CURTISS WRIGHT
Surface Technologies

Enhancing Fatigue Lifetimes and Precision Component Shaping by Laser Peening

Jon Rankin, Jack Campbell and Lloyd Hackel
Metal Improvement Company

Prepared for OSD - JTEG
November 26, 2013

Metal Improvement Company
Subsidiary of Curtiss-Wright Corporation

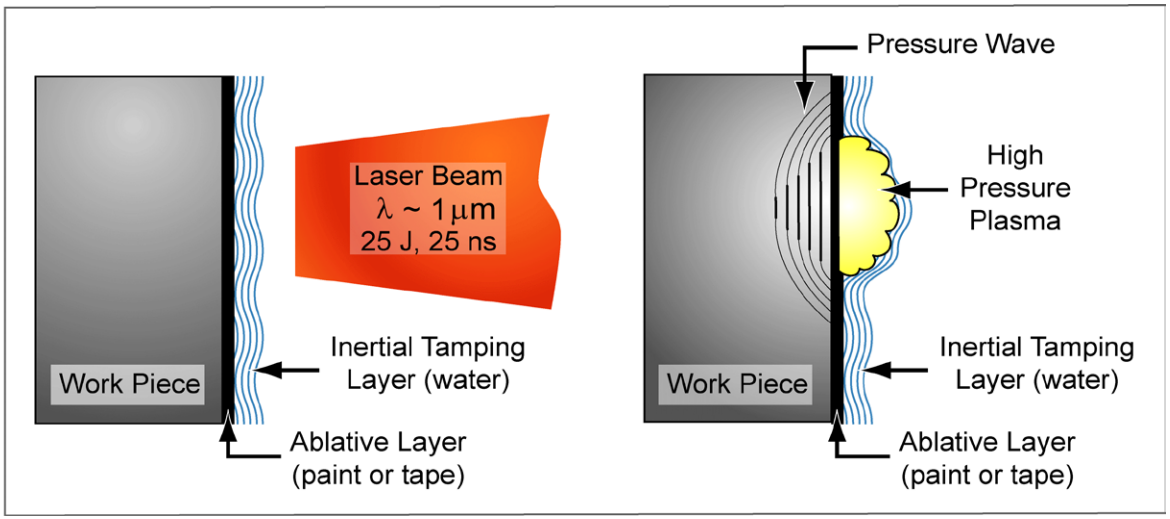
Enhancing the performance of metals and materials

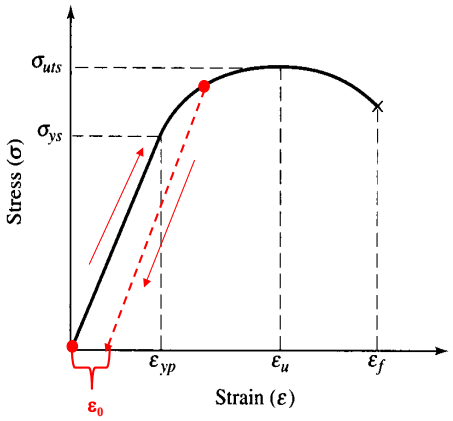
Presentation outline

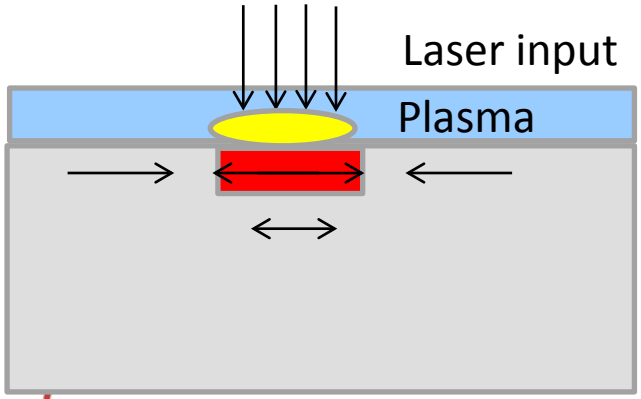
- Background on laser peening
- Current commercial and military applications
- Engineering residual stress and strain through finite element analysis of laser peening
- Case studies in fatigue and forming applications

CURTISS WRIGHT Surface Technologies

Laser Peening employs advanced laser technology and shock physics



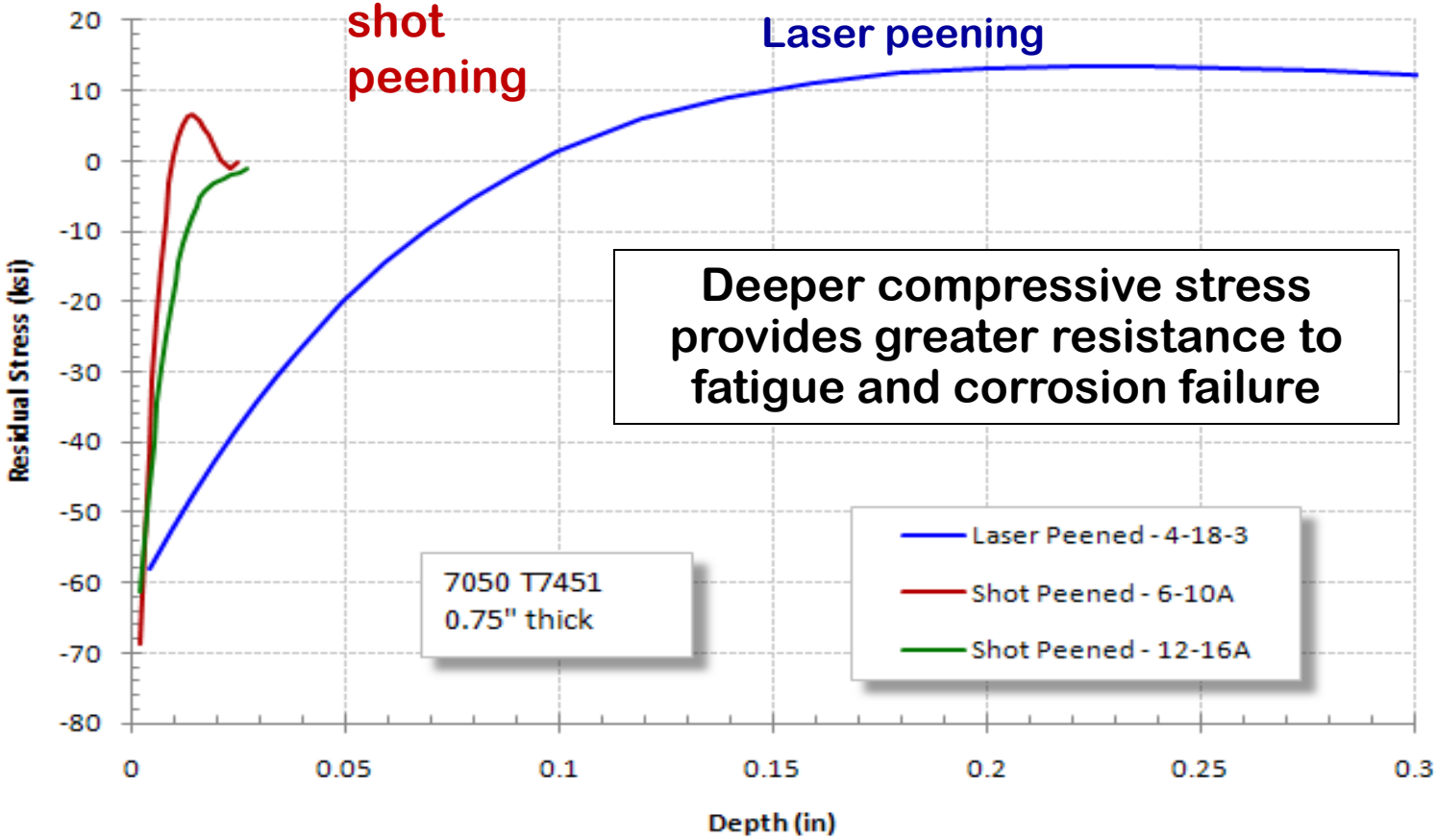




- **Plasma pressure plastically compresses metal in normal direction**
- **Metal expands transversely to conserve volume**
- **Surrounding material resists, setting up compressive field**
- **Compensating tensile stress develops safely subsurface**

CURTISS WRIGHT Surface Technologies

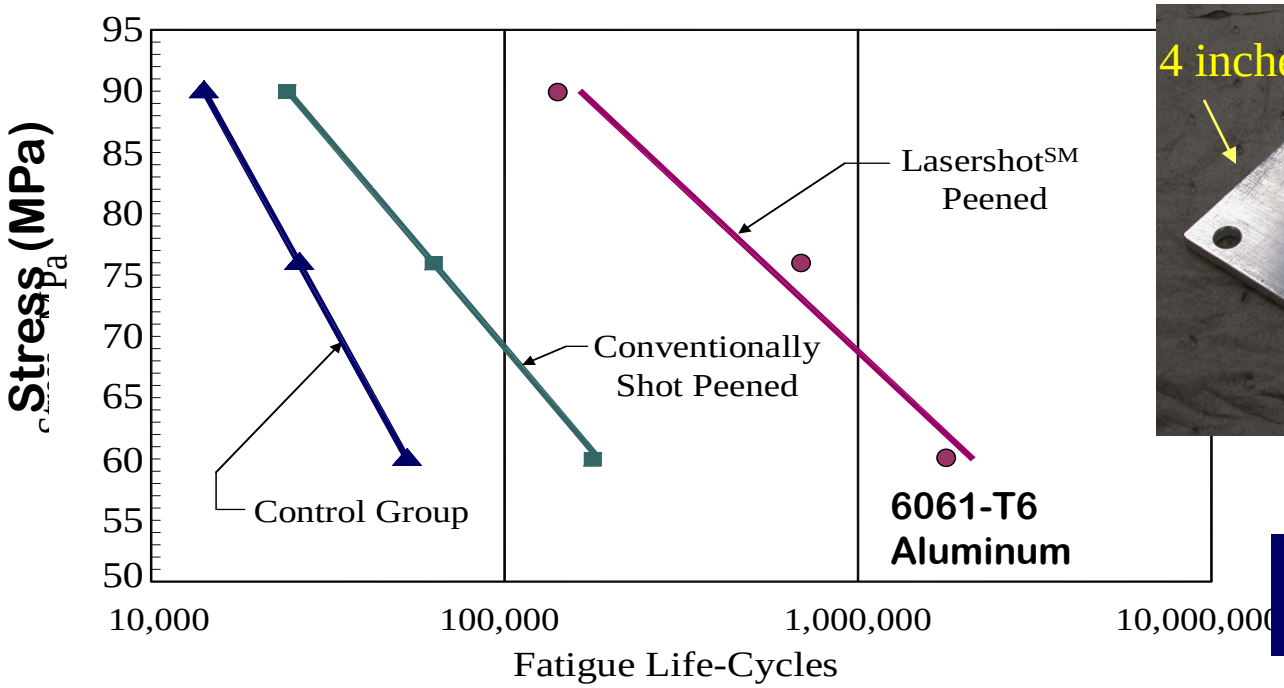
Laser peening compressive stress in aluminum is 10x deeper than shot peening

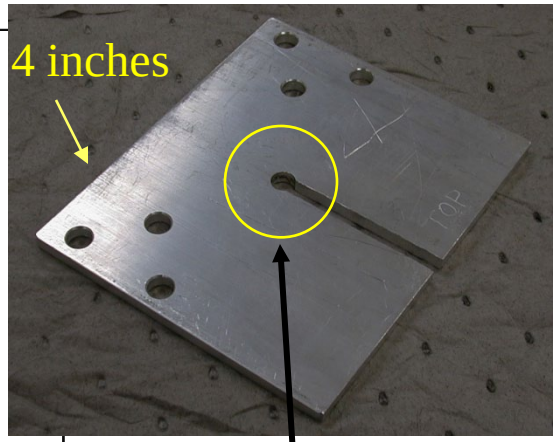


CURTISS WRIGHT Surface Technologies

Laser peening enables as much as 10x lifetime improvement for fatigue

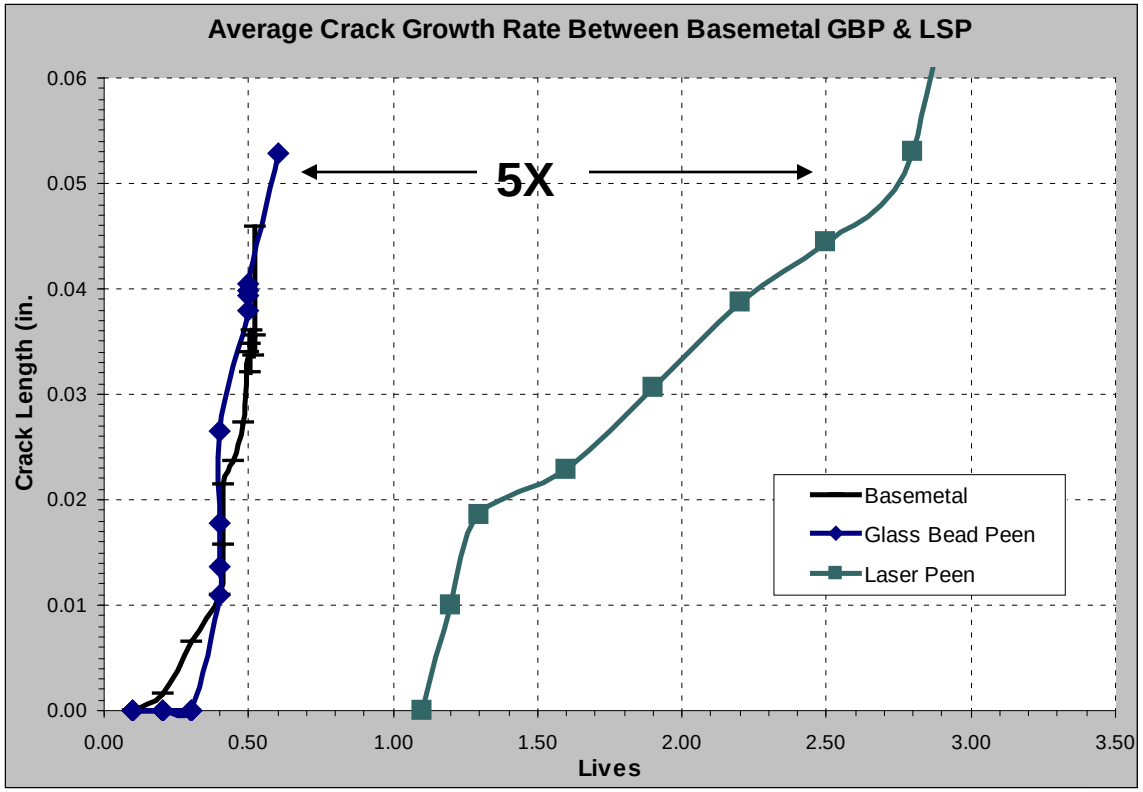
Deeper level of residual stress greatly enhances fatigue lifetime of beyond that of conventional surface treatments



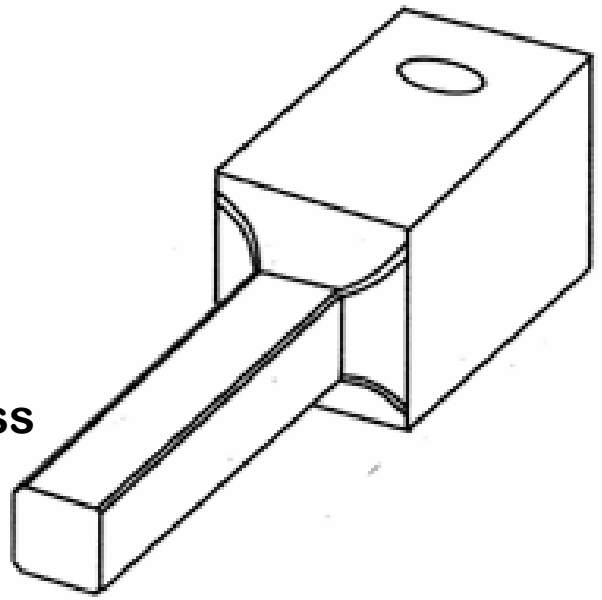


CURTISS WRIGHT Surface Technologies

F-22 structure development - Laser peening delays crack initiation and growth rate



Laser peening increases life by 5X compared to either base metal or glass bead peening in Ti6/4.

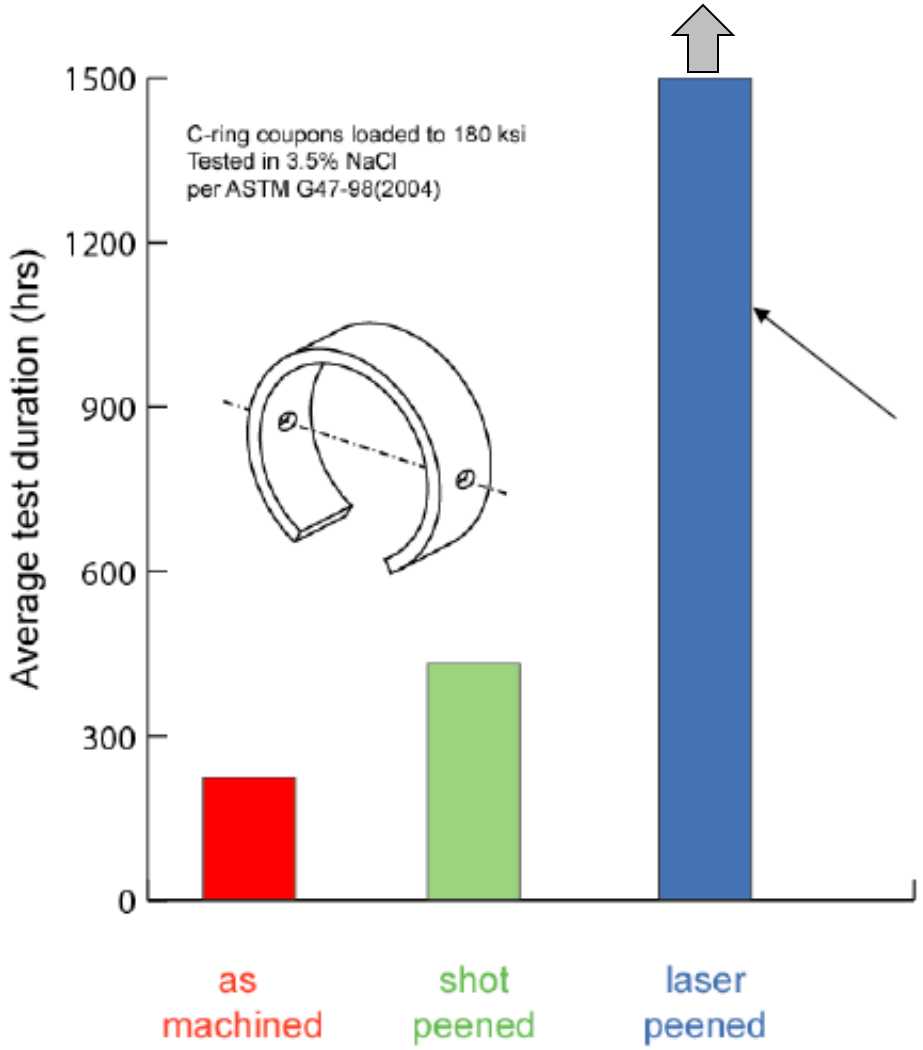


Cantilever beam specimen mimics stress concentration in component.

CURTISS WRIGHT Surface Technologies

CURTISS WRIGHT
Surface Technologies

Laser peening mitigates Stress Corrosion cracking in 300M Steel*



- Experiment terminated at two months
- Laser-peened coupons did not fail

* Data generated for MIC by T. Pistochini & Prof M. Hill

UCDAVIS

Solving the fatigue failure of Ti engine blades launched laser peening in 2002

Laser peening is being applied to eliminate fatigue failure in high value commercial jet engines.

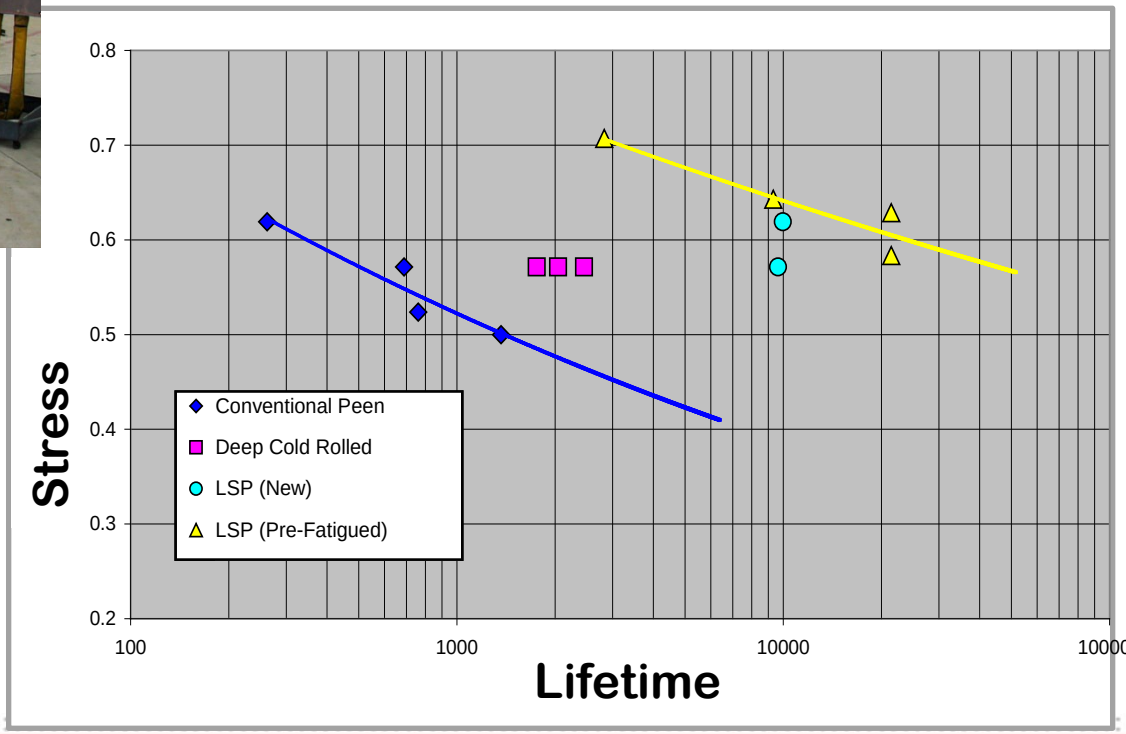
See Australian Transportation Safety Board Report 8/01 "Examination of a Failed Blade …. Boeing 777-300, A6-EMM" http://www.atsb.gov.au/aviation/tech-rep/8-01/8-01_Final.pdf)

CURTISS WRIGHT Surface Technologies

Laser peening extends lifetime of commercial jet engine blades by > 20x – saves $Ms annually

Boeing 777 with MIC laser peened blades

Over 40,000 blades have been treated for engines powering Boeing 777s , A340s and the new Boeing 787s and A350s

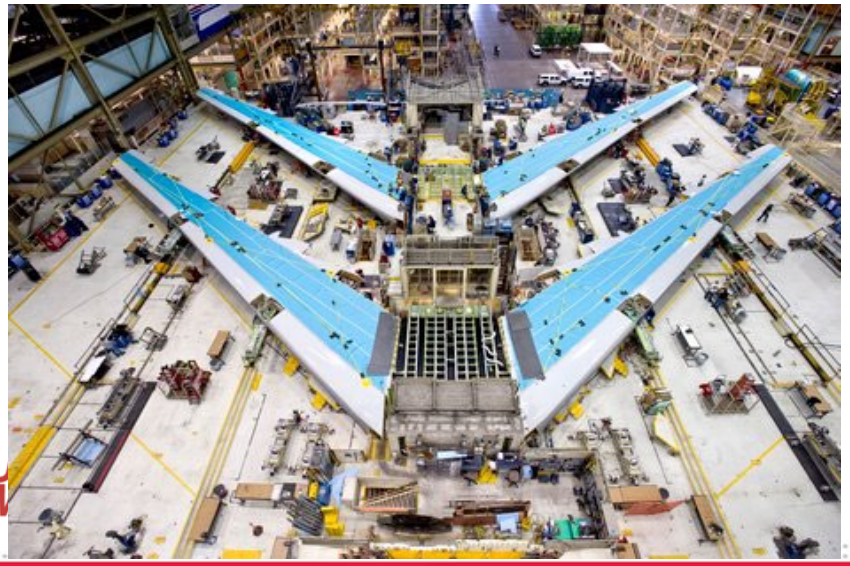


CURTISS WRIGHT Surface Technologies

MIC laser peening forms thick sections of wing panels for the new 747-8

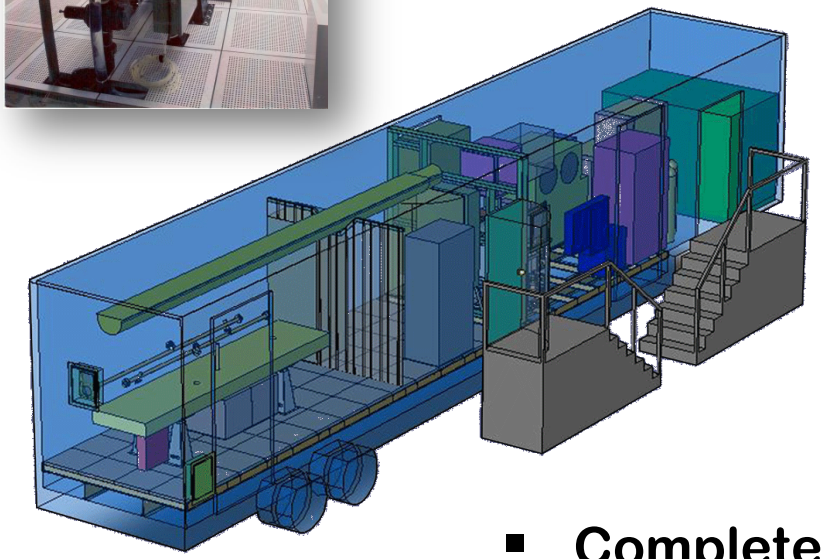
Wing skin panels are in laser peen forming production

World's first aircraft with laser formed panels delivered 2011



Transportable laser peening systems enable field applications such as F-22 crack prevention

MIC's unique high power laser



- Completely self-contained, the transportable system needs only electrical power, compressed air and water (~1gpm)

CURTISS WRIGHT
Surface Technologies

MIC laser peening can be done at overhaul facilities

- Laser peening can be easily transported to facilities for on-site processing
- F-22 processing moving to Hill AFB

CURTISS WRIGHT Surface Technologies

Test results for F-22 structure show significant improvement from Laser Peening

Laser peening deployed on F-22 at Lockheed Palmdale in April 2011

Weibull Analysis Benefit Factors	
GBP (t>0)	*9.0*
GBP (t=0)	*6.1*
LSP (t=0)	*6.0*
LSP over GBP (t>0)	*30.2*
LSP over GBP (t=0)	*19.2*

CURTISS WRIGHT Surface Technologies

*GBP = glass bead peening, LSP = Laser shock peening

Laser peening of integrally bladed rotors (IBRs) is fully qualified and in production for commercial aircraft engines

Laser beam director robot

Tamping layer water robot

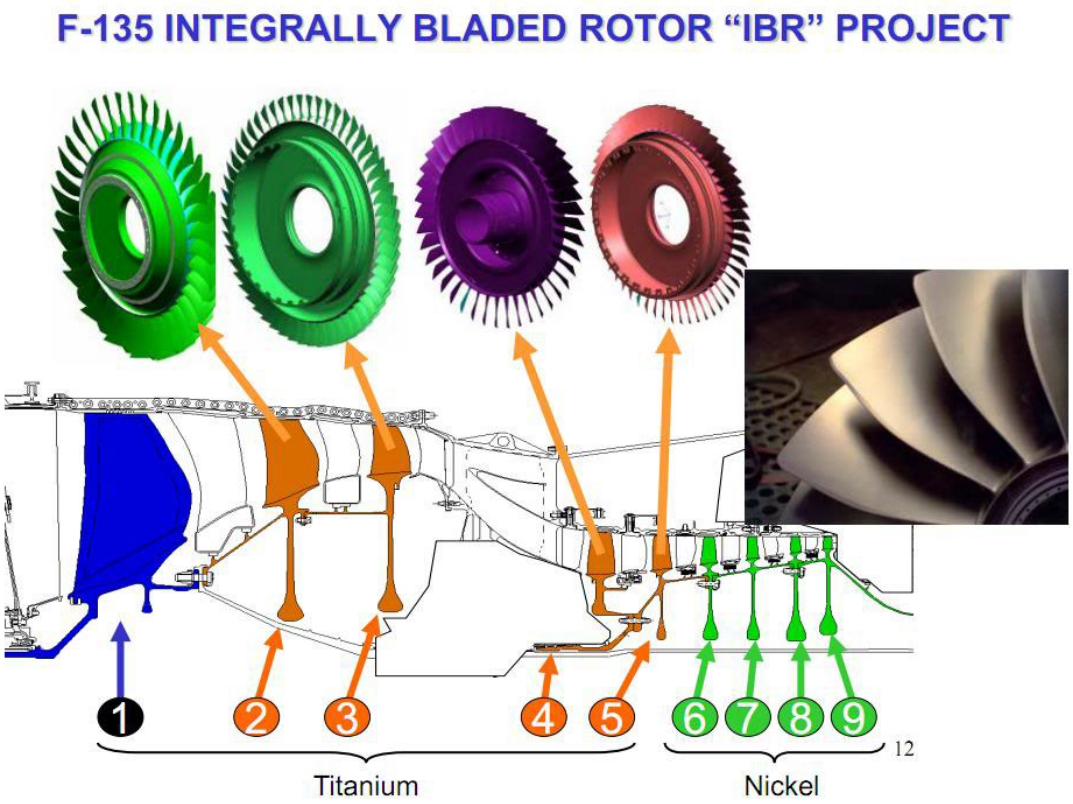
IBR handling robot

Robotics maintain precision process control

Set up and peening is a straightforward extension of the well developed production process.

CURTISS WRIGHT Surface Technologies

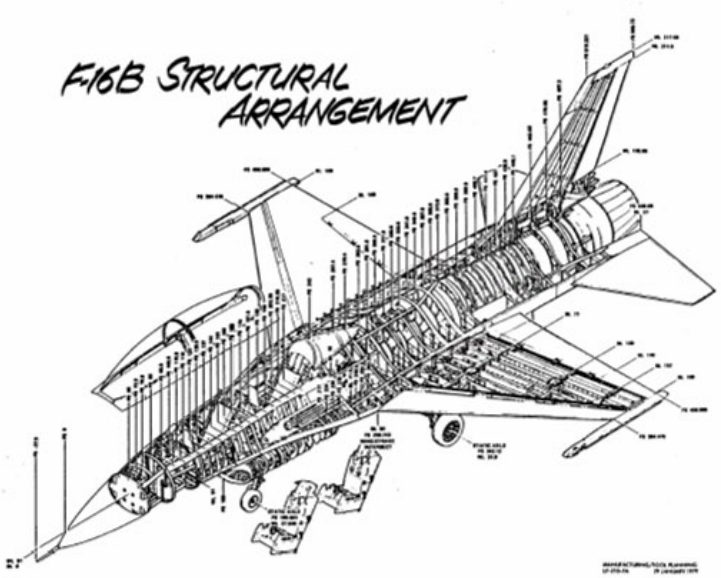
Laser peening technology has been developed and qualified for production IBR work



Peening of IBRs for fatigue crack and FOD protection would generate an operational cost reduction for F-135 deployment

CURTISS WRIGHT
Surface Technologies

An opportunity: Laser peening of F-16 structure can minimize replacements and costs – could be done at Hill AFB at low cost



ZONE	P/N	Designation	Work Type
FS 309.80	16B5231-888	UPPER BULKHEAD	REWORK
FS 325.80	16B5241-827	LH - UPPER BULKHEAD	REWORK
FS 325.80	16B5241-828	RH - UPPER BULKHEAD	REWORK
FS 341.80	16B5251-737	UPPER BULKHEAD	REWORK
FS 357.80	16B5261-883	UPPER BULKHEAD	REWORK
FS 309.80	16B5232-807	LH - LOWER BULKHEAD	REWORK
FS 309.80	16B5232-808	RH - LOWER BULKHEAD	REWORK
FS 325.80	16B5242-805	LOWER BULKHEAD	REWORK
FS 357.80	16B5262-847	LOWER BULKHEAD	REWORK
FS 341.80	16B5250-551	LOWER BULKHEAD	NEW
FS 446.1	16B6211-123	UPPER BULKHEAD	REWORK
FS 446.1	16B6212-91	LOWER BULKHEAD	NEW
FS 462.80	16B6215-25	BULKHEAD	REWORK
FS 479.55	16B6223-69	UPPER BULKHEAD	NEW

Presentation outline

- Background on laser peening
- Current commercial and military applications
- Engineering residual stress and strain through finite element analysis of laser peening
- Case studies in fatigue and forming applications

CURTISS WRIGHT Surface Technologies

CURTISS WRIGHT Surface Technologies

Laser peening for fatigue and forming

- Overview of process modeling

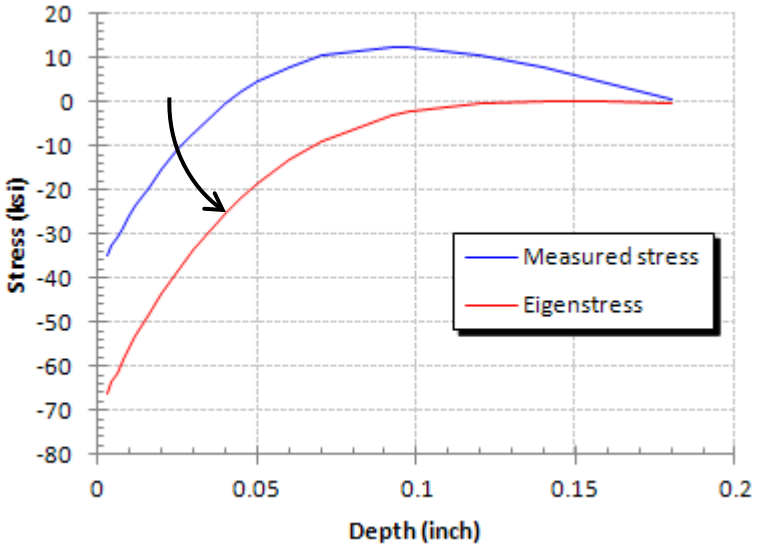
- Case studies in laser peening for fatigue
  - T45 hook
  - F35 hook
  - F-18 Y508 shear tie

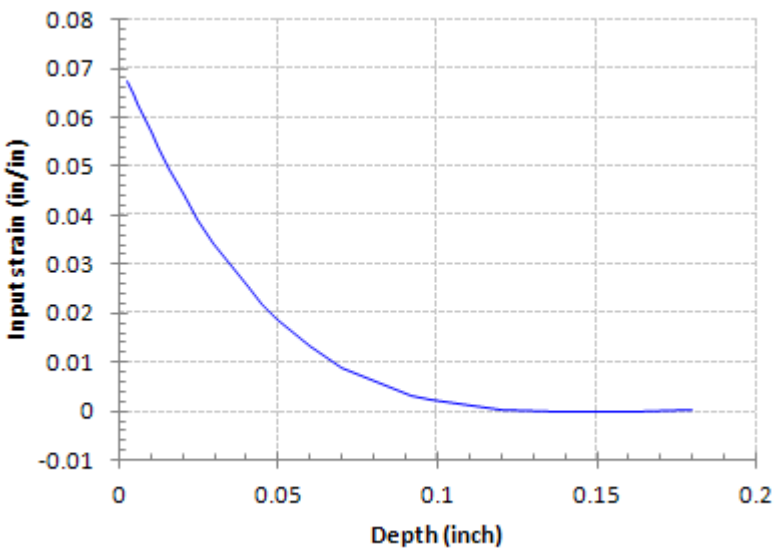
- Laser peening for forming and form correction
  - Forming of integrally stiffened panels
  - Forming and correction of thin panels

