ASM Residual Stress Technical Committee Meeting, Oct. 2023, Virtual

Development of the Residual Stress Standard AS7045™

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Development of a Residual Stress Standard

ABSTRACT

In the past ten to fifteen years, significant progress toward the understanding and management of residual stresses in metallic structure has been made under the auspices of numerous Metals Affordability Initiative (MAI) projects, Small Business Innovative Research (SBIR) projects, USAF program funded projects, and many others. In January of 2020, the ASM International Technical Committee on Residual Stress formed a sub-committee on residual stress standards development, whose goal is to promote the development of standards and specifications for the measurement, modeling, understanding and management of residual stress. This activity has resulted in a draft AMS standard, the purpose of which is to provide uniform methods for defining, quantifying and classifying the residual stress in metallic structural alloy products and finished parts. Such quantification and classification may be required when residual stresses within components can impact further in-process distortion during machining or other methods, and when residual stresses within components can impact final component mechanical properties and performance.

The draft standard establishes residual stress classification criteria in terms of residual stress category and class. The currently defined residual stress categories are: 1) bulk residual stress, or near zero controlled residual stress, 2) joining residual stress, or tensile controlled residual stress, 3) engineered residual stress, or compressive controlled residual stress, and 4) targeted residual stress, or other residual stress not characterized as Category 1, 2 or 3. Within each category, there are four residual stress classes which identify the range of stress needed to achieve a given level of quality assurance or product performance, as well as a fifth class for reporting purposes only. In general terms, the residual stress classes are: A) tightly controlled, B) moderately controlled, C) loosely controlled, D) uncontrolled, and E) report only. The standard provides process guidance with regard to product or part zoning and then residual stress assessment within a zone. Residual stress assessment within a zone can be accomplished either by measurement or modeling, or a combination of the two. Finally, the product or part is classified according to the assessed value of residual stress within the zone. This presentation will include a high level summary of the standard, the current status of the standard (in terms of its release), and several examples of the potential application of the standard.

Development of a Residual Stress Standard

ASM Technical Committee on Residual Stress
Subcommittee on Residual Stress Standard Development

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Development of a Residual Stress Standard

- Background
- Initial residual stress standard development
- Current SAE residual stress standard
- Summary

Background

- The understanding of residual stresses and their effects can be critical to the optimization of the manufacturability and performance of aerospace structural components.
- Residual stresses (RS) can be of several types and result from many different processes:
  - ***Manufacturing-process-induced, “bulk” RS***:
    - Caused by quenching, forging, heat treating, etc.…
    - May be <5% to > 50% TYS in magnitude
    - Results in distortion, fatigue and damage tolerance impacts
  - ***Joining RS***:
    - Caused by welding, brazing, diffusion bonding, etc.…
    - May be <5% to > 50% TYS in magnitude
    - Results in distortion, fatigue and damage tolerance impacts
  - ***Engineered RS***:
    - *Intentionally induced by cold-expansion, LSP, LPB, peening, etc…*
    - *May exceed 75% YS locally, usually has steep stress gradient.*
    - *Applied intentionally to improve durability and damage tolerance*
  - ***Others***

Background

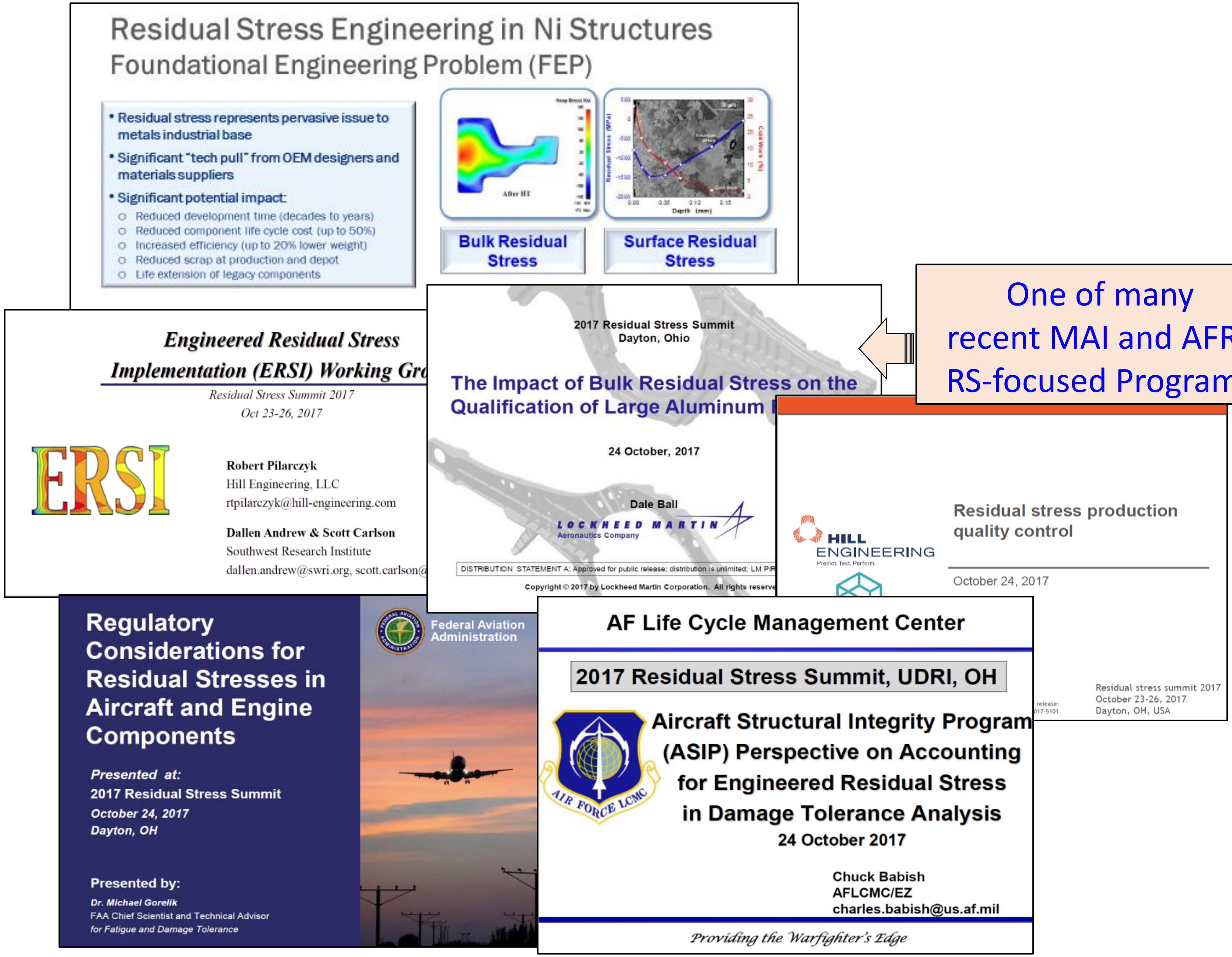
- **Historically:** residual stresses have been accounted for on an ad-hoc basis by modifying manufacturing / fabrication processes in order to mitigate their effects, or by intentionally introducing them to improve structural performance – but in neither case, explicitly quantifying them.
- **Detrimental (tensile) RS are typically mitigated** by modifying or adding processing steps:
  - *Modified quench, heat treatment protocols,*
  - *Mechanical or thermal stress relief,*
  - *etc.*
- **Beneficial (compressive) RS are frequently introduced** by applying post production processes:
  - *In the case of beneficial RS, many specifications require that the RS be installed but do not allow the associated performance benefit (typically increased fatigue life) to be considered for margin calculation,*
  - *When RS benefit is allowed for design, effects on strength and life (DaDT) must be quantified and validated by empirically-based "point solutions," and in many cases, very expensive and time consuming qualification programs must be performed.*

