High Energy Processes on Aircraft – Structural Integrity Considerations and Lessons Learned AVT-302 Research Workshop on Paint Removal Technologies for Military Vehicles

Presented by
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Presentation to

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- **NATO AVT-302 Committee**

Reference Materials

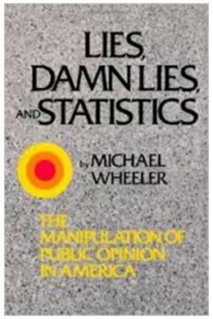
1. http://index.heritage.org/military/2015/chapter/us-power/us-air-force/#identifier_9_16
2. SAE MA4872, Paint Stripping of Commercial Aircraft – Evaluation of Materials and Processes, SAE Aerospace, Aerospace Standard, September, 2010
3. Laser Cutting Metallurgical Report, A-10 ASIP, June 2008 (exact reference unavailable)
4. "S. Carlson, Qualification of Advanced Structural Sustainment Tools/Processes within the ASIP Environment – Perfect Point™ E-Drill™," USAF ASIP Conference, November, 2012
5. D. Andrew & J. Macha, "Two T-38 Test Programs: Sealant Removal – Enemy #1, T-38 ASIP Summit XIV," Southwest Research Institute, January 2017
6. ASM Handbook, Volume 13, "Corrosion", p.592, Fig.11, 1996
7. J. Calcaterra, "Effect of Manufacturing Variability on Air Force Systems", ASIP 2008

Reference Materials continued

8. R. Pilarczyk, S Carlson & G. Stowe, "'Is ASIP Still Alive'" The A-10 Lower Wing Skin Cracking Issue of 2008-2009," USAF ASIP Conference, November 2009
9. The New Weibull Handbook, Fourth Edition, by Dr. Robert B. Abernethy, March 2003
10. A Reliability Analysis Approach to Fatigue Life Variability of Aircraft Structures, Whittaker, Air Force Materials Laboratory, Air Force Systems Command, WPAFB, 1969.
11. Optimization of Aircraft Laser Coating Removal Processes, Final Report, No. W91ZLK-10-D-005, Feb 12 2014, by Concurrent Technologies Corporation
12. Final Draft Fatigue Data Analysis Report, RFQ No. CTC-P-13-0160, Richard C. Rice and Jana Rubadue, Battelle, Nov 22 2013

CAVEATS

- **The opinions expressed are those of myself and the coauthors**
- **I am not a statistician**
  - "Lies, Damn Lies and Statistics"
    - *Phrase popularized by Mark Twain*
      - *Interesting book by Michael Wheeler*



- **Weibull is not necessarily the best way to analyze fatigue data ---**
    - *It is an alternative method utilized by commercial aerospace manufacturers*
- **The focus is on the material behavior as a result of the processing → specifically paint removal**
  - Emphasis on high energy processes (plasma, laser, etc.)
    - I am *not* an expert on lasers or plasma

Presentation Overview

- **Pace of technology**
- **What are some potential challenges from high energy processes?**
- **What does any change from the baseline suggest?**
  - Protecting the airworthiness baseline and structural integrity is paramount!
    - Fatigue/durability
    - Nondestructive Inspections
    - Corrosion
    - Sustainability, etc.
- **Characterizing the microstructure**
  - Initial Discontinuity State (IDS) - Baseline
  - Evolving Discontinuity State (EDS)
- **Distributions and Weibull analyses**
- **Evaluation criteria suggestions**
  - *Evaluations to ensure the candidate process does not compromise the airworthiness baseline*
- **Engineered protections to prevent damage**
- **Conclusions & Recommendations**

The Pace of Technology

	Aircraft						
	A-10	T-38	F-16	KC-135	B-52	B-1	F-22A
2005	1977	1961	1978	1957	1955	1986	2005
Original Count	716	1146	2230	803	744	104	187
Projected Retirement Age*	60	70	36	83	80	52	?

*Estimated by age of remaining assets and projected date of retirement.

Age range: 1955-2017

- **27 years old: Average age of USAF aircraft in 2015**

Reference: 1

Technology circa 1966






The New York Times.

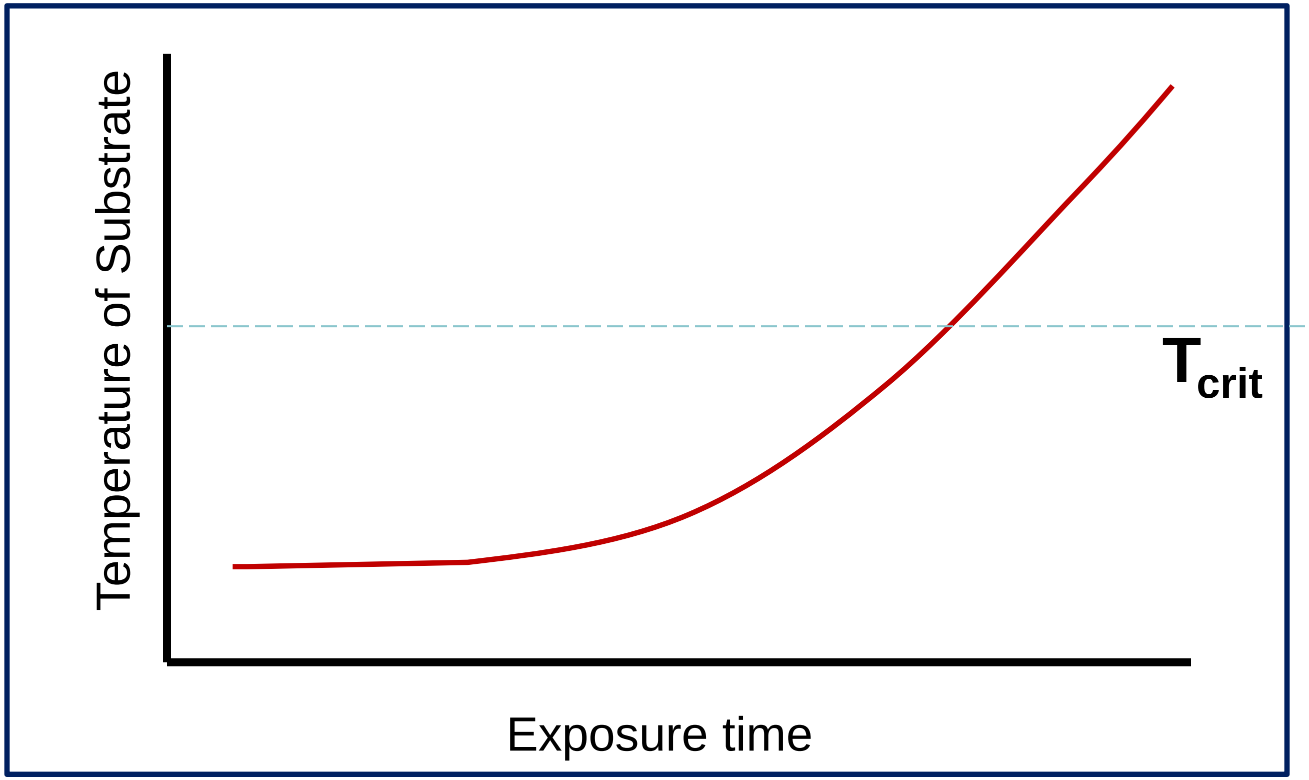
KENNEDY'S VICTORY WON BY CLOSE MARGIN; HE PROMISES FIGHT FOR WORLD FREEDOM; EISENHOWER OFFERS 'ORDERLY TRANSITION'

Similar Technology Today

Caution is advisable as new processes emerge.

High Energy Process Damage

- **High Energy systems utilize *HEAT* to do the work**



T_{crit}: Critical temperature below which no change to the micro-structure occurs

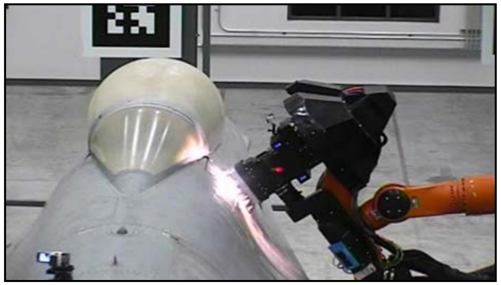
Reference: 2

SAE MA 4872: "Substrate temperature shall not exceed 80 ºC or 180ºF

Potential Thermally Induced Damage

- **Damage goal:**
  - Preferred: NONE
  - Accepted: Minimized impact to airworthiness: predictable, sustainable, detectable, repairable

- **Change to microstructure**
  - Durability
  - Widespread fatigue damage (WFD)
  - Multiple site damage (MSD)
  - Multiple element damage (MED)
  - Damage tolerance potentially altered
  - Fail safety potentially compromised
  - Surface integrity
    - Any change or compromise to the structure surface or protection system

