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Dayton, Ohio

The Impact of Bulk Residual Stress on the Qualification of Large Aluminum Forgings

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The Impact of Bulk Residual Stress on the Qualification of Large Aluminum Forgings

ABSTRACT

When new materials and processes are adopted for use in primary structural components of man-rated military aircraft, the aircraft manufacturer must demonstrate to the procuring agency that five process factors have been met; these are: stability, producibility, characterized mechanical and physical properties, predictability of performance, and supportability. The adoption of aluminum forgings for large, monolithic, primary airframe components of a current military aircraft has prompted the development of new analytical and experimental procedures which address forging process induced bulk residual stress explicitly. While the presence of these residual stresses has played a role in each of the five process factors cited above, significant effort has been directed toward understanding their impact on mechanical properties and predictability of performance in particular. After the completion of several R&D projects spanning nearly ten years, which involved the development and validation of these new procedures, the procuring agencies' system program office has qualified the large forging material and processes, and it has approved the use of explicit residual stress methods for the design and qualification of primary structural components made from these forgings.

In this presentation, a brief overview of the steps that were taken in order to qualify the forgings and the explicit residual stress methods will be given. In addition, one of the aforementioned R&D projects leading to these qualifications will be described.

The Impact of Bulk Residual Stress on the Qualification of Large Aluminum Forgings

⇨ BACKGROUND

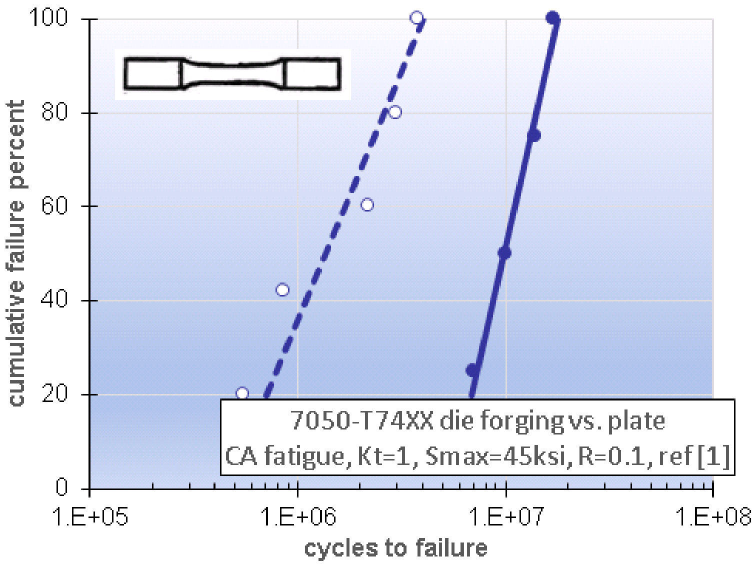
- Standard Qualification Process
- Steps Taken Toward a New Approach
- Looking Ahead

Impact of Bulk Residual Stress on Forging Qualification: Background

- Almost since introduction of aluminum for aircraft construction, forgings have been product form of choice for applications requiring high property retention in thick sections, typically bulkheads, spars and frames

- Desirable performance characteristics of die forged aluminum (versus other product forms) derive from the multi-directional plastic straining, breakup of original cast structure, and micro-porosity healing which occur during the full thermo-mechanical processing sequence (upset, forge, quench, compression stress relieve, and artificially age) [1]

- For example, Bucci et.al. showed that 7050-T7452 die forgings can have significantly better fatigue and fatigue crack growth performance than comparable -T7451 plate [1]



Impact of Bulk Residual Stress on Forging Qualification: Background

- **Historically, aluminum forgings were also selected during design based on manufacturing affordability considerations; use of forgings (especially precision forgings) can reduce the ratio of stock to finished part weight and volume ("buy-to-fly" ratio) as well as machining costs**

- **More recently, development of new alloys which permit retention of mechanical properties in very thick sections (up to 12 inches, 30.5 cm) [2] [3] has fueled the move by airframe original equipment manufacturers (OEMs) toward structural unitization [4] [5] [6]**

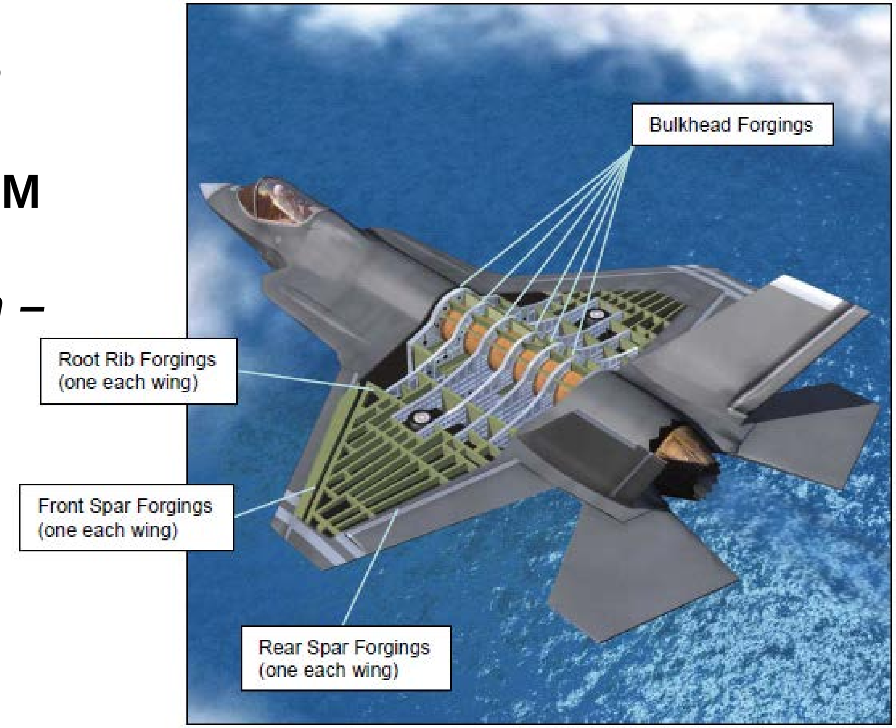
- **Such unitization can lead to both weight saving (fewer fasteners, better efficiency), and significant manufacturing cost savings (reduced touch labor)**