- Program pay-off

Overview of modeling concept

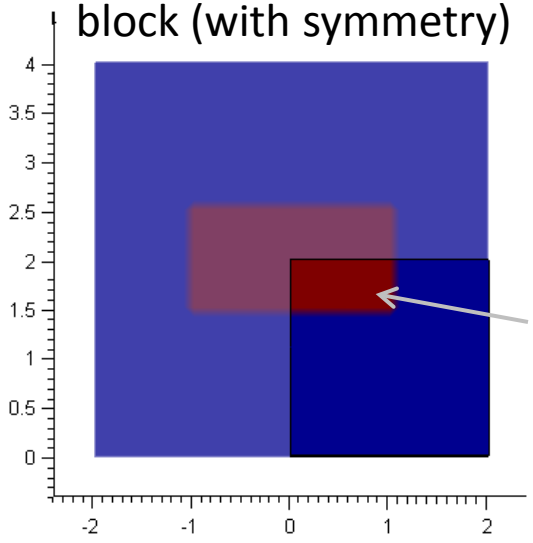
- Analysis input is computed from experimental measurements
- Part is modeled using continuum (3D) elements in ABAQUS
- Set a thermal initial condition based on Eigenstrain and let the model equilibrate – result shows the new shape and stress state of the part



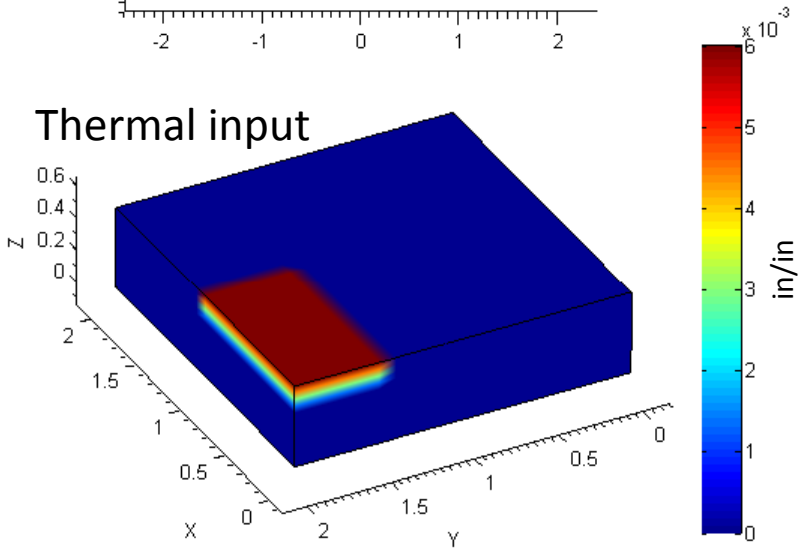


Example: FEA model of laser peening a simple block

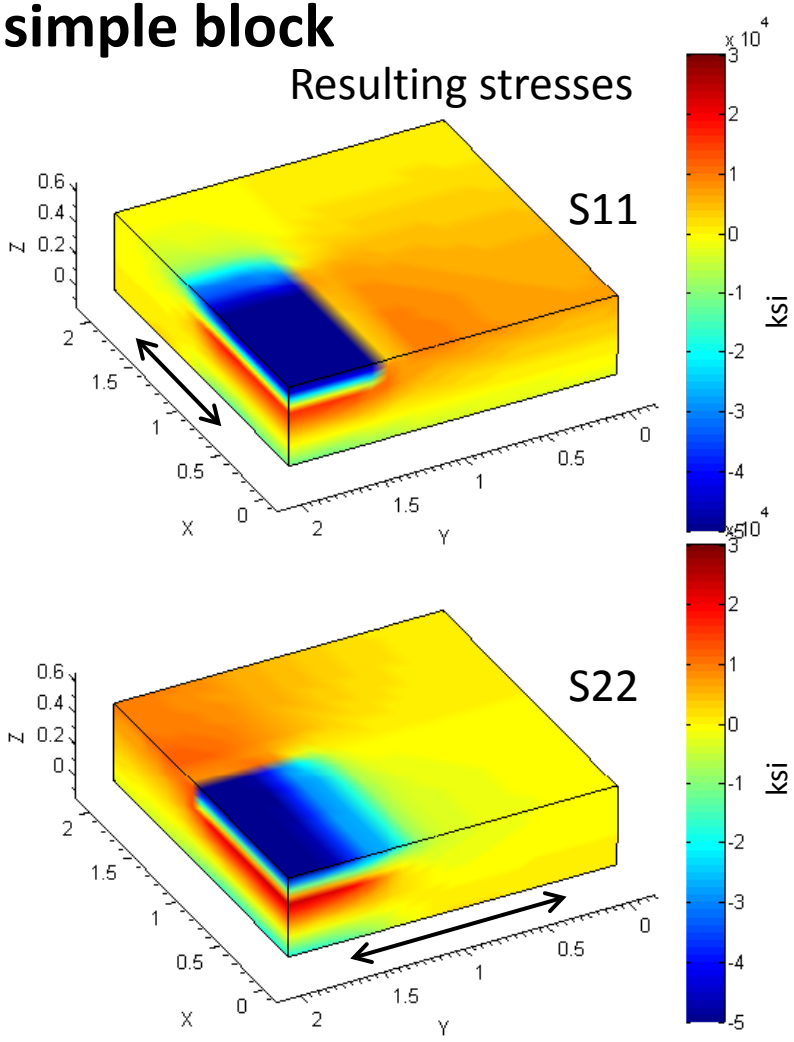
Simulate peening a patch on a block (with symmetry)



Thermal input



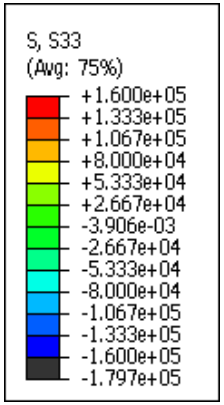
Resulting stresses



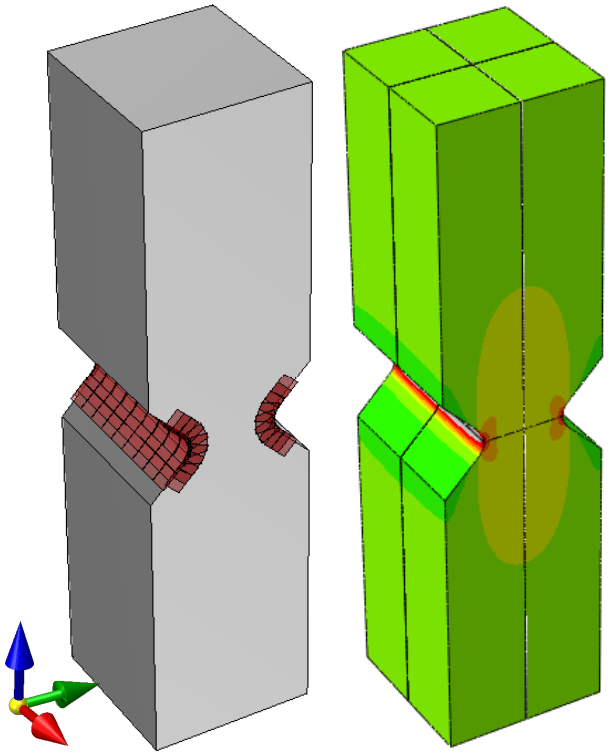
Results can be interrogated for stress, strain or displacement

FEA simulation of a fatigue specimen

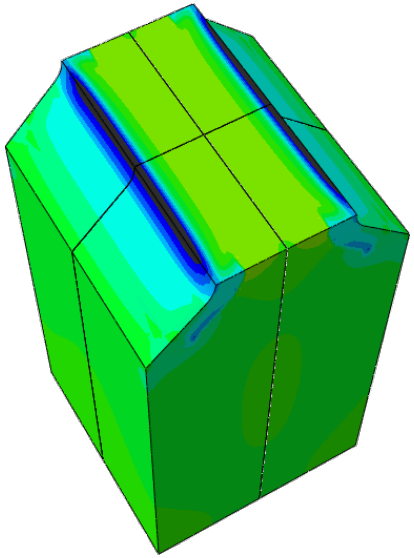
FEA predicts a 28% reduction in peak stress by laser peening the stress riser



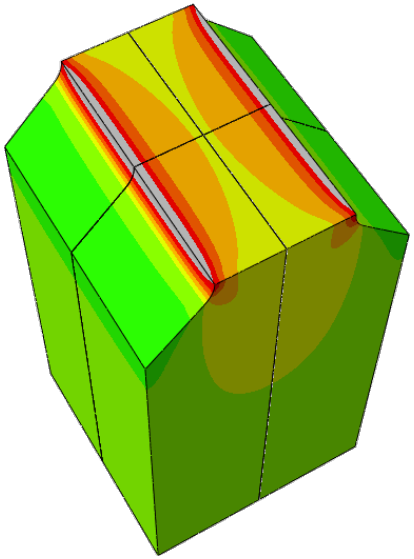
Without peening, under load



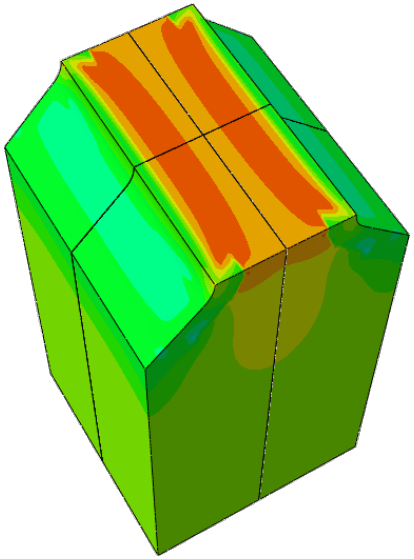
Laser peening pattern



Effect of laser peening (without load)

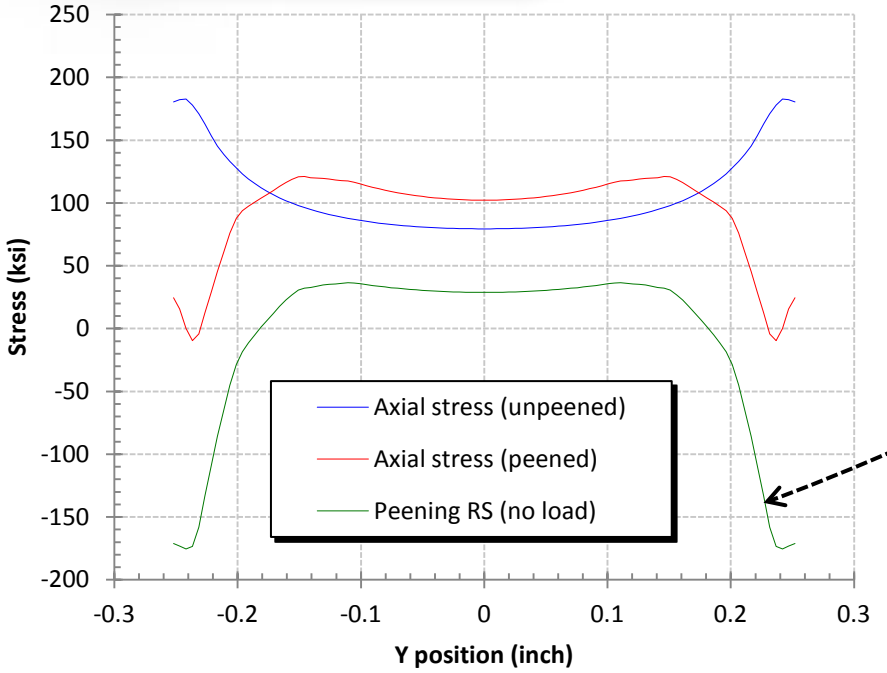


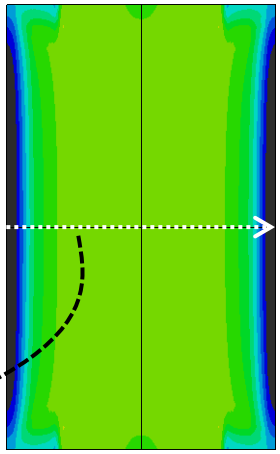
Without peening – Peak axial stress is 183 ksi

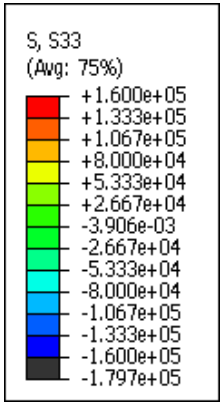


With laser peening – Peak axial stress is 132 ksi

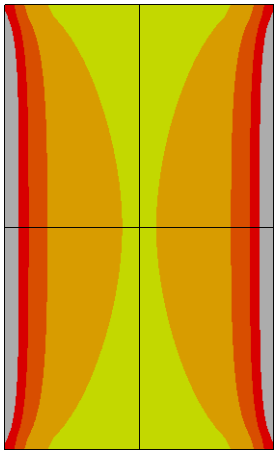
FEA predicts 28% reduction in peak RS with laser peening



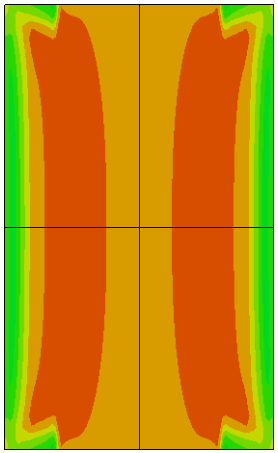




Effect of laser peening (without load)



Without peening – Peak axial stress is 183 ksi



With laser peening – Peak axial stress is 132 ksi

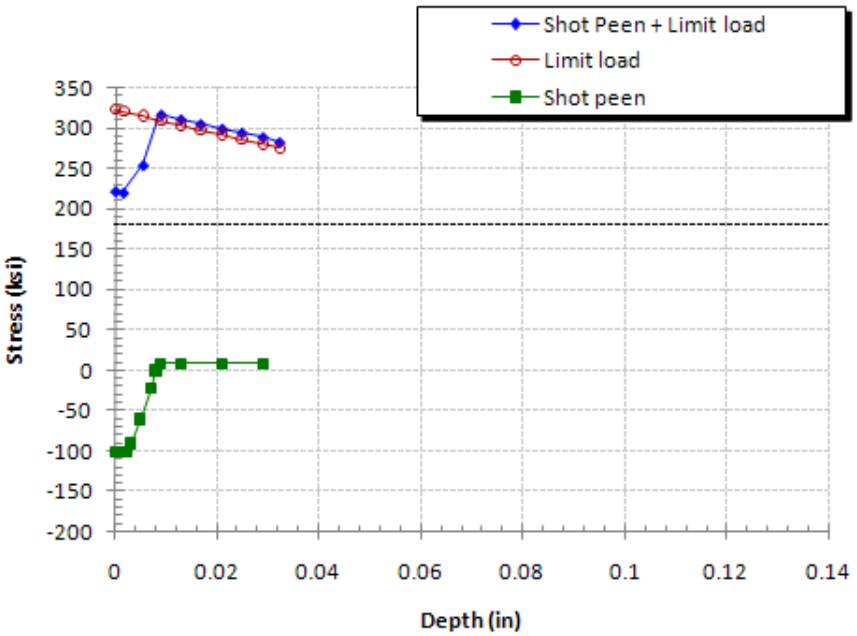
CURTISS WRIGHT Surface Technologies

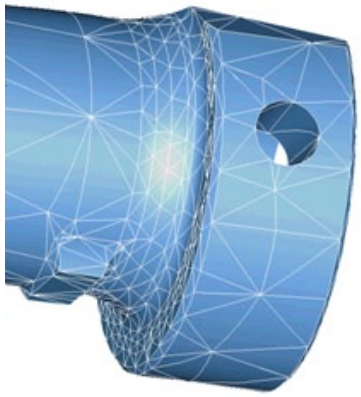
Laser peening for fatigue and forming

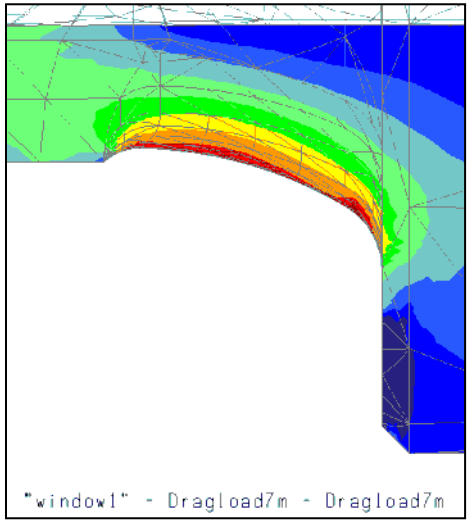
- Overview of process modeling
- Case studies in laser peening for fatigue
  - T45 hook
  - F35 hook
  - F-18 Y508 shear tie
- Laser peening for forming and form correction
  - Forming of integrally stiffened panels
  - Forming and correction of thin panels
- Program pay-off

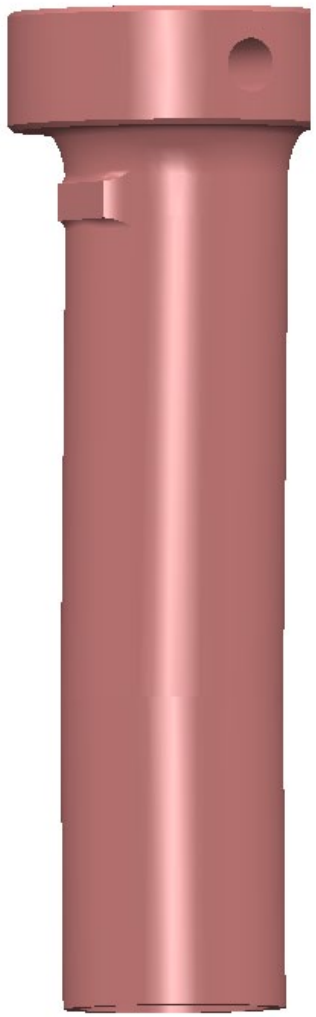
Case study: T45 hook shank

OEM provided elastic FEA data for the hook shank and a solid model



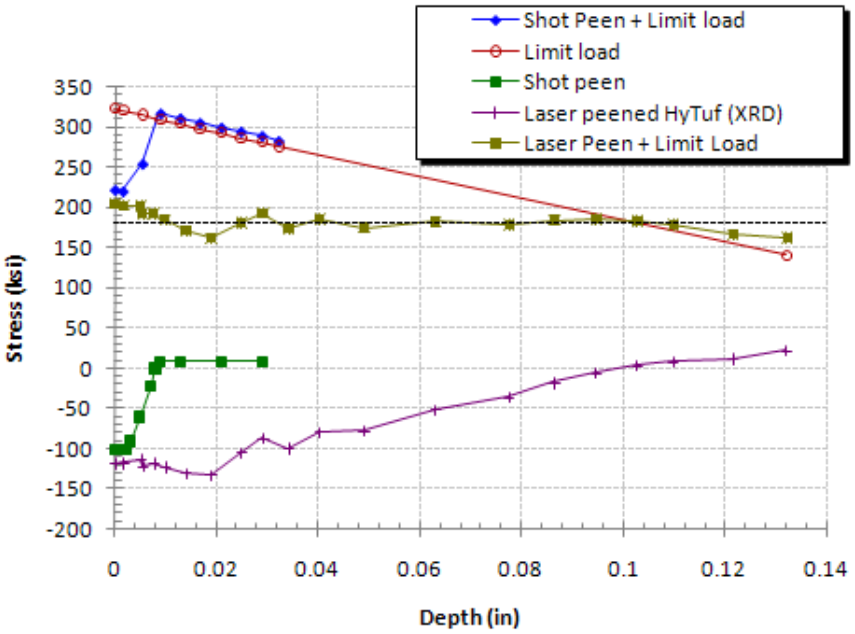


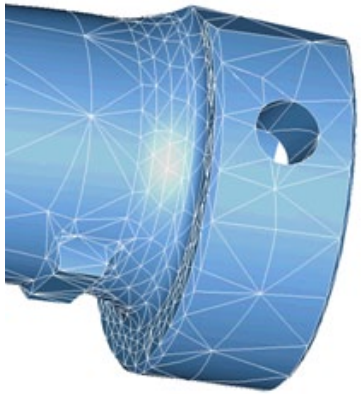


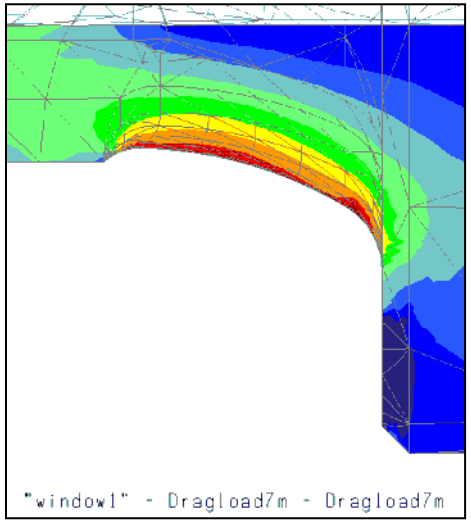


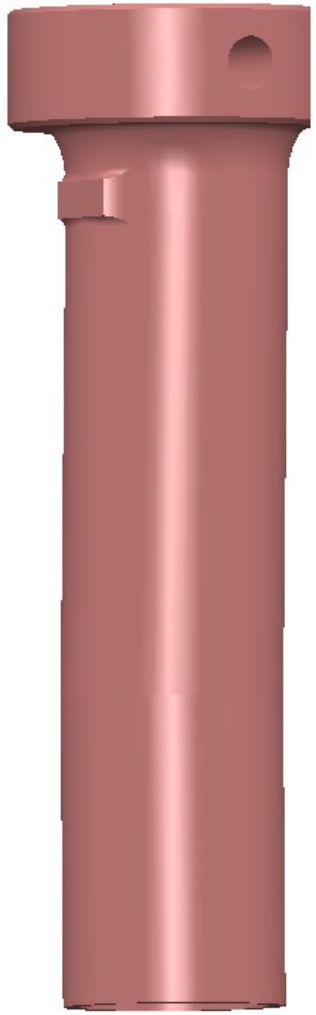
Case study: T45 hook shank

OEM provided elastic FEA data for the hook shank and a solid model





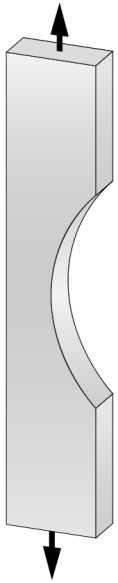




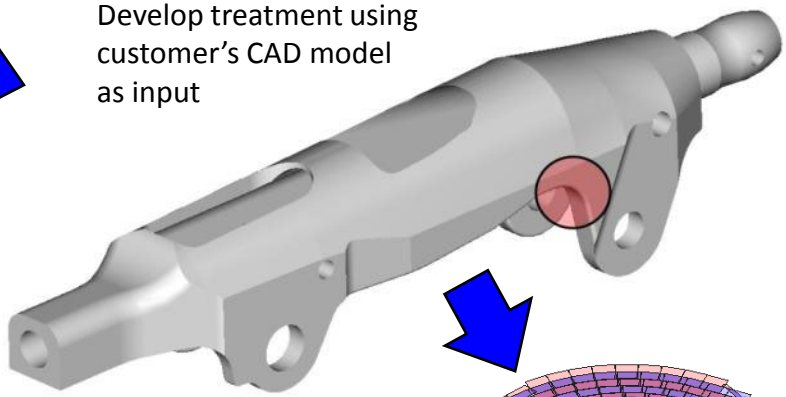
CURTISS WRIGHT
Surface Technologies

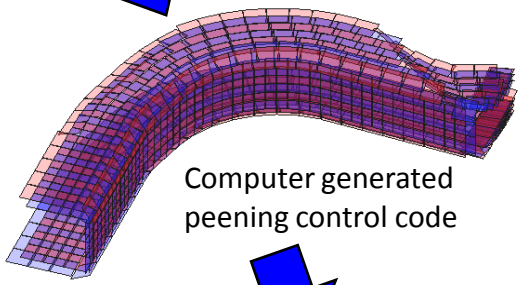
Modeling is integral for implementing laser peening

Testing of coupons in representative service condition

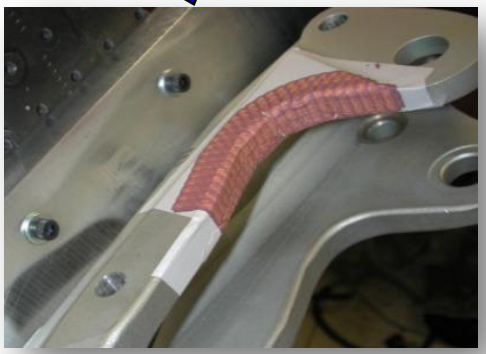


Develop treatment using customer's CAD model as input



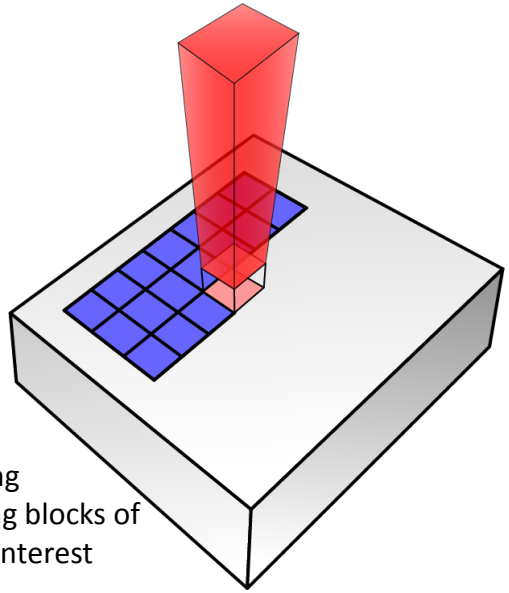


Computer generated peening control code



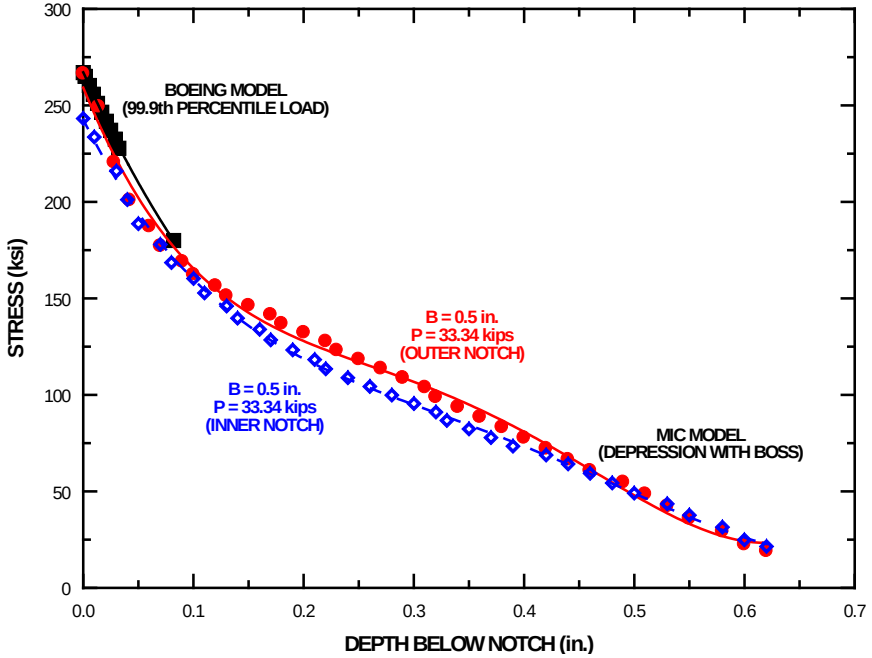
Treatment of actual components

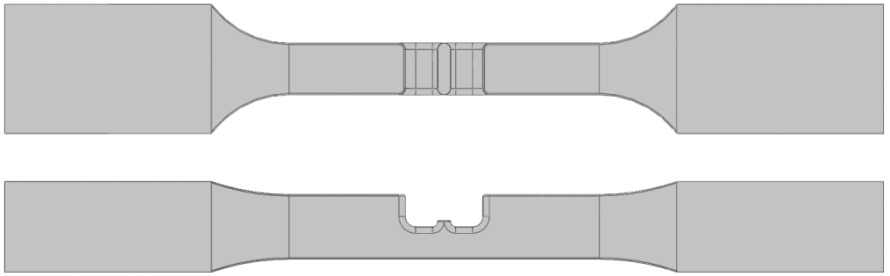
Validation testing of service components

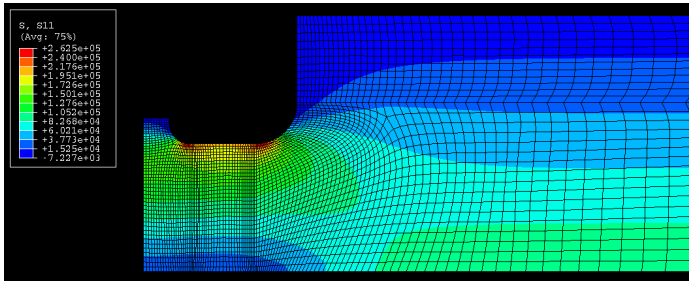


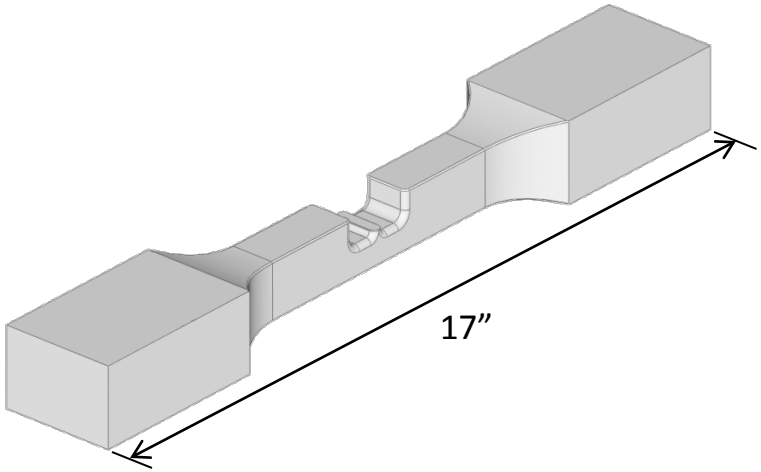
Establish peening parameters using blocks of the material of interest

Use finite element analysis to design a test coupon









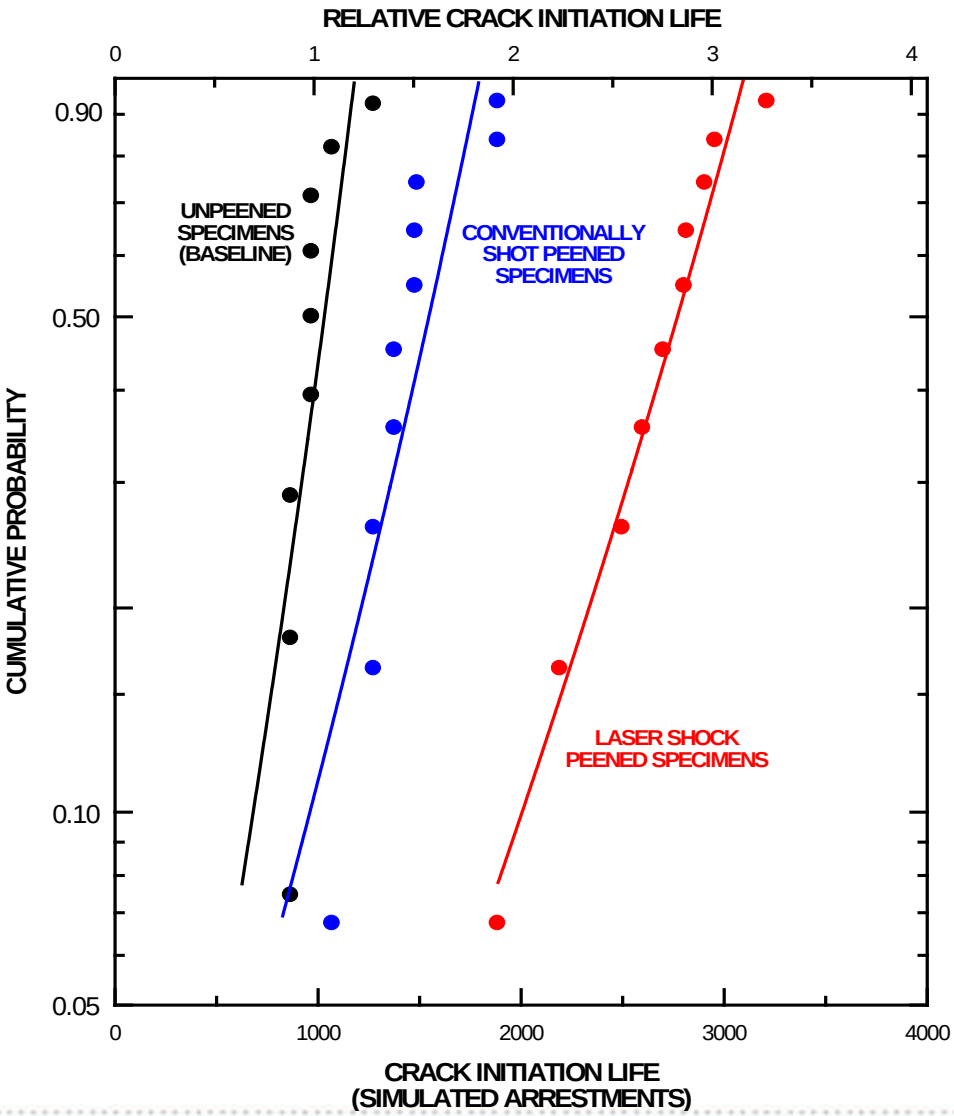
Coupon testing at NAVAIR - Pax River

- Tested at NAVAIR on a 100 kip fatigue frame with OEM provided load spectrum
- Each application of the spectrum represented 102 arrestments
- After each spectrum pass the coupon was examined under load and magnification for cracks
- Any visually detectable crack terminates the test

CURTISS WRIGHT Surface Technologies

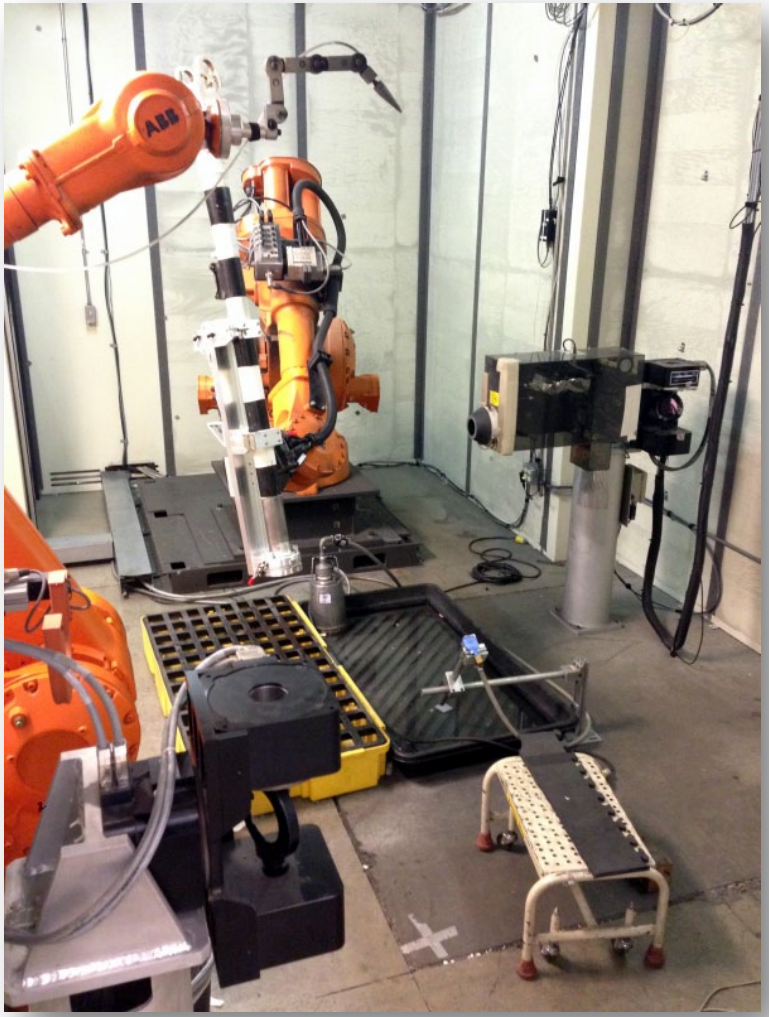
Fatigue results: LP gives 2.5x life improvement

- Performing S-basis estimate for crack initiation life results in:
  - 439 arrestments for unpeened (1x)
  - 423 arrestments for shot peened (0.97x)
  - 1102 arrestments for laser peened (2.5x)
- Analysis generalizes performance of large population of tests from limited testing



CURTISS WRIGHT
Surface Technologies

T45 hook shank is now in production in Livermore CA



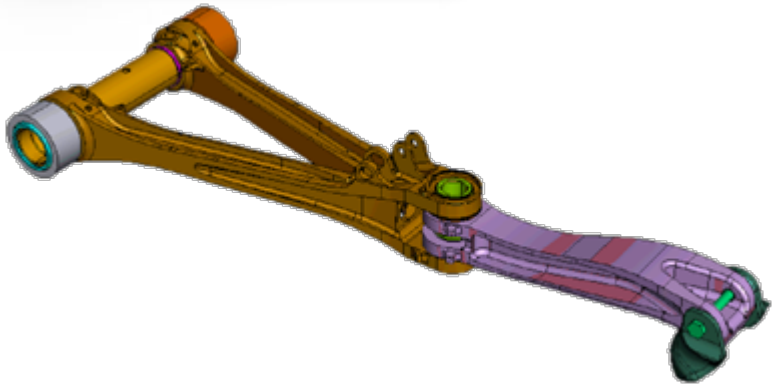
CURTISS WRIGHT Surface Technologies

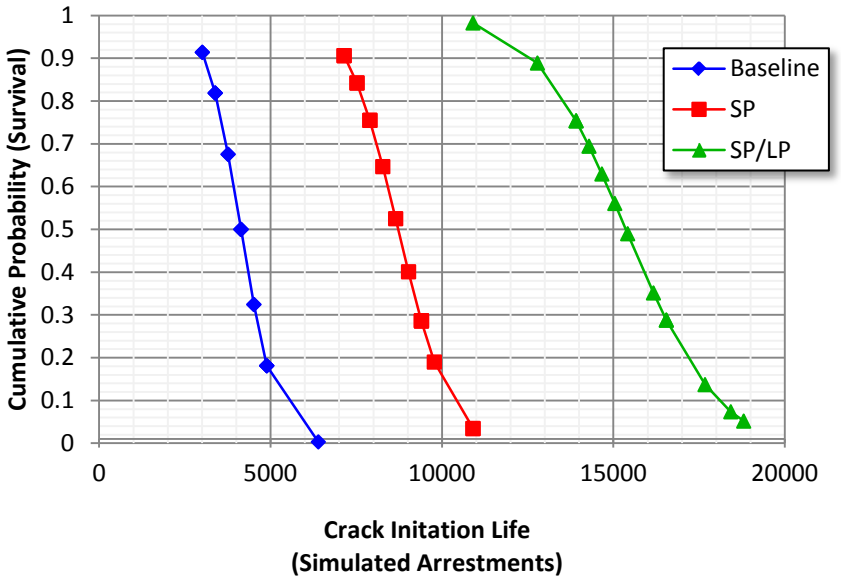
Laser peening for fatigue and forming

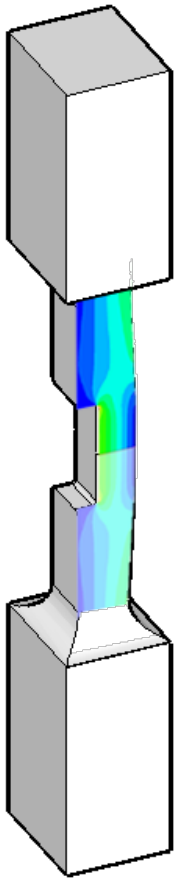
- Overview of process modeling
- Case studies in laser peening for fatigue
  - T45 hook
  - F35 hook
  - F-18 Y508 shear tie
- Laser peening for forming and form correction
  - Forming of integrally stiffened panels
  - Forming and correction of thin panels
- Program pay-off

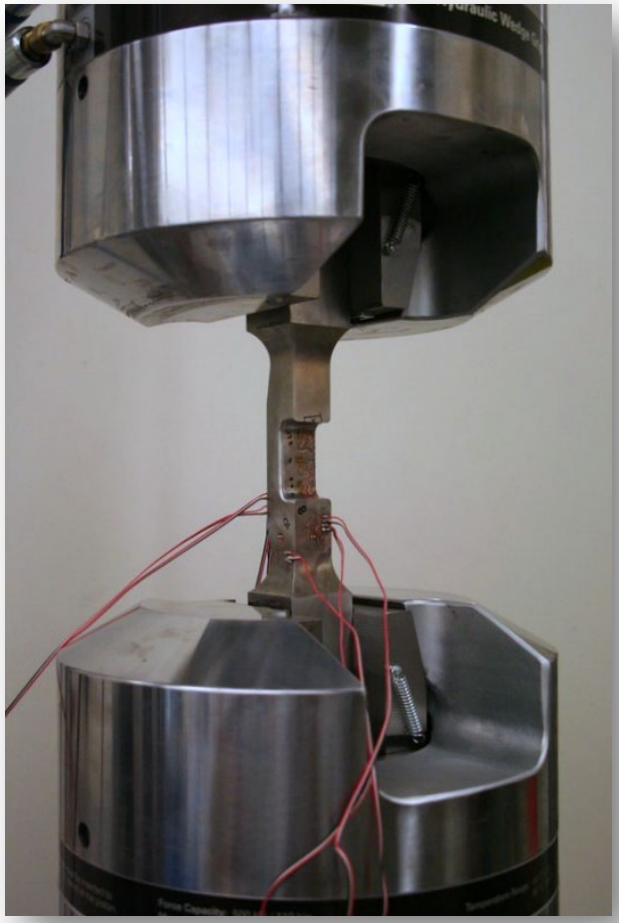
CURTISS WRIGHT Surface Technologies

Case study: F35 hook shank – T45 used as roadmap for program









NORTHROP GRUMMAN

LOCKHEED MARTIN

NAVAIR NAVAL AIR SYSTEMS COMMAND

STORK Fokker

CURTISS WRIGHT Surface Technologies

Laser peening for fatigue and forming

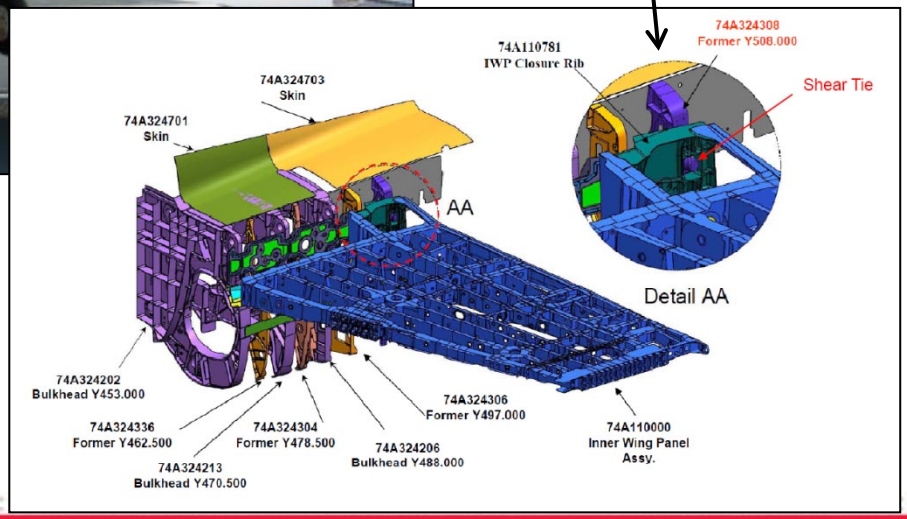
- Overview of process modeling
- Case studies in laser peening for fatigue
  - T45 hook
  - F35 hook
  - F-18 Y508 shear tie
- Laser peening for forming and form correction
  - Forming of integrally stiffened panels
  - Forming and correction of thin panels
- Program pay-off

CURTISS WRIGHT
Surface Technologies

Case study: F-18-Y508 Shear Tie is a fatigue life limit for useful lifetime of aircraft

Y508 former shear tie provides critical load transfer from wing to fuselage

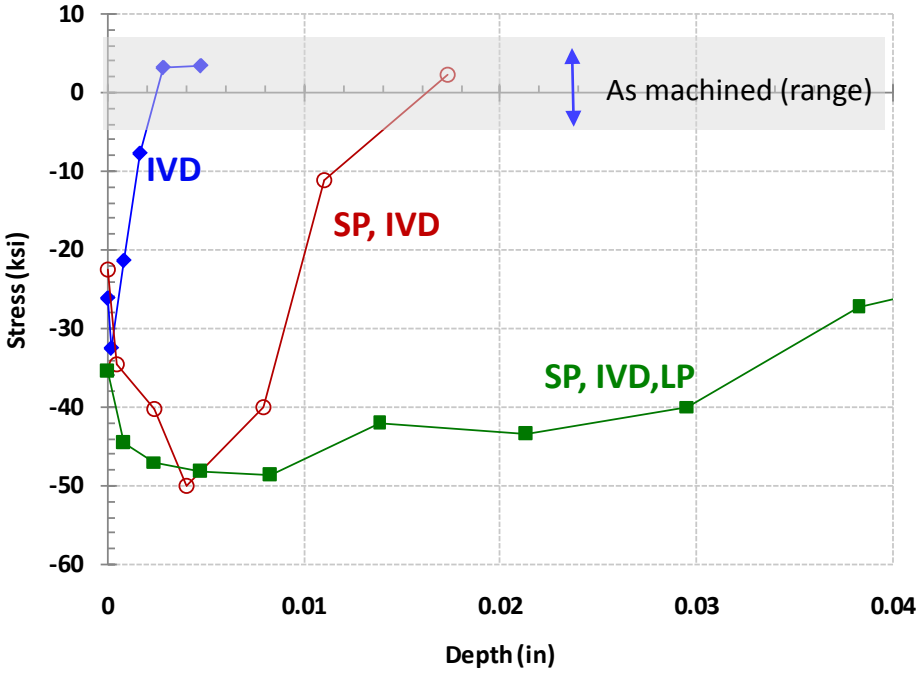
Replacing shear tie bulkhead has serious consequences for overhaul costs



Laser peening dramatically increases depth of compressive residual stress

- As-machined and surface pickled (per NAVAIR spec)
- Ion vapor deposition coating (IVD)
- Shot peen (SP)* then IVD coating (current Y508 treatment)
- Shot peen* IVD coating then Laser peen (LP)**

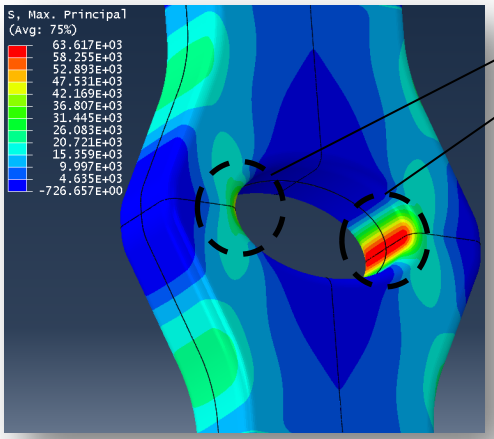
RS vs. depth for three post-treatment processes used on the Y508 coupons

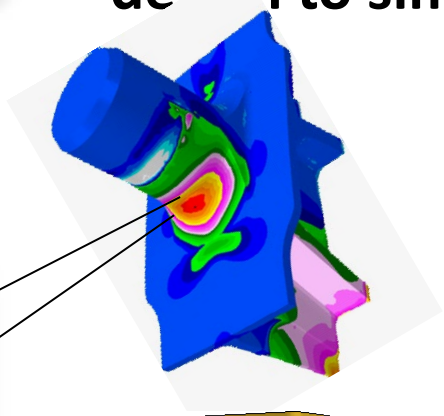


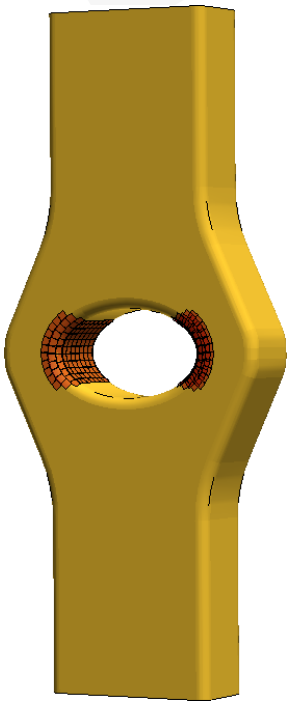
*Shot peen: per PS14023 at 0.006-0.010A intensity, 230-280 shot

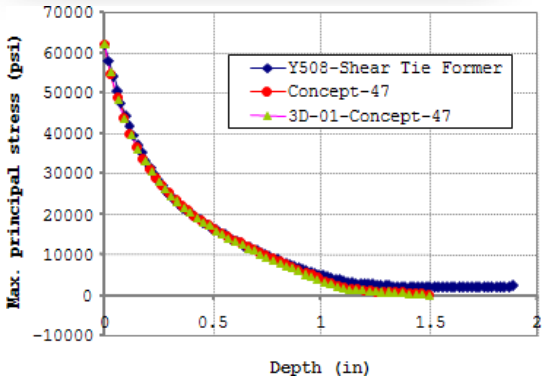
** Laser peen: 4GW/cm^2, 18ns, 3-layers, tape

We adopted a uniaxial “dual-sided” coupon design to simulate the shear tie hot-spot







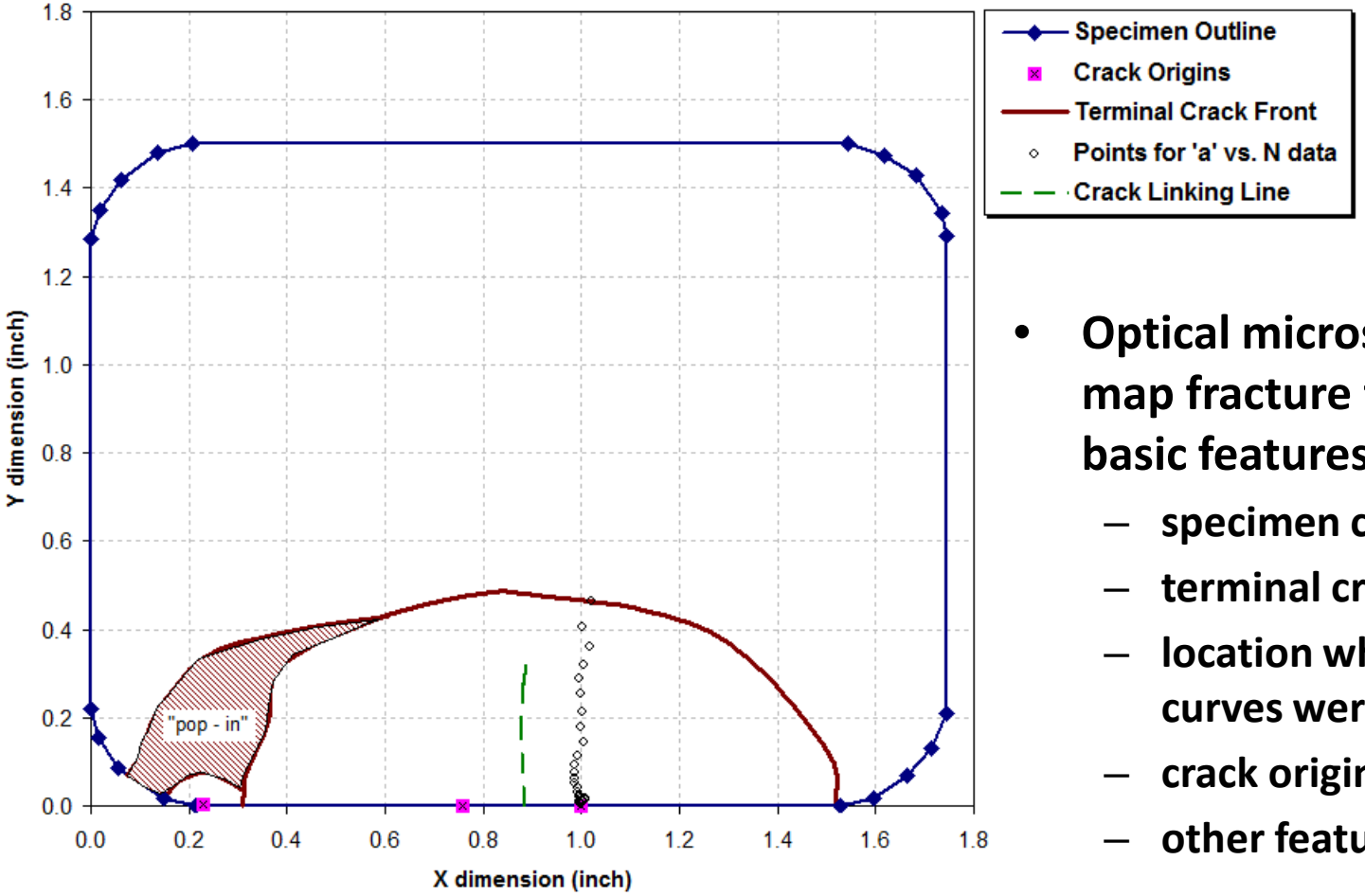


Benefits of dual-sided design

- Accurate simulation of shear tie compressive and tensile bending stresses (at surface and vs. depth)
- Relative ease of fabrication and post processing
- Modest displacement allows high test rate (~5-6Hz)
- Sufficient access for laser peening
- Symmetric uniaxial loading on fatigue test system

CURTISS WRIGHT
Surface Technologies

Fracture face mapping enables crack growth measurements



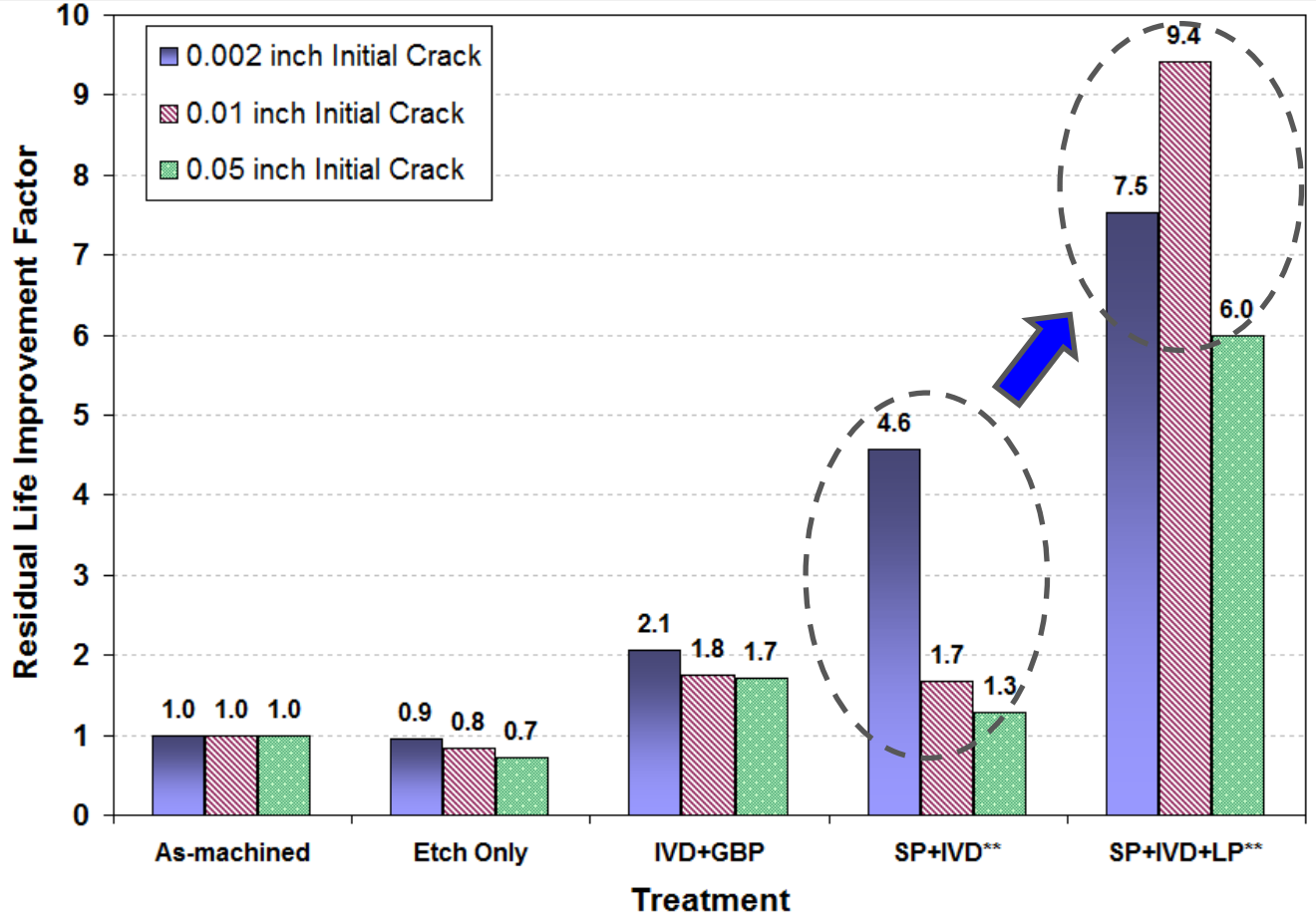
- Optical microscopy used to map fracture faces and show basic features
  - specimen cross-section
  - terminal crack front
  - location where crack growth curves were extracted
  - crack origins
  - other features of interest

APES, INC.
analytical processes / engineered solutions

CURTISS WRIGHT
Surface Technologies

Key result: **Without exception, laser peening offers significant life improvement over other processes**

Results from crack growth measurements:
Addition of LP to SP+IVD improves life by 1.6 to 5.5X over SP+IVD alone

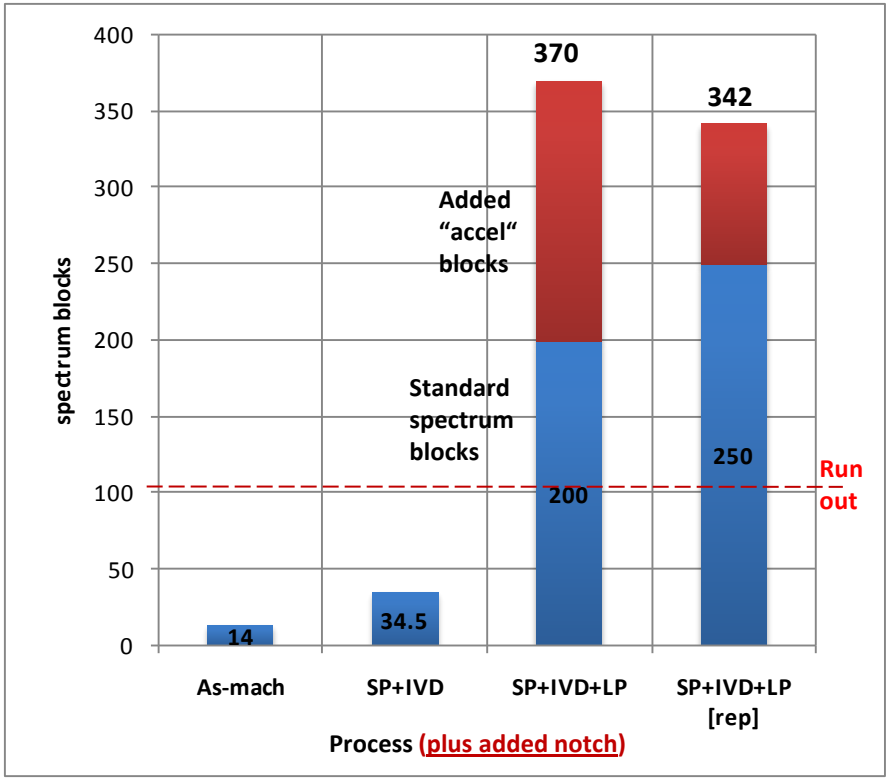


CURTISS WRIGHT Surface Technologies

Key result: LP offers dramatic fatigue improvement in the presence of flaws

Effect of added flaws

- Plunge EDM used to add a half-penny notch to coupon high stress regions
- Notches added after SP+IVD and LP
- Measurements by Mills (AP/ES) show notch planar dimensions are 0.0213" x 0.0103" (+/- ~0.0003").
- Laser peening improved fatigue life of notched coupons ~10X



CURTISS WRIGHT Surface Technologies

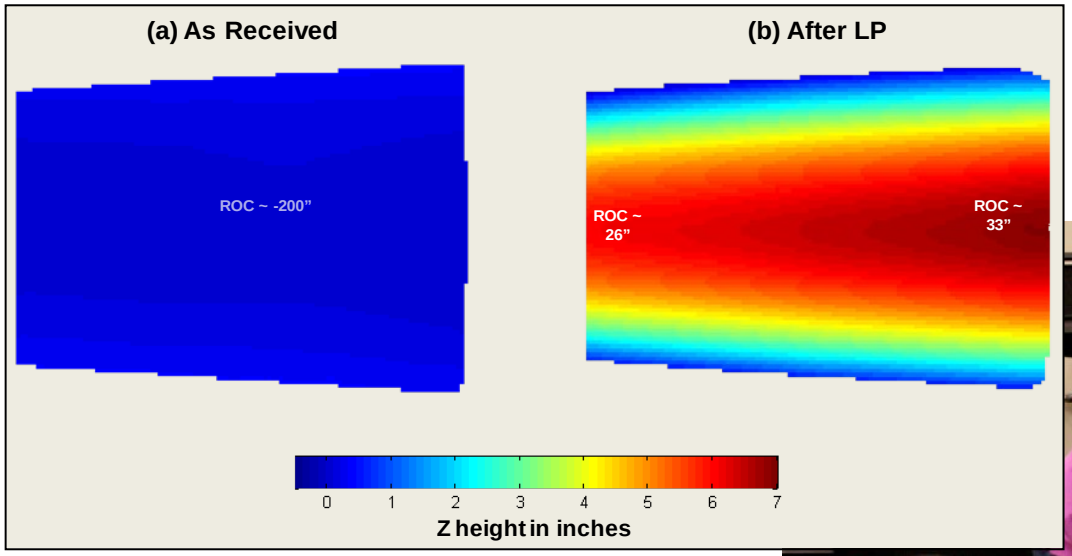
Laser peening for fatigue and forming

- Overview of process modeling
- Case studies in laser peening for fatigue
  - T45 hook
  - F35 hook
  - F-18 Y508 shear tie
- Laser peening for forming and form correction
  - Forming of integrally stiffened panels
  - Forming and correction of thin panels
- Program pay-off

Case study: Laser-peen-forming (LPF) integrally stiffened panels

- Curtiss Wright was funded by the US Air Force* to demonstrate laser-peen-forming integrally stiffened panels.

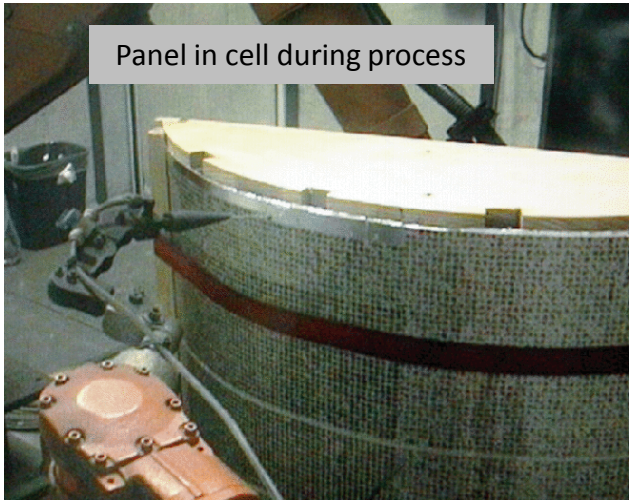
Example of laser peen forming a flat integral-stringer panel into conical shape



Contour plots show the panel shape (a) before and (b) after LP.

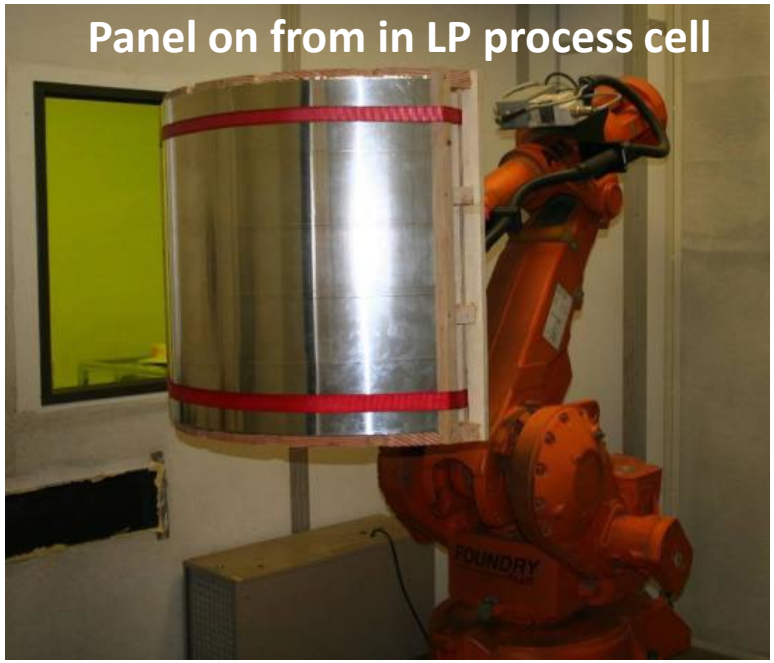
* AFMC AFRL/RXMP : Project oversight Howard Sizek

Simple tooling and fixtures enable rapid demonstration and proto-typing



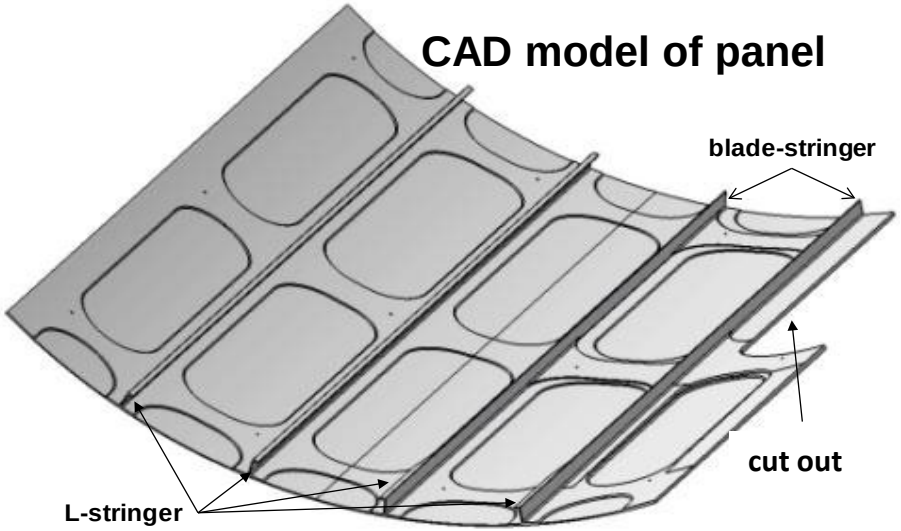
Wood forms offer several advantages:

- Low cost
- High strength
- Light weight
- Rapid fabrication
- Easily modified/adapted



Case Study: LP forming integrally stiffened panel with reinforced cut-out

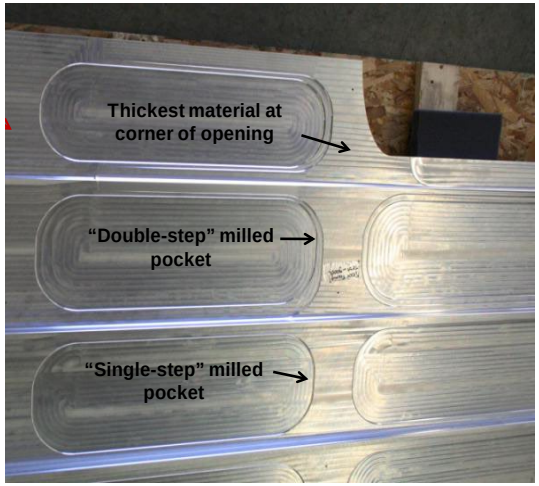
CAD model of panel



Goal: LP form panel to cylindrical shape (40” ROC)

As-received panel

Panel has significant stiffener thickness variations around the cut-out



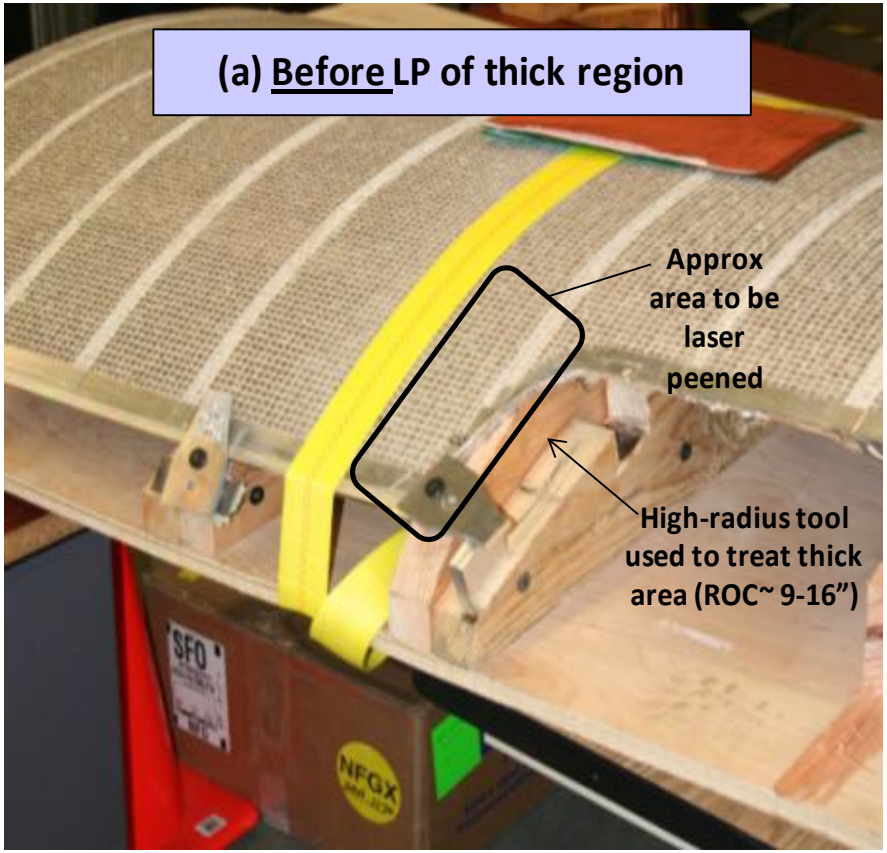
“Cut-out” panel ready for LP

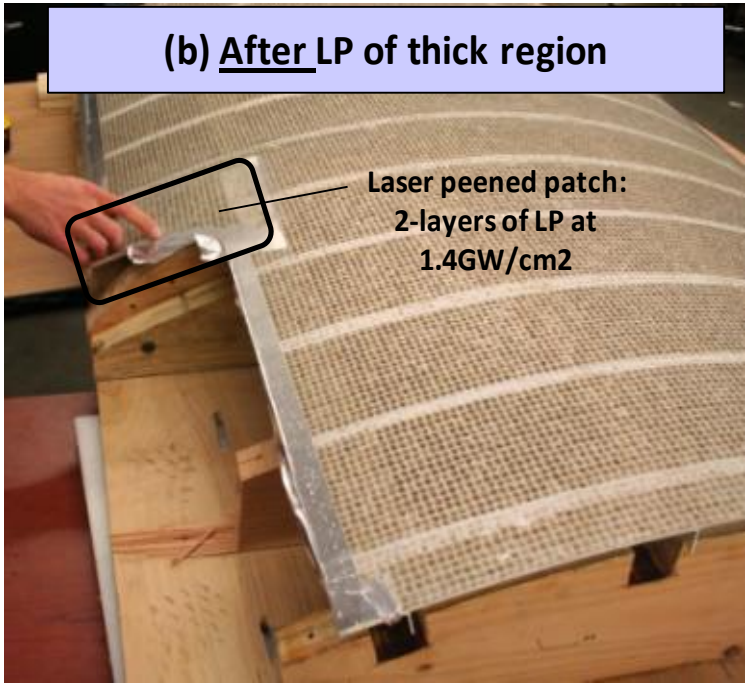
Panel material:
Aluminum 2024-T351

Top-half peened first, then bottom-half

CURTISS WRIGHT Surface Technologies

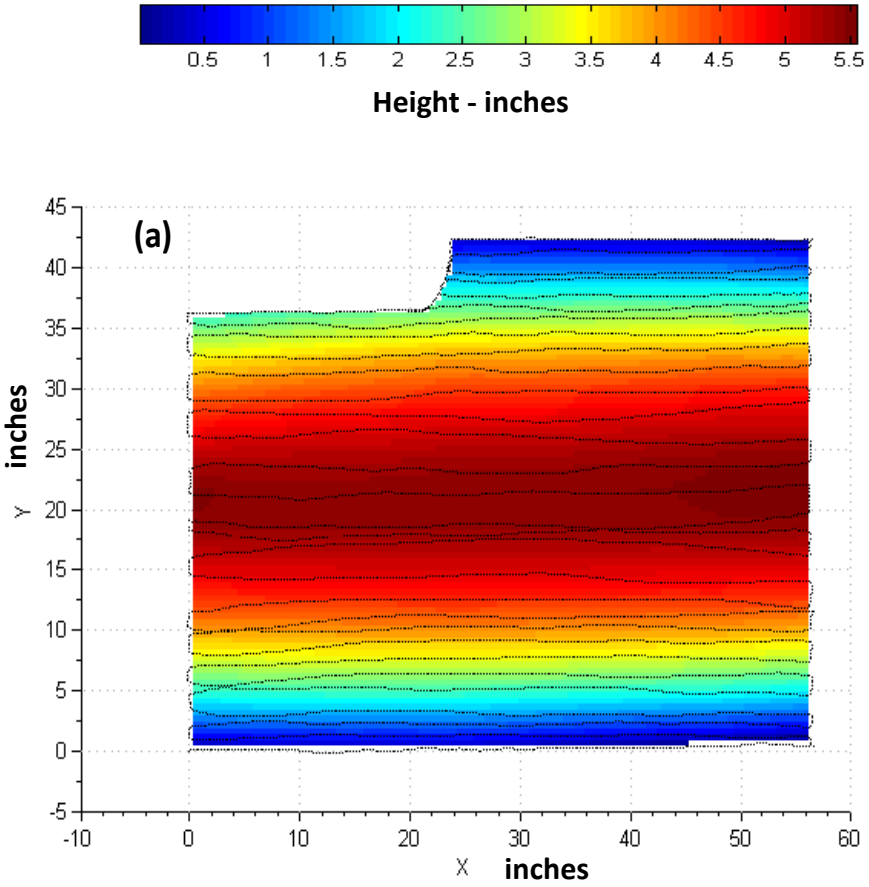
LP of thicker material near the cut out



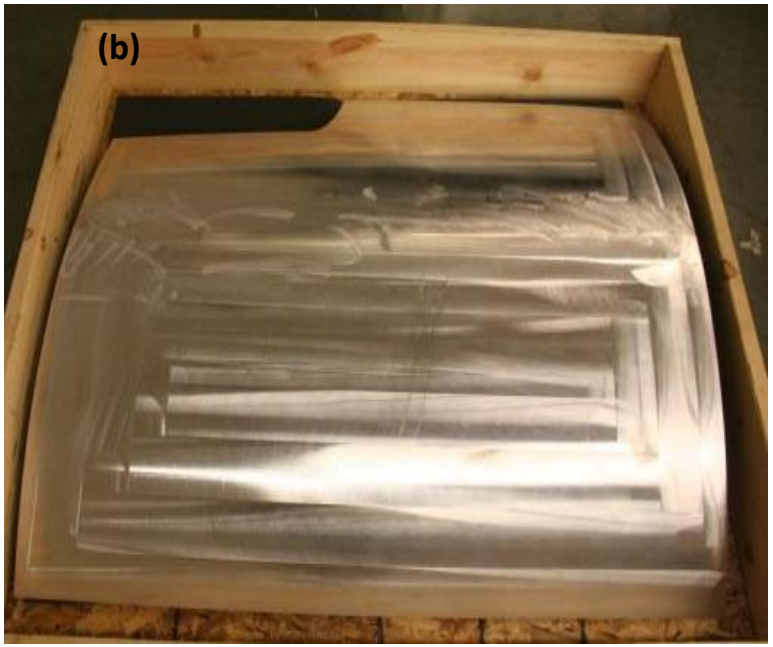


Again note the use of simple, low cost, fixtures enabling rapid proto-typing with LP forming

ISP panel with cut-out after LP forming



In shipping box and ready to ship to customer

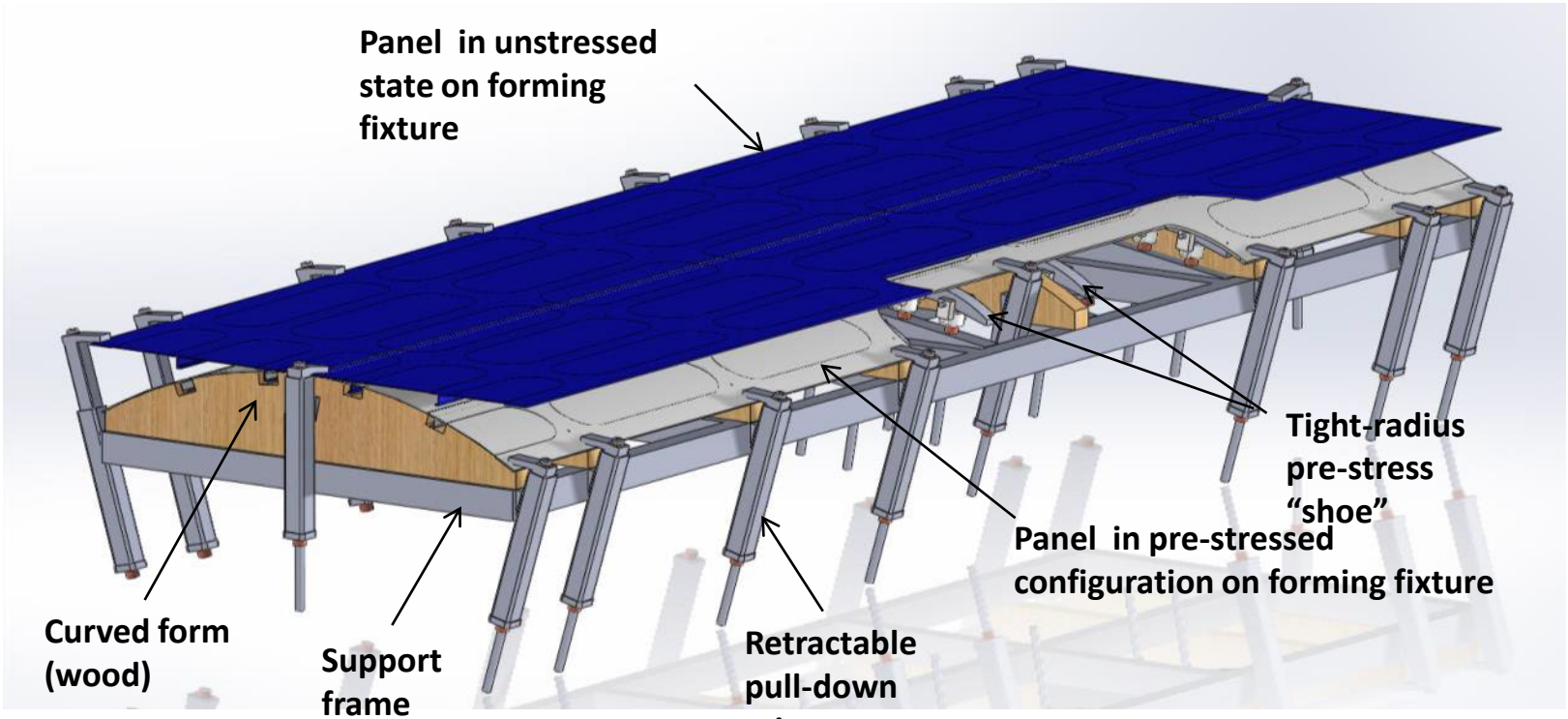


CURTISS WRIGHT Surface Technologies

MIC evaluated scale-up of LP forming cut-out panels

GOAL: Demo low-cost, rapid prototype forming of full scale IS panels

Prototype panel nominally 12' x 4'



CURTISS WRIGHT Surface Technologies

LP forming IS panels: conclusions

- Laser peen forming has been demonstrated to custom-shape integrally stiffened panels (ISP) for advanced aircraft fabrication.
- Panels containing L, J or T types of stringers as well as stiffened pocket regions were supplied by OEM's with specific advanced forming applications and goals.
- This work lead to our contact with Chris Root at NAVAIR FRC-SW

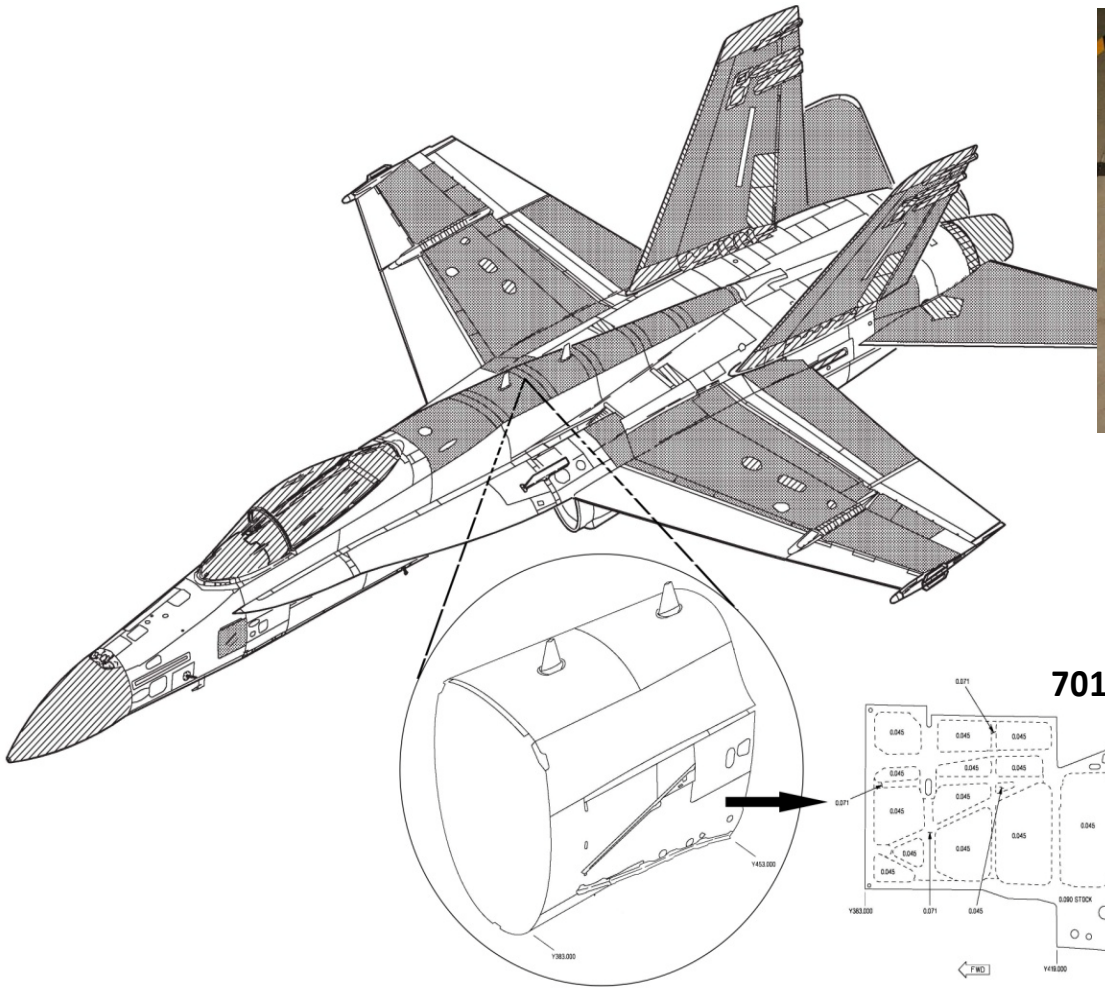
In 2012 NAVAIR inquired about LP corrective-forming of 701 fuselage skin panels on the F-18

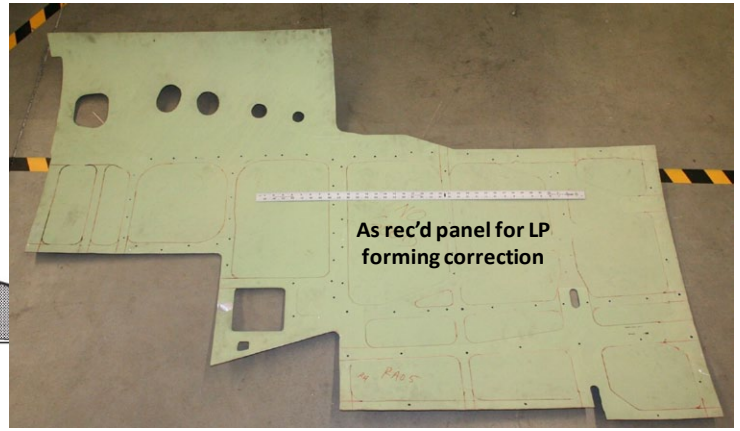
CURTISS WRIGHT Surface Technologies

Laser peening for fatigue and forming

- Overview of process modeling
- Case studies in laser peening for fatigue
  - T45 hook
  - F35 hook
  - F-18 Y508 shear tie
- Laser peening for forming and form correction
  - Forming of integrally stiffened panels
  - Forming and correction of thin panels
- Program pay-off

A number of F-18 701 skins require form correction



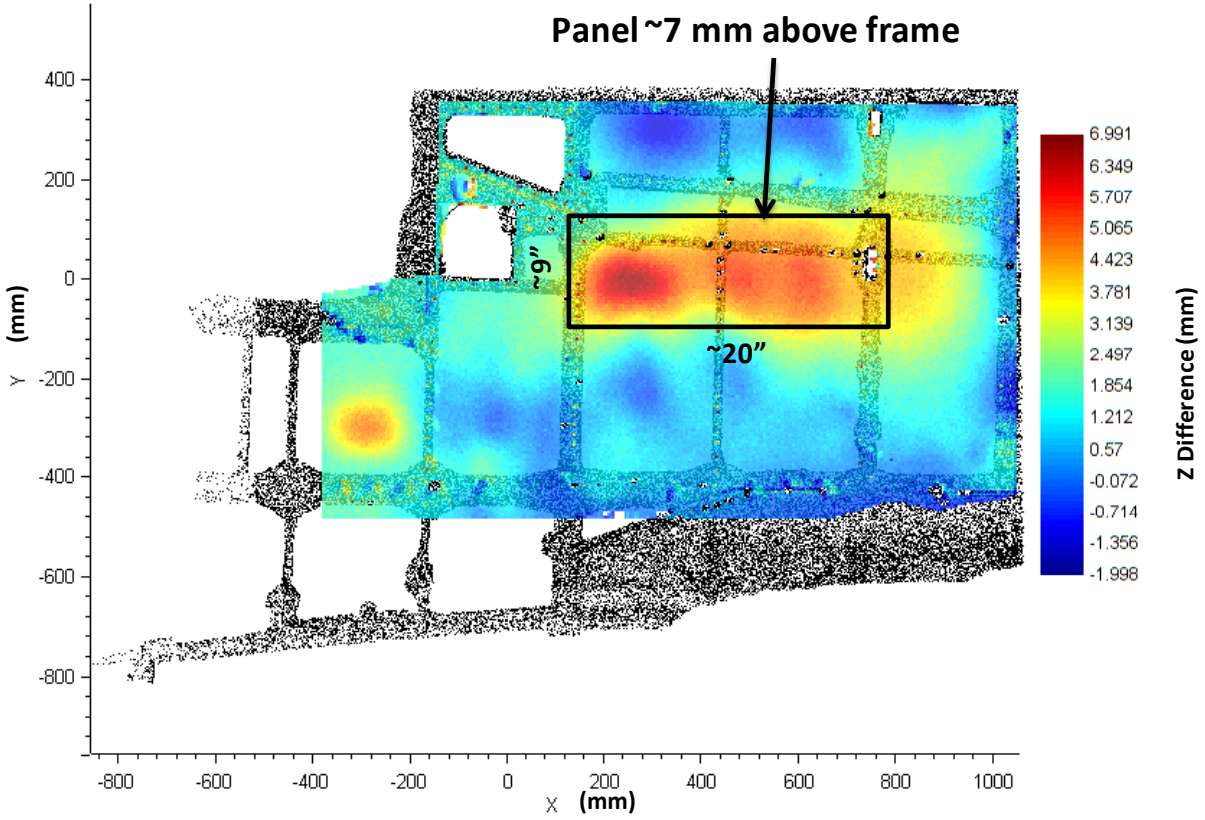


701-skin

CURTISS WRIGHT
Surface Technologies

MIC has worked with NAVAIR to quantify skin shape departure

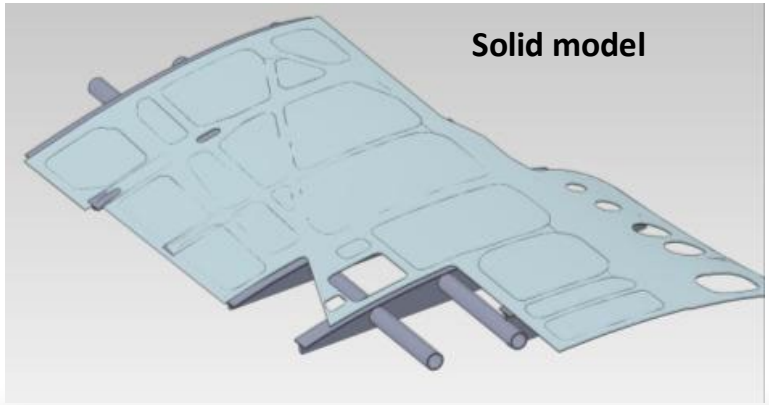
Example of one skin that was carefully characterized, showing typical departures



CURTISS WRIGHT
Surface Technologies

Test skins have been received at MIC and were the focus of the NCMS contract effort

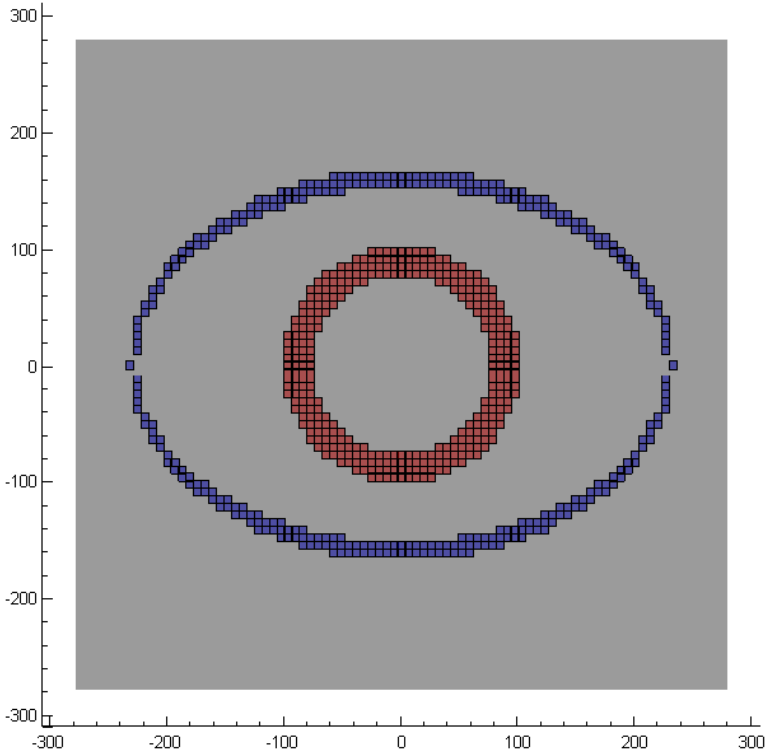
(a) Check fixture



(b) Panel installed on fixture

A model was needed to simulate LP response of thin panels

- 22”x22” square 0.09” thick Al7075 panel
- Initially flat (measured spherical curvature of R~1500”)
- Generate a LP pattern which produces an asymmetric depression >0.1”
  - Utilize separated narrow LP rings to minimize shots

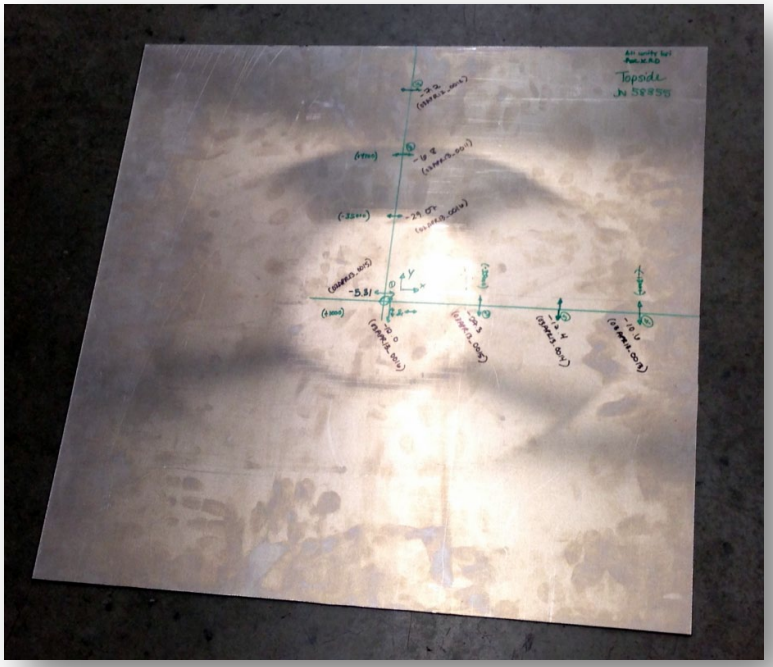


Red = IML peening – 332 shots
Blue = OML peening – 322 shots

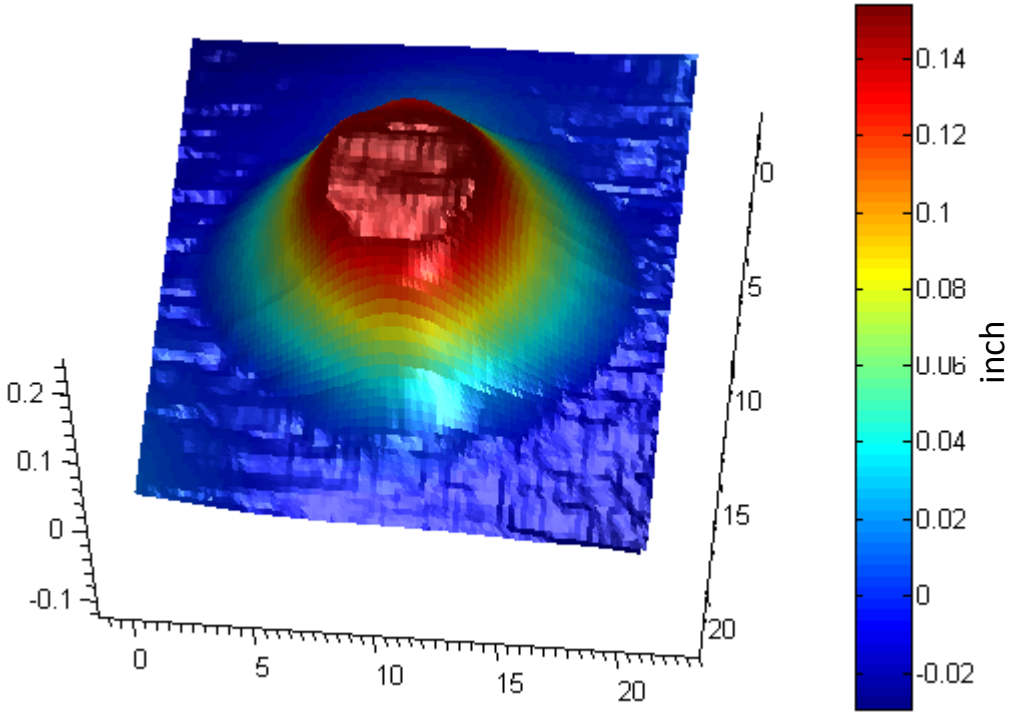
Panel will move towards the IML

CURTISS WRIGHT
Surface Technologies

Forming demonstration tested the model - 22” x 22” panel



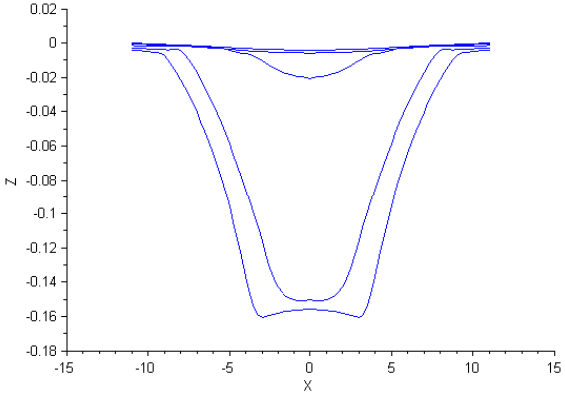
22” x 22” panel after laser peening



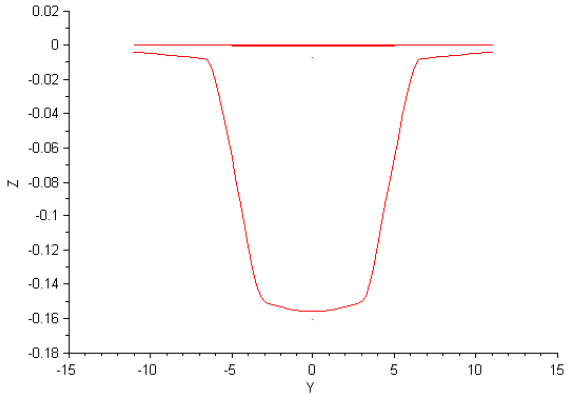
Experimentally scanned shape after laser peening

FEA results matched measurement well

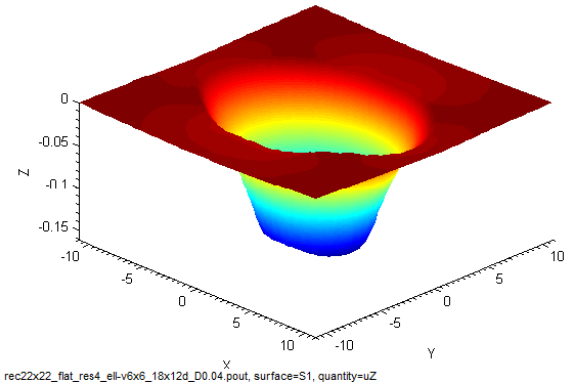
FEA simulation result



Y-profiles

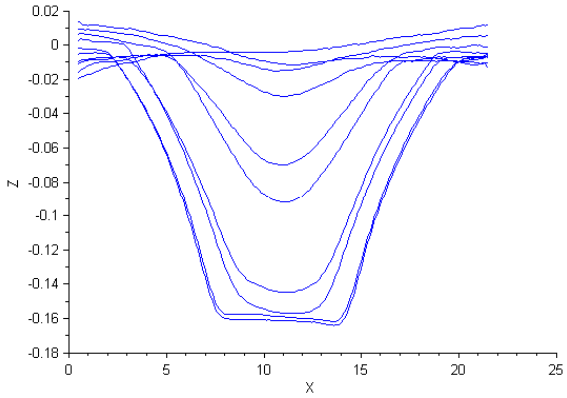


X-profiles

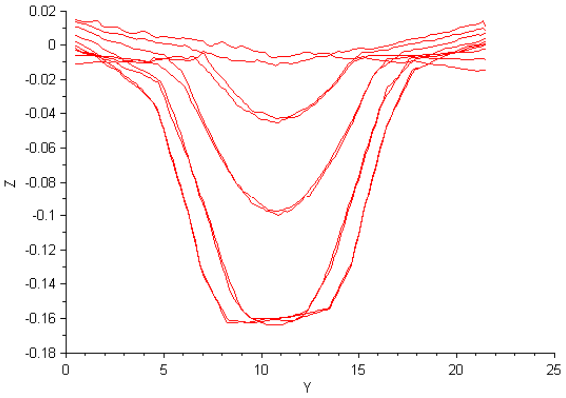


3-d contour

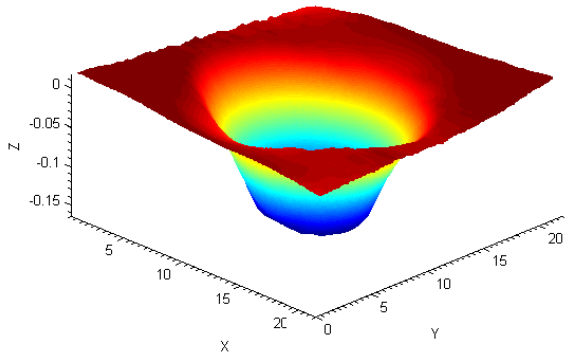
Experimental measurement



Y-profiles

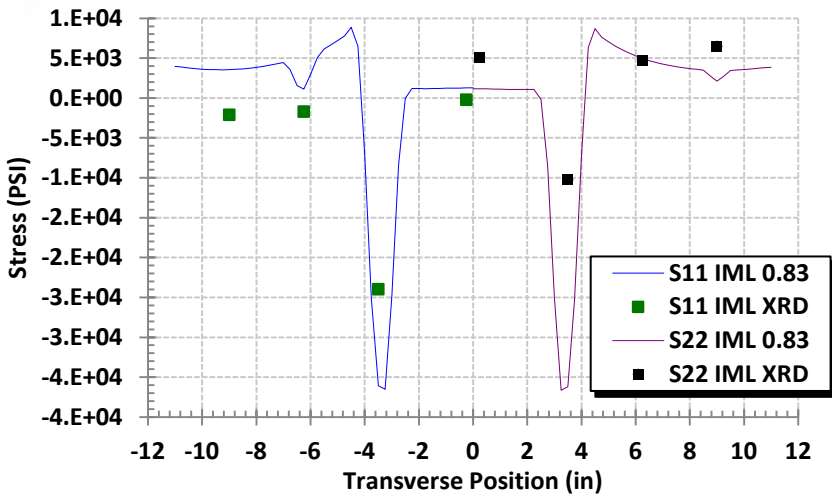


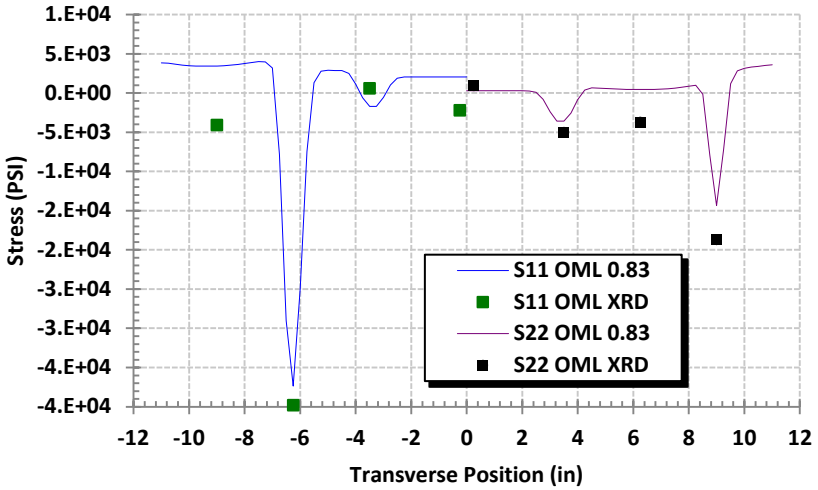
X-profiles

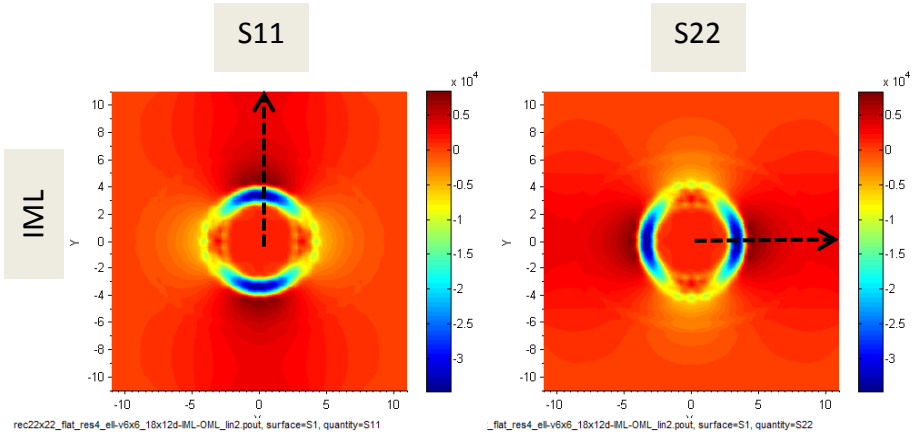


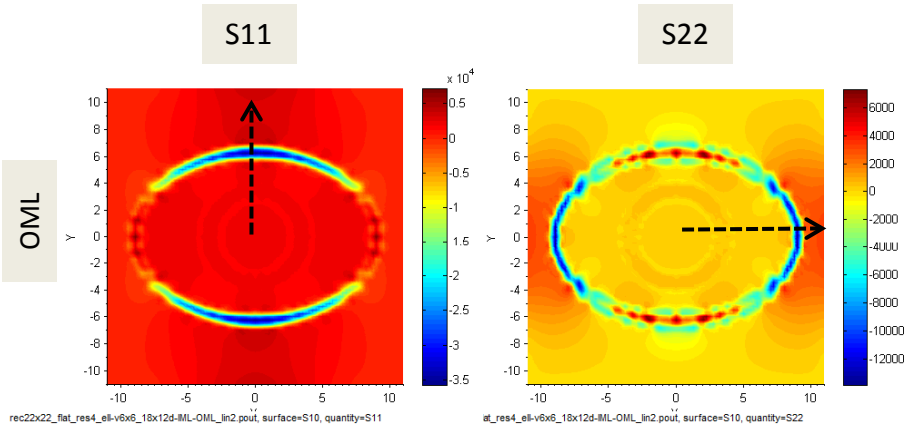
3-d contour

Surface stress (XRD) is consistent with model predictions









CURTISS WRIGHT Surface Technologies

Laser peening for fatigue and forming

- Overview of process modeling
- Case studies in laser peening for fatigue
  - T45 hook
  - F35 hook
  - F-18 Y508 shear tie
- Laser peening for forming and form correction
  - Forming of integrally stiffened panels
  - Forming and correction of thin panels
- Program pay-off

CURTISS WRIGHT Surface Technologies

The OSD cost-shared 701 skin program has had high pay-off

- Military examples:
  - Better understanding of IS panel forming
  - F15 tail actuator
  - F15 speed brake
  - A10 re-winging
  - AH-64 tail mounts
  - CH-47 side frames
  - F35 floor panel

- Commercial applications:
  - Gas turbine hardware
  - Nuclear reactor weld mitigation
  - Passenger-to-freighter conversion
  - Low-cost manufacture of limited production panels (retrofits, prototypes)