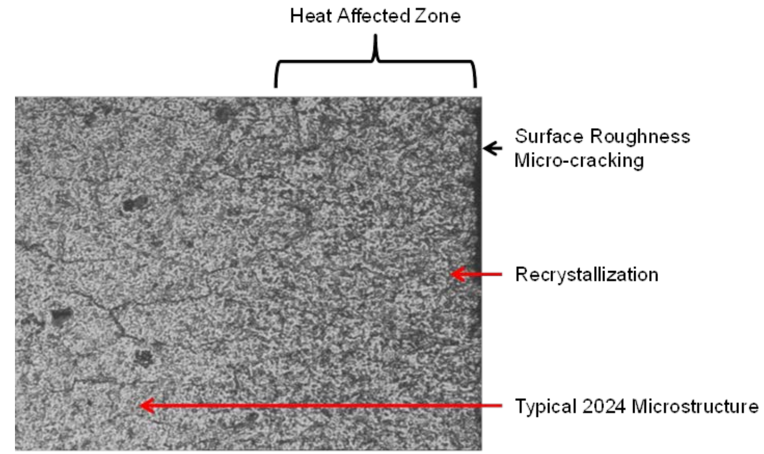


Potential Damage *continued…*

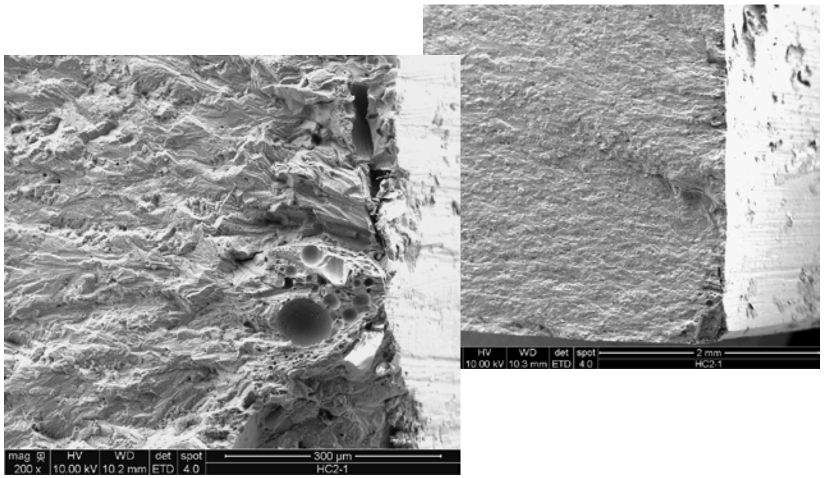
- **NDI responsiveness considerations**
  - Physics of the method?
    - Probability of detection?
    - Threshold of detection?
    - Cracks hidden by process?
- **Corrosion prevention and control considerations**
  - Change in galvanic differences?
  - Coatings and other protections still viable?
  - Primer/paint adhesion?
- **Ability for Maintenance to respond**
  - Detectability (…is damage detectable?)
  - Reparability (…is damage reparable?)
  - Reliability (…what is the reliability of the repair?)
- **Introduction of residual stresses?**
- **Are the evaluations representative?**

High Energy Processes – Lessons Learned

- **Laser Cutting (USAF 2007)** *Reference: 3*
  - Microstructure changed
  - H.A.Z. & recast layer
  - Micro-cracking
  - Surface integrity/durability degraded
  - 94% durability downgrade for 2024-T3
  - AA-07-02 *(Airworthiness Advisory, Oct. 10, 2007)*

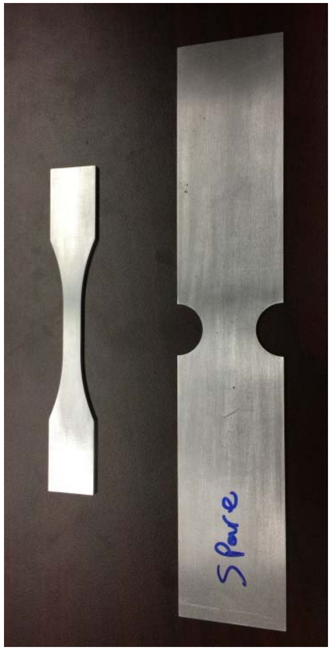


- **Plunge Rotating EDM (USAF 2011)** *Reference: 4*
  - Microstructure changed
  - H.A.Z. & recast layer
  - Micro-cracking
  - Surface integrity/durability degraded
  - 96% durability downgrade for 2024-T351
  - Damage undetectable after ‘cleaned-up’



• USAF Fiber Laser Sealant Removal Experiment: Parameters

Material	Max Stress (ksi)	Stress Ratio	Thickness (inch)	Kt		Dwell Time (seconds)	# of passes	Coupon Designation
7075-T6 sheet	40	0.1	0.032	1.0		N/A	N/A	32-1.0-B-1,2,3
						10	N/A	32-1.0-D10-1,2,3
						30	N/A	32-1.0-D30-1,2,3
						N/A	30	32-1.0-P30-1,2,3
				1.6		N/A	N/A	32-1.6-B-1,2,3
						10	N/A	32-1.6-D10-1,2,3
						30	N/A	32-1.6-D30-1,2,3
						N/A	30	32-1.6-P30-1,2,3
			0.090	1.0		N/A	N/A	90-1.0-B-1,2,3
						10	N/A	90-1.0-D10-1,2,3
						30	N/A	90-1.0-D30-1,2,3
						N/A	30	90-1.0-P30-1,2,3
				1.6		N/A	N/A	90-1.6-B-1,2,3
						10	N/A	90-1.6-D10-1,2,3
						30	N/A	90-1.6-D30-1,2,3
						N/A	30	90-1.6-P30-1,2,3



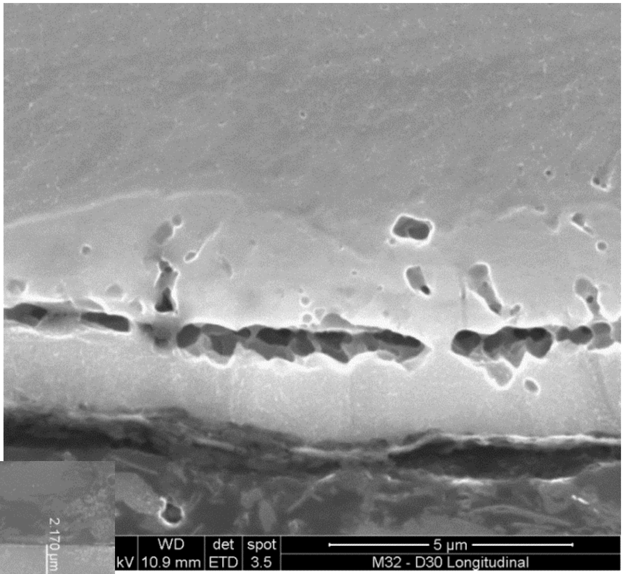
Fatigue Coupon

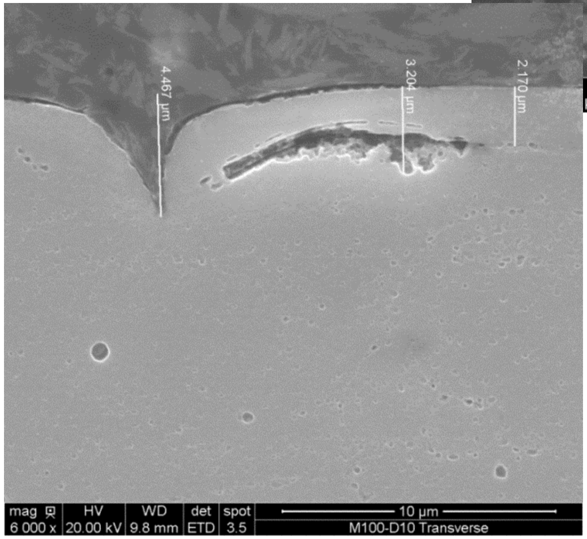
No process controls for these experiments…
Likely represents a near worst case scenario…

Reference: 5

Metallographic Examination

- **All pulsed regions were sectioned in longitudinal and transverse directions and examined**
- **Common microstructural features:**
  - Surface and subsurface discontinuities
  - micro-cracking
  - Recast layer
  - Voids
- **Many DISCONTINUITIES**
  - Many opportunities for crack nucleation