Background

- **Today:** producers and users of RS bearing products and parts are moving away from simple phenomenological accommodation of residual stresses and their effects, toward explicit quantification of them and explicit inclusion of them in all stages of engineering design, analysis, fabrication, test, and operational support.
- This paradigm shift is being enabled by significant advances in:
  - *RS measurement technologies,*
  - *Manufacturing process simulation which can predict the formation of residual stresses,*
  - *Structural analysis which can predict the effects of residual stress on strength and life.*
- **For process-induced and joining RS** – to achieve:
  - *Reduced component development, manufacturing and assembly costs,*
  - *Reduced impact on strength, durability and damage tolerance capability.*
- **For engineered RS** – to achieve:
  - *Improved HCF and associated damage tolerance,*
  - *Increased LCF life and LCF damage tolerance.*

Background

- Increasing research directed toward residual stress measurement and modeling:
  - *AFRL / MAI projects,*
  - *AFRL SBIRs,*
  - *ERSI,*
  - *Many others.*



One of many recent MAI and AFRL RS-focused Programs

Background

- This **new residual stress management paradigm** will enable:
  - *Manufacturing quality control improvement,*
  - *Structural performance enhancement.*
- In a recent Metals Affordability Initiative (MAI) project, "LM07: Residual Stress Management in Aluminum Structure," an effort was made to lay out the steps required for residual stress management for aerospace applications – this included addressing RS variability, the impact of that variability on performance, and the necessity for quality assurance metrics.
- This led to significant document review to assess current practice and metrics:
  - *High (system) level MIL specifications / standards:*
    - *JSSG-2006, MIL-HDBK-1587, and downstream documents,*
    - *JSSG 2007A, MIL-STD-2014, and downstream documents,*
    - *Structural integrity documents: MIL-HDBK-1783B, MIL-STD-1530D,*
    - *Very limited mention of RS (for metals), except "minimize," "avoid adverse..."*
    - *Mechanical properties specify A or B-Basis, or S-Basis, except use of "average" for da/dN*
    - *No explicit coverage of "engineered RS," except shot peening machined surfaces*
    - *Most of these documents are seldom revised (sometimes for decades)*
    - *Changes to MIL-HDBK-1587 and MIL-A-22771D required to explicitly address residual stress were deemed unlikely to occur in the near term.*

Background

- Assessment of current practice and metrics (cont'd):
  - *MIL standards for NDI:*
    - *MIL-STD-2154, Inspection, Ultrasonic, Wrought Metals, Process for*
  - *AMS specifications for forgings:*
    - *AMS2375E, AMS4333D, AMS4403A*
    - *Some recommended revisions were drafted to address bulk, process-induced RS – changes to AMS2375E were considered to be a good alternative way to invoke proposed RS STD-XXXX,*
    - *Best path for development of proposed RS STD appeared to be through AMS (likely a years-long project).*
- It was found that successful, broad implementation of RS management would require significant, integrated demonstration of RS measurement methods, analytical and experimental tools, and the development of measurement and quality assurance standards.
- **It was concluded that a stand-alone RS standard was needed …**
- And it was determined that this RS measurement/quality standard should be pursued through the SAE Aerospace Metals and Engineering Committee (AMEC):
  - *AMS approach is more conducive to commercial applications*
  - *Intent was to make as broad as possible, pending feedback from AMEC.*

