Regulatory Considerations for Residual Stresses in Aircraft and Engine Components

Presented at:

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Disclaimer

The views presented in this talk are those of the author and should not be construed as representing official Federal Aviation Administration position, rules interpretation or policy

Outline

- Residual stress in the context of F&DT
- Regulatory Considerations
- Examples and Summary

Structural Integrity

- Structural integrity is the condition which exists when a structure is sound and unimpaired in providing the desired level of structural ***safety***, performance, ***durability***, and supportability

Reference: MIL-STD-1530C

areas of primary interest to the FAA

What Causes Failures?

Frequency of Failure Mechanisms *)

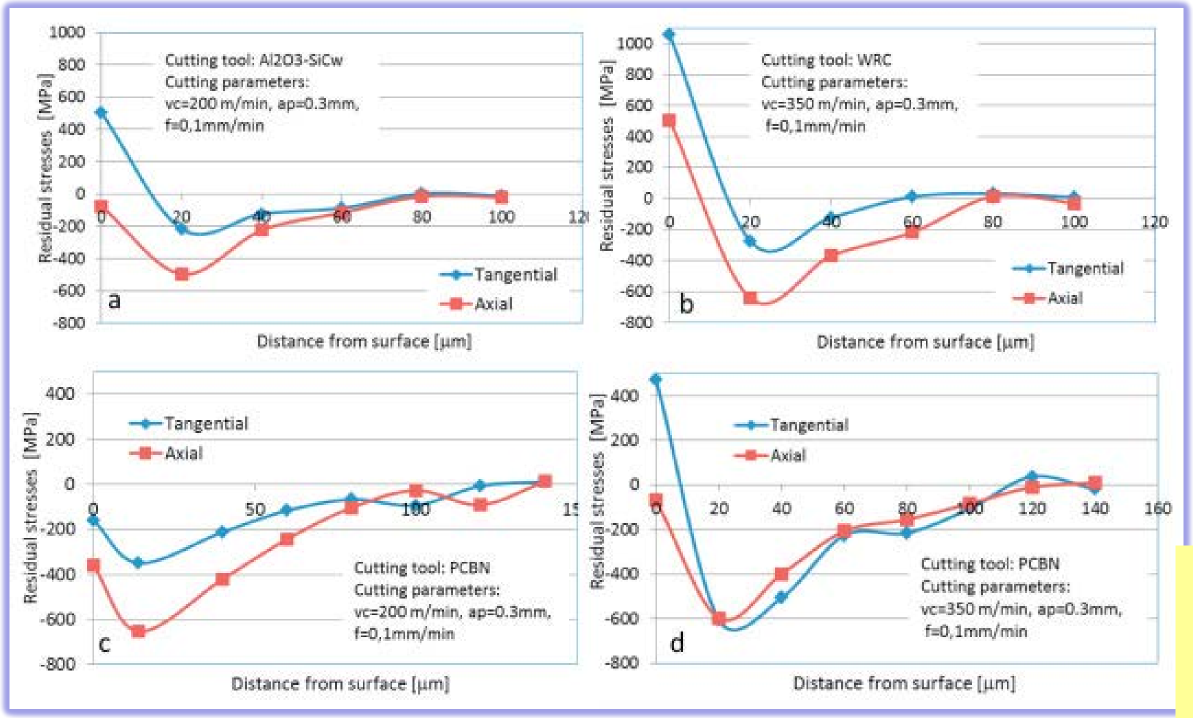
Failure Mechanism	% Failures *(Aircraft Components)*
Fatigue	55%
Corrosion	16%
Overload	14%
Stress Corrosion Cracking	7%
Wear / abrasion / erosion	6%
High temperature corrosion	2%

***) *Source*: Why Aircraft Fail, S. J. Findlay and N. D. Harrison, in Materials Today, pp. 18-25, Nov. 2002.**

- **Fatigue is the Predominant Failure Mode in Service**
- ***Residual Stresses Can Either Contribute to, or Mitigate Fatigue and Fracture Issues***

Residual Stress – Friend or Foe…

- ***Unfavorable*** **near-surface RS resulting from machining may significantly reduce component's LCF life (by 10x or more)…**



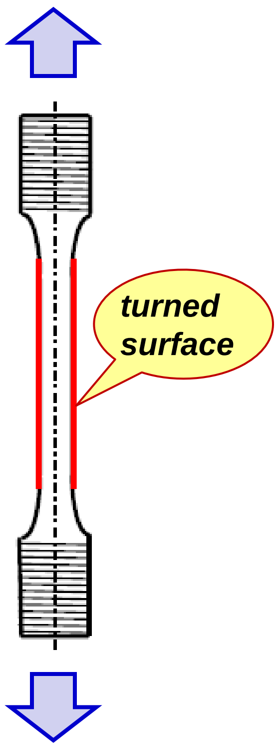
Challenge:
Magnitude (and even sign) of RS can be a function of:

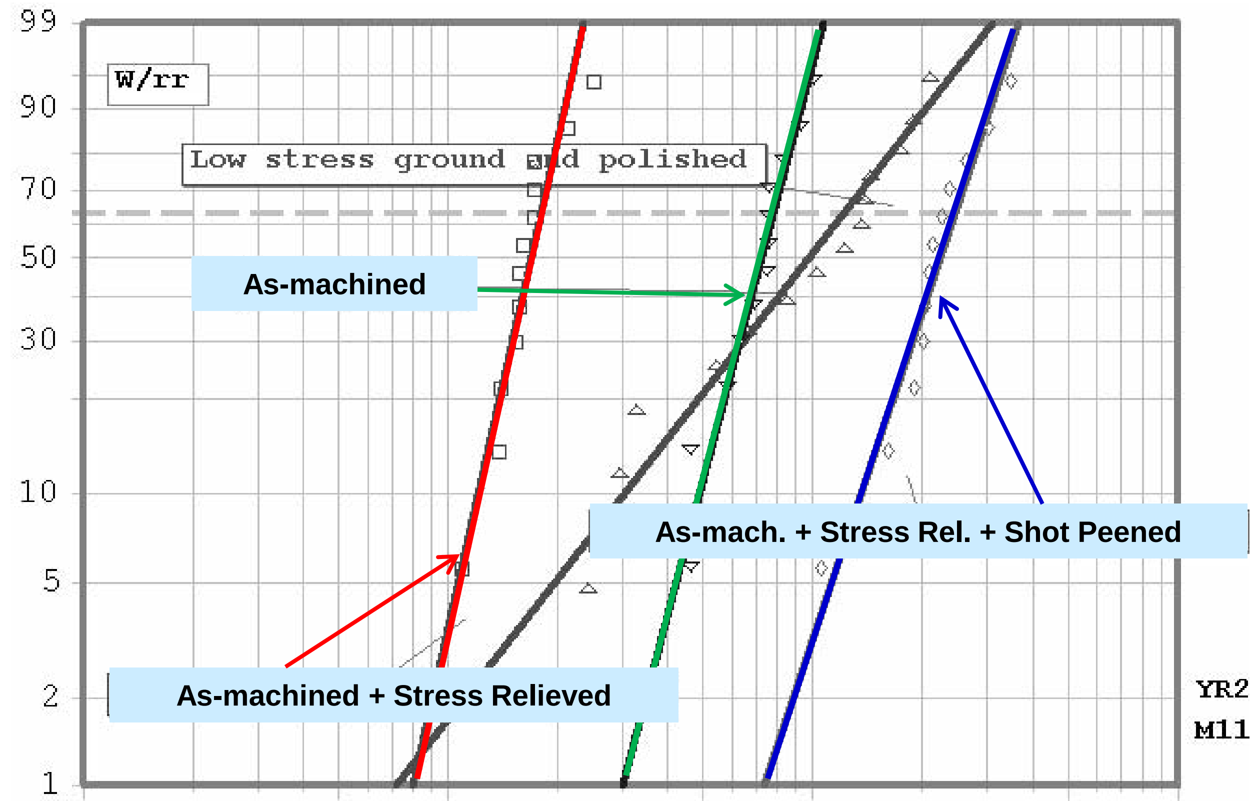
- ***Cutting speed***
- ***Cutting tool / insert***
- ***Cutting direction***
- ***Etc.***

Reference: J. Zhou et al, "*Analysis of Subsurface Microstructure and Residual Stresses in Machined Inconel 718 with PCBN and Al2O3SiCw Tools*", 2014, Procedia CIRP, (13), 150-155.

- ***Favorable*** **(machining-induced or engineered) RS may improve component's LCF life (by 10x or more) → *see next slide***

Example: Effect of Machining, Peening and Stress Relief on LCF

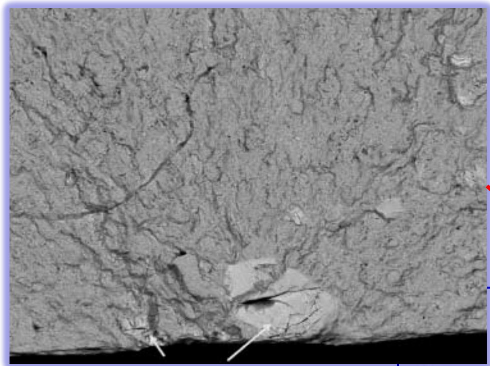




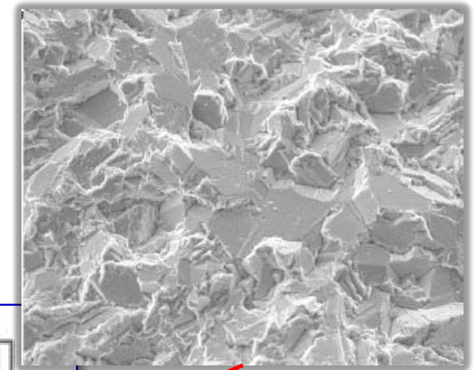
Probability Plot of LCF Test Data for 4 Batches of Ti 6-4 Specimens

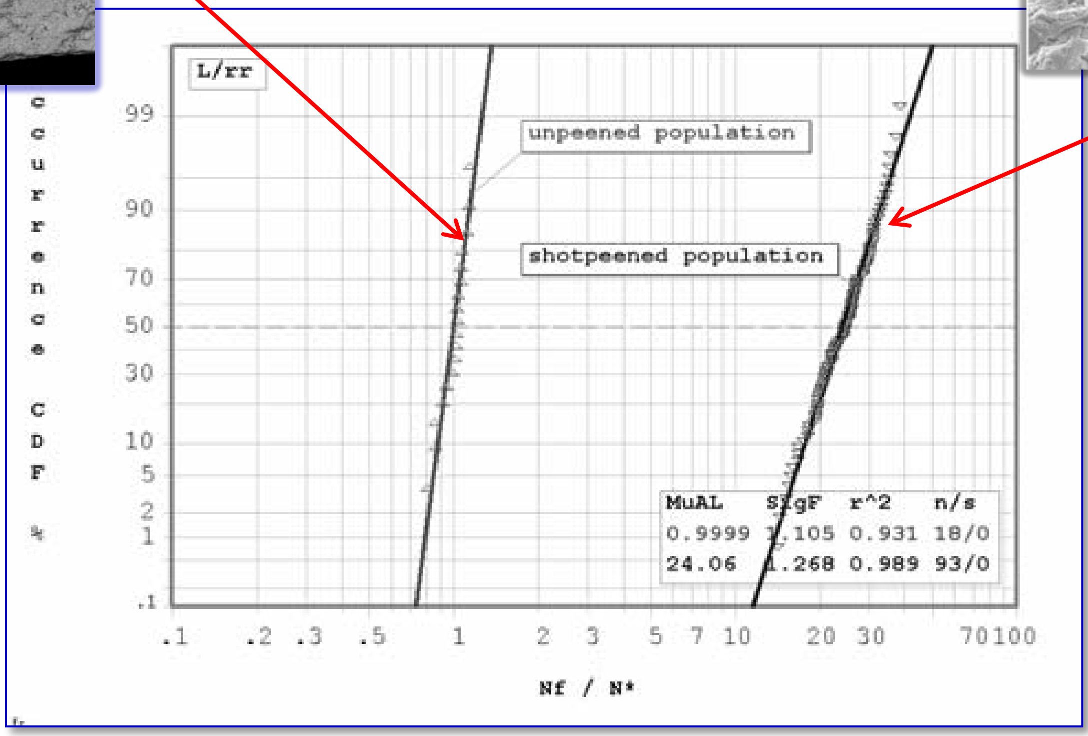
Reference: M. Gorelik et al, "*Role of Quantitative NDE Techniques in Life Management of Gas Turbine Components*", GT2006-91337, Proceedings of TurboExpo 2006, Barcelona, May 8-11 2006.