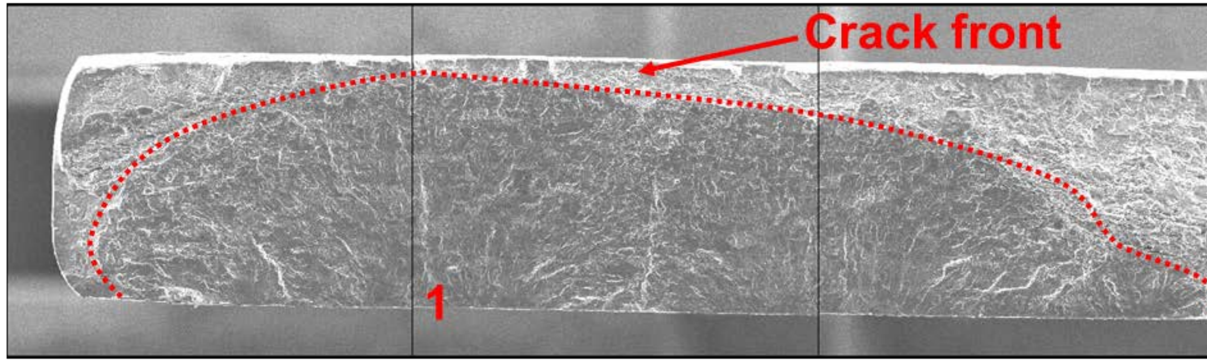


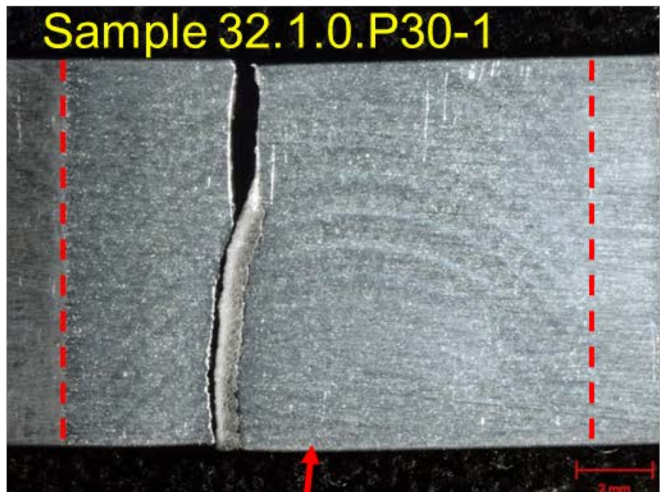


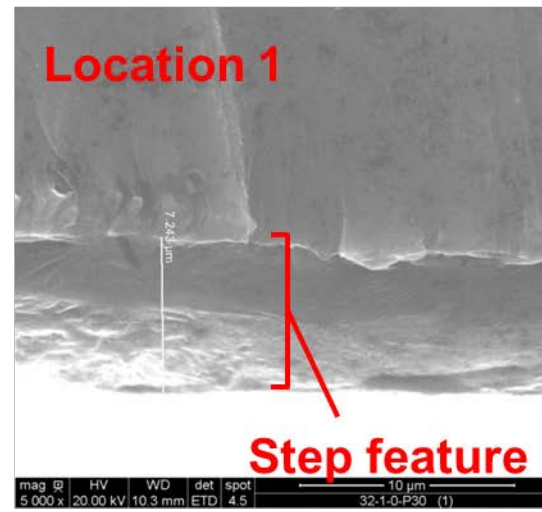
Reference: 5

Fatigue Samples

- **Test sample cracks originated at pulsed surface**
- **Ratchet marks indicate numerous individual crack nucleation sites**
  - ➢ MSD
- **Origin region exhibited discontinuous step feature with similar dimensions to recast zone**







Reference: 5

Fiber Laser Sealant Removal: Fatigue Testing

Material	Thickness (inch)	Kt	Dwell Time (seconds)	# of passes	Coupon Designation	Life (cycles)	Notes
7075-T6 sheet	0.032	1	N/A	N/A	32-1.0-B-1,2,3	8,540,303	3/3 Samples Run-Out
			10	N/A	32-1.0-D10-1,2,3	45,050	99.5% Knockdown
			30	N/A	32-1.0-D30-1,2,3	34,102	99.6% Knockdown
			N/A	30	32-1.0-P30-1,2,3	26,995	99.7% Knockdown
		1.6	N/A	N/A	32-1.6-B-1,2,3	4,377,733	2/3 Samples Run-Out
			10	N/A	32-1.6-D10-1,2,3	85,050	98.1% Knockdown
			30	N/A	32-1.6-D30-1,2,3	41,328	99.1% Knockdown
			N/A	30	32-1.6-P30-1,2,3	65,680	98.5% Knockdown
	0.09	1	N/A	N/A	90-1.0-B-1,2,3	6,531,630	2/3 Samples Run-Out
			10	N/A	90-1.0-D10-1,2,3	53,487	99.2% Knockdown
			30	N/A	90-1.0-D30-1,2,3	52,781	99.2% Knockdown
			N/A	30	90-1.0-P30-1,2,3	61,950	99.1% Knockdown
		1.6	N/A	N/A	90-1.6-B-1,2,3	7,873,343	1/1 Sample Run-Out
			10	N/A	90-1.6-D10-1,2,3	TBD	*Incomplete*
			30	N/A	90-1.6-D30-1,2,3	TBD	
			N/A	30	90-1.6-P30-1,2,3	TBD	

Many discontinuities induced by the process.

Reference: 5

DISCONTINUITIES
are an interruption of the structure

- **<u>Types of DISCONTINUITIES</u>**
  - Initial Discontinuity State (IDS)
    - GEOMETRIC ($IDS_{geometry}$)
      - Notches, radii, etc.
    - MATERIAL ($IDS_{material}$)
      - Constituent particles, voids, porosity, etc.
    - MANUFACTURING ($IDS_{manufacturing}$)
      - Surface gouges, grinding, embedded particles, scratches, etc.
  - Evolving Discontinuity State (EDS)
    - Environment dependent
    - Service loading (usage) induced
    - Maintenance and sustainment process induced

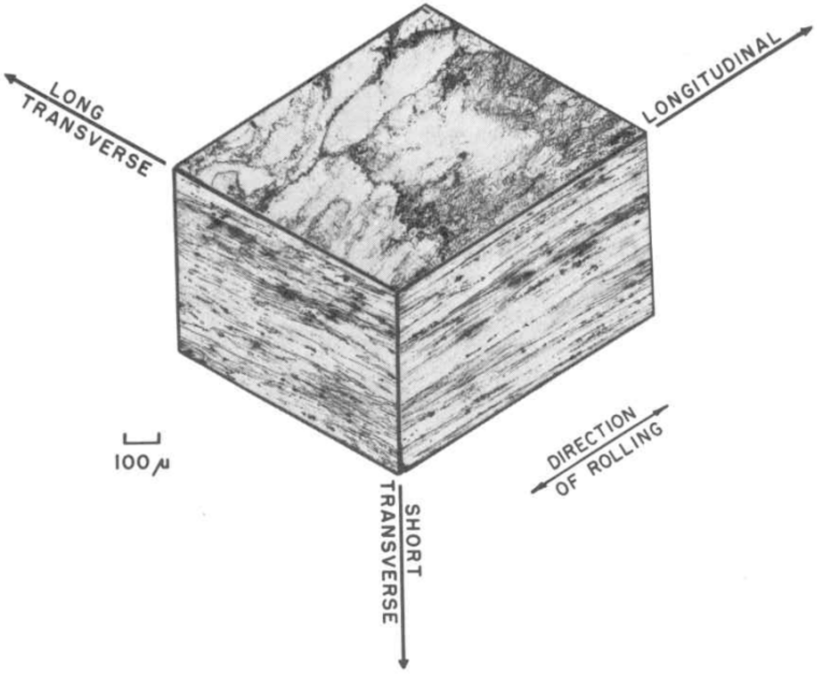
Baseline / pristine condition

Changes to baseline with time, usage, inspections, repairs, paint/strip cycles, etc.

IDS (Initial Discontinuity State)

Examples of Initial Discontinuities

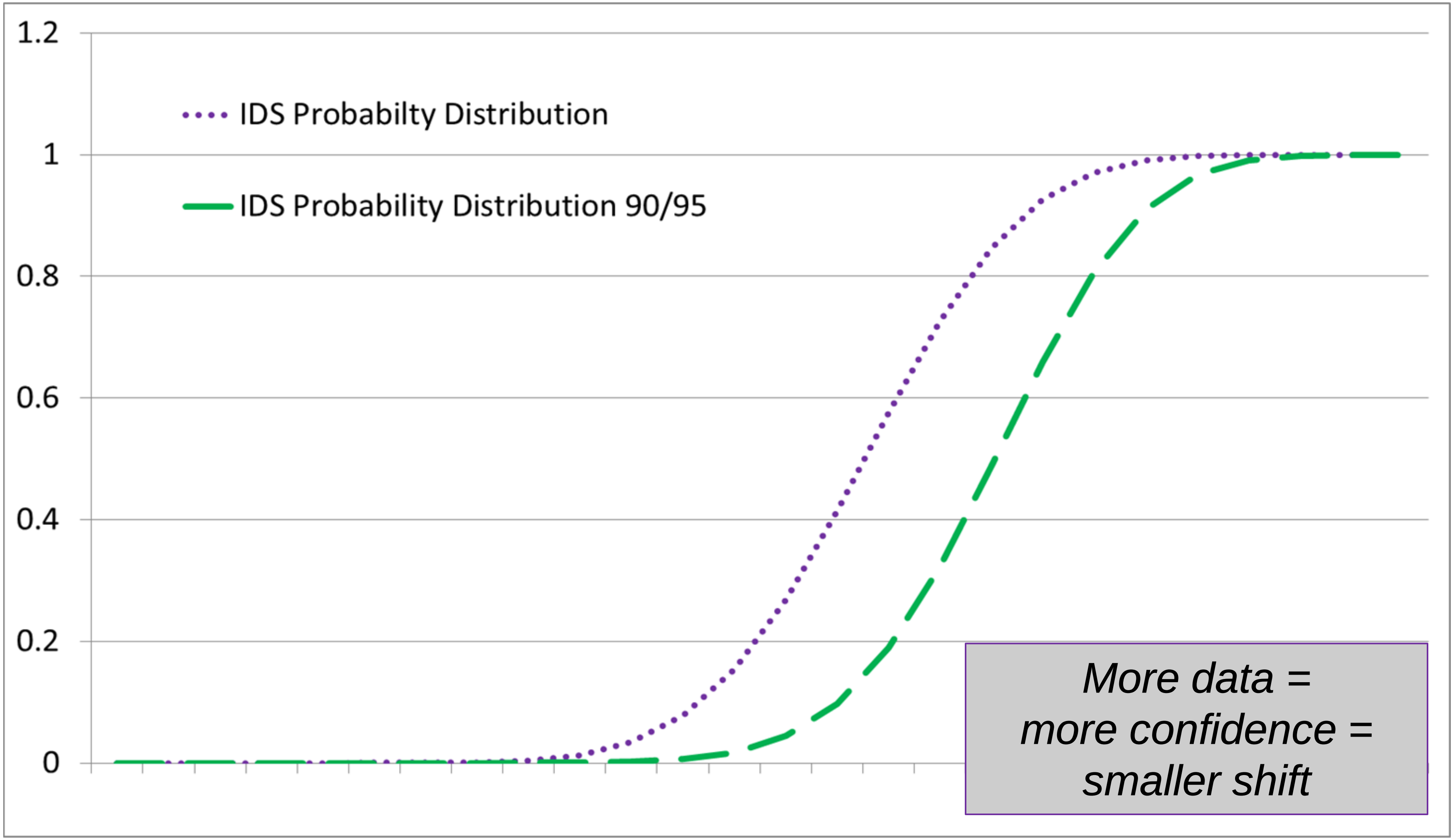
- Constituent Particles
- Grain Size
- Grain Shape
- Grain Orientation
- Porosity
- Voids
- Inclusions
- Various *Phases*
- Manufacturing
- Assembly
- Processing
- Etc.