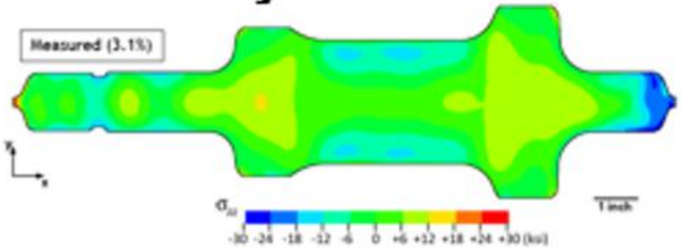
Initial RS standard development

Desired attributes and content for proposed RS standard:

1. *Provide broadly applicable guidance for RS management,*
    - *Basis for communication and contracting between customer and suppliers,*
    - *Be broadly applicable – to most if not all structural metals and forms,*
    - *Ensure critical content is addressed for specification of measurement methods, modeling practice, quality assurance, data records, and acceptance criteria,*
    - *Provide for zoning of parts where various RS criteria may be applied,*
    - *Address multiple types (categories) of residual stresses,*
    - *Address multiple classes (levels) of residual stress for each type.*
2. *Define acceptable methods for RS measurement*
    - *Provide brief definitions and characteristics.*
    - *Provide guidance on appropriate range of application for each method*
3. *Provide for flexibility in use of RS modeling and measurement*
    - *Provide guidance for RS determination by measurement only*
    - *Provide guidance for use of "model only" determination of RS.*
    - *Provide guidance for use of "model-assisted" RS determination.*

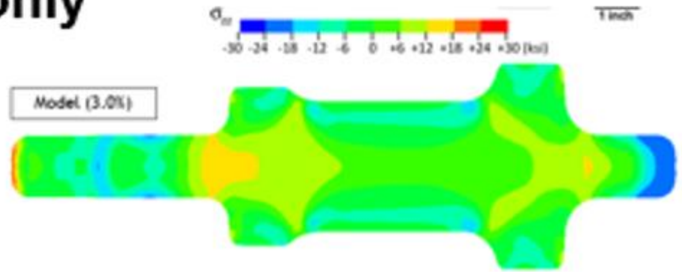
Initial RS standard development

- Provide for flexibility in use of RS modeling and measurement
  - **Measurement only**



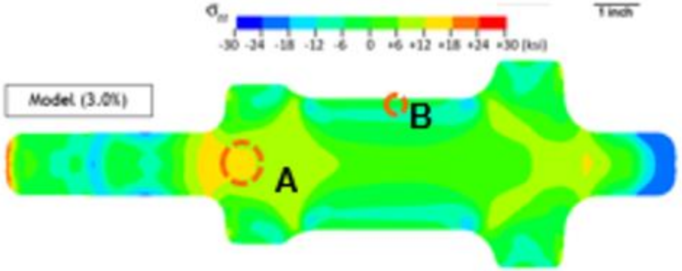
Qualifying RS is based on measured data

  - **Model only**



Qualifying RS is based on computed data alone

  - **Model-assisted measurement**



Qualifying RS at location A is inferred based on measured data at location B, and computed relationship between A and B

Note that RS modeling is regarded critical to broad implementation of RS in design and structures assessments.

Current SAE RS standard

- The standard provides guidance for residual stress management:
  - *Classification (type and magnitude)*
  - *Quality control*
  - *Documentation*
- The standard establishes residual stress classification criteria for product / part / zone:
  - *Residual stress **CATEGORY**:*
    - Cat 1: Bulk residual stress, or near zero controlled residual stress
    - Cat 2: Joining residual stress, or tensile controlled residual stress
    - Cat 3: Engineered residual stress, or compressive controlled residual stress
    - Cat 4: Targeted residual stress, or other residual stress not characterized as Cat 1, 2 or 3
  - *Residual stress **CLASS**:*
    - Class A: Tightly controlled residual stress
    - Class B: Moderately controlled residual stress
    - Class C: Loosely controlled residual stress
    - Class D: Uncontrolled residual stress
    - Class E: Report only

Current SAE RS standard

- The standard establishes residual stress category and classification criteria:

Category	Class	Tolerance Band[1]
1	A	$\lvert RS_{assess} \rvert \leq 5\% F_{ty}$
	B	$5\% F_{ty} < \lvert RS_{assess} \rvert \leq 20\% F_{ty}$
	C	$20\% F_{ty} < \lvert RS_{assess} \rvert \leq 50\% F_{ty}$
	D	$\lvert RS_{assess} \rvert > 50\% F_{ty}$
	E	Report requirement only
2	A	$RS_{assess} \leq 10\% F_{ty}$
	B	$10\% F_{ty} < RS_{assess} \leq 25\% F_{ty}$
	C	$25\% F_{ty} < RS_{assess} \leq 50\% F_{ty}$
	D	$RS_{assess} > 50.1\% F_{ty}$
	E	Report requirement only
3	A	$RS_{assess} \leq -80\% F_{ty}$
	B	$-80\% F_{ty} < RS_{assess} \leq -50\% F_{ty}$
	C	$-50\% F_{ty} < RS_{assess} \leq 0\% F_{ty}$
	D	$RS_{assess} > 0$
	E	Report requirement only
4	A	$\lvert RS_{assess} - RS_{target} \rvert \leq 5\% F_{ty}$
	B	$5\% F_{ty} < \lvert RS_{assess} - RS_{target} \rvert \leq 20\% F_{ty}$
	C	$20\% F_{ty} < \lvert RS_{assess} - RS_{target} \rvert \leq 50\% F_{ty}$
	D	$\lvert RS_{assess} - RS_{target} \rvert > 50\% F_{ty}$
	E	Report requirement only

(1) F_{ty} is defined as tensile yield strength.