- **However, large aluminum forgings (esp. 7XXX-series) are known to retain quench induced residual stresses. Cold compression stress relief significantly reduces, but does not completely eliminate these stresses**

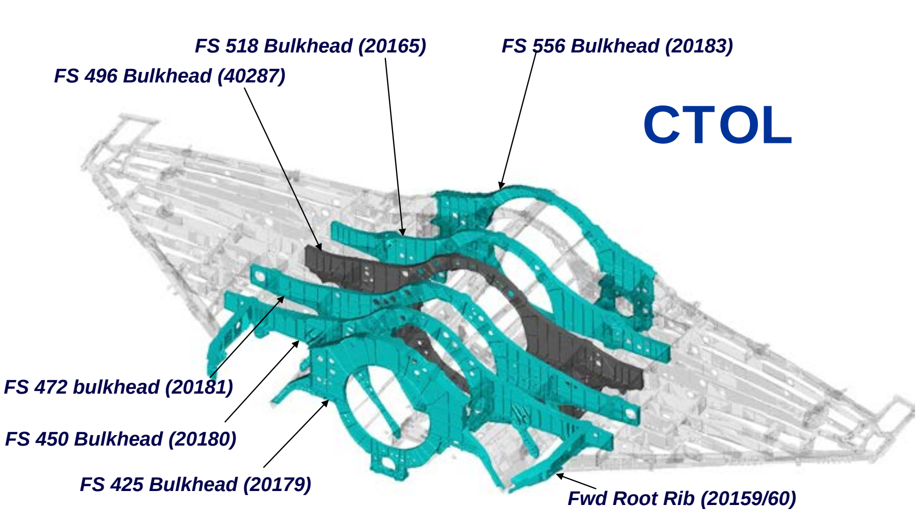
- **Result is significant variability in mechanical properties [7] [8] [9]**

Impact of Bulk Residual Stress on Forging Qualification: Background

- **Large aluminum forgings were adopted for use on F-35 during early SDD (2004):**
  - ***Structural unitization – single forged / machined parts replaced multi-part designs***
  - ***Significant weight savings – 10-15% over built-up plate design***
  - ***Significant manufacturing cost savings – 50% reduction in buy-to-fly ratio, reduced machining / assembly costs, reduced touch labor***
- **Collaboration took place between LM Aero and Alcoa**
  - ***Forging / machined part design – additional coverage for risk abatement***
  - ***7085 material characterization (mechanical properties)***
  - ***Forging residual stress characterization***

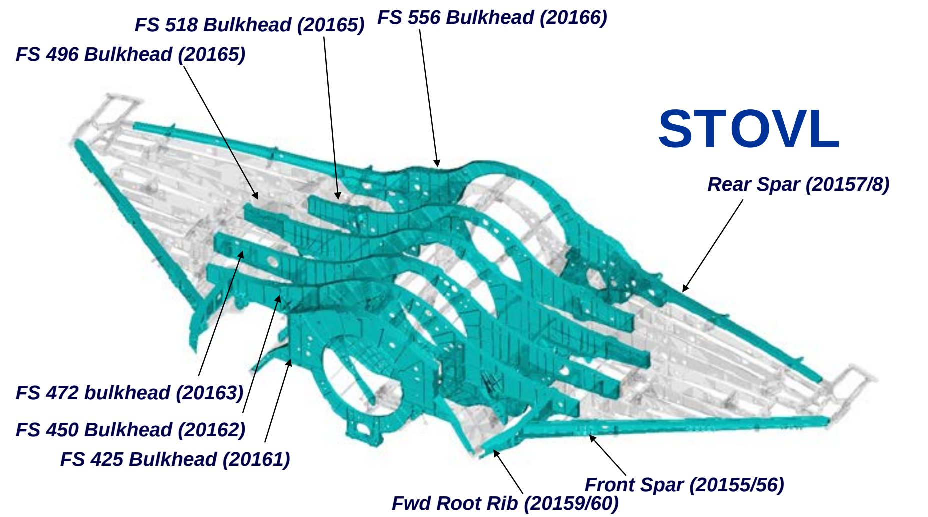


Impact of Bulk Residual Stress on Forging Qualification: Background



Highlighted Alcoa 7085-T7452 Forgings

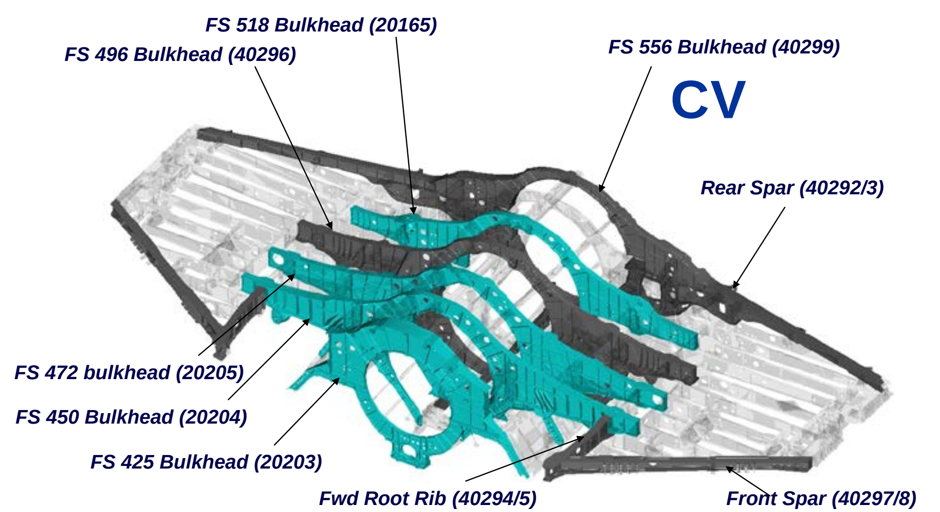
Highlighted Alcoa Ti-6-4 Eli Forgings



All Highlighted Parts From Alcoa 7085-T7452 Forgings

New Alcoa Technologies Applied:

- New forge alloy 7085-T7452
- Very large, monolithic die forgings
- Forgings designed for manufacturing
- CAD modeled "Signature Cold Work Process" (superior stress relief product)



Highlighted Alcoa 7085-T7452 Forgings

Highlighted Alcoa Ti-6-4 Eli Forgings

Impact of Bulk Residual Stress on Forging Qualification: Background

- **All stakeholders (LM Aero, Alcoa, JPO) recognized that**
  - ***forged parts contain residual stresses***
  - ***presence of detrimental (tensile) residual stresses***
    - **can confound material property data (esp. fatigue crack growth rate data) if not accounted for**
    - **may result in premature cracking if not accounted for in design**
  - ***effects of these would have to be addressed***

- **Baseline design approach (SDD through LRIP8) was to use mechanical properties with *implicit* (built-in) *residual stress***

- **Updated design (LRIP9 and on) approach uses intrinsic (residual stress free) material properties with *explicit residual stress***

The Impact of Bulk Residual Stress on the Qualification of Large Aluminum Forgings

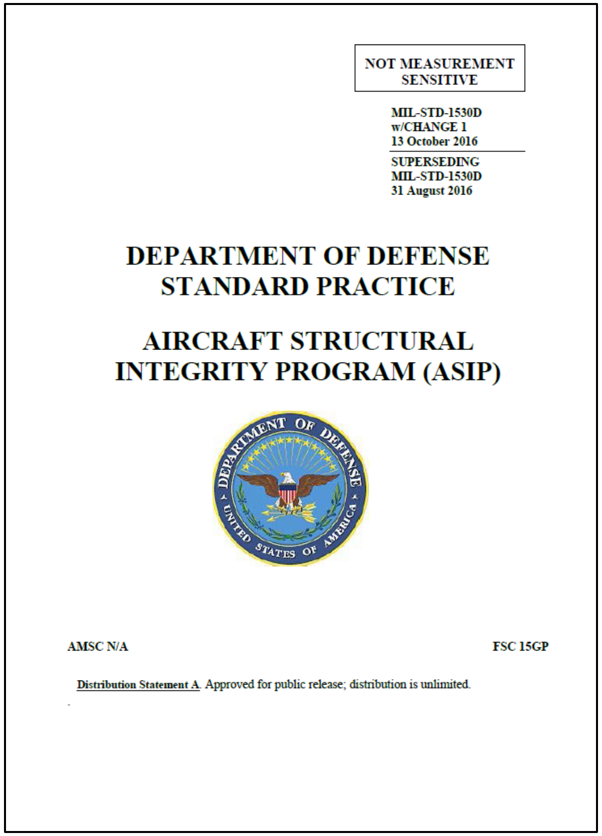
- **Background**

⇨ **STANDARD QUALIFICATION PROCESS**

- **Steps Taken Toward a New Approach**
- **Looking Ahead**

Impact of Bulk Residual Stress on Forging Qualification:
Standard Qualification Process

- **Guidance for selection / use of material, processes and joining methods (M&P&JM) given in MIL-STD-1530 [10], ASIP Task 1**
  - ***5.1.7 Selection of materials, processes, joining methods, and structural concepts (Lincoln's five factors)***
    - **5.1.7.1 Stability**
    - **5.1.7.2 Producibility**
    - **5.1.7.3 Characterization of mechanical and physical properties**
    - **5.1.7.4 Predictability of structural performance**
    - **5.1.7.5 Sustainability**



NOT MEASUREMENT SENSITIVE

MIL-STD-1530D
w/CHANGE 1
13 October 2016

SUPERSEDING
MIL-STD-1530D
31 August 2016

DEPARTMENT OF DEFENSE
STANDARD PRACTICE

AIRCRAFT STRUCTURAL
INTEGRITY PROGRAM (ASIP)

AMSC N/A FSC 15GP

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- **And in MIL-STD-1530, ASIP Task 2**
  - ***5.2.1 Material and structural allowables.***

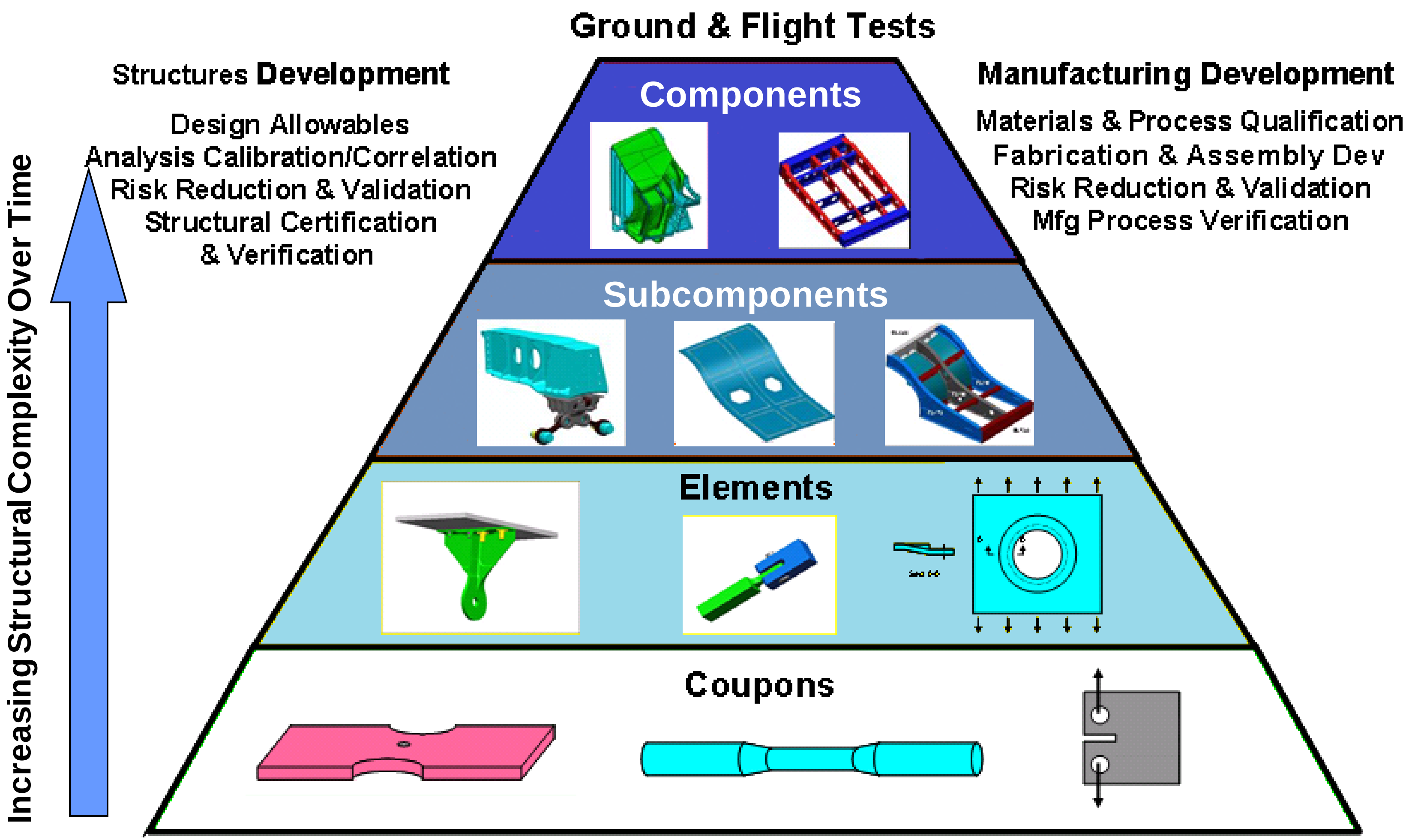
Impact of Bulk Residual Stress on Forging Qualification:
Standard Qualification Process

- **Standard materials characterization:**

physical properties	static mechanical properties	fatigue & fracture properties	environ-mental properties	producibility	qualification
density	elastic moduli	S-N fatigue	temperature	castability	material specs.
thermal expansion	Poisson's ratio	notch sensitivity	humidity	formability	process specs.
heat capacity	tensile yield & ultimate strength	cyclic stress vs. strain	chemical resistance	deformation characteristics	approved suppliers
thermal conductivity	compressive yield & ultimate strength	e-N fatigue	wear	weldability	repair methods
	elongation	fatigue crack growth rate	corrosion resistance	machinability	safety
	shear strength	fracture toughness	oxidation resistance	assembly	
	brg strength	SCC		chemical processing	
		special design factors		inspection methods	

Impact of Bulk Residual Stress on Forging Qualification:
Standard Qualification Process

- **Standard building block approach [11]:**

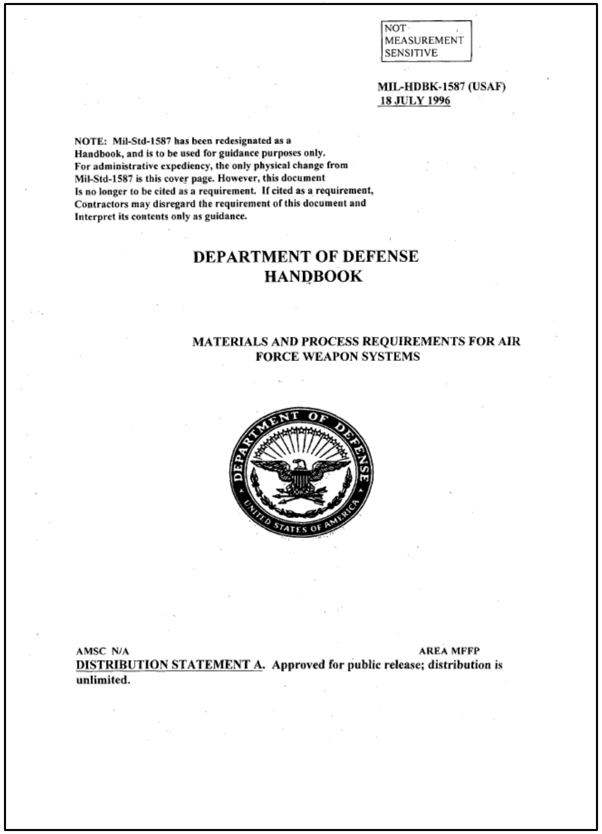


Parallels and Supports Aircraft Development

Impact of Bulk Residual Stress on Forging Qualification:
Standard Qualification Process

- **Guidance for standard material qualification process given in MIL-HDBK-1587 [12]**
  - ***4.1 Material Selection***
  - ***5.2.1.4.2 Specifications***
    - **5.2.1.4.2.1 Material Acquisition Specification**
    - **5.2.1.4.2.2 Material Qualification Specification**
    - **5.2.1.4.2.3 Process Specification**

- **Guidance for forgings specifically**
  - ***5.3.1 Forging Practices***
    - **5.3.1.1 Forging Design**
    - **5.3.1.2 Forging Surfaces**



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MIL-HDBK-1587 (USAF)
18 JULY 1996

NOTE: Mil-Std-1587 has been redesignated as a Handbook, and is to be used for guidance purposes only. For administrative expediency, the only physical change from Mil-Std-1587 is this cover page. However, this document Is no longer to be cited as a requirement. If cited as a requirement, Contractors may disregard the requirement of this document and Interpret its contents only as guidance.

DEPARTMENT OF DEFENSE
HANDBOOK

MATERIALS AND PROCESS REQUIREMENTS FOR AIR FORCE WEAPON SYSTEMS

AMSC N/A AREA MFFP

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No guidance given regarding explicit characterization of residual stresses or their effects

The Impact of Bulk Residual Stress on the Qualification of Large Aluminum Forgings

- **Background**
- **Standard Qualification Process**

⇨ **STEPS TAKEN TOWARD A NEW APPROACH**

- **Looking Ahead**

Impact of Bulk Residual Stress on Forging Qualification: Toward a New Approach

- **Recent (since 2000) advances in computational and experimental mechanics have led to the development of an advanced structural design / analysis approach in which bulk residual stresses are addressed explicitly, rather than being accounted for through conservative material properties, correction factors, or other approximate means**

- **Some of the key advancements were:**
  - ***Development of the capability to predict forging process induced residual stresses [13]***
  - ***Development of the capability to measure residual stress using the contour method [14]***
  - ***Development of the adjusted compliance ratio (ACR) method for the extraction of confounding residual stress effects from fatigue crack growth rate (FCGR) data [15]***

Impact of Bulk Residual Stress on Forging Qualification: Toward a New Approach

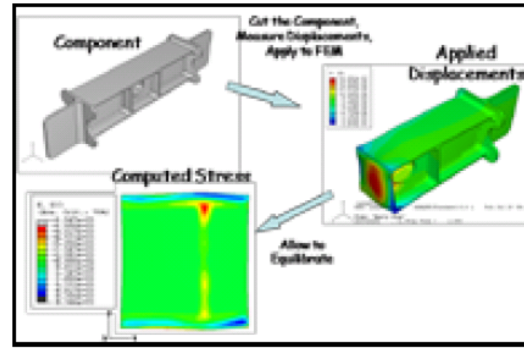
- **The viability of this approach requires:**
  - ***Validation of models for prediction of forging process induced residual stresses (largely by comparison to measured data)***
  - ***Quantification of uncertainty/error in residual stress measurement techniques***
  - ***Quantification of residual stress variability in parts machined from forgings (part to part variability)***
  - ***Validation of models for the inclusion of residual stress in life calculation***

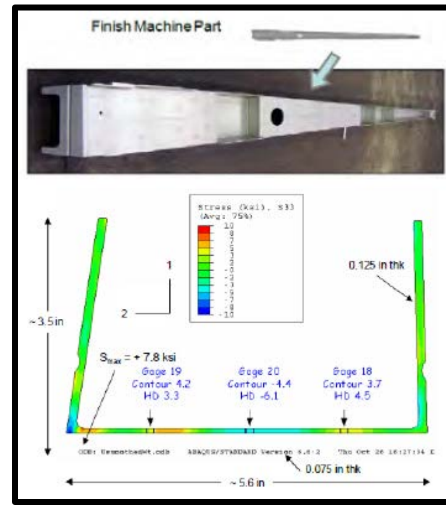
- **Numerous studies (past & present) conducted in an effort to validate models and forging process induced residual stresses in production parts**
  - ***Alcoa / LM R&D***
  - ***AFRL sponsored MAI programs***
  - ***AFLR sponsored SBIRs***

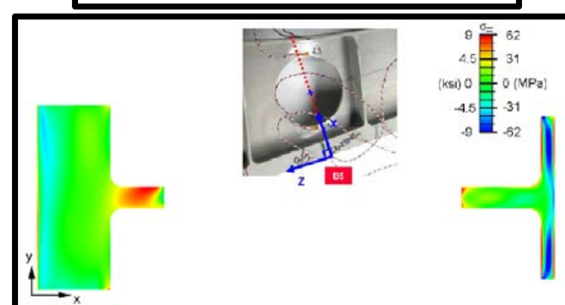
Impact of Bulk Residual Stress on Forging Qualification:
Toward a New Approach

Alcoa / Lockheed Martin Joint Efforts to Measure Residual Stresses in Production Scale Parts, ref: James [16]

- **F-35 Rear Spar (2004-2005)**
  - *Hole-drilling survey (through and blind holes)*
- **F-35 Rear Spar Machined Sub-component (2004-2005)**
  - *Hole-drilling survey (through and blind holes)*
  - *Contour method*
  - *Alcoa wide groove method*
- **F-35 Inner Front Spar (2006)**
  - *Hole-drilling survey (through)*
  - *Contour method*
- **F-35 Bulkhead (2008)**
  - *13 measurement sites in 10 regions*
  - *Criteria: measurement confidence, key design features, model validation*
  - *Hole drilling, contour, and slitting methods were used*







Impact of Bulk Residual Stress on Forging Qualification:

Toward a New Approach

- **A Metals Affordability Initiative (MAI) program (BA-11) was conducted between 2011 and 2016 to further develop and demonstrate this advanced structural design / analysis approach [17]**
- **The BA-11 team consisted of:**
  - ***Govt: AFRL***
  - ***OEMs: Boeing, Lockheed Martin, Northrop Grumman, Rolls-Royce***
  - ***Supplier: Alcoa***
  - ***Subcontractors: Hill Engineering, ESRD, SwRI***
- **Effects of forging process induced bulk residual stresses on both machining distortion and fatigue life were studied at both the coupon and large component level**

BOEING

LOCKHEED MARTIN
Aeronautics Company

ALCOA

NORTHROP GRUMMAN

Rolls-Royce

Hill Engineering, LLC
Engineering structural integrity

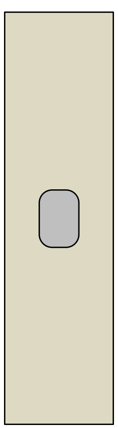
Southwest Research Institute

esrd

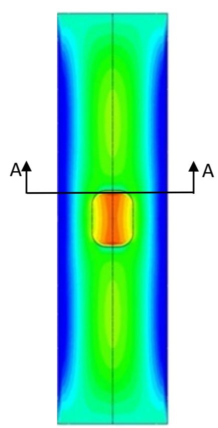
Impact of Bulk Residual Stress on Forging Qualification:
Toward a New Approach

MAI BA-11 (cont'd):

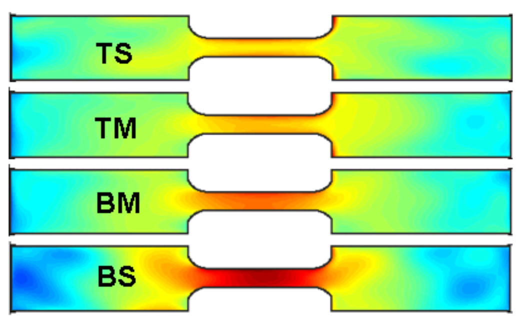
- **Task 3** **demonstrated significant improvement in the fidelity of fatigue crack initiation (FCI) and fatigue crack growth (FCG) analyses**
  - ***confounding RS effects were extracted of from mat'l property data***
  - ***forging RS was explicitly included in the subsequent fatigue analyses***



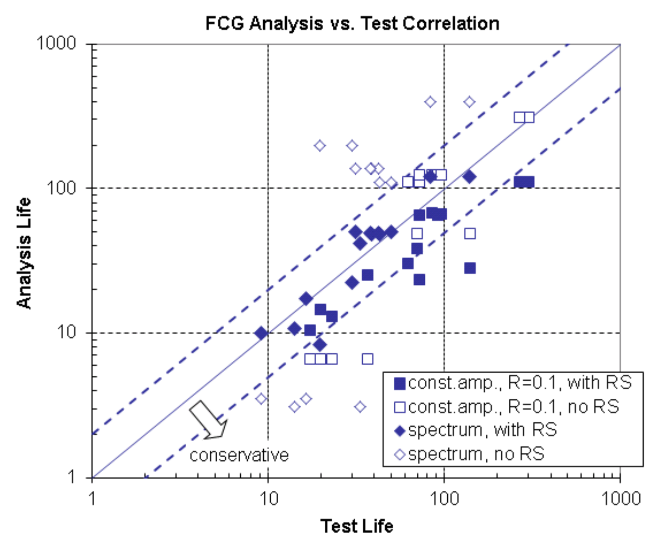
design feature coupon, DF3: centered machined pocket



computed residual stress



measured residual stress on section A-A for different coupon positions

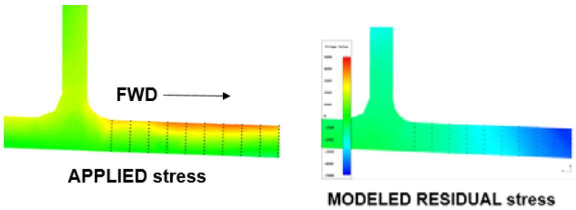


analysis vs. test correlation improves with explicit inclusion of residual stress

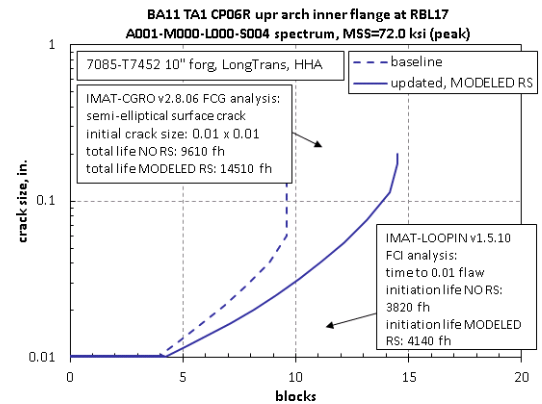
Impact of Bulk Residual Stress on Forging Qualification: Toward a New Approach

MAI BA-11 (cont'd):

- **Task 4 demonstrated that advanced design approach does scale to the structural level, and that its use can result in components that are either lighter or more durable (or both) than their traditionally designed counterparts**



- **Forging process induced bulk RS in finished parts**
  - ***computed by ATC (ICME demonstration)***
  - ***measured by Hill Engineering (contour method) & ATC (hole drilling)***



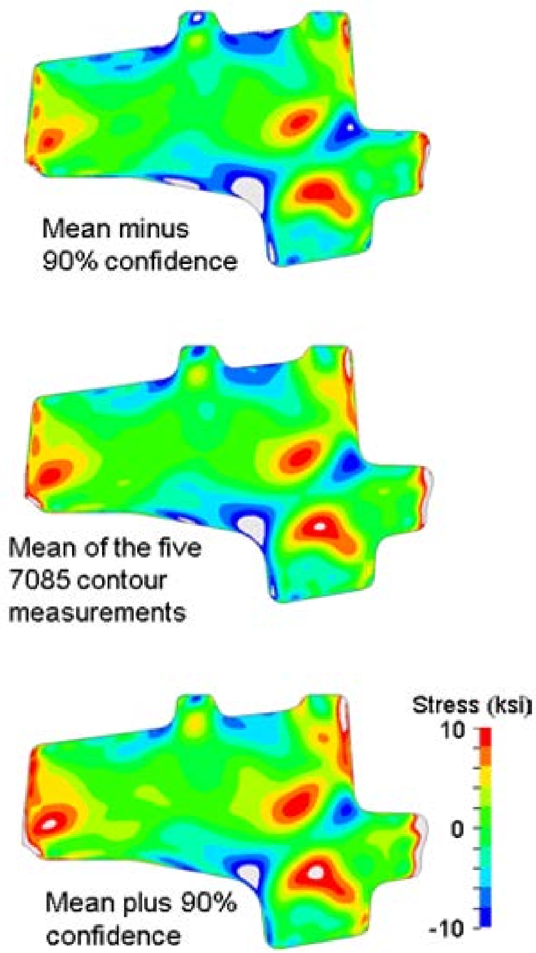
- **Two large fatigue test components designed and built by LM (ICSE demonstration)**
  - ***TA1 – baseline configuration***
  - ***TA2 – re-design guided by RS modeling***

- **Large component fatigue tests conducted at AFRL**
  - ***Very successful Govt. / Industry collaboration***

Impact of Bulk Residual Stress on Forging Qualification:

Toward a New Approach

- **A follow-on MAI program (LM-07) has been awarded and is now underway, expected PoP is Q4 2017 through Q2 2019**
- **The objectives of the LM-07 project are to:**
  - ***Quantify the uncertainty in both forgings and machined parts***
    - **RS variability within a part**
    - **Part-to-part variability**
  - ***Quantify the uncertainty in fatigue life resulting from uncertainty in RS***
  - ***Further develop RS digital thread (measurement data requirements, analysis data requirements, transfer formats/protocols***
  - ***Further develop business model (material specs, QC reqts, etc.)***
- **The LM-07 team consists of:**
  - ***Lockheed Martin, Boeing, Northrop Grumman***
  - ***Arconic, ATEP, Constellium, Hill Engineering***



RS variability in Al forgings, Ref: James et.al. [16]

Impact of Bulk Residual Stress on Forging Qualification: Toward a New Approach

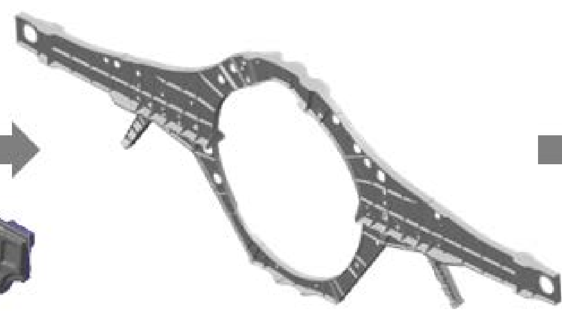
AFRL SBIR AF121-113: Residual Stress Engineering for Aerospace Structural Forgings

- **Phase 1 awarded to Hill Engineering (2012)**
  - ***LM provided informal support***
  - ***Emphasis on development of RS quality management system***
- **Phase 2 awarded to Hill Engineering (2013 thru 2015)**
  - ***LM provided formal (subcontracted) support***
  - ***Continued development of RS quality management system***
- **Phase 2 extension awarded to Hill Engineering (2017)**
  - ***LM will provide formal (subcontracted) support***
  - ***Project will address RS uncertainty quantification***
  - ***Companion to MAI LM-07***

Impact of Bulk Residual Stress on Forging Qualification:
Toward a New Approach

- **The explicit residual stress design / structural analysis approach has been adopted by the F-35 program which is currently using it for ongoing full scale durability test support analyses, as well as for current and future design / redesign / retrofit activities involving large aluminum forgings.**

forging



machined part

F-35

General application of this approach for the design / analysis of precision aluminum forgings may require that bulk residual stresses and their effects be addressed in the qualification / specification of such forgings

The Impact of Bulk Residual Stress on the Qualification of Large Aluminum Forgings

- **Background**
- **Standard Qualification Process**
- **Steps Taken Toward a New Approach**

⇨ **LOOKING AHEAD**

Impact of Bulk Residual Stress on Forging Qualification: Looking Ahead

Management of Manufacturing Process Induced (bulk) Residual Stresses can enable:

- **Performance Improvement**
  - ***RS management is a direct enabler of large unitized structure***
  - ***Demonstrated a 10-15% weight savings providing a corresponding range increase***
- **Manufacturing Cost Reduction**
  - ***RS management is a direct enabler of large unitized structure, which enables reduced manufacturing cost (reduced BTF, reduced part count, reduced touch labor)***
  - ***Manufacturing costs further reduced when machining distortion effects are mitigated through RS management***
- **Sustainment Cost Reduction**
  - ***RS management during design can lead to SIGNIFICANT cost savings during the operational phase of a program due to the reduction or elimination of either scheduled inspections or modifications or repairs***
  - ***These savings are expected to be even larger once RS variability is included in the digital thread***

Impact of Bulk Residual Stress on Forging Qualification: Looking Ahead

- **Residual stress management can best be affected through qualification, specification requirements**

- **Suggest development of new / updated qualification process that addresses residual stress explicitly, keeping in mind that –**

- **Any new M&P or Joining Method should satisfy Lincoln's 5 factors:**
  1. ***Stabilized material and/or material processes***
     - **Material qualification and acceptance specifications**
     - **Processing specification and acceptance standards**
     - **Manufacturing instructions**
  2. ***Producibility***
     - **Scale-up, inspectability**
  3. ***Characterized mechanical properties***
  4. ***Predictability of structural performance***
  5. ***Supportability***
     - **Repairability, inspectability**

Impact of Bulk Residual Stress on Forging Qualification: Looking Ahead

- Suggest revision of MIL-HDBK-1587:

1 *Add section 5.1.2.3 to address aluminum forgings*

5.1.2 Aluminum
5.1.2.1 Heat Treatment
5.1.2.2 Forming and Straightening
5.1.2.3 Forging

1 *Modify section 5.3.1.1 and add section 5.3.1.3 to address residual stress quantification*

5.3.1 Forging Practices
5.3.1.1 Forging Design
5.3.1.2 Forging Surfaces
5.3.1.3 Forging Residual Stresses

Impact of Bulk Residual Stress on Forging Qualification: Looking Ahead

1 Suggest revision of MIL-HDBK-1587 (cont'd):

5.3.1.1 Forging design. Forgings shall be produced in accordance with MIL-F-7190 for steel, MIL-A-22771 or QQ–A467 for aluminum, and MIL-F-83142 for titanium or industry and contractor specifications for alloys not covered by the above specification. The forging dimensional design must consider forging allowances such as parting line with regard to final machining such that short transverse grains (end grains) are minimized at the surface of the part. After the forging techniques (including degree of working) are established, the first production forging shall be sectioned and etched to show the grain flow pattern, to determine mechanical properties at critical design points, and to measure any retained, forging process induced, bulk residual stress. This sectioning will be repeated after any major change in the forging technique. The internal grain flow shall be such that the principal stresses are in the direction of flow as limited by forging techniques. The pattern shall be essentially free from re-entrant or sharply folded flow lines. All such information shall be retained by the contractor and made available to the procuring activity for review.

Impact of Bulk Residual Stress on Forging Qualification: Looking Ahead

1 Suggest revision of MIL-HDBK-1587 (cont'd):

5.3.1.3 Forging residual stress. Process induced bulk residual stresses which are retained in structural forgings after the completion of all aging, cold working, stress relieving, or other finishing processes, shall be measured at critical design points. The contractor shall establish the residual stress measurement locations and methods. The measured tensile residual stresses shall be less than 15% of the yield strength of the material. All measurement data shall be retained by the contractor and made available to the procuring activity for review.

Impact of Bulk Residual Stress on Forging Qualification: Looking Ahead

1 Suggest revision of forging specification – add specific residual stress requirements:

– *X Requirements*

X.1 Qualified producers
X.2 Chemical composition
X.3 Heat treatment
X.4 Mechanical properties
X.5 Stress-corrosion cracking
X.6 Defects
X.7 Grain-flow characteristics
X.8 Residual stress
X.9 Traceability
X.10 Qualification
X.11 Tolerances
X.12 Marking of forgings
X.13 Workmanship

The residual stress pattern shall conform to specified forging drawing approved by the acquiring activity

Impact of Bulk Residual Stress on Forging Qualification: Looking Ahead

1 **Suggest revision of forging specification – add specific QA provision for residual stress:**

- ***Y Quality assurance provisions***

  Y.1 Responsibility for inspection

  Y.2 Classification of tests

  - **Y.2.1 acceptance tests**
  - **Y.2.2 qualification/requalification tests**
  - **Y.2.3 first article tests**
  - **Y.2.4 periodic tests**

  Y.3 Sampling

  - **Y.3.1 tests**
  - **Y.3.2 examination**
    - **Y.3.2.1 surface defects**
    - **Y.3.2.2 internal defects**
    - **Y.3.2.3 grain flow**
    - **Y.3.2.4 residual stress**
    - **Y.3.2.5 stress corrosion**
    - **Y.3.2.6 electrical conductivity**

After the forging technique is established for a required size and shape, one sample from first production lot shall be selected for the residual stress examination. This examination shall be repeated after a change in forging technique

Impact of Bulk Residual Stress on Forging Qualification: Looking Ahead

1 Suggest revision of forging specification – add specific QA provision for residual stress:

- *Y quality assurance provisions (cont'd)*
  - Y.4 Methods of tests and examination
    - Y.4.1 chemical analysis
    - Y.4.2 mechanical properties
    - Y.4.3 examination for marking
    - Y.4.4 visual inspection of surface defects
    - Y.4.5 penetrant inspection
    - Y.4.6 internal defects
    - Y.4.7 grain flow
    - Y.4.8 residual stress
    - Y.4.9 resistance to stress-corrosion cracking
    - Y.4.10 electrical conductivity
  - Y.5 Rejection and retests
    - Y.5.1 rejection
    - Y.5.2 retests

After the forging technique is established for forging a required size and shape, a sample unit forging shall be examined to determine bulk residual stress. This examination shall be repeated after any change in the forging technique. Location of residual stress measurements shall be such as to represent principal sections of the forging, or as agreed upon between the contractor and the forging supplier or between the acquiring activity and the forging supplier or contractor.

Impact of Bulk Residual Stress on Forging Qualification: Looking Ahead

1. **Suggest revision of forging specification (cont'd):**
   - ***Consider option or addendum, to be agreed upon between the contractor and the forging supplier or between the acquiring activity and the forging supplier, for creation and delivery of a computed residual stress map***
   - ***This residual stress map shall be recreated after any change in the forging technique***

3. **Suggest standardization of methods for extraction of residual stress effects from mechanical properties:**
   - ***Use methods for extraction of residual stress effects from mechanical property data (e.g. ACR-Knorm approach for fatigue crack growth rate testing, ASTM E647)***

4. **Suggest continued validation and adoption of methods which improve predictability of structural performance**
   - ***Use measured or validated modeled residual stress in strength, fatigue, fatigue crack growth, and residual strength analyses of structural components machined from forgings***

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- **In summary:**
  - **The detrimental effects of tensile RS can be mitigated and/or managed during design by establishing and imposing appropriate requirements for their location, spatial distribution and magnitude, and for the inclusion of their effects during design structural analyses.**

Impact of Bulk Residual Stress on Forging Qualification: References

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