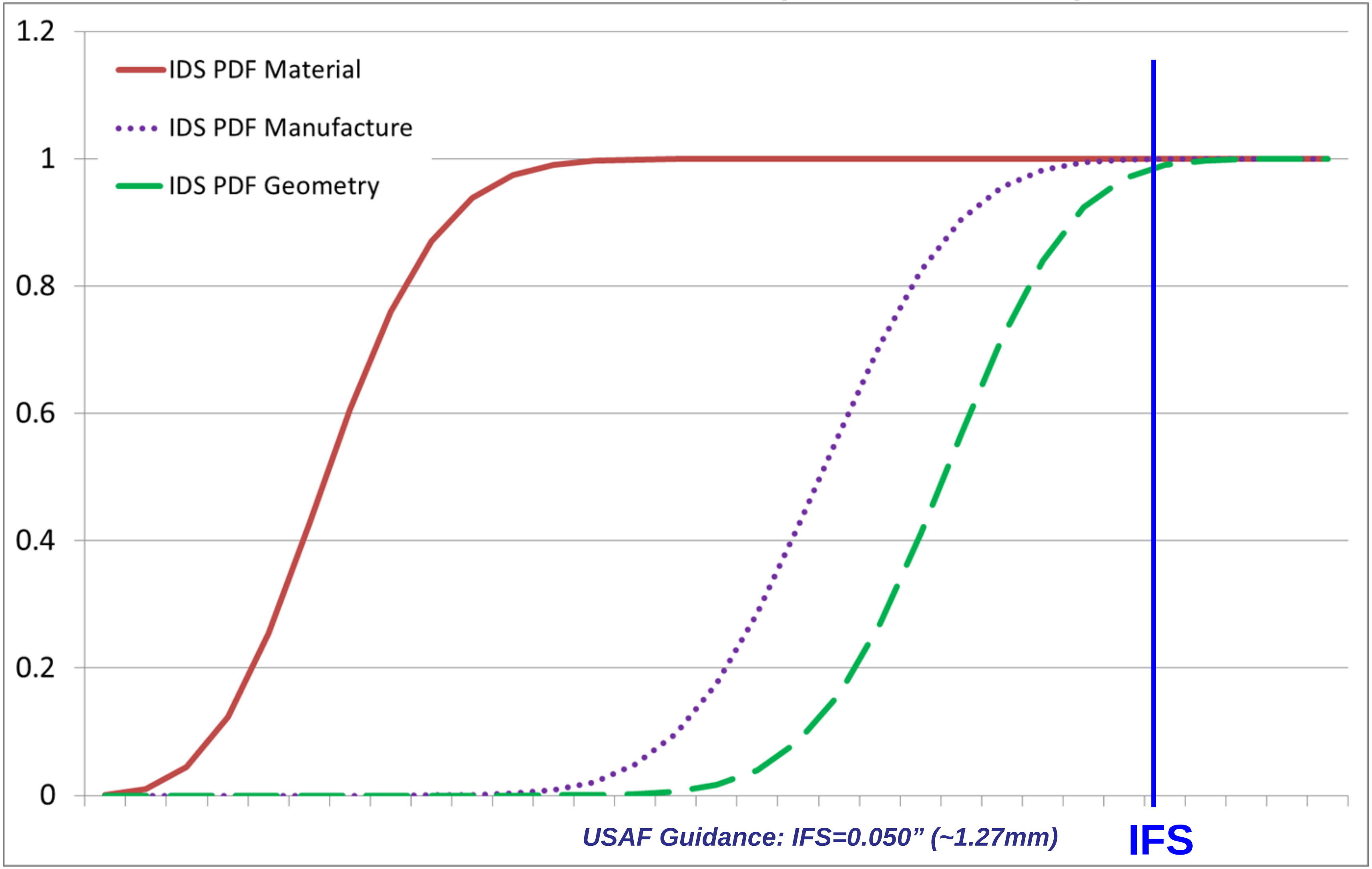
Distributions can be used to characterize *PROBABILITY*

Reference: 6

IDS Distribution (Notional)

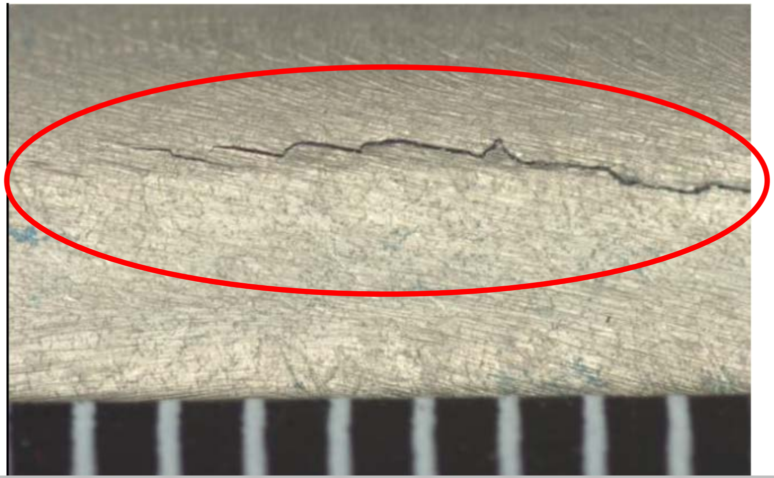


IDS Distribution (Notional)

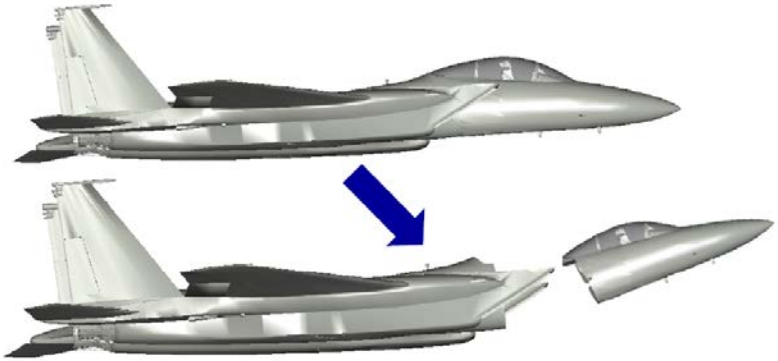


IDS$_{manufacturing}$

- **Multiple nucleation sites**
  - Widespread fatigue damage
  - Multisite damage
- **Machining marks**
- ***IFS – DID NOT WORK***