Example: Mitigating Effect of Material Inclusions with Shotpeening

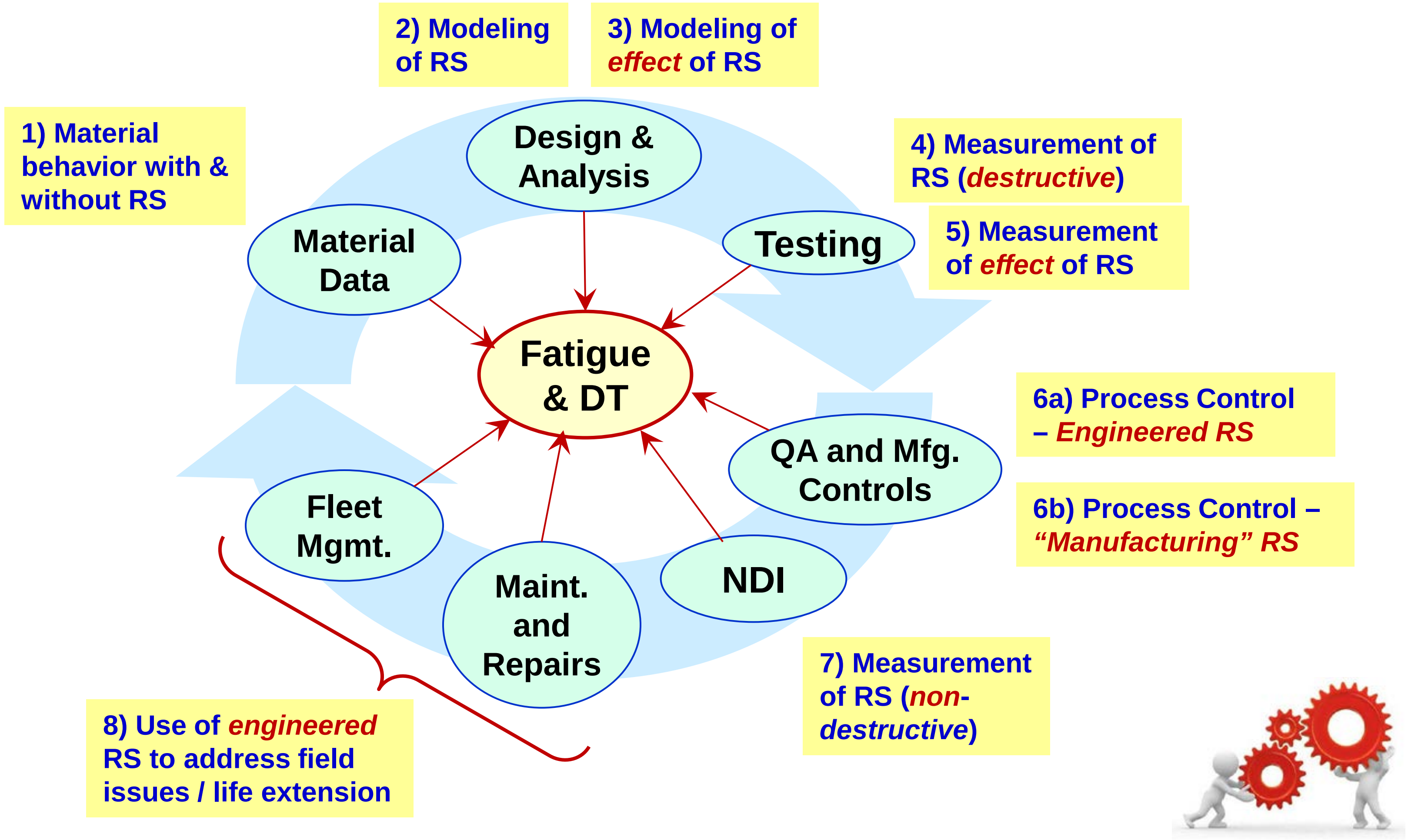


Reference: M. Gorelik et al, "*Role of Quantitative NDE Techniques in Life Management of Gas Turbine Components*", GT2006-91337, Proceedings of TurboExpo 2006, Barcelona, Spain, May 8-11, 2006.