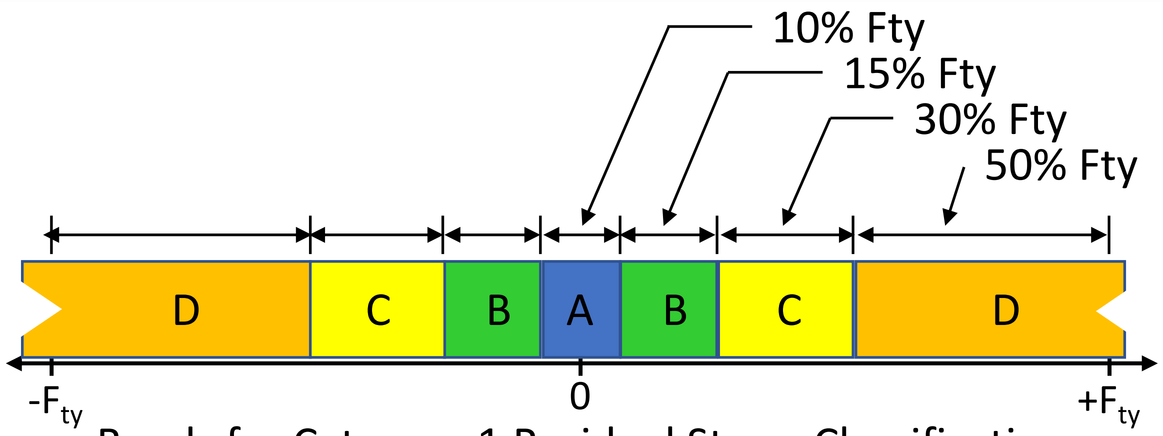
Category 1 Residual Stress

- **Category 1, Bulk RS or near zero controlled RS:**
  - *Typically produced by material production, process, or forming,*
  - *Generally bulk in nature,*
  - *Can be managed first by applying post-production processes such as mechanical cold working thermal stress relieving to reduce or eliminate them, and second by assessing the value of residual stress at one or more critical locations and demonstrating by analysis or test that if the assessed residual stress is within a known range (class) then the product or part will meet its design performance requirements,*
  - *The objective is generally to identify and limit the presence of detrimental tensile residual stresses, however, there are scenarios in which the objective could be to control compressive residual stress because compression at one location is an indicator of equilibrating tension at another location.*

Category 1 Residual Stress Classification

- Four classes with stress bands prescribed in terms of material yield strength, and a fifth for reporting purposes only

Class A (Very low stress):	$-5\% \ F_{ty} \leq RS_{assess} \leq 5\% \ F_{ty}$
Class B (Low stress):	$-20\% \ F_{ty} \leq RS_{assess} < -5\% \ F_{ty}$ or $5\% \ F_{ty} < RS_{assess} \leq 20\% \ F_{ty}$
Class C (Medium stress):	$-50\% \ F_{ty} \leq RS_{assess} < -20\% \ F_{ty}$ or $20\% \ F_{ty} < RS_{assess} \leq 50\% \ F_{ty}$
Class D (High stress):	$RS_{assess} < -50\% \ F_{ty}$ or $50\% \ F_{ty} < RS_{assess}$
Class E:	*Report only*



Bands for Category 1 Residual Stress Classification

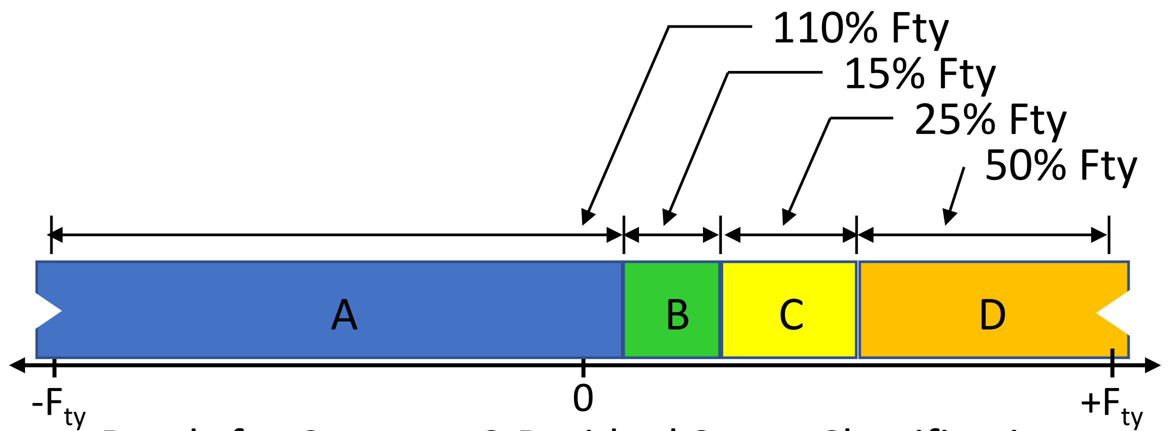
Category 2 Residual Stress

- **Category 2, Joining RS or tensile controlled RS:**
  - *Typically generated by processes such as welding (arc, electron beam, laser, pressure or friction, etc.), thermal or kinetic deposition processes, soldering, etc.*
  - *Typically confined to the vicinity of the joint or deposit.*
  - *Can be managed first by applying post-weld or post-deposition processes such as heat treating or cold working to reduce or eliminate the residual stresses, and second by assessing the value of residual stress at one or more critical locations and demonstrating by analysis or test that if the assessed residual stress is within a known range (class) then the product or part will meet its design performance requirements.*
  - *The objective is generally to identify and limit the presence of detrimental tensile residual stresses*