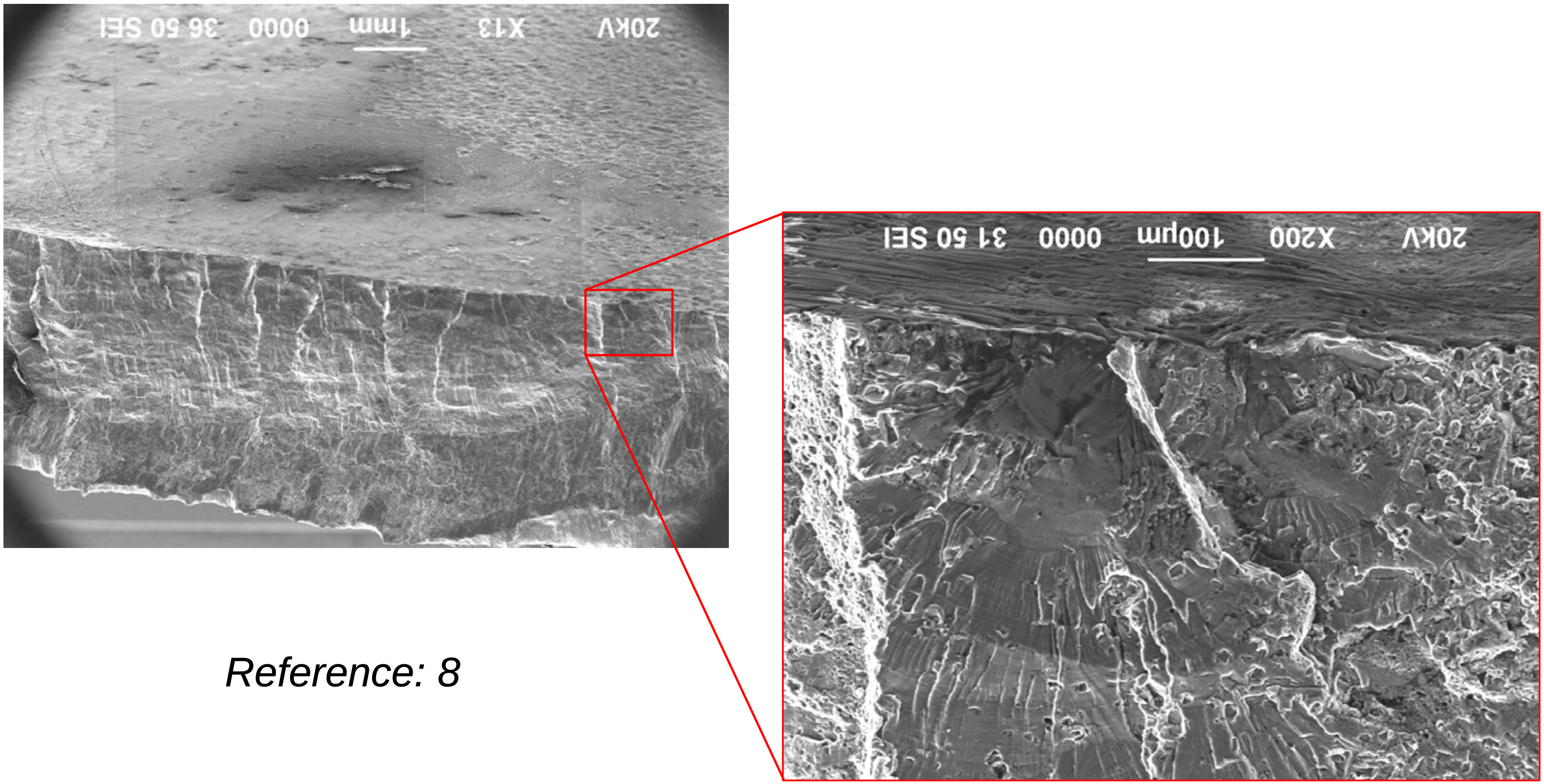
Example: Secondary Crack – surface as machined
(Cracking from accident aircraft)



Based on Pilot Testimony

Reference: 7

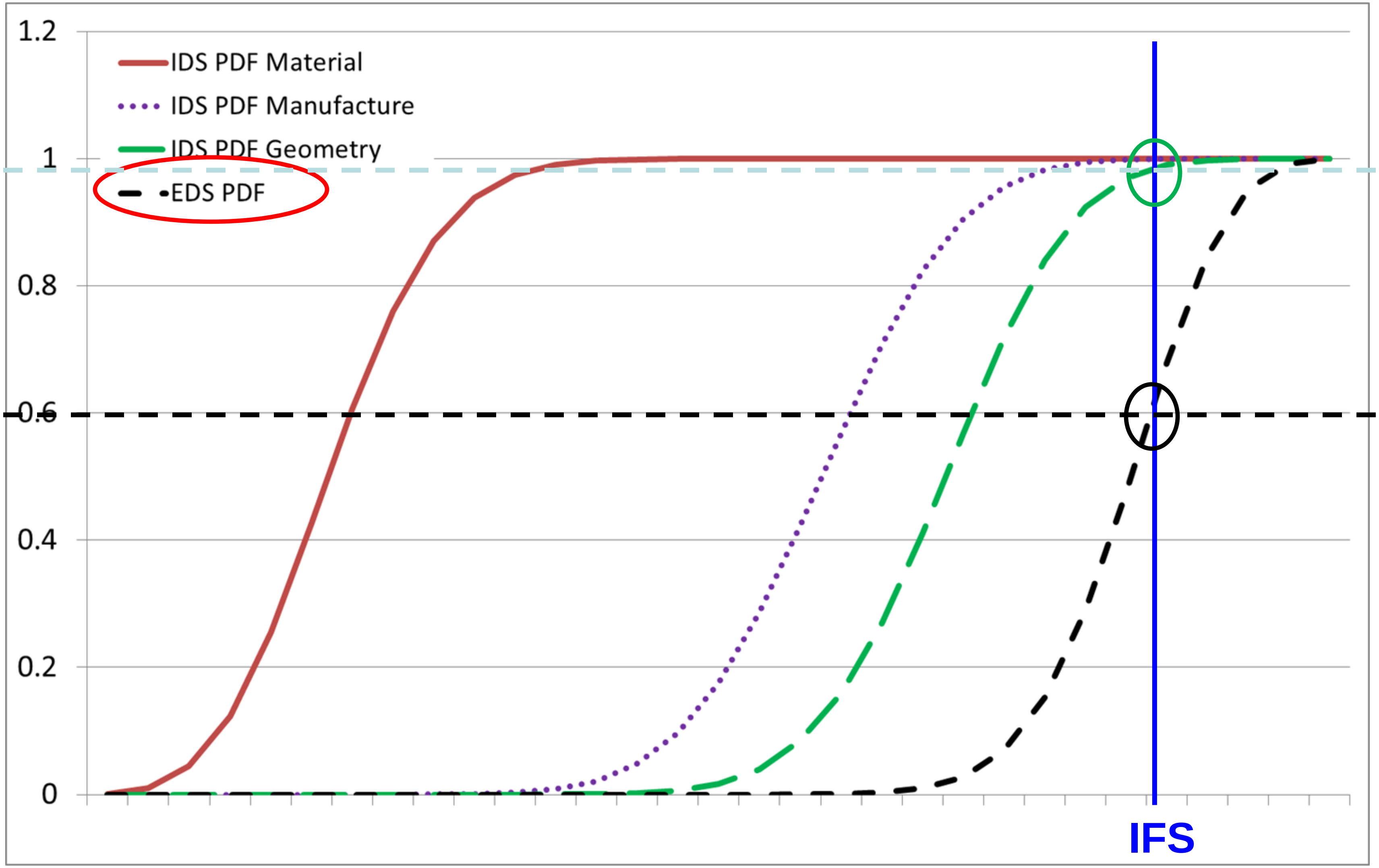
Pitting Corrosion EDS; Leads to Fatigue (MSD)



Reference: 8

Removed from a USAF aircraft in 2008

IDS & EDS Distribution (Notional)