System-Level View of F&DT Discipline
… *and related RS considerations*



All elements of the system are essential to ensure safety …

Industry Trends (*in RS context*)

- **Moving towards more aggressive design and manufacturing practices**
  - ***Faster, hotter, lighter, lower cost…***
- **Development of RS *measurement* technologies**
- **Development of RS *modeling* technologies**
- **Development of ICME frameworks**
- **Digital twin / digital thread**
- **…**

Pre-realignment AIR Structure *(prior to 7-23-17)*

AIR = *FAA Aircraft Certification Service*

Transport Airplane Directorate
(14 CFR Part 25)

Small Airplane Directorate
(14 CFR Part 23)

Engine and Propeller Directorate
(14 CFR Parts 33, 35)

As of July 23, 2017, the Divisions and Directorates listed below no longer exist as part of AIR's organizational structure; as part of *AIR Transformation*, the personnel, functions, and responsibilities of these offices have been incorporated into the Functional Divisions (*see next slide*)

Rotorcraft Directorate
(14 CFR Parts 27, 29)

- **Eng & Mfg Division (HQ)**
- **4 Directorates**
- **Multiple Cert offices**

14 CFR Part 25 Regulations - Materials

(Transport Category Aircraft)

§ 25.603 Materials

The suitability and durability of materials used for parts, the failure of which could adversely affect safety, must —

- ***a) Be established on the basis of experience or tests;***
- b) Conform to approved specifications (such as industry or military specifications, or Technical Standard Orders) that ensure their having the strength and other properties assumed in the design data; and
- c) Take into account the effects of environmental conditions, such as temperature and humidity, expected in service.

§ 25.605 Fabrication Methods

- a) The methods of fabrication used must produce a consistently sound structure. If a fabrication process (such as gluing, spot welding, or heat treating) requires close control to reach this objective, the process must be performed under an approved process specification.
- b) Each new aircraft fabrication method ***must be substantiated by a test program.***

No Allowance for Modeling or Analysis

14 CFR Part 25 Regulations - Materials

(Transport Category Aircraft)

§ 25.613 Material Strength Properties and Design Values

a) Material strength properties must be ***based on enough tests*** of material meeting approved specifications *to establish design values on a statistical basis*.

b) Design values must be chosen to minimize the probability of structural failures *due to material variability*.

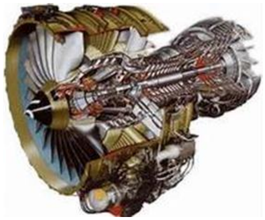
d) The *strength, detail design, and fabrication* of the structure must minimize the probability of disastrous fatigue failure, particularly at points of stress concentration.

e) Greater design values may be used if a ‘‘premium selection’’ of the material is made in which a *specimen of each individual item* is *tested before use*.

No Allowance for Modeling or Analysis

14 CFR Part 33 Regulations - Materials

(Aircraft Engines)



§ 33.15 Materials

The suitability and durability of materials used in the engine must—

a) Be ***established on the basis of experience or tests***; and

b) Conform to approved specifications (such as industry or military specifications) that ensure their having the strength and other properties assumed in the design data.

No Allowance for Modeling or Analysis

ICME Enablers for Qualification…
(… and Certification ?)

- **Multi-scale modeling**
- **Uncertainty Quantification (UQ)**
- **Models *Verification and Validation* (V&V)**

Key for qualification *(…and certification?)* ***applications***

Examples of "Model-Friendly" Domains

- **Damage Tolerance → Part 25 (AC 25.571-1D)**
  - **In general, "analysis supported by test evidence" is accepted**
- **Damage Tolerance → Part 33 (AC 33.70-1)**
  - **Analysis is accepted (e.g. stress, heat transfer, crack growth, …)**
    - **However, "…*the analysis approach should be validated against relevant test data*"**
  - **"The *probabilistic approach* to damage tolerance assessment is one of two elements *necessary to appropriately assess damage tolerance…*"**
- **AC 20-146 "*Methodology for Dynamic Seat Certification by Analysis*"**
  - **Needs to be validated by test**
  - **One of the few example of "certification by analysis"**
  - ***Rational Analysis* - an analysis based on good engineering principles, judgment, and/or *accepted methodology* (AC 25.562-1b)**

"Crawl → Walk → Run" Approach

Process Level

Material Development → ***Material Qualification*** → ***Product Certification***

System Level

"Minor" Effect → ***"Major" Effect*** → ***"Hazardous" and above***

Component Level

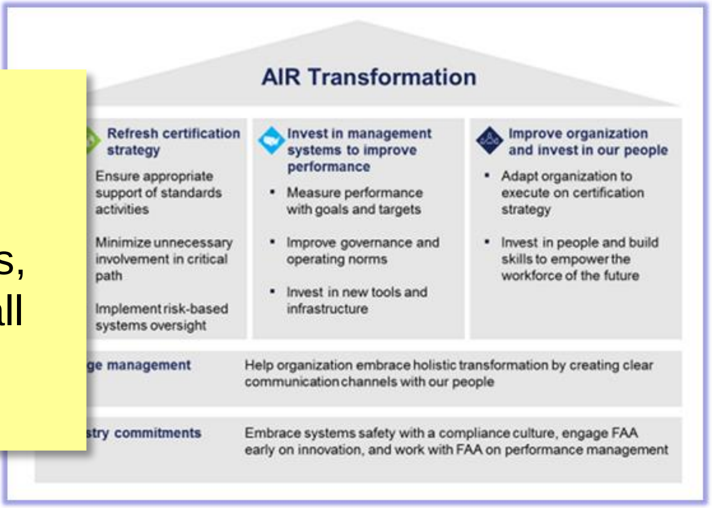
Static Properties → ***Fatigue Properties***

AIR Transformation *(effective 7-23-17)*

Aircraft Certification Service (AIR)

- **Policy and Innovation**
- **Compliance and Airworthiness**
- **System Oversight**
- **Organizational Performance**
- **Foundational Business**

The **Policy & Innovation Division** *supports aerospace innovation* by creating novel means of compliance, develops and maintains AIR regulations, manages the CSTA program and overall fleet safety, as well as educational outreach.