Category 2 Residual Stress Classification

- Four classes with stress bands prescribed in terms of material yield strength, and a fifth for reporting purposes only

Class A (Very low stress):	$RS_{assess} \leq 10\% F_{ty}$
Class B (Low stress):	$10\% F_{ty} < RS_{assess} \leq 25\% F_{ty}$
Class C (Medium stress):	$25\% F_{ty} < RS_{assess} \leq 50\% F_{ty}$
Class D (High stress):	$RS_{assess} > 50\% F_{ty}$
Class E:	*Report only*



Bands for Category 2 Residual Stress Classification

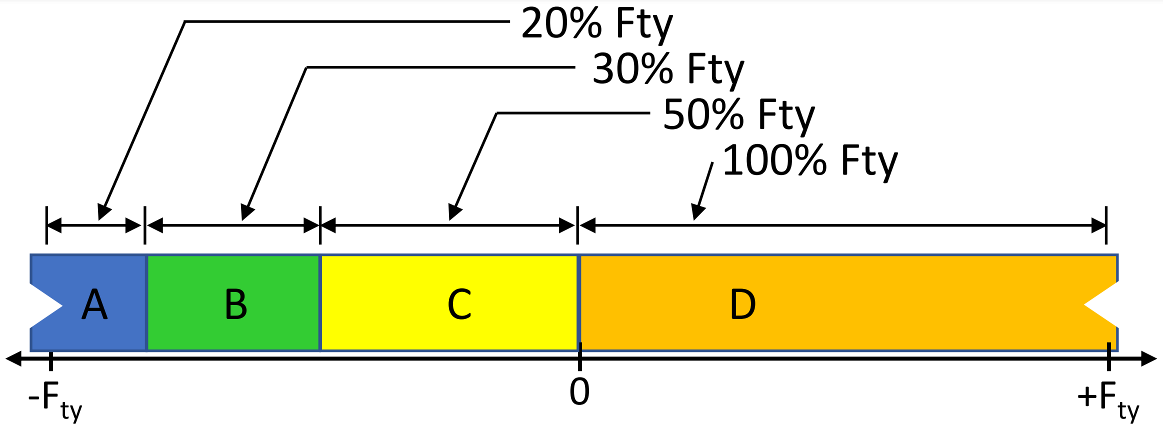
Category 3 Residual Stress

- **Category 3, Engineered RS, or compressive controlled RS:**
  - *Typically installed using controlled plastic deformation at specific (critical) locations within a product or part,*
  - *Generally localized in nature,*
  - *Can be managed first by ensuring that the installation process is properly executed and second by assessing the value of residual stress at one or more critical locations and demonstrating by analysis or test that if the assessed residual stress is within a known range (class) then the product or part will meet its design performance requirements,*
  - *The objective is virtually always to ensure that sufficient, beneficial compressive residual stress has been installed.*

Category 3 Residual Stress Classification

- Four classes with stress bands prescribed in terms of material yield strength, and a fifth for reporting purposes only

Class A (Very low stress):	$RS_{assess} \leq -80\%\ F_{ty}$
Class B (Low stress):	$-80\%\ F_{ty} < RS_{assess} \leq -50\%\ F_{ty}$
Class C (Medium stress):	$-50\%\ F_{ty} < RS_{assess} \leq 0\%\ F_{ty}$
Class D (High stress):	$RS_{assess} > 0$
Class E:	*Report only*



Bands for Category 3 Residual Stress Classification

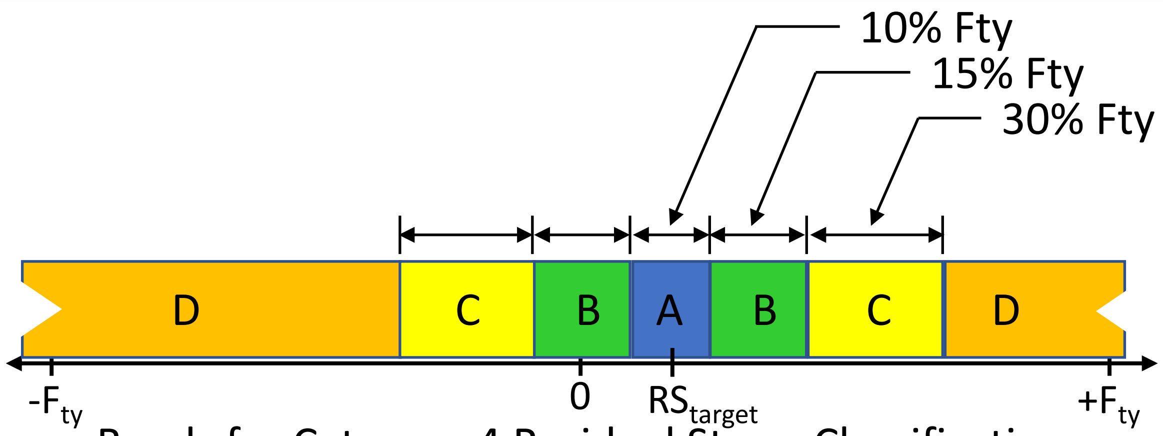
Category 4 Residual Stress

- **Category 4, Targeted RS:**
  - *General category in which the specifier defines a target value of RS and the product or part is classified according to how close (in magnitude) the assessed value of residual stress is to the target value*
  - *This category can be used when the required target value of residual stress does not match any of the implied target values of the other categories*
    - RS_{target}=0 for Categories 1 and 2
    - RS_{target}=-Fty for Category 3
  - *This category can also be used for any RS stress not characterized as category 1, 2 or 3, for example machining induced stresses or coating application (thermal or chemical) stresses which and tend to be very localized in nature*