Two-Parameter Weibull Distribution

$$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}}$$

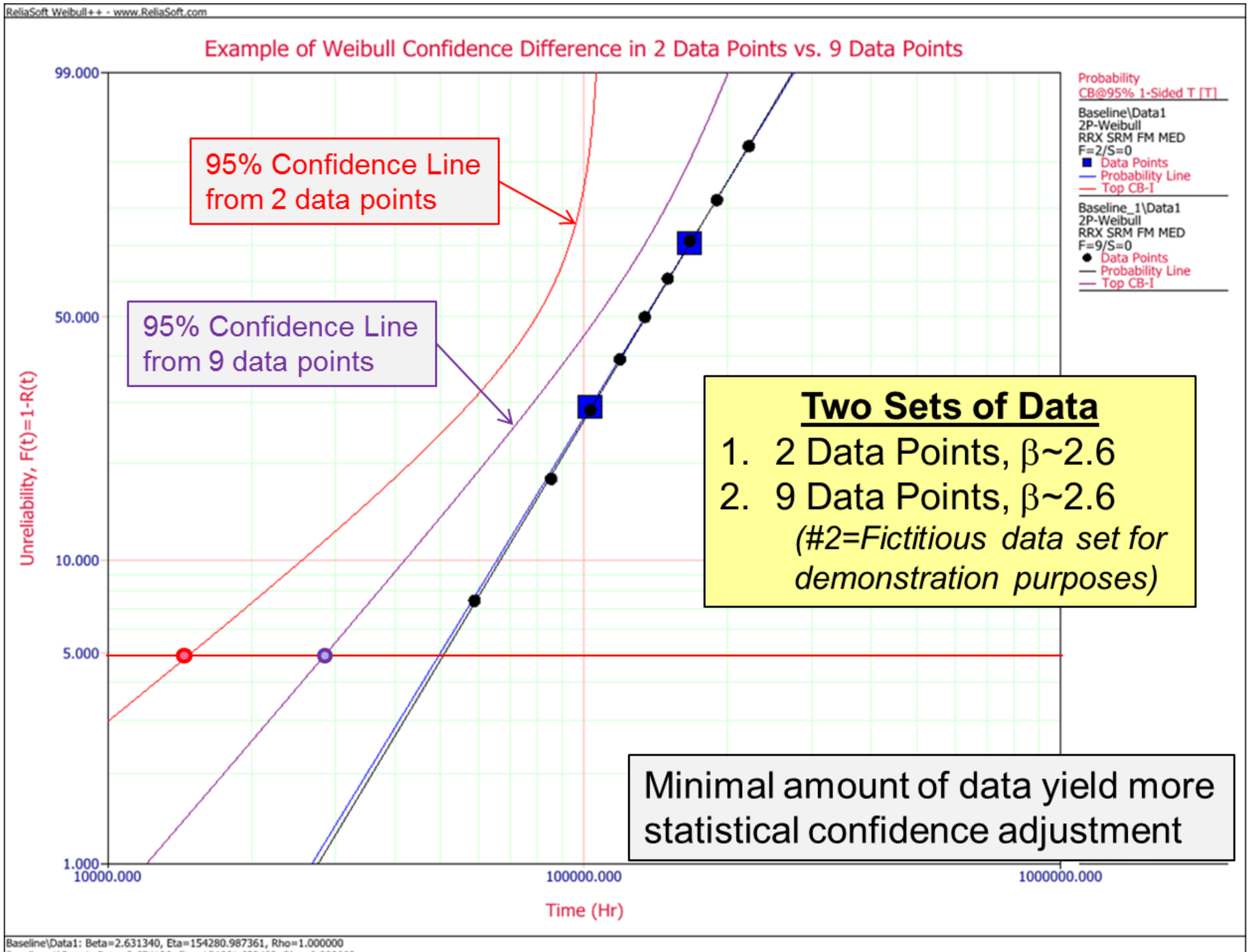
- F(t): Unreliability or 1-R(t) where R(t): Reliability
- t: failure time (cycles, usage, etc.)
- η: (Eta) characteristic life or scale parameter
  - Life where the Weibull line intersects 63.2% probability
- β: (Beta) slope or shape parameter
- e: 2.718281828, the base for natural logarithms

Waloddi Weibull 1887-1979; Photo by Sam C. Saunders

Waloddi Weibull
(1887 – 1979)
Claimed function:
"…may sometimes render good service."
U.S. Air Force funded Weibull's work until 1975

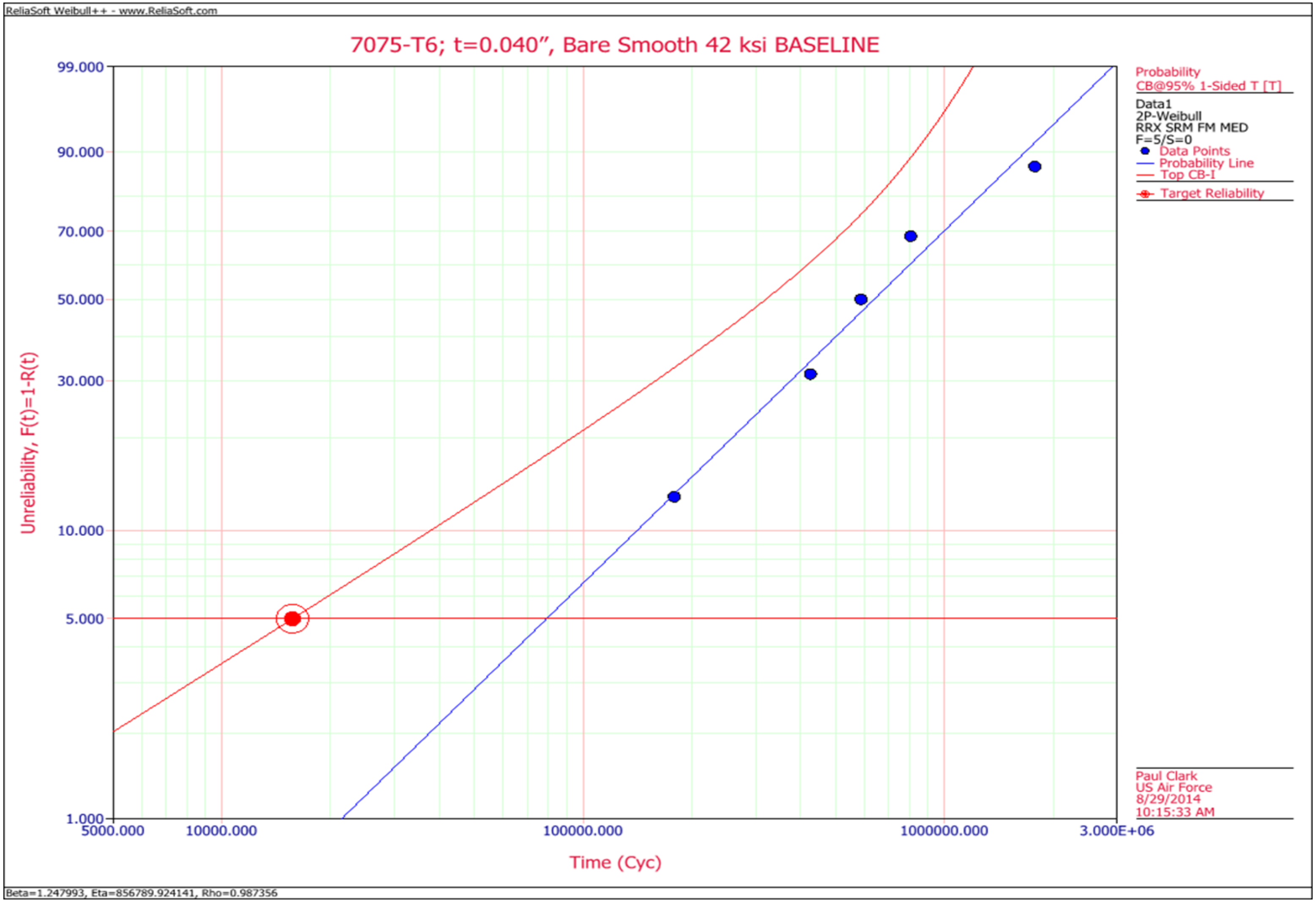
Reference: 9

Confidence Adjustment - Data

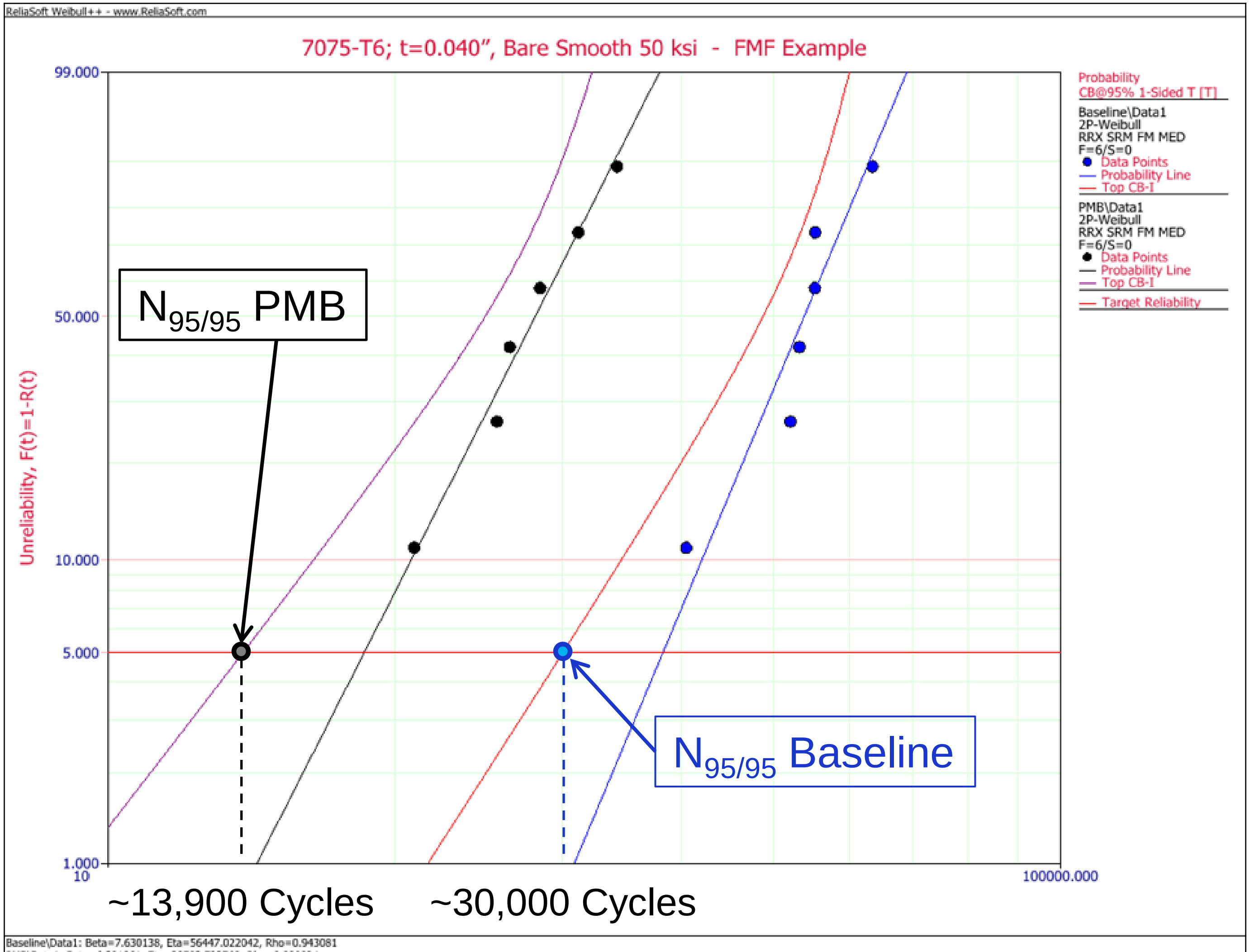


Reference 10 for Weibull Analysis
References 11 & 12 for Paint Removal Data

Confidence Adjustment - Variance



Fatigue Modification Factor (FMF)



