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Measurements Sub-group Update

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Topics for Today

Measurements of stress at Legacy vs New CX holes (HE)

Measurements of Stresses at Cracked CX Holes (Carlson)

Recent Near-surface Stress Measurements (Castle)

Recent Near-bore Stress Measurements (HE)

Concept for Large Hole Experiments (HE)

Recent Cross-method Residual Stress Validations

- LSP, Al 7050T7451
- Die forgings, Al 7085-T74 and 7085-T7452

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Measurements Sub-group Update

Legacy vs New CX Residual Stress Evaluations

Legacy vs New CX Residual Stress Evaluations

Purpose: Compare coldworked holes from legacy assets to new manufactured coupons

- Legacy assets were all high hour wings and had mixed usages

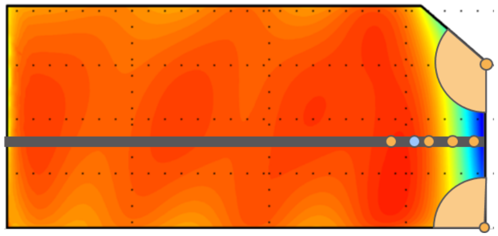
Performed ~200 measurements in teardown assets from 2 USAF aircraft types

- All assets had significant flight history

Performed ~100 measurements in new manufactured coupons

- That match geometry and materials in teardown assets

For each measurement complied:

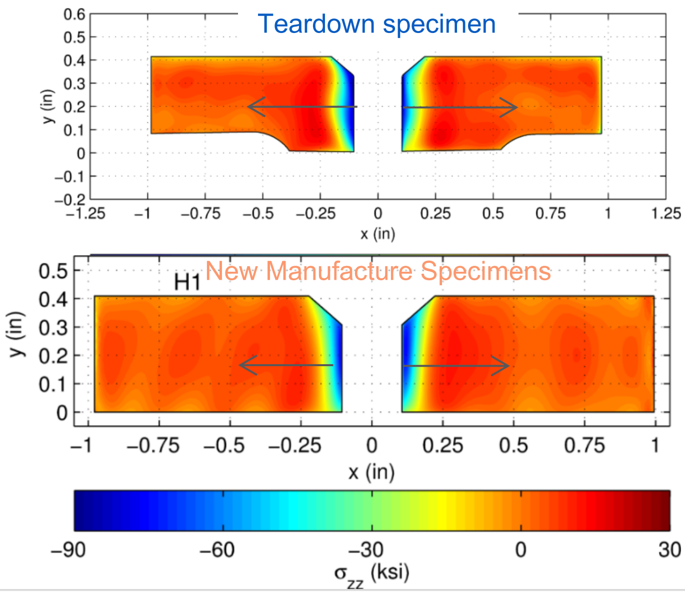


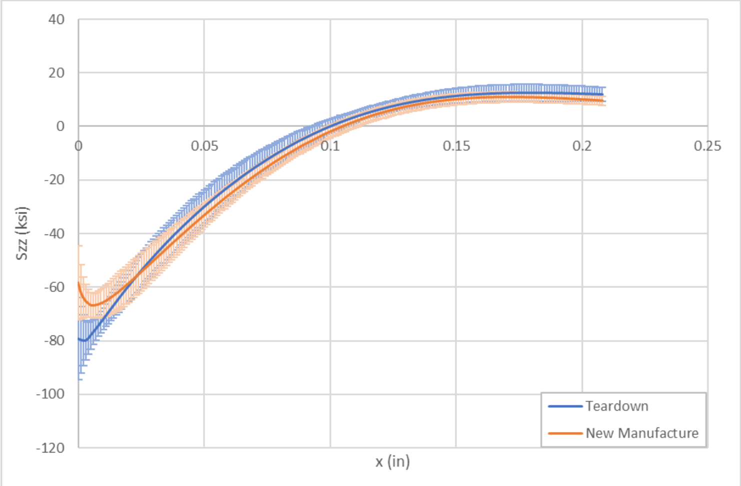
- Contour plot of residual stress
- Line plot of mid-thickness residual stress
- Tabulation of stress field characteristics
  - Stress at specific normalized distances: 0.125*r, 0.25*r, 0.50*r, 0.75*r
  - Depth of zero-crossing
  - Separate for LH and RH side, where geometry is different
  - Mean and standard deviation within 0.050” radial zone centered at:
    - Entry surface
    - Exit surface / countersink knee (if applicable)

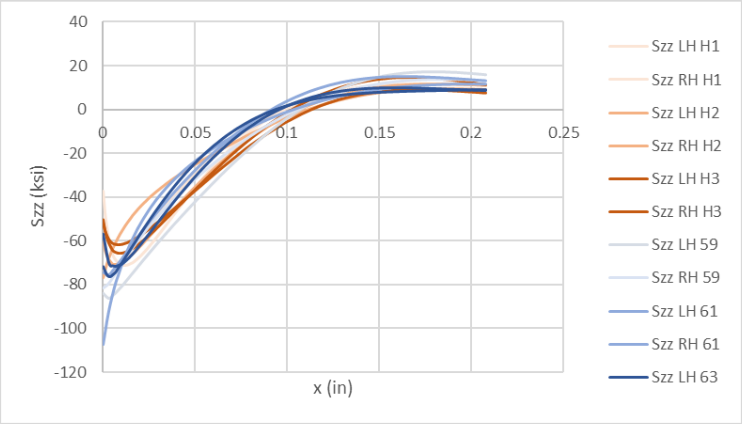
For each group of similar holes characterize differences:

- Statistical analysis: compare means and standard deviations
- Spatial field difference: Contour plots of difference between means of new manufacture and teardown

Legacy vs New CX Comparison #1

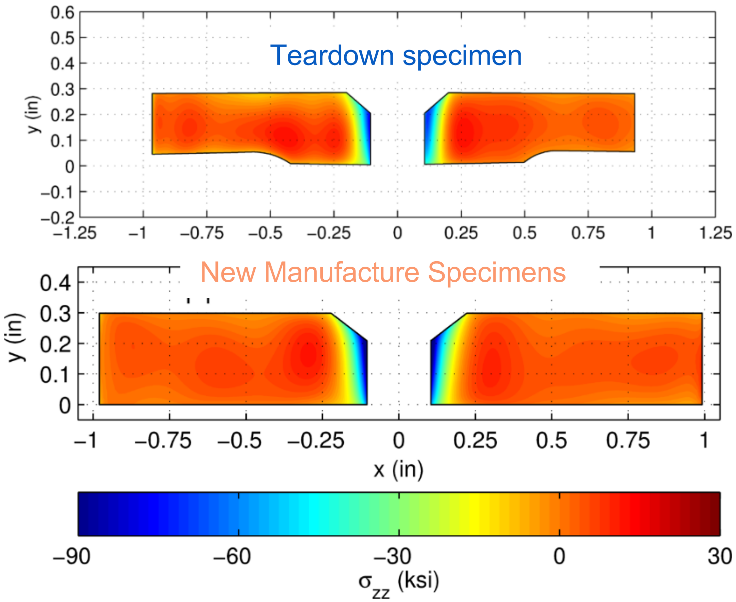


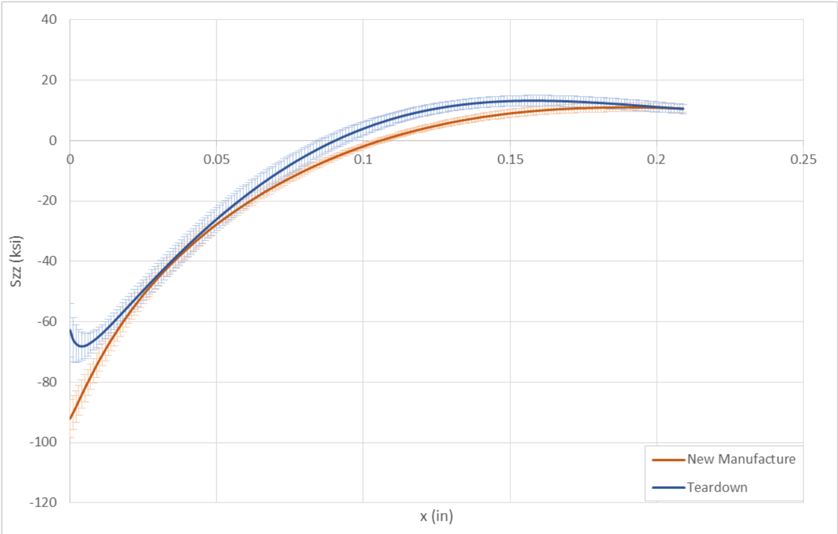


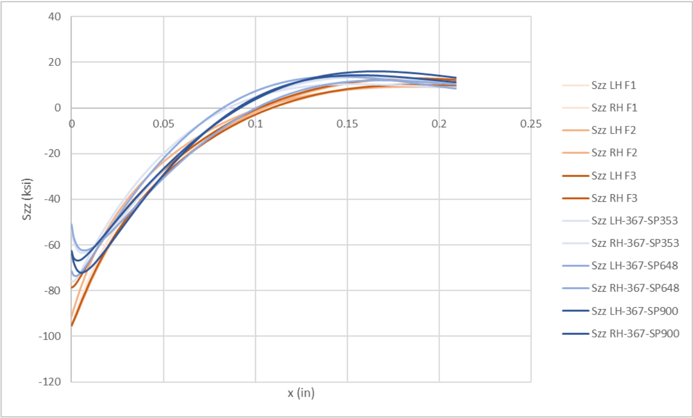


Sample ID	Midthickness 0.125*rad	Midthickness 0.25*rad	Midthickness 0.5*rad	Midthickness 0.75*rad	Depth at crossover (midthickness)	Point Value of Entrance	Avg RS in 0.05" Radius Entrance	Standard Deviation of Avg RS in 0.05" Radius CSK Entrance	Point Value CSK Knee	Avg RS in 0.05" Radius CSK knee	Standard Deviation of Avg RS in 0.05" Radius CSK Knee
L-59	-75.54	-62.37	-38.23	-17.06	0.11	-41.55	-42.52	12.53	-64.33	-67.77	8.86
R-59	-64.36	-50.39	-28.75	-12.05	0.11	-64.08	-30.42	14.86	-71.14	-54.33	12.20
L-61	-62.45	-48.14	-24.19	-5.89	0.09	-28.52	-34.95	9.23	-63.39	-59.91	10.61
R-61	-60.65	-41.99	-20.82	-7.91	0.10	-39.61	-33.14	13.49	-76.55	-60.63	14.44
L-63	-66.68	-53.25	-26.83	-7.67	0.10	-14.52	-37.40	8.14	-62.45	-61.08	10.12
R-63	-63.46	-46.85	-20.96	-5.06	0.09	-35.68	-34.90	11.51	-69.72	-56.33	13.47
L-H1	-65.31	-50.67	-26.36	-8.31	0.10	-20.19	-35.79	8.86	-62.90	-58.60	10.04
R-H1	-70.67	-60.17	-31.85	-9.90	0.10	-39.71	-33.49	9.47	-41.25	-62.40	8.67
L-H2	-50.49	-38.61	-23.31	-11.22	0.11	-34.93	-28.68	9.45	-69.66	-51.47	10.46
R-H2	-67.34	-55.92	-32.30	-13.30	0.11	-22.62	-35.97	9.23	-53.31	-66.29	8.02
L-H3	-60.45	-53.04	-34.46	-16.40	0.11	-40.85	-36.05	8.28	-57.51	-56.82	5.93
R-H3	-64.40	-55.64	-33.52	-13.27	0.10	-23.61	-32.05	6.60	-50.19	-65.40	8.68
Mean	**-65.52**	**-50.50**	**-26.63**	**-9.27**	**0.10**	**-37.33**	**-35.56**	**11.63**	**-67.93**	**-60.01**	**11.62**
Stdev	**4.84**	**6.32**	**5.93**	**4.12**	**0.01**	**14.94**	**3.76**	**2.33**	**5.03**	**4.23**	**1.94**
Mean	**-63.11**	**-52.34**	**-30.30**	**-12.07**	**0.11**	**-30.32**	**-33.67**	**8.65**	**-55.80**	**-60.17**	**8.63**
Stdev	**6.43**	**6.79**	**4.05**	**2.62**	**0.01**	**8.44**	**2.68**	**1.00**	**9.08**	**5.15**	**1.47**
Residuals (Td-NM)	**-2.41**	**1.84**	**3.67**	**2.79**	**-0.01**	**-7.01**	**-1.88**	**2.98**	**-12.13**	**0.16**	**2.98**

Legacy vs New CX Comparison #2

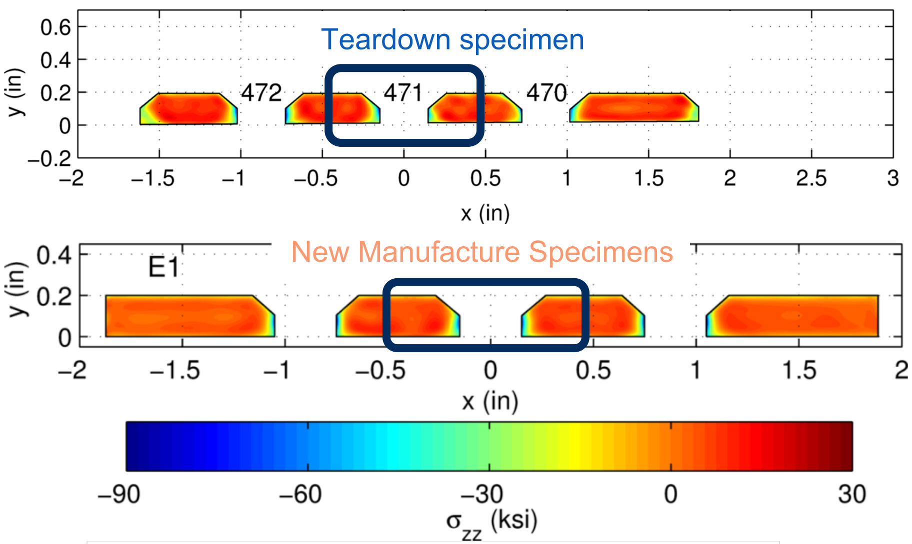


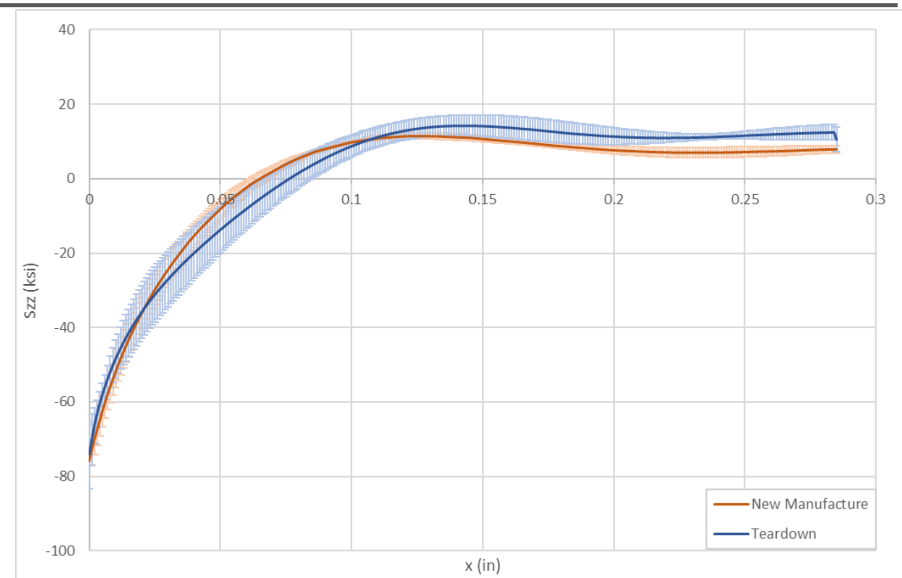


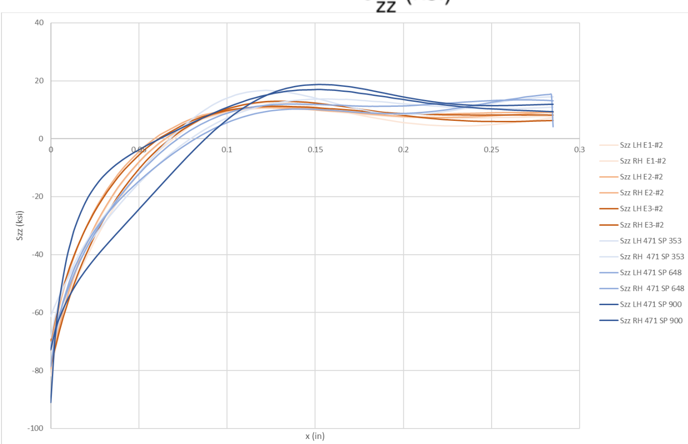


Sample ID	Midthickness 0.125*rad	Midthickness 0.25*rad	Midthickness 0.5*rad	Midthickness 0.75*rad	Depth at crossover (midthickness)	Point Value of Entrance	Avg RS in 0.05" Radius Entrance	Standard Deviation of Avg RS in 0.05" Radius	Point Value CSK Knee	Avg RS in 0.05" Radius CSK knee	Standard Deviation of Avg RS in 0.05" Radius
L-367-SP-353	-57.75	-40.98	-16.85	-1.76	0.09	-45.86	-39.54	11.79	-76.97	-55.74	14.75
R-367-SP-353	-59.44	-47.42	-23.56	-5.23	0.09	-28.27	-40.02	8.30	-60.03	-57.68	9.85
L-367-SP-648	-59.55	-49.30	-27.55	-9.76	0.10	-27.42	-43.94	9.54	-87.46	-58.51	12.76
R-367-SP-648	-61.16	-44.86	-18.70	-0.89	0.08	-39.95	-41.40	12.06	-51.24	-54.08	11.07
L-367-SP-900	-59.16	-46.32	-23.50	-5.73	0.09	-36.75	-34.98	10.61	-61.42	-57.69	9.70
R-367-SP-900	-66.43	-52.31	-25.40	-5.25	0.09	-17.48	-40.14	8.34	-68.11	-68.06	11.08
L-F1-A-1	-66.56	-48.51	-25.17	-10.31	0.11	-63.75	-44.42	15.80	-107.97	-68.49	19.65
R-F1-A-1	-66.81	-48.83	-25.43	-10.67	0.11	-57.40	-43.72	14.68	-106.92	-69.89	19.04
L-F2-A-1	-61.15	-43.57	-21.43	-7.87	0.10	-64.50	-45.22	14.04	-109.29	-69.40	18.99
R-F2-A-1	-70.03	-52.05	-27.35	-10.88	0.11	-51.73	-43.98	14.33	-96.44	-69.07	17.17
L-F3-A-1	-61.32	-46.53	-24.88	-9.58	0.10	-24.47	-36.79	8.08	-89.53	-63.45	15.88
R-F3-A-1	-69.31	-51.50	-27.41	-11.69	0.11	-70.21	-45.59	18.01	-98.54	-69.59	16.78
Mean	**-60.58**	**-46.86**	**-22.59**	**-4.77**	**0.09**	**-32.62**	**-40.00**	**10.11**	**-67.54**	**-58.62**	**11.54**
Stdev	**2.80**	**3.53**	**3.70**	**2.90**	**0.01**	**9.32**	**2.67**	**1.51**	**11.87**	**4.47**	**1.75**
Mean	**-65.86**	**-48.50**	**-25.28**	**-10.16**	**0.11**	**-55.34**	**-43.29**	**14.16**	**-101.45**	**-68.32**	**17.92**
Stdev	**3.50**	**2.88**	**1.99**	**1.21**	**0.00**	**14.98**	**2.98**	**3.02**	**7.18**	**2.22**	**1.38**
Residuals (Td-NM)	**5.28**	**1.63**	**2.69**	**5.39**	**-0.02**	**22.72**	**3.29**	**-4.05**	**33.91**	**9.69**	**-6.38**

Legacy vs New CX Comparison #3







Sample ID	Midthickness 0.125*rad	Midthickness 0.25*rad	Midthickness 0.5*rad	Midthickness 0.75*rad	Depth at crossover (midthickness)	Point Value of Entrance	Avg RS in 0.05" Radius Entrance	Standard Deviation of Avg RS in 0.05" Radius	Point Value CSK Knee	Avg RS in 0.05" Radius CSK knee	Standard Deviation of Avg RS in 0.05" Radius
L-471-SP-353	-38.27	-23.51	-1.98	9.88	0.08	-32.82	-32.63	9.52	-85.89	-41.64	17.17
R-471-SP-353	-36.42	-20.73	4.01	16.06	0.07	-71.76	-32.80	12.26	-108.57	-30.08	22.33
L-471-SP-648	-37.22	-21.54	-2.28	8.35	0.08	-62.31	-42.46	15.71	-100.42	-33.44	18.77
R-471-SP-648	-38.21	-20.14	1.92	10.94	0.07	-114.88	-40.84	12.70	-76.90	-29.88	19.33
L-471-SP-900	-45.72	-32.40	-7.94	11.57	0.09	-38.19	-42.59	8.96	-104.07	-41.04	20.04
R-471-SP-900	-22.24	-8.55	3.94	13.42	0.06	-83.09	-32.75	16.34	-106.09	-25.65	24.46
L-F1-A-1	-41.79	-21.34	2.96	11.94	0.07	-52.82	-34.58	11.09	-74.22	-34.79	20.55
R-F1-A-1	-37.72	-16.80	3.93	10.29	0.07	-62.93	-37.82	14.91	-73.87	-33.44	21.08
L-E2-A-2	-30.98	-11.99	5.89	10.65	0.06	-82.34	-34.28	12.85	-69.24	-28.34	21.92
R-E2-A-2	-37.04	-16.46	4.25	10.75	0.07	-40.32	-40.24	11.91	-55.55	-33.76	20.10
L-E3-A-2	-31.14	-13.04	5.02	10.80	0.06	-88.50	-34.31	12.03	-70.76	-27.72	20.41
R-E3-A-2	-40.33	-19.53	3.55	12.17	0.07	-62.43	-40.65	12.49	-75.57	-32.47	20.94
Mean	**-36.35**	**-21.15**	**-0.39**	**11.70**	**0.08**	**-67.18**	**-37.35**	**12.58**	**-96.99**	**-33.62**	**20.35**
Stdev	**7.01**	**6.98**	**4.21**	**2.49**	**0.01**	**27.67**	**4.65**	**2.78**	**11.59**	**5.91**	**2.40**
Mean	**-36.50**	**-16.53**	**4.27**	**11.10**	**0.07**	**-64.89**	**-36.98**	**12.55**	**-69.87**	**-31.75**	**20.83**
Stdev	**4.16**	**3.29**	**0.96**	**0.70**	**0.00**	**16.44**	**2.74**	**1.19**	**6.75**	**2.72**	**0.58**
Residuals (Td-NM)	**0.15**	**-4.62**	**-4.66**	**0.60**	**0.01**	**-2.29**	**-0.37**	**0.03**	**-27.13**	**-1.87**	**-0.49**

Legacy vs New CX Summary

Comparisons completed to date show no statistically significant difference between

Residual stresses at CX holes in teardown assets and

Residual stresses at CX holes in newly manufactured coupons

But, there are some differences in the data sets

- Largest differences are in areas of largest scatter in underlying populations
  - Scatter in populations may be due to combined effects of process variation and measurement uncertainty
- In single populations of replicate holes, sample-to-sample variations are similar in new manufacture and teardown
  - May indicate similar degree of process quality

In the present data, we see no measurable effect of service loading on residual stresses in cold worked holes

Finalizing work and completing comparisons (teardown vs. new manufacture)

Detailed investigation where "differences" are observed in Level I comparison

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Measurements Sub-group Update