Category 4 Residual Stress Classification

- Four classes with stress bands prescribed in terms of material yield strength, and a fifth for reporting purposes only

Class A (Very low stress):	$\lvert RS_{assess} - RS_{target} \rvert \leq 5\% \, F_{ty}$
Class B (Low stress):	$5\% \, F_{ty} < \lvert RS_{assess} - RS_{target} \rvert \leq 20\% \, F_{ty}$
Class C (Medium stress):	$20\% \, F_{ty} < \lvert RS_{assess} - RS_{target} \rvert \leq 50\% \, F_{ty}$
Class D (High stress):	$\lvert RS_{assess} - RS_{target} \rvert > 50\% \, F_{ty}$
Class E:	*Report only*



Bands for Category 4 Residual Stress Classification

Current SAE RS standard

The standard provides information and guidance on commonly used RS measurement techniques:

Measurement Technique	Applicable Standards or Citation	Typical Precision[1] (%Fty)	Application Region	Suggested Characteristic Residual Stress Definition[2]
Hole drilling[3]	ASTM E837	±3 to ±5	Useful for residual stress assessment at locations within 0.080 inch (2 mm) of material surface	Mean of of measured values in specified direction, taken at depths between 25% and 100% of maximum measurement depth, at specified surface location (point)
Ring core[3]	Schajer 2013	±3 to ±5	Useful for residual stress assessment at locations within 0.240 inch (6 mm) of material surface	Mean of of measured values in specified direction, taken at depths between 25% and 100% of maximum measurement depth, at specified surface location (point)
Deep Hole drilling	Schajer 2013	±2 to ±3	Useful for residual stress assessment at locations greater than 0.040 inch (1 mm) from material surface	Maximum magnitude of measurement values in specified direction, taken at depths between 25% and 100% of maximum measurement depth, at specified surface location (point)
Slotting[3]	Schajer 2013	±2 to ±3	Useful for residual stress assessment at locations within 0.120 inch (3 mm) of material surface	Mean of of measured values in direction normal to slot, taken at depths between 25% and 100% of maximum measurement depth, at specified surface location (point)
Slitting	Schajer 2013	±2 to ±3	Useful for residual stress assessment along one-dimensional path at locations greater than 0.020 inch (0.5 mm) from material surface	Maximum magnitude measurement values in direction normal to slit, taken at depth greater than 0.020 inch (0.5 mm).
Contour method	Schajer 2013	± 2 to ±3	Useful for residual stress assessment over two-dimensional cross-section at locations greater than 0.040 inch (1 mm) from material surface	Maximum magnitude measurement values in direction normal to cutting plane, taken at depth greater than 0.040 inch (1 mm).

Relaxation-based residual stress measurement techniques and characteristic values

Current SAE RS standard

The standard provides information and guidance on commonly used RS measurement techniques:

Measurement Technique	Applicable Standards or Citation	Typical Precision[1] (%Fty)	Application Region	Suggested Characteristic Residual Stress Definition[2]
X-ray diffraction, lab source[3]	EN15305, SAE HS-784, ASTM E915, ASTM E2860	±4 to ±5	Useful for residual stress assessment at surface locations only	Measured value in specified direction at specified surface location (point)
X-ray diffraction with layer removal, lab source[3]	EN15305, HS-784, ASTM E915, ASTM E2860	±4 to ±5	Useful for residual stress assessment at locations within 0.080 inch (2 mm) of material surface	Maximum magnitude of measured values in specified direction at specified location
X-ray diffraction, high energy source	Schajer 2013	±5 to ±15	Useful for residual stress assessment at locations greater than 0.020 inch (0.5 mm) from material surface	Maximum magnitude of measured values in specified direction at specified location
Neutron diffraction	Schajer 2013	±5 to ±15	Useful for residual stress assessment at locations greater than 0.040 inch (1 mm) from material surface	Maximum magnitude of measured values in specified direction at specified location