Public-facing AIR Transformation Web Site:

https://www.faa.gov/about/office_org/headquarters_offices/avs/offices/air/transformation/

Concept of Innovation Centers

DRAFT

- *Key element of the new AIR **Policy & Innovation** function*
- *Provides robust mechanism **to address new technologies*** and MOC (means of compliance)
  – Late awareness can result in project delays
- Be more proactive prior to the initial project application
  – Identify new technology or MOCs beyond the scope of existing regulations and policy
- Supports FAA efforts to streamline certification process
- Success is dependent on OEMs buying into the concept
  – Early engagement
  - Company proprietary / intellectual property concerns

Emerging technologies similar to AM will be addressed by Innovation Centers once they are implemented

Excerpts from FAA Regulations (*relative to RS*)

Part 33 [*engine*]

- **Rules – *No references found***
- **AC 33.70-1 "Guidance Material for Aircraft Engine Life-Limited Parts Requirements"**
  - 8.b (7) (e) 2 [Damage Tolerance Assessment / surface damage monitoring] - Use beneficial *residual stresses* due to finishing processes, such as shot peening, if appropriate and if data supports the ability of the process to slow or suppress the growth of the damage.

Part 25 [*transport airplane*]

- **Rules / ACs - *No references found***
- **PS-ANM-25-22 "*Repair Deferral Limitations for Known Cracks*"**
  - 5.4.4 Preload and *residual stresses* in the structure should be well understood and accounted for in the analysis.

Part 29 [*transport rotorcraft*] – *No references found*

Part 23 [*general aviation*]

- **AC 23-13A "Fatigue, Fail-Safe, and Damage Tolerance Evaluation of Metallic Structure for Normal, Utility, Acrobatic, and Commuter Category Airplanes"**
  - This S-N data (*Appendix 2*) is applicable to conventional built-up aluminum structure with no fittings (other than continuous splice fittings), no parts with high *residual stresses*, …

Limited Guidance Relative to Residual Stress Considerations in Design and Fleet Management

Example of Legacy Practices

Reference: T. Swift, "*Fail-Safe Design Requirements and Features, Regulatory Requirements*", AIAA / ICAS International Air and Space Symposium and Exposition, Dayton, OH 2003 [https://arc.aiaa.org/doi/abs/10.2514/6.2003-2783].

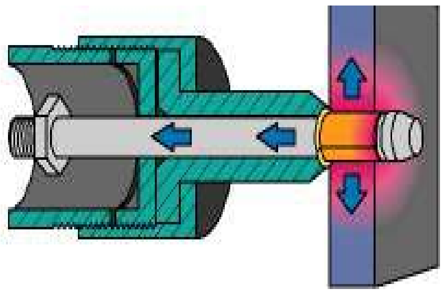
"… If the fastener hole is cold expanded, the beneficial effects of *compressive residual stresses will retard the growth* of the standard 0.05" crack.

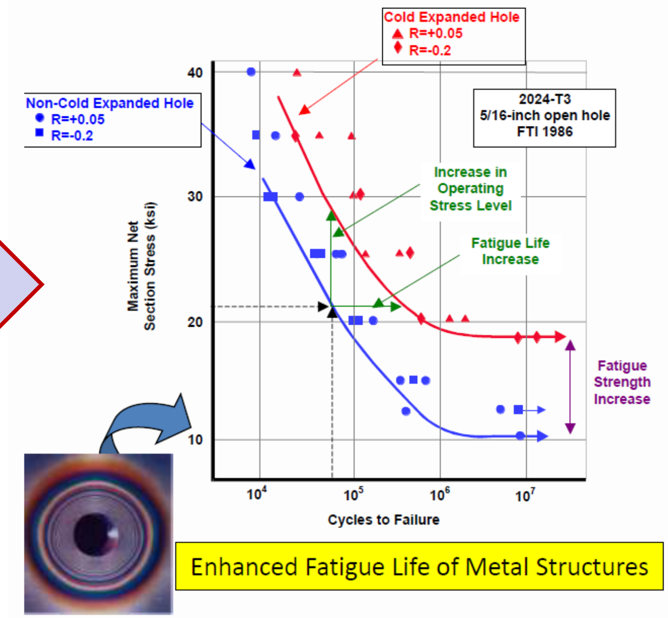
However, *accounting for the non-linear stress distributions in calculating stress intensity factors has been difficult*.

To avoid this complication an *equivalent initial crack size* of 0.005" has been used to conservatively account for the residual stress field.

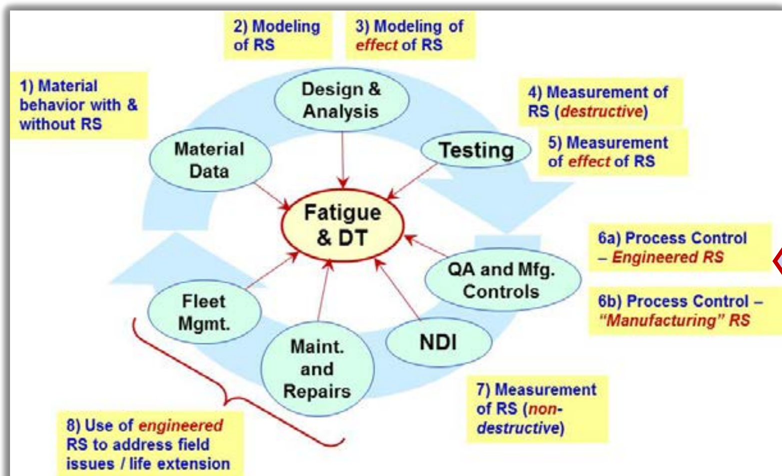
… An equivalent initial crack 0.03" radius has been used to simulate the effects of residual compressive stresses induced with machine driven fasteners …"

Example: Cold Expansion of Holes





Reference: L. Reid, "*Cost Effective Structural Repair Solutions for Damaged and Discrepant Holes in Metals and Composites*", AA&S 2014.