Contour Measurements in Cracked Coupons

Provided by Scott Carlson, SwRI

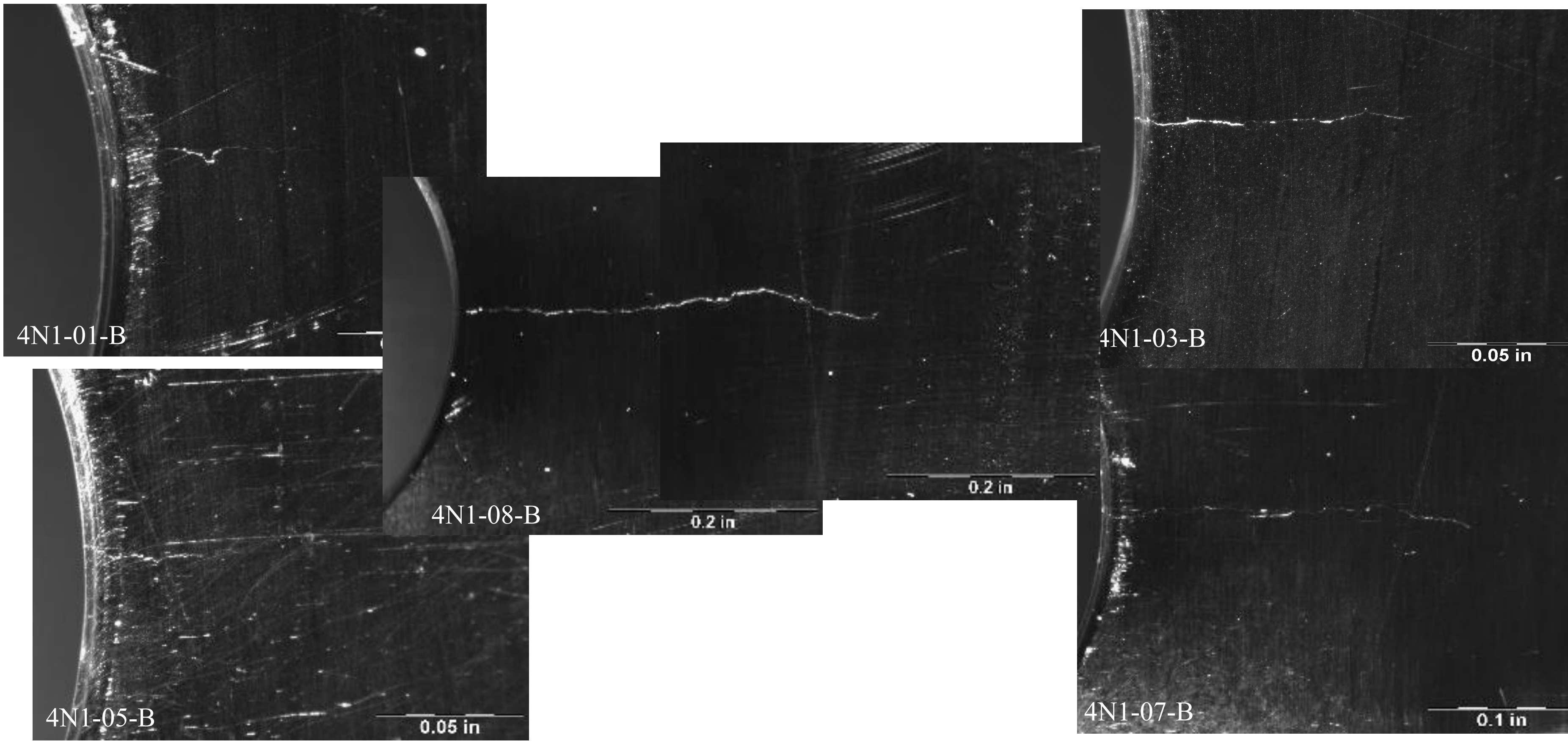
From Scott Carlson: Influence of a Fatigue Crack

- Hypothesis:
  - *"The presence of a fatigue crack changes the residual stress field induced by the Cold Expansion (Cx) process within aerospace-grade aluminum alloys, namely 2024-T351 and 7075-T651"*
- Procedure for Testing Hypothesis
  - Develop baseline Cx coupons, no fatigue crack coupons
  - Develop fatigue cracks via constant amplitude loading in identical Cx coupons
    - Range of crack sizes, stress = 25ksi or 26.5ksi, R = 0.1
  - Focus on "Low" applied expansion level for all Cx holes

2024-T351 Coupons							
Specimen ID	**Mandrel Entrance Face Crack (inch)**	**Gauge Width (inch)**	**Gauge Thickness (inch)**	**Initial Ream Diameter (CMM (inch)**	**% CX**	**Final Ream Diameter (inch)**	**RS Specimen Length (inch**
4N1-01-B	0.0797	4.0000	0.2545	0.4771	3.23%	0.4990	5.0030
4N1-02-B	0.0798	4.0030	0.2550	0.4768	3.29%	0.4997	5.0035
4N1-03-B	0.0974	4.0025	0.2548	0.4772	3.21%	0.4997	5.0028
4N1-04-B	0.0962	4.0022	0.2555	0.4771	3.23%	0.4990	5.0022
4N1-05-B	0.1259	4.0027	0.2557	0.4771	3.23%	0.4980	5.0023
4N1-06-B	0.1214	4.0023	0.2555	0.4770	3.25%	0.4990	5.0025
4N1-07-B	0.2515	4.0020	0.2555	0.4770	3.25%	0.4995	5.0030
4N1-08-B	0.4974	4.0013	0.2550	0.4770	3.25%	0.4995	5.0030
AVERAGE		***4.0020***	***0.2552***	***0.4770***	***3.24%***	***0.4992***	***5.0028***
STDEV		***0.0009***	***0.0004***	***0.0001***	***0.03%***	***0.0006***	***0.0004***

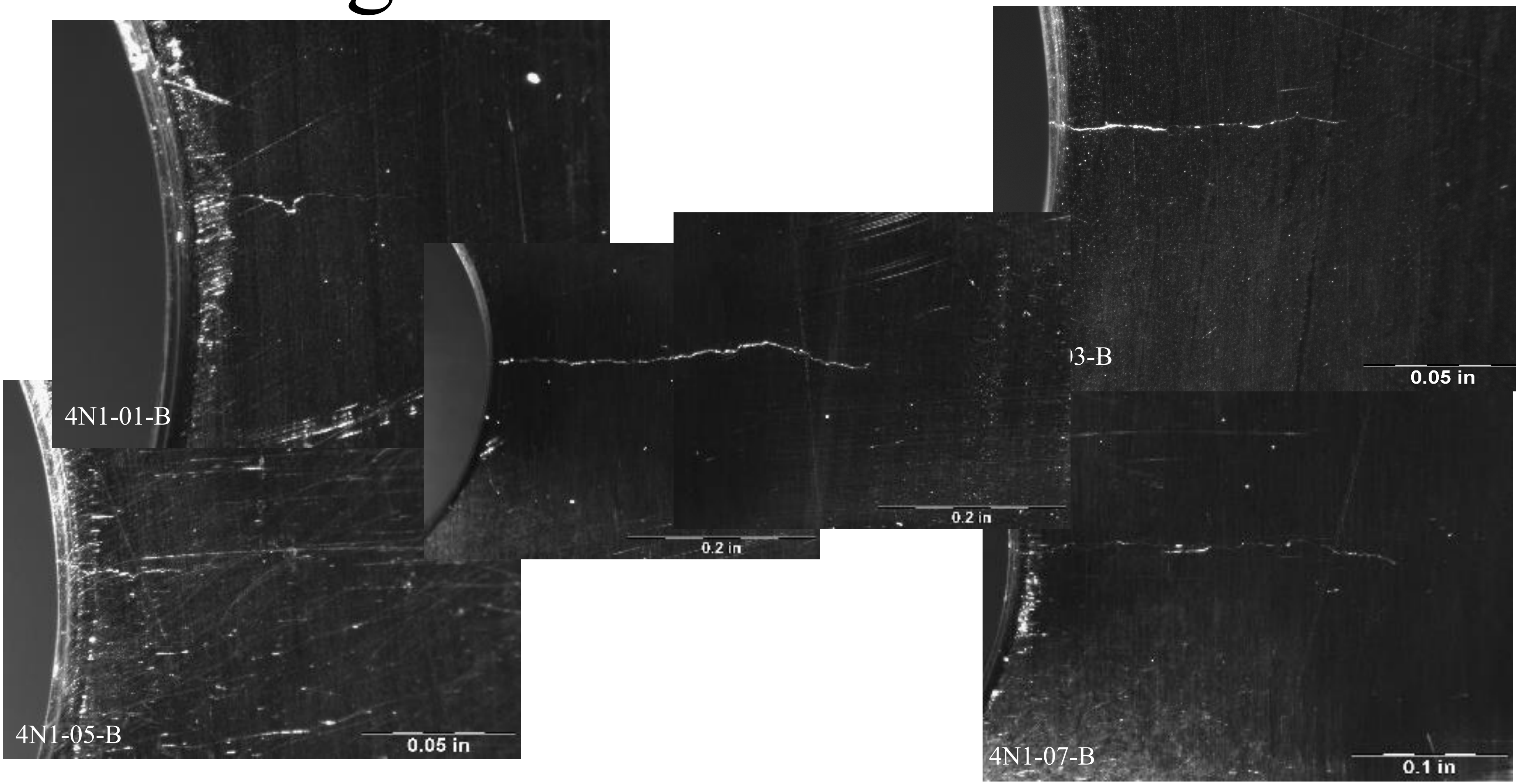
7075-T651							
Specimen ID	**Mandrel Entra Face Crack (ir**	**Gauge Width (inch)**	**Gauge Thicknes (inch)**	**Initial Rean Diameter (CMM) (incl**	**% CX**	**Final Ream Diameter (incl**	**RS Specime Length (inc**
4N1-01-D	0.0793	4.0028	0.2495	0.4766	3.34%	0.4988	5.0023
4N1-02-D	0.0807	4.0023	0.2510	0.4768	3.29%	0.4990	5.0022
4N1-03-D	0.0972	4.0017	0.2508	0.4769	3.27%	0.4993	5.0020
4N1-04-D	0.1015	4.0015	0.2500	0.4770	3.25%	0.4985	5.0025
4N1-05-D	0.1253	4.0020	0.2505	0.4769	3.27%	0.4992	5.0033
4N1-06-D	0.1235	4.0027	0.2507	0.4770	3.25%	0.4980	5.0020
4N1-07-D	0.2505	4.0020	0.2505	0.4767	3.31%	0.4983	5.0023
4N1-08-D	0.5017	4.0022	0.2512	0.4769	3.27%	0.4992	5.0030
AVERAGE		***4.0021***	***0.2505***	***0.4769***	***3.28%***	***0.4988***	***5.0025***
STDEV		***0.0005***	***0.0005***	***0.0001***	***0.03%***	***0.0005***	***0.0005***

Fatigue Cracks in 2024-T351



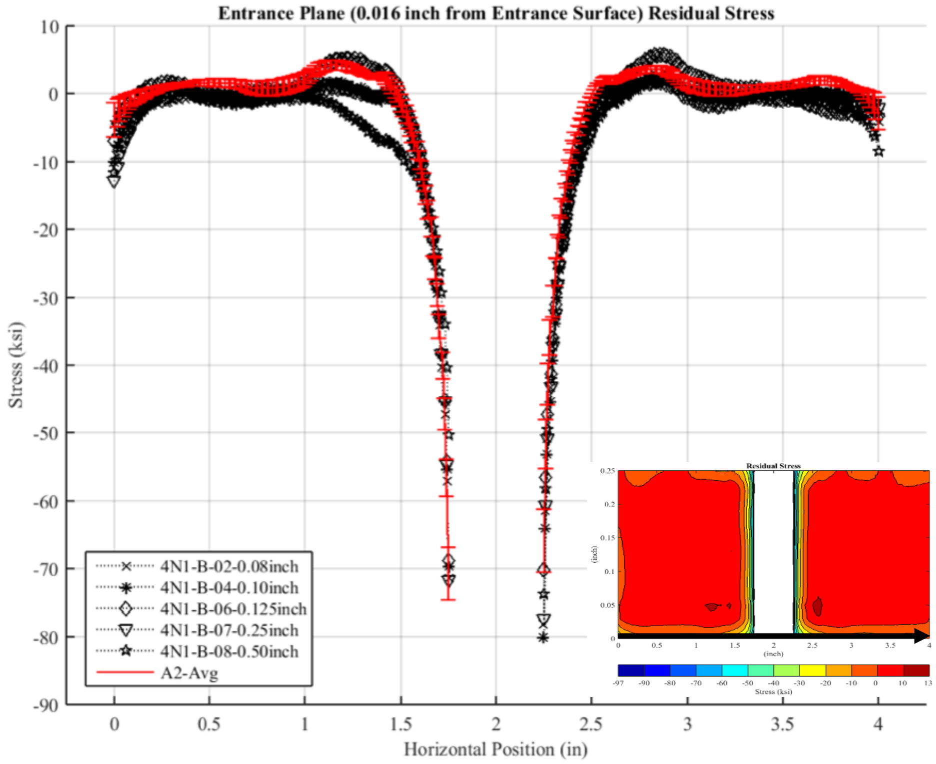
Provided by Scott Calrson

Fatigue Cracks in 7075-T651



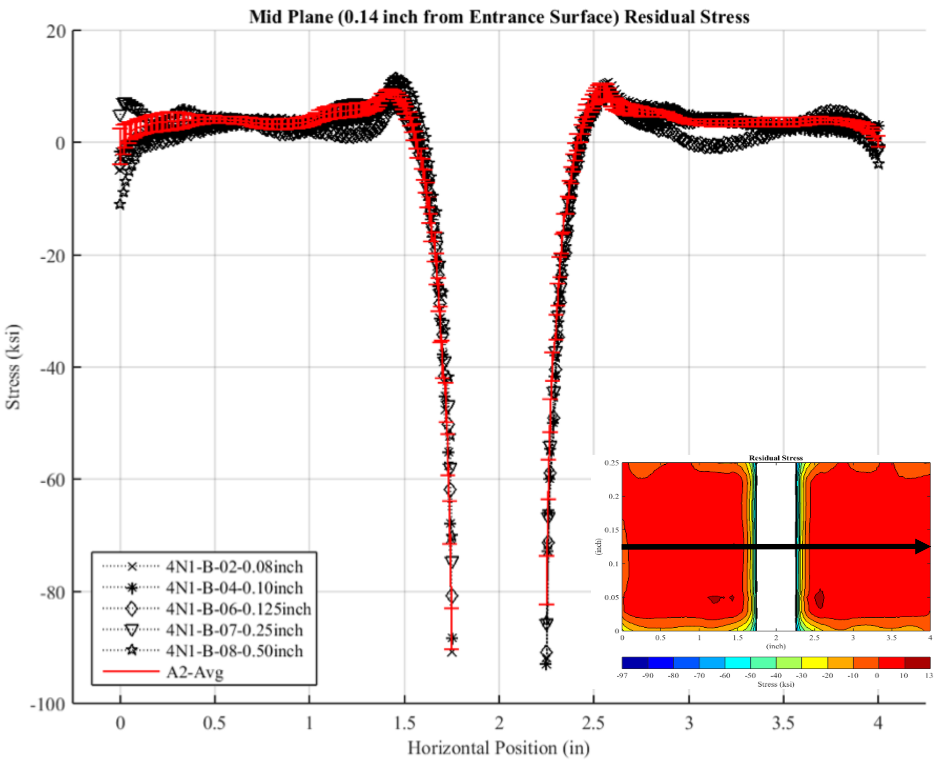
Provided by Scott Calrson

Residual Stresses in 2024-T351



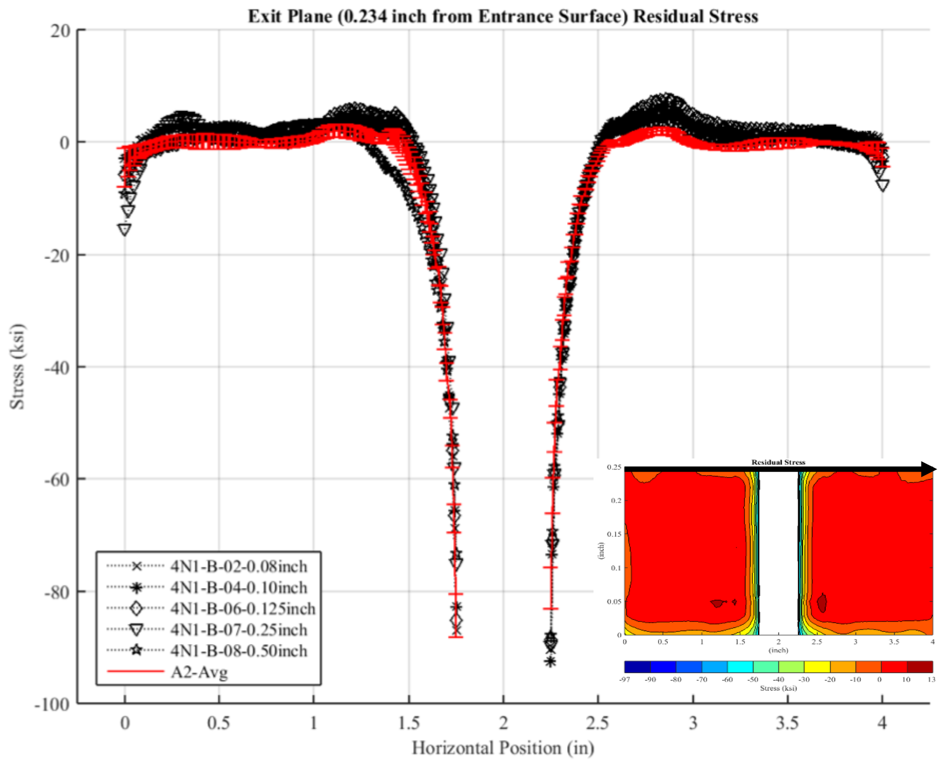
Provided by Scott Calrson

Residual Stresses in 2024-T351



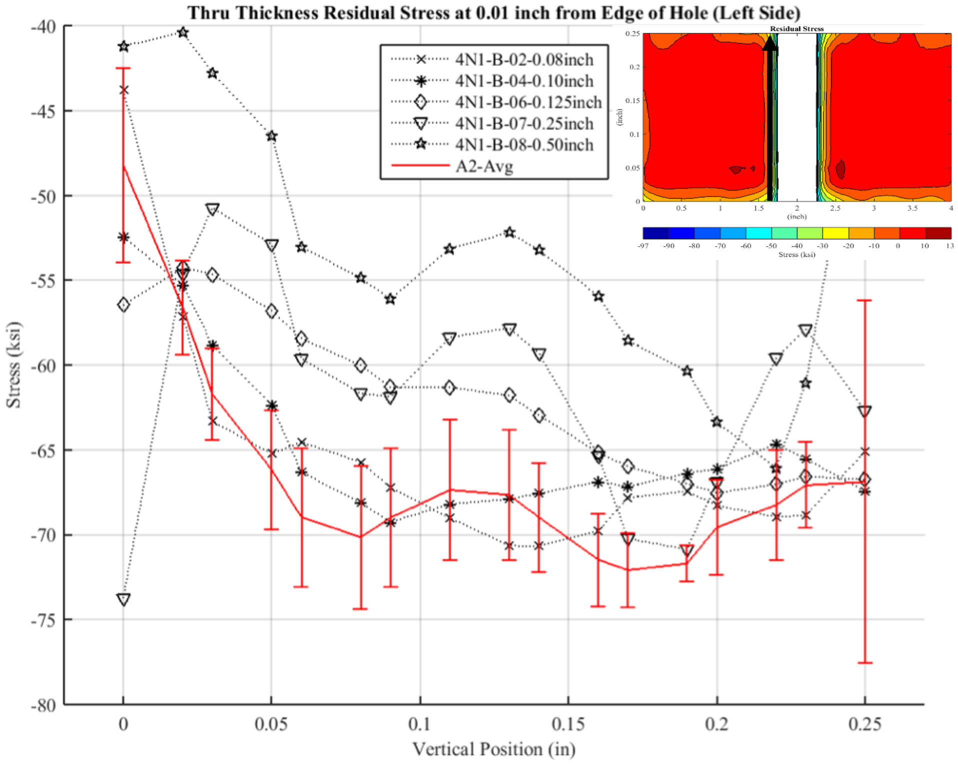
Provided by Scott Calrson

Residual Stresses in 2024-T351



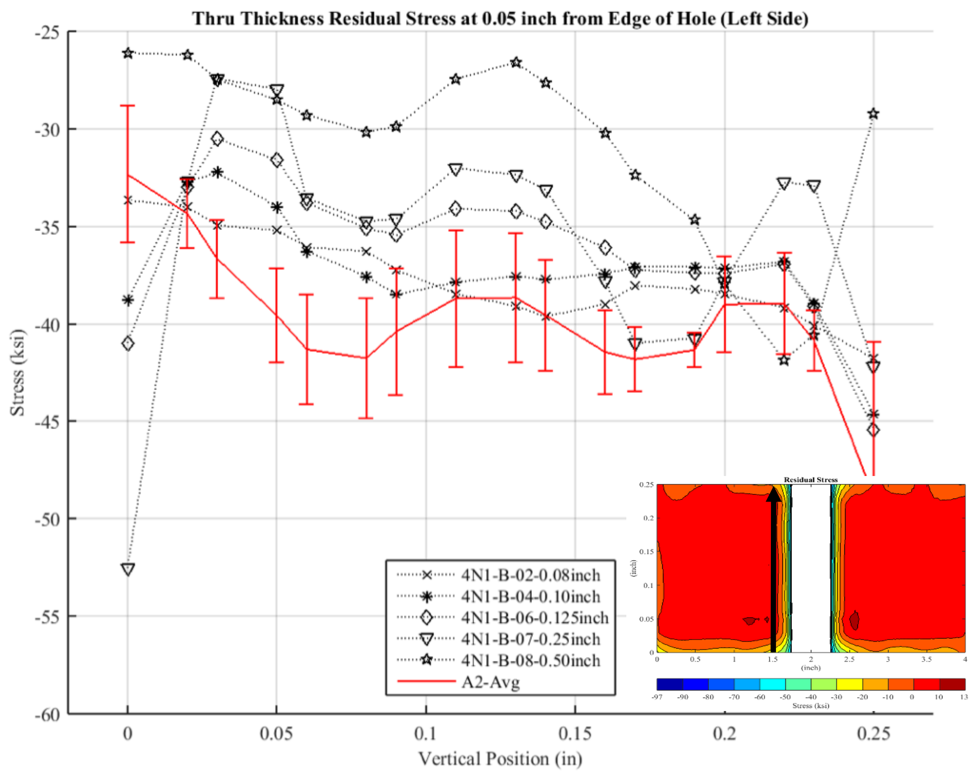
Provided by Scott Calrson

Residual Stresses in 2024-T351



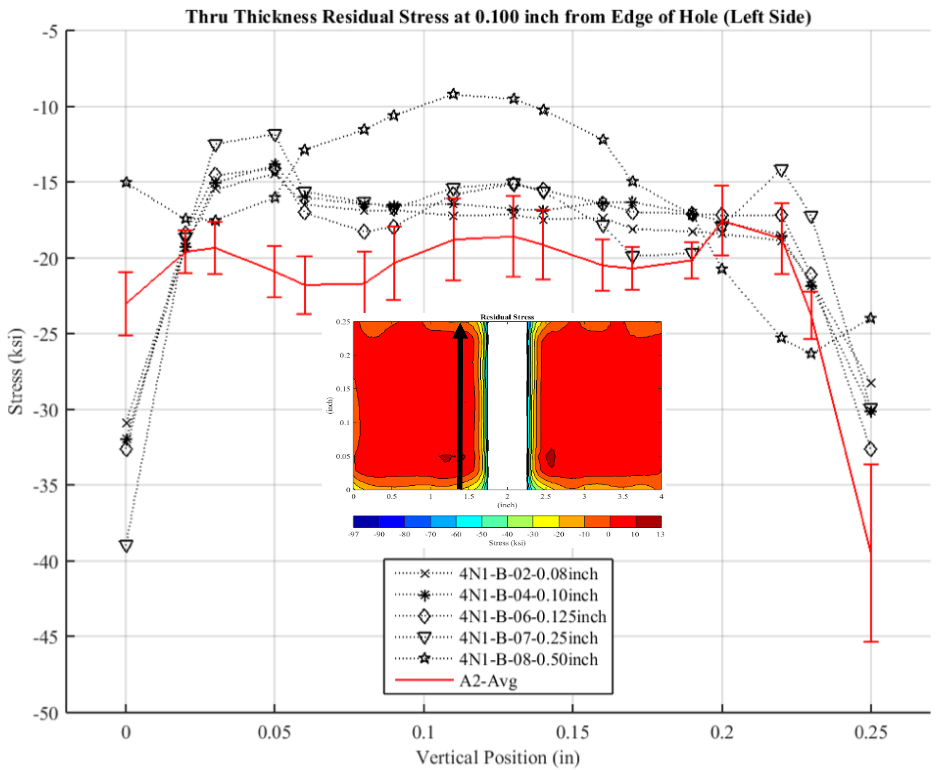
Provided by Scott Calrson

Residual Stresses in 2024-T351



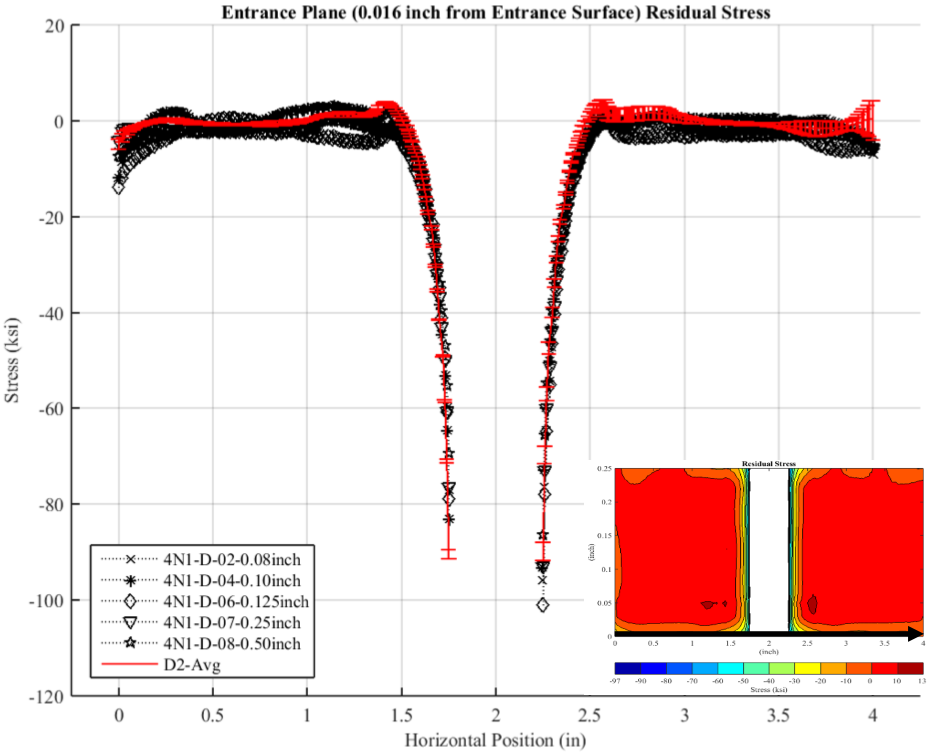
Provided by Scott Calrson

Residual Stresses in 2024-T351



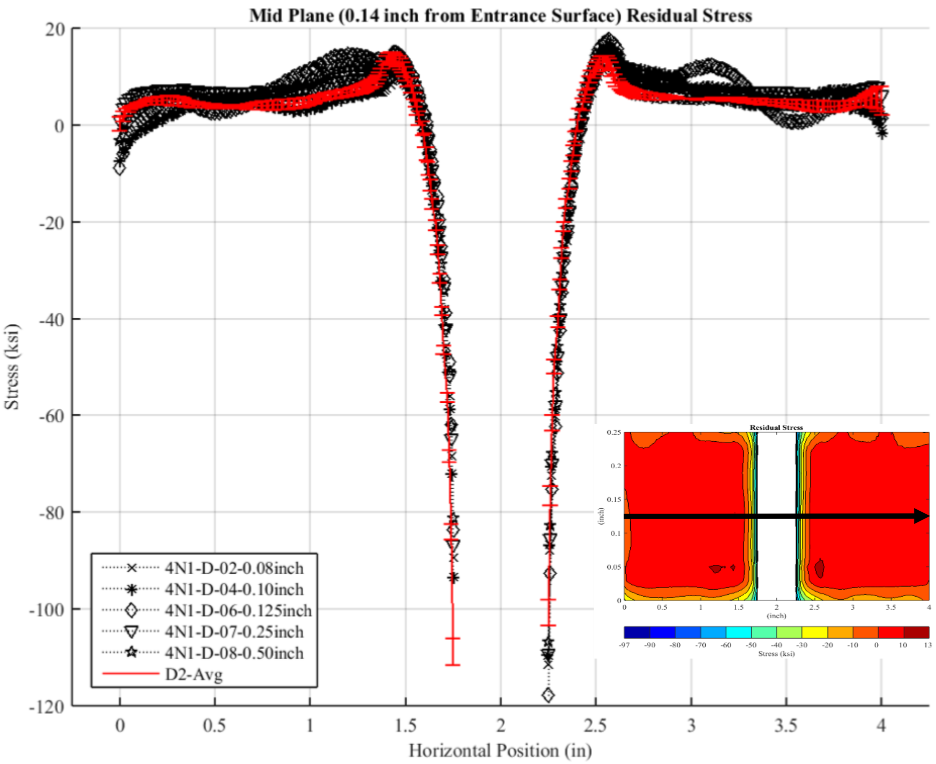
Provided by Scott Calrson

Residual Stresses in 7075-T651



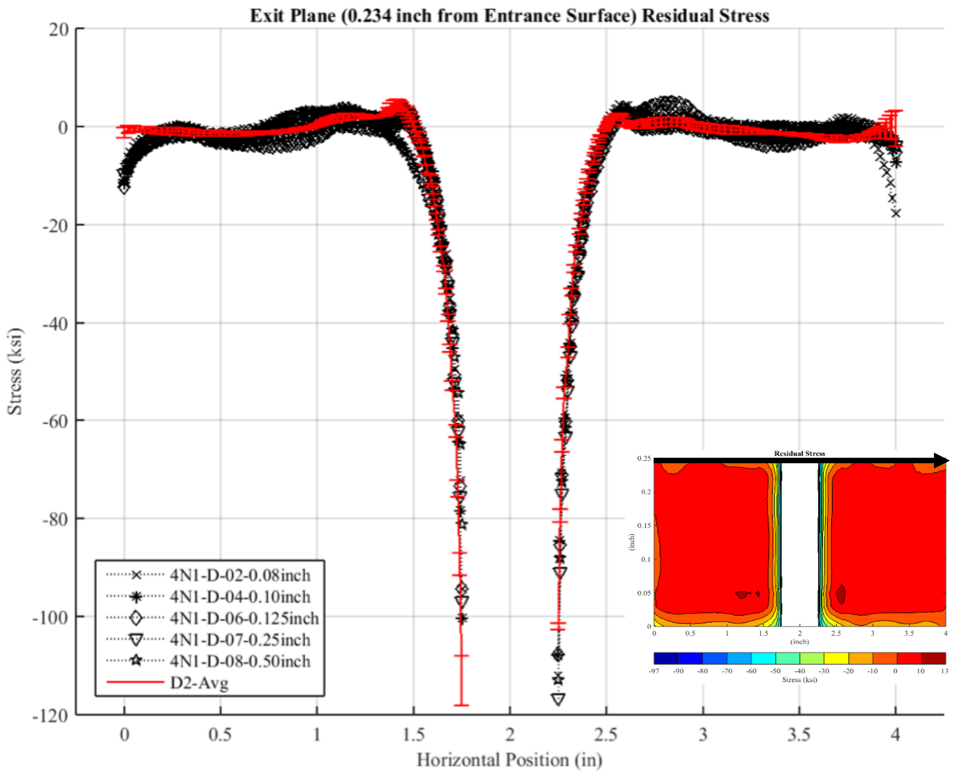
Provided by Scott Calrson

Residual Stresses in 7075-T651



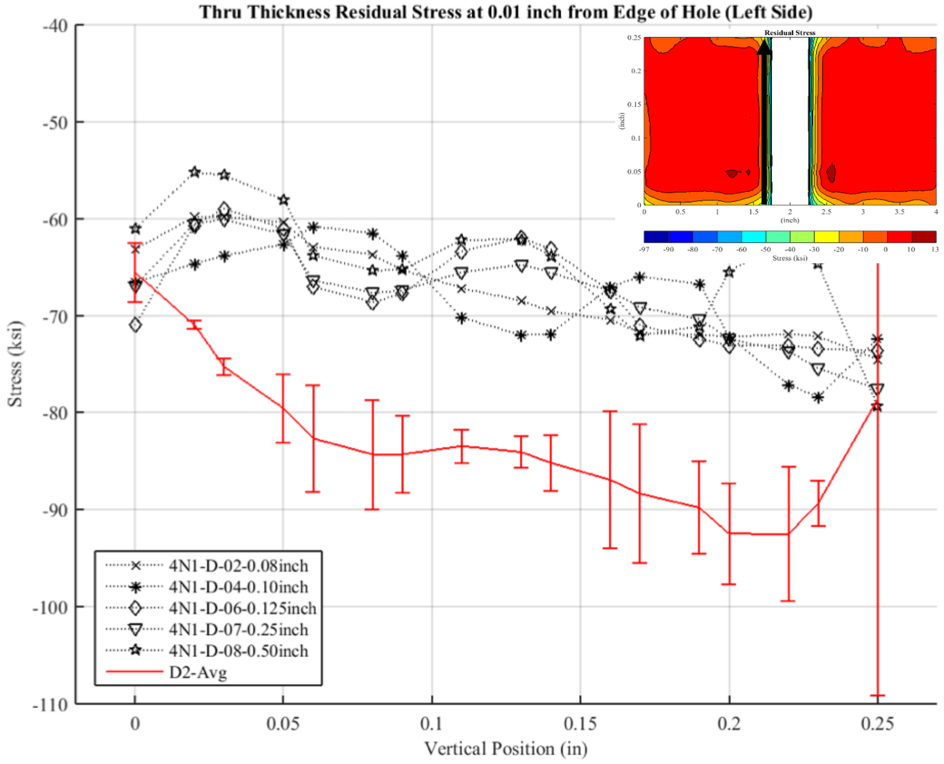
Provided by Scott Calrson

Residual Stresses in 7075-T651



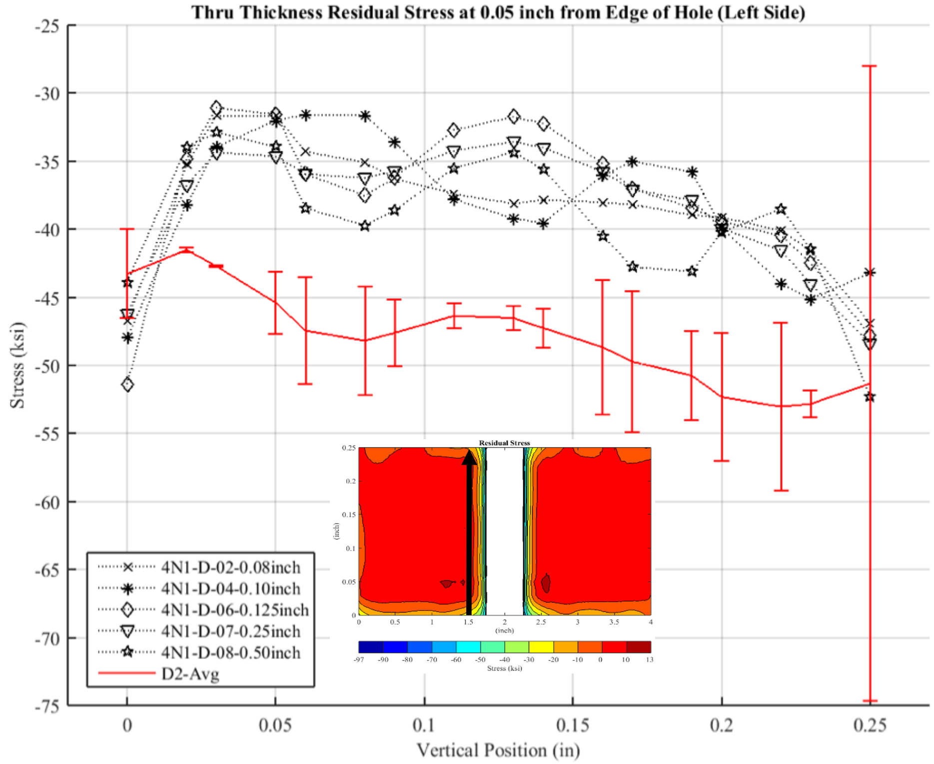
Provided by Scott Calrson

Residual Stresses in 7075-T651



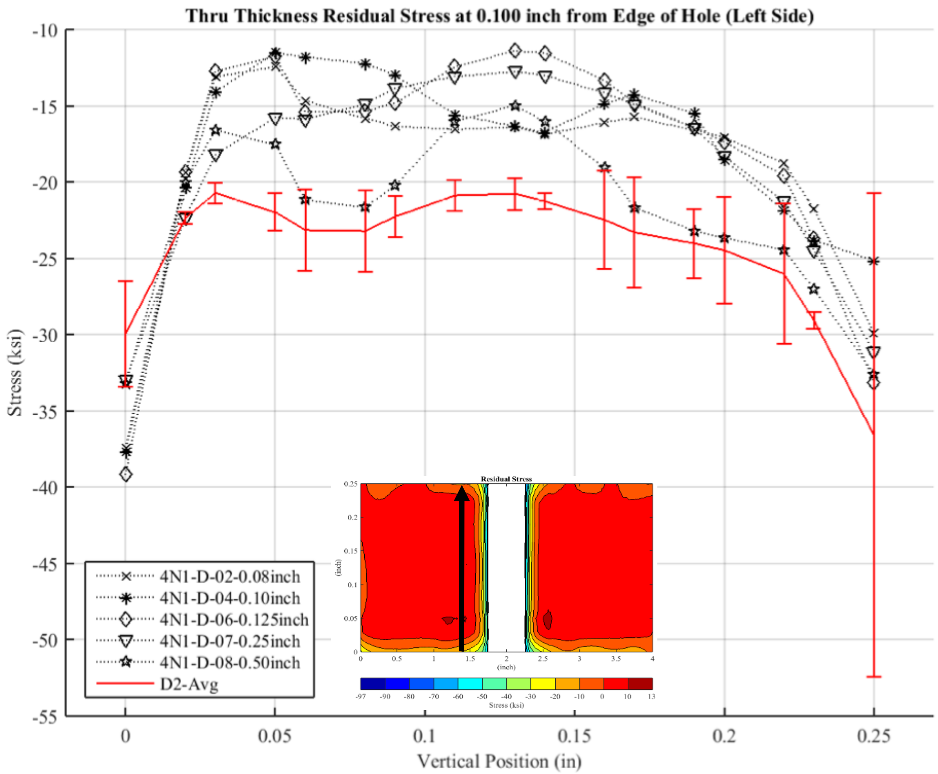
Provided by Scott Calrson

Residual Stresses in 7075-T651



Provided by Scott Calrson

Residual Stresses in 7075-T651



Provided by Scott Calrson

Conclusions

- It is possible to capture the effect of a fatigue crack via the Contour Method
- A fatigue crack has an effect on the residual stress field introduced via the Cold Expansion (Cx) process
  - For 2024-T351 the magnitude of the effect is related to crack size
  - For 7075-T651 the magnitude effect is does not seem to be related to the crack size

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Measurements Sub-group Update

Near-surface Measurements at a CX Hole

Provided by James Castle, Boeing

Reliable Measurement of Sub-Surface Residual Stress for Understanding Fatigue Performance

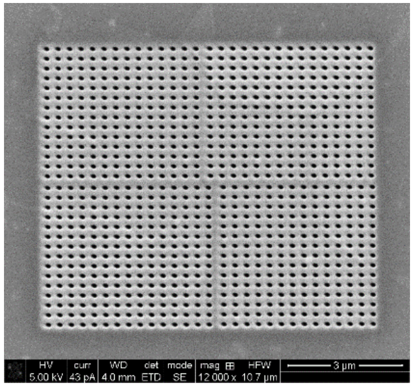
Elizabeth Burns[1,2], Joseph Newkirk[1], James Castle[2], Jennifer Creamer[2], Matt Watkins[3]

[1]Department of Materials Science & Engineering, Missouri University of Science and Technology, Rolla, MO USA
[2]Boeing Research and Technology, Saint Louis, MO, USA
[3]Engineering Software Research and Development (ESRD), Inc., Saint Louis, MO, USA

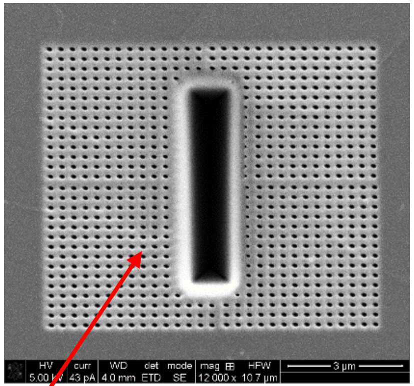
MISSOURI S&T

Micro-slotting method

1. Milled pattern of small surface dots and obtained electron image
2. Milled slot and obtained electron image
3. Determined original stress state of imaged region:
   - Input images and text file of FE surface displacements for reference stress into MATLAB DIC program

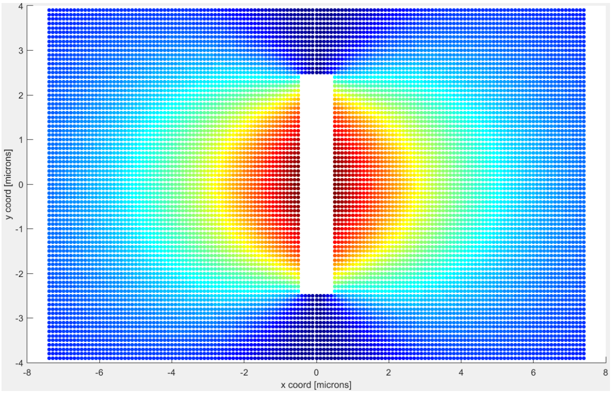


1



2

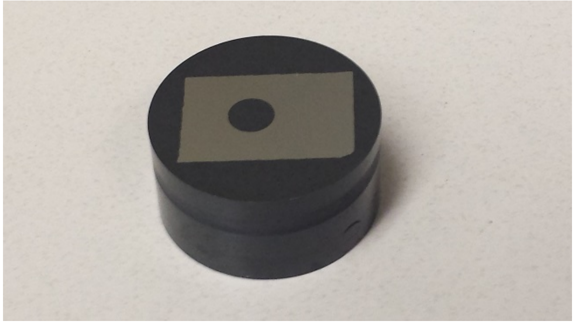
Micro-slot length: 0.005 mm

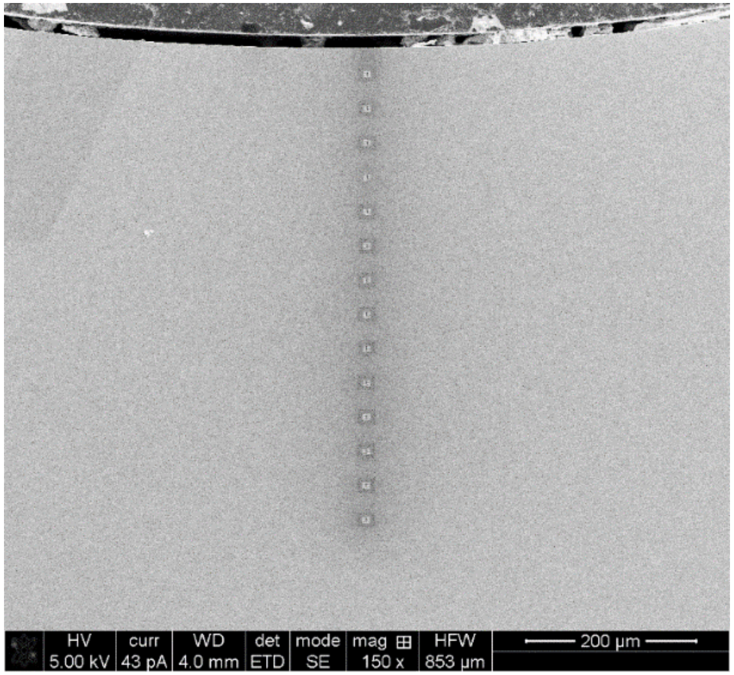


3

Micro-slotting Procedure

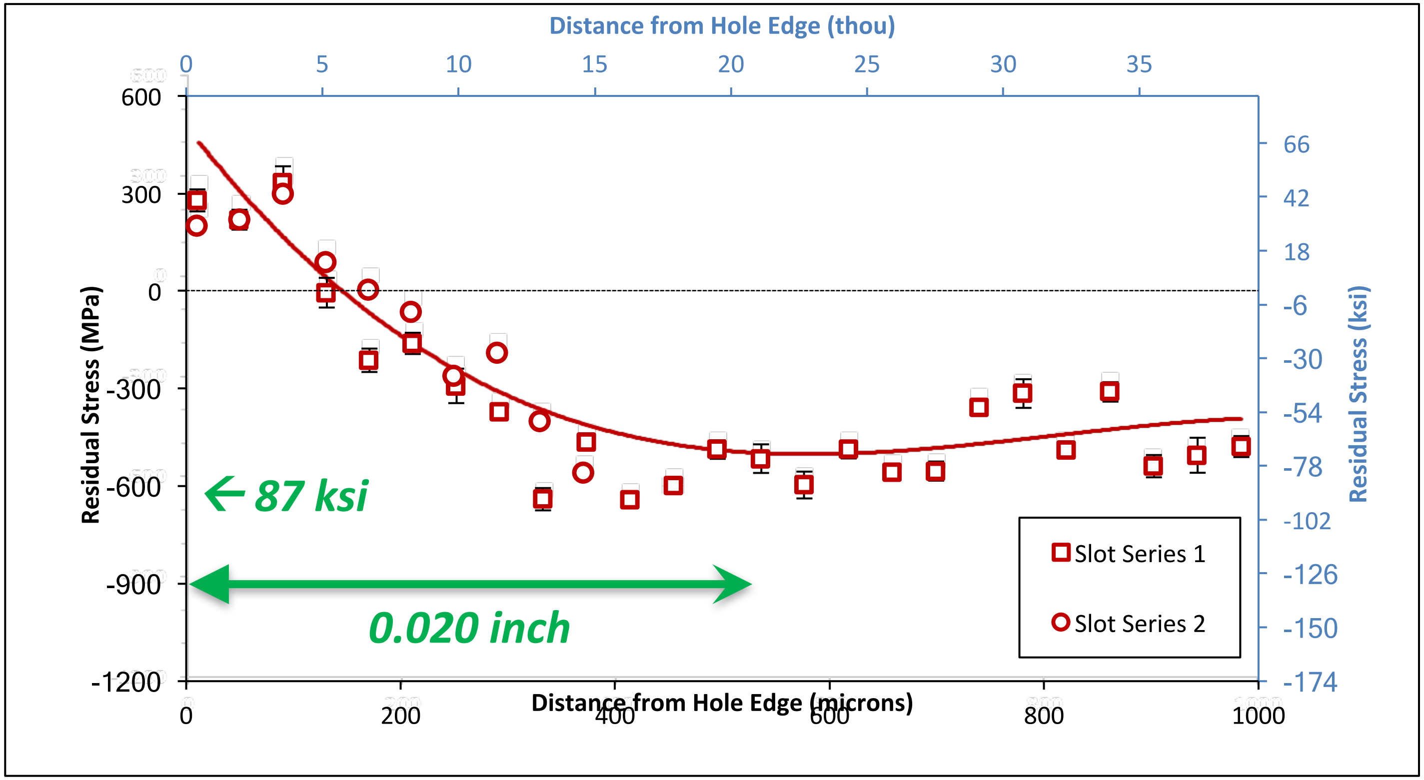
- Processed coupons were sectioned and polished
- Series of slots were milled using "best practice" procedure
  - Planar samples – as a function of distance below the surface
  - Hole samples – as a function of distance from the hole edge
- Slot size: 5x1x7 μm
- Slots were vertically spaced ≥ 25 μm (~1 thou)





Cold worked hole with reaming step

Measurements are reported as an average and standard deviation of residual stress for each slotted region



Two series of measurements superimposed show a small tensile stress at hole edge (most likely due to reaming process) followed by deep compressive stress

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Measurements Sub-group Update

Near-bore Measurements at CX Hole

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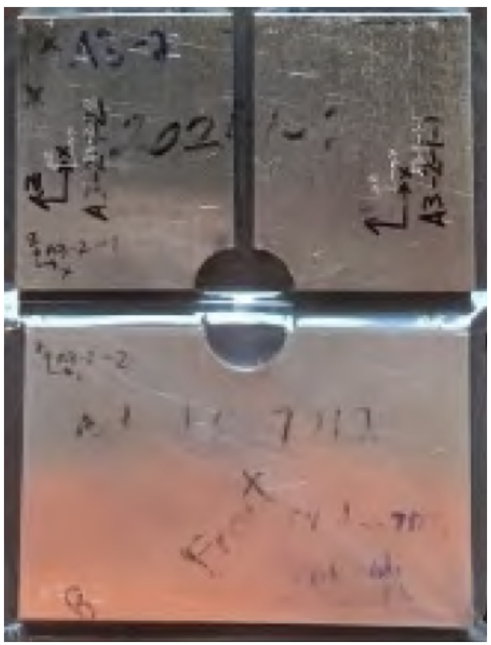
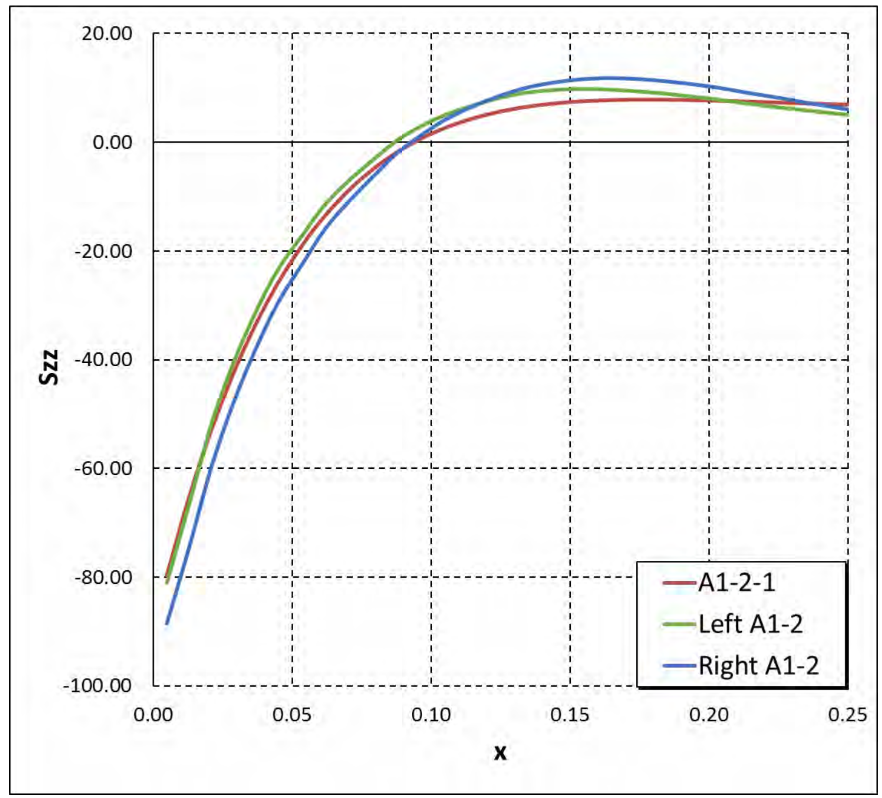
Predict. Test. Perform.

Measurements of near-bore residual stress

Slitting method measurements following contour

- Corrected for prior contour measurement
- For 2024-T351, no significant difference in results

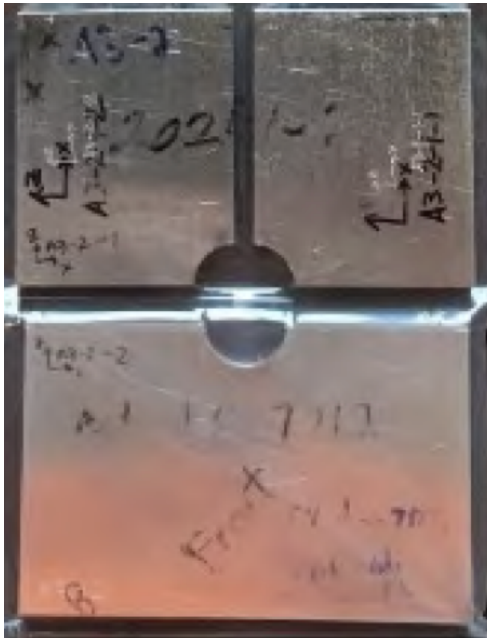


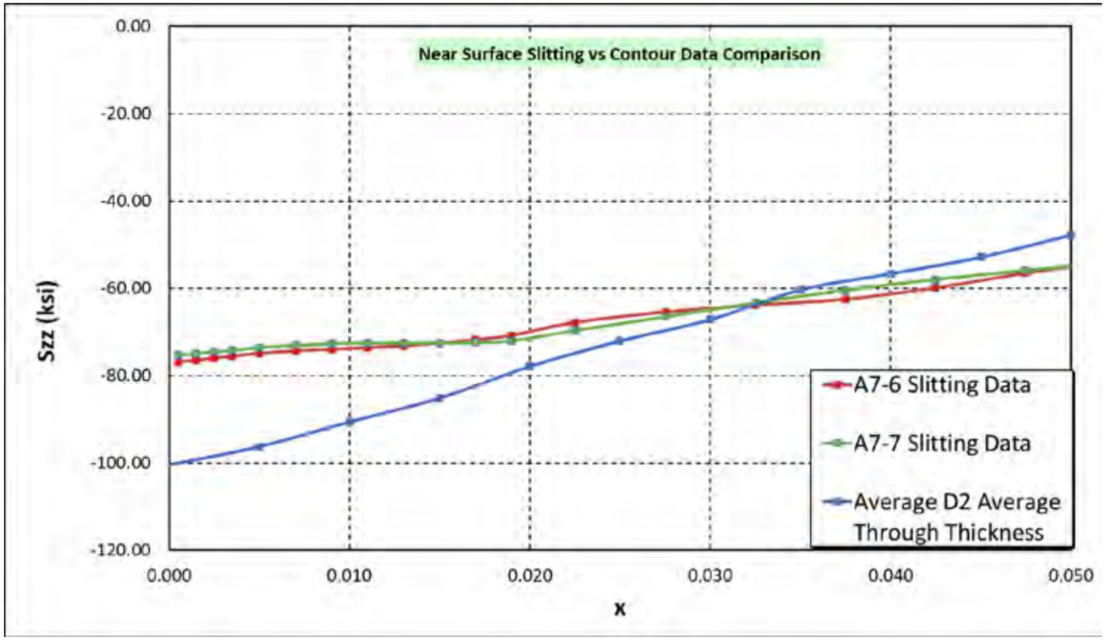


Measurements of near-bore residual stress

Slitting method measurements following contour

- Corrected for prior contour measurement
- For 7075-T651 significant difference in results within 0.020” of the bore





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Measurements Sub-group Update

Large Hole CX Evaluation

Coupon Design

Objective

- Develop a coupon that scales-up the stress field
- Develop and interrogate measurement data

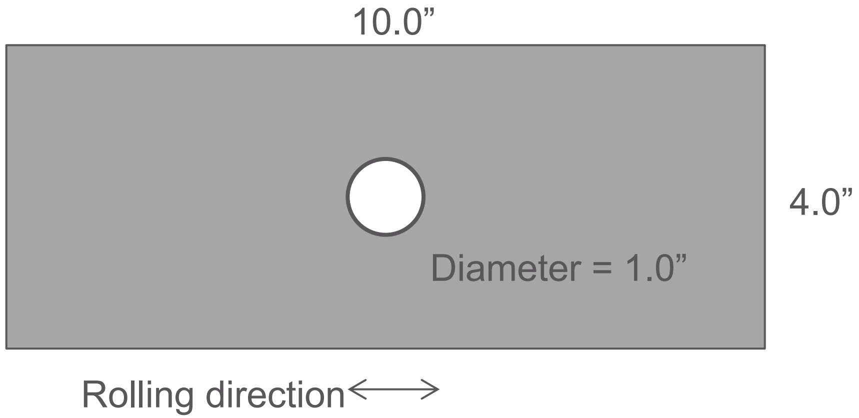
Coupon attributes

- Large diameter
  - Maximize length scale of “near-surface” and “near-bore” regions
- Long enough to facilitate fatigue testing
- Wide enough to minimize edge margin effects

Material types

- 7075-T651
- 2024-T351

Comments from group?



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Measurements Sub-group Update

Recent Cross-Method Validations

Quality of residual stress data (model or measurement)

Judging the quality of residual stress data is difficult

- Models are non-linear and model inputs are uncertain
- Direct residual stress measurements are not possible
  - Always determined indirectly
    - Lattice spacing, cut-induced deformation, correlation with magnetic properties
  - No one method meets all needs (e.g., bulk vs near-surface)
    - Use multiple techniques, data fusion
- Lack of truth data

Three approaches to assessing quality of measurement data

- Measurement repeatability – determines precision (but not accuracy)
  - Intralaboratory (repeatability)
  - Interlaboratory (reproducibility)
- Cross-method validation – shows consistency (but not accuracy)
  - Best when methods use different physics (e.g., mechanical and diffraction)
- Phenomenological correlation – shows usefulness
  - Provides the most relevant truth data
  - Focused on impact of residual stress on component
    - e.g., Fatigue life or Distortion

Residual stress measurement

Residual stress measurement is challenging

- Impossible to “see” residual stress
- Requires indirect measurement
  - Measure something else (e.g., strain release) and “infer” residual stress

Many “accepted” RS measurement methods

- Each method has advantages and disadvantages
- No gold standard
- “Best method” depends on specific application

Selection of RS measurement technique

Depth of RS measurement	Required accuracy
Magnitude of stress gradients	Spatial variation of RS
Number RS components	Material property variations
Geometry	Application specific concerns
Destructiveness	Required equipment
Measurement time	Cost
Portability	Required expertise
Material handling	

Important questions to consider

- What does anticipated residual stress field look like?
- How will the measurement data be used?

Experimental technique is important

Consider replicate measurements

Consider multiple methods

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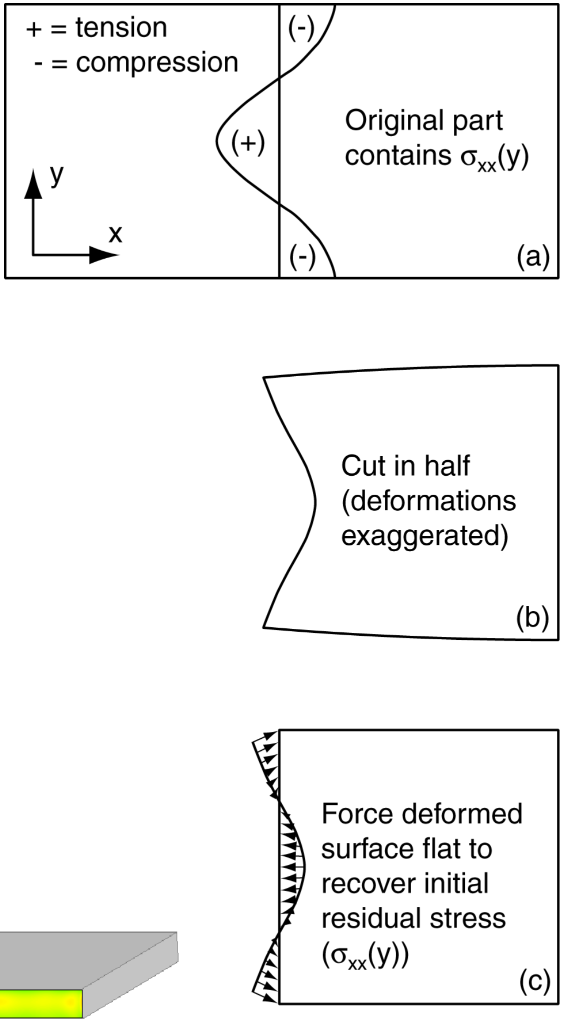
38

Contour method overview

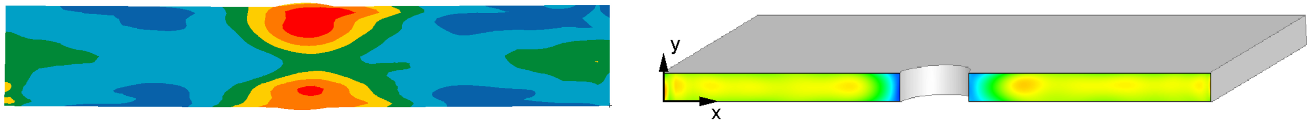
Contour method steps

- Part contains unknown RS (a)
- Cut part: stress release ⇒ deformation (b)
- Measure deformation of cut surfaces
- Apply reverse of average deformation to FE model of body (c)
- Map of RS normal to surface determined
- Same procedure holds for 3D

Cut → measure → FEM → residual stress



- Contour method can generate a 2D map of residual stress normal to a plane



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39

Diffraction methods principle

Subject a crystalline material to incident radiation

Radiation will diffract from crystal lattice planes via Bragg's law

- $\lambda = 2d\sin\theta$

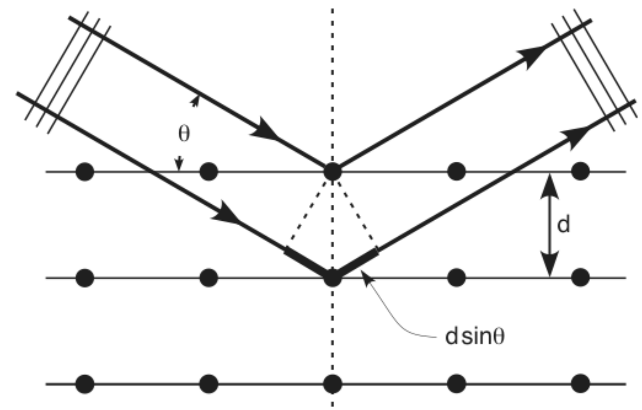
By measuring θ and knowing λ we can obtain lattice spacing *d*

Compare with unstressed lattice spacing d_0

Get elastic strains

Calculate stress

Requires statistics – average over many diffracting grains



public domain image via Wikipedia Creative Commons

$$\varepsilon_i = \frac{d - d^0}{d^0}$$

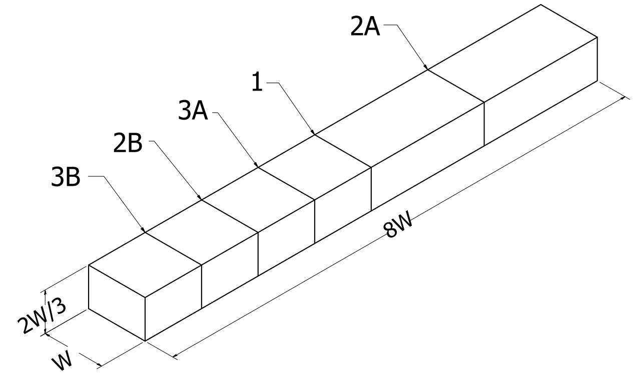
$$\sigma_i = \frac{E(1-\nu)}{(1+\nu)(1-2\nu)}\left[\varepsilon_i + \frac{\nu}{1-\nu}(\varepsilon_j + \varepsilon_k)\right]$$

Map fields by making multiple point measurements

40

Repeatability: contour in quenched bar

Contour method stress mapping



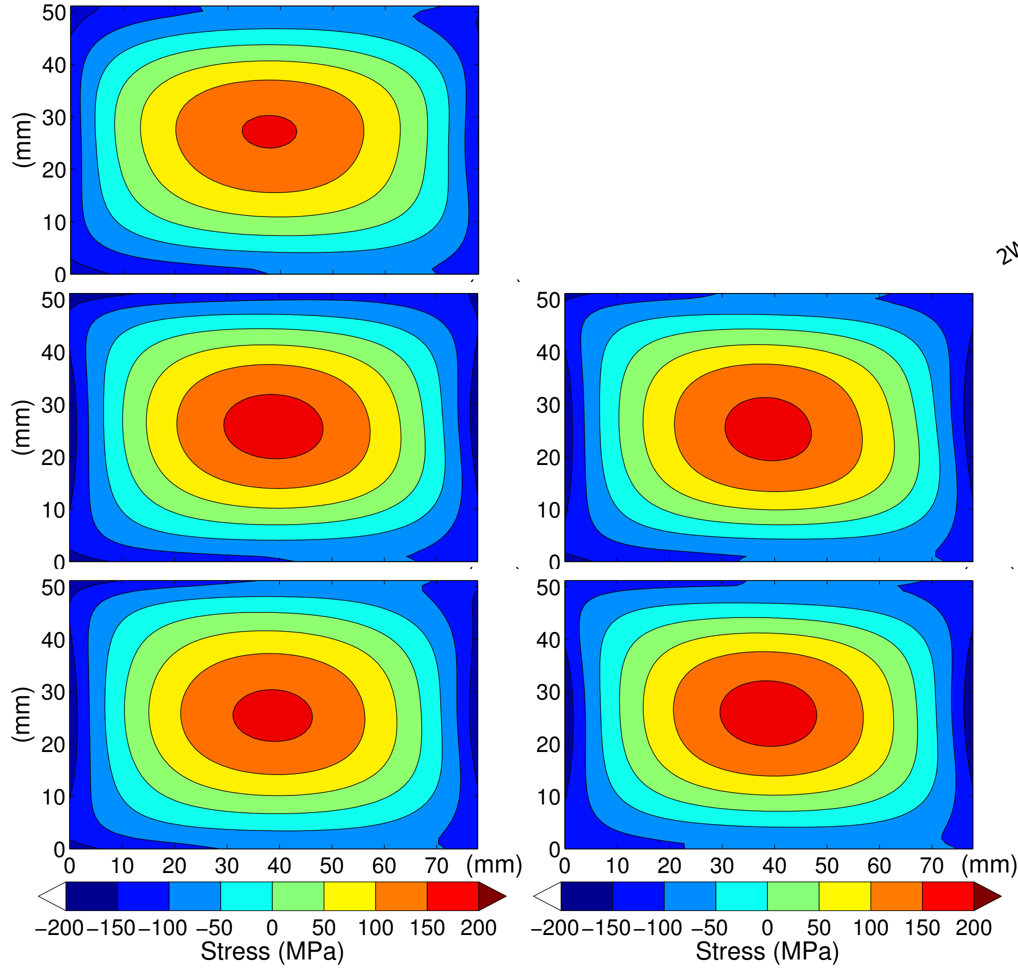
Cut 1

Cut 2A

Cut 2B

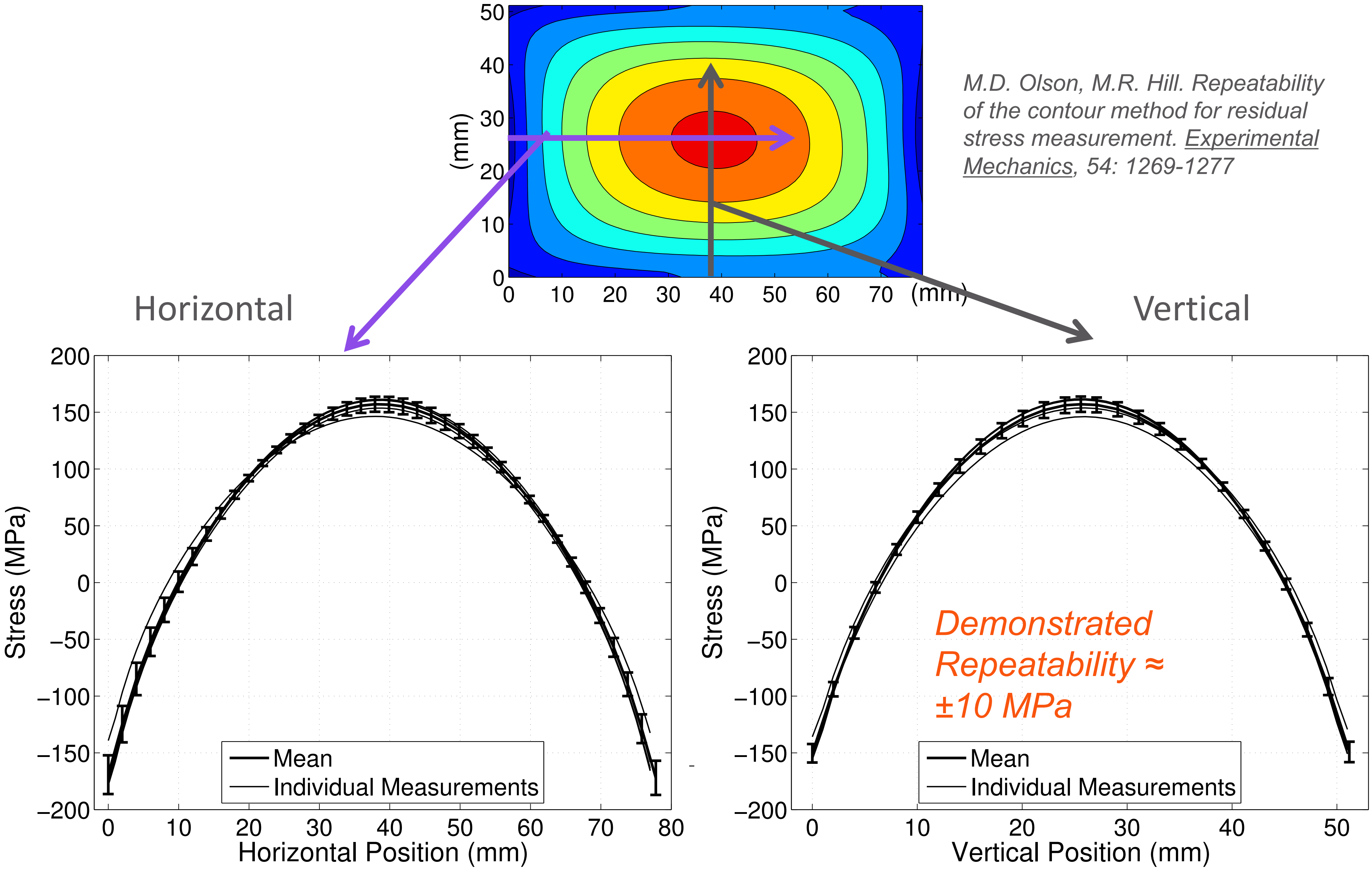
Cut 3A

Cut 3B



M.D. Olson, M.R. Hill. Repeatability of the contour method for residual stress measurement. Experimental Mechanics, 54: 1269-1277

Repeatability: contour in quenched bar



M.D. Olson, M.R. Hill. Repeatability of the contour method for residual stress measurement. Experimental Mechanics, 54: 1269-1277

Demonstrated Repeatability ≈ ±10 MPa

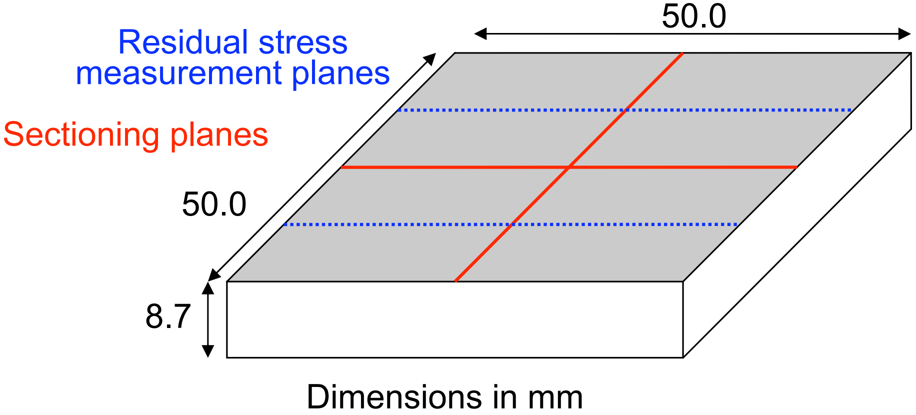
Example: cross-method validation in peened plate

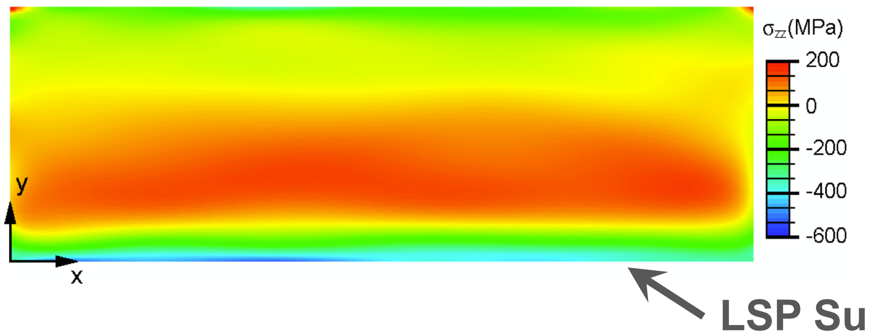
Uniformly LSP entire surface of Ti-6Al-4V plate

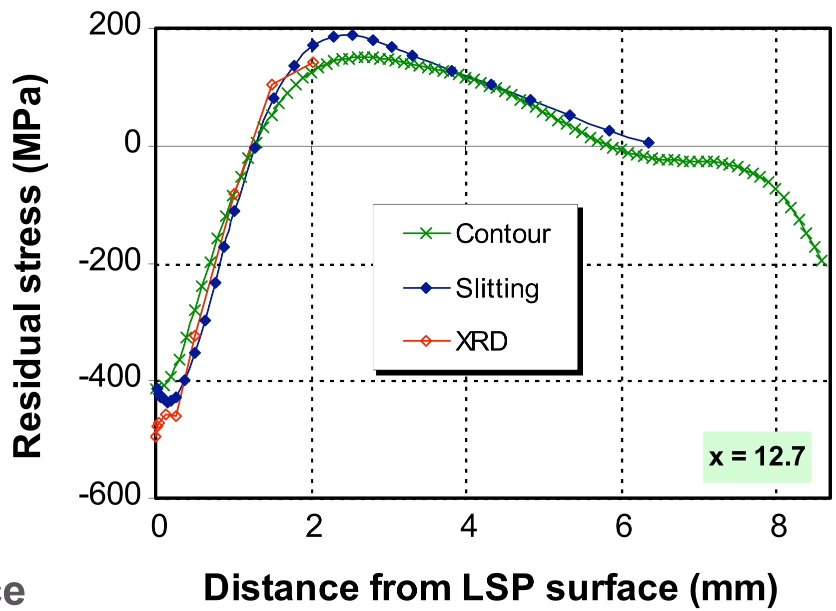
Cut into 4 block coupons
- Each 25 x 25 x 8.7 mm

Measure residual stress
- Slitting, Contour, X-ray diffraction

Good agreement in methods
- Residual stress field that meets assumptions of methods
- Uniform microstructure, equiaxed grains







Example: cross-method validation in ring and plug

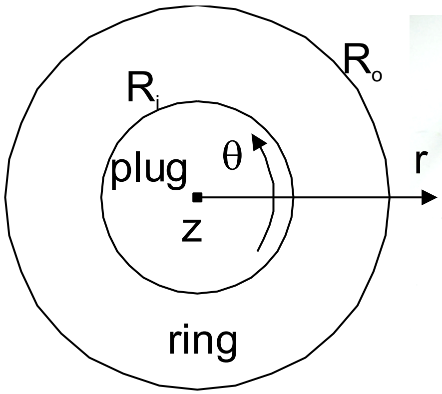
Ring and plug specimen

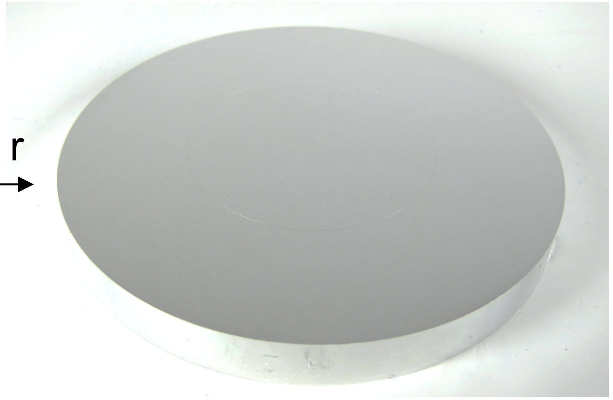
- 2.0 inch diameter plug
- 4 inch diameter ring
- AA2024-T351

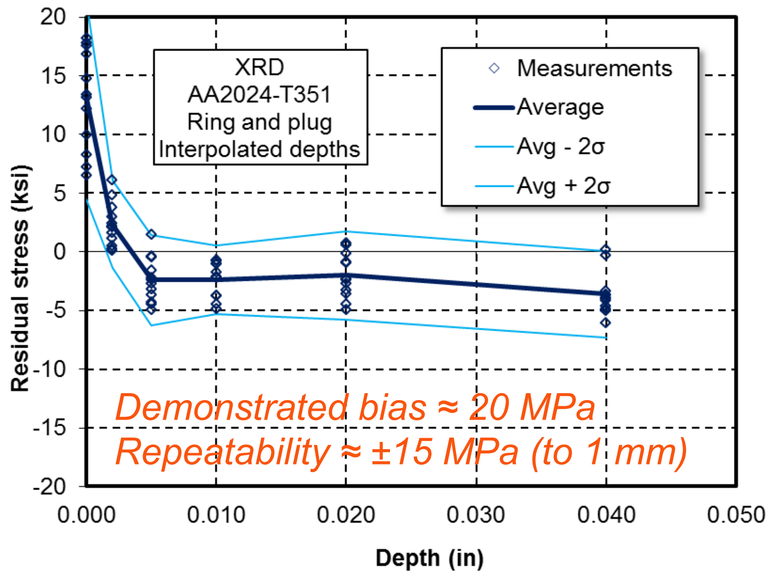
Expect -6.0 ksi in "plug" (40 MPa)

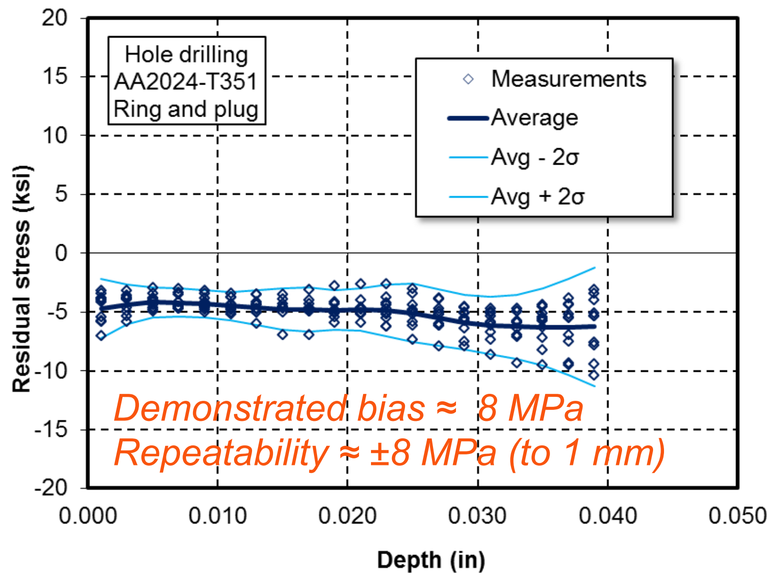
12 replicate measurements

- Depth profiles to 1 mm



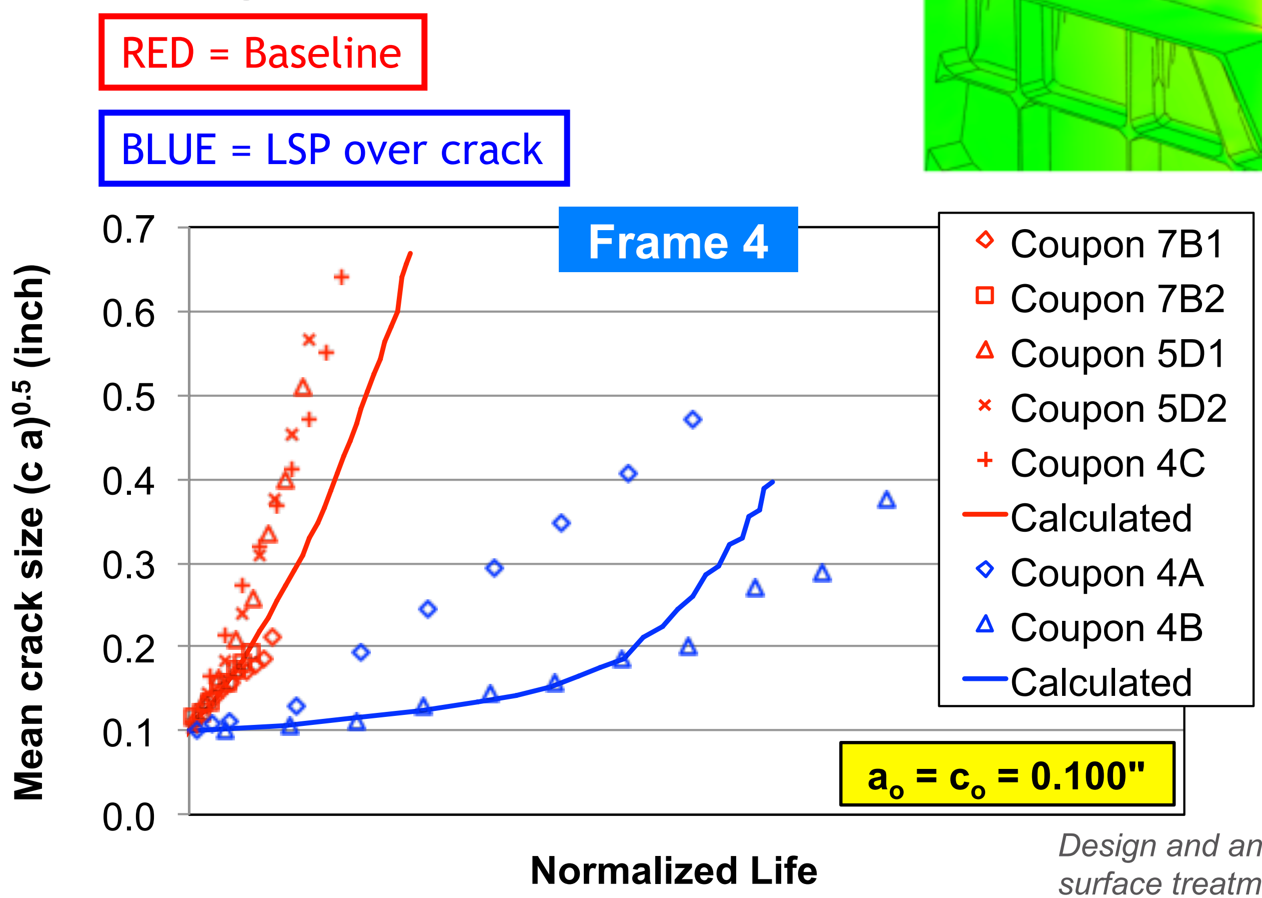


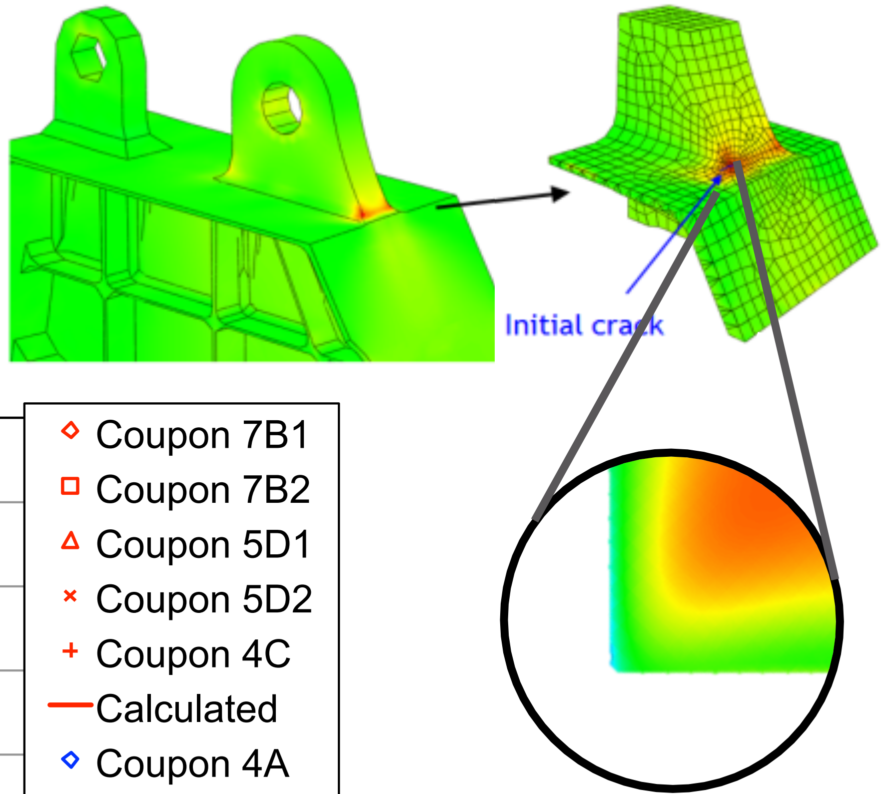




Fatigue test correlation

F-22 fatigue life improvement





Compressive RS from laser shock peening

Design and analysis of engineered residual stress surface treatments for enhancement of aircraft structure, M.R. Hill, et al, 2012 ASIP Conference, San Antonio, TX

Some prior cross-method validation in Al 7XXX

References:

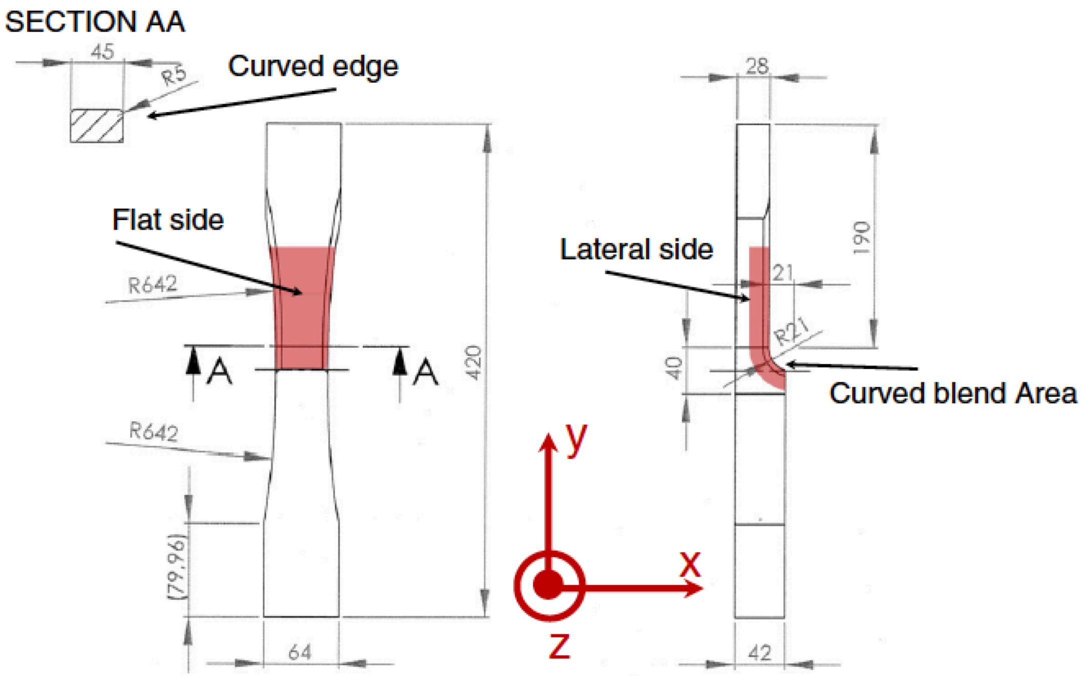
- Coratella, et al (Fitzpatrick group in UK)
  - Laser shock peened aluminum (7050 T7451)
  - http://dx.doi.org/10.1016/j.surfcoat.2015.03.026
- Hill Engineering work supported by AFRL
  - Cold compression stress relief in aluminum die forgings (7085 T7452 and T74)
  - “Engineering Residual Stress in Aerospace Forgings,” Proceedings of the International Conference on Residual Stress, Sydney, July 2016.

LSP 7050 aluminum

Evaluation RS from LSP

Residual stress data from

- Eigenstrain model
- Bulk measurements
  - Contour
  - Synchrotron XRD
  - Neutron diffraction
- Near surface measurements
  - Hole drilling
  - Lab XRD



Good care in work

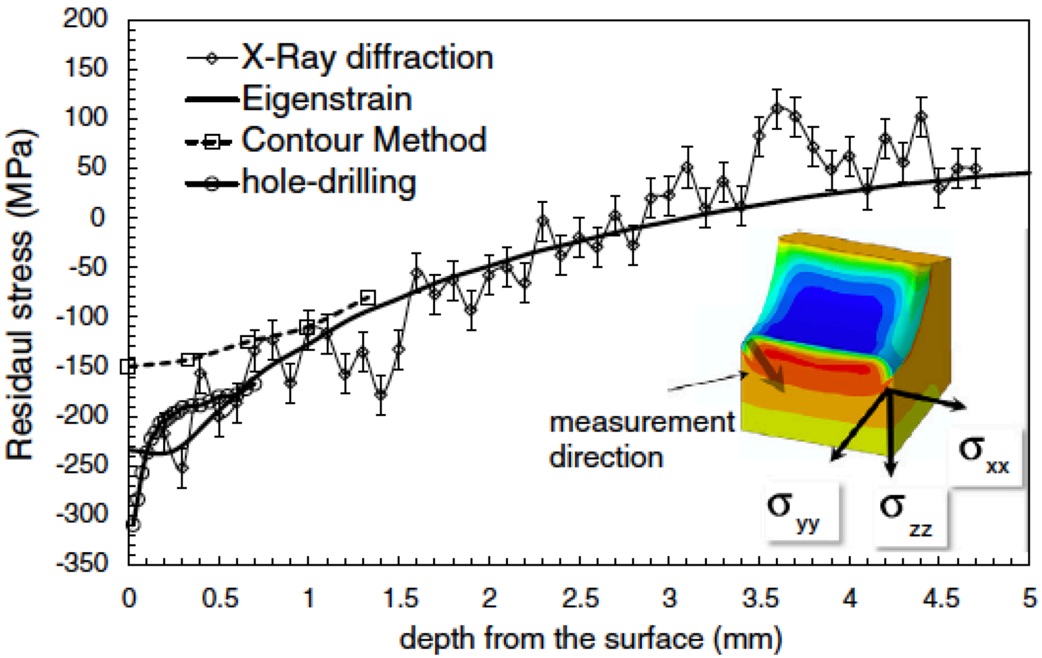
Reasonable correlation between data sets

Read the paper if you have time

LSP 7050 aluminum: Example results

Overall reasonably good correlation

Substantial differences point-wise and in trend



LSP 7050 aluminum: Example results

Overall reasonably good correlation

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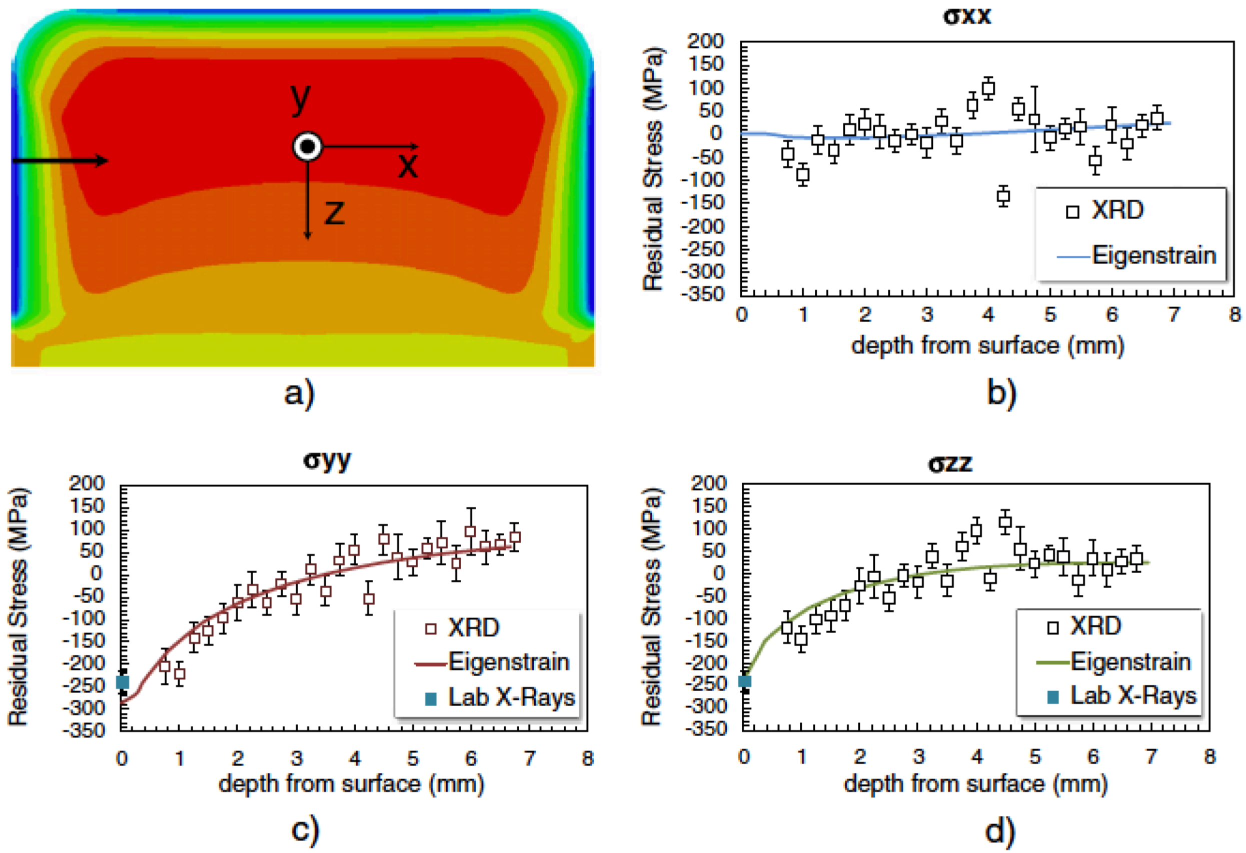
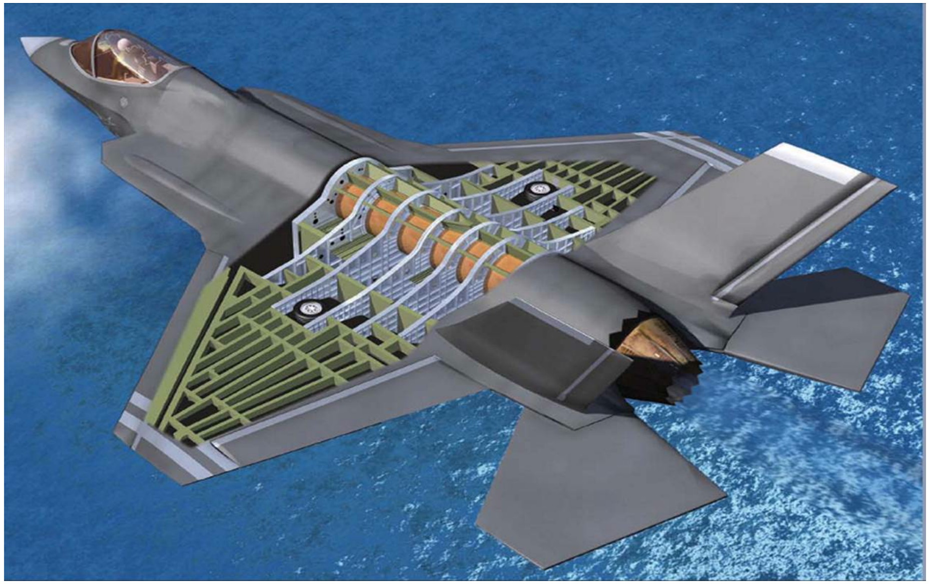


7085 T7452 die forgings

Cold compressed die forgings

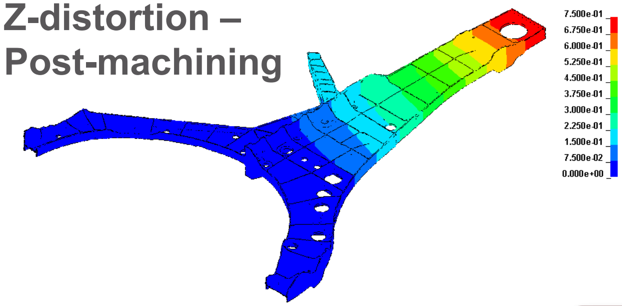
- Before cold compression: relatively high stress (±30 ksi)
- After cold compression: relatively low level of stress (±10 ksi)
- Large parts

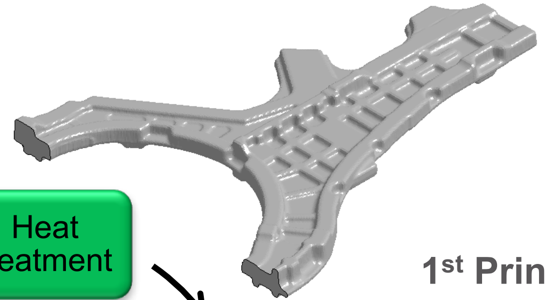
Large Forged Bulkhead (19.5 x 6.5 ft)
http://www.alcoa.com/



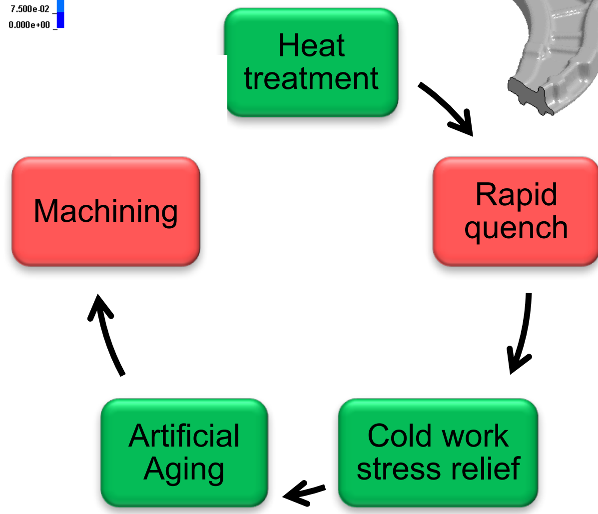
Alcoa model for aluminum forgings

Z-distortion – Post-machining

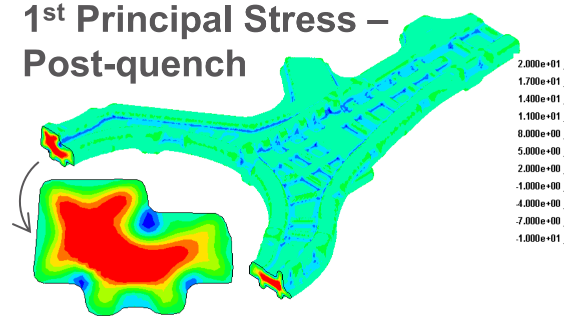




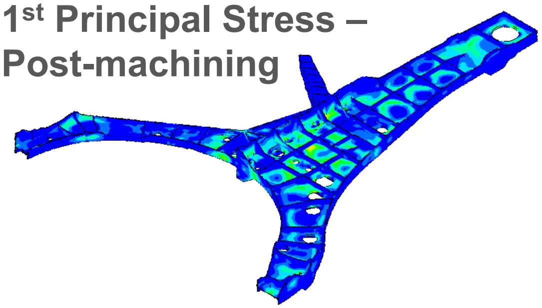
Heat treat Al 7085 @ elevated temperature ~895ºF



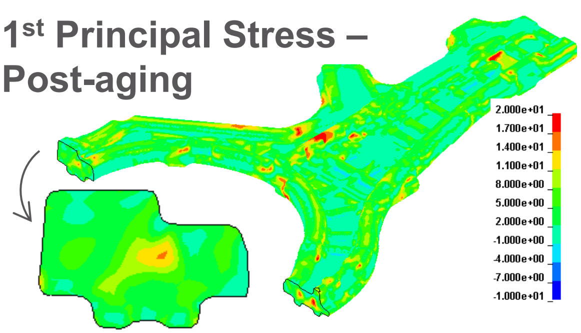
1st Principal Stress – Post-quench



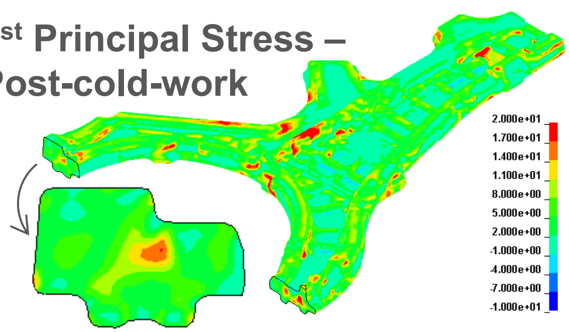
1st Principal Stress – Post-machining



1st Principal Stress – Post-aging



1st Principal Stress – Post-cold-work

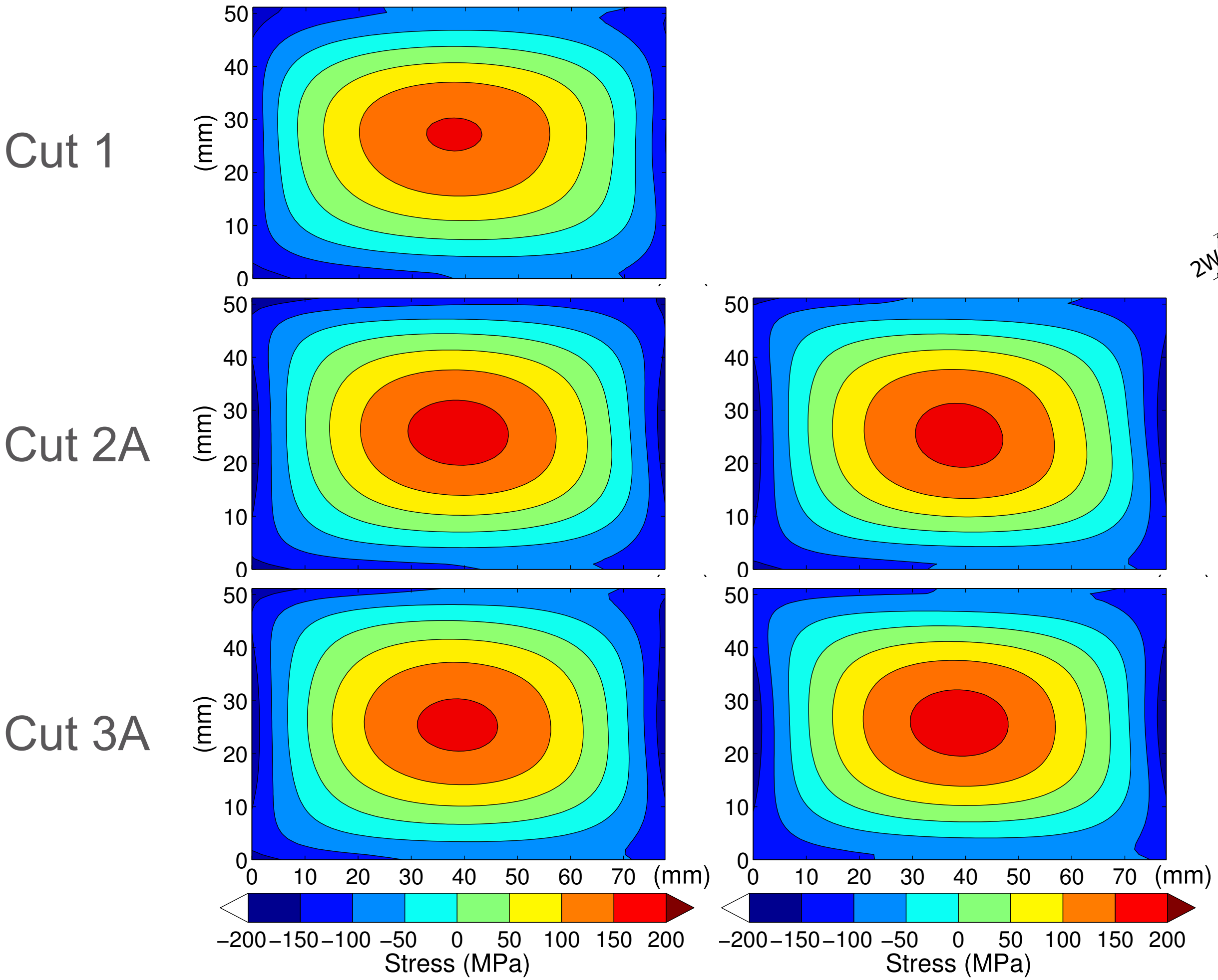


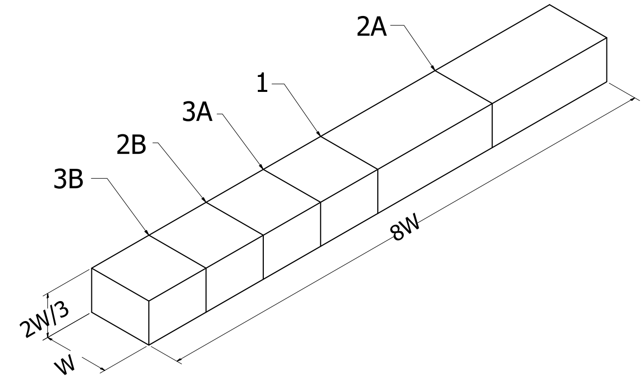
Process induced bulk residual stress finite-element model and validation measurements of an aluminum alloy forged and machined bulkhead, J.D. Watton, A.T. DeWald, et al., 2015 ASIP Conference, San Antonio, TX

Public Release 88ABW-2015-5301

Measurement precision: repeatability in quenched bar

Contour method stress mapping





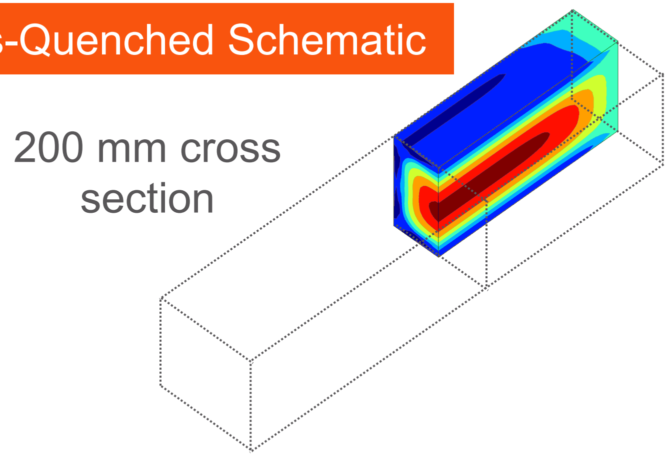
M.D. Olson, M.R. Hill. Repeatability of the contour method for residual stress measurement. Experimental Mechanics, 54: 1269-1277

Cross-method validation in large hand forging

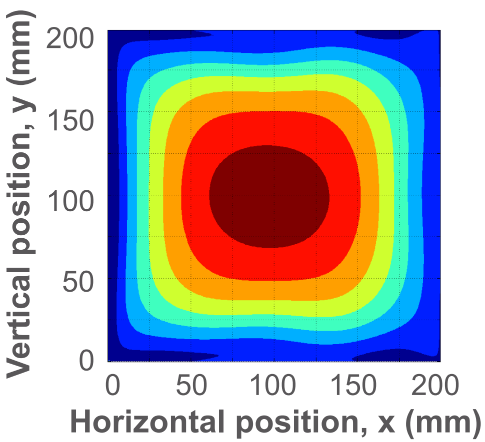
200 mm square-section quenched bar

Validation of Residual Stress Fields Determined from Material Process Models, M.R. Hill. A.T. DeWald, 2012, MS&T Symposium on ICME, Pittsburgh, PA

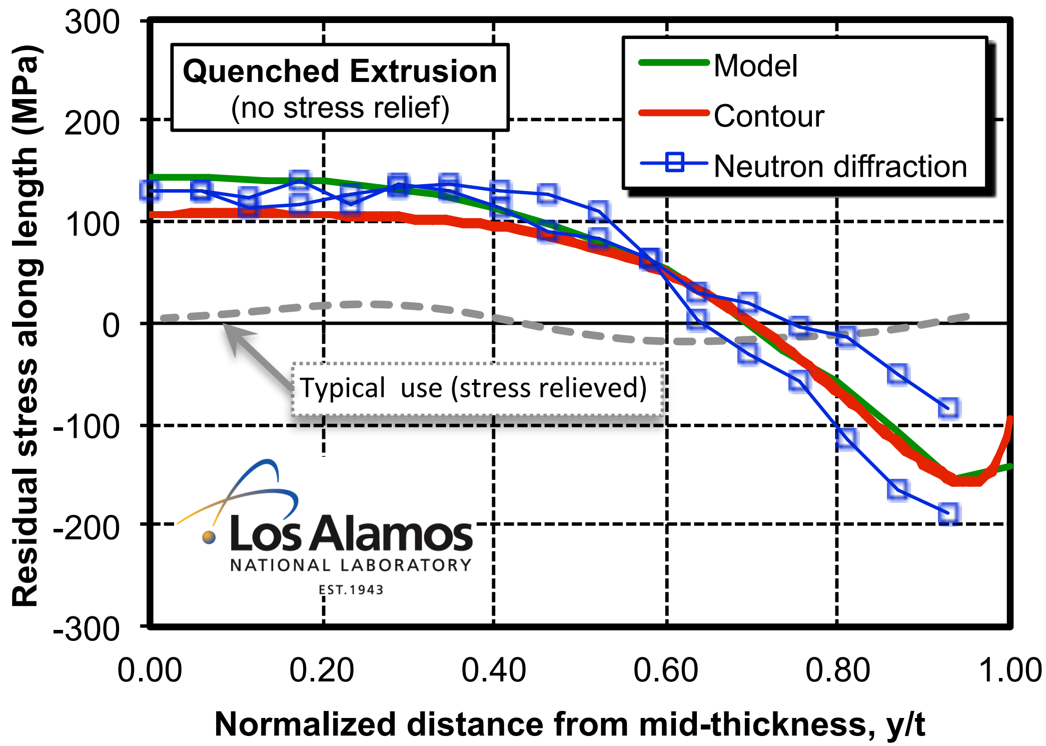
As-Quenched Schematic



Contour measurement



Validation: Quench model (Alcoa), Contour (HE), and Neutrons (LANL, UC Davis)



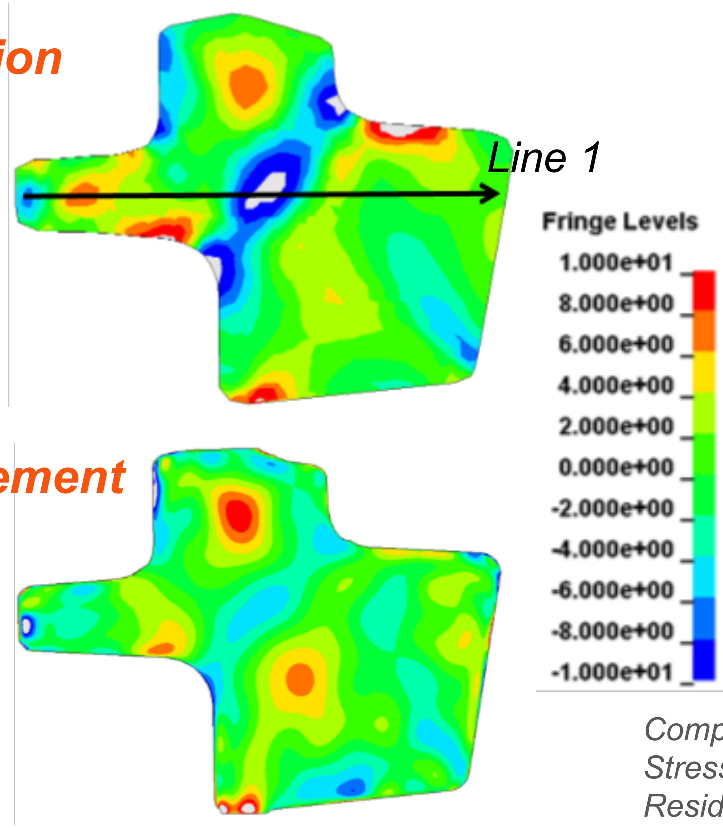
Model validation in aerospace die forging

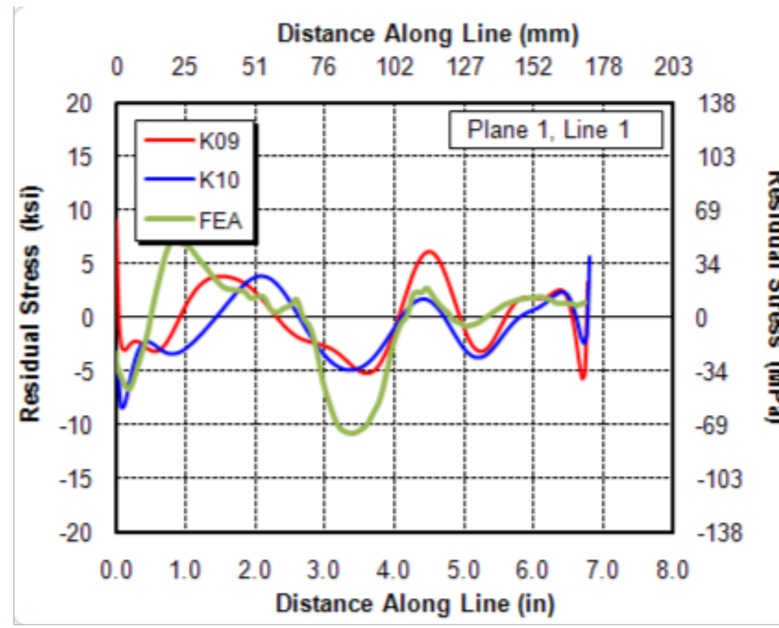
Model to measurement correlation – small, 7085 die forgings
Stress relieved condition

- Not shown, but important: measurement precision, model uncertainty

Simulation

Measurement



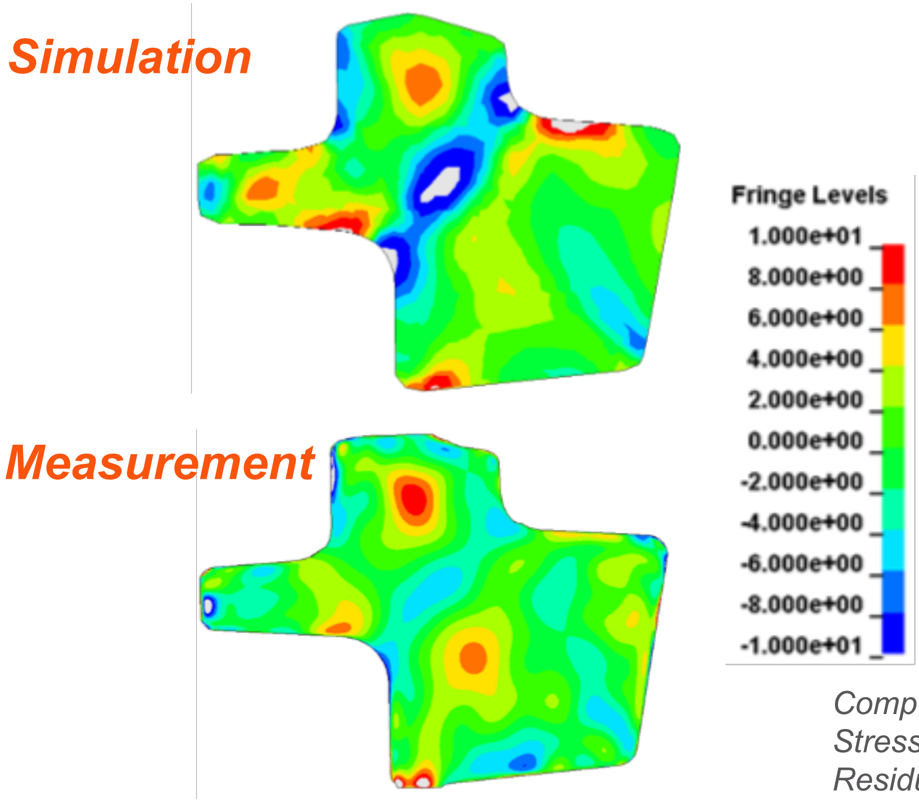


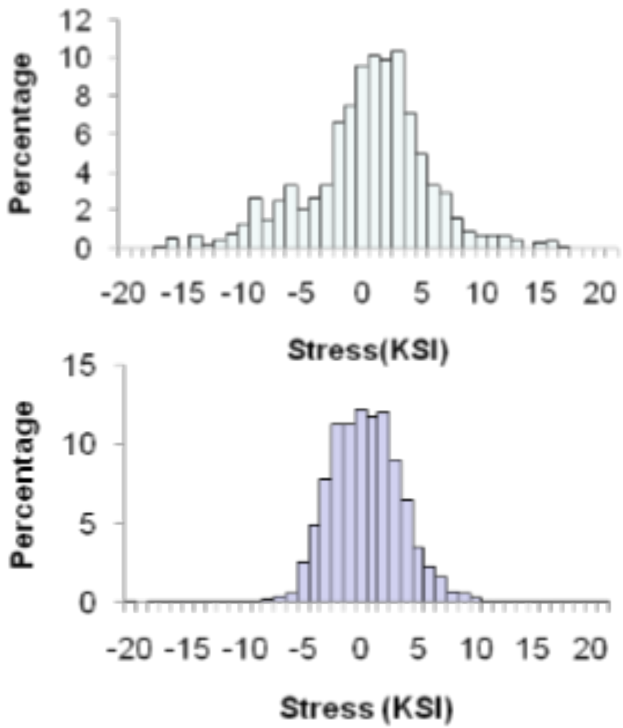
Computational Modeling and Optimization of Bulk Residual Stress in Monolithic Aluminum Die Forgings, J.D. Watton, 2010 Residual Stress Summit, Tahoe City, CA

Model validation in aerospace die forging

Model to measurement correlation – small, 7085 die forgings
Stress relieved condition

- Measurements confirm ability of model to estimate residual stress levels and distribution



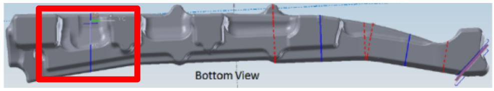


Computational Modeling and Optimization of Bulk Residual Stress in Monolithic Aluminum Die Forgings, J.D. Watton, 2010 Residual Stress Summit, Tahoe City, CA

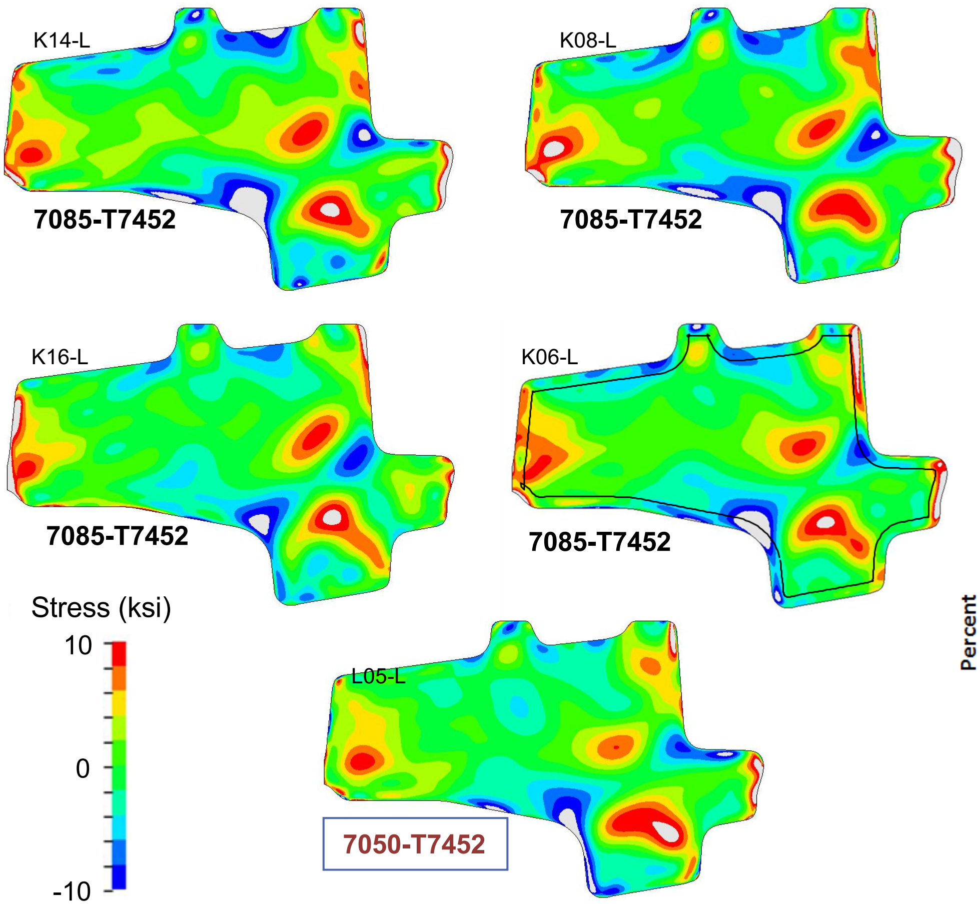
Process consistency in aerospace die forging

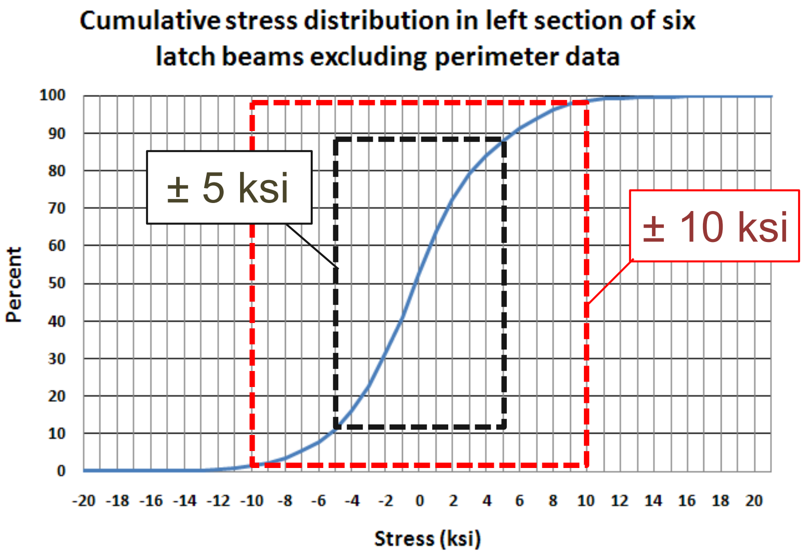
Contour measurements in 6 forgings

(Mark James, Alcoa, 2012 Aeromat)

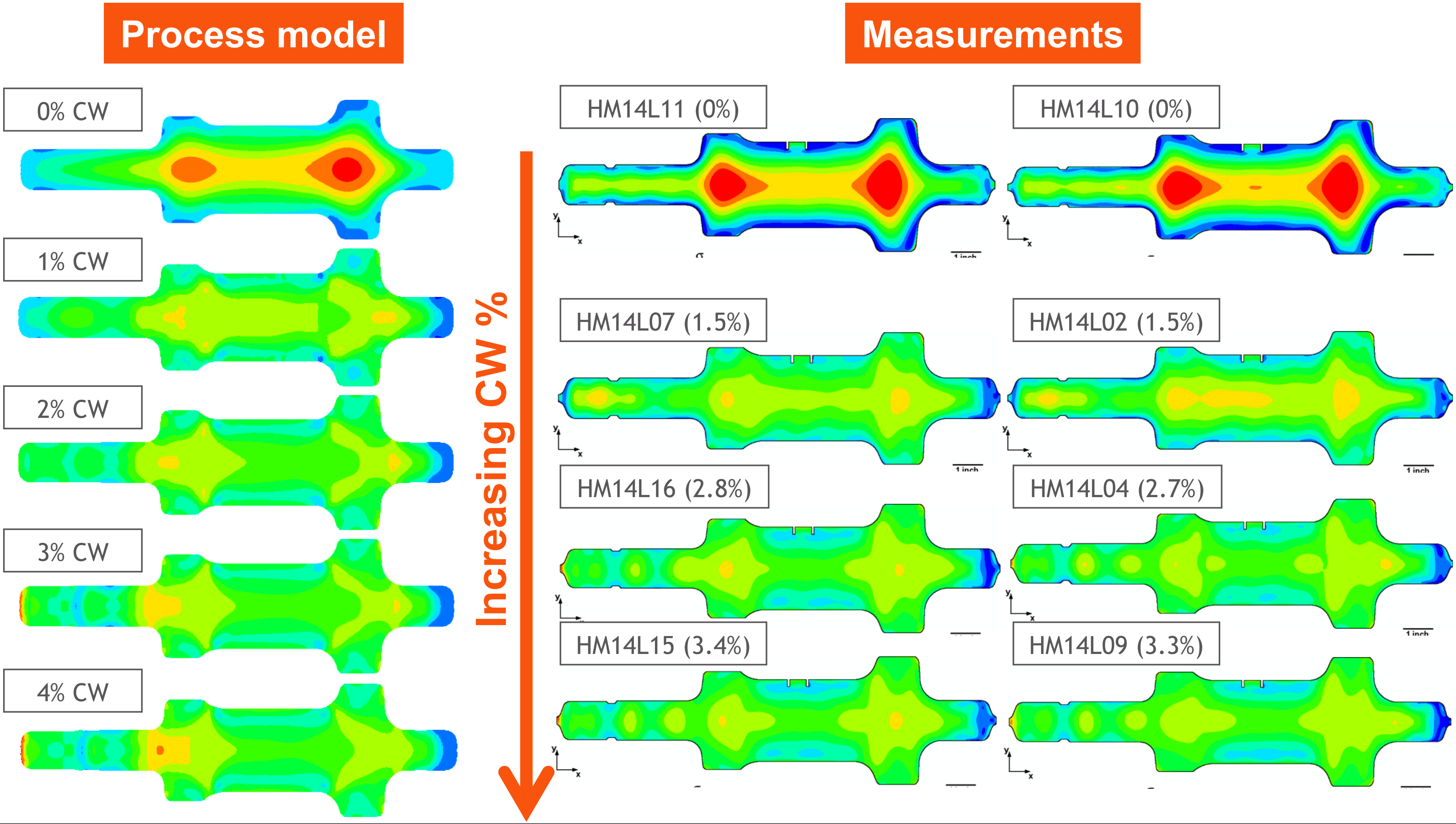


MAI Export Control Clearance:
88ABW-2012-3018



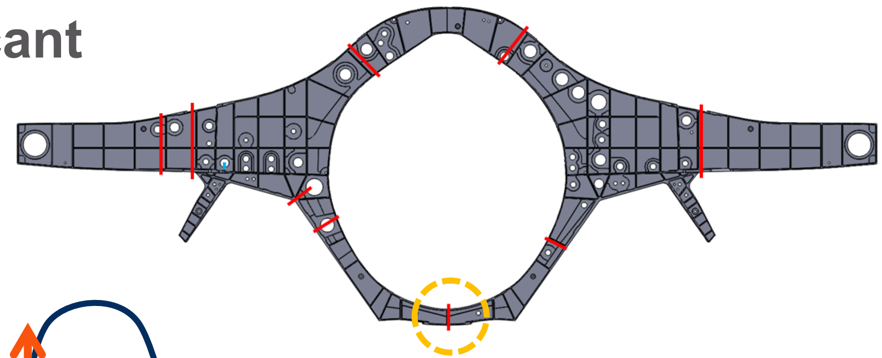


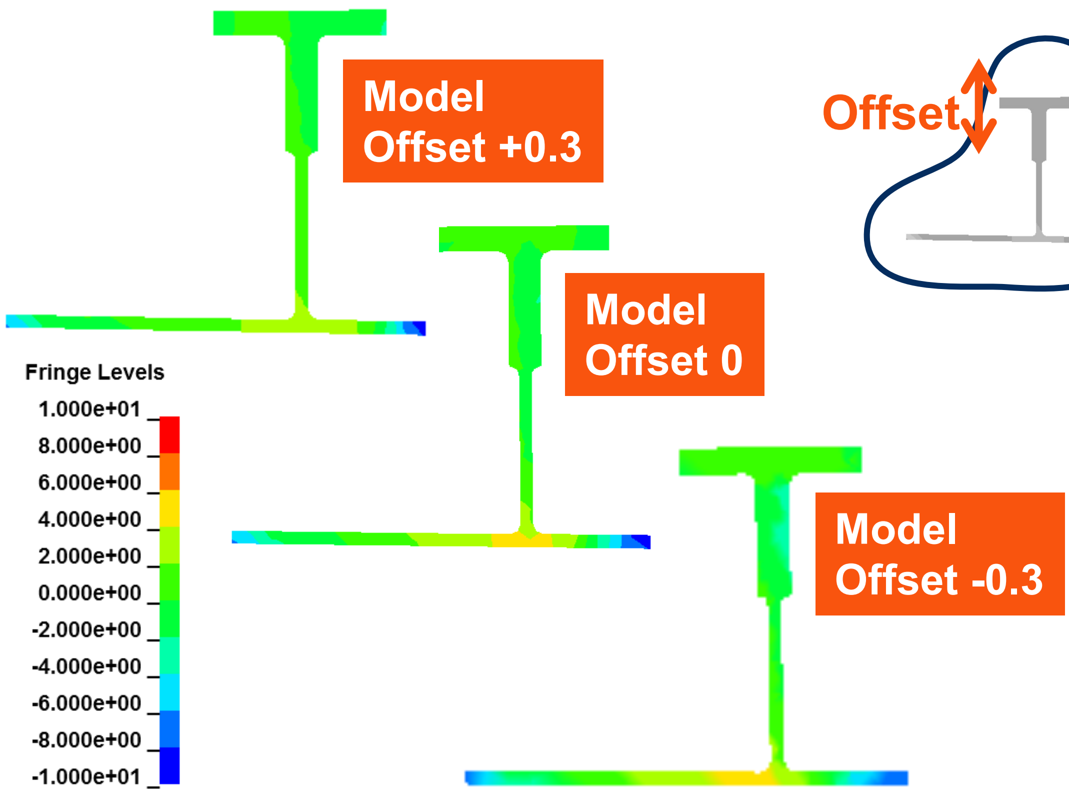
Validation of process sensitivity in aero die forging

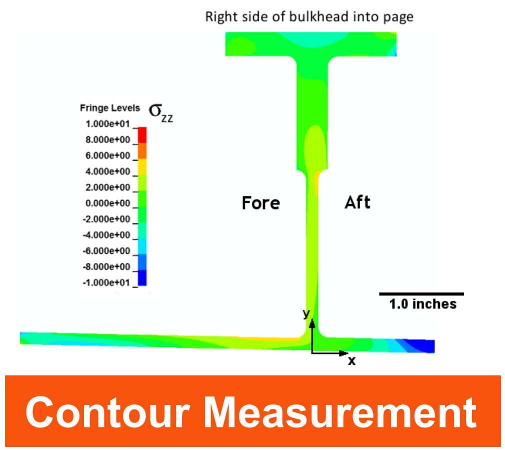


Validation of residual stress in machined parts

Part placement (offset) has a significant effect on RS model output





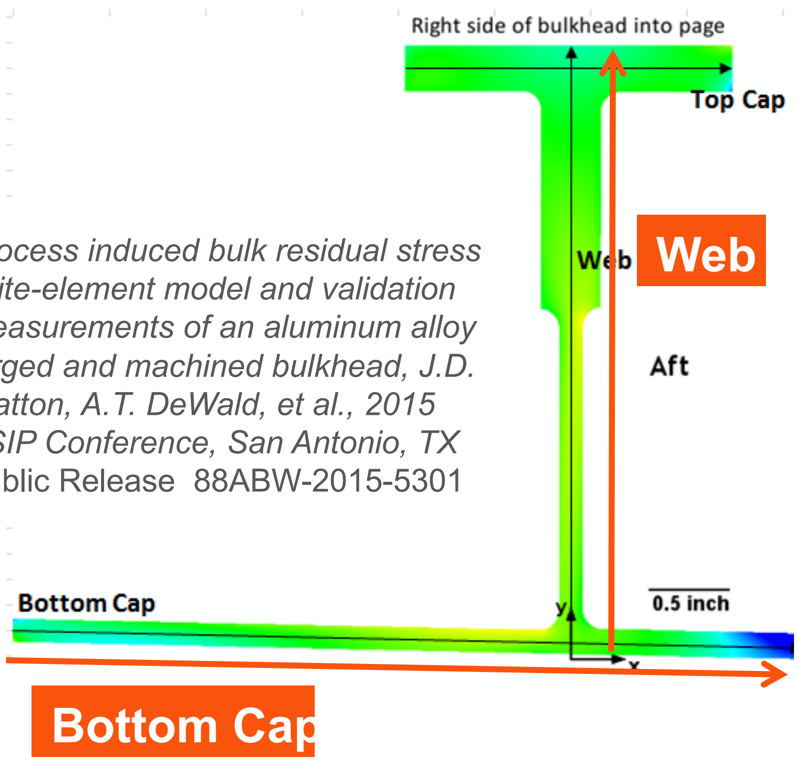


Process induced bulk residual stress finite-element model and validation measurements of an aluminum alloy forged and machined bulkhead, J.D. Watton, A.T. DeWald, et al., 2015 ASIP Conference, San Antonio, TX Public Release 88ABW-2015-5301

Validation of residual stress in machined parts

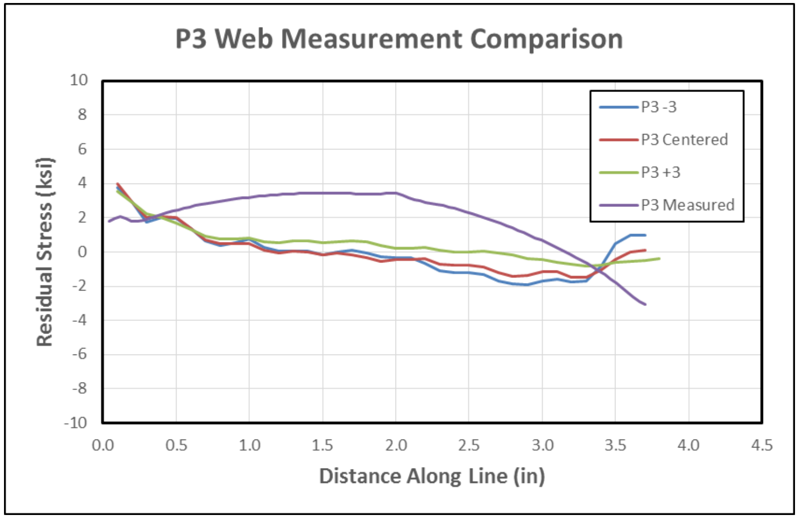
Validation of residual stress in machined component

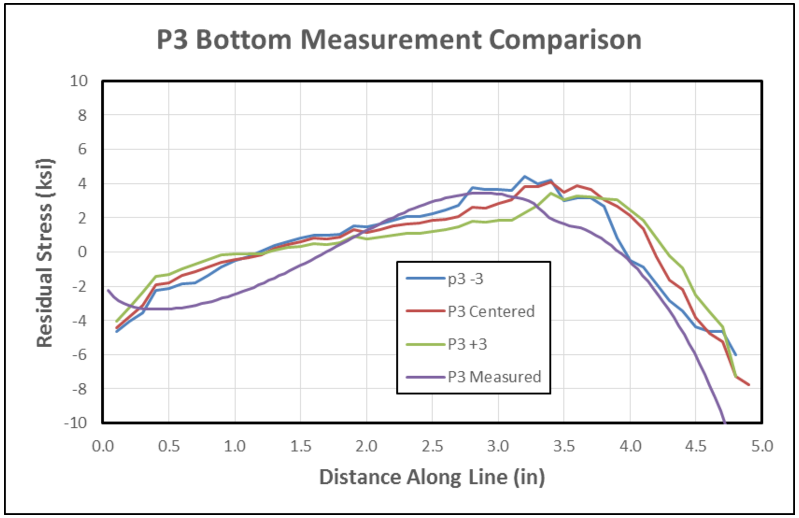
- Agreement within ±3 ksi



Process induced bulk residual stress finite-element model and validation measurements of an aluminum alloy forged and machined bulkhead, J.D. Watton, A.T. DeWald, et al., 2015 ASIP Conference, San Antonio, TX

Public Release 88ABW-2015-5301

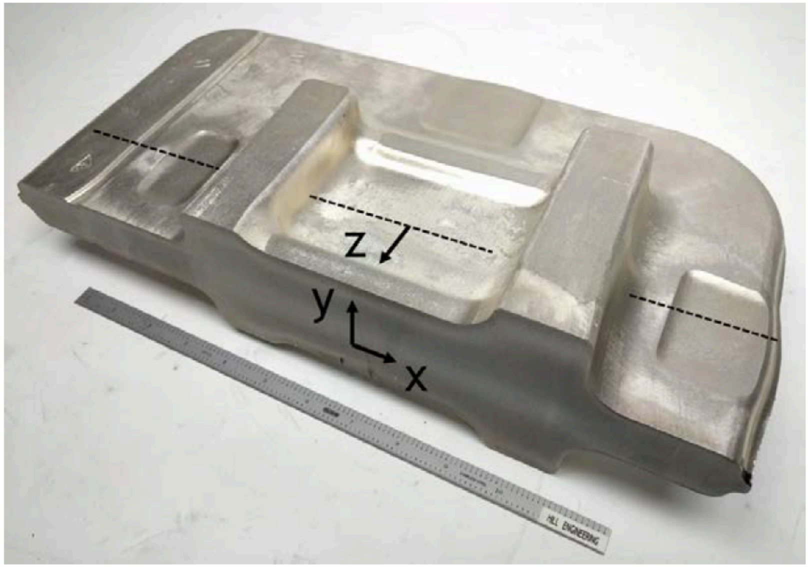


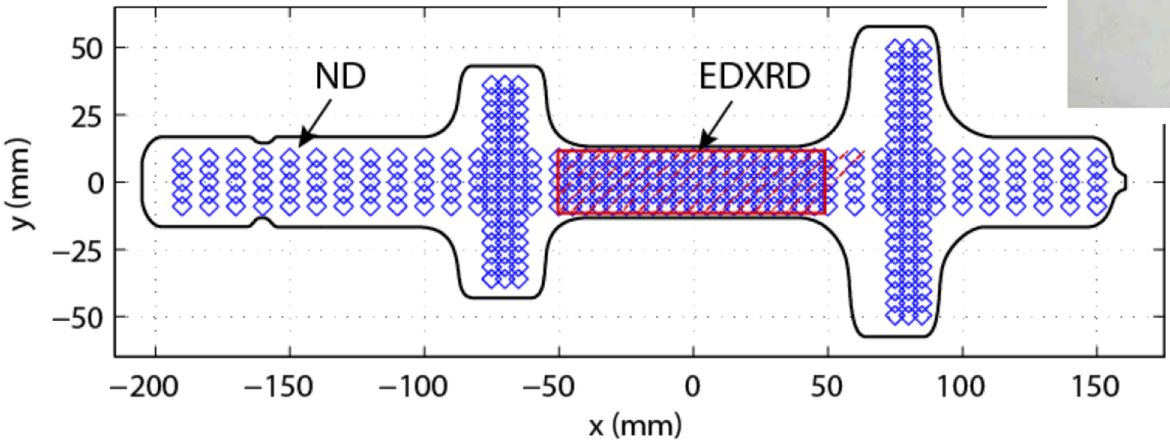


Die Forgings: Recent cross-method validation

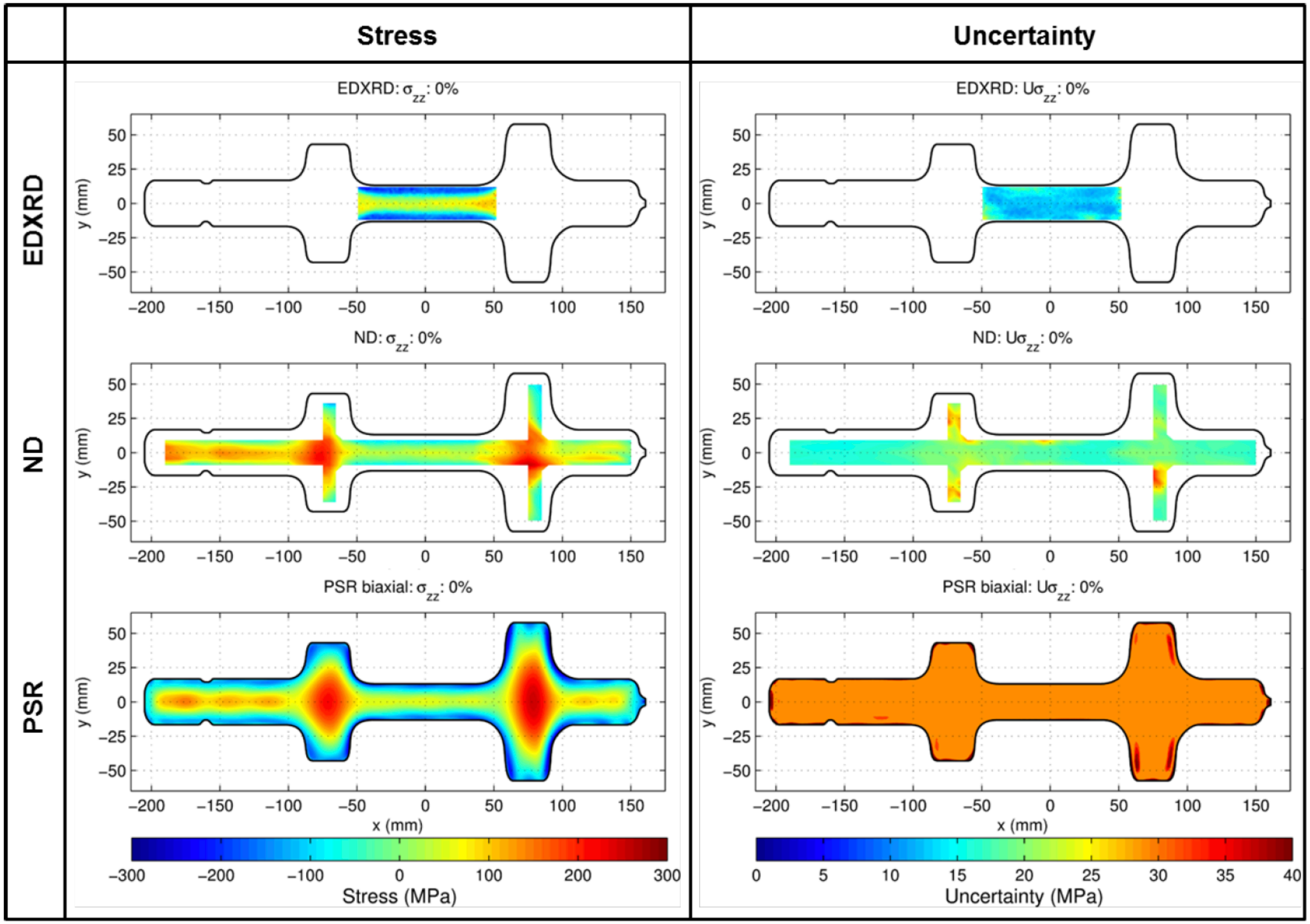
Ref: Olson, Spradlin, et al, 2017, Multi-Technique Residual Stress Measurement Comparison in 7085-T7452 Aluminum Die Forgings (to appear)

- PSR biaxial mapping (HE)
  - Contour + Slitting
- Neutron diffraction (SNS)
  - Sampling volume: 5 x 5 x 5 mm
- EDXRD (synchrotron, APS)
  - Sampling volume: 0.1 mm x 1 mm x 7°

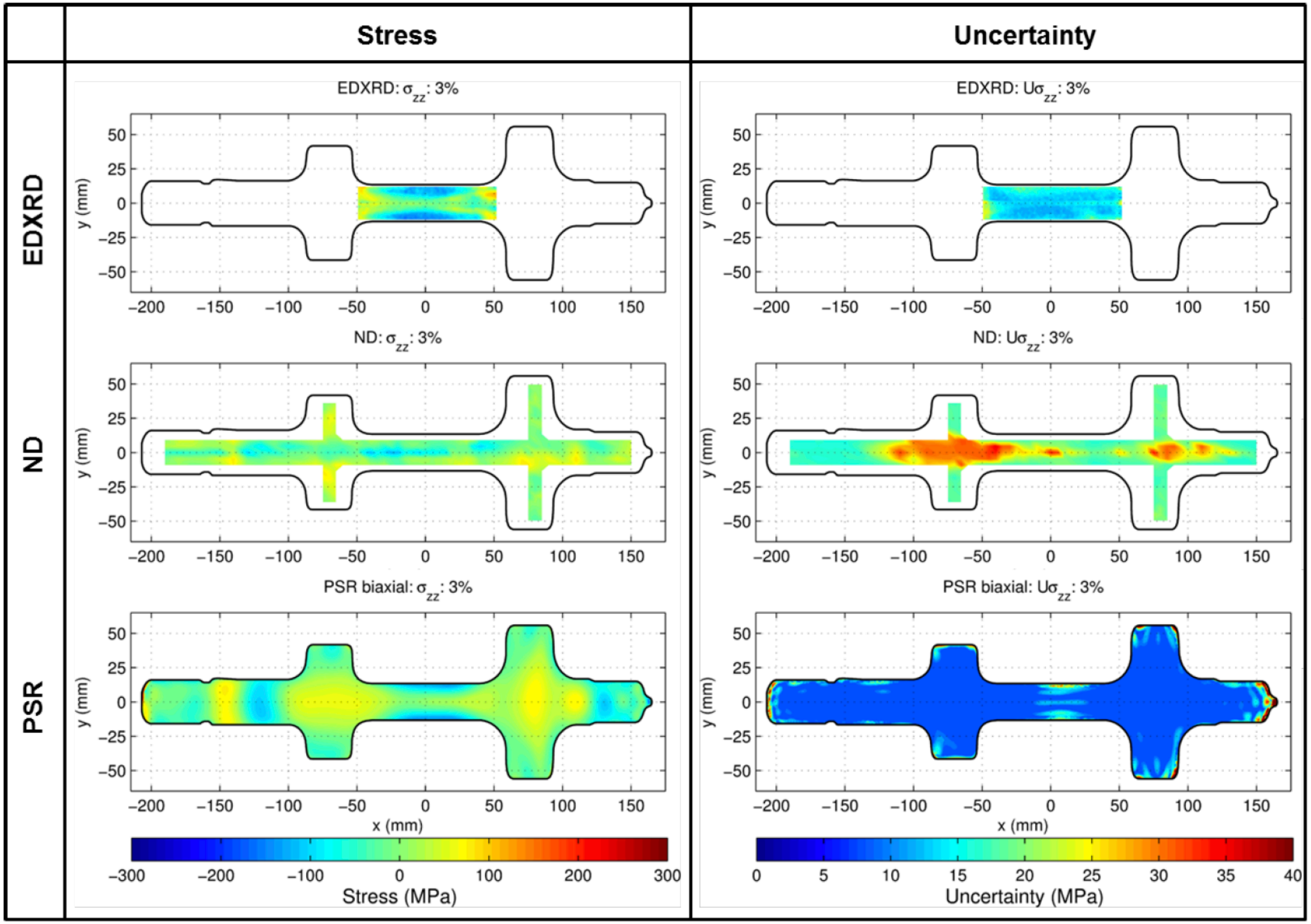




Die Forgings: AQ σ_{zz} inter-method comparison



Die Forgings: 3% CW σ_{zz} inter-method comparison



Die Forgings: 3% CW σ_{zz} inter-method comparison

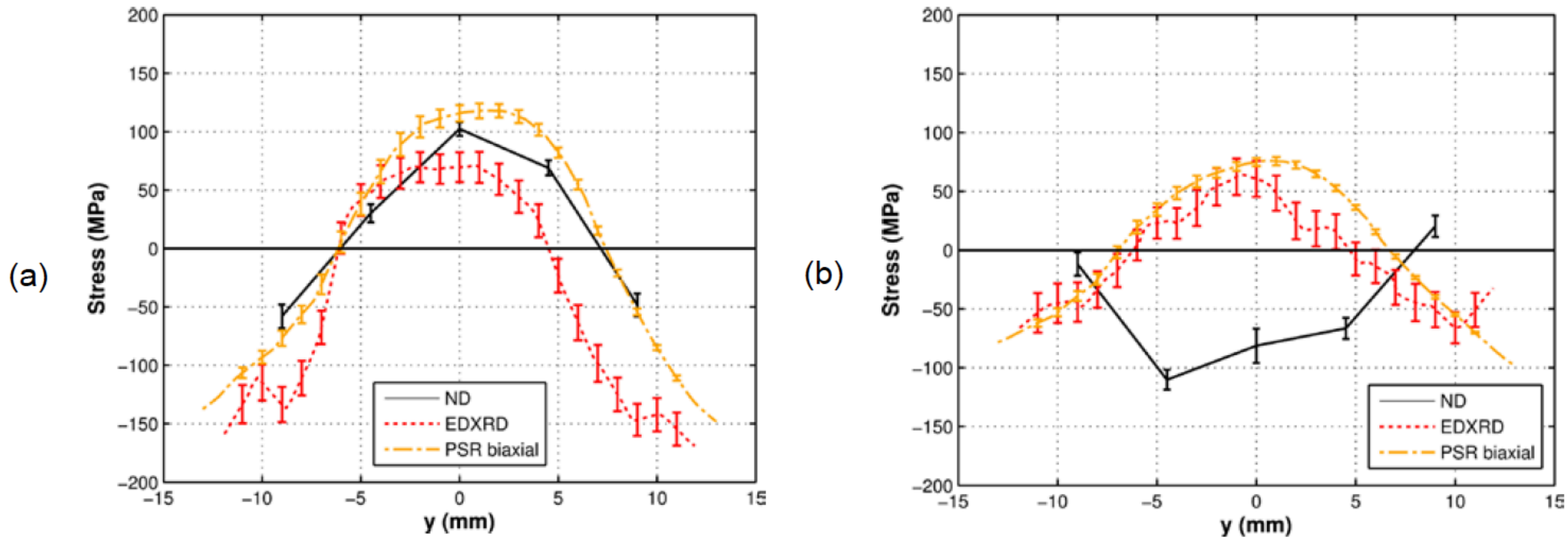


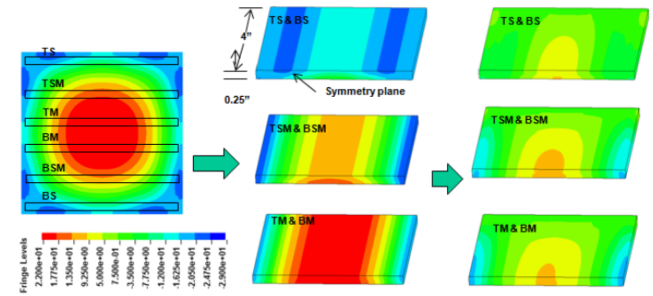
Figure 14: Line plots of the σ_{xx} stress from each of the measurement techniques along the line at x = 0 for the (a) 0% and (b) 3% cold-working conditions

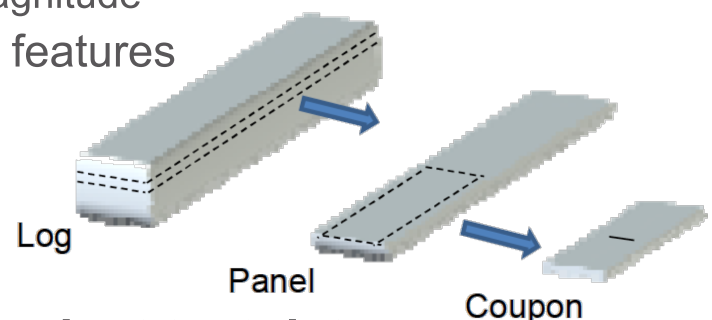
Validation of the impact of RS on fatigue analysis

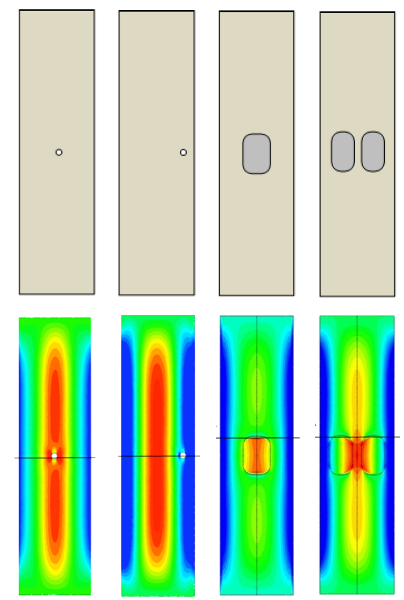
Fatigue crack initiation and crack growth tests

Develop set of coupons with range of residual stress

- Start with large quenched log with high residual stress (up to 150 MPa)
- Remove panels at various positions
  - Range of residual stress magnitude
- Make coupons with design features
  - Centered hole (+RS)
  - Offset hole (–RS)
  - Center pocket (+RS)
  - Double pocket (+RS)







Validate fatigue analysis against test data

- Crack initiation
- Crack growth

Include or ignore residual stress in analysis

The Impact of Forging Residual Stress on Fatigue in Aluminum, D.L. Ball, M.A. James, et al. http://arc.aiaa.org/doi/abs/10.2514/6.2015-0386

Validation of the impact of RS on fatigue analysis

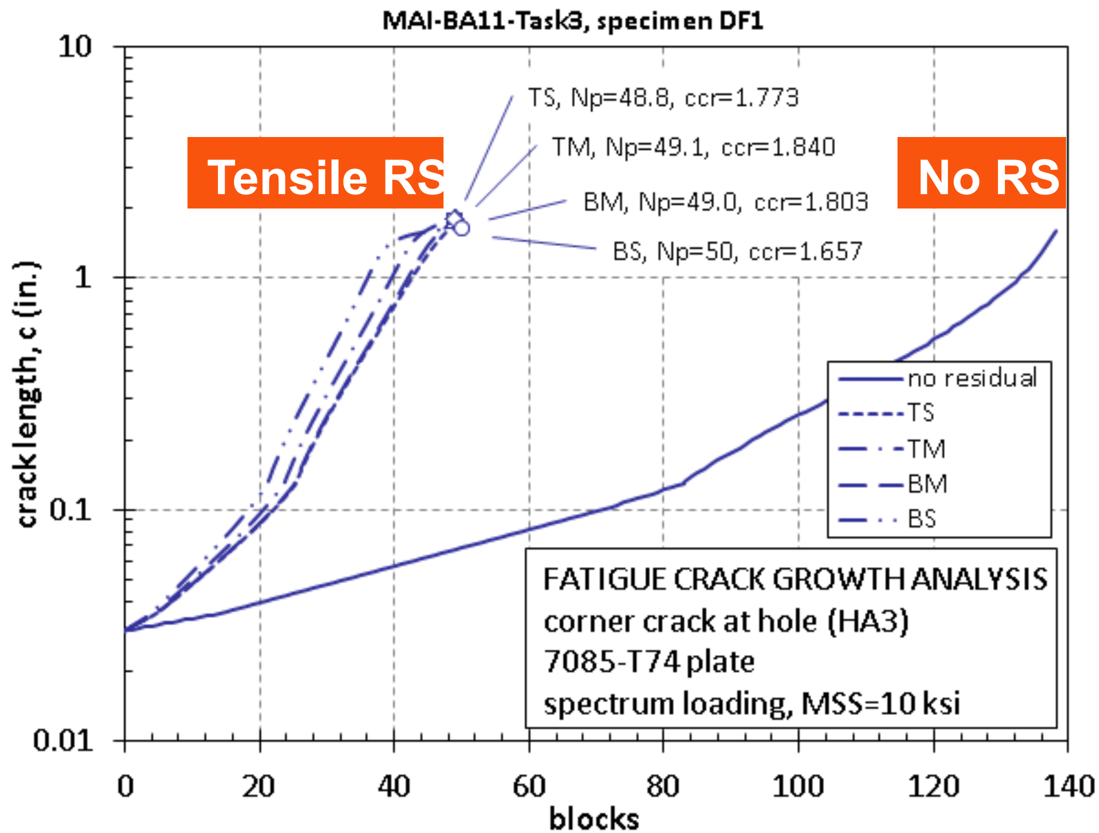
Fatigue Crack Growth Analysis

- Use superposition to include residual stress in LEFM analysis
- Most accurate for tensile residual stress

Tensile RS can cause significant increase in crack growth rate

- Decrease in life compared to baseline (no RS)

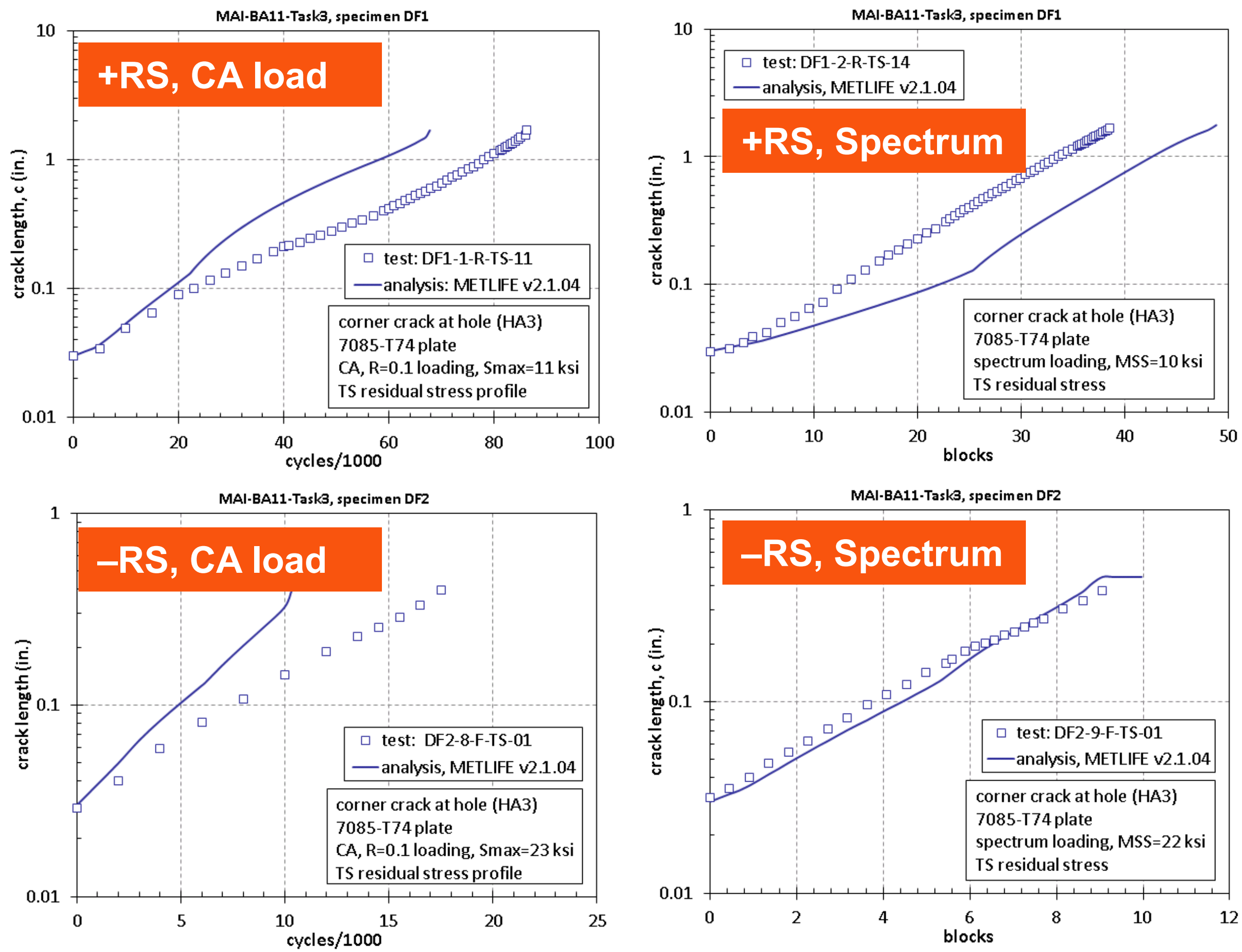
The Impact of Forging Residual Stress on Fatigue in Aluminum, D.L. Ball, M.A. James, et al. http://arc.aiaa.org/doi/abs/10.2514/6.2015-0386



Validation of the impact of RS on fatigue analysis

FCG models correlate reasonably well with test data

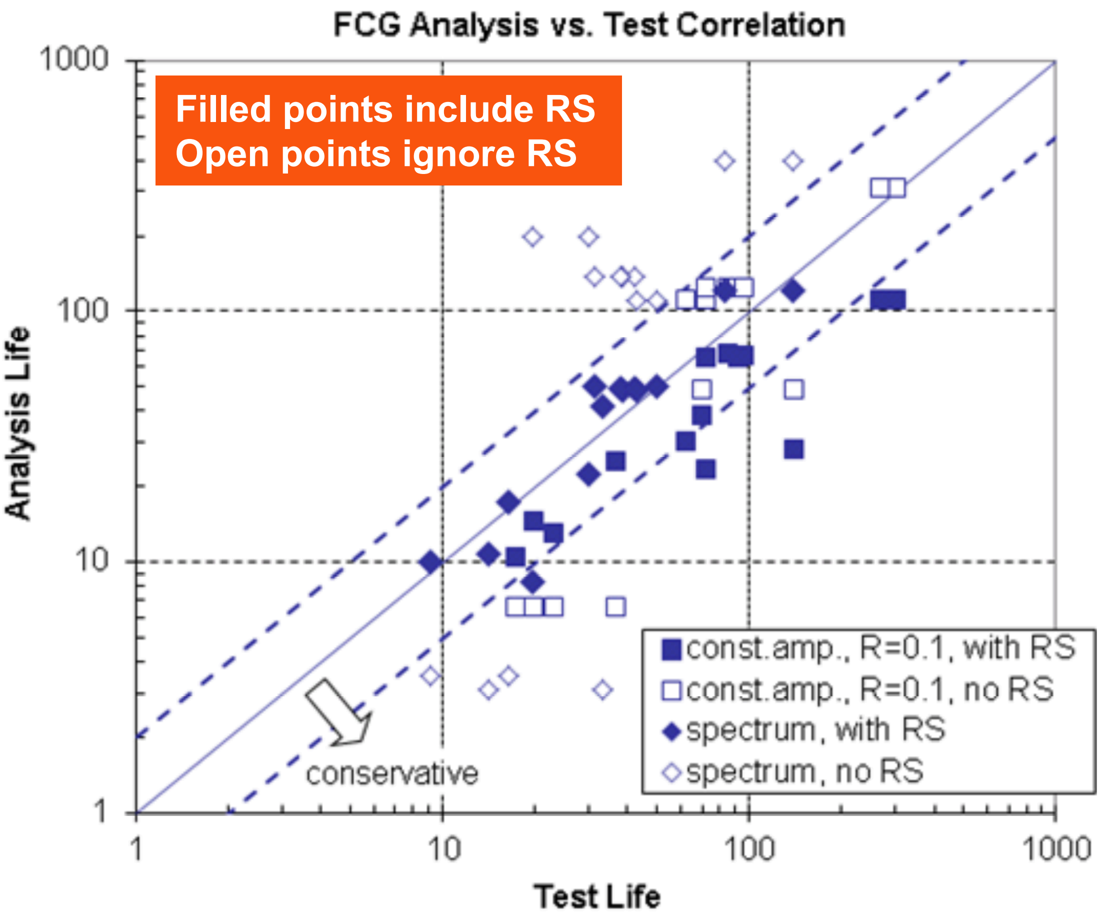
- Residual stress
  - Tensile
  - Compressive
- Loading
  - Spectrum
  - Constant Amplitude

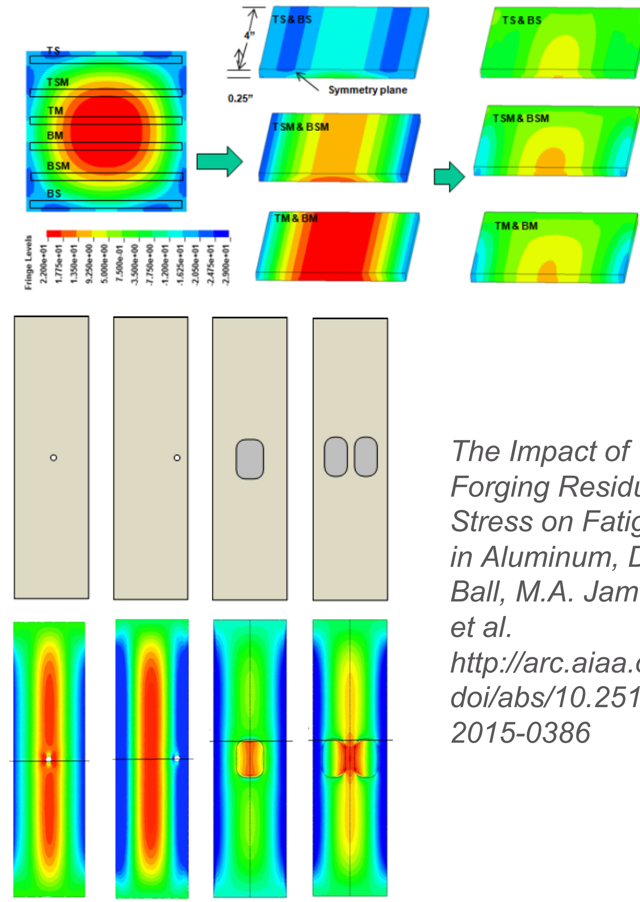


The Impact of Forging Residual Stress on Fatigue in Aluminum, D.L. Ball, M.A. James, et al. http://arc.aiaa.org/doi/abs/10.2514/6.2015-0386

Validation of fatigue in parts removed from forgings

Fatigue crack growth tests: correlation of 6 unique coupon types in material with high residual stress





The Impact of Forging Residual Stress on Fatigue in Aluminum, D.L. Ball, M.A. James, et al. http://arc.aiaa.org/doi/abs/10.2514/6.2015-0386

Summary of Topics for Today

Measurements of stress at Legacy vs New CX holes (HE)

- Data to date suggest legacy CX consistent with lab practices
- Data to date suggest no effect of service loading on RS (lower skin)

Measurements of Stresses at Cracked CX Holes (Carlson)

- Residual stress in cracked CX holes is changed from stress in new holes
  - Effect related to crack size in 2324-T351, but not related to crack size in 7075-T651

Recent Near-surface Stress Measurements (Castle)

- Near-surface stresses, near the bore edge may be tensile in a small area

Recent Near-bore Stress Measurements (HE)

- Slitting data for 2324-T351 CX holes consistent with contour data
- Slitting data for 7075-T651 CX holes less compressive than contour data with 0.02” of the bore

Concept for Large Hole Experiments (HE)

- Large holes with lower gradients that will be easier to measure

Recent Cross-method Residual Stress Validations (LSP and Die forgings)

- Provided data from prior programs to convey challenges and opportunities in cross-method residual stress validation data