$$FMF = \frac{\sim 13{,}900 \text{ Cycles}}{\sim 30{,}000 \text{ Cycles}}$$

FMF ~ 0.46

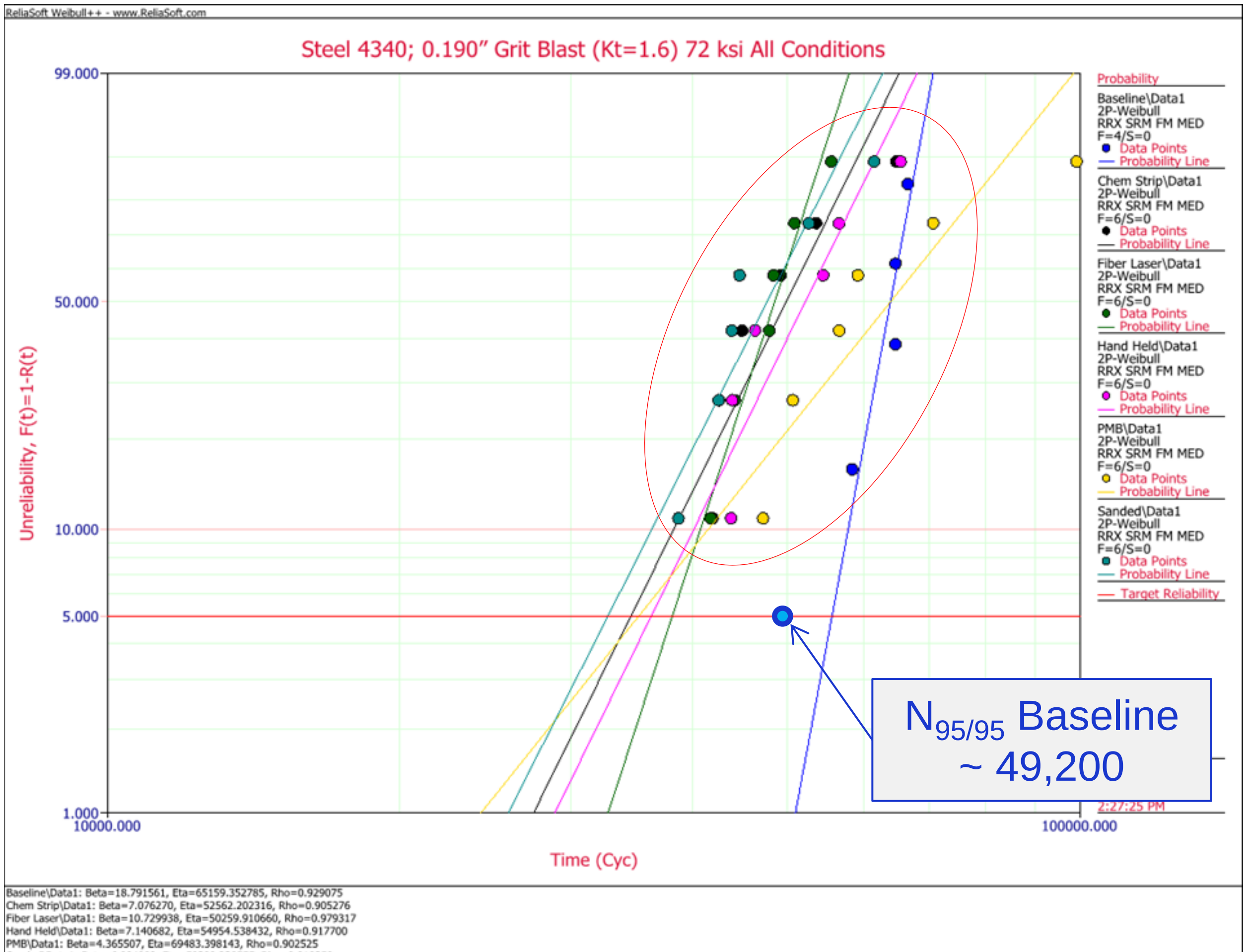
Experimental Data

- Baseline
  - Material tested as received → "un-processed"
    - *Exception*: Steel Baseline were grit-blasted
- Fiber Laser Depaint
  - Continuous wave 6 kW fiber laser, stripped to substrate (5 cycles)
- Hand Held Laser Depaint
  - Q-Pulsed 300 W Nd:YAG laser, stripped to substrate (5 cycles)
- Plastic Media Blast (PMB) Depaint
  - IAW Air Force T.O. 1-1-8, Type V, stripped to substrate (5 cycles)
- Hand Sanded Depaint (Dual Action Sander)
  - IAW Air Force T.O. 1-1-8, stripped to substrate (5 cycles)
- Chemical Strip Depaint
  - IAW Air Force T.O. 1-1-8, Cee-Bee® R-256, stripped to substrate (5 cycles)

- **Compatible**
- **Difficult to Utilize**
- **Impossible to Draw Useful Conclusions**

It is recognized that these categories are subjective. They are use for demonstrative purposes.

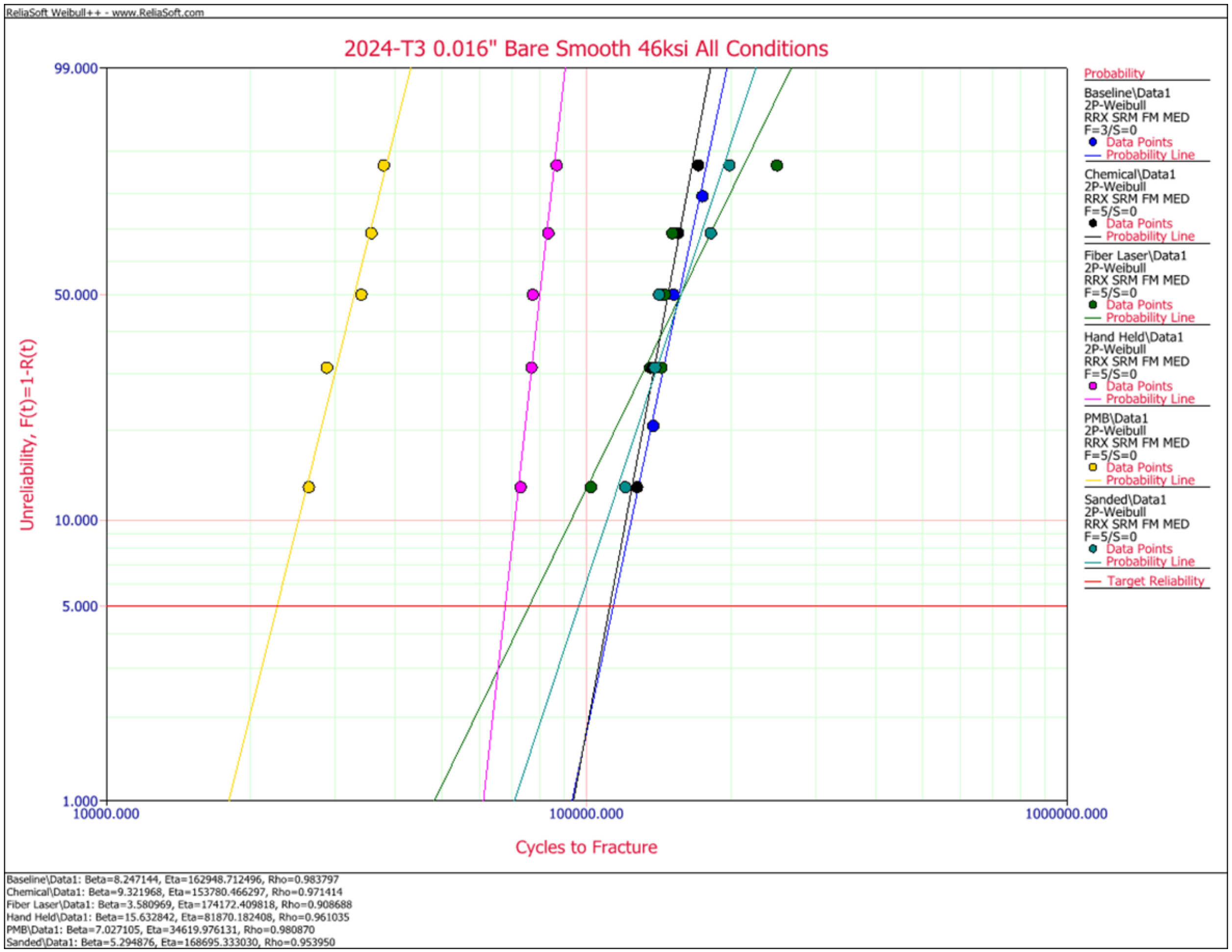
Compatible



- **Compatible Betas (4.37-10.7) *except…***
- **Baseline**
  - **β~18.8**
    - **Minimal confidence adjustment**
- **Large beta has impact on FMF**
  - **Perhaps artificially low FMF for processes investigated**