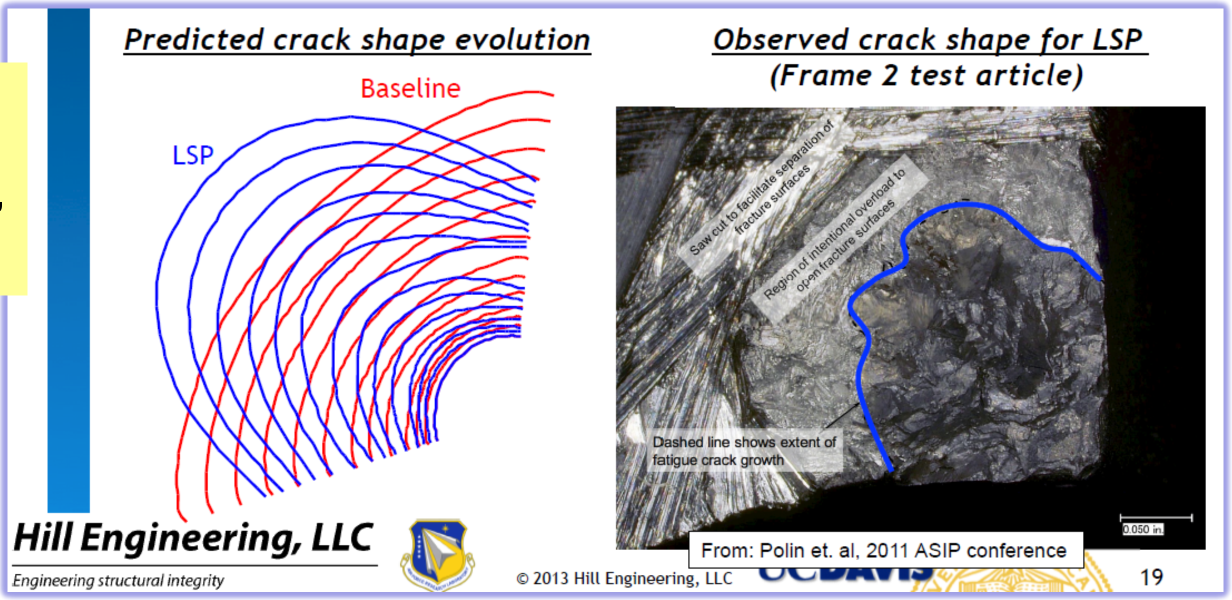


- **Important practical applications for sustainment and new products**
- **Applied to safety-critical parts**
- **Good candidate for working through the *system-level* considerations (*p. 9*)**

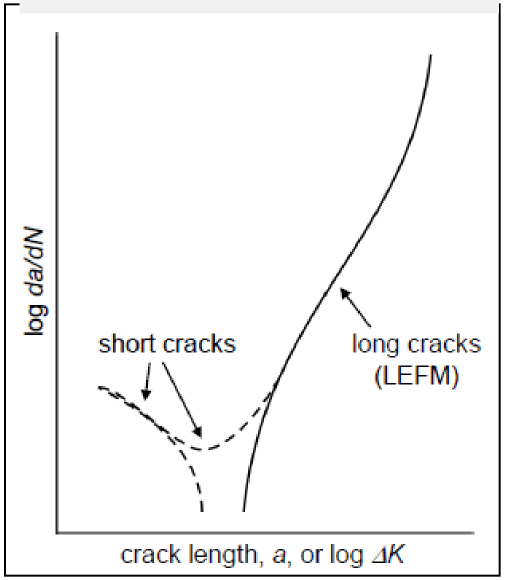
➢ **Opportunity to move from legacy *empirical* criteria to *model-based* framework (*but need V&V !*)**

Fracture Mechanics Considerations

<u>Reference</u>: M. Hill et al, "*Correlation of 3D fatigue crack growth in residual stress bearing materials*", AFGROW Workshop, Sept. 10-11, 2013.

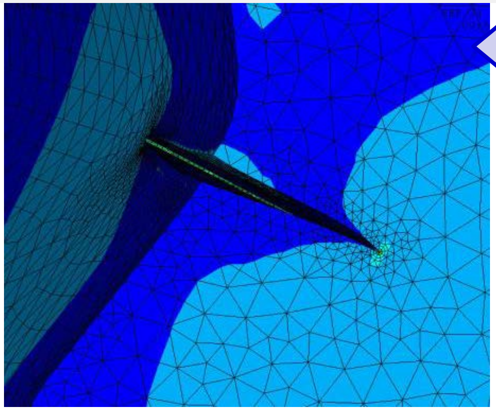


Short Crack Behavior

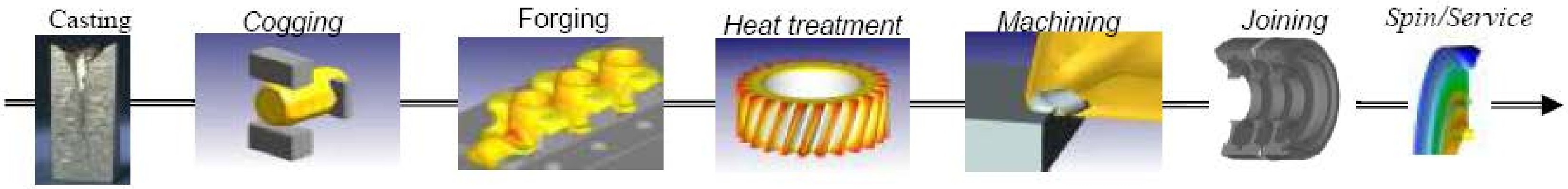


Complex geometries and stress fields, and small scales (e.g. near-surface RS gradients) require application of advanced Fracture Mechanics concepts *such as 3-D FM and short crack behavior*.