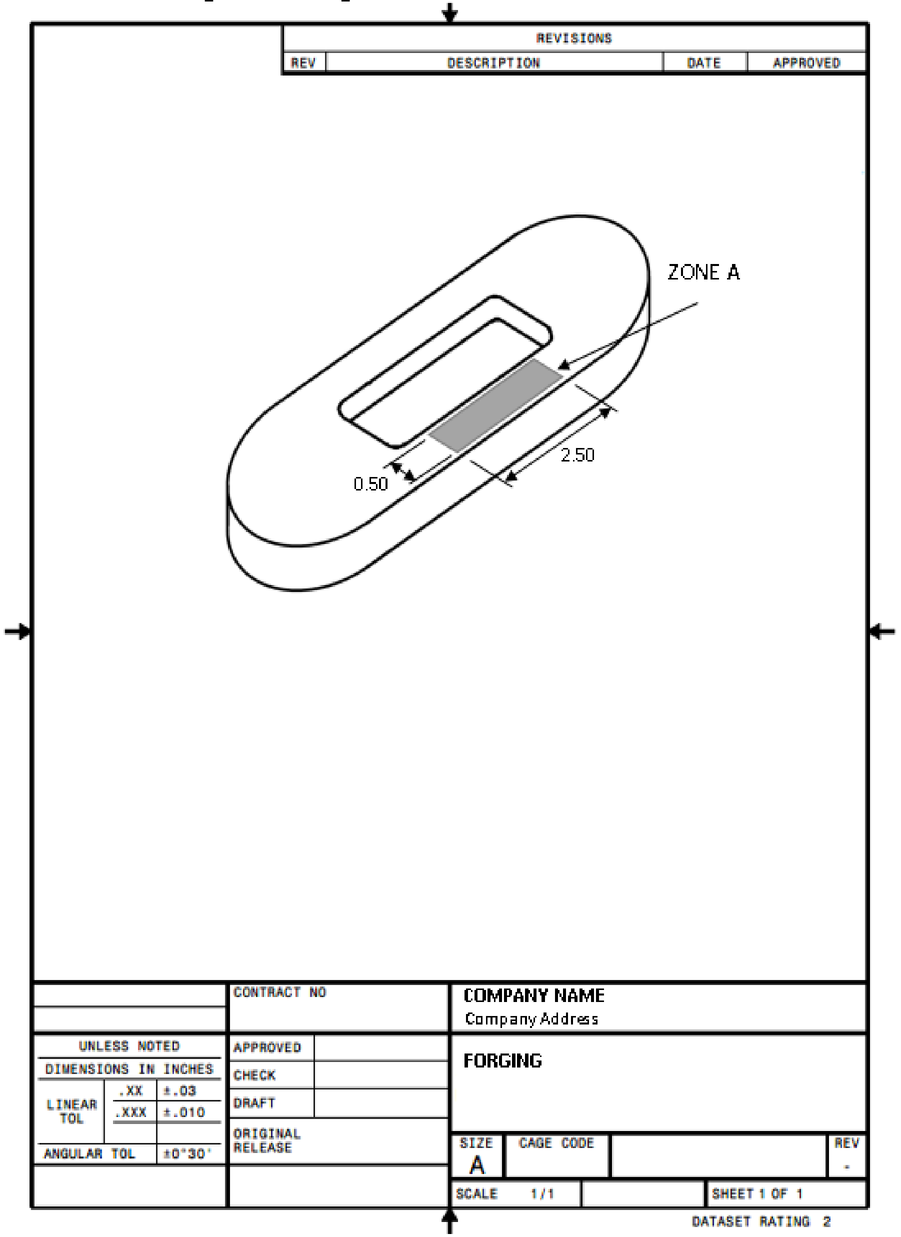
Diffraction-based residual stress measurement techniques and characteristic values

Current SAE RS standard

The standard provides guidance on procedure:

- Product or part is zoned
- Residual stress is “assessed” within a zone – residual stress assessment can be accomplished by:
  - ***measurement****, or*
  - ***modeling****, or*
  - *a combination of the two*
- The product or part is classified according to the assessed value of residual stress within the zone
- NOTE: uncertainty in selected residual stress assessment technique (modeling or measurement), must be considered when assigning class – meaning uncertainty associated with assessment technique must be less than stress band width associated with the class

