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Measurements Sub-group Update

Topics for Today

Contour method round robin

Measurements of residual stress at legacy versus new CX holes

Residual stress quality system

Large CX hole experiments

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Measurements Sub-group Update

Contour Method Round Robin

Contour Method Round Robin

Organization: Scott Carlson, Marcus Stanfield, Mark Thomsen

- Efforts by 6 participating labs (mix of industry, government, academia)

Purpose: Provide initial assessment of contour method inter-laboratory repeatability

- Contour consists of cutting, measuring, data analysis, stress analysis
- Current focus on data analysis and stress analysis

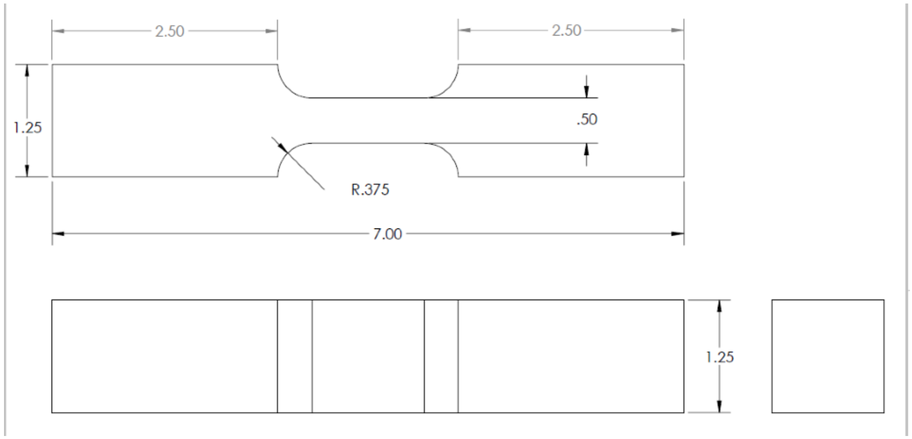
Approach

- Subject is an elastic-plastic bent beam (prior benchmark)
- Multi-phase program of blind analyses (participants don't interact)
  1. Pure calculation, using simulation derived stress field and surface data
  2. Controlled experiment
- For each phase:
  - Provide same data sets to all participants (surface profiles)
  - Request submission of estimated residual stress field
  - Assess submissions
  - Discuss results
  - Document findings

Contour Method Round Robin

Phase 1 description

- Context is a simulation of an elastic-plastic bent beam
  - Classical residual stress experiment used for method validation
- Simulation performed by SwRI
  - Bend beam in four-point configuration
  - Cut beam (remove symmetry constraints)
  - Extract surface profile of deformed surface
  - Add noise
- Send to surface profiles to participants for blind analysis
- Collect and assess results returned
  - Compare submissions to simulation benchmark (known stress)



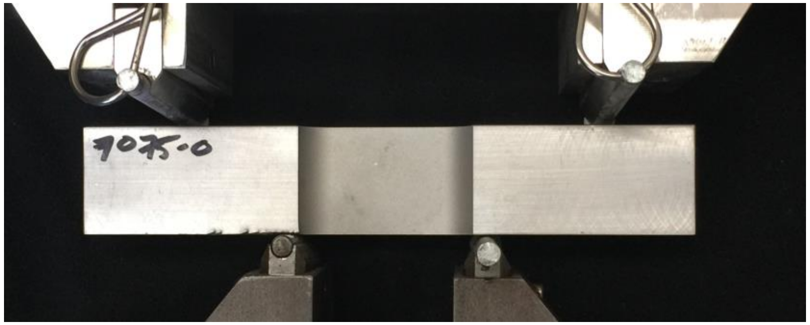
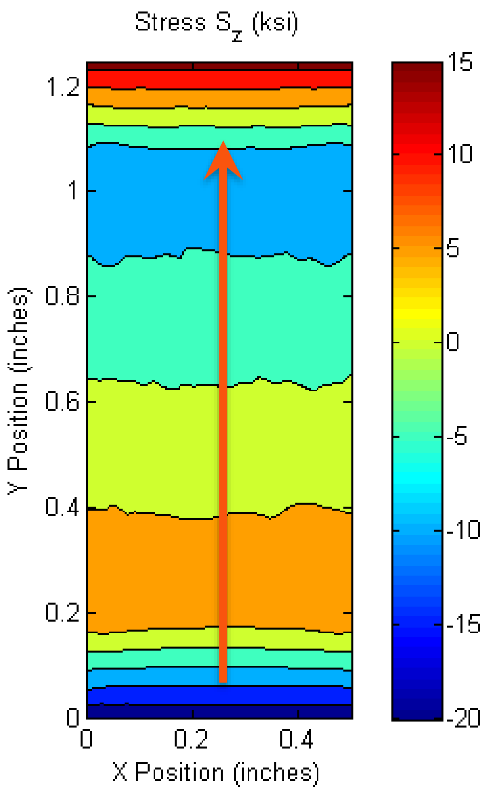


Photo of experimental set-up corresponding to simulation

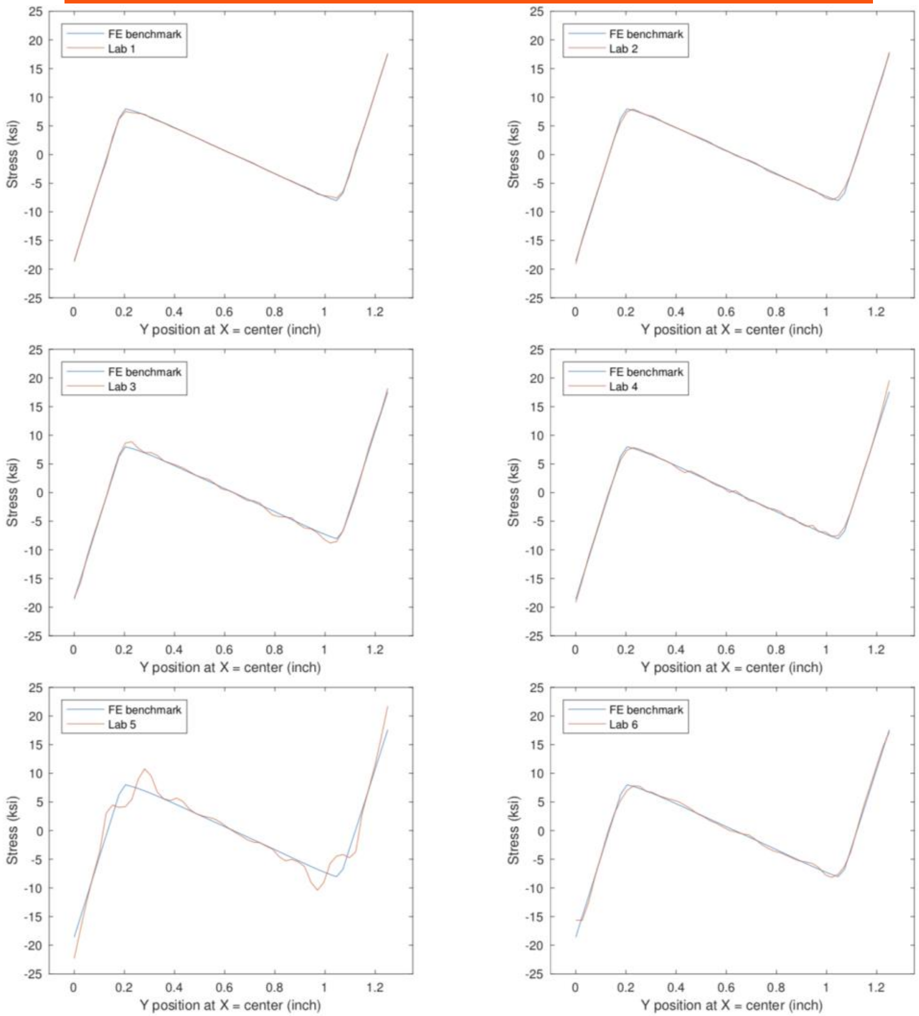
Contour Method Round Robin

Phase 1 results

Example submission



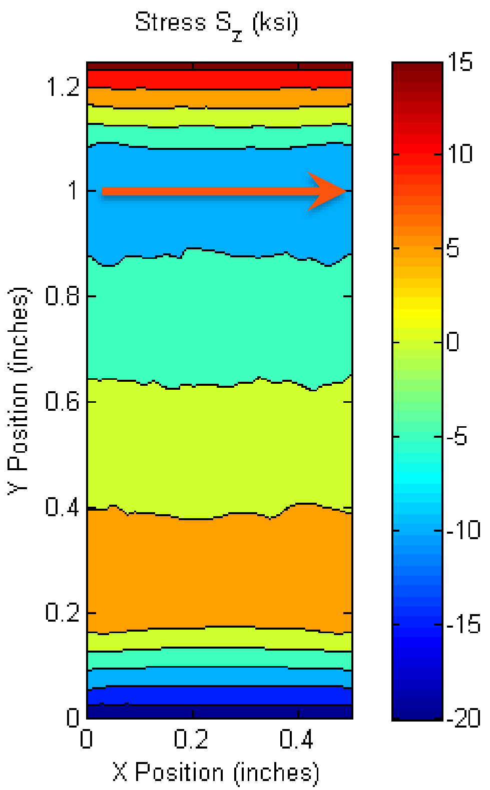
Line plots of each submission with FE benchmark



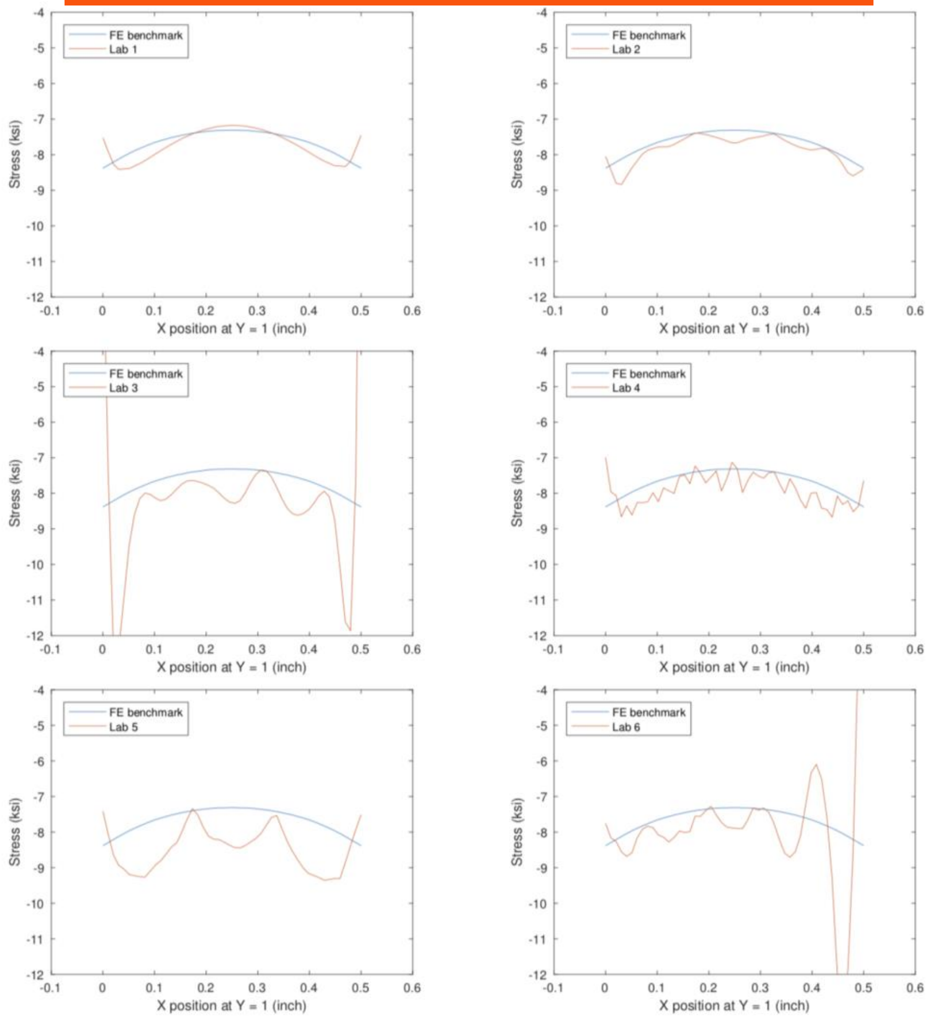
Contour Method Round Robin

Phase 1 results

Example submission



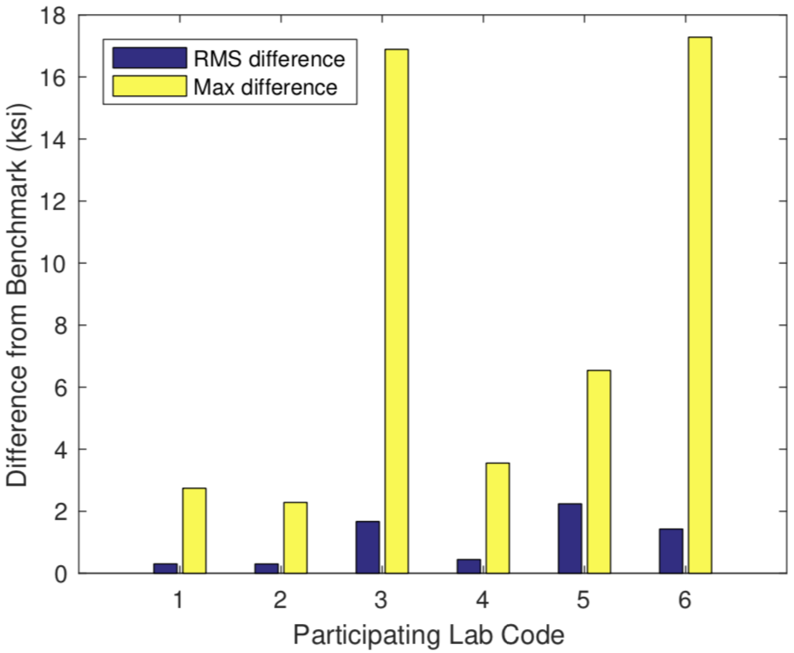
Line plots of each submission with FE benchmark



Contour Method Round Robin

Phase 1 results

- Given the same input data, participants return results very similar to the benchmark simulation stress field
  - RMS difference with benchmark better than 2 ksi
  - Some participant results had localized differences in stress
    - Consistent with those labs using approaches with less smoothing



Phase 2 uses experimental data

- Work nearly complete

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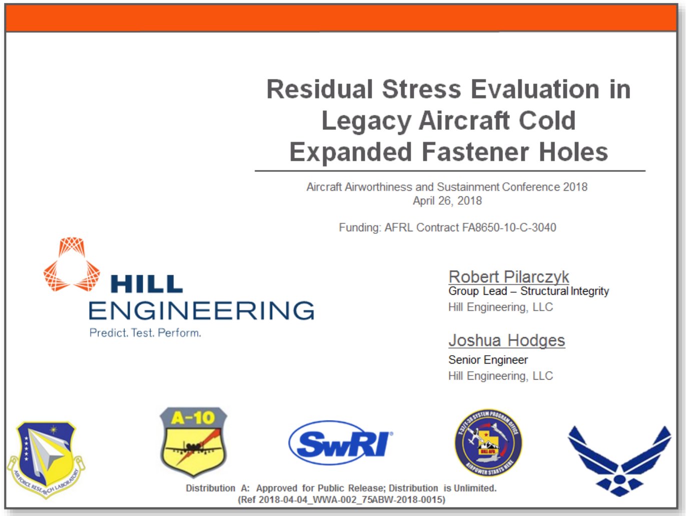
Measurements Sub-group Update

Legacy vs New CX Residual Stress Evaluations

Note: this is an excerpt taken from here:



Residual Stress Evaluation in Legacy Aircraft Cold Expanded Fastener Holes

Aircraft Airworthiness and Sustainment Conference 2018
April 26, 2018

Funding: AFRL Contract FA8650-10-C-3040

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Distribution A: Approved for Public Release; Distribution is Unlimited.
(Ref 2018-04-04_WWA-002_75ABW-2018-0015)

Co-Authors

Tremendous team supporting program:

- A-10 & T-38 Aircraft Structural Integrity Teams
  - Dr. Mark Thomsen
  - Dr. Mike Blinn
- Air Force Research Lab
  - Dr. Pam Kobryn
  - Scott Wacker
- Southwest Research Institute (SwRI)
  - Dallen Andrew
  - Dr. Scott Carlson
- Hill Engineering
  - Dr. Mike Hill
  - Dr. Adrian DeWald

Program Overview & Approach

Overview

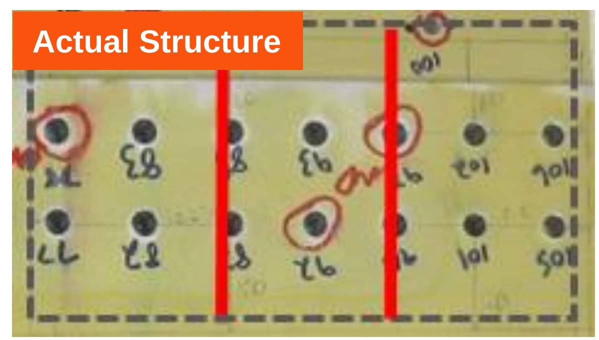
- Investigate cracking and residual stress at Cx holes from retired fleet assets to understand if there is a degradation over time as a result of loading or environment

Approach

- Full A-10 wing teardown – disassembly, NDI, fractography, RS measurement
- Residual stress measurements of legacy assets (A-10/T-38)
- Residual stress measurements of newly manufactured specimens
  - Replicate legacy asset configurations
- Compare/contrast residual stresses between new manufacture and teardown coupons

Lab Coupons

? =


Actual Structure

History of Teardown Assets

A-10 asset

- (1) Center Wing Assembly
- Location details:
  - Lower wing structure (skins/spars)
  - 2000 series aluminum
  - Production and depot rework Cx
- Usage details:
  - Predominantly tension loads – 40-85% FTY (peak)
  - Negligible compression ~ -5 ksi
- Service history:
  - Service life: 33 years
  - SLEP: 2004
  - Retirement: 2012
  - Average usage severity
  - Moderate EFH

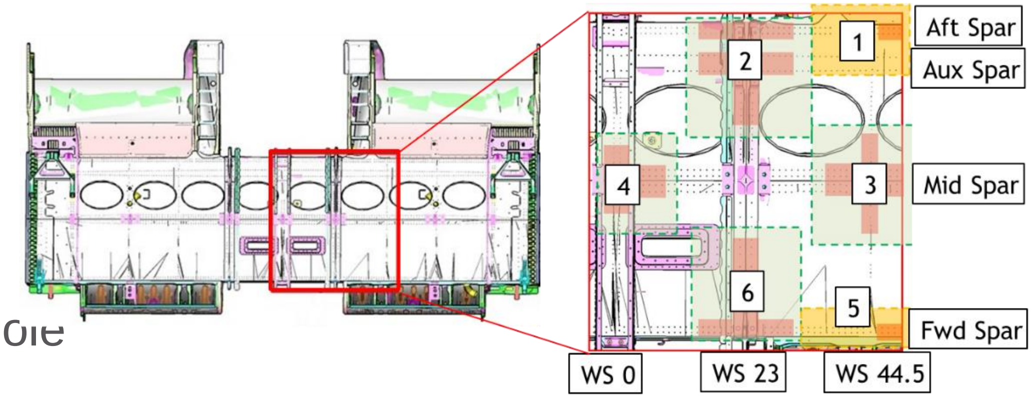
❑ T-38 assets

- (3) Wing Assemblies
- Location details:
  - Lower wing skin
  - 7000 series aluminums
  - Production and TCTO Cx
- Usage details:
  - Predominantly tension loads - 35-70% FTY (peak)
  - Negligible compression ~ -10 ksi
- Service history:
  - Service life: 12-26 years
  - Retrofit Cx: 1999-2002
  - Retirement: 2006-2010
  - Mix of severe and moderate usage
  - Moderate – High EFH

Disassembly & Teardown

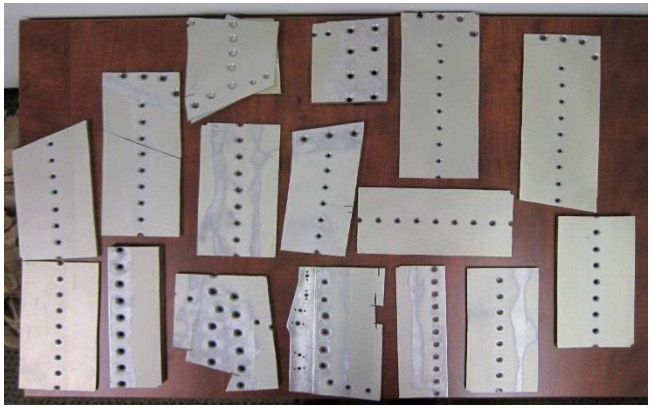
Full A-10 Center Wing teardown

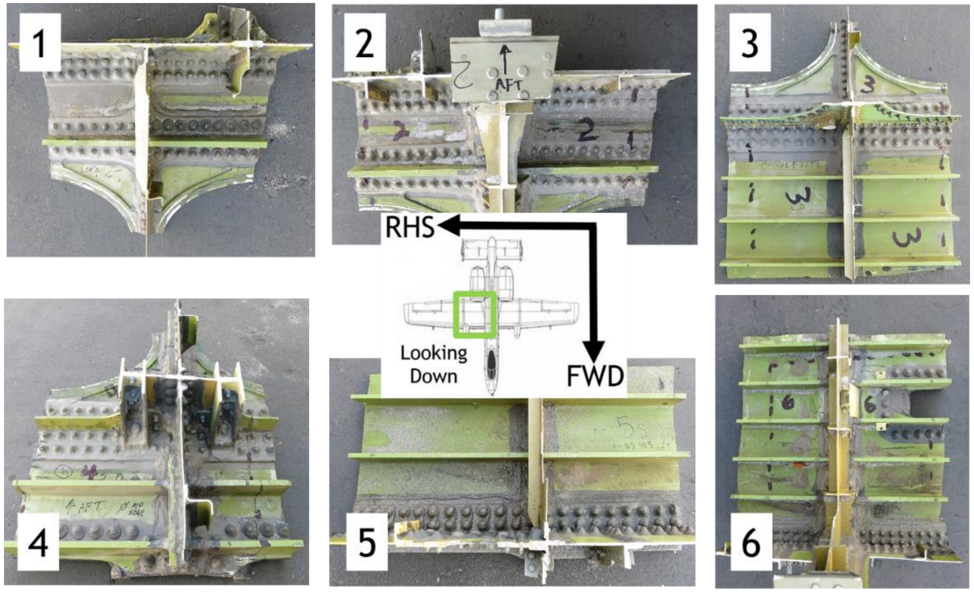
- Sectioning
- Fastener removal per USAFA PASTA
- Coating removal
- Non-destructive inspections
- Failure Analysis
  - Only (1) confirmed crack at Cx hole



T-38 Wings previously torn-down

- Excised coupons received for program





Residual Stress Measurement Plan – A-10

Approach

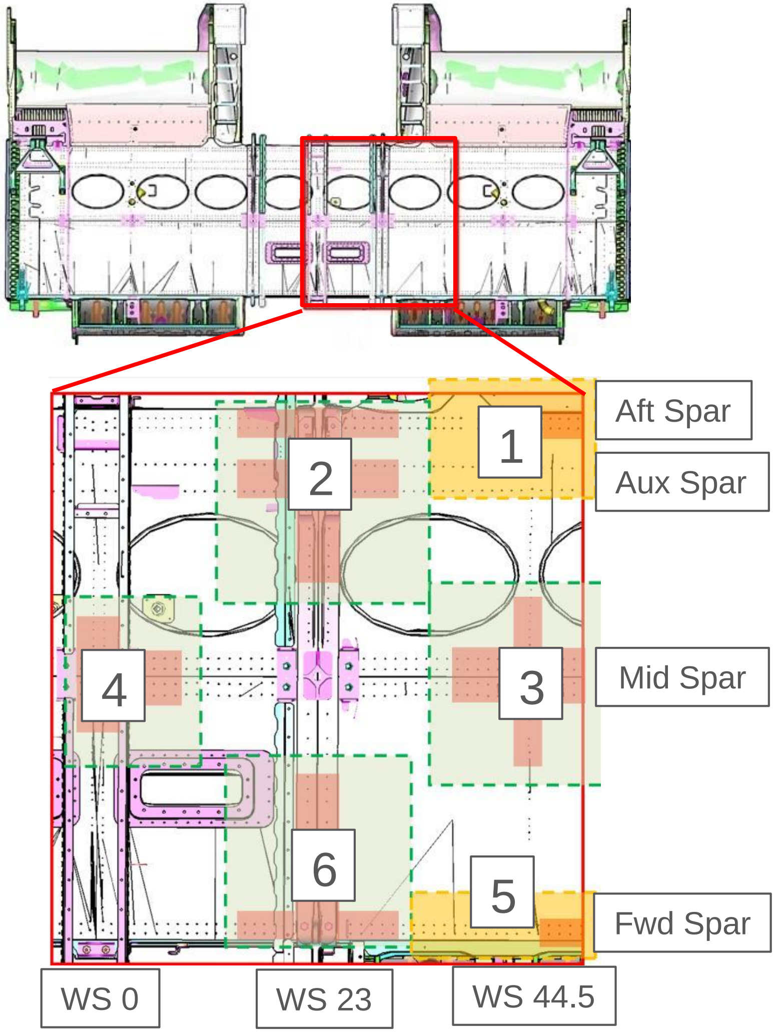
- Cover the scope of A-10 lower wing fatigue critical locations
- Lower skins and spars

Primary considerations:

- Range of peak stresses
- Production and rework Cx
- Varying thicknesses
- Varying hole sizes
- Production vs. rework holes

Scope of Measurements

- 146 teardown holes
- 72 new manufacture holes



Residual Stress Measurement Plan – T-38

Approach

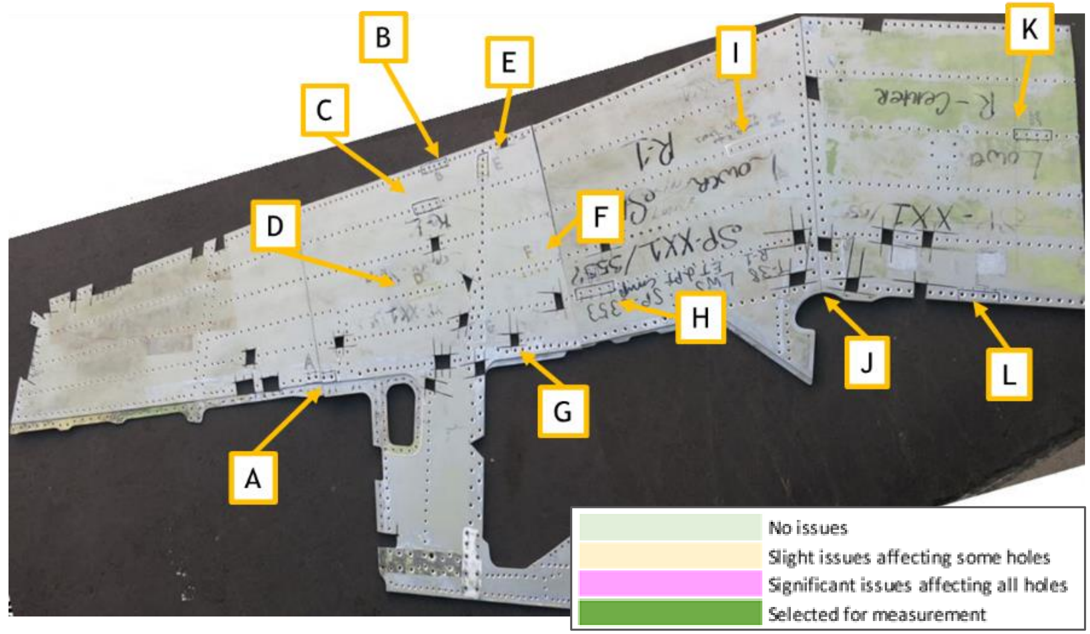
- Wing #SP900
  - Breadth of locations
- Wings #SP353 and #SP648
  - Variability between wings

T-38 primary considerations:

- Fatigue critical locations
- Range of peak stresses
- Production & field Cx
- Varying thicknesses

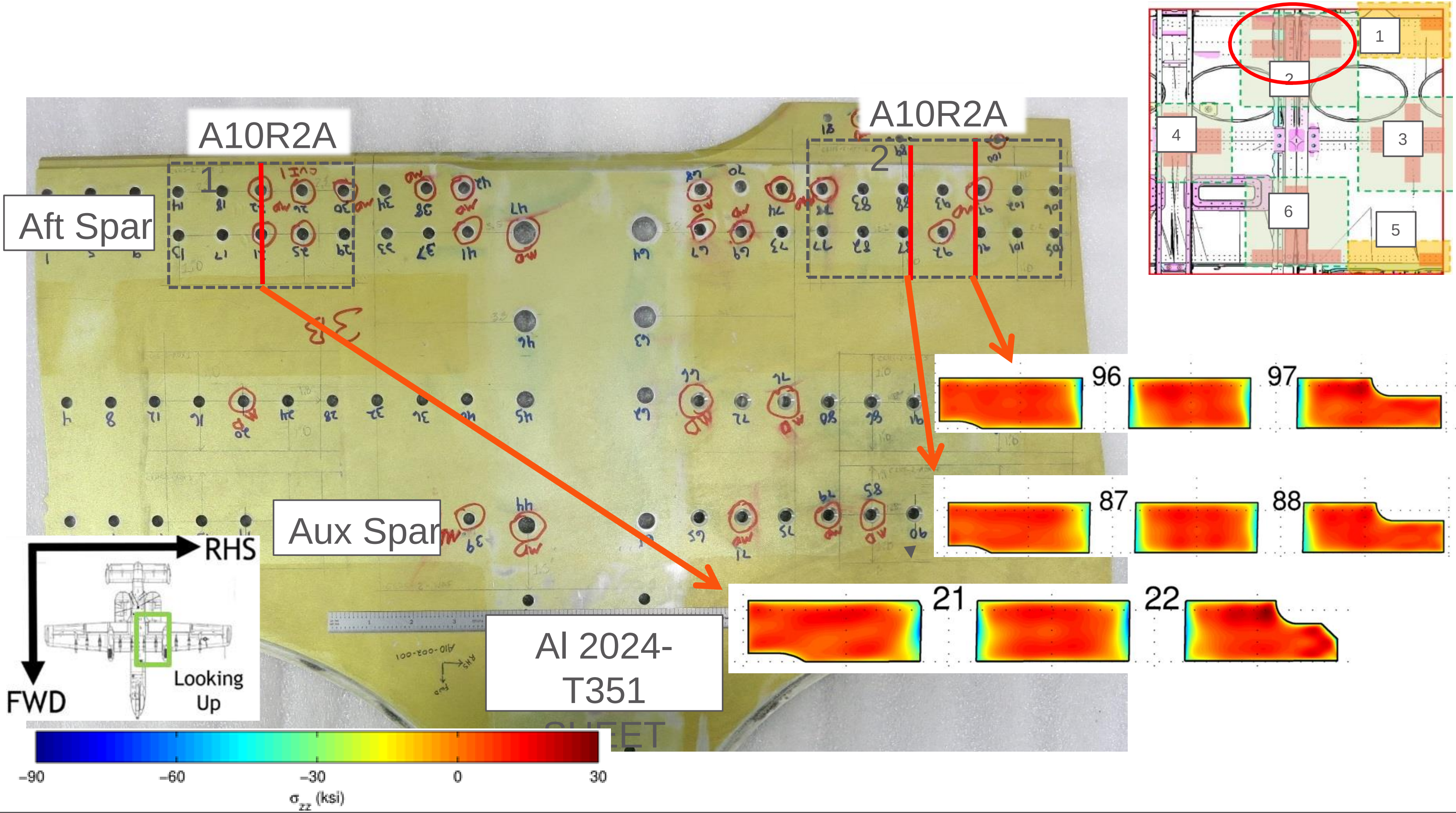
Scope of Measurements

- 57 teardown holes
- 33 new manufacture holes

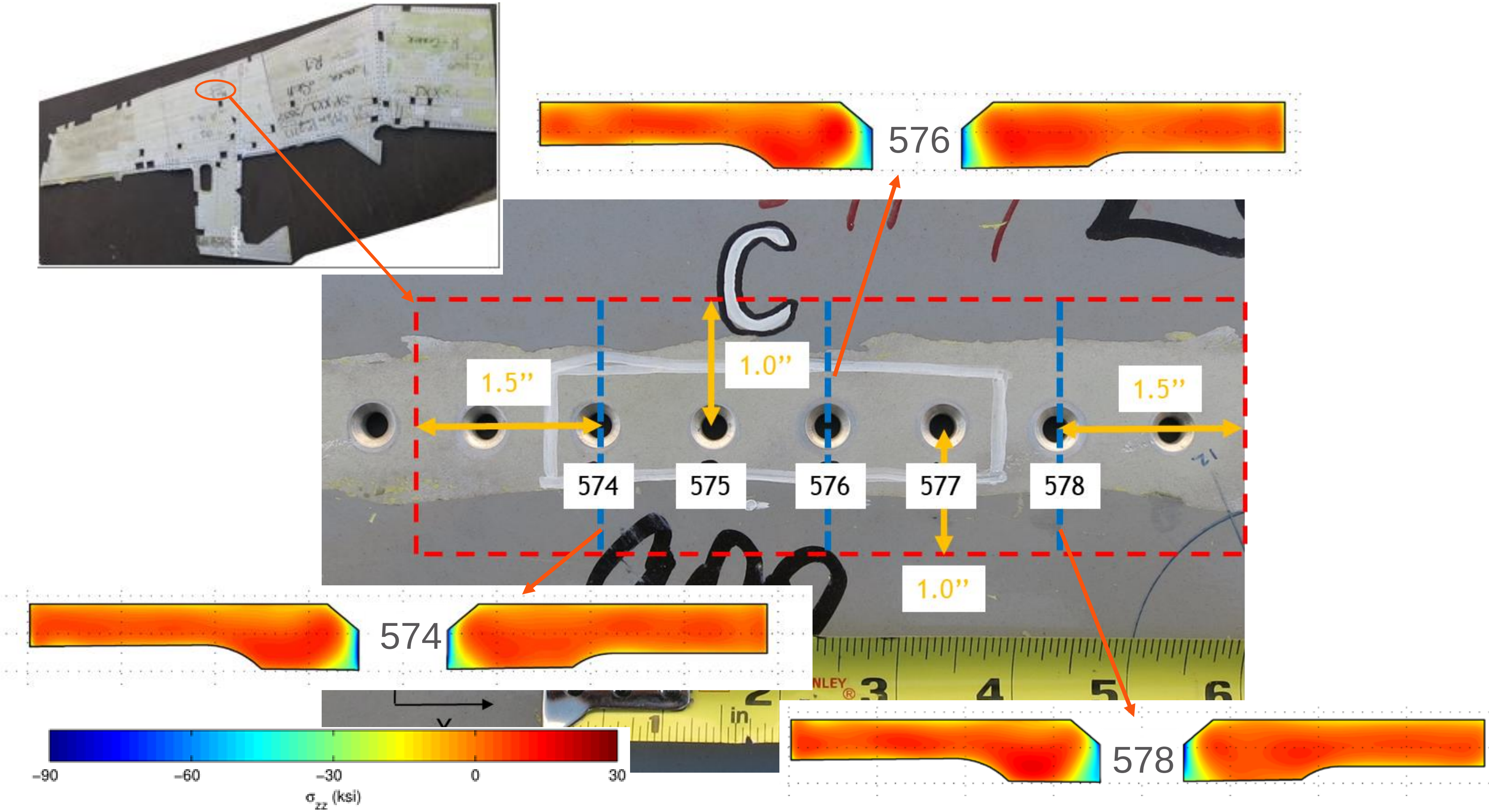


Location	SP 353 RHS	SP 648 LHS	SP 648 RHS	SP 900 LHS	SP 900 RHS
A	Cuts between holes	Hole oversized 0.31"	2 holes damaged	Hole removed	Good
B	Good	Good	Good	Good	Hole OS 0.26"
C	Damage to 3 holes	Removal near hole	Good	Good	Good
D	Good	Cut near hole (0.5")	Good	Good	Cut right of hole, 1.48"
E	Good	Hole dmg, OS 0.32"	Cut near hole, minor dam	Good	Cut below hole, 0.35"
F	Good	Cut left of hole, 1.45"	Cut right of hole (1.35")	Cuts 1.25", hole damage	Cut Left 1.52" Left
G	Cut near 3 of 6 holes	Cuts near 3 of 6 holes	Cuts near 2 of 6 holes	Good	Majority Removed
H	Good	Good	Good	Good	Good
I	Good	Good	Good	Good	Cut Between 296, 297
J	Compromised	Good	Good	#198, #210 dmg	Compromised
K	Good	Good	Good	Cut 1.16" below, above	Good
L	Cut 7/8" near hole	Good	Good	Good	Cut right of hole, 0.5"

Teardown Measurement Results – A-10



Teardown Measurement Results – T-38



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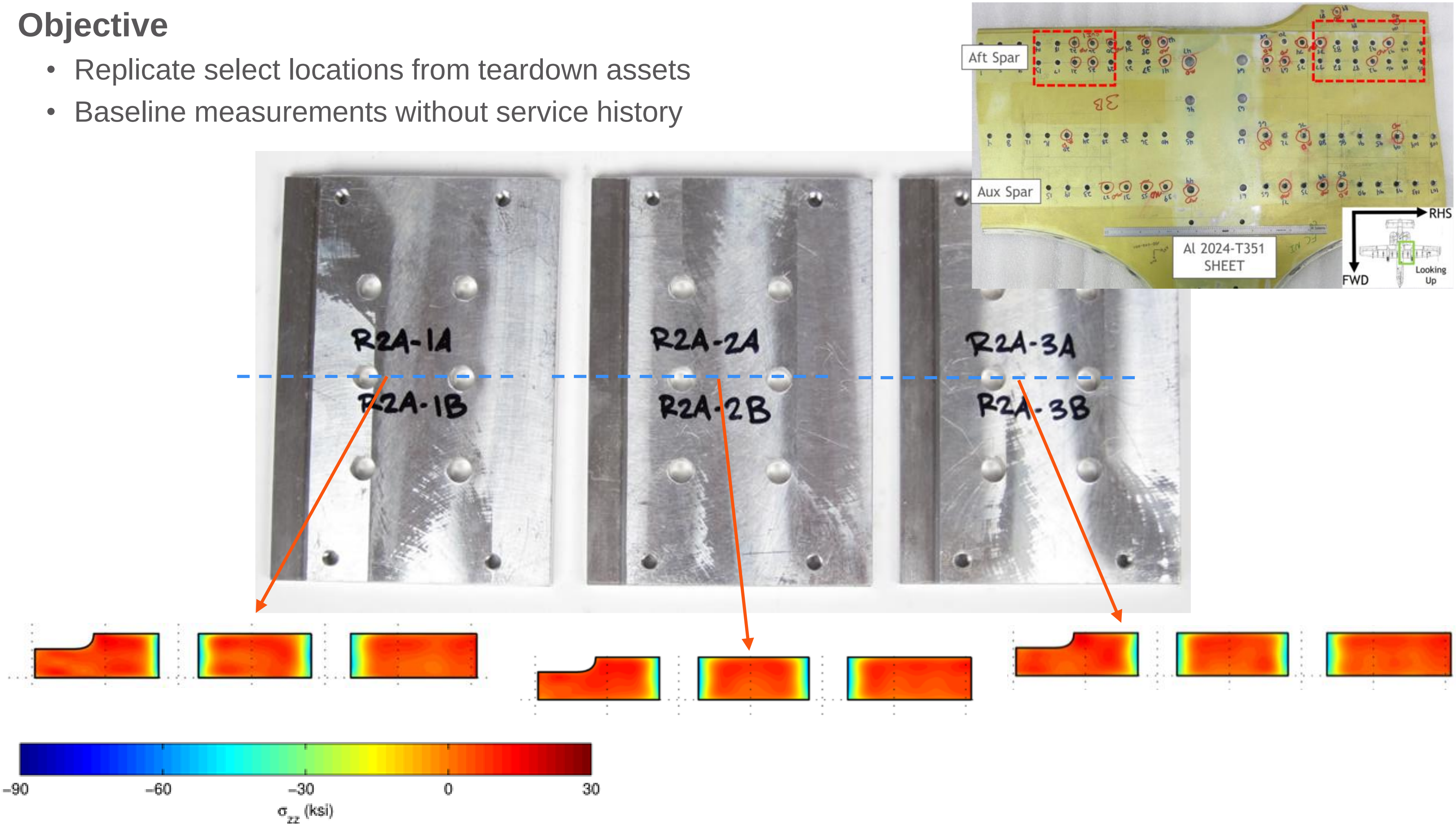
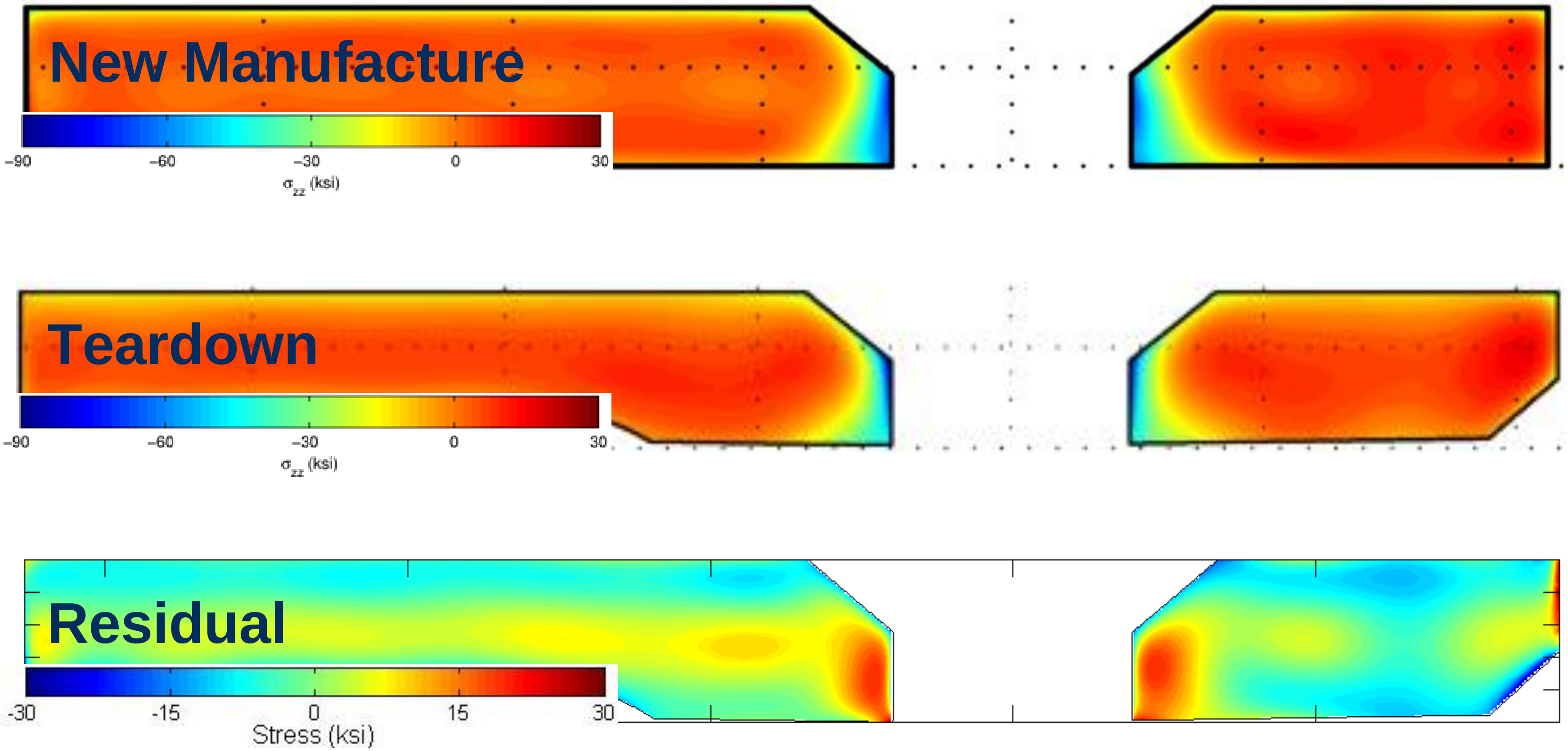
New Manufacture Measurement Results

Objective

- Replicate select locations from teardown assets
- Baseline measurements without service history

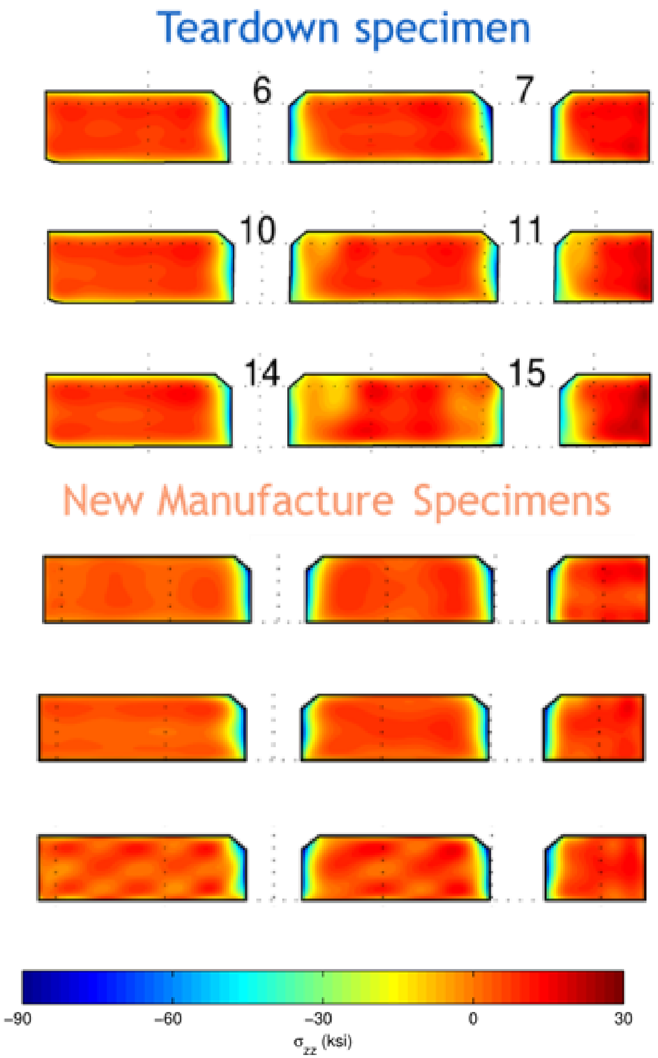


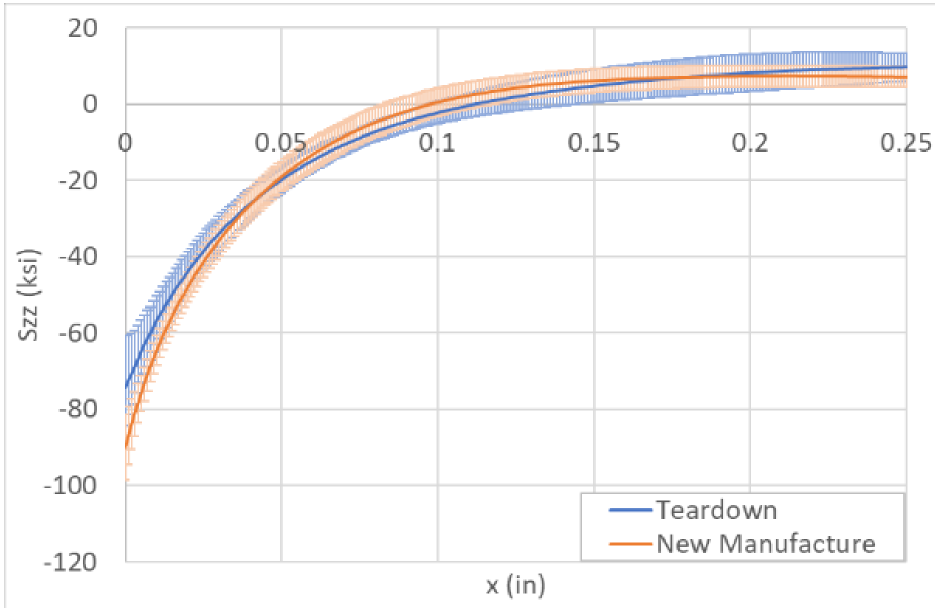
New vs. Teardown Comparisons



What is considered significant?

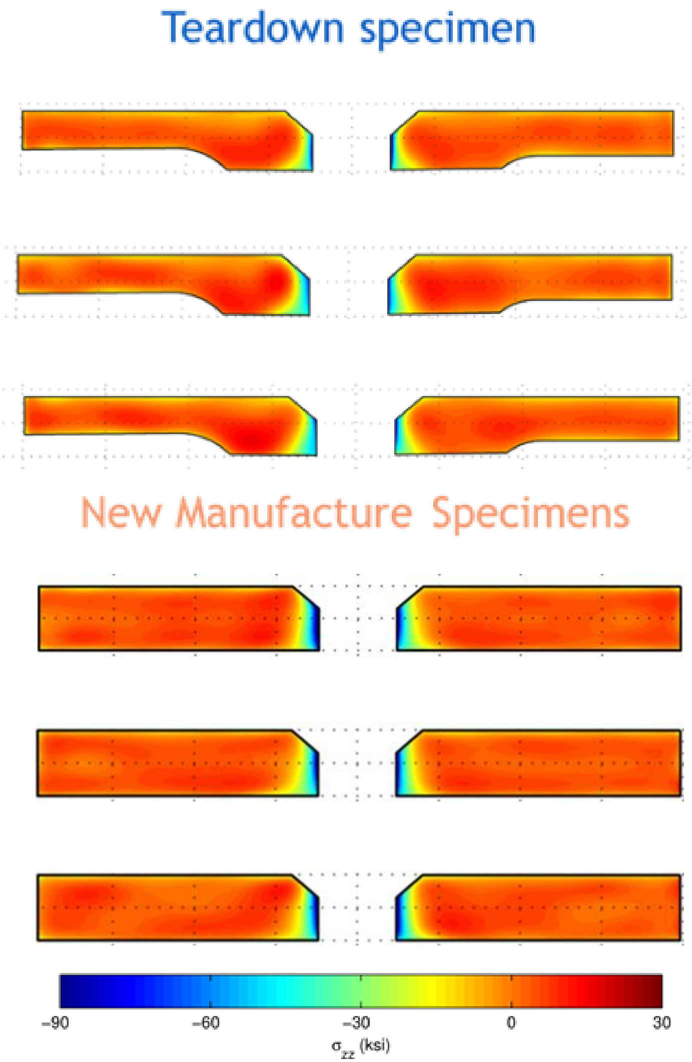
Level I Analysis - Comparison Results (A-10) Section R3.1P

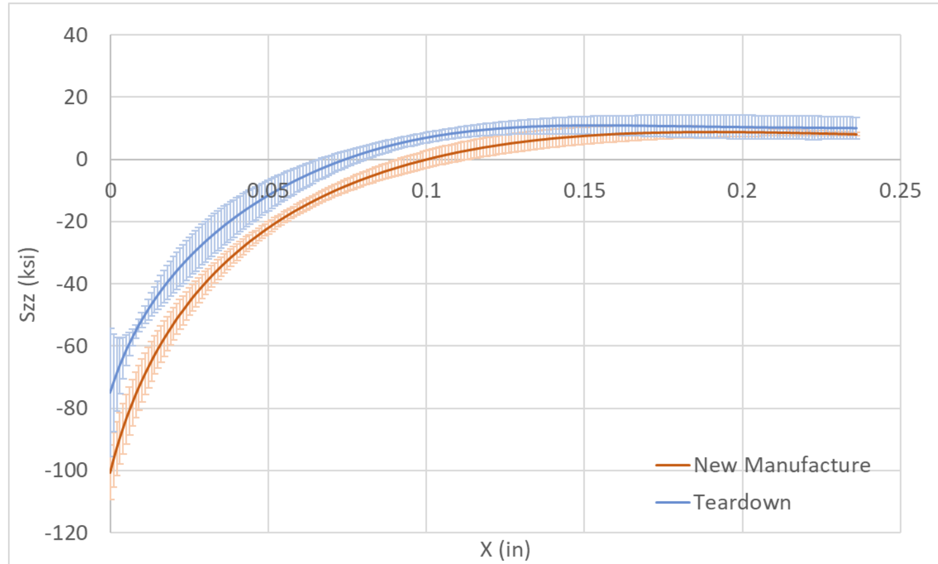




Sample ID	Midthickness 0.125*rad (ksi)	Midthickness 0.25*rad (ksi)	Midthickness 0.5*rad (ksi)	Midthickness 0.75*rad (ksi)	Depth at crossover (midthickness) (in)	Point Value of Entrance (ksi)	Avg RS in 0.05" Radius Entrance (ksi)	Point Value CSK Knee (ksi)	Avg RS in 0.05" Radius CSK knee (ksi)
Mean	**-47.15**	**-31.04**	**-12.29**	**-2.60**	**0.13**	**-51.30**	**-34.67**	**-77.92**	**-44.59**
Stdev	**5.17**	**4.10**	**2.71**	**2.99**	**0.04**	**21.61**	**6.68**	**16.67**	**10.37**
Mean	**-52.82**	**-32.95**	**-10.82**	**-0.19**	**0.10**	**-49.72**	**-31.57**	**-98.82**	**-55.33**
Stdev	**3.68**	**3.91**	**3.91**	**3.65**	**0.02**	**21.46**	**3.05**	**14.72**	**2.64**
Residuals (Td-NM)	5.68	1.91	-1.46	-2.42	0.03	-1.58	-3.09	20.90	10.74
P Value	0.00	0.13	0.15	0.05	0.02	0.43	0.08	0.00	0.00
Significant	Yes	No	No	Yes	Yes	No	No	Yes	Yes

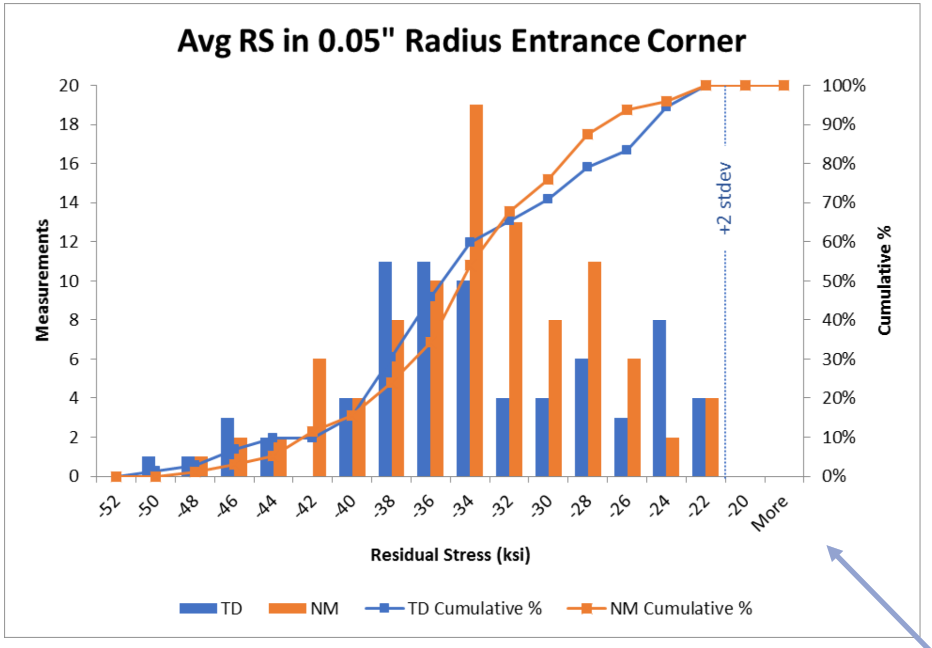
Level I Analysis - Comparison Results (T-38) Section C

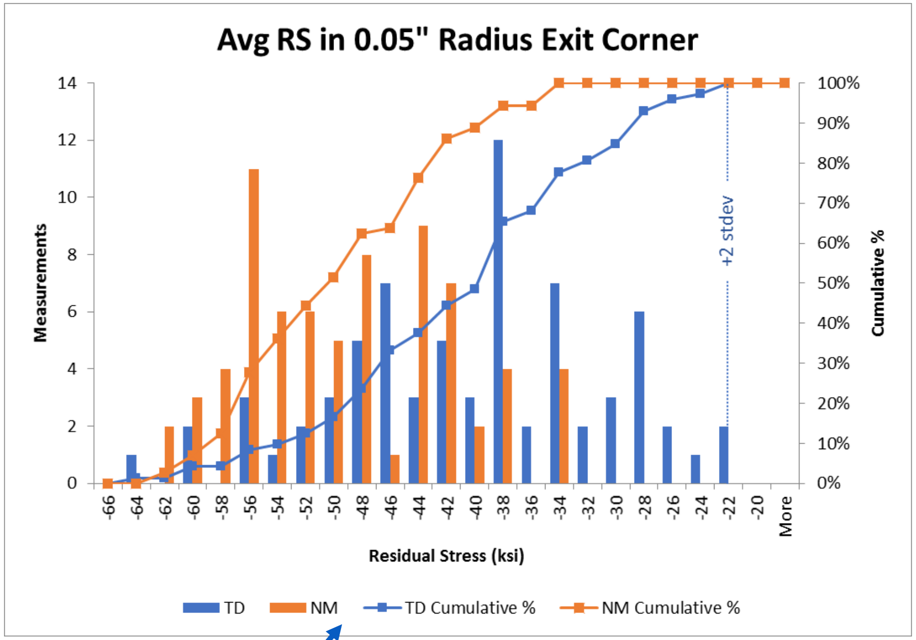


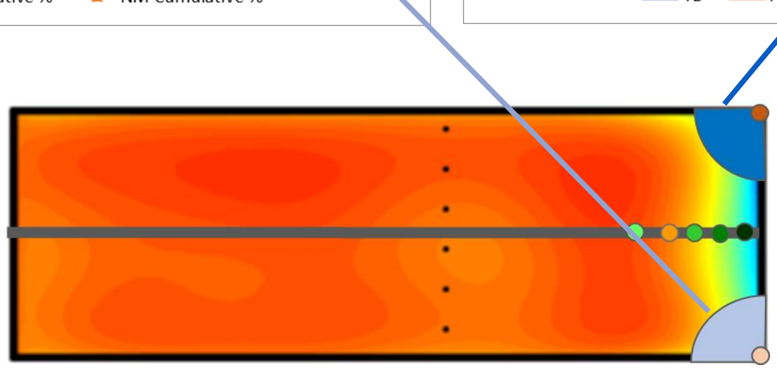


Sample ID	Midthickness 0.125*rad (ksi)	Midthickness 0.25*rad (ksi)	Midthickness 0.5*rad (ksi)	Midthickness 0.75*rad (ksi)	Depth at crossover (midthickness) (in)	Point Value of Entrance (ksi)	Avg RS in 0.05" Radius Entrance (ksi)	Point Value CSK Knee (ksi)	Avg RS in 0.05" Radius CSK knee (ksi)
Mean	**-42.64**	**-26.04**	**-6.11**	**4.67**	**0.07**	**-41.00**	**-40.14**	**-76.26**	**-31.94**
Stdev	**4.81**	**6.48**	**3.85**	**1.83**	**0.01**	**18.30**	**2.85**	**11.50**	**3.94**
Mean	**-59.31**	**-38.63**	**-15.11**	**-2.53**	**0.10**	**-48.86**	**-49.02**	**-101.18**	**-49.57**
Stdev	**5.80**	**3.56**	**1.65**	**2.51**	**0.01**	**19.58**	**4.44**	**12.11**	**4.67**
Residuals (Td-NM)	16.67	12.59	9.01	7.20	-0.03	7.86	8.87	24.92	17.63
P Value	0.00	0.00	0.00	0.00	0.00	0.24	0.00	0.00	0.00
Significant	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes

Summary of Comparisons







Conclusions

Extensive program completed which provides insight into residual stress of retired fleet assets

300+ residual stress measurements accomplished

- Teardown vs. new manufacture comparisons

Significant residual stress remained in all evaluated teardown locations

- No “missed Cx” locations

Initial level I comparisons complete

- Comparable stresses observed between teardown and new manufacture coupons with significant overlap

A “Manage To” residual stress profile may be a practical approach for incorporation into USAF DTAs

- +2 Stdev

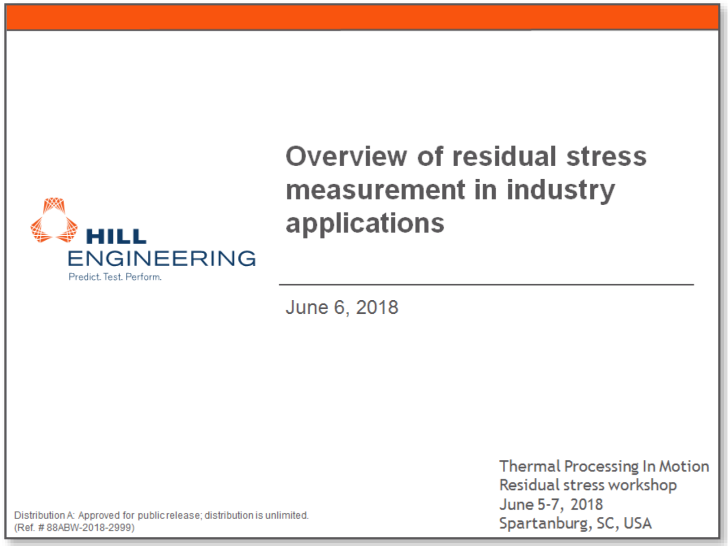
MORE WORK TO DO

- Wealth of information within dataset
- How do these results impact fleet management decisions?

Measurements Sub-group Update

Residual Stress Quality System

Note: this is an excerpt taken from here:


Overview of residual stress measurement in industry applications

June 6, 2018

Thermal Processing In Motion
Residual stress workshop
June 5-7, 2018
Spartanburg, SC, USA

Distribution A: Approved for public release; distribution is unlimited.
(Ref. # 88ABW-2018-2999)

Acknowledgements

Authors: Adrian DeWald and Michael Hill

Collaborators

- Much of this work is closely linked to recent programs that involved collaboration with the following organizations and individuals
  - Pratt & Whitney: Iuliana Cernatescu, Dave Furrer, and Bob Morris
  - Arconic: Mark James, John Watton, Dave Selfridge, Dustin Bush, and Brandon Bodily
  - Lockheed Martin: Dale Ball and Mark Ryan
  - Air Force Research Laboratory: Bill Musinski, Mike Caton, and Reji John

Residual stress in design and manufacture

Historical design approach: residual stress is a known unknown

- Remove where possible (thermal or mechanical stress relief)
- Conservatively manage effects on degradation (fatigue, SCC, creep)
  - Conservative assumptions (i.e., tensile residual stress fields)
  - Inspect, repair, replace
  - Costs escalate with system age
- Take minimal credit for beneficial compressive residual stress

Emerging design approach: residual stress part of specifications

- Known residual stresses in parts (requires measurements, models, and validation metrics)
- Include residual stress in materials and process engineering
  - Trade studies
  - Quality program
- Directly account for residual stress effects on performance

Motivations for residual stress control

The following are some common examples of residual stress related concerns during procurement and design

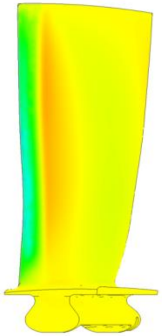
Concern: tensile residual stress causing premature/unexpected failure

- Desire a material/part that has low-magnitude residual stress
  - I.e., avoid putting outlier residual stress parts into service

Concern: large and/or inconsistent residual stress levels impacting machining

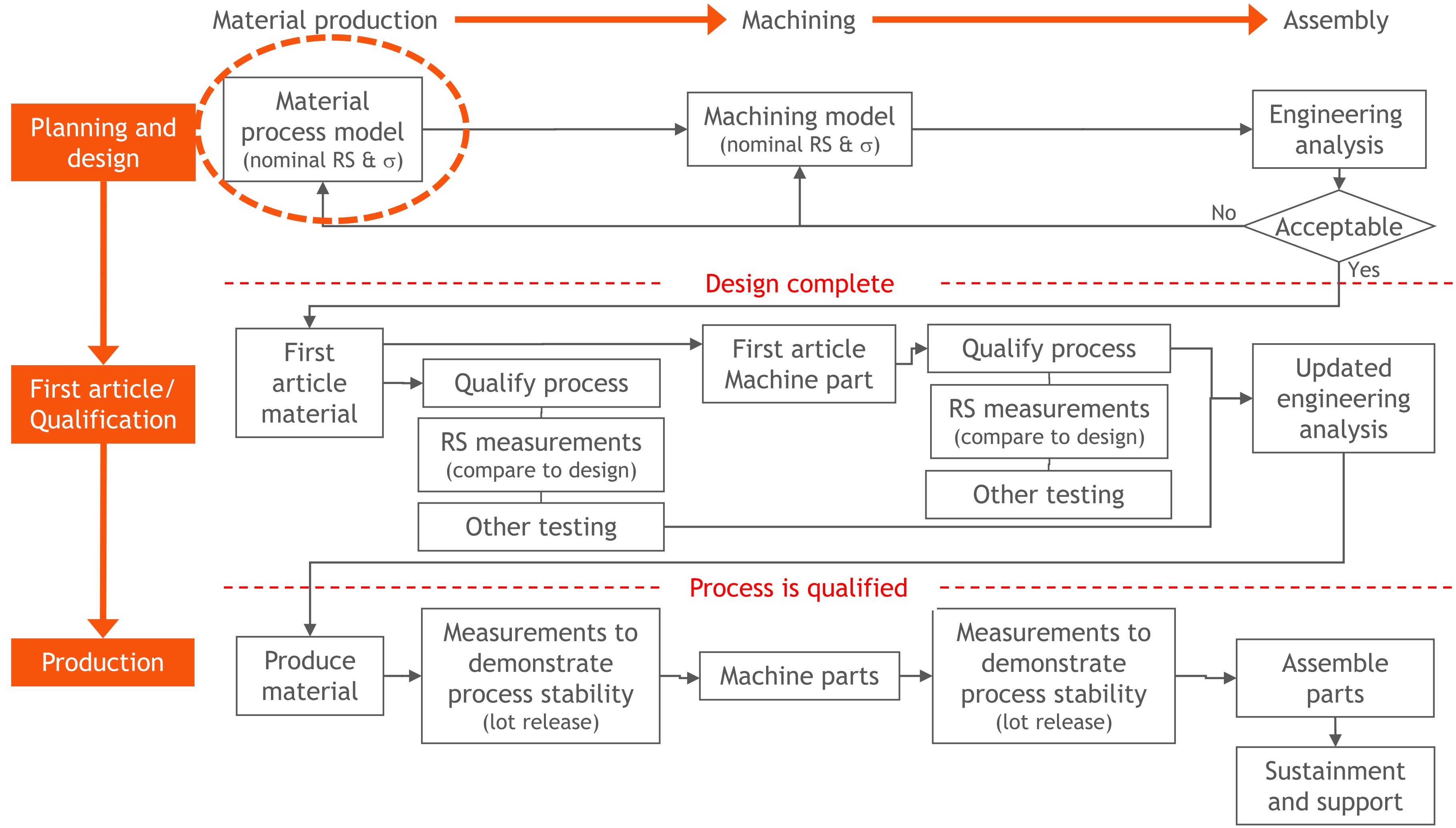
- Desire a material/part that has consistent or low-magnitude residual stress

Concern: ensure presence of beneficial compressive residual stress



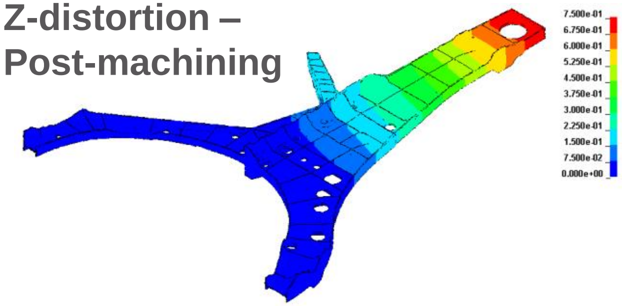
- Desire local regions of compressive residual stress in critical locations from engineering processes
  - Also avoid high levels of compensating tensile residual stress

Residual stress information flow

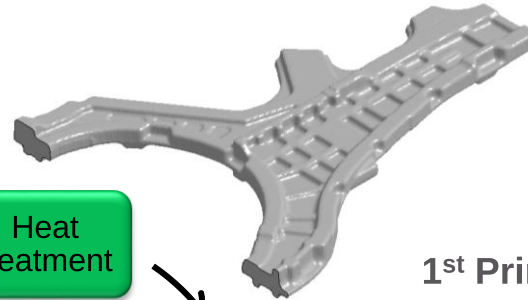


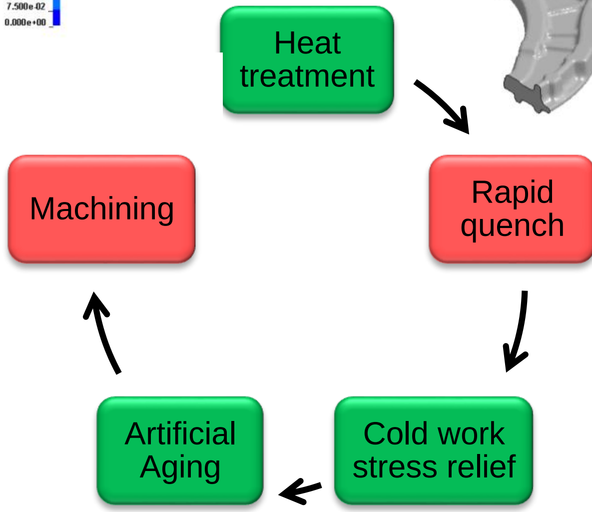
Example: manufacturing & machining models

Z-distortion – Post-machining



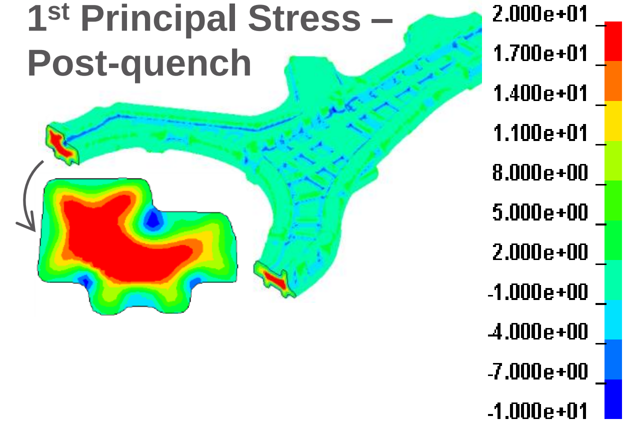
Heat treat Al 7085 @ elevated temperature



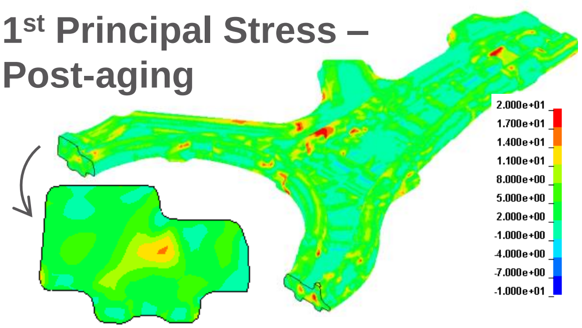


1st Principal Stress – Post-machining

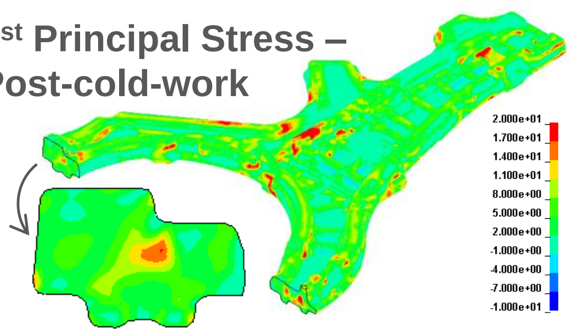
1st Principal Stress – Post-quench



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

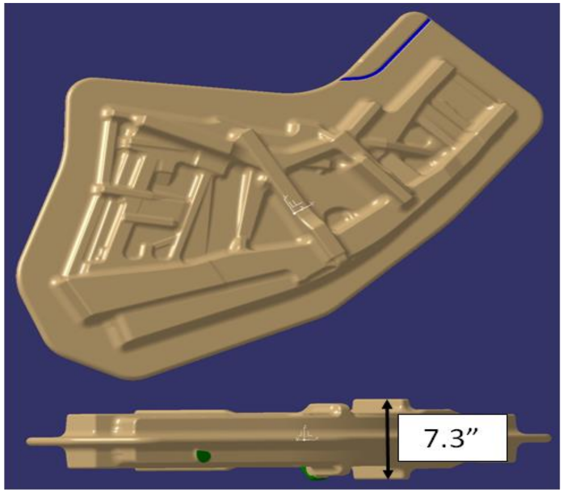
Public Release 88ABW-2015-5301

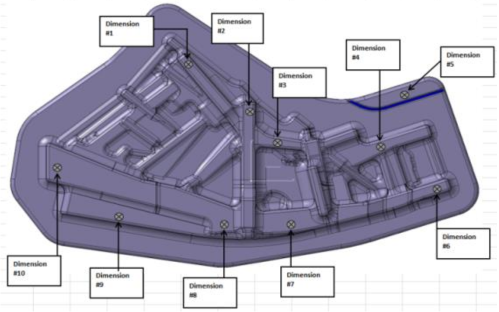
C-5 end fitting forging

Part description

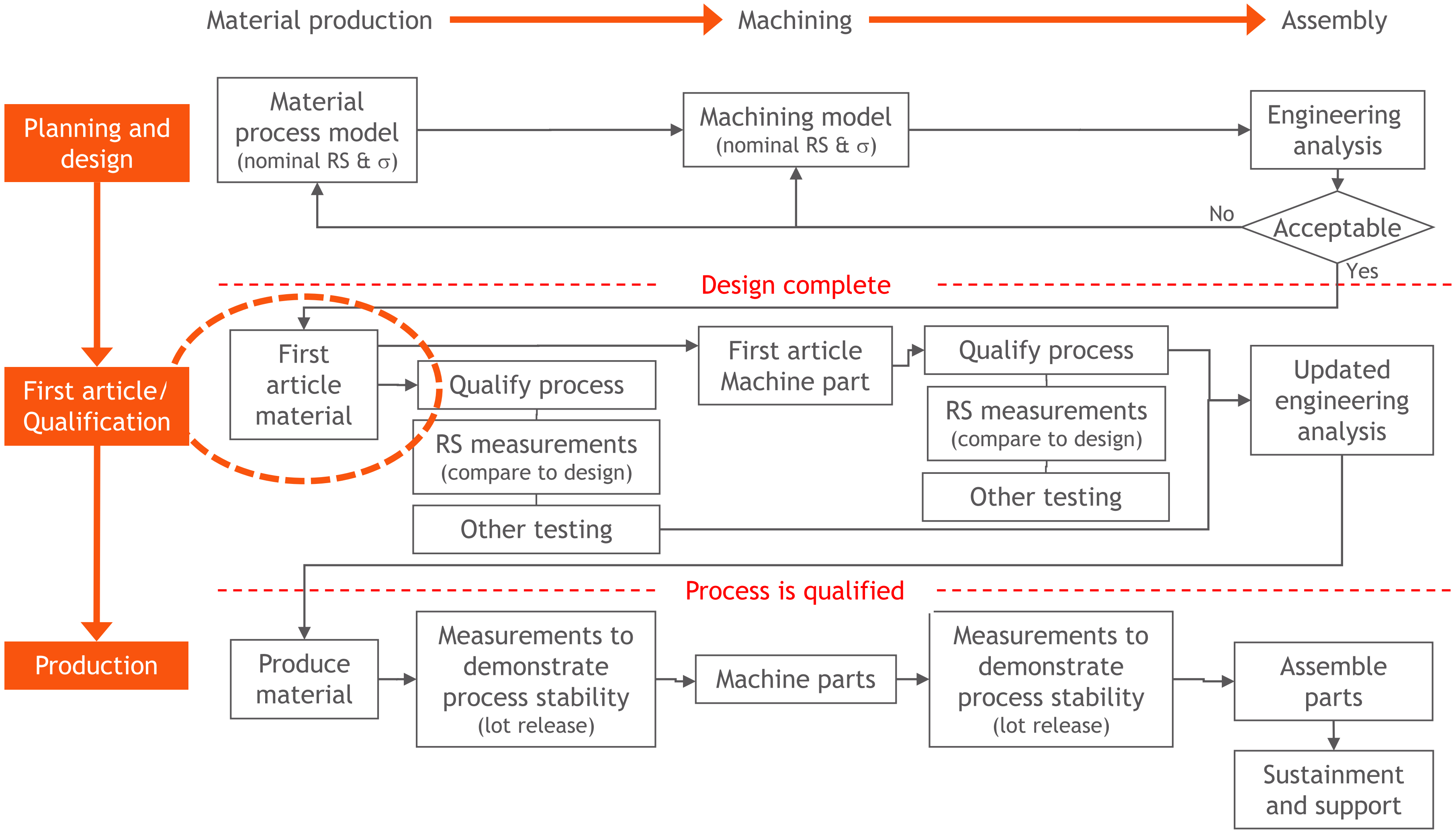
- Material: 7085-T7452
- Die-forging
- Varying amounts of cold work: 0% to 4%
  - 1% to 5% is “acceptable” for production
  - 16 parts manufactured

Part Number	Job Number	Average Cold Work	Pressure
GA120276	HM14L10	0.0%	N/A
GA120276	HM14L11	0.0%	N/A
GA020276A	HM14L07	1.4%	9.9
GA020276A	HM14L02	1.4%	9
GA020276B	HM14L01	1.6%	9.6
GA020276B	HM14L08	1.8%	10.1
GA020276	HM14L03	3.0%	14
GA020276	HM14L04	3.0%	14
GA020276	HM14L16	3.0%	14.8
GA020276	HM14L14	3.1%	14.8
GA020276	HM14L06	3.1%	14.5
GA020276	HM14L05	3.3%	14.8
GA020276	HM14L12	3.4%	14.8
GA020276	HM14L13	3.4%	14.8
GA020276C	HM14L15	3.6%	14.8
GA020276C	HM14L09	3.6%	14.8





Residual stress information flow

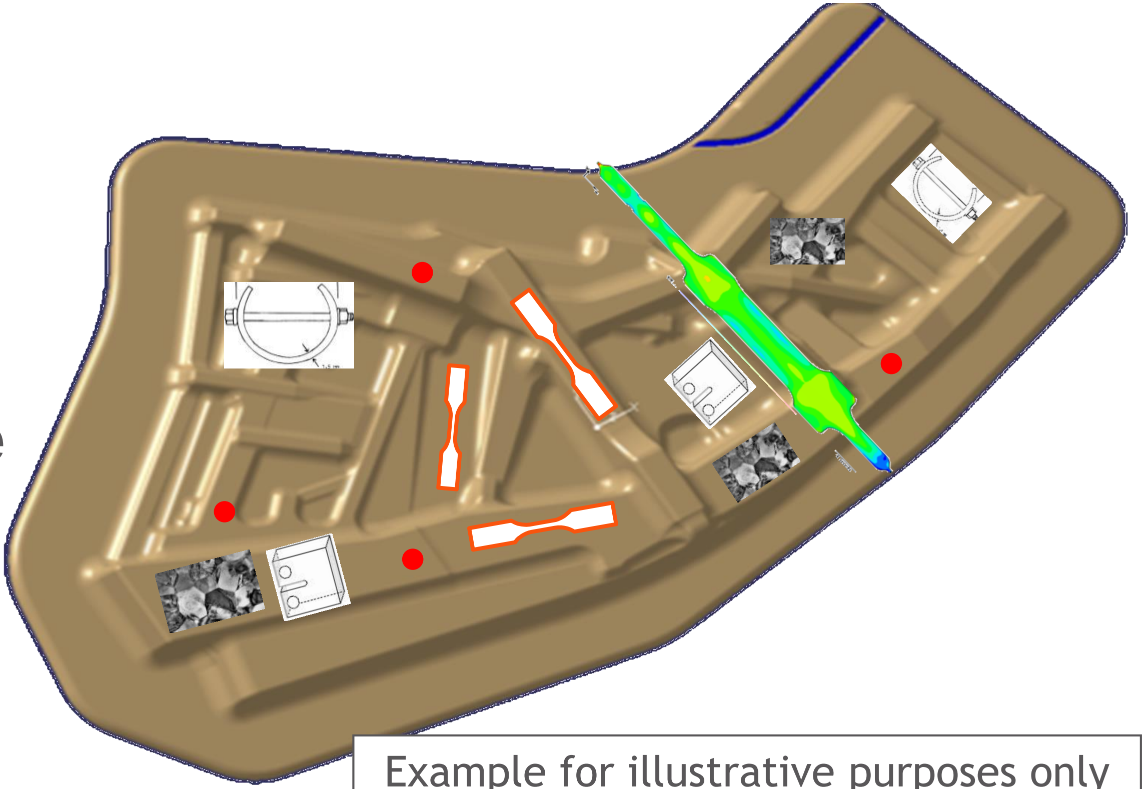


Example: first article qualification

First articles often require extensive testing to validate critical properties and characteristics

- Size/dimensions
- Chemical composition
- Mechanical properties
- Stress-corrosion cracking
- Defect assessment
- Microstructure/Grain-flow

Residual stress can be handled similarly

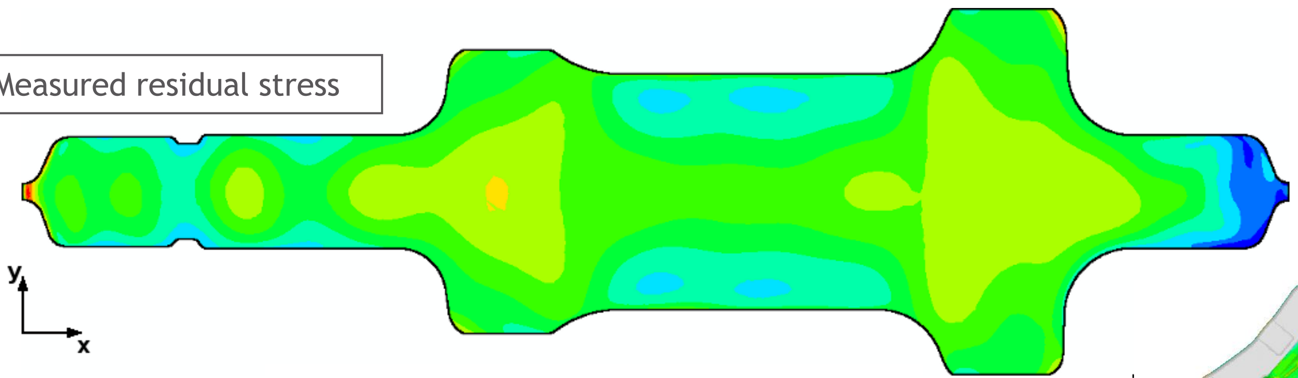


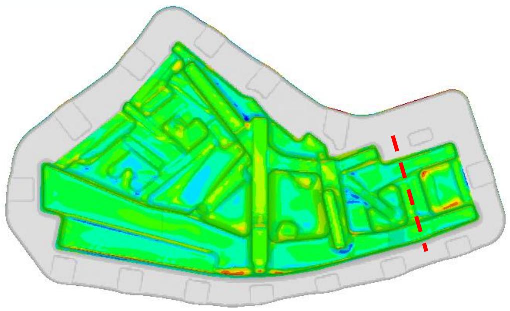
Example for illustrative purposes only

Example: first article qualification validation

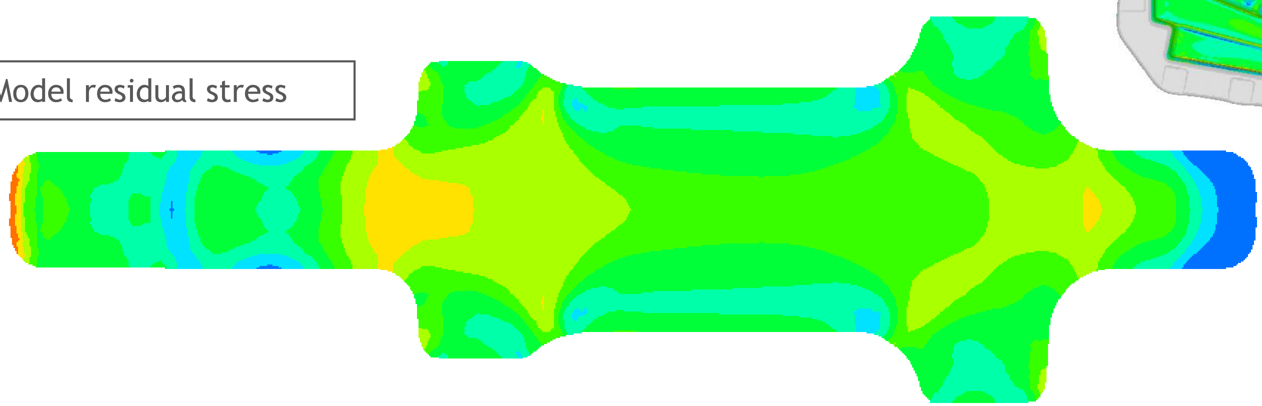
Favorable comparison between measurement and model

Measured residual stress

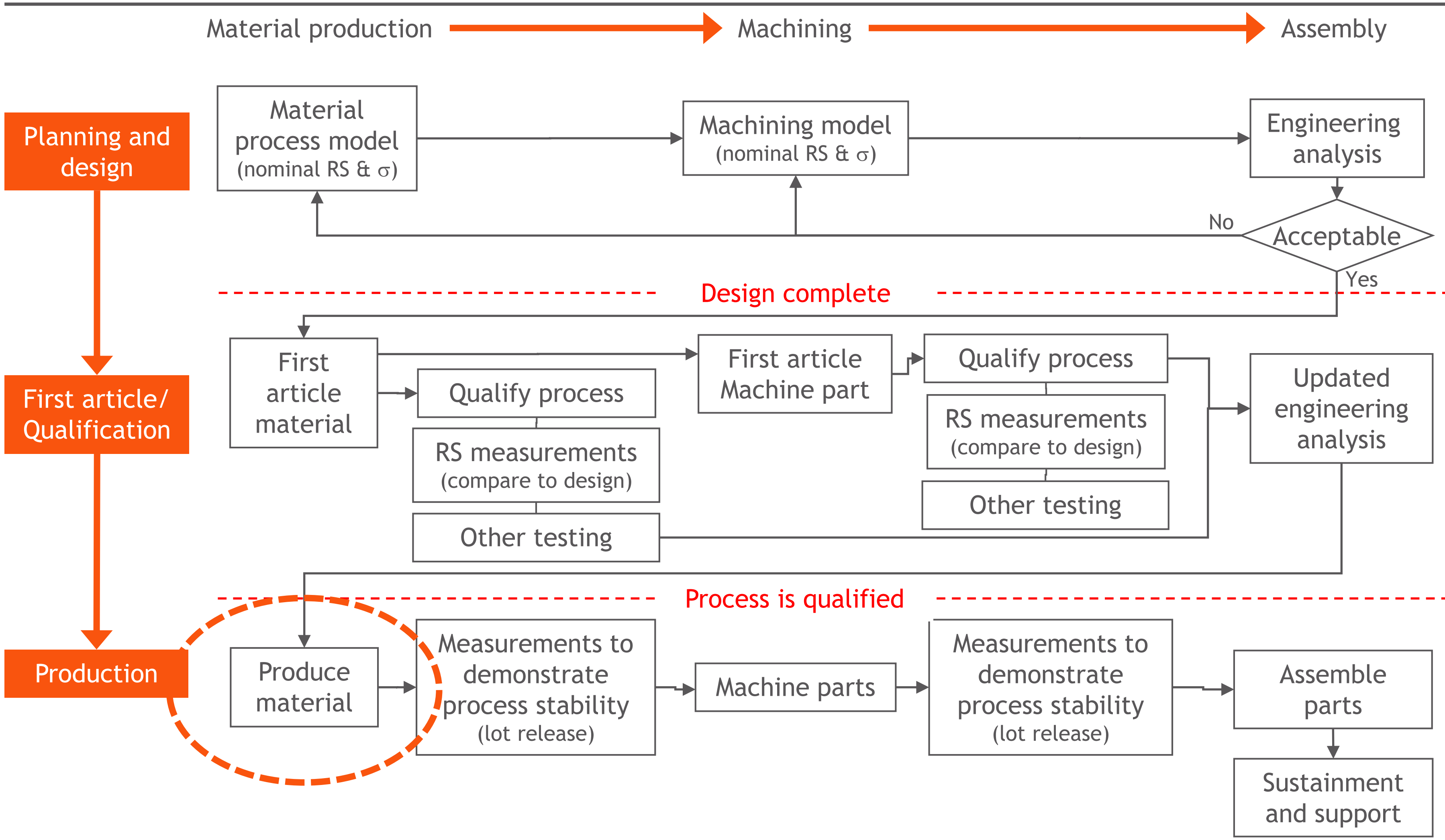




Model residual stress



Residual stress information flow



Example: production surveillance testing

Define measurement locations

- Select in an intelligent manner designed to provide maximum insight and usefulness
- Often useful to perform measurements in regions of excess material

Consider the influence of various factors

- Locations of expected tensile residual stress residing inside of machined part
- Level of sensitivity between residual stress and processing/manufacturing
- Measurement access/applicability
- Locations of likely failure (e.g., applied stress hot spots)
- Difficult to inspect

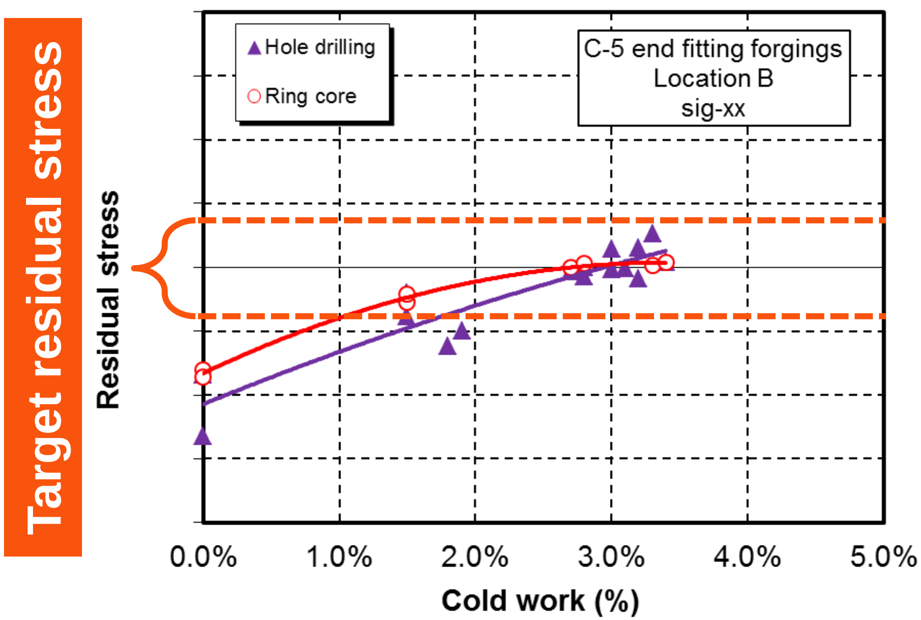
Measurement locations established through collaborative discussion between stakeholders

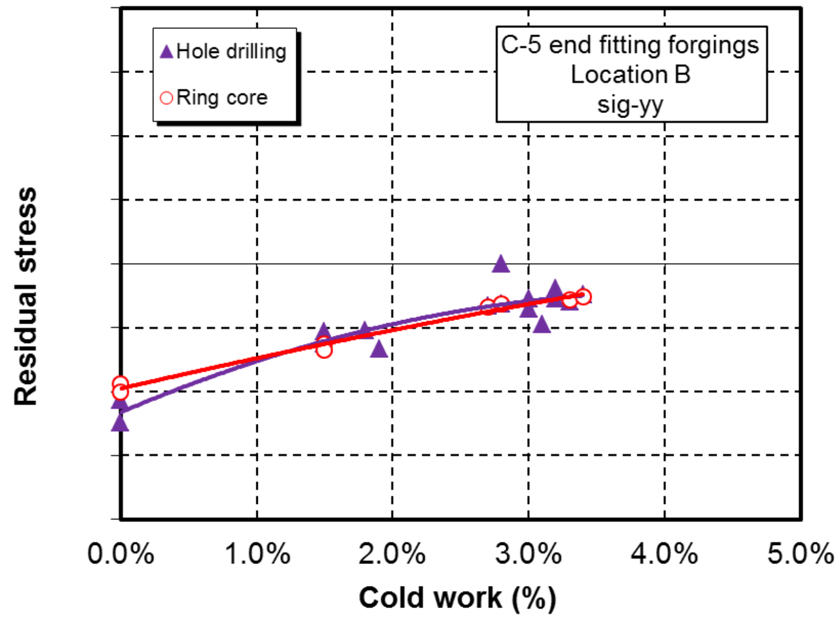
- OEM – understanding of locations critical to structural performance
- Material producer – understanding of locations important to manufacturing
- Testing laboratory – understanding of measurement technology/applicability

