Mitigation of Fatigue and Pre-Cracking Damage in Aircraft Structures Through Low Plasticity Burnishing (LPB)

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ASIP 2007

Palm Springs, CA

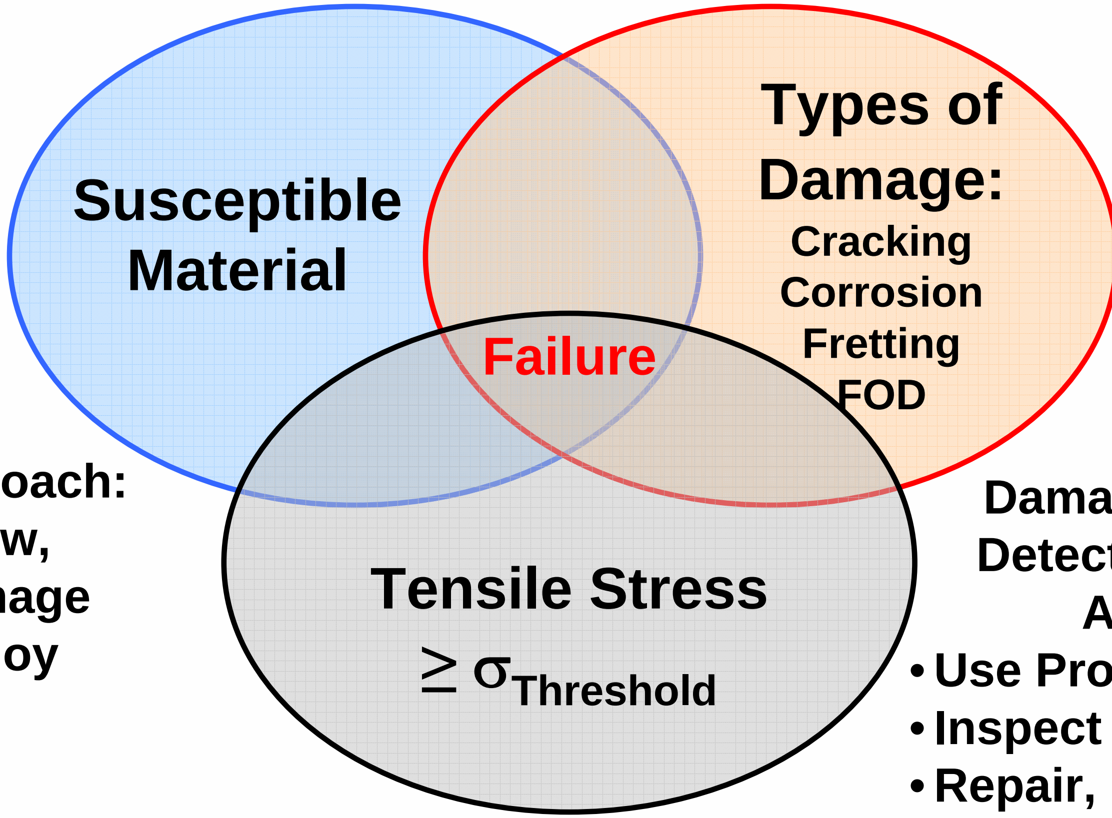
December 4 – 6, 2007

Acknowledgement

LPB Design, Implementation, and RS Measurement Conducted at Lambda Technologies

Part Design and Fatigue Testing Conducted at AFRL

Damage/Failure Susceptibility Diagram



Materials Approach: Develop new, tougher, damage resistant alloy

Damage Prevention, Detection & Control Approach:

- Use Protective Coatings
- Inspect for FOD, Cracks
- Repair, Blend Damage
- Replace Parts

Residual Stress Approach: "Mechanical Suppression" of Tensile Stresses – No need to change material/design & Improved damage tolerance

Outline

- **Residual Stress Design Method**
- **LPB Process**
  - **Technology**
  - **Tools**
  - **Design Protocol**
  - **Production and Turnkey Installation**
- **Example of LPB to Mitigate Fatigue/Pre-Cracking Damage in AA2024-T851 Aircraft Structures**
- **Conclusions**
- **List of Current LPB Applications**

RESIDUAL STRESS DESIGN METHOD

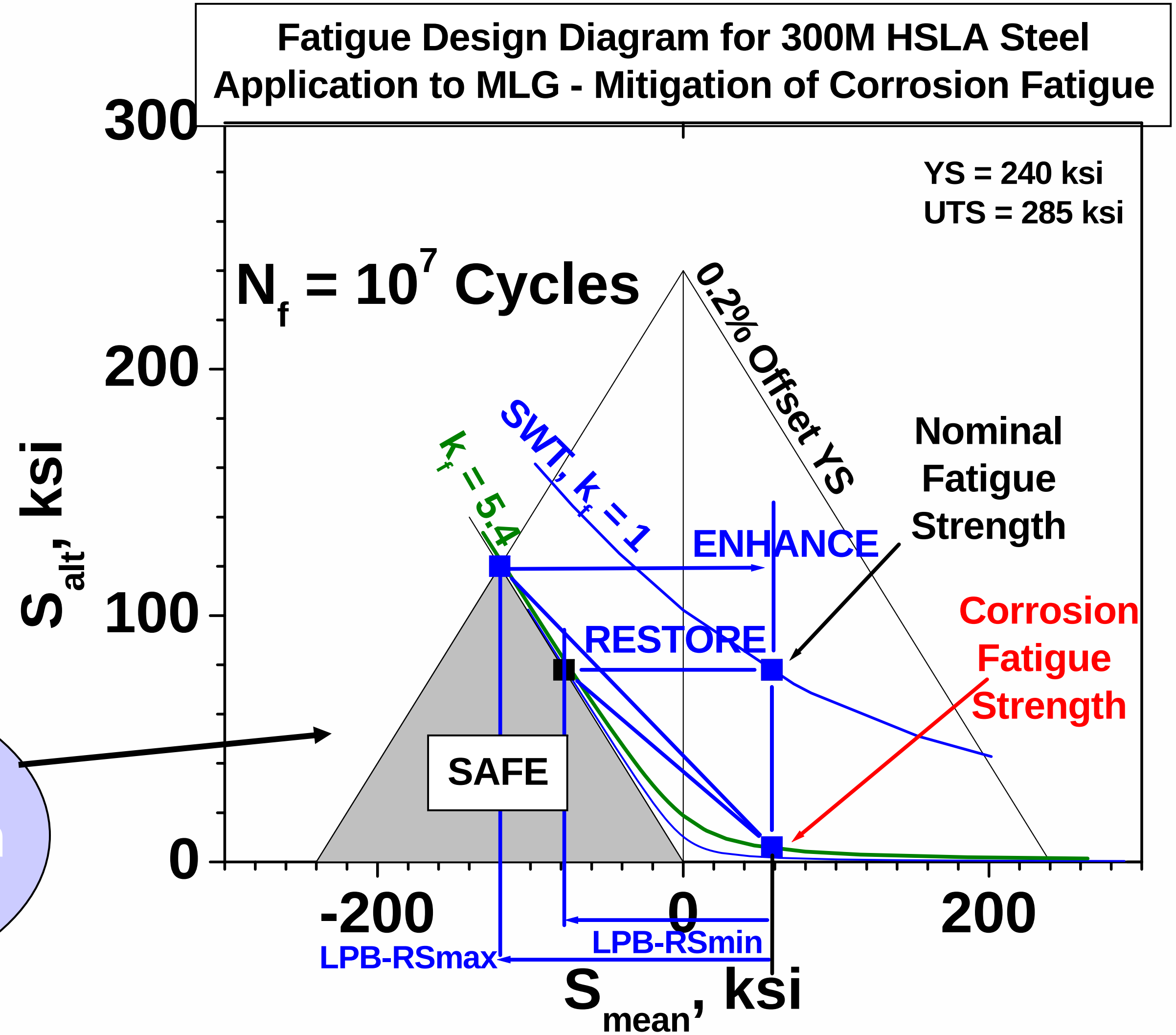
Residual Stress Design Method

- RS Design based on FDD (Fatigue Design Diagram – Lambda Patent Pending)
- FDD is a novel adaptation of Haigh Diagram
- SWT model is used to extend Haigh Diagram into compressive mean stress regime
- Neuber's k_t or k_f is used to account for damage
- Predicts RS_{min} to restore performance and RS_{max} to enhance performance
- RS optimization based on other design factors like part-distortion, location/magnitude of compensatory tension, etc.