Example problem 1 – bulk residual stress in a forging

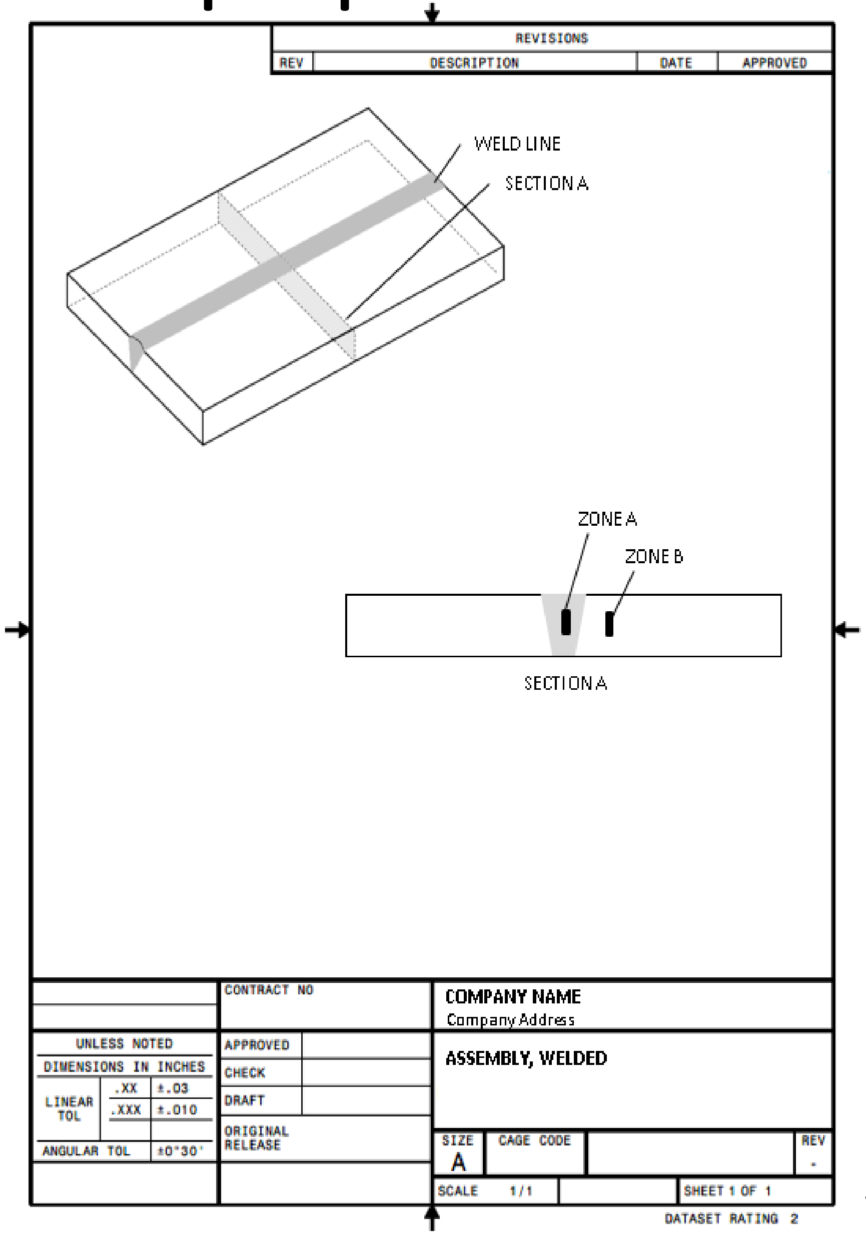


Suggested drawing notes:

NOTES:
1. FORGE AND INSPECT PER XXX-XXXX.
2. FOR CMM INSPECTION PROFILE TOLERANCES SEE XXX.
3. PROFILE TOLERANCES TO BE USED FOR PART ACCEPTANCE CRITERIA.
4. MEASURE SURFACE RESIDUAL STRESS IN ZONE A BY HOLE DRILLING.
   RESIDUAL STRESS TO BE CAT 1, CLASS A IN ZONE A PER AS7045.

If the design requirement is that the RS be 0±3 ksi, then specifier could call out category 1, class A.

Example problem 2 – welding residual stress

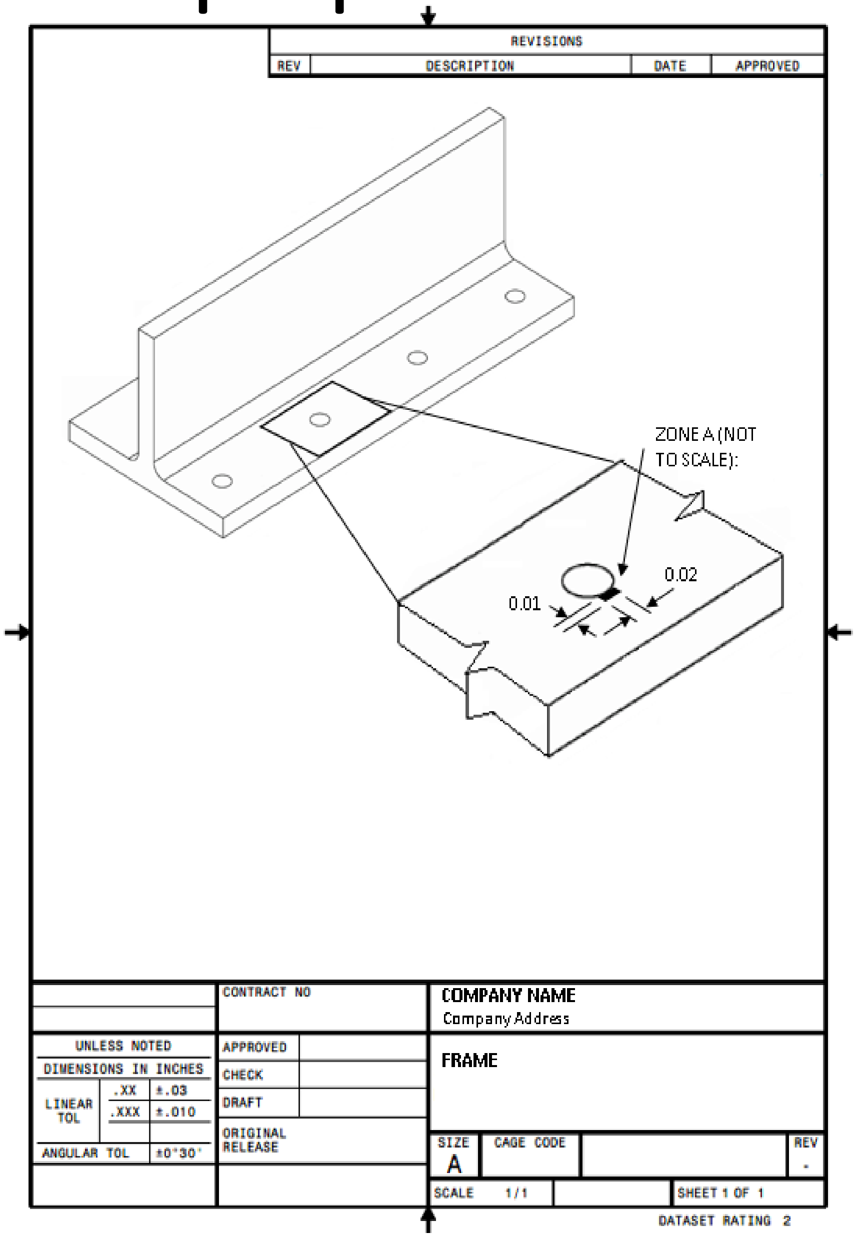


Suggested drawing notes:

NOTES:
1. INSTALL WELD AND INSPECT PER XXX-XXXX.
2. MEASURE RESIDUAL STRESS ON SECTION 'A' BY CONTOUR METHOD.
   RECORD RESIDUAL STