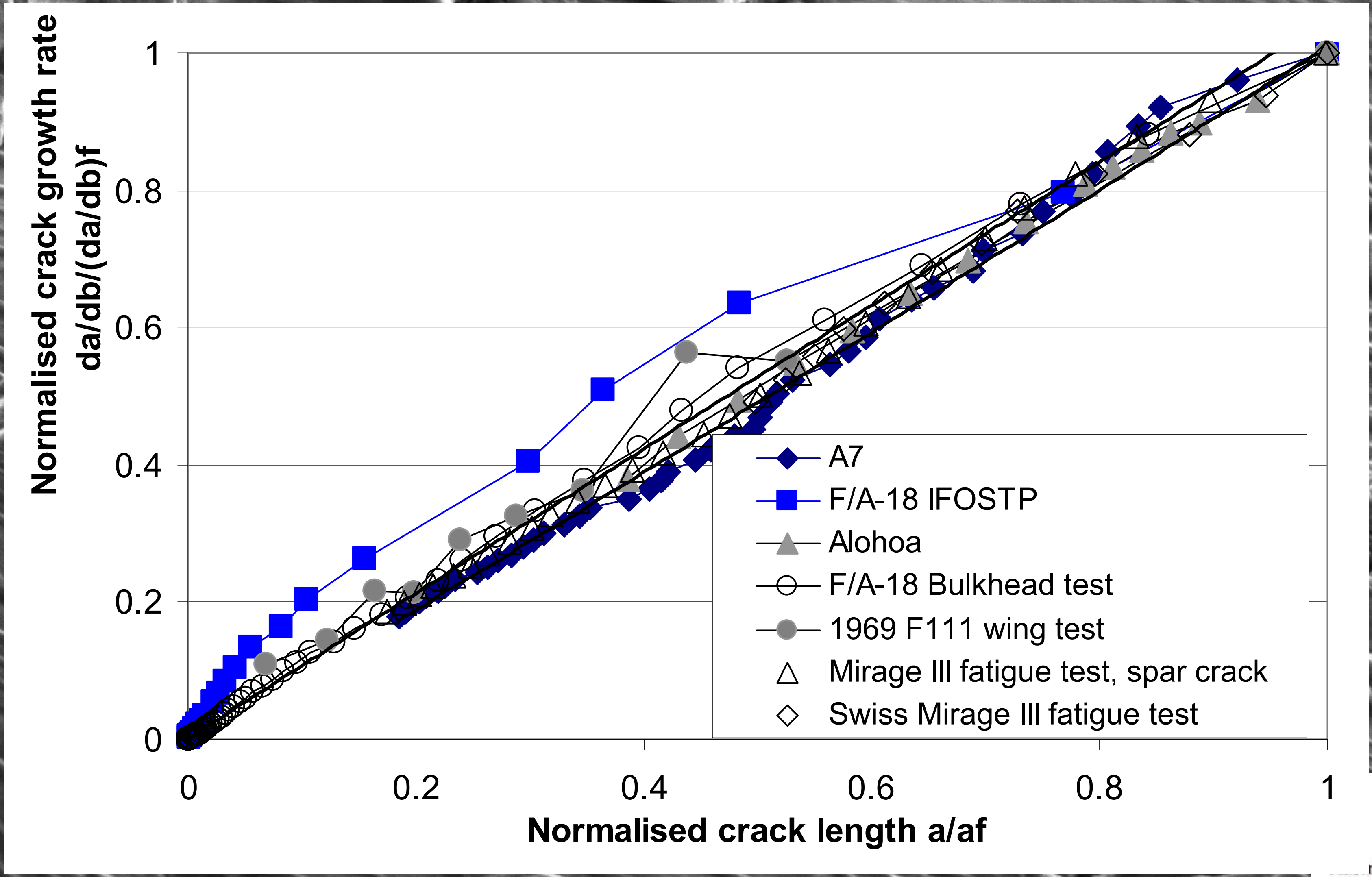
Proof: 5 full scale aircraft tests, 2 real aircraft flight data: From microns to 10's mm's



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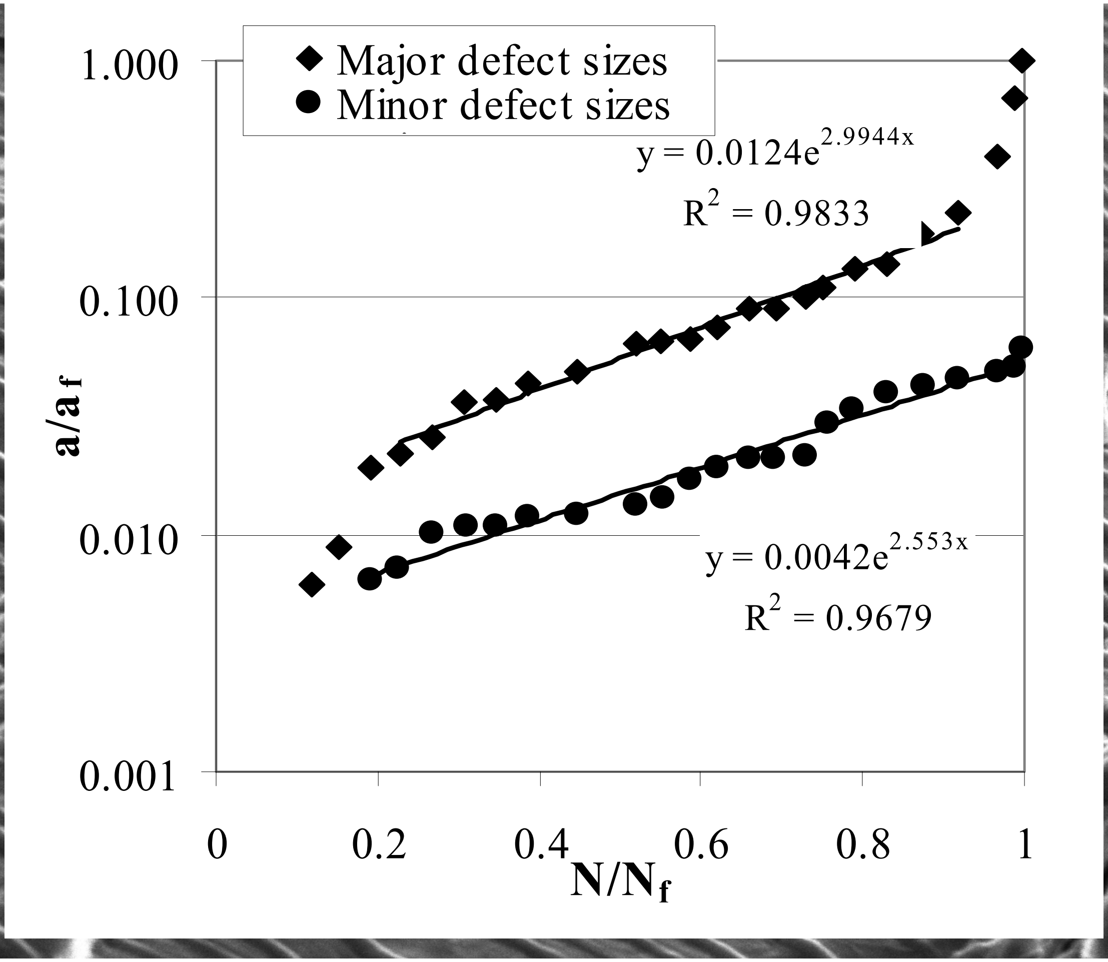
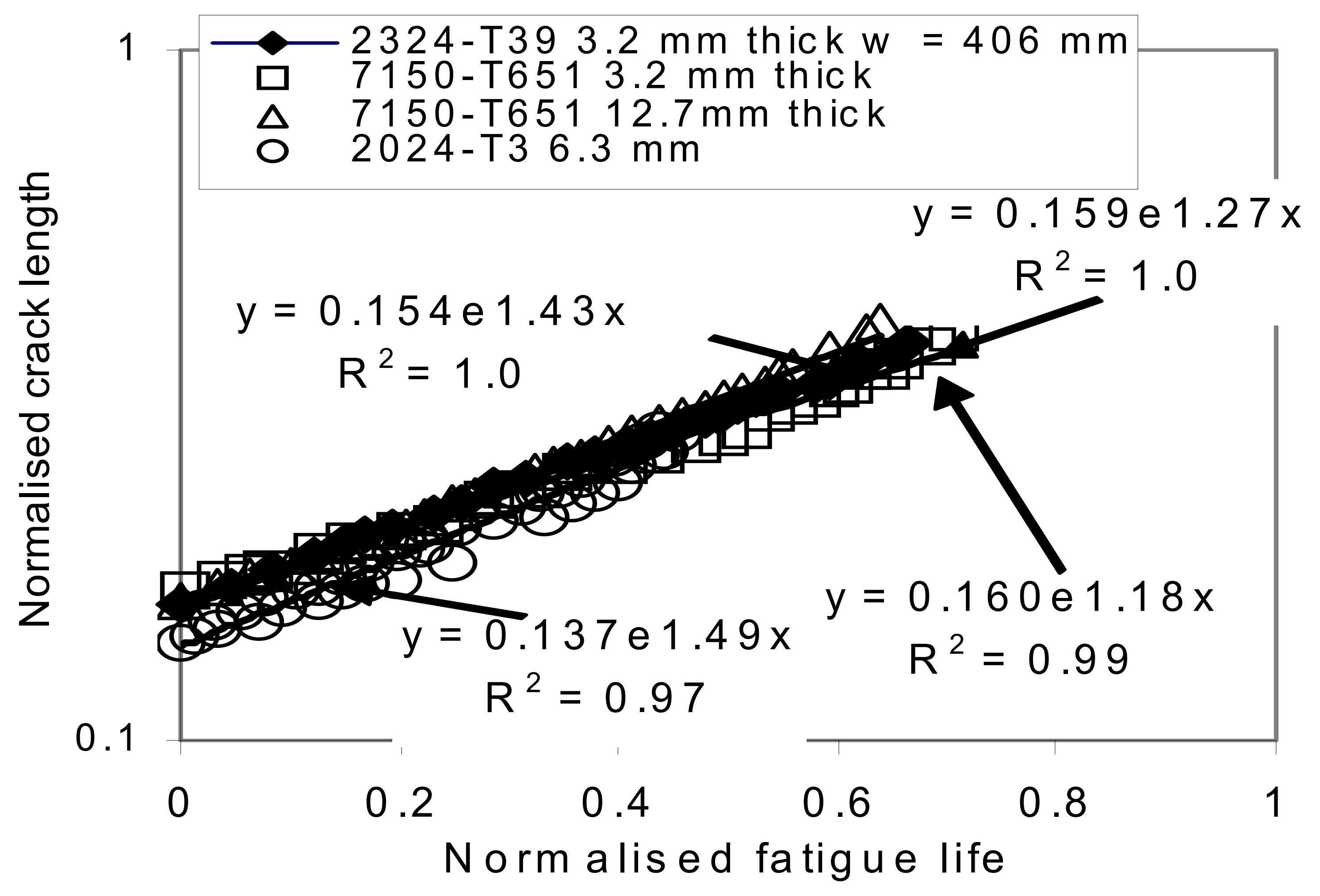
D. Angelova and R. Akid, "A normalization of corrosion fatigue behaviour: an exampl using an offshore structural steel in chloride environments", Fatigue Fract Engng Mater Struct, 22, 409–420, 1999.



20 micron < a < 2 mm Note that in the later stages the crack is tearing.

Proof: Boeing 767 and 757 Materials Characterisation Data Base Boeing constant amplitude crack growth data,



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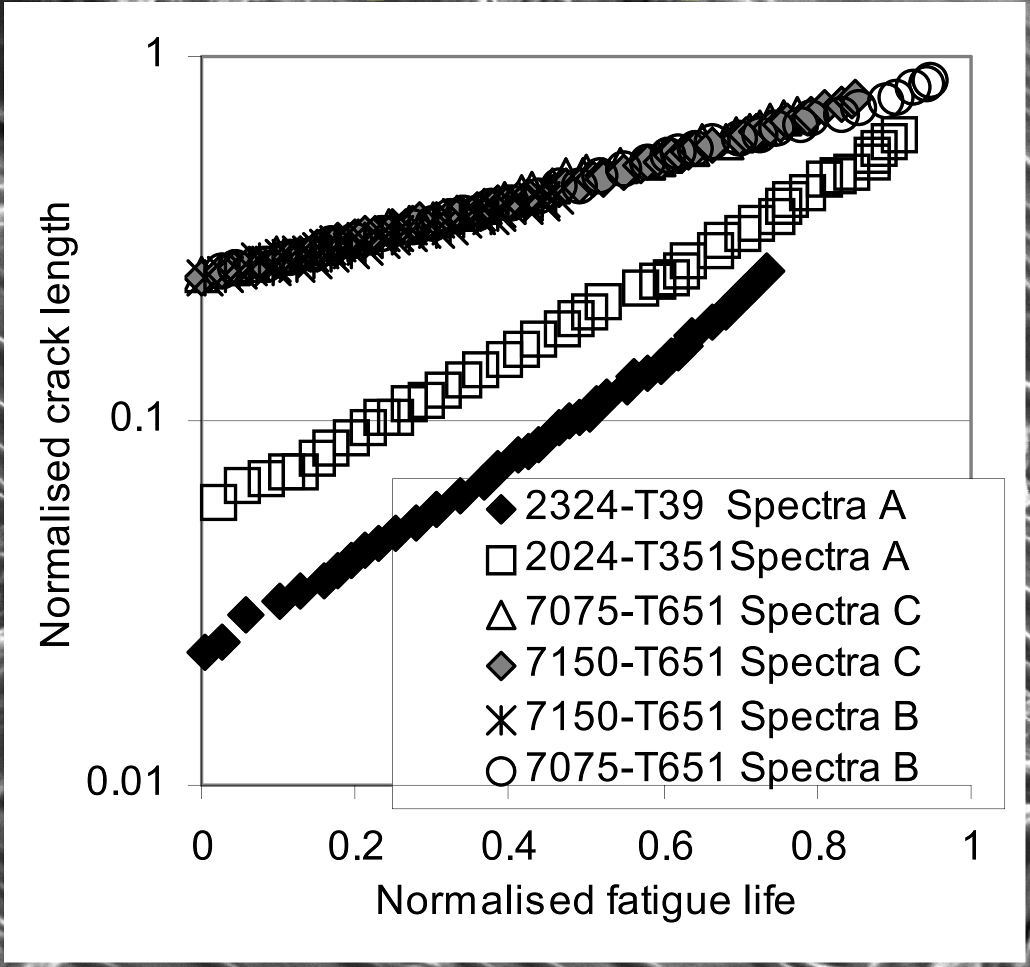
Yet more Proof: Boeing crack growth data for tests under various transport load spectra



M. Miller, V. K. Luthra, and U. G. Goranson, "Fatigue Crack Growth Characterization of Jet Transport Structures", Presented at 14th Symposium of the International Conference on Aeronautical Fatigue (ICAF), Ottawa, Canada, June 10-12, 1987.

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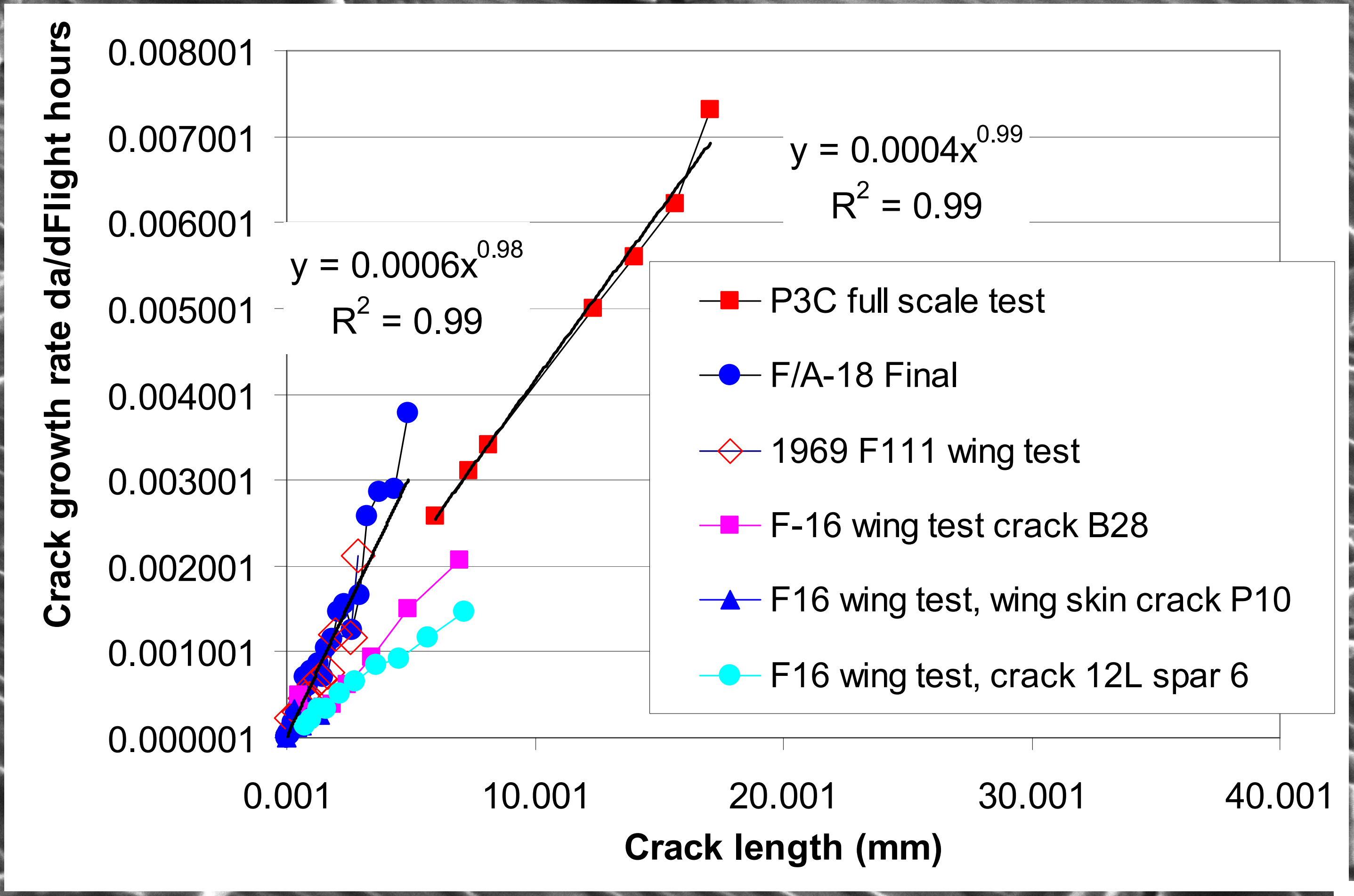
Comparison of F-16 wing test, P3C full scale test, F/A-18 Centre Barrel (Final) & the 1969 F-111 wing test crack growth rates per flight hour



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DSTO F/A-18 Fatigue Test Program FINAL

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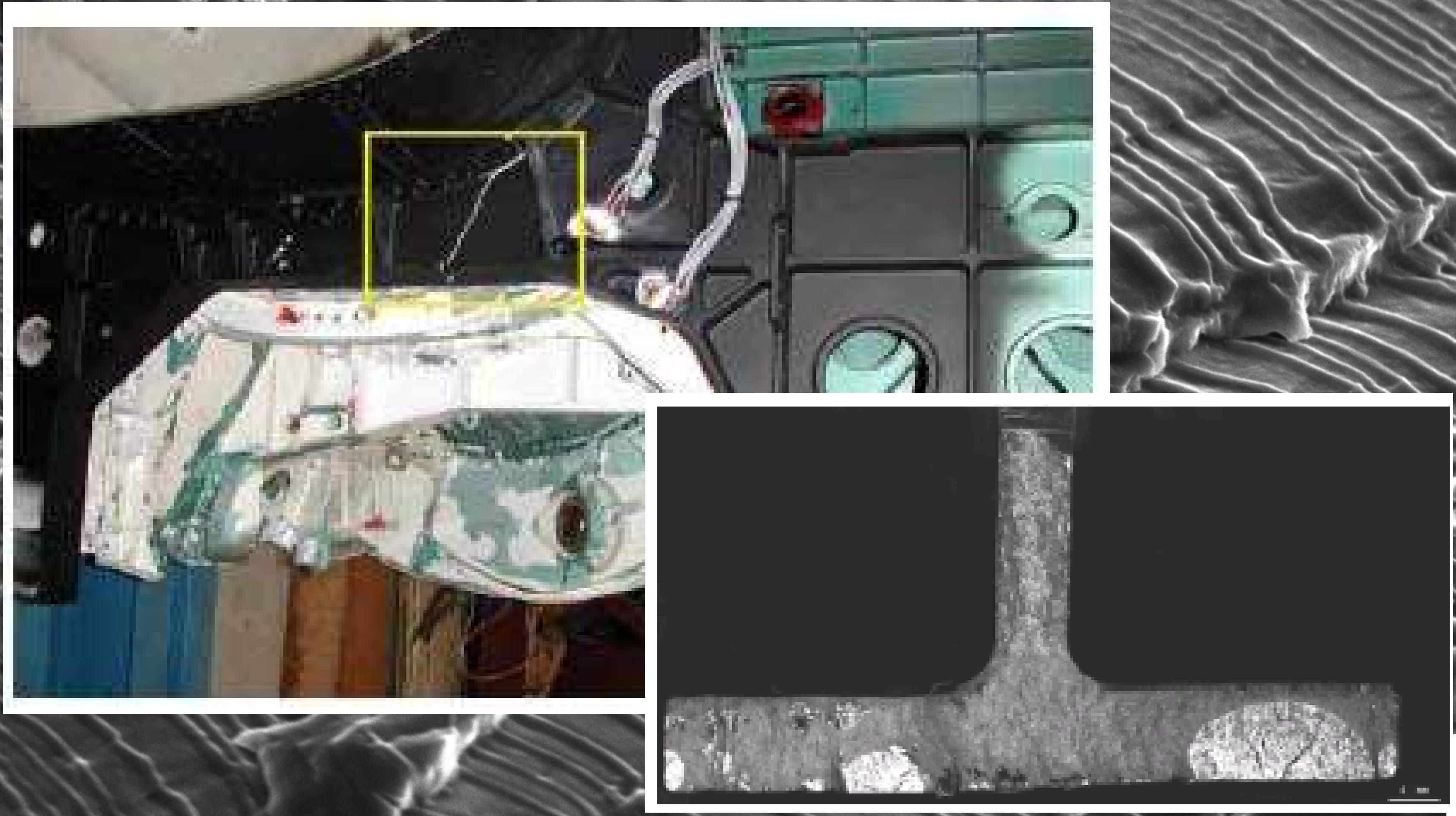
F/A-18 Bulkhead

Y488 Bulkhead Failure From ~30 micron corrosion pits



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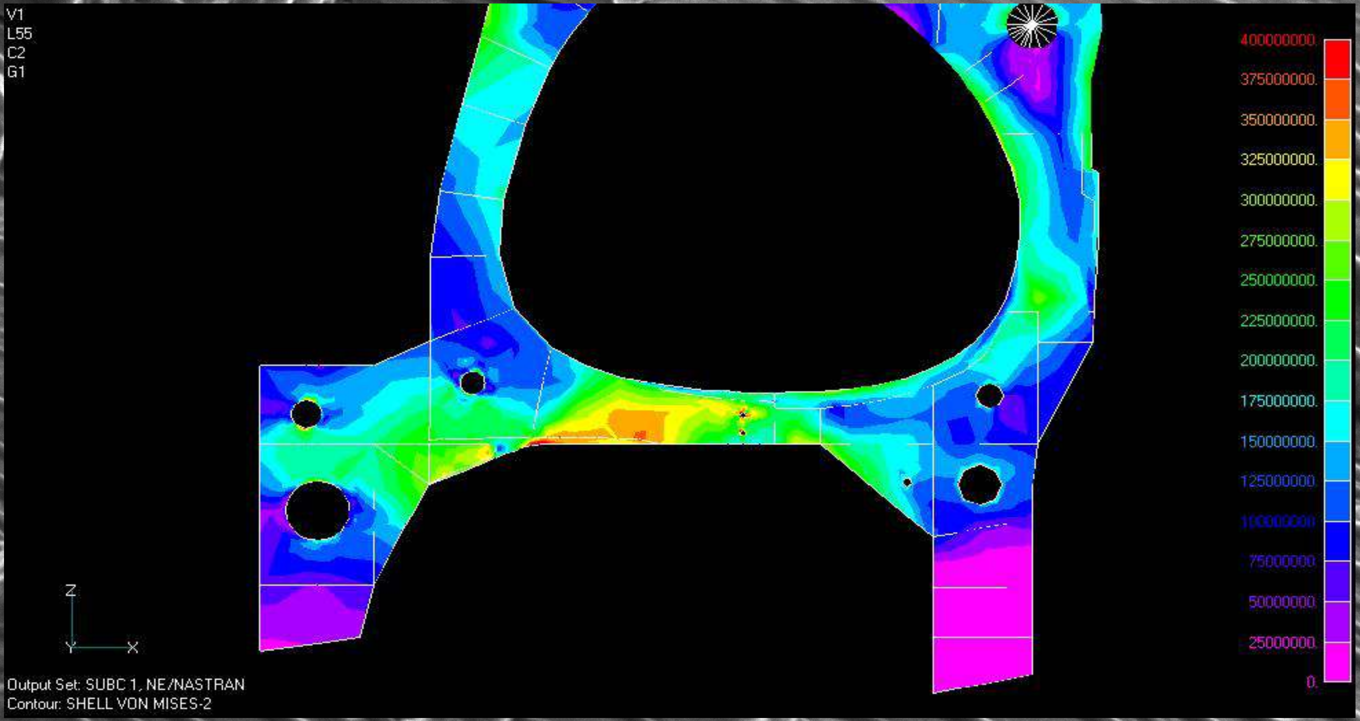
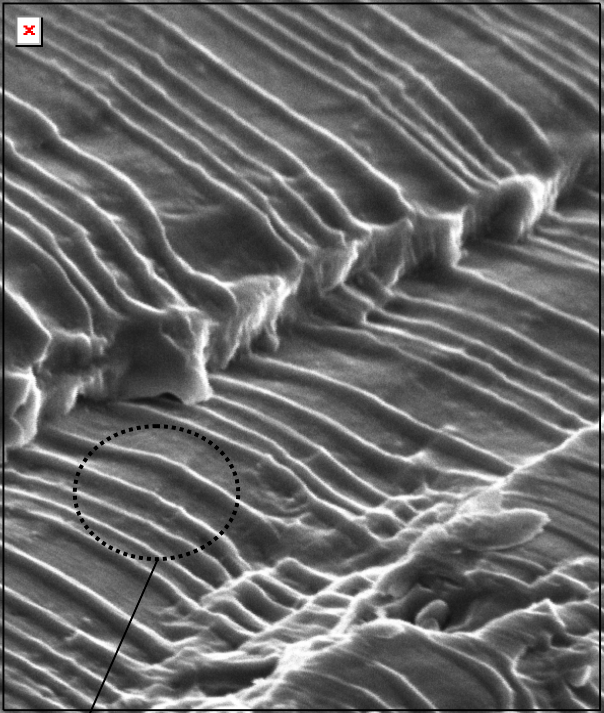
NEi-NASTRAN Finite Element Model of the Bulkhead





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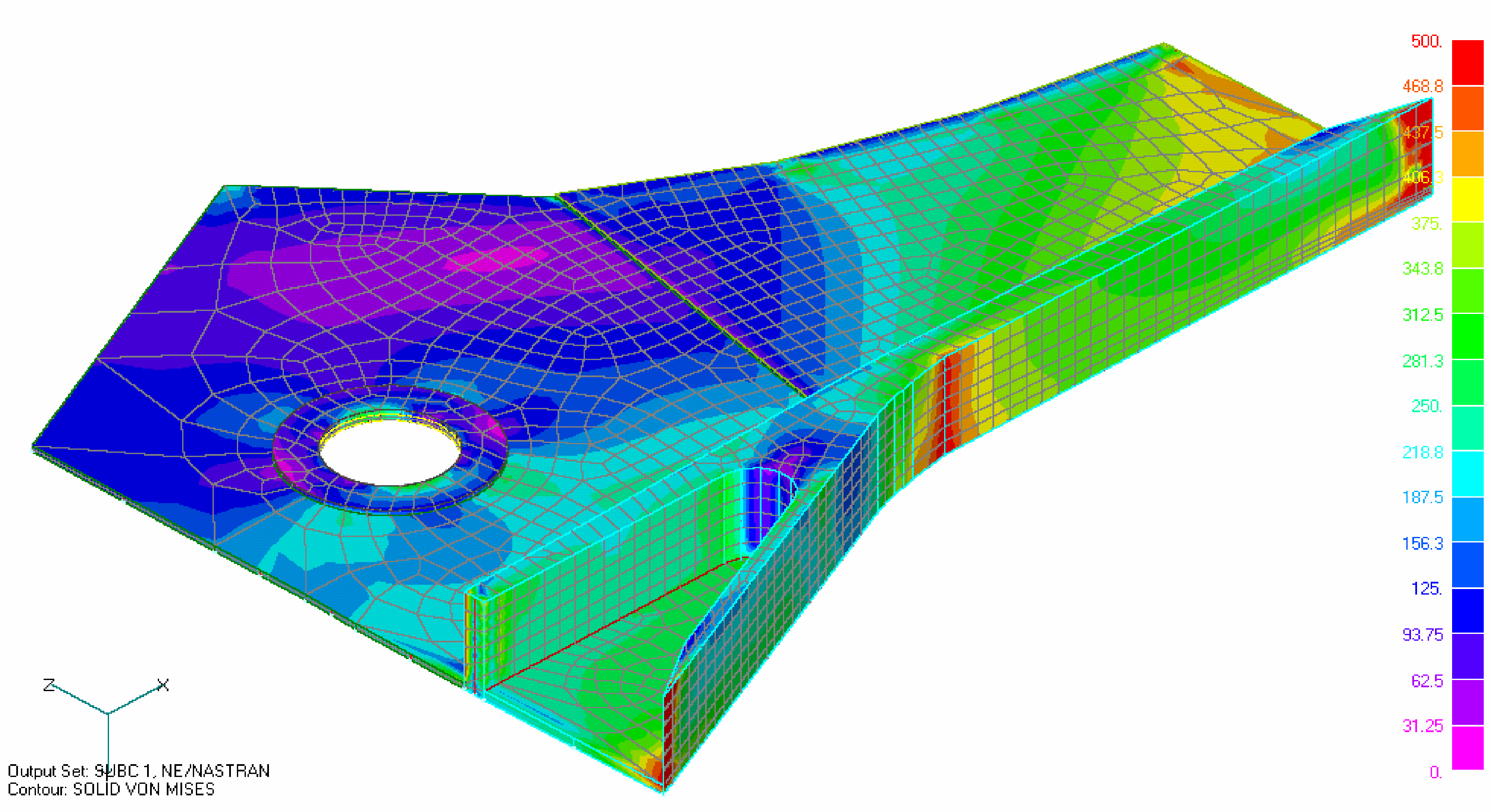
NEi-NASTRAN Von Mises Stresses



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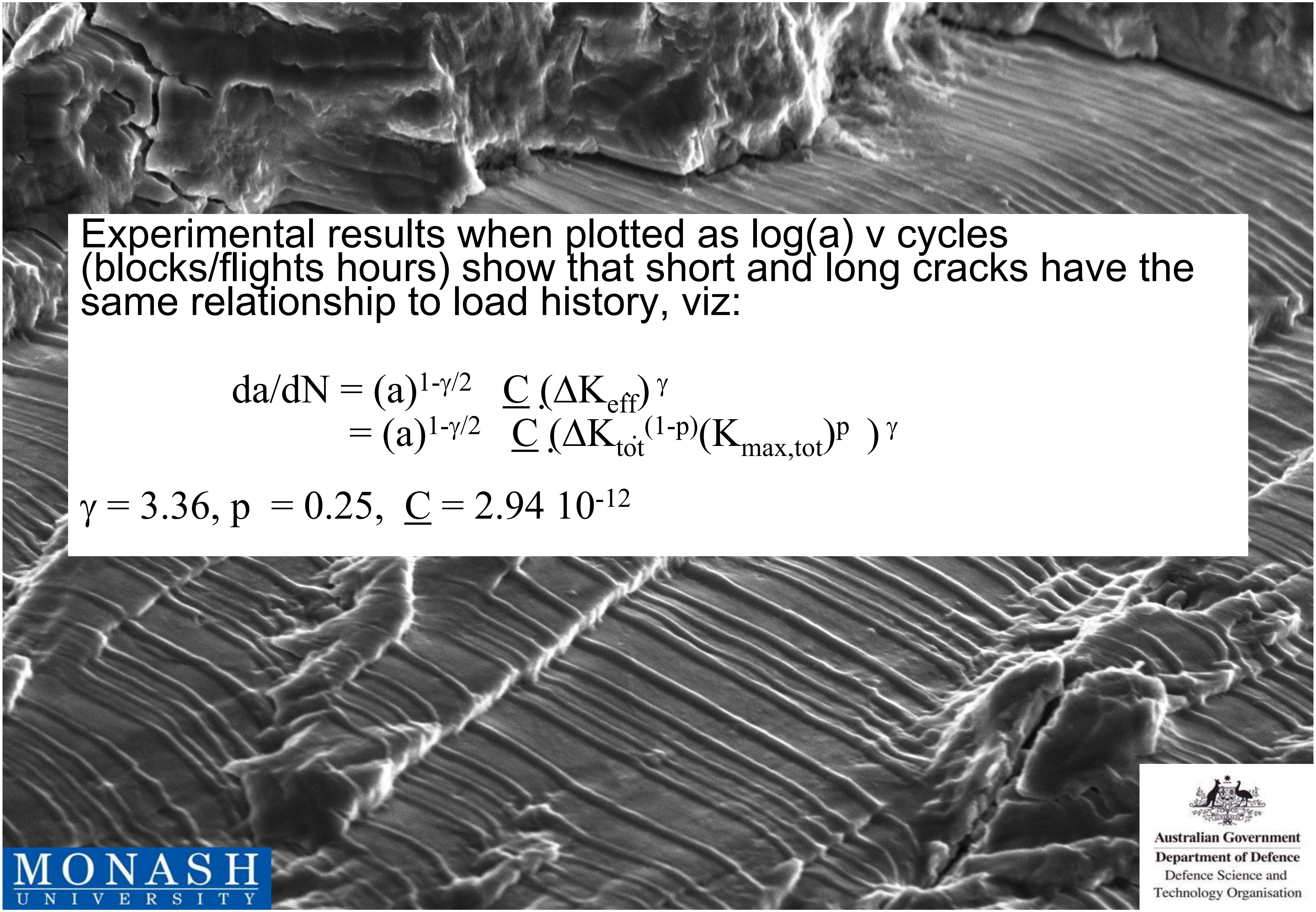


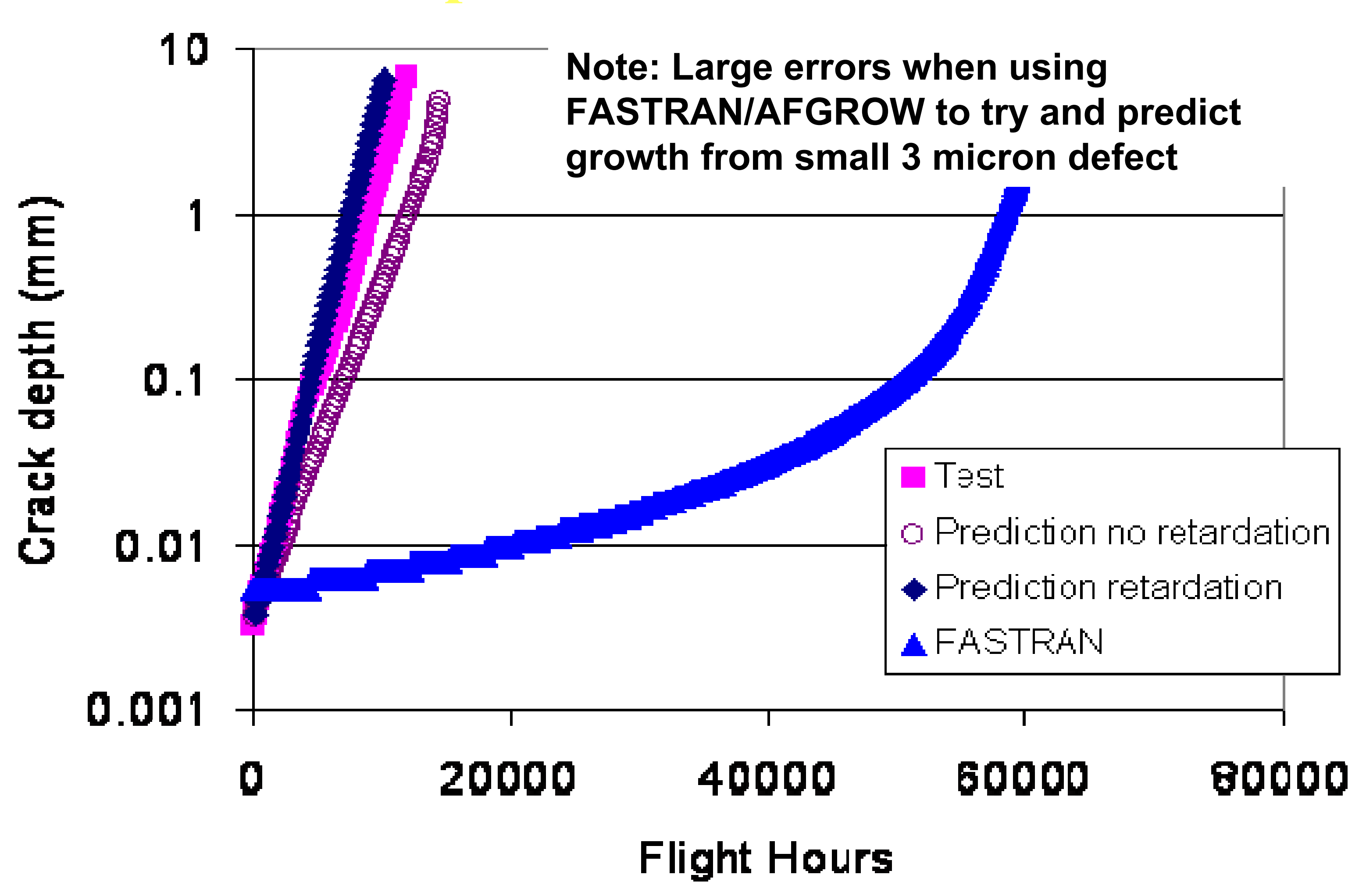
Experimental results when plotted as log(a) v cycles (blocks/flights hours) show that short and long cracks have the same relationship to load history, viz:

$$da/dN = (a)^{1-\gamma/2} \; \underline{C} \, (\Delta K_{eff})^{\gamma}$$

$$= (a)^{1-\gamma/2} \; \underline{C} \, (\Delta K_{tot}^{(1-p)} (K_{max,tot})^{p} \;)^{\gamma}$$

$\gamma = 3.36$, $p = 0.25$, $\underline{C} = 2.94\ 10^{-12}$

Comparison with FASTRAN



Note: Large errors when using FASTRAN/AFGROW to try and predict growth from small 3 micron defect

- Comparison of experiment with predictions and with FASTRAN II predictions using DSTO and US crack growth data as input

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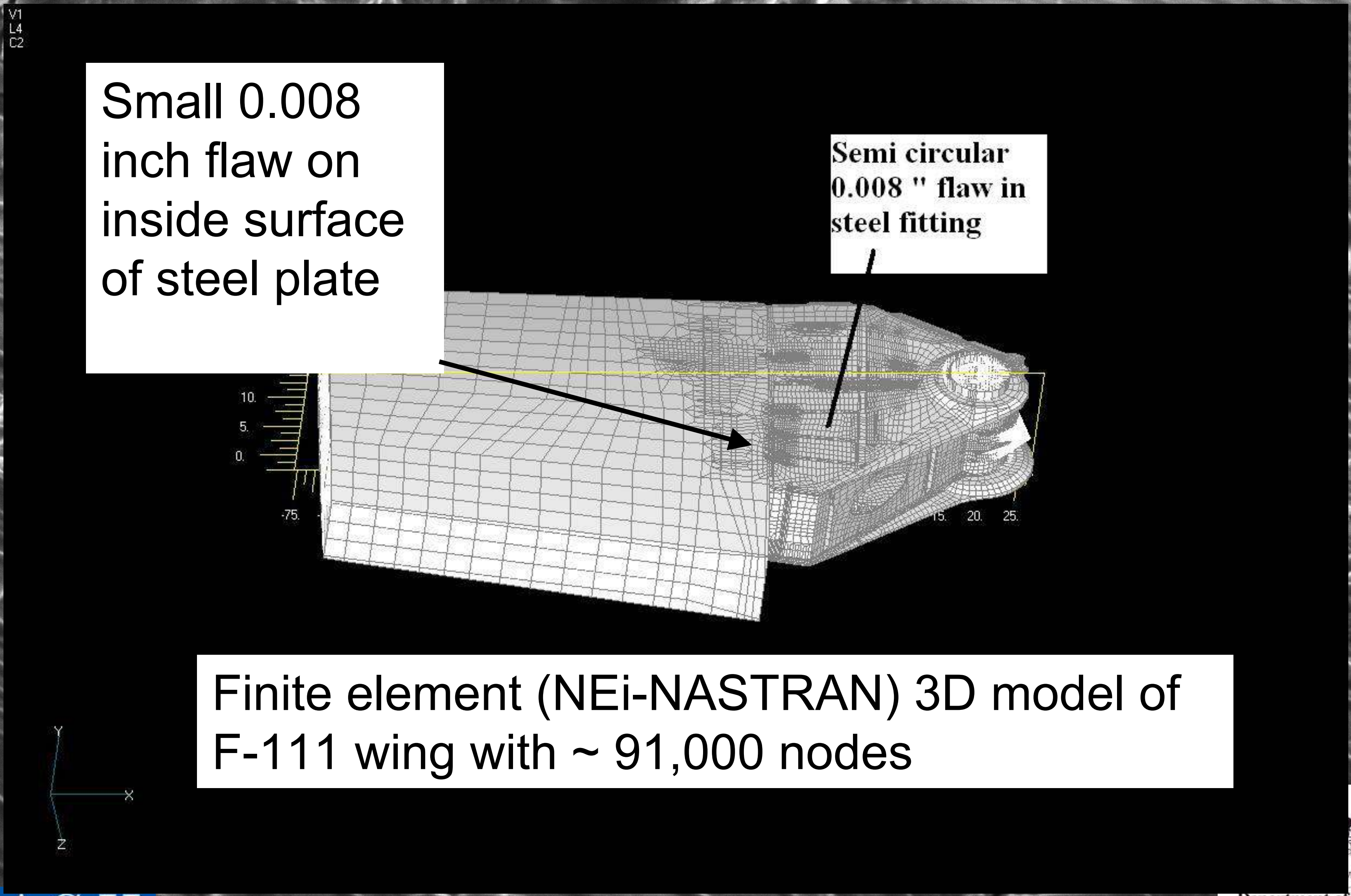
- Same conclusions reached as part of a USAF/General Dynamics evaluation of small crack growth

  J. M. Potter and B. G . W. Yee, “Use of Small Crack Data to Bring About and Quantify Improvements to Aircraft Structural Integrity”, Proceedings AGARD Specialists Meeting on Behavior of Short Cracks in Airframe Structure, Toronto , Canada , 1982.

- No discernable short crack - long crack effect

The 1969-70 F111 Full Scale Fatigue Test



Small 0.008 inch flaw on inside surface of steel plate

Semi circular 0.008 " flaw in steel fitting

Finite element (NEi-NASTRAN) 3D model of F-111 wing with ~ 91,000 nodes

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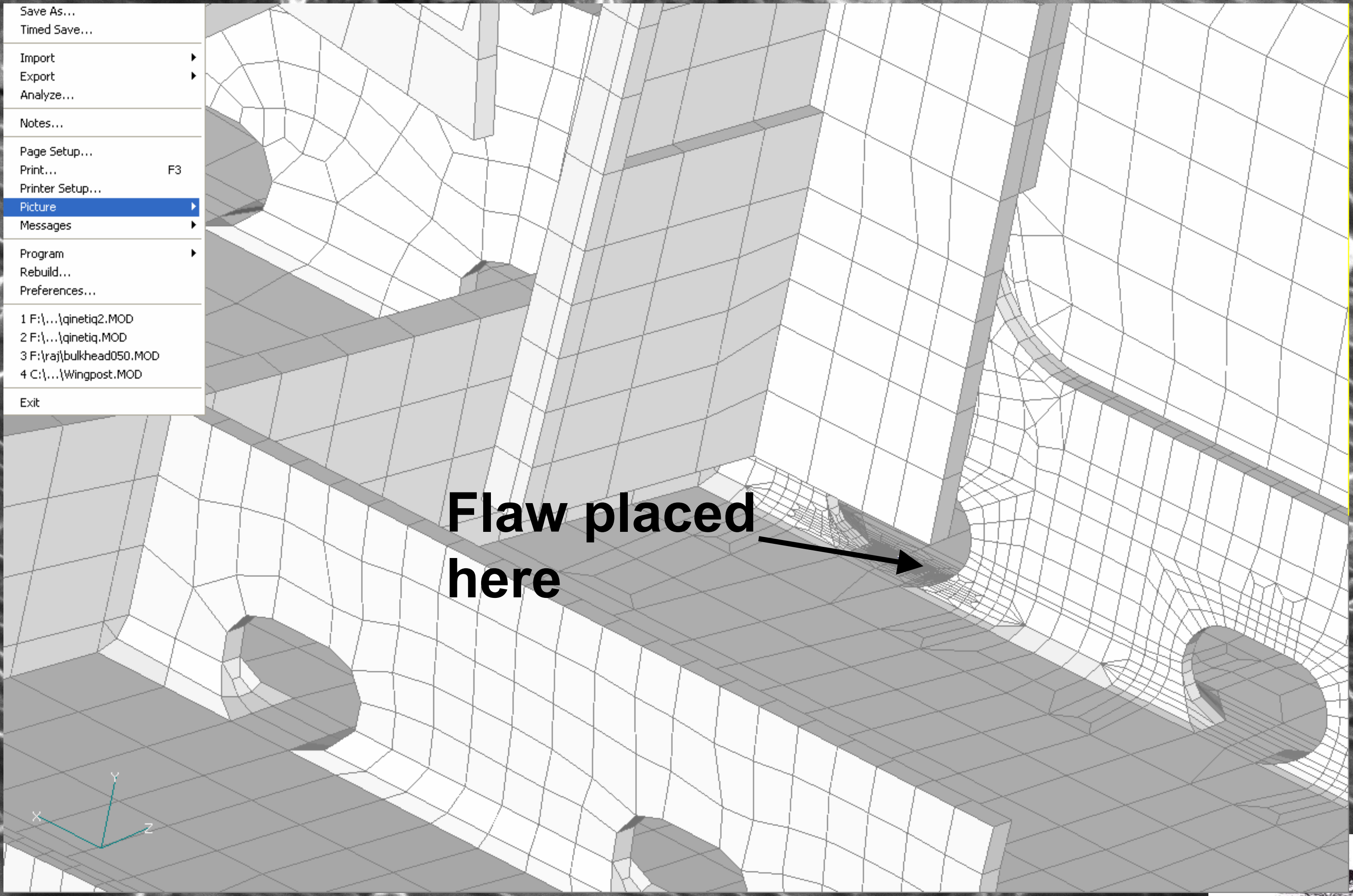
Location of a 0.008" semi-elliptical surface flaw



Flaw placed here

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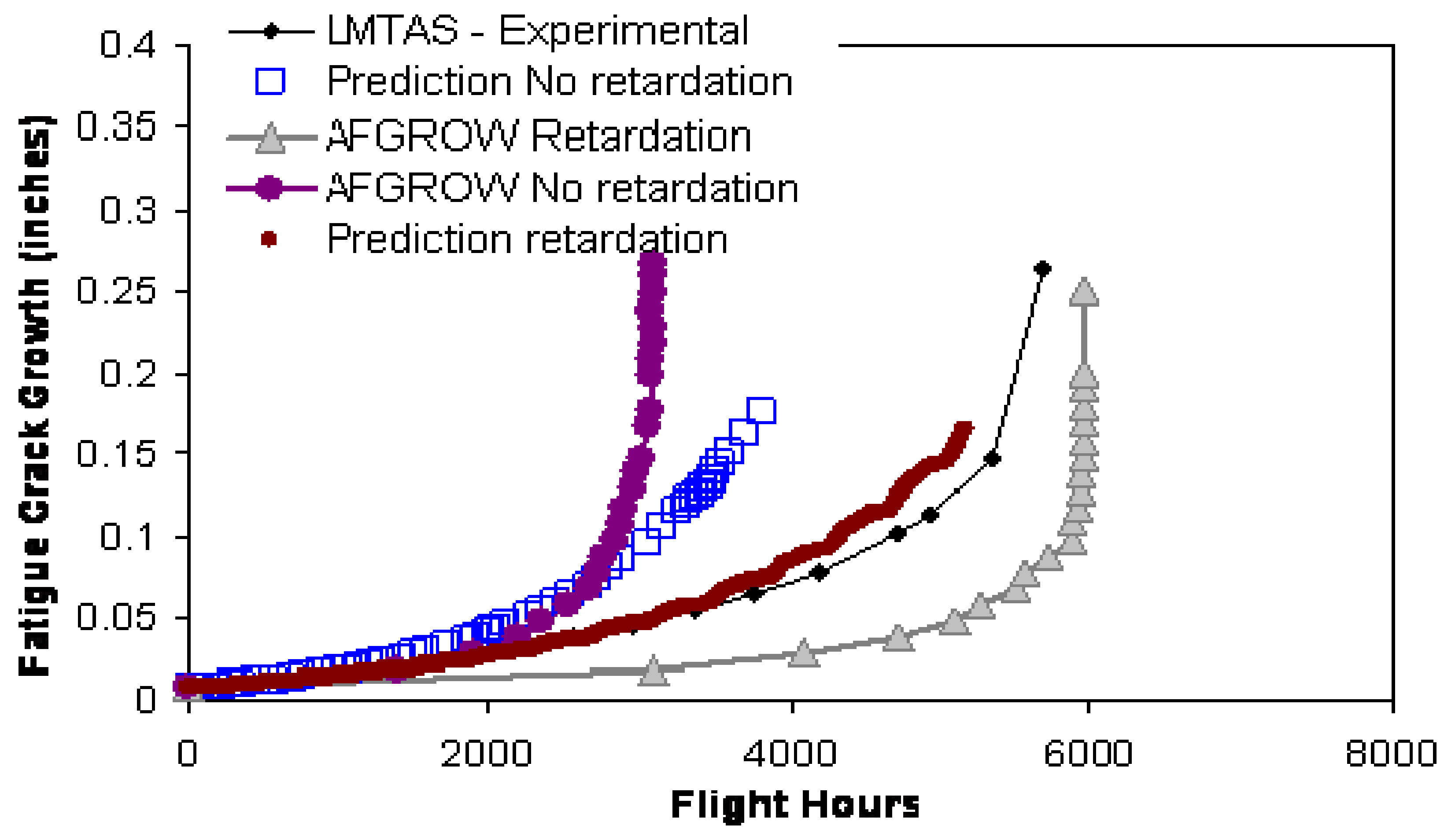
Technical Details

- Analysis uses 3D (generalised) weight functions for semi elliptical, quarter elliptical flaws at an arbitrary notch.
- Total fatigue life analysis time ~ 2 minutes on an Intel P4 2 GHz processor.
- Uses uncracked finite element model only.
- No crack modeling or special mesh refinement needed.
- Analysis directly interfaced with NEi-NASTRAN
- Arbitrary load spectra, geometry, flaw geometries, etc.

Life Prediction: Crack growth in F-111 wing model under General Dynamics (Lockheed) test spectra and comparison with 1970's crack growth data



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Why is this important ?

- The scientific basis for all of the current fatigue crack growth laws, AFGROW, FASTRAN, NASGRO, etc, is invalid in Region I.
- Region I is the region in which a crack will spend most of its life.
- For small cracks growth will generally initially lie in Region I.
- Cracks arising due to corrosion damage will generally initially lie in Region I.
- The current similitude based methodology is non conservative for small sub mm cracks in highly stressed components, i.e. it is both incorrect and unconservative.
- Methodology used to evaluate materials fatigue characterisation tests for crack growth in Region I is invalid.

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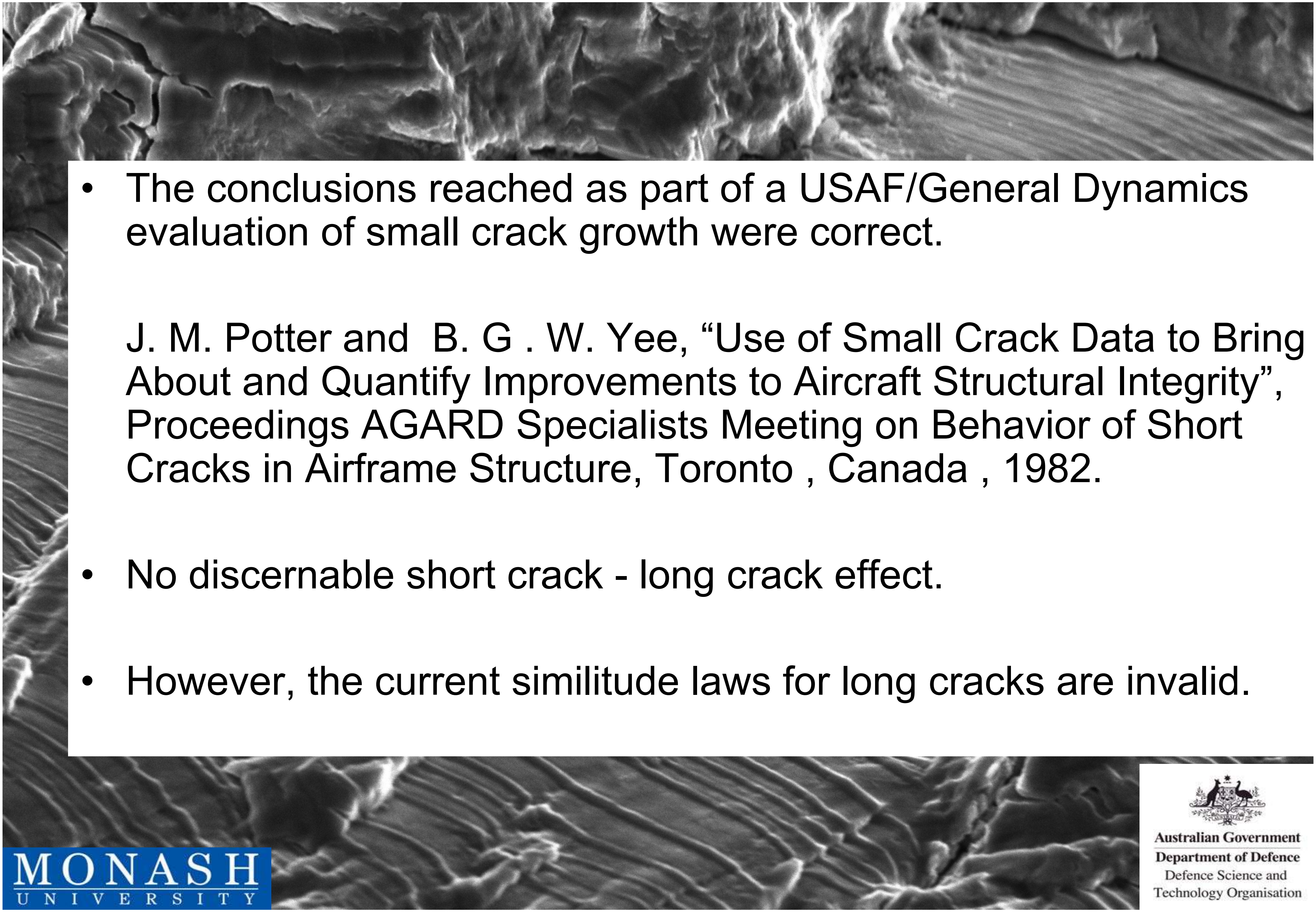

- The conclusions reached as part of a USAF/General Dynamics evaluation of small crack growth were correct.

  J. M. Potter and B. G . W. Yee, “Use of Small Crack Data to Bring About and Quantify Improvements to Aircraft Structural Integrity”, Proceedings AGARD Specialists Meeting on Behavior of Short Cracks in Airframe Structure, Toronto , Canada , 1982.

- No discernable short crack - long crack effect.

- However, the current similitude laws for long cracks are invalid.

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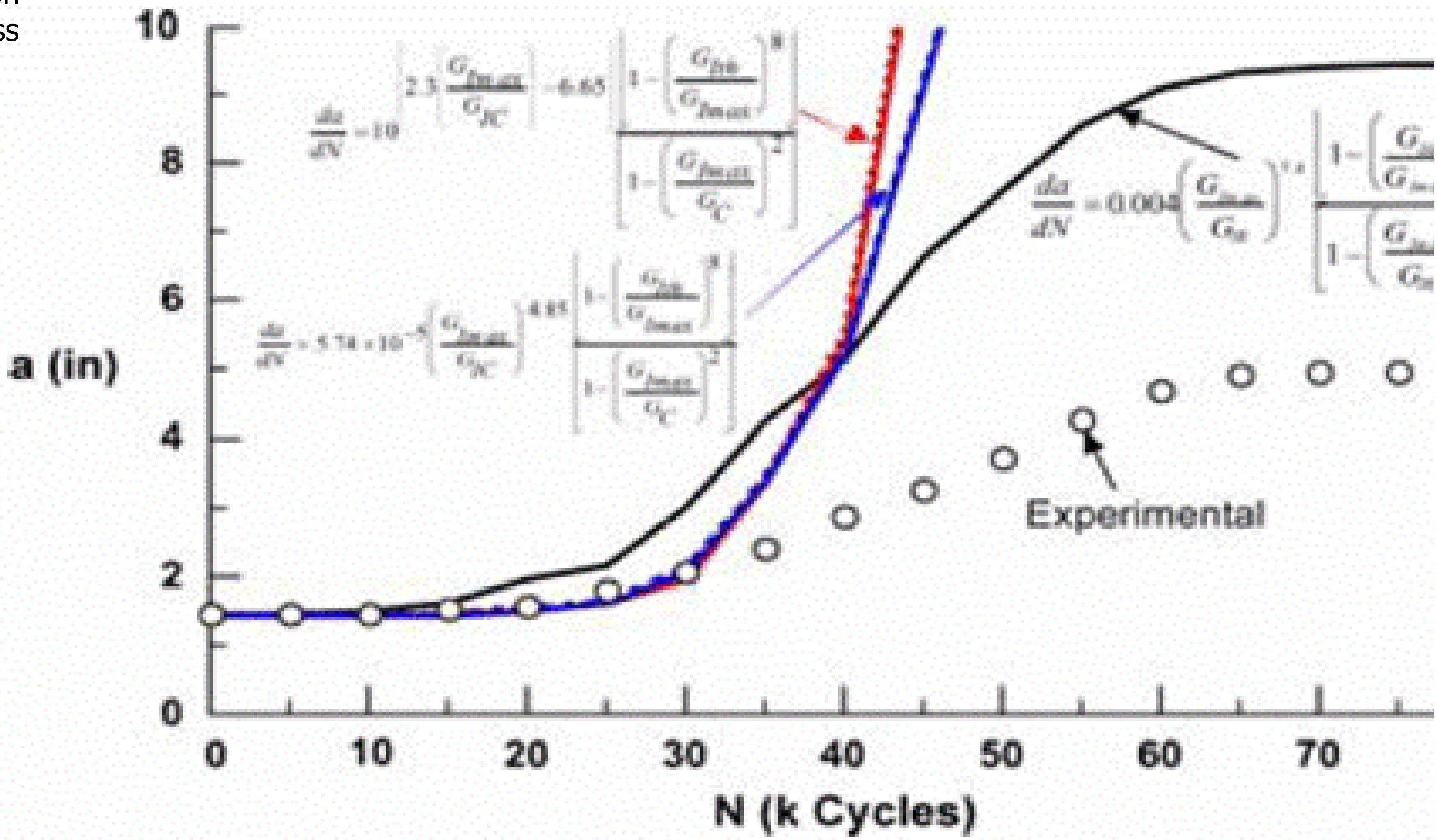
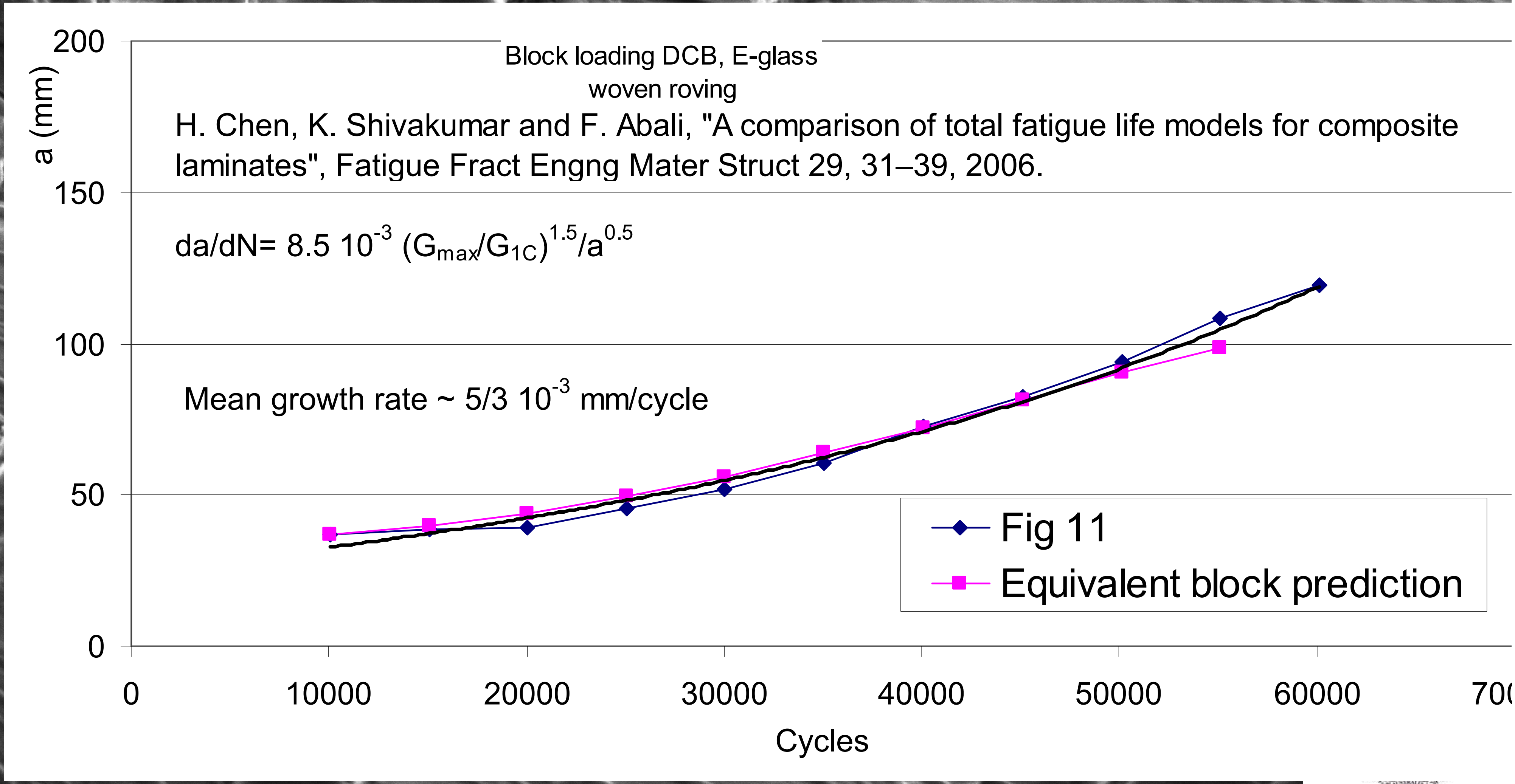
Mode I delamination growth in an E-glass DCB specimen



H. Chen, K. Shivakumar and F. Abali, "A comparison of total fatigue life models for composite laminates", Fatigue Fractures of Engineering Materials & Structures, 29, 31–39, 2006.



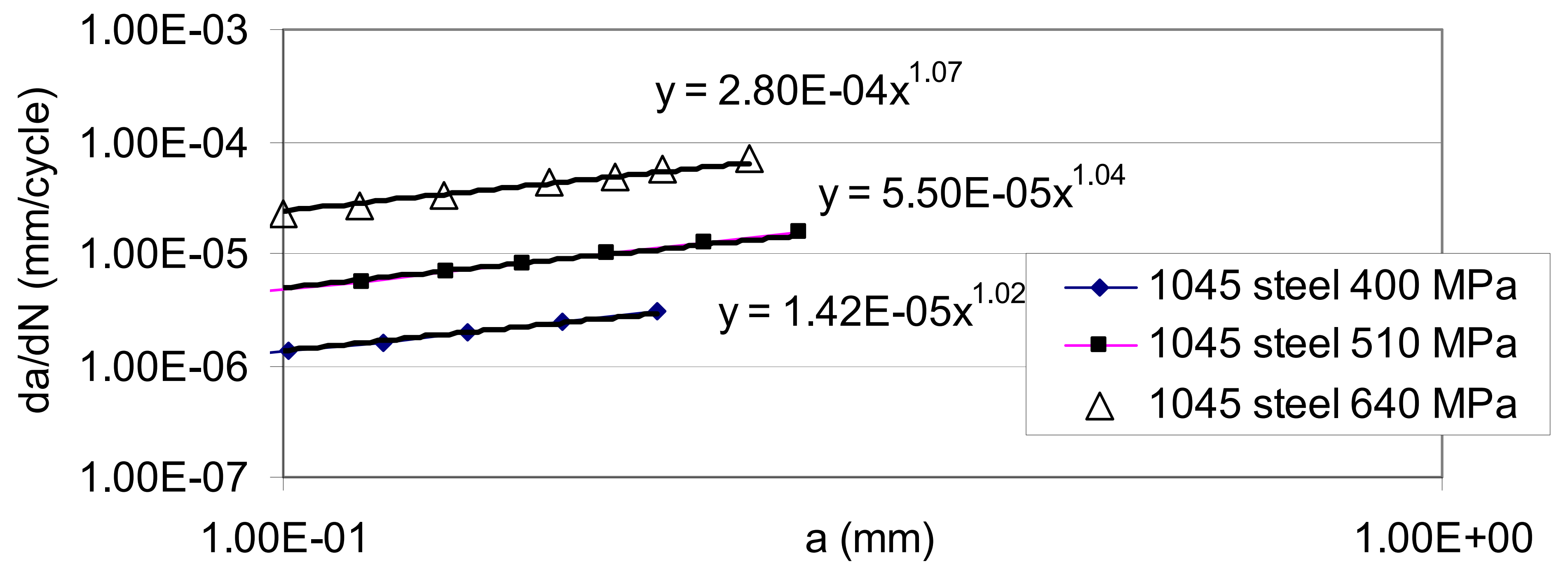
Block loading DCB, E-glass woven roving

H. Chen, K. Shivakumar and F. Abali, "A comparison of total fatigue life models for composite laminates", Fatigue Fract Engng Mater Struct 29, 31–39, 2006.

$da/dN = 8.5\ 10^{-3}\ (G_{max}/G_{1C})^{1.5}/a^{0.5}$

Mean growth rate ~ 5/3 10^{-3} mm/cycle

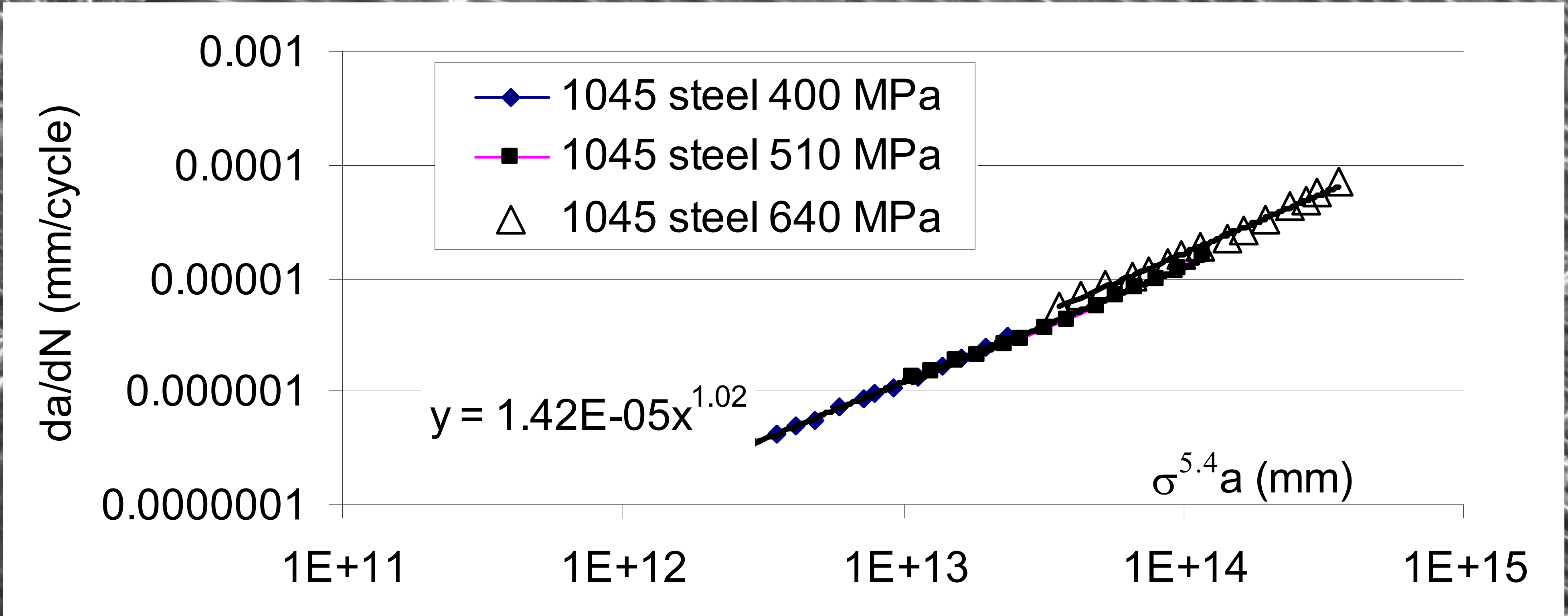
M. T. Yu and T. H. Topper, The effects of materials strength, stress ratio, a compressive overload in the thresho behavior of a SAE 1045 steel. J. Engng *Mater. Technol., Trans. ASME IM,* **19- (1985).**



0.025 mm < a < 0.7 mm

More Proof Near Micron size flaws:

M. T. Yu and T. H. Topper, The effects of materials strength, stress ratio, and compressive overload in the threshold behaviour of SAE 1045 steel. J. Engng *Mater Technol, Trans. ASME,* **19-25 (1985).**



0.025 mm < a < 0.7 mm

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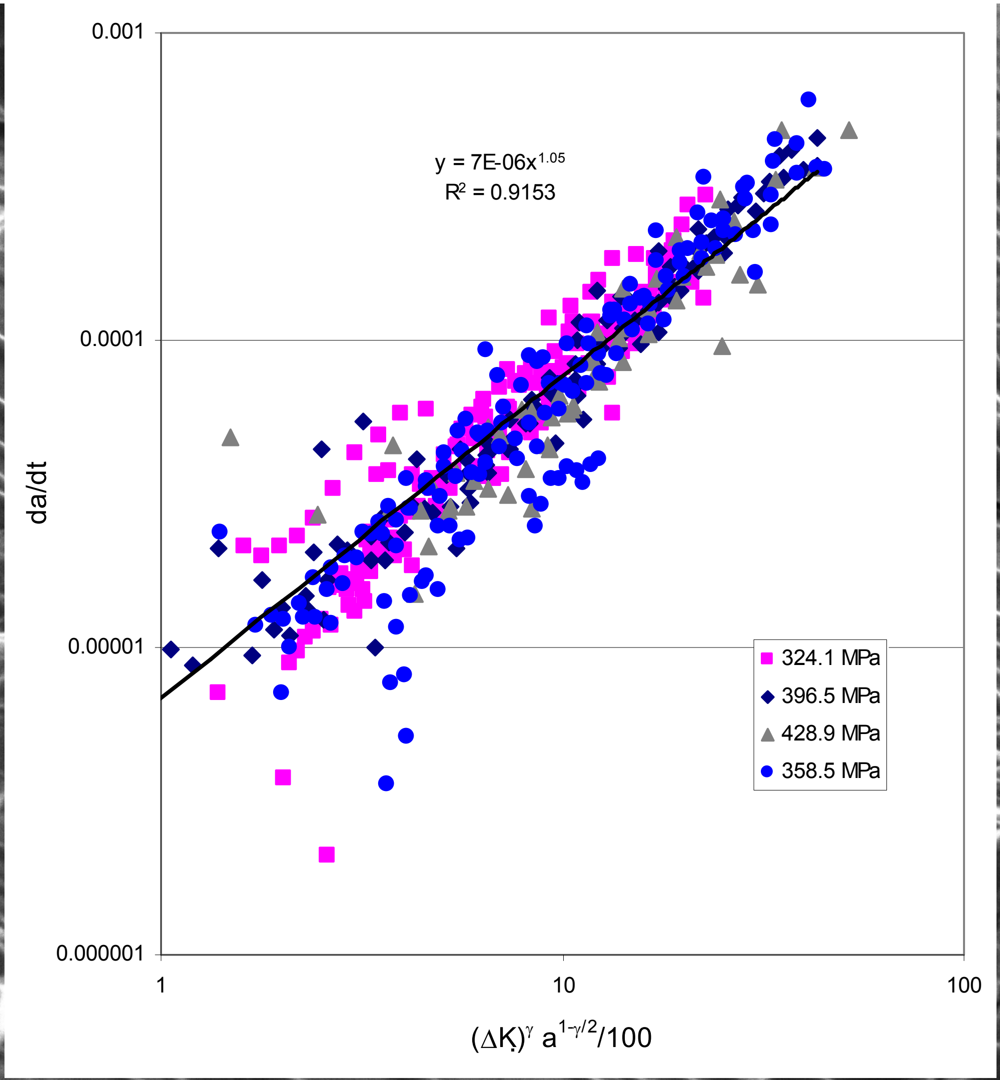
F/A-18 Coupon test Results, APOL load sequence

$\gamma = 3.36$

$p = 0.25$

Crack lengths from 3 microns to 3 mm's



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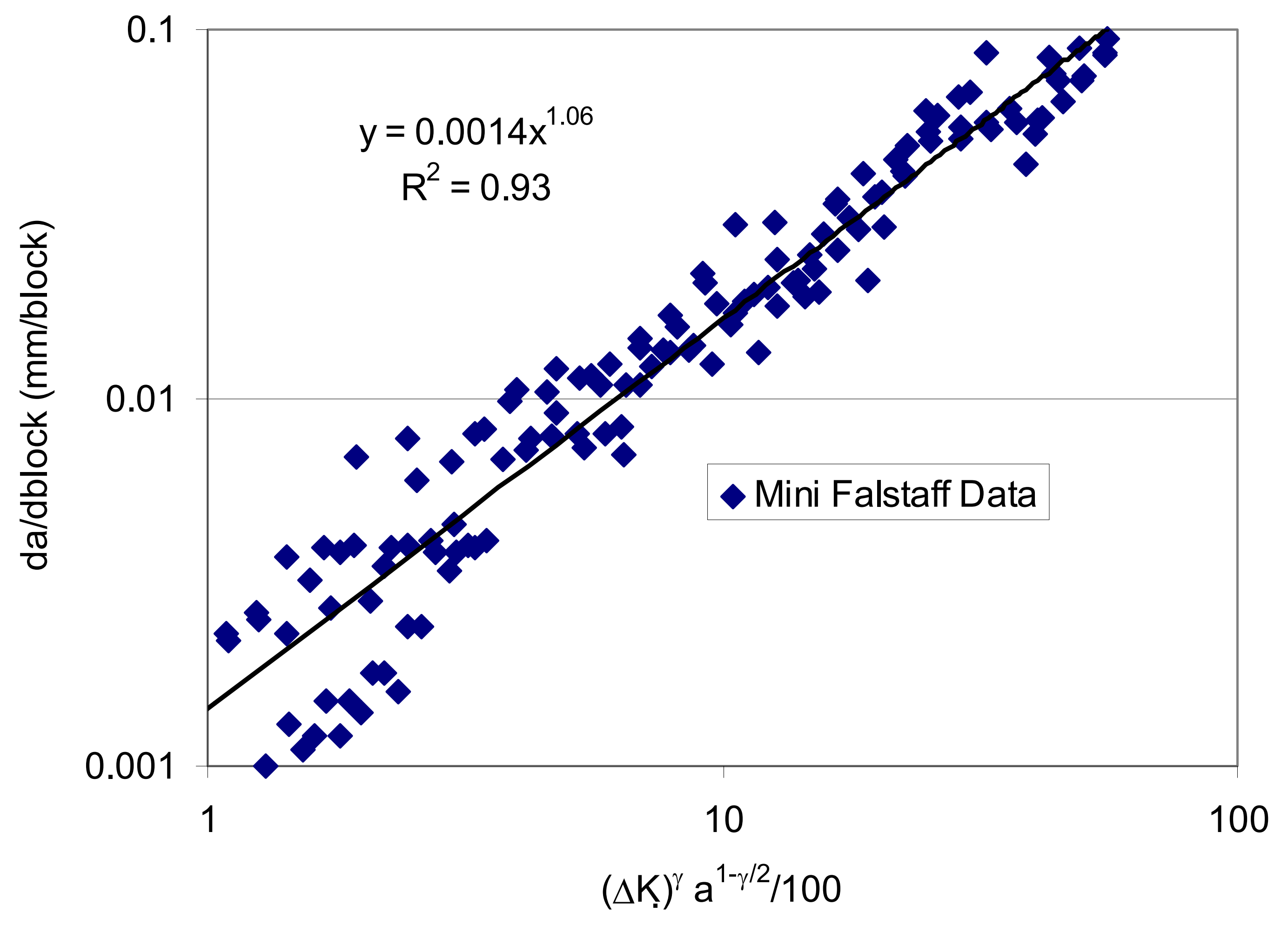
F/A-18 Coupon test Results, Mini-Falstaff load sequence

γ= 3.36

p= 0.25



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