Residual Stress Design Method

FDD Predicts that Compressive RS Restores or Enhances Performance

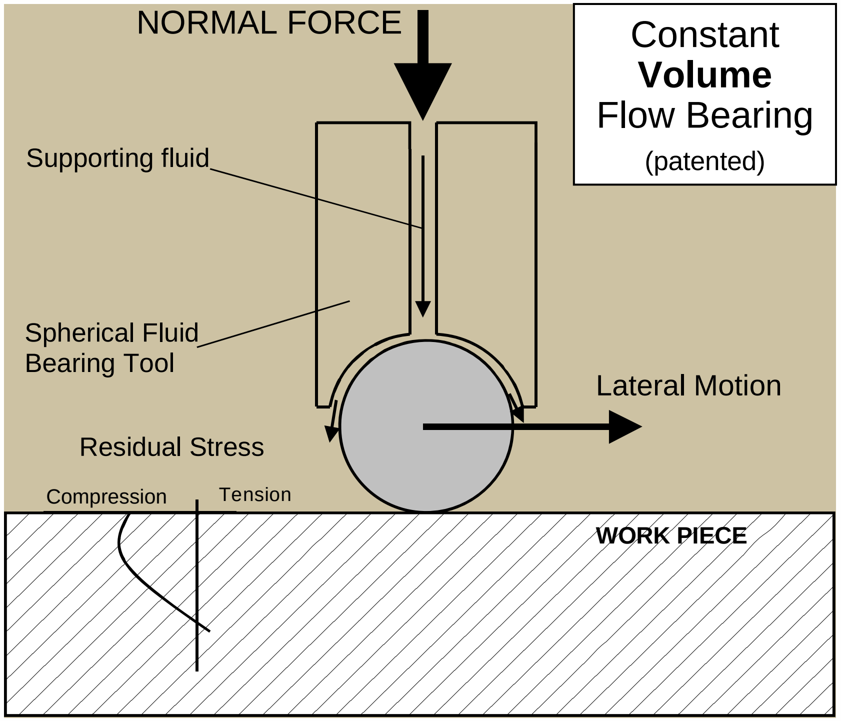
No Mode I Crack Growth in "SAFE" Region

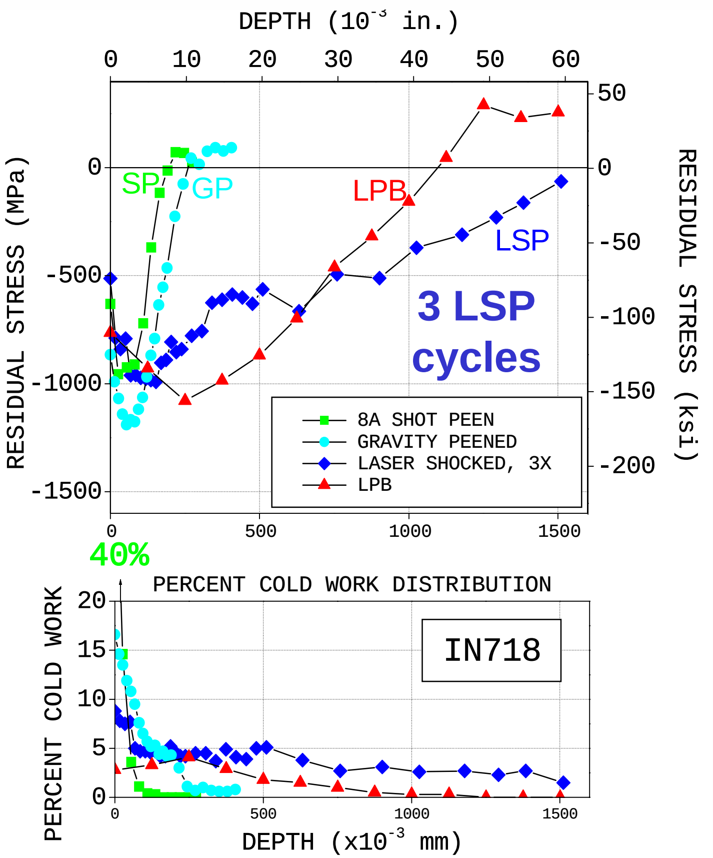


LPB
PROCESS

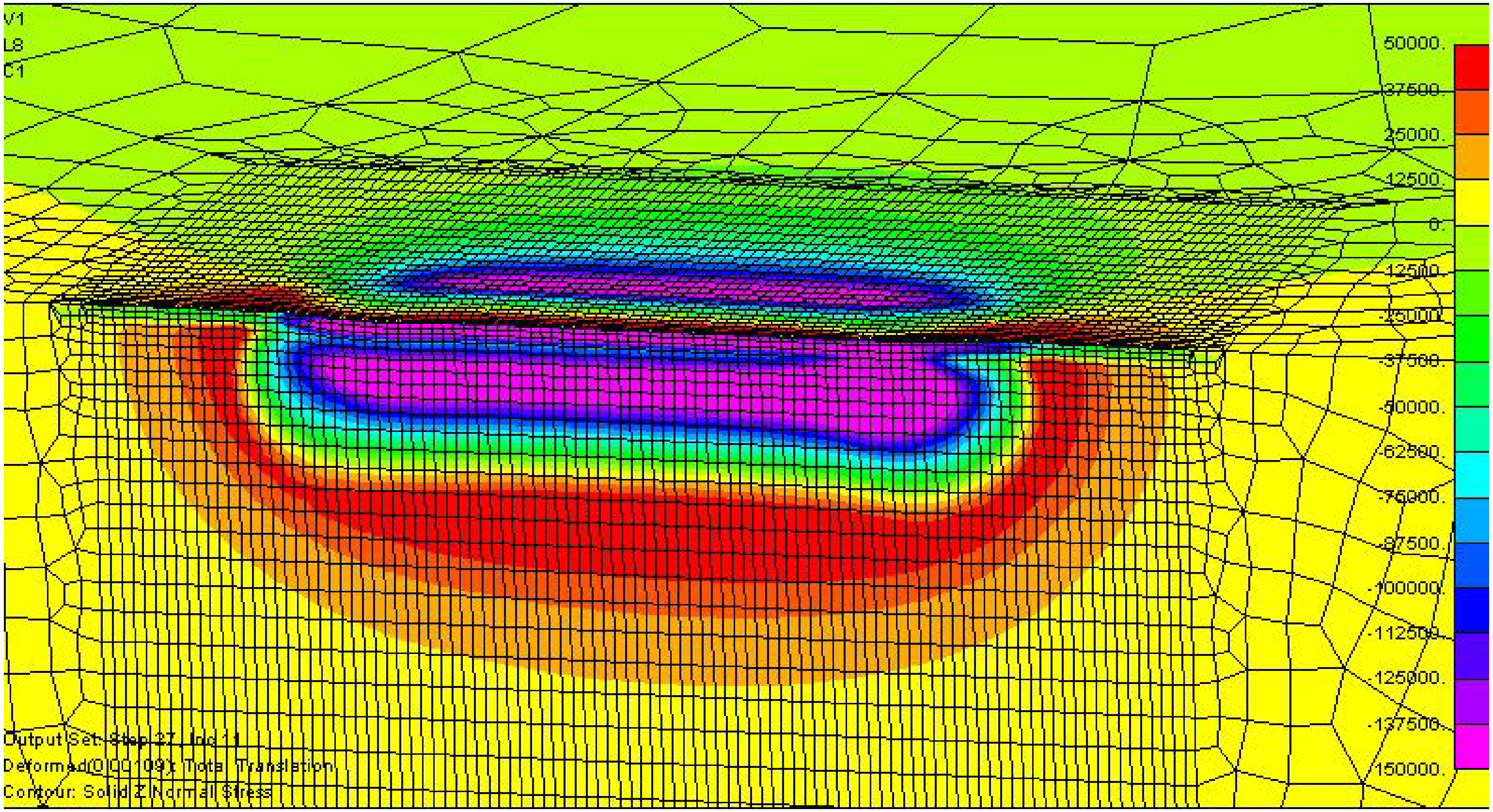
LPB Technology

- High-hardness ball is rolled, under pressure, over surface
- Single pass provides deep compression
- Patented hydrostatic bearing with constant volume flow
- Low cold work provides stable compression



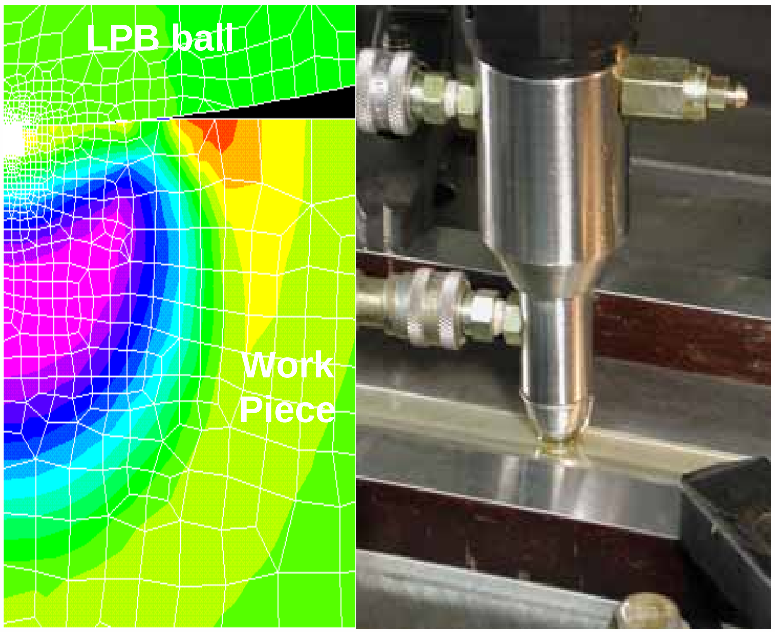


Single Pass FEA Model of LPB Process Showing the Development of Surface and Subsurface Compression

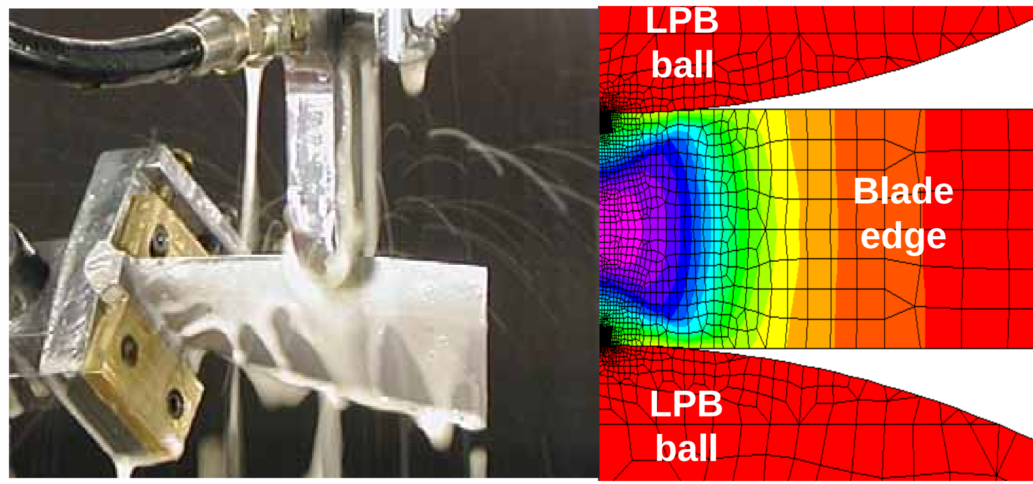


LPB Tool Technology

Single-Point Tool for thick pieces or one-sided application



Caliper Tool for thin pieces, providing through thickness compression



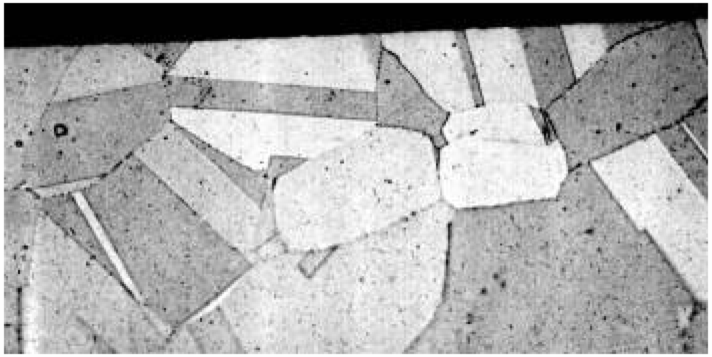
Through-thickness compression in compressor blade LE

Disk slot tools and inside calipers for ID bores built in 2006

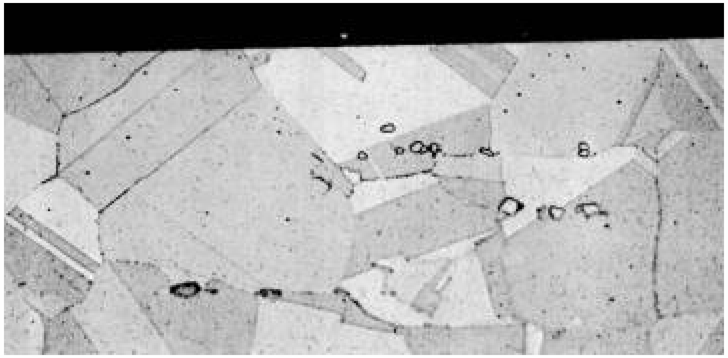
LPB Causes No Surface Damage

- **No metallographically detectable damage at 500x**
- **Improved Surface Finish <10 μin.**
- **Finish varies with LPB parameters: force, feed, ball type and size.**

LPB Generated Surface in IN718



Perpendicular to lay 500x



Parallel to lay 500x

Residual Stress Stability

Fatigue benefit is lost if residual compression relaxes.

- **Thermal Relaxation**
  - Cold work increases dislocation density
  - High dislocation density increases both rate and amount of relaxation
- **Overload (Mechanical) Relaxation**
  - Cold work creates yield strength depth gradient
  - Subsequent deformation is not uniform
- **Cyclic Relaxation**
  - Not significant in HCF at R = Smin/Smax > 0

Low Cold Work = Stable Compression

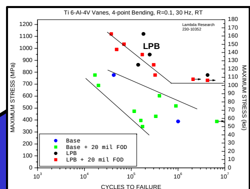
Compressive Stress Field Design Protocol

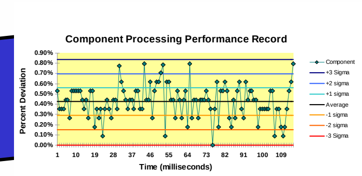
Designed Surface Enhancement

Statistical Quality Control

Processing Tools & Code

Fatigue Life Validation

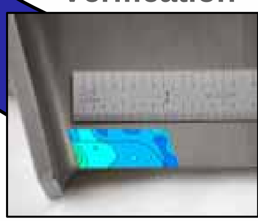




Turn Key Production

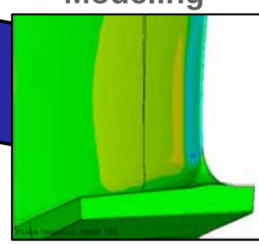
Providing Total Solutions

Compression Verification

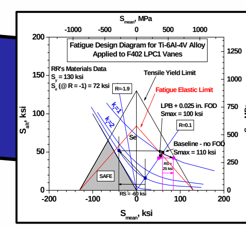


For Fatigue & Stress Corrosion Cracking

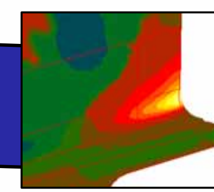
Residual Stress Modeling



Fatigue Design



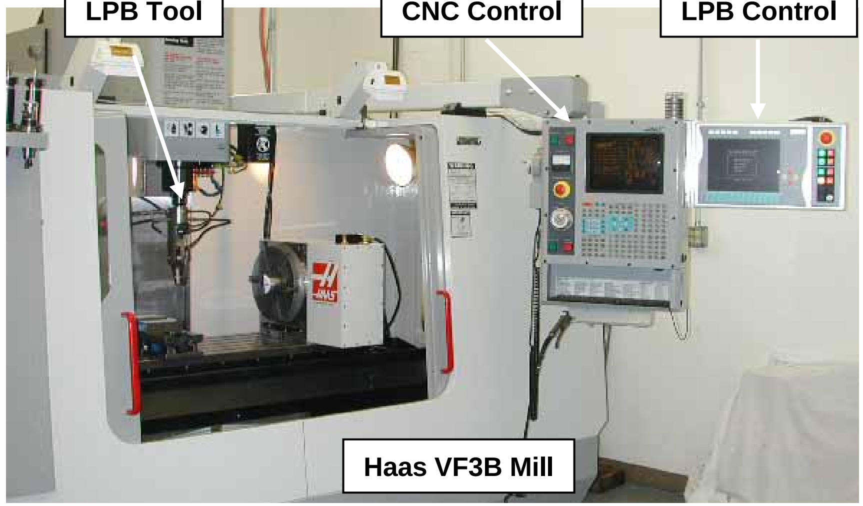
Applied Stresses



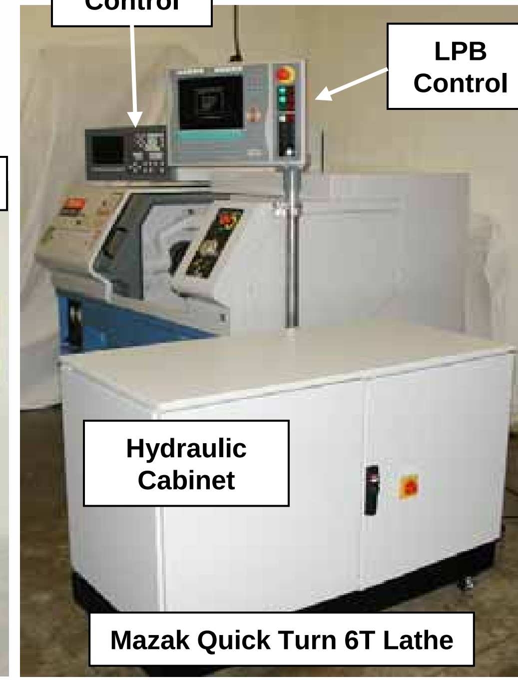
Total Engineering Solution: Ti-6-4 Vane

LPB Production

6-axis



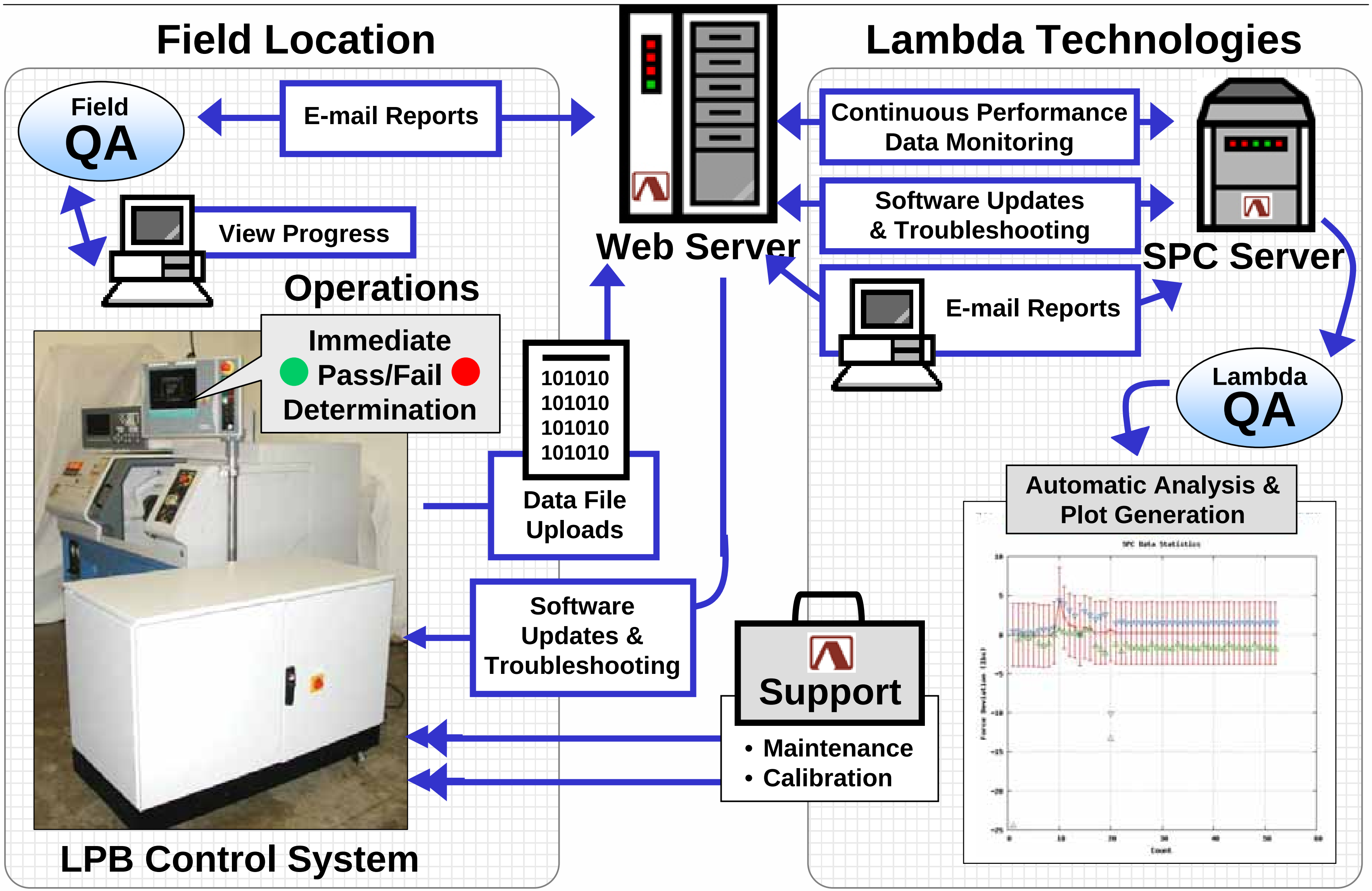
4- and 5-axis



3-axis

- **Machining-like operation using typical CNC machine tools or robots**
- **Highly automated…minimal operator intervention**
- **Low capitalization costs…use *existing* CNC machines**
- **Shop floor compatible…no specialized facilities**

Turn Key Field Installation



LPB MITIGATES FATIGUE AND PRE-CRACKING DAMAGE IN AA2024-T851

Objective of the Test Program

To mitigate pre-cracking and fatigue damage through low plasticity burnishing (LPB) treatment in AA2024-T851 parts simulating two different features of airframe structure

PART DESIGN, FATIGUE TEST ARTICLES AND VARIABLES

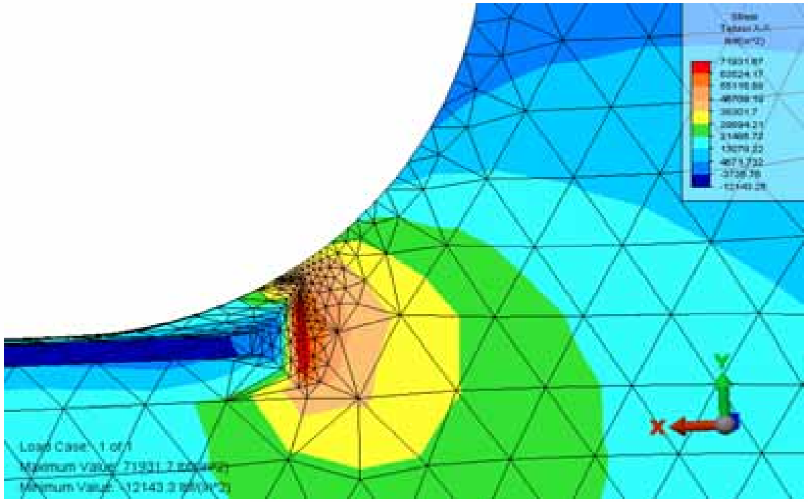
AIR FORCE RESEARCH LABORATORY

LAMBDA TECHNOLOGIES

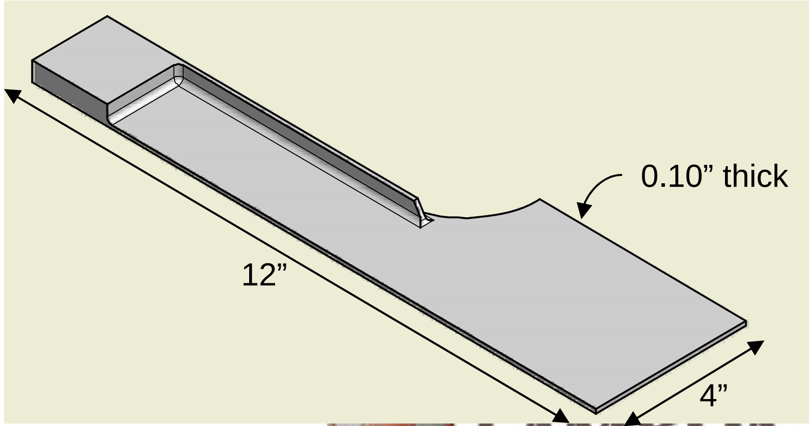
Part A (Complex)

- Material: Al 2024 T851
- Loading (uniaxial) – Two load cases
  1. Design stress: Constant amplitude, Max stress 11.4 ksi (approximately 30,000 cycles to failure)
  2. 10% over design stress: Constant amplitude, Max stress 12.5 ksi
- R = 0.01 (ratio of min to max stress)
- Pre-crack status (0.05 in.) = yes, no
- 3-6 repetitions per test case

Part A – Applied Stress @ 4500 lb Uniaxial Load



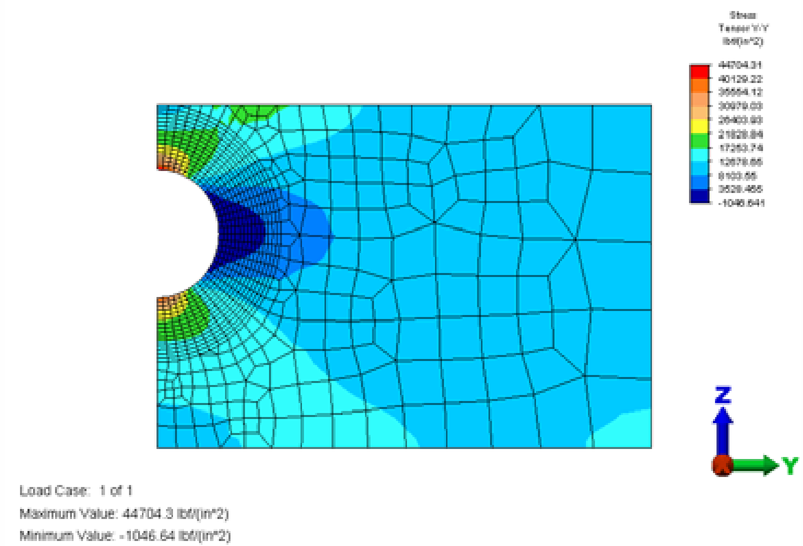
Max Stress in X-direction +72 ksi

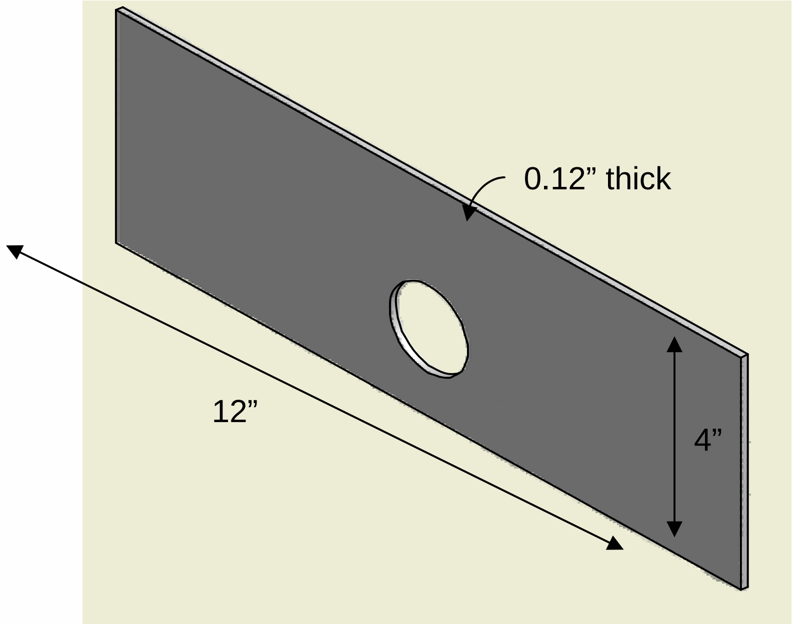


Part B (Simple)

- Material: Al 2024 T851
- Loading (uniaxial) – Two load cases
  1. Design stress: Constant amplitude, Max stress 11.5 ksi (approximately 30,000 cycles to failure)
  2. 10% over design stress: Constant amplitude, Max stress 12.5 ksi
- R = -1 (ratio of min to max stress)
- Pre-crack status (0.05 in.) = yes, no
- 3-6 repetitions per test case

AXIAL APPLIED STRESS FOR 11 KSI FAR FIELD





RESIDUAL STRESS DESIGN, IMPLEMENTATION & MEASUREMENT

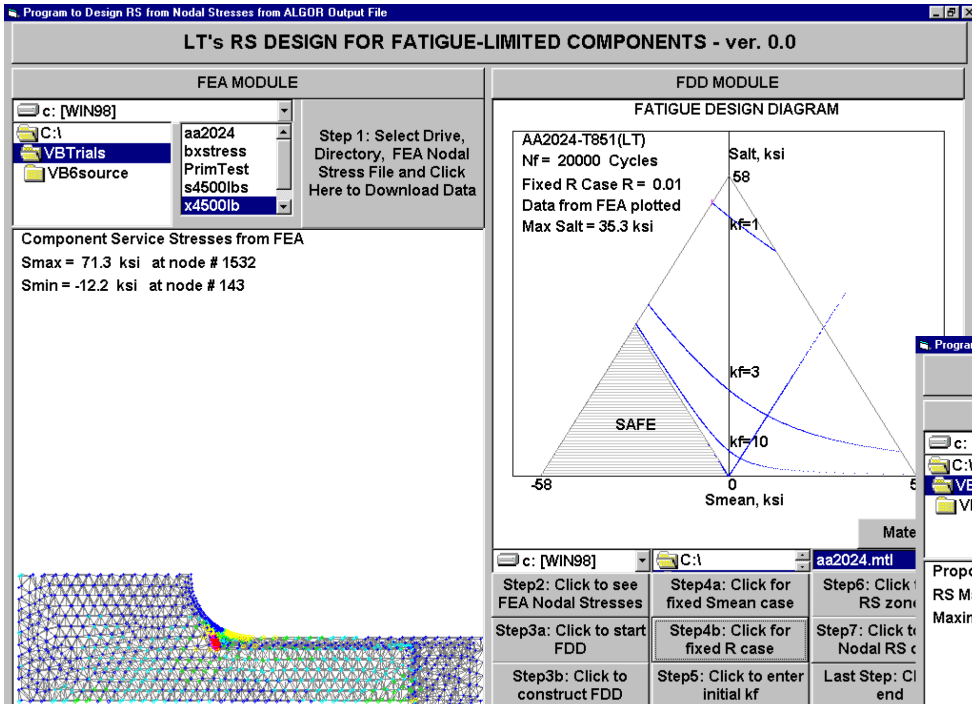
Compressive RS is designed using Lambda's FDD (Fatigue Design Diagram) method

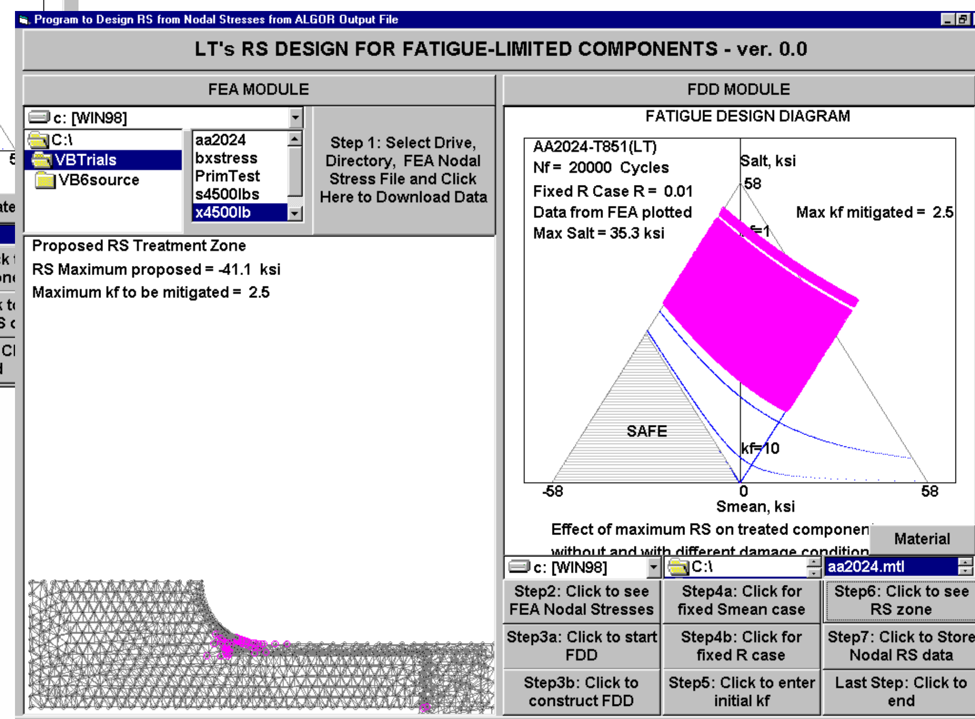
Both controlled magnitude and depth of compression introduced at critical locations through LPB treatment

RS measured by x-ray diffraction method

LPB DESIGN – FDD METHOD

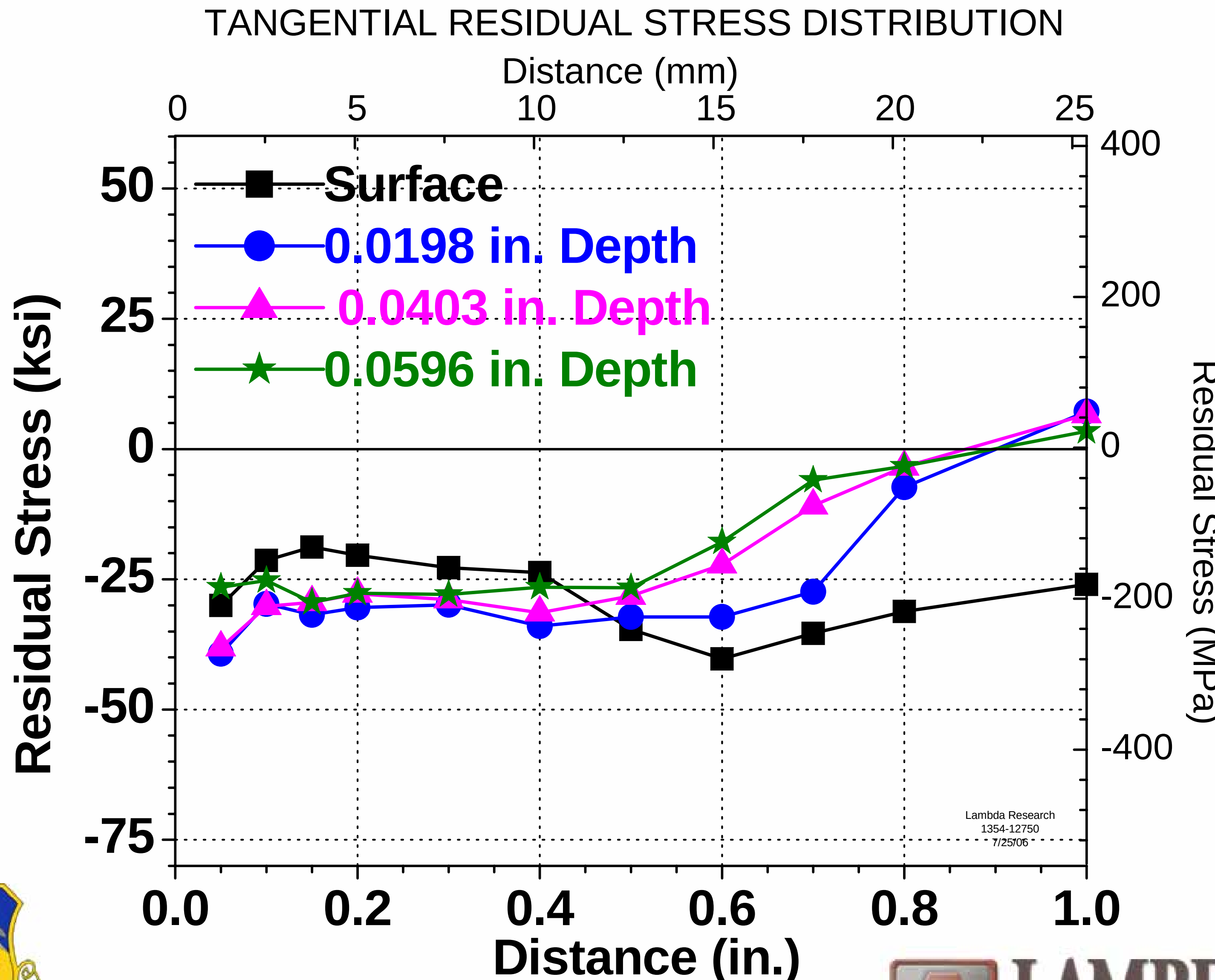
Compressive RS magnitude & locations to mitigate damage are determined by FDD (Fatigue Design Diagram)



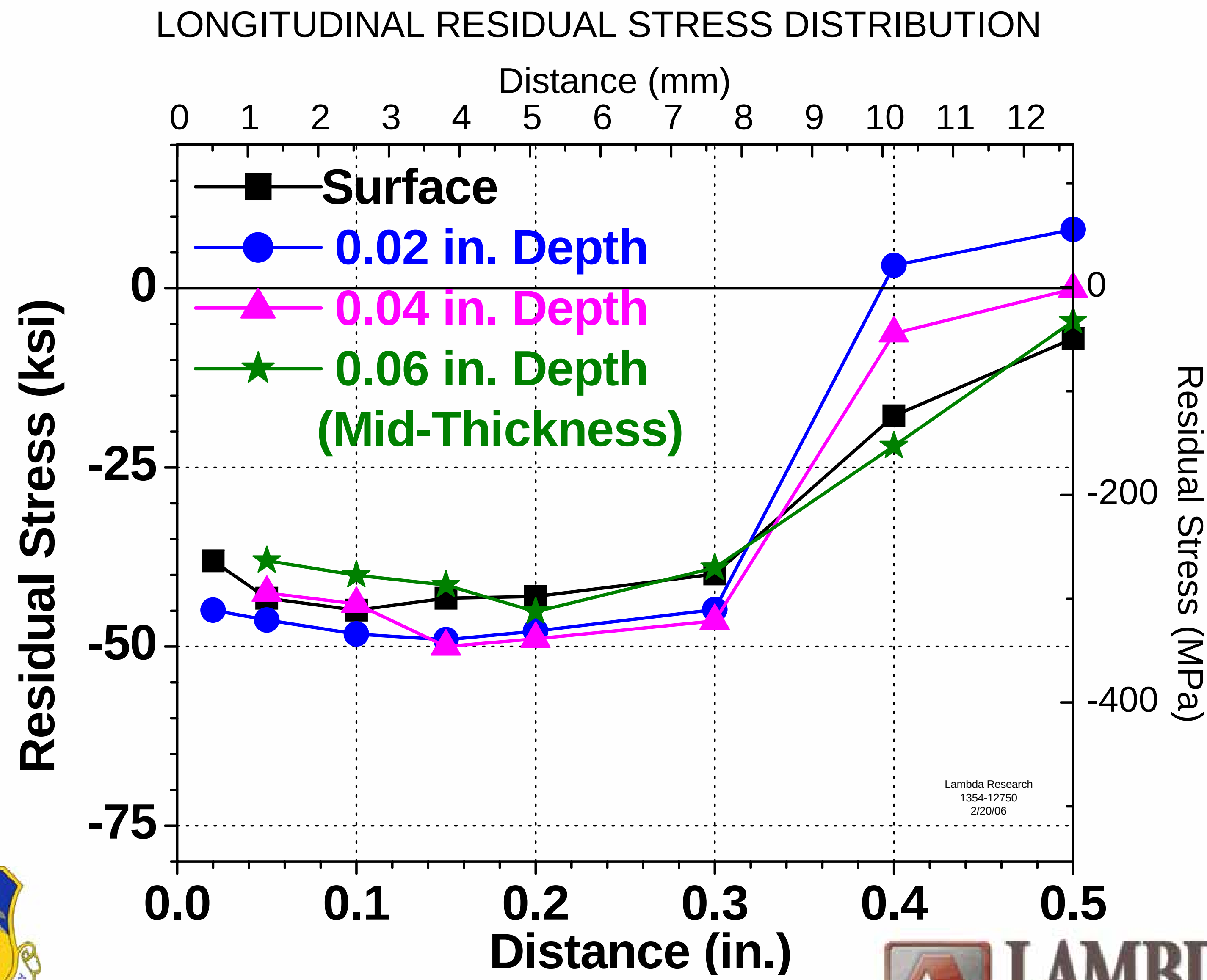


RESIDUAL STRESS MEASUREMENTS

Residual Stresses – Part A (Complex)



Residual Stresses – Part B (Simple)

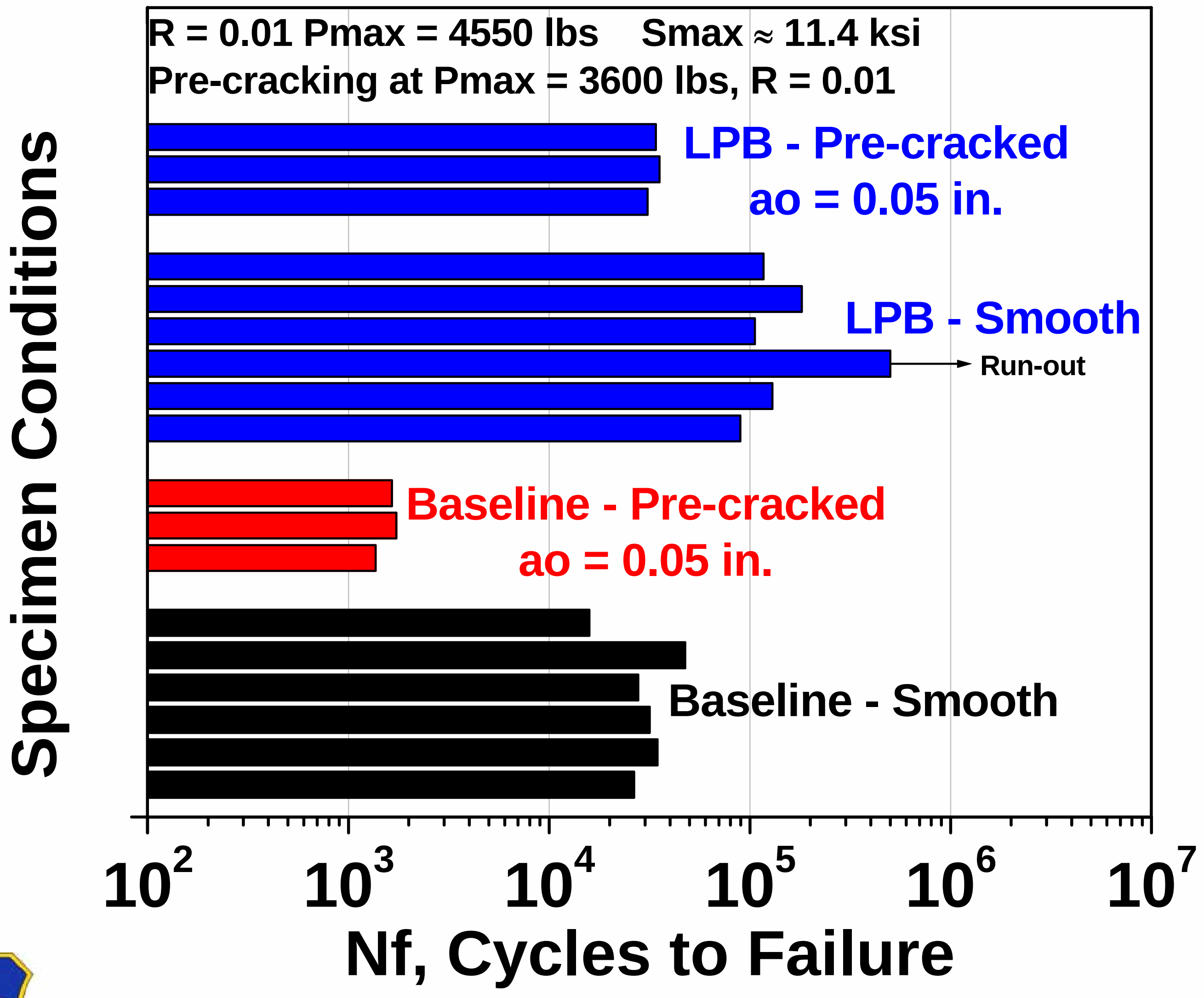


LAMBDA TECHNOLOGIES

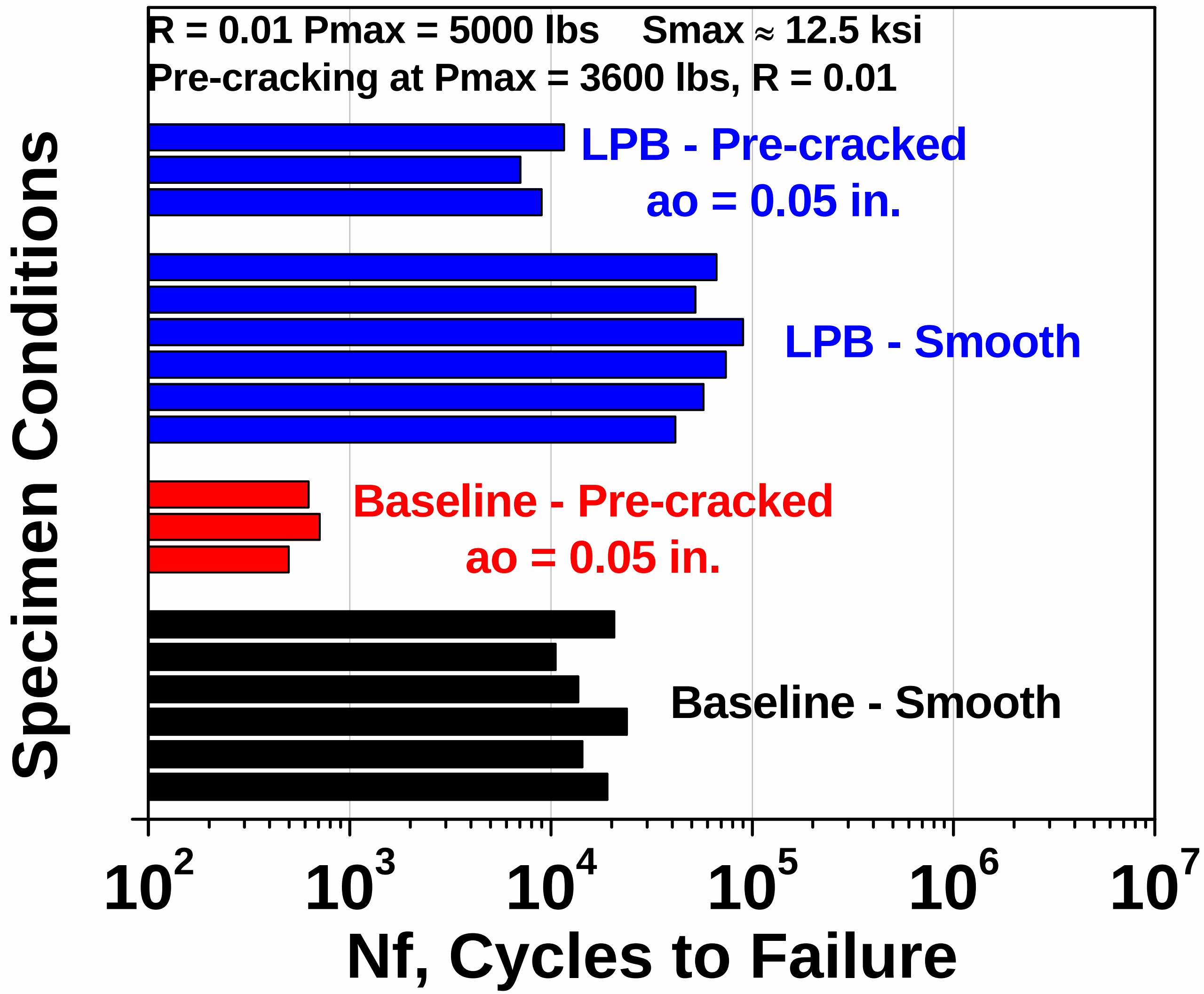
Summary of Fatigue Test Results

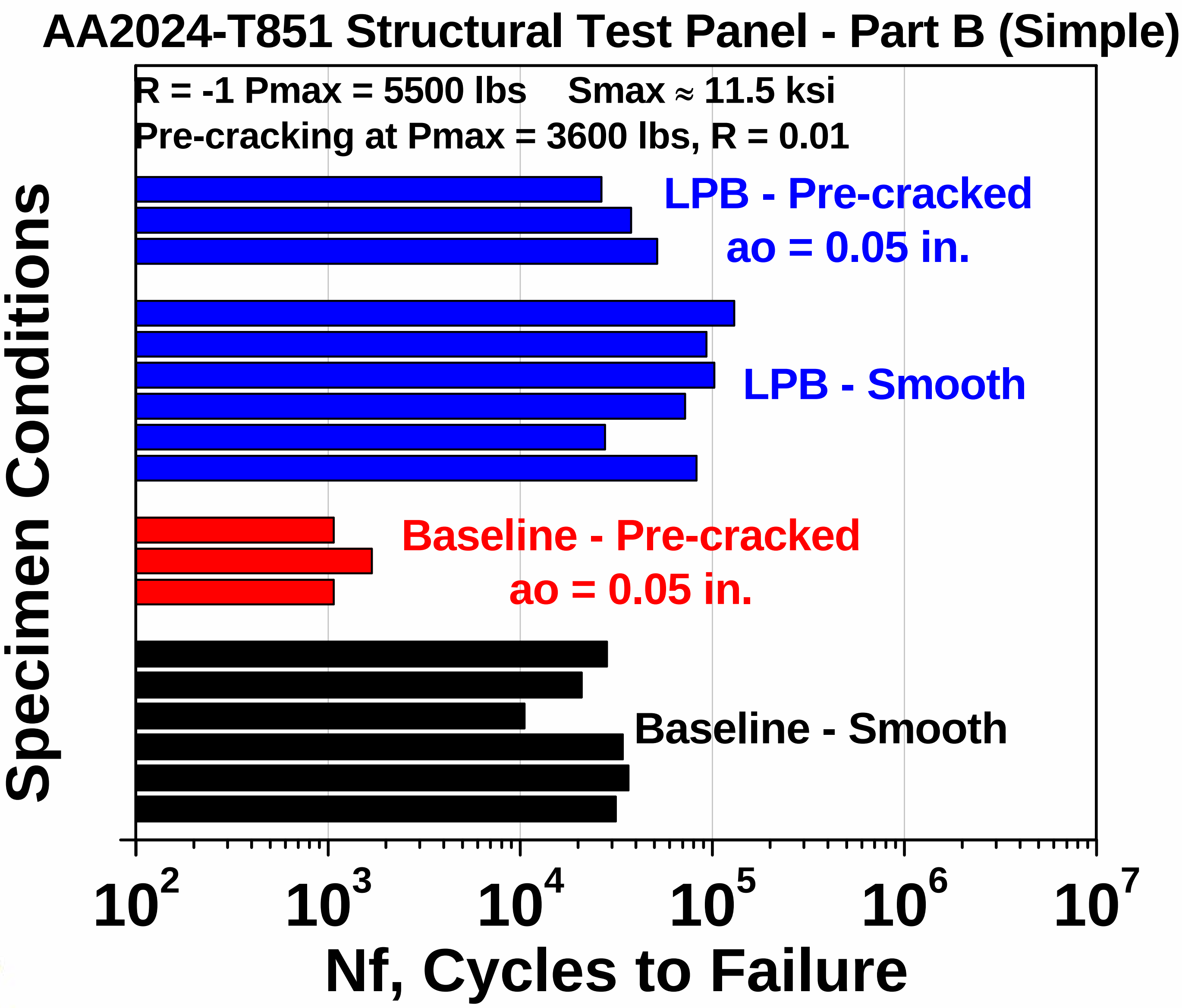
- **Fatigue life of the smooth undamaged part was decreased by a factor of 20 due to 0.050 in. precracking damage**
- **LPB improved fatigue life of smooth undamaged part by nearly a factor of 5**
- **LPB completely mitigated the precracking damage by restoring fatigue performance to that of a smooth undamaged part**

AA2024-T851 Structural Test Panel - Part A (Complex)

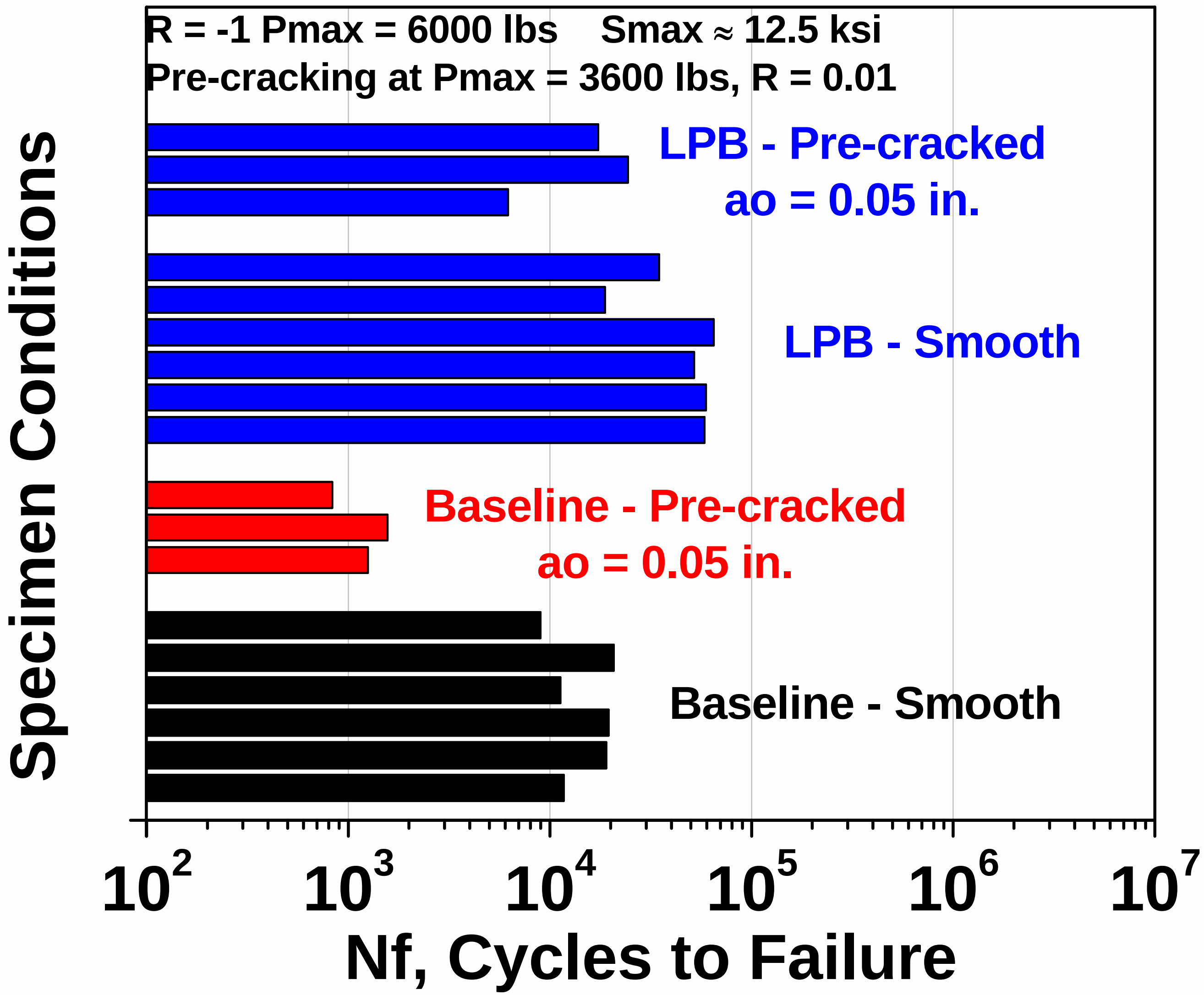


AA2024-T851 Structural Test Panel - Part A (Complex)




AA2024-T851 Structural Test Panel - Part B (Simple)
R = -1 Pmax = 5500 lbs Smax ≈ 11.5 ksi
Pre-cracking at Pmax = 3600 lbs, R = 0.01
LPB - Pre-cracked
ao = 0.05 in.
LPB - Smooth
Baseline - Pre-cracked
ao = 0.05 in.
Baseline - Smooth
Specimen Conditions
10^2
10^3
10^4
10^5
10^6
10^7
Nf, Cycles to Failure

AA2024-T851 Structural Test Panel - Part B (Simple)



Summary

- **The magnitudes and locations of needed compressive RS were determined by the FDD (Fatigue Design Diagram) Method**
- **LPB treatment was designed to introduce the intended compressive RS into the locations chosen for Parts A and B**
- **RS distribution in the treated parts was verified by x-ray diffraction method**
  - **In Part A (Complex) nominally uniform compressive RS of –30 ksi was achieved up to mid-thickness at critical locations**
  - **In Part B (Simple) nominally uniform compressive RS of –45 ksi was achieved up to mid-thickness at critical locations**

Summary (cont'd)

- **Fatigue test results validated predictions**
  - **LPB almost doubled the fatigue life of both smooth parts A & B**
  - **In both Parts A & B, pre-cracks (0.05 in. long) reduced the fatigue life by nearly an order of magnitude**
  - **In both Parts A & B, LPB fully restored the fatigue life of the pre-cracked (of length 0.05 in.) parts to that of smooth baseline parts**
  - **The benefits of LPB were consistently evident at both stress levels of 11.5 and 12.5 ksi**
  - **The benefits of LPB were consistently evident at both stress ratios (R) of 0.01 and -1**