3D Fracture Mechanics



Integration with Manufacturing
Process Simulation



Link DEFORM output with DARWIN input

- Finite element geometry (nodes and elements)
- Finite element stress, temperature, and strain results
- Residual stresses at the end of processing / spin test
- Location specific microstructure / property data
- Tracked location and orientation of material anomalies

Reference: C. McClung, "*Structural Integrity Assessment for Aviation Parts with Inherent or Induced Material or Manufacturing Anomalies*", presented at the 2nd FAA – AFRL AM Workshop, Aug. 30-Sept. 1, 2016, Dayton, OH.

Influence of Location-Specific Residual Stress and Microstructure on Life & Risk

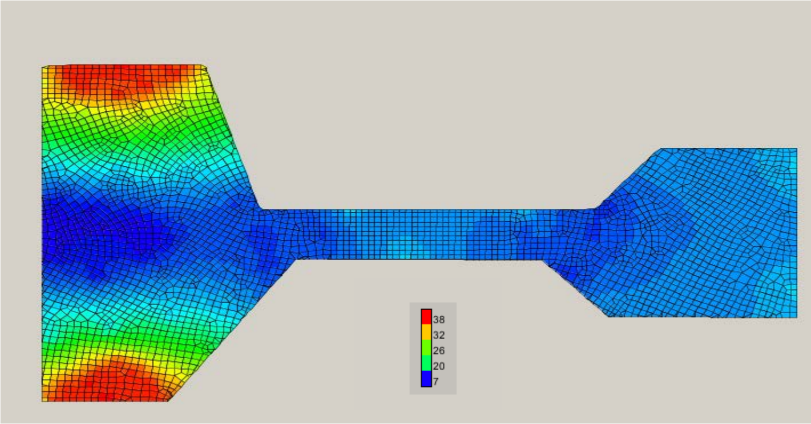
ANSYS
ABAQUS
DEFORM

Stress
Results
Files

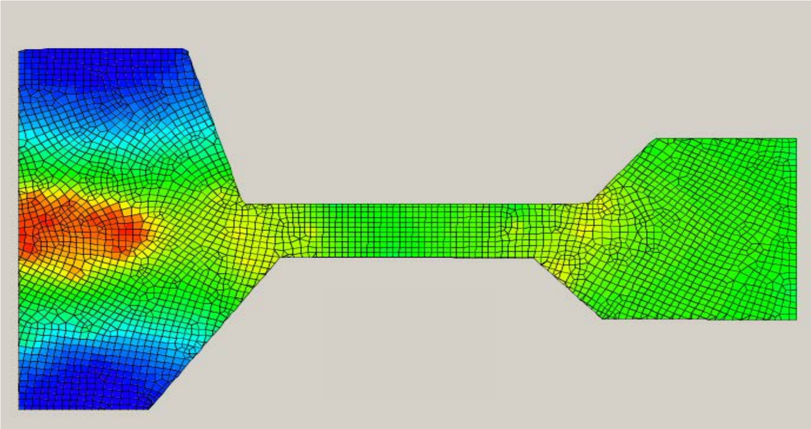
DARWIN

DEFORM

Grain Size
Results
File



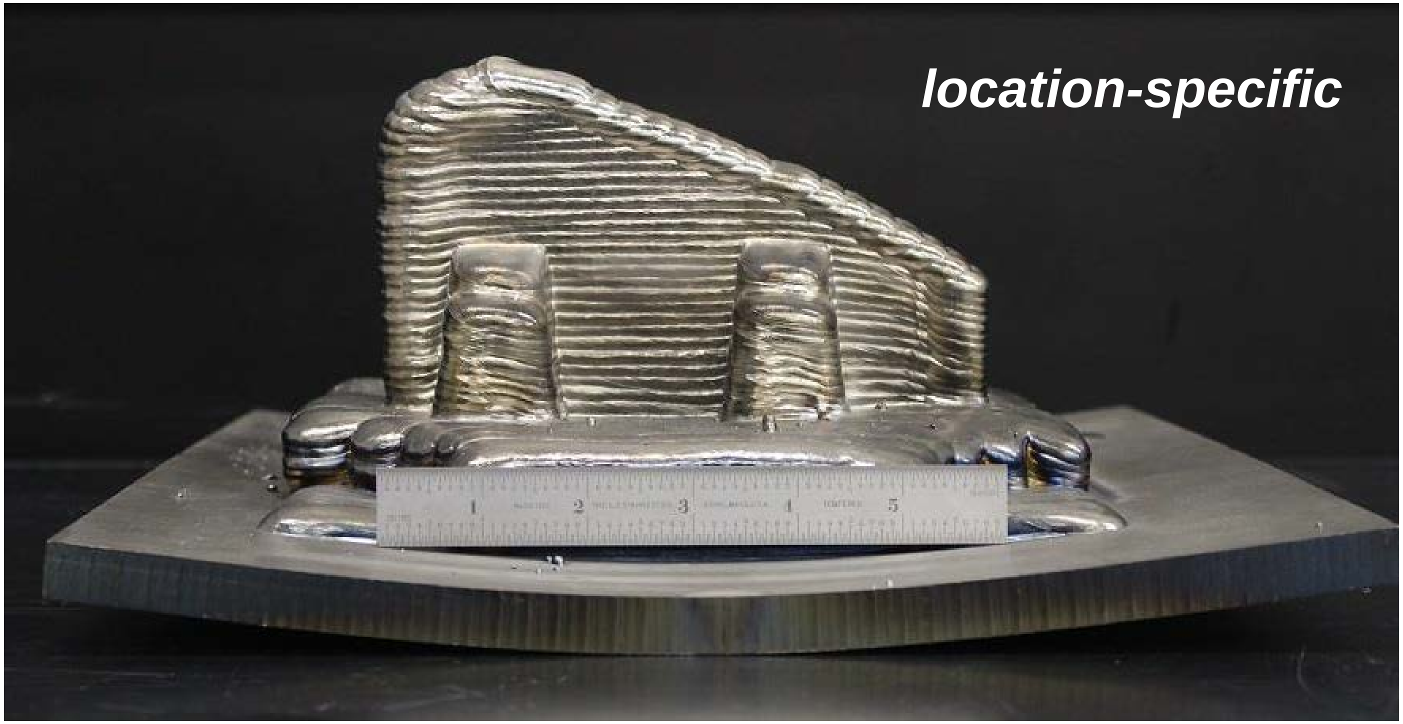
grain size contours



crack growth rate multiplier

Reference: C. McClung, "***Structural Integrity Assessment for Aviation Parts with Inherent or Induced Material or Manufacturing Anomalies***", presented at the 2nd FAA – AFRL AM Workshop, Aug. 30-Sept. 1, 2016, Dayton, OH.

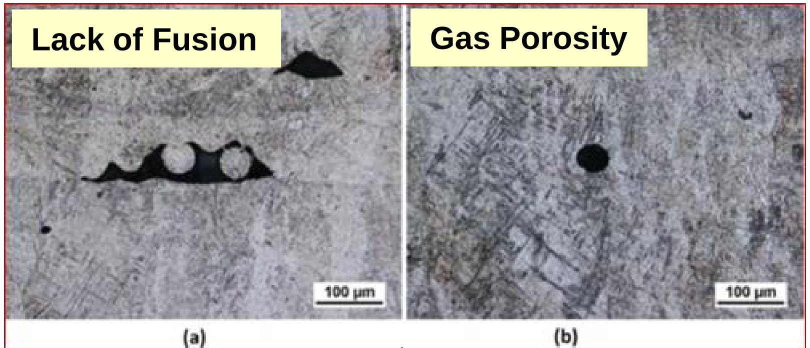
Residual Stresses in AM Parts



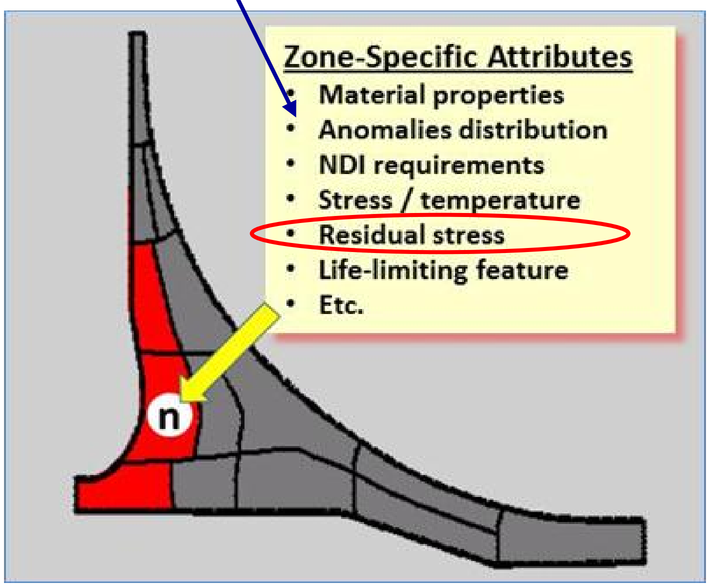
Crack Initiation (LCF)

Crack Propagation (DT)

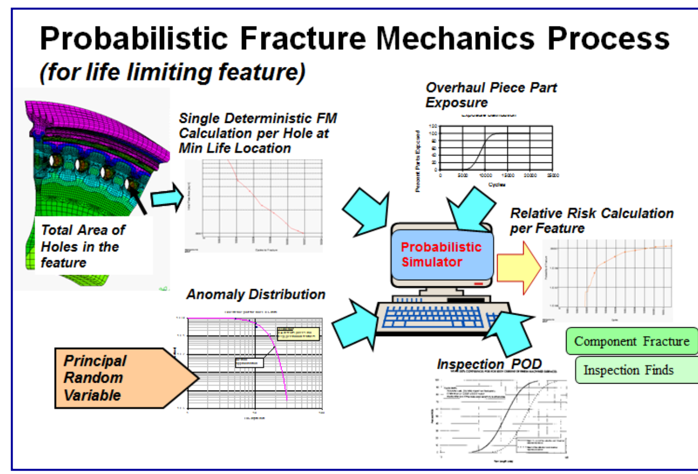
AM Part Zoning Considerations



- AM parts are uniquely suited for ***zone-based evaluation***
- Concept is similar to zoning considerations for castings…
- … however, modeling represents a viable ***alternative to empirical*** "casting factors"



*One Assessment Option – PFM *)*



***) PFM - Probabilistic Fracture Mechanics**

<u>Reference</u>: M. Gorelik, "*Additive Manufacturing in the Context of Structural Integrity*", International Journal of Fatigue 94 (2017), pp. 168–177.

Summary

- **As RS modeling and measurement methods become more mature, their use in the context of Life Management of safety-critical parts in Aviation continues to expand**
- **Agencies may need to consider additional regulatory guidance (*in collaboration with industry*)**
- ***Modeling and Simulation* methods (e.g. ICME frameworks) become more prevalent, but not fully mature yet**
  - ***Key enablers:* *V&V, U&Q, updated regulations***

Questions…

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