Fatigue Modification Factors (FMF)				
Automated Fiber Laser	**Hand Held Laser**	**PMB**	**Sanded**	**Chemical**
0.65	0.57	0.46	0.50	0.53

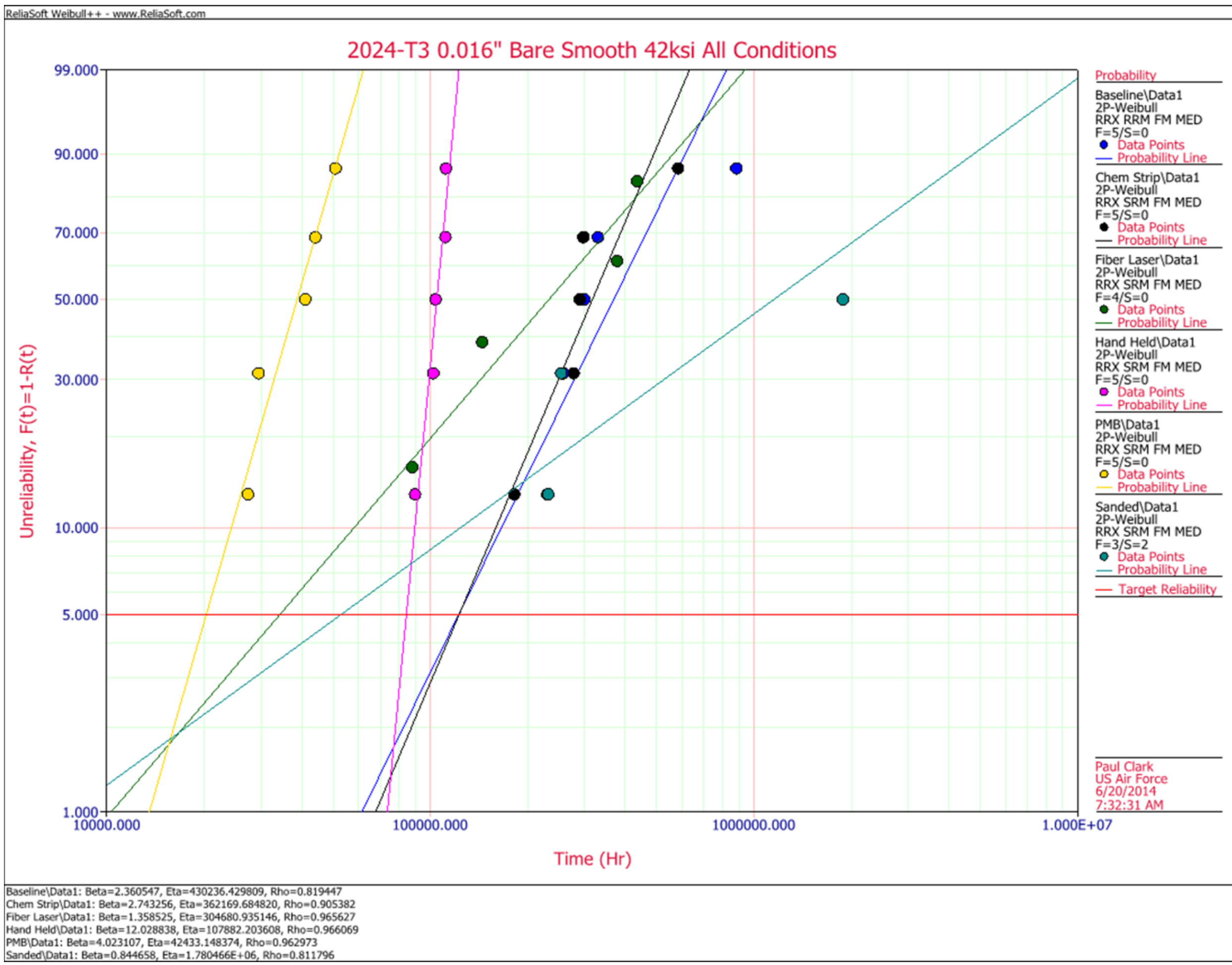
Difficult to Utilize



- **Compatible Betas (5.29-9.32) *except…***
- **Fiber Laser**
  β~3.58
- **Hand Held Laser**
  β~15.3
- **Relatively comparable for $N_{95/95}$**
- **FMF_{Chem} is positive**

Fatigue Modification Factors (FMF)				
Automated Fiber Laser	Hand Held Laser	PMB	Sanded	Chemical
0.51	0.71	0.20	0.78	1.08

Impossible to Draw Useful Conclusions



- **Betas mixed (0.84-12.0)**
- **Compatible groups:**
  1. **Baseline & Chemical**
  2. **Others NOT**
- **Baseline**
  - **Lower beta (2.36)**
- **Sanded lowest life at high R(t), yet test data highest overall**
  β~0.84
  - **Seen in FMF_{Sanded}**
    ~96% knockdown
- ***No consistency in data or results…***

Fatigue Modification Factors (FMF)				
Automated Fiber Laser	**Hand Held Laser**	**PMB**	**Sanded**	**Chemical**
0.137	1.550	0.265	0.038	1.261

Evaluation Criteria Suggestions

- **SAE MA4872 – Aerospace Standard**
  - Title: "Paint Stripping of Commercial Aircraft – Evaluation of Materials and Processes"
    - "The OEMs were directly involved in the development of the requirements and test methods."
- **BASELINE is the foundation**
    - A compromised baseline = questionable comparisons
- **Regarding the process to be evaluated**
  - Will the process affect airworthiness and/or sustainment?
- **Generating, collecting, and analyzing data**
  - Consider a 'round robin' (multiple labs)
    - Demonstrates a robust test protocol
    - More data means more confidence
  - Consider incorporating Weibull analysis
    - Improved understanding of variability and statistical confidence

Engineered Protection Considerations

- **Preserving the airworthiness baseline and structural integrity of aircraft is paramount!**
- **Engineer solutions to prevent damage to structure**
- **Prevent damage from abuse (accidental or intentional)**
  - Prevent users from ‘turning up the heat’
- **Examples**
  - Locked controls for power intensity settings
  - Motion, temperature and contrast sensors
- **Methods for detecting and repairing damage**
- **Analysis tools for assessing life and inspection intervals from unexpected damage and subsequent repairs**

Training technicians is insufficient.

Lessons Learned

- **Processes that induce heat (thermal utilization) have the potential to alter the microstructure**
  - Can lead to widespread fatigue damage
  - Degradation to durability
  - Compromises to structural integrity
  - Compromises to airworthiness
- **Processes may induce damage that is not detectable through NDI**
  - May lead to a quality escape and potential threat
- **Weibull Analysis**
  - Can be flexible and beneficial for capturing variability and confidence
  - It is NOT a "one-size-fits-all-needs" analysis tool
- **Murphy was an optimist**

Conclusions

- **Technology is advancing rapidly**
  - It is our duty to understand the impact of new processes *prior* to implementation to minimize unintended consequences
- **Lasers and other high energy processes show great promise for improving the removal of paint**
- **High energy processes have the potential to induce compromises to structural integrity**
- **Evaluations should be thorough and standardized**
- **Weibull Distribution**
  - Another way of looking at the data
  - Can help reveal *not-so-obvious* characteristics of data
  - Good representation of variability

Recommendations

- **Understand the impact to airworthiness and sustainment**
  - Investigate and understand failure mechanisms
- **Engineer methods and processes to protect structure**
- **Control the application of high energy processes**
- **Take advantage of lessons learned**
- **Utilize existing or develop standards for evaluation**
  - SAE MA4872 (Aerospace Standard – Paint Stripping)
  - EZ-SB-13-001 (Material Substitution Guidelines - Metallics)
- **Take experiments and Test Protocol Development**

…*<u>one step at a time</u>*

Thank you for your attention.

Are there any questions?

Images and Internet References

1. https://www.google.com/search?q=Lies,+Damn+Lies+and+Statistics+book&client=firefox-a&rls=org.mozilla:en-
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