Residual stress production quality control

October 24, 2017

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Residual stress summit 2017
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Dayton, OH, USA

Acknowledgements

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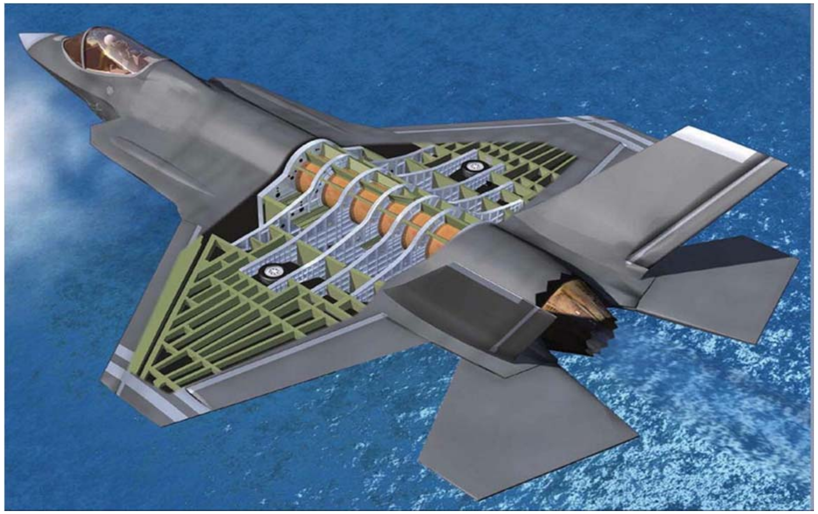
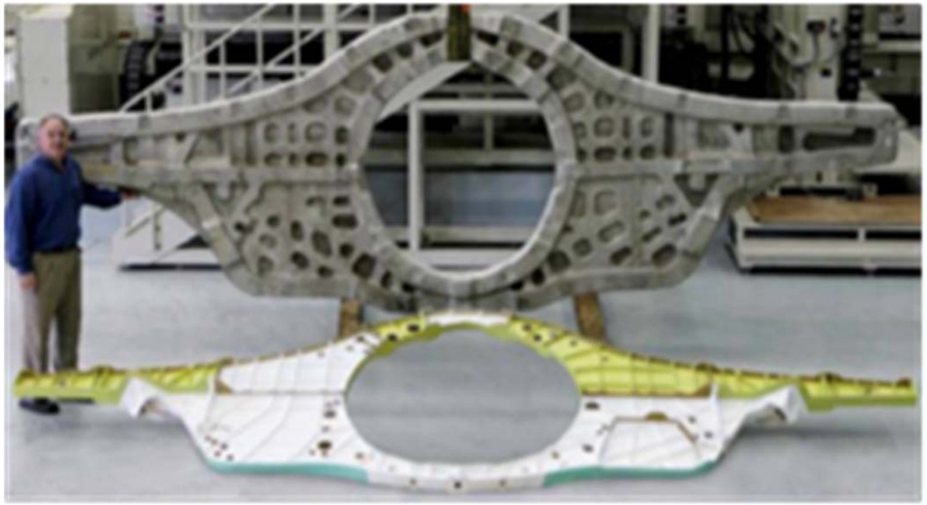
- Arconic: Mark James, John Watton, Dave Selfridge, Dustin Bush, and Brandon Bodily
- Lockheed Martin: Dale Ball
- Air Force Research Laboratory: Bill Musinski, Mike Caton, and Reji John

Background

Aerospace components are being produced from large forgings with complex geometry

- Reduced weight
- Reduced manufacturing costs
- Improved properties
- Improved structural performance

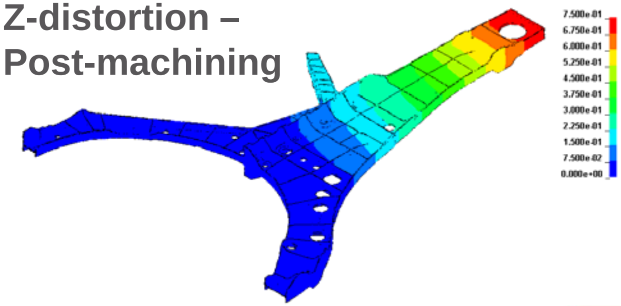




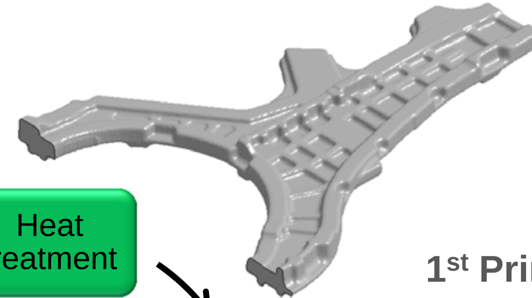
Example large F-35 bulkhead forging

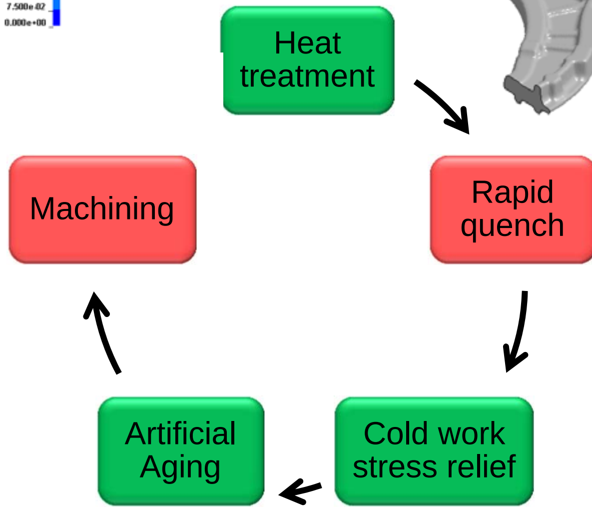
Typical aluminum forging manufacturing

Z-distortion – Post-machining

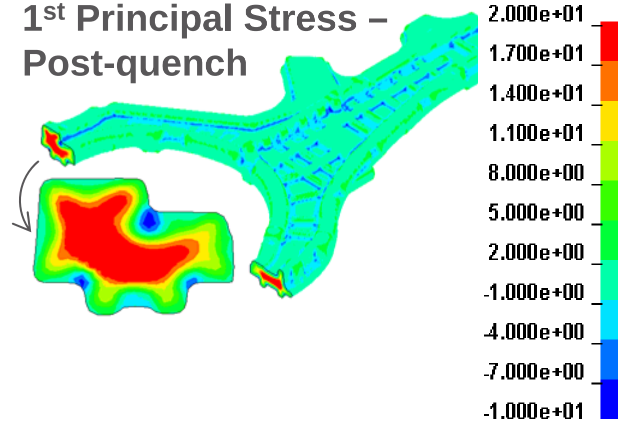


Heat treat Al 7085 @ elevated temperature

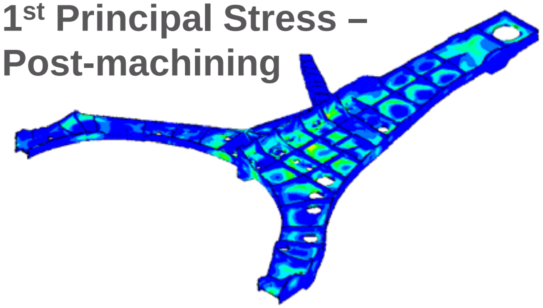




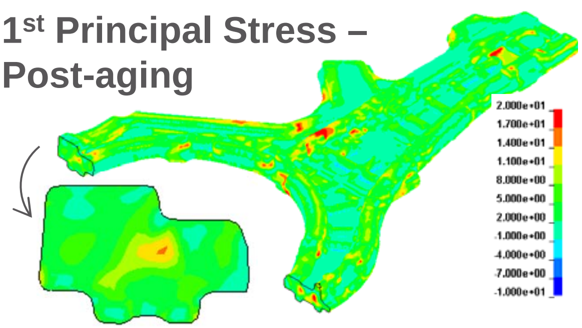
1st Principal Stress – Post-quench



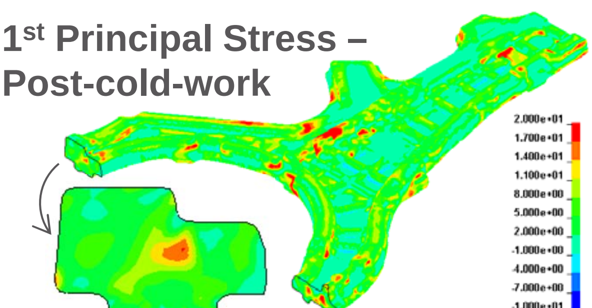
1st Principal Stress – Post-machining



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

Residual stress effects in aluminum structure

Residual stress magnitude is generally small

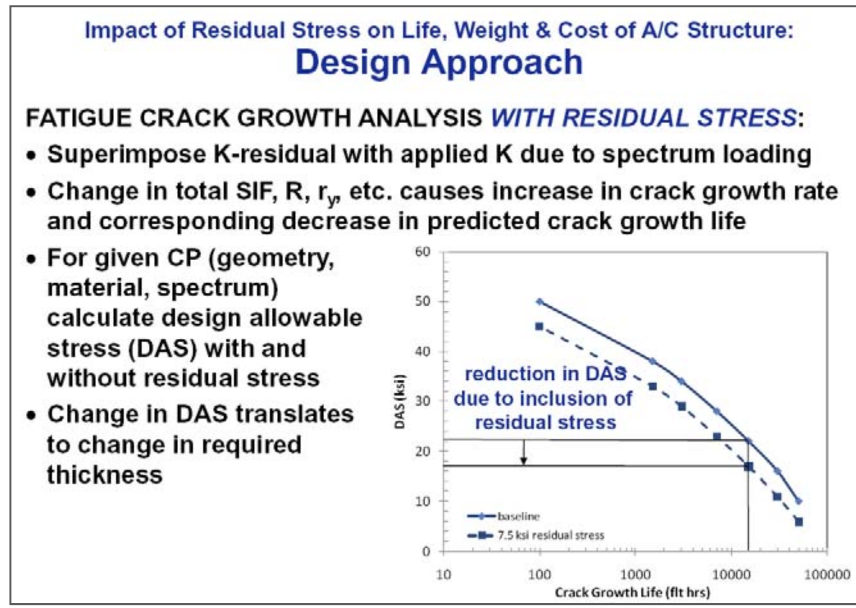
- Less than +/- 10 ksi
- But significant enough to affect performance

Distortion during machining of thin-walled components

- Large amount of material removed
- Long length scales

Residual stresses affect fatigue performance

- Tensile stresses reduce life



Dale Ball, Residual Stress Summit, 2010

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

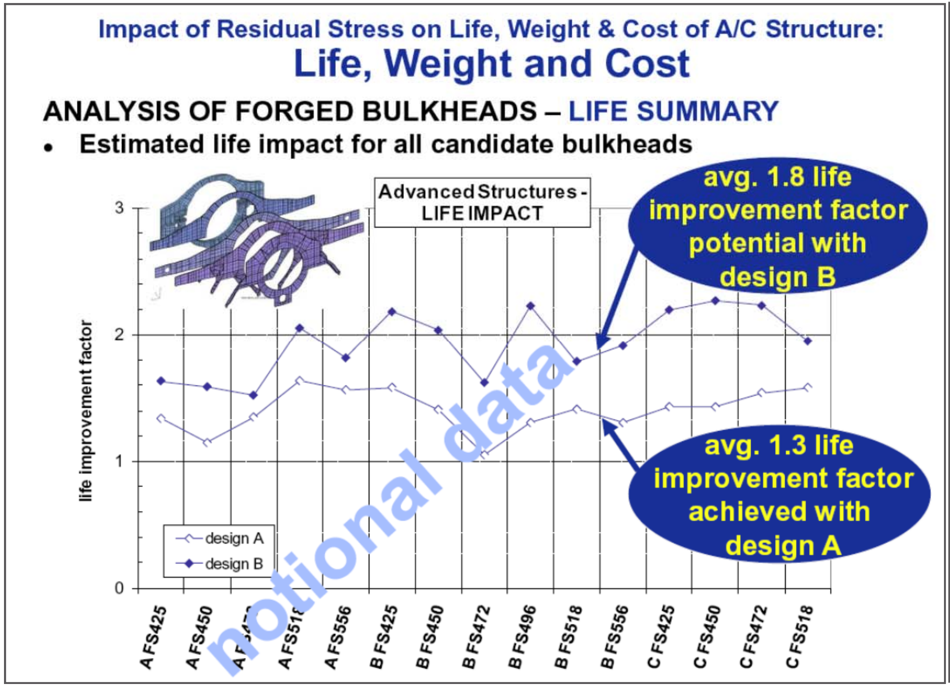
Emerging design approach: residual stress part of specifications

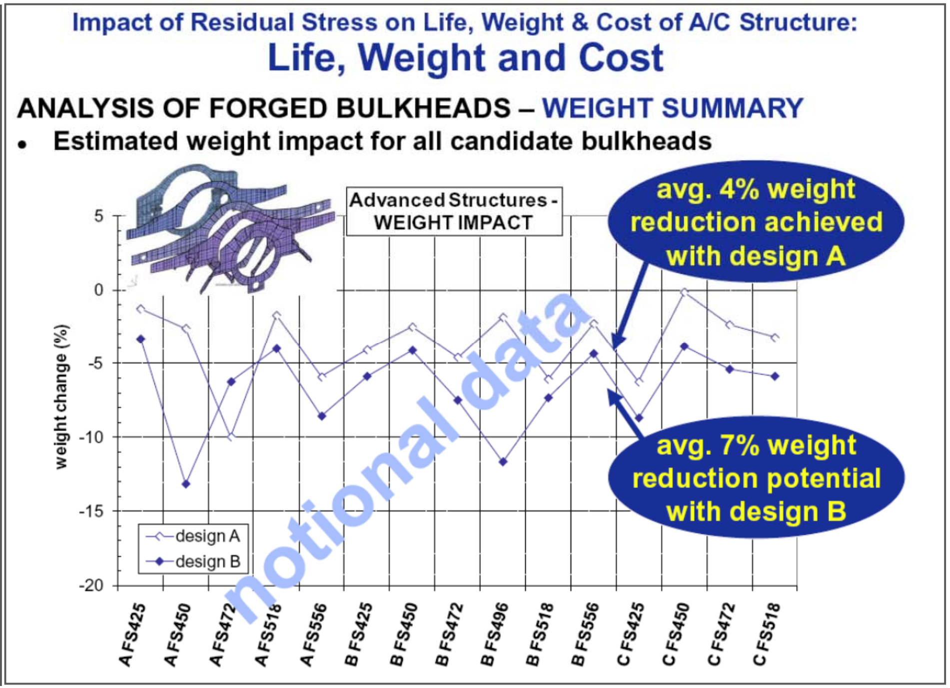
- Known residual stresses in parts from validated models (requires measurements, and validation metrics)
- Include residual stress in materials and process engineering
  - Trade studies
  - Quality program
- Account for residual stress effects on performance

Residual stress opportunity

With improved design methods that account for residual stress effects there is the potential to improve overall component life *and* reduce airframe weight

- Optimization problem: get metal in the correct place





Dale Ball, Residual Stress Summit, 2010

Residual stress opportunity

Formula for realizing benefits of design for residual stress

- Analysis/design tools that incorporate residual stress effects (e.g., machining distortion and fatigue/damage tolerance)
- Known and repeatable residual stress distribution in machined parts
- Known and repeatable residual stress distribution in raw forgings

Many of the tools required for this are in development or exist today

One important missing ingredient is a quality system to enable the process

Quality system concept

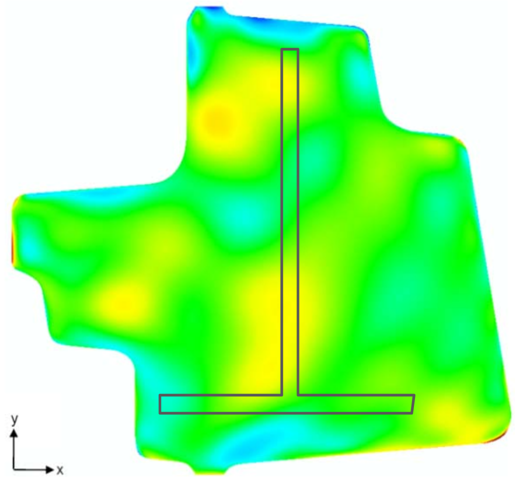
Residual stresses in “as quenched” condition for thick sections

- Compressive around exterior, tensile on the interior
- Relatively high magnitude residual stress at this stage

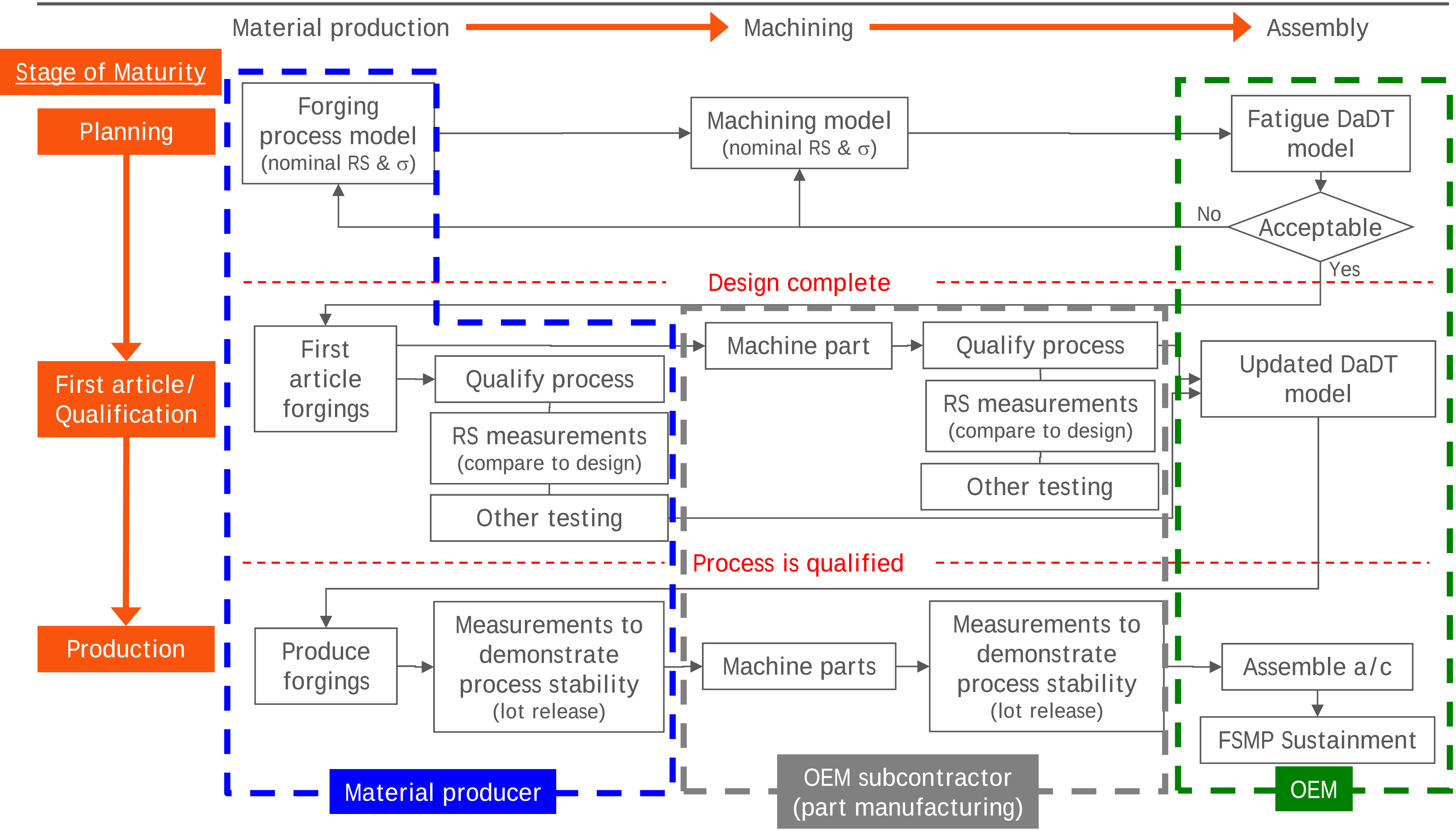
Residual stress magnitude and distribution is greatly reduced through cold work stress-relief and subsequent artificial aging

Key concepts for quality system

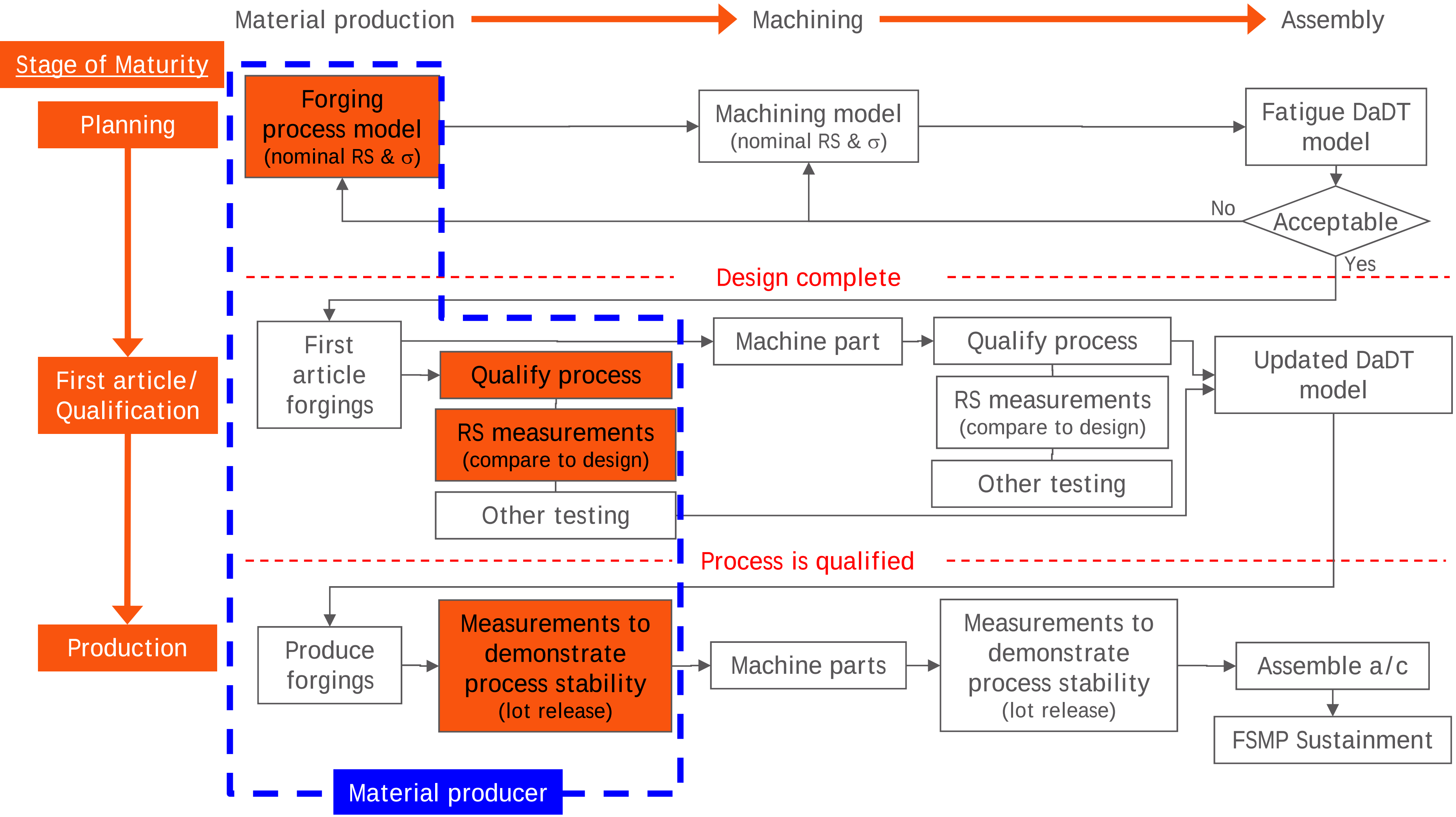
- Utilize 3D process models to design and optimize the forging process
- Use advanced measurement techniques to qualify first article
- Use recurring residual stress measurements to verify consistency over time
  - Use process model to establish correlation



Communicating residual stress information



Communicating residual stress information



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Quality system demonstration specimen overview

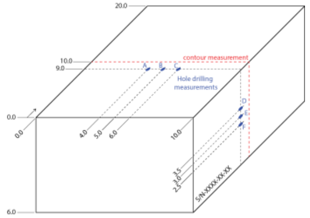
Four specimen types (Material: 7085-T7452)

- Range of cold working (in most cases)
- Predict residual stress using forging process model
- Measure residual stress

Sections from die-forgings

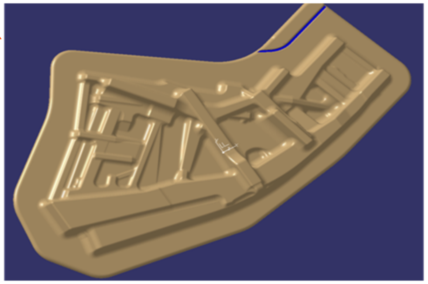
Rectangular hand forgings

- Rectangular body: 6” (ST) x 20” (L) x 10” (LT)



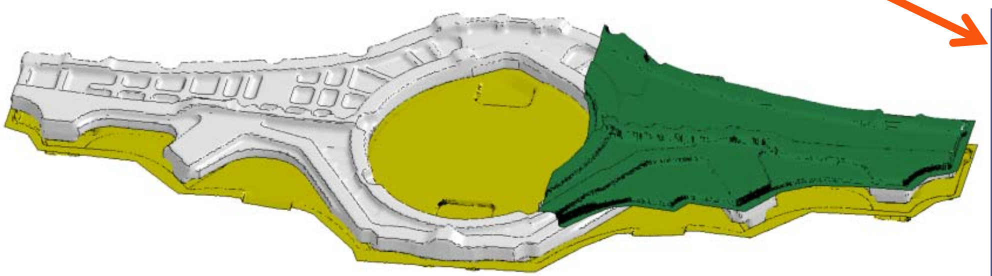
C-5 end fitting die forgings

- Single strike die forging, complex shape



Bulkhead

- Very large and complex

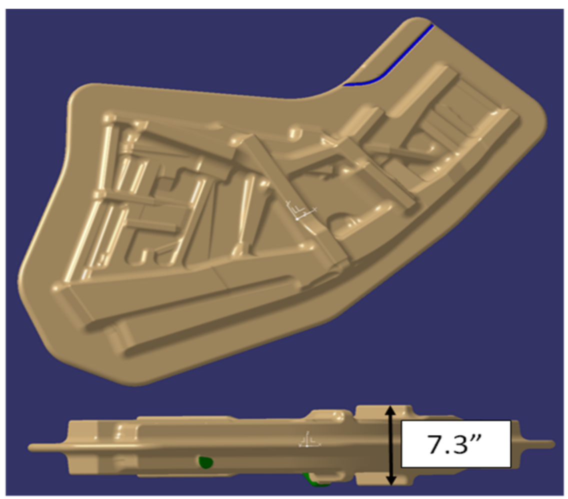


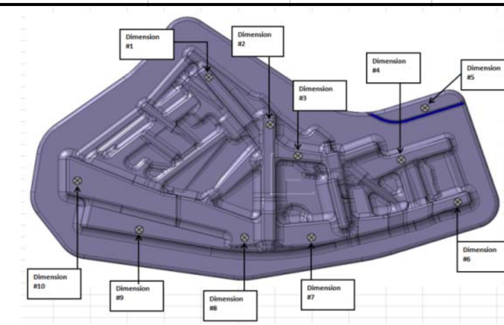
C-5 end fitting forging

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 measurement methods

Variety of accepted RS measurement methods

- Each method has advantages and disadvantages
- “Best method” depends on needs of specific application

Use three methods to demonstrate quality system

Hole drilling

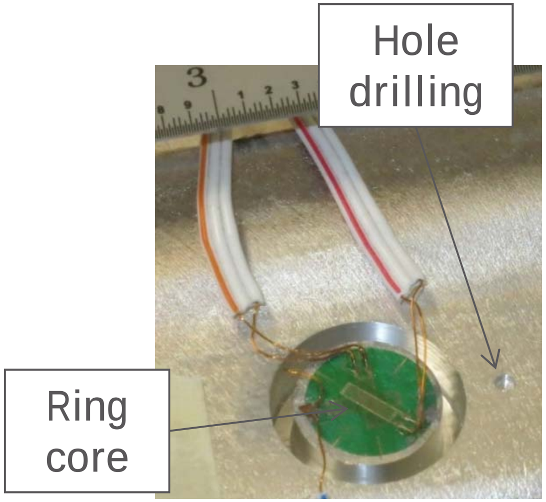
- Incrementally drill hole into test coupon
- Measure strain release near perimeter
- 1D stress profile versus depth (3 components, 0.040”)

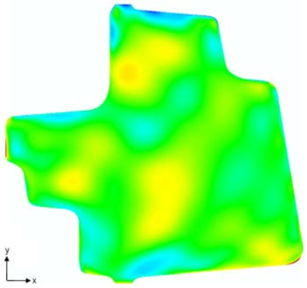
Ring core

- Incrementally trepan core into test coupon
- Measure strain release inside core
- 1D stress profile versus depth (3 components, 0.250”)

Contour

- 2D stress map on cross section (1 component)
- Bulk residual stress measurement





Residual stress measurement location selection

It is not feasible to measure residual stress everywhere, so a set of defined measurement locations is required

- Select in an intelligent manner designed to provide maximum insight and usefulness

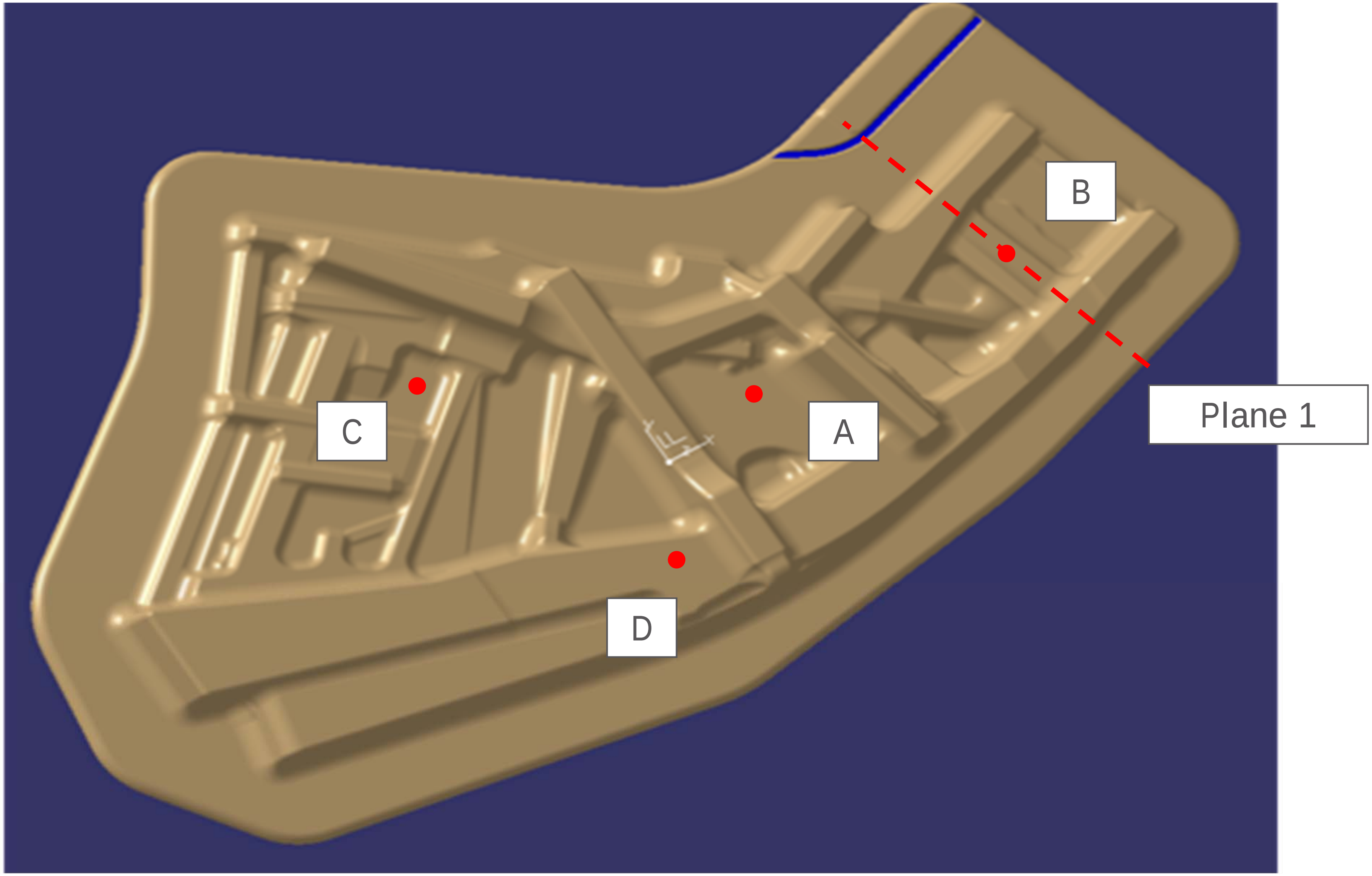
Measurement locations established through collaborative discussion between stakeholders

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

Consider the influence of various factors

- Locations of expected tensile residual stress residing inside of machined part
- Level of sensitivity between residual stress and cold work
- Measurement access/applicability
- Applied stress hot spots
- Locations of structural significance
- Difficult to inspect
- Very costly to repair

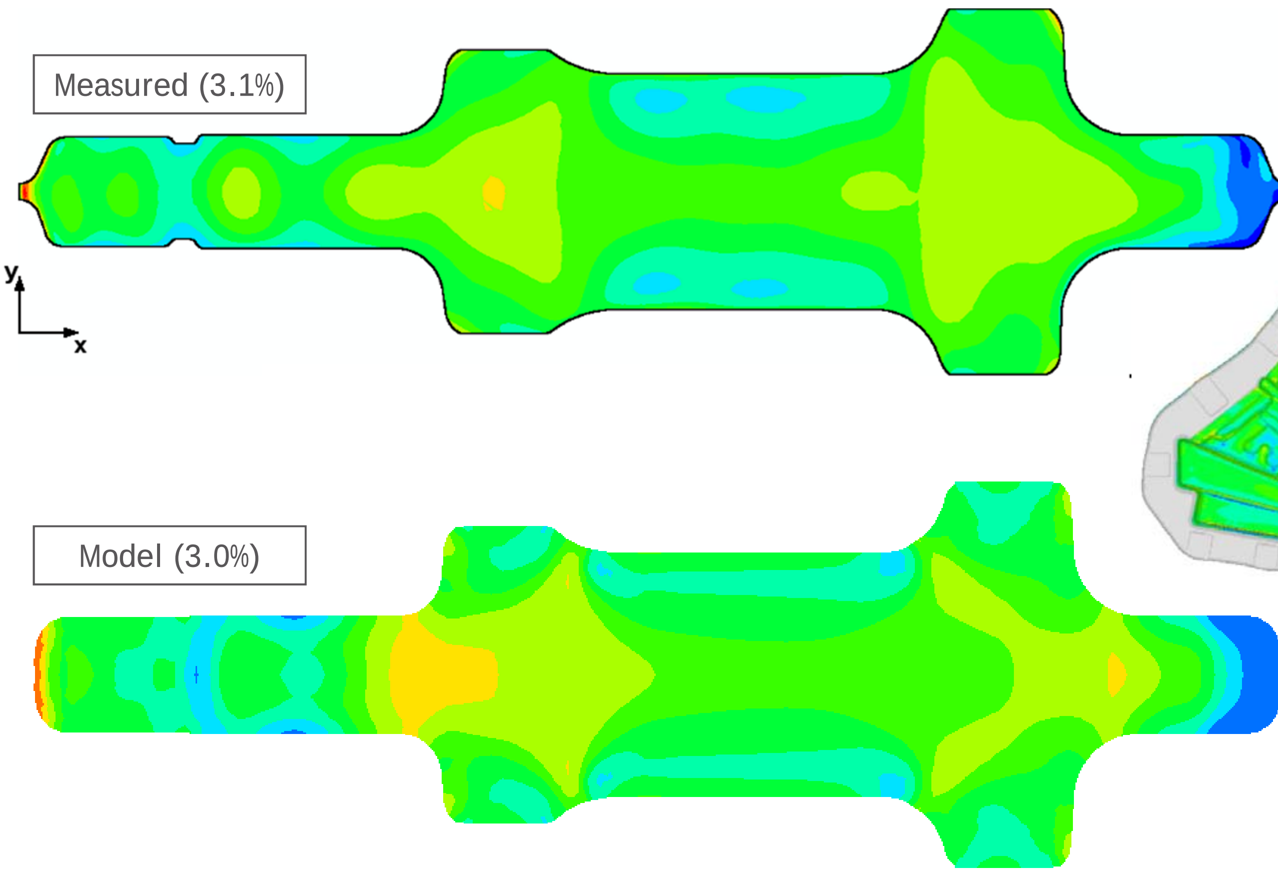
C-5 end fitting forging measurement locations

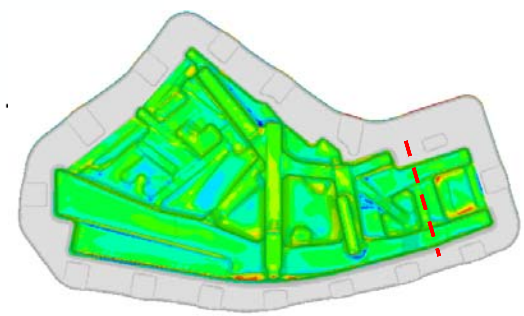


First article validation example

Favorable comparison between measurement and model

- 3% cold work condition

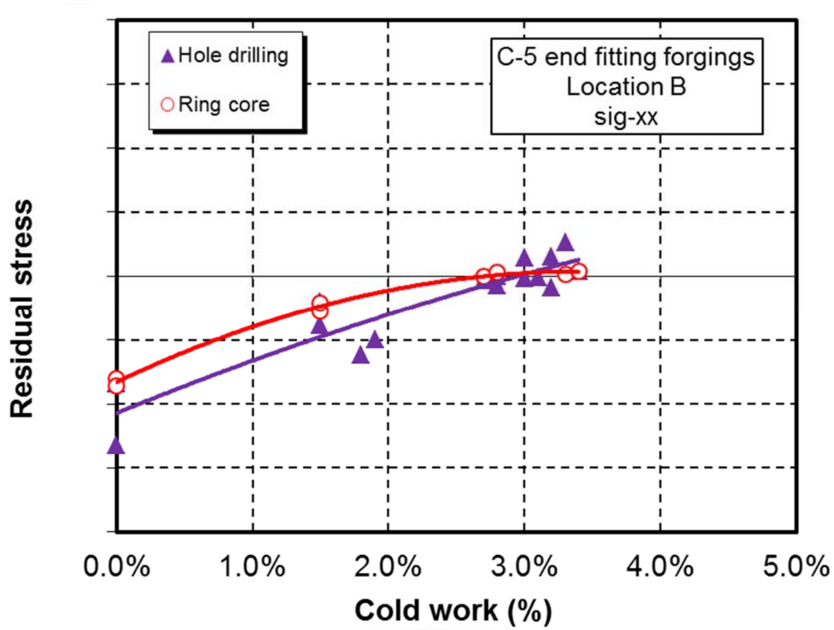


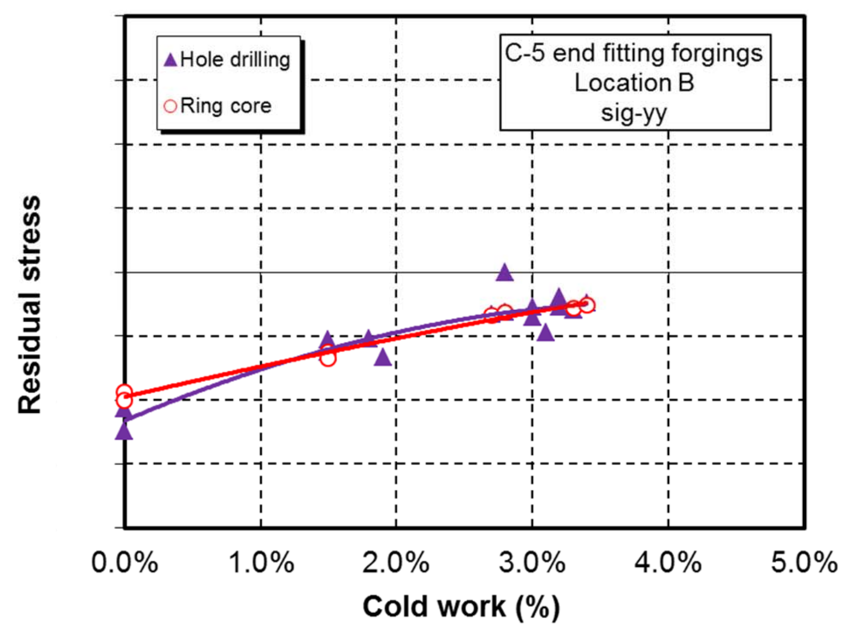


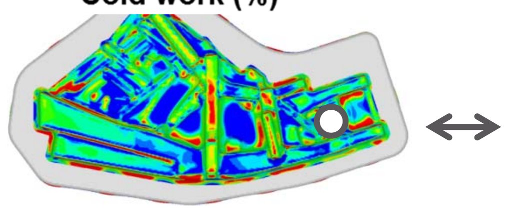
Cold work process sensitivity (near-surface)

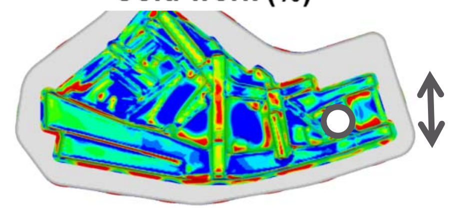
Near surface residual stress varies with cold work

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

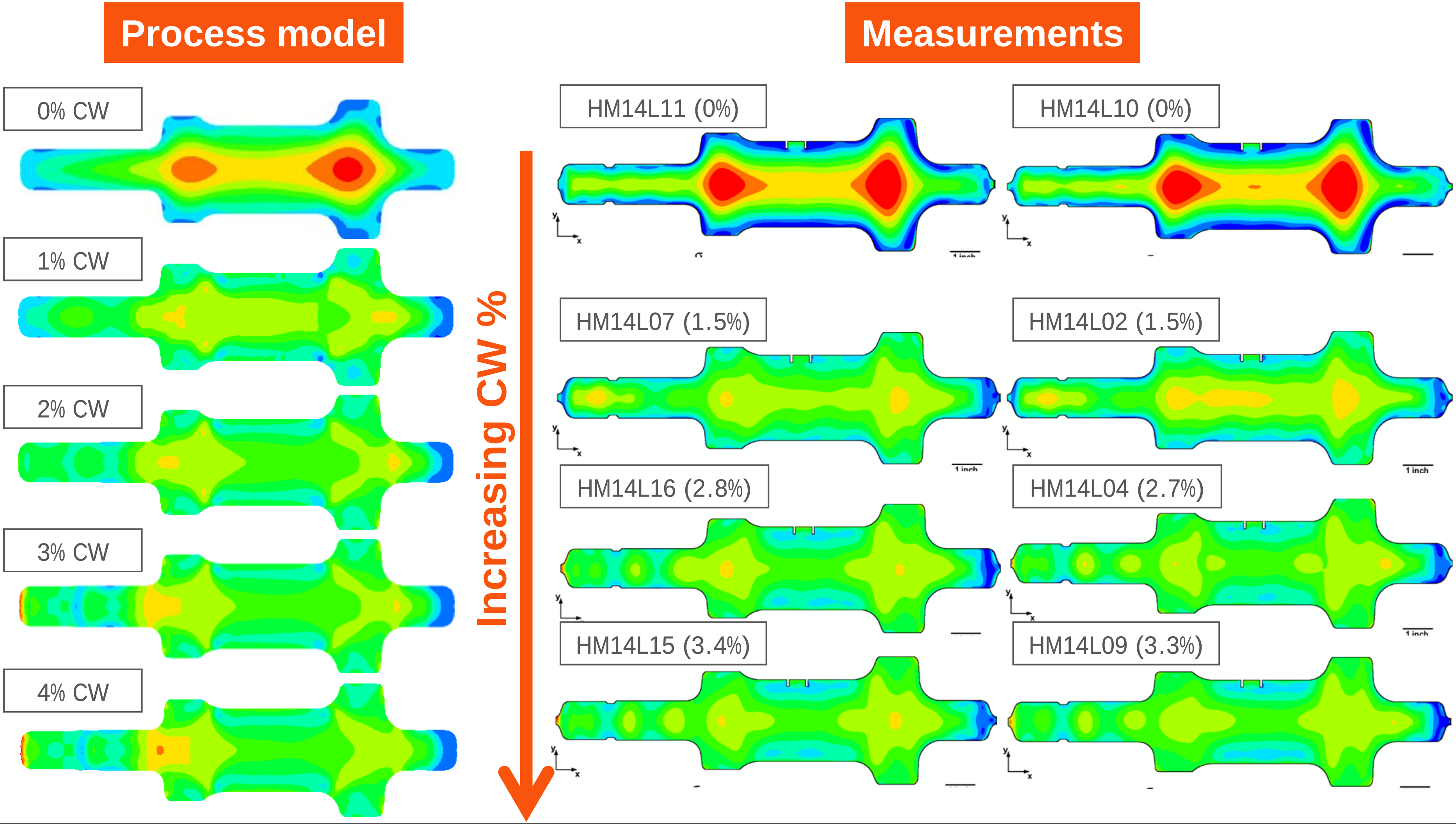








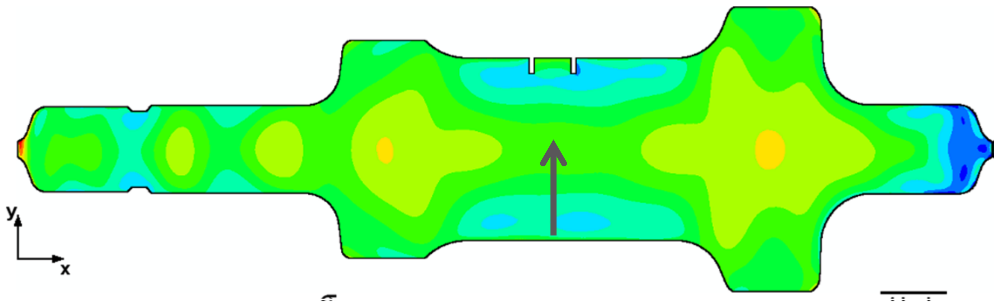
Cold work process sensitivity (bulk)

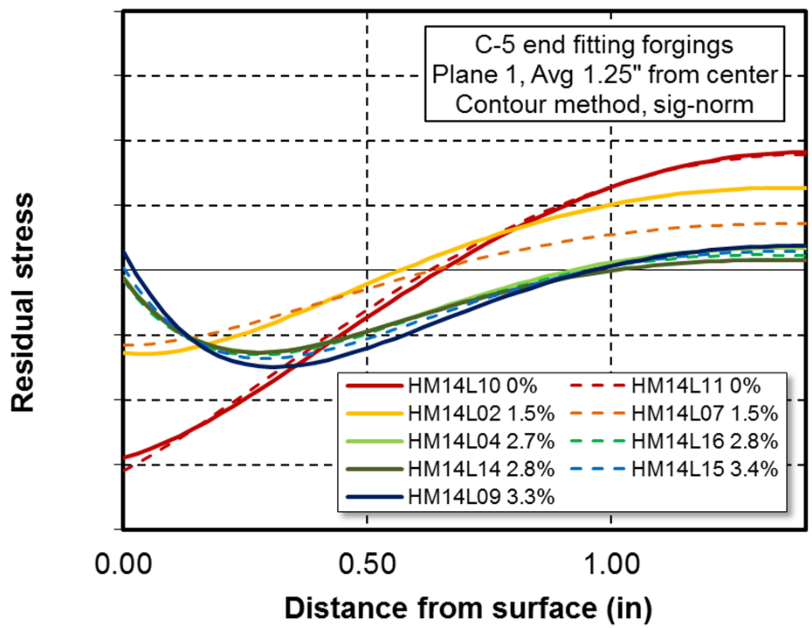


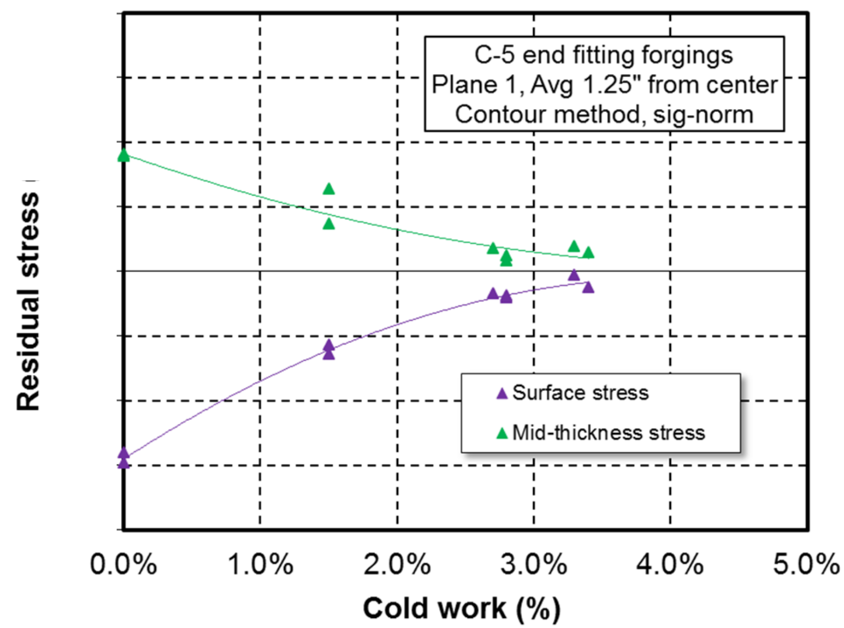
Cold work process sensitivity (summary)

Interior and near-surface residual stress both trend towards zero with increasing cold work

- Relationship can be used to support quality system







C-5 end fitting forging residual stress summary

Residual stress measurements show correlation with the amount of applied cold work

- This trend is observable at every location measured
- The correlation between residual stress and cold work is location dependent
  - Thick sections like ribs and stiffeners appear to show more sensitivity to cold work than thin sections like webs

The residual stress measurements are repeatable enough to resolve the variation with cold work

There is correlation between the measurements and the model

- Trend and shape agree better than absolute magnitudes
- The correlation is better at thicker sections in the forging

There is strong correlation between near surface and interior residual stress

Next steps - large forgings

Quantify residual stress in large aluminum bulkhead forgings

- Previous work mostly in “small” forgings (single strike)

Estimate expected part-to-part residual stress variability for large aluminum bulkhead forgings

- Define uncertainty bounds to use in design

Develop comparisons between residual stress measurements and process models

Prepare a residual stress quality system specification to support procurement of aluminum forgings

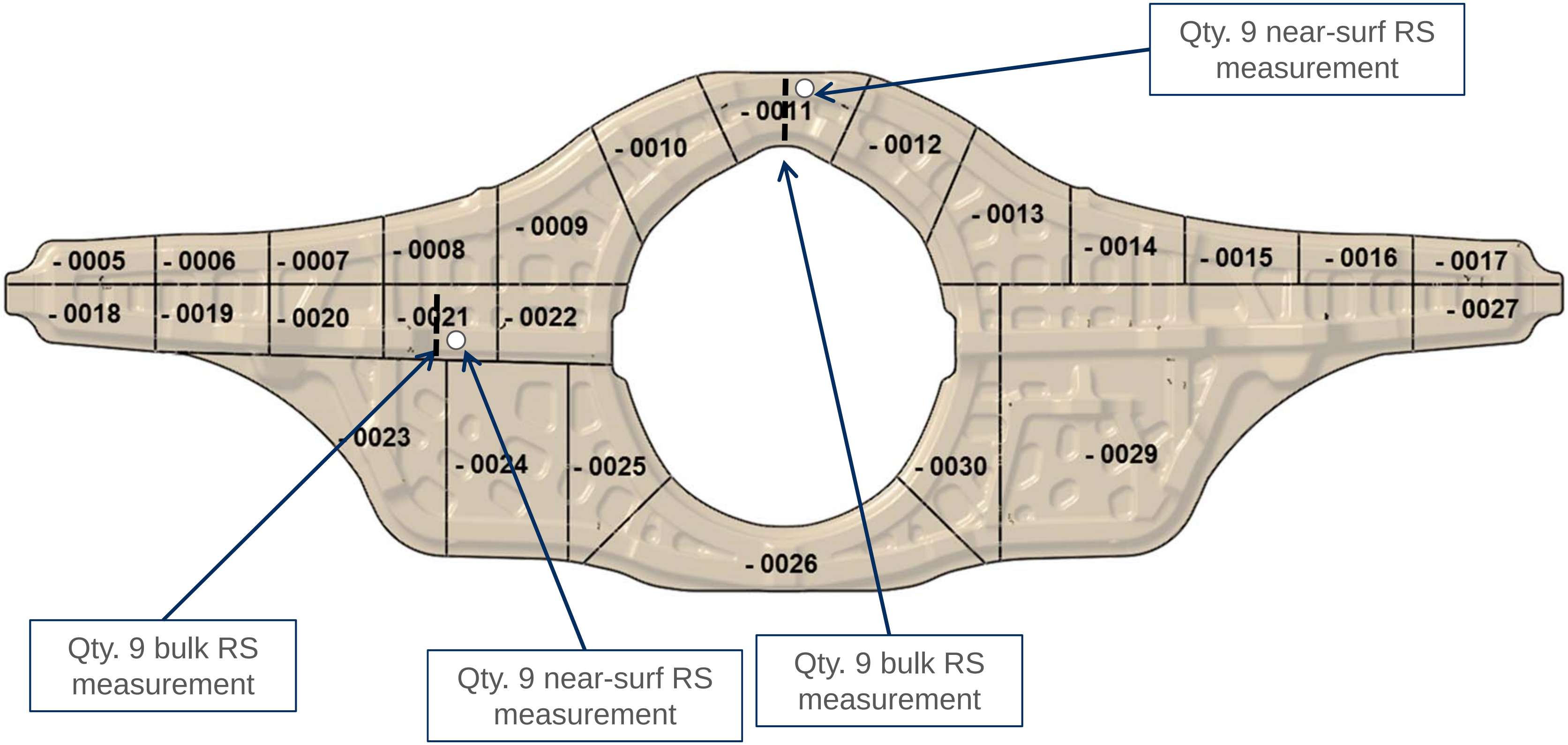
Large forging material

Sections from large bulkhead forgings used for demonstration

Large forging material

Sections from 9 replicate forgings available

- Select locations for residual stress measurement based on established criteria (structurally significant, tensile residual stress, etc.)



Summary comments

Quality system provides traceable information on residual stress

- Able to demonstrate and track the degree of consistency in a quantitative and meaningful way
- Enables uses of residual stress information in design
- Material supplier has traceable residual stress record
- OEM can plan for more aggressive designs (reduced weight, reduced cost)

Forgings and machined parts with more consistent residual stress levels provide:

- More consistent performance of machined parts (improved safety, reduced sustainment costs)
- More consistent machining (fewer rejections, fewer issues with distortion)
- Can plan for more aggressive machining plans e.g., fewer flips (no need to account for large variability)

Summary comments

Breaking new ground for residual stress

- Validated process models will move residual stress from *known-unknown* to *known-known*
- Business case forecasts significant *cost-savings* from residual stress engineering
  - Manufacturing, operation, and sustainment

Key concepts for residual stress quality system

- Utilize 3D process models to optimize the forging process
- Use advanced measurement techniques to qualify first article
- Use recurring residual stress measurements to verify consistency over time

Working to validate quality system concept on large forgings

The team approach enables technological progress on key issues

- Material supplier – raw materials, processing
- Manufacturer – processing, forging, machining, distortion, assembly
- Designer – failure processes, loading, environment
- Operator – maintenance, sustainment, life extension
- Regulator – safety, certification
- Technical experts

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