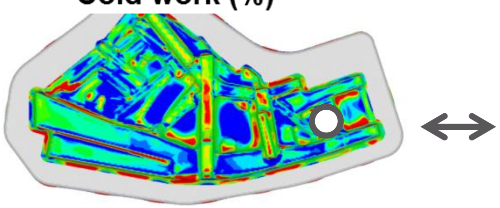
Cold work process sensitivity (near-surface)

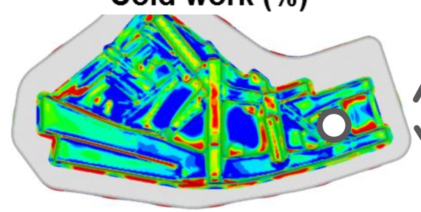
Near surface residual stress varies with cold work

- Similar trend for hole drilling and ring core
- Confirms sensitivity between residual stress and cold work



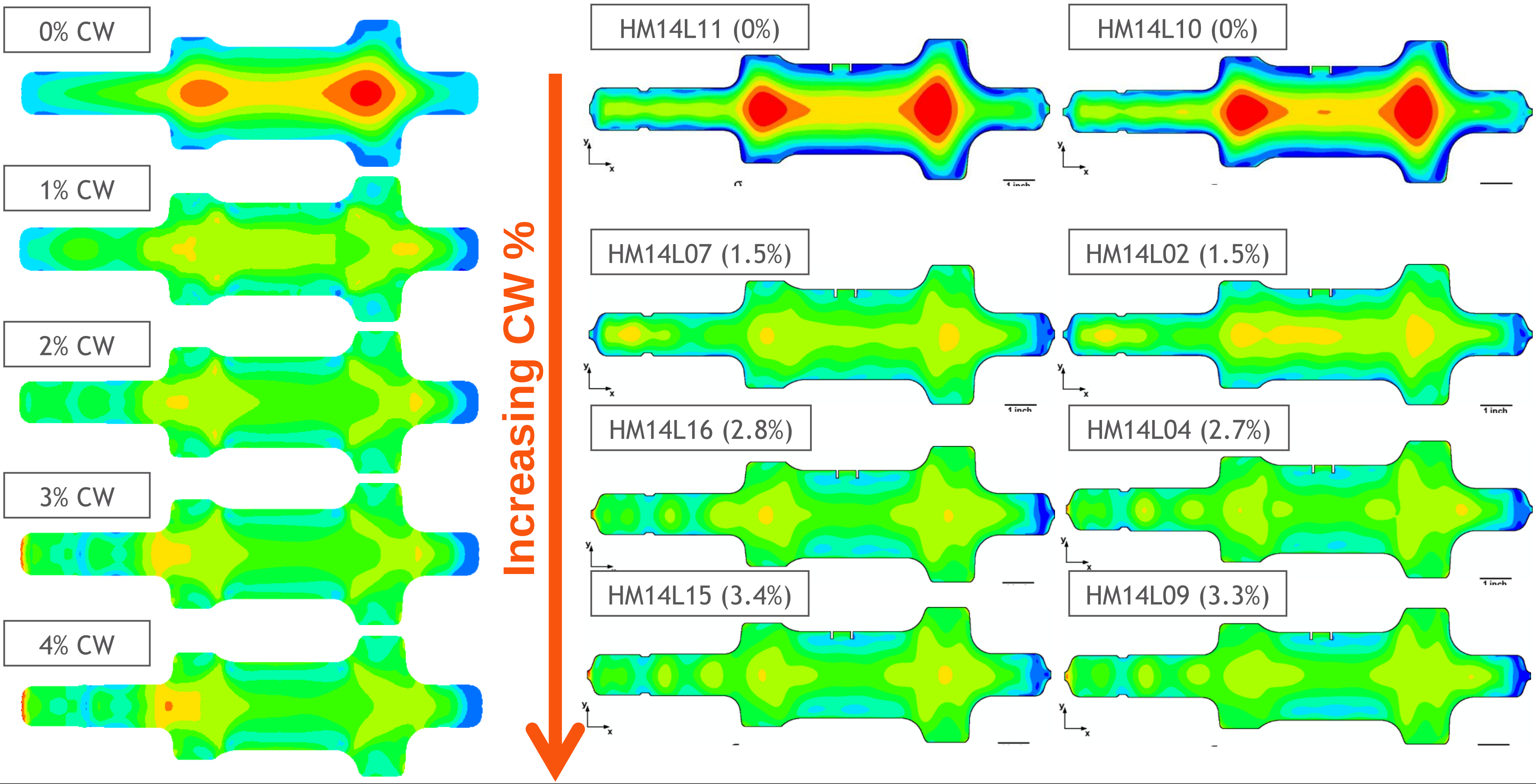






Cold work process sensitivity (bulk)

Process model | **Measurements**



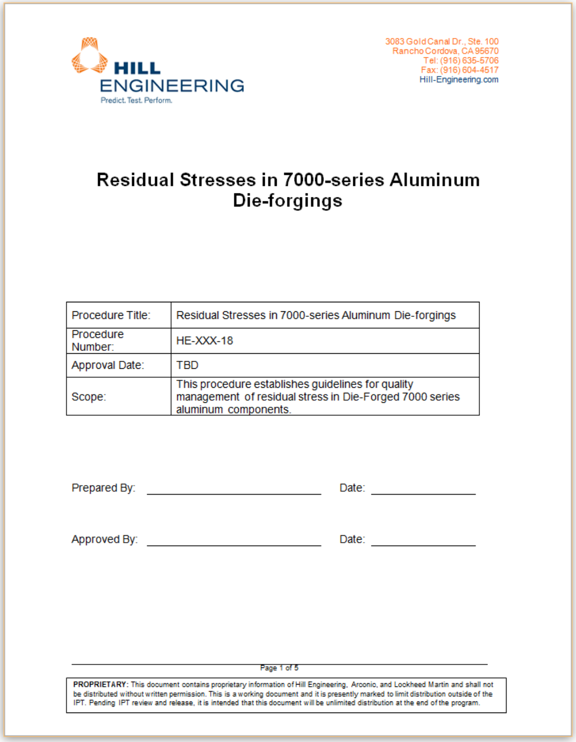
Residual stress quality system documentation

Consistent set of language, specifications, and requirements are required to enable explicit treatment of residual stress during design and procurement

- Developed a template for a residual stress controlled material procurement specification
- Actively working to seek updates to MIL and AMS specifications/standards

Key elements

- Residual stress requirements
  - Specified on drawings
- Process modeling plays a key role (full-field)
- Residual stress measurements at select locations
- Define first article acceptance criteria
- Define ongoing surveillance testing requirements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Residual Stresses in 7000-series Aluminum Die-forgings

Procedure Title:	Residual Stresses in 7000-series Aluminum Die-forgings
Procedure Number:	HE-XXX-18
Approval Date:	TBD
Scope:	This procedure establishes guidelines for quality management of residual stress in Die-Forged 7000 series aluminum components.

Prepared By: ____________________ Date: ____________

Approved By: ____________________ Date: ____________

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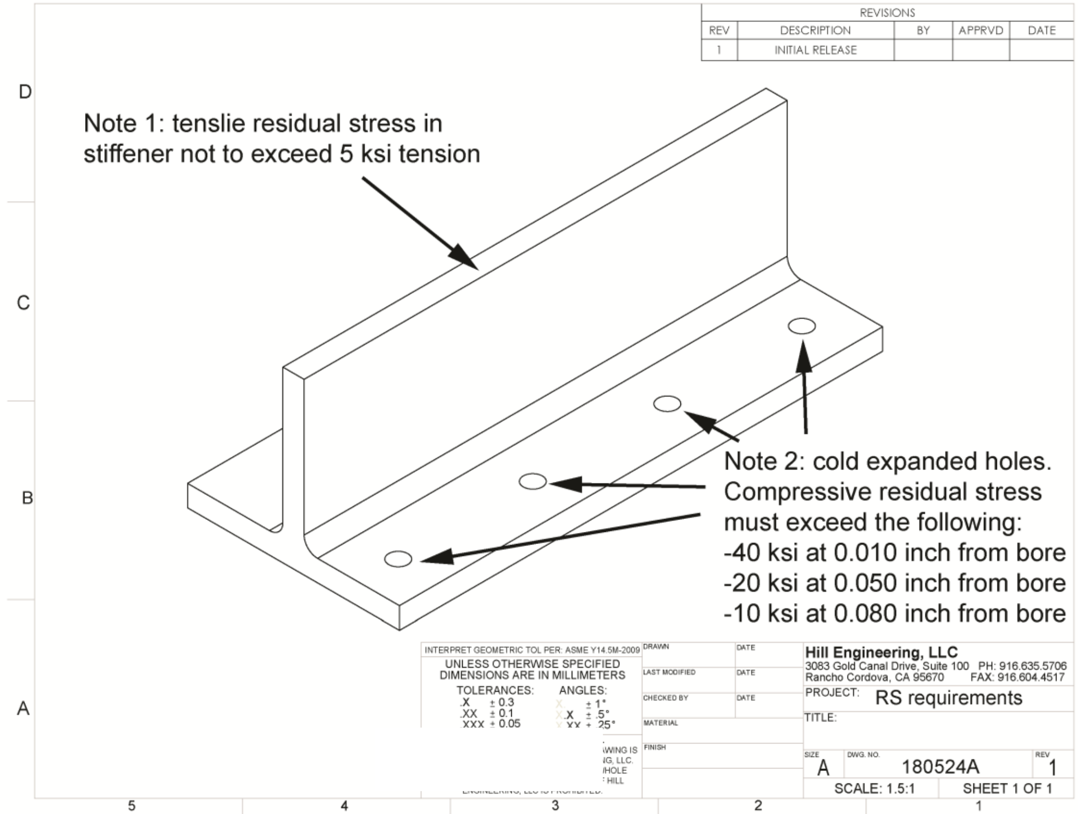
Residual stress requirements example

Part specific residual stress requirements should be specified on the engineering drawing

- Simple illustration shown
- Exclude tensile residual stress where it would impact performance
- Specify compressive residual stress where necessary to meet performance requirements



Where do we go from here

Actively manage residual stress throughout the product life cycle

Tools are available to define residual stress as a component attribute that is flowed throughout a supply-chain

- Engineering drawings contain part-specific requirements
- Specifications and standards define the general approach and requirements (internal and industry)
- Measurements and modeling quantify residual stress

Purchase raw material that has consistent residual stress

- Specify appropriate requirements and engage material producers

Methods exist to include residual stress in product life analysis

- Need to validate the models to ensure accuracy

Develop quality systems for residual stress and execute to certify products

Measurements Sub-group Update

Large Hole CX Evaluation

Large Hole CX Evaluation

Objective

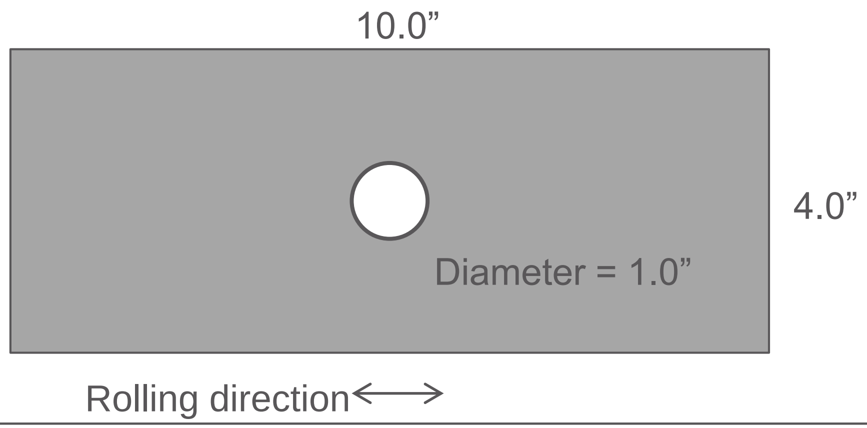
- Develop a coupon that scales-up the stress field
- Develop and interrogate measurement data

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



Large Hole CX Evaluation

Current status

- Initial contour method measurements are complete
  - Residual stress consistent with scaling of geometry
  - Residual stress data is very consistent specimen-to-specimen
- Planning for next set of experimental testing is complete
  - Additional residual stress measurement methods
  - Fatigue testing

Summary of Topics for Today

Contour Method Round Robin

- Given the same input data, participants return results very similar to the benchmark simulation stress field
- Phase 1 complete, Phase 2 ongoing

Measurements of Stress at Legacy vs New CX Holes

- Legacy CX consistent with current production practices
- No evidence of “missed” holes

Residual Stress Quality System

- Program looked at manufacturing induced residual stress (unintended)
- Developed an approach for quality management of residual stress processes (cold working)
- Many similarities with engineered residual stress processes

Large Hole Experiments

- Large holes with lower gradients that will be easier to measure
- Initial work is promising, continuing to evaluate further

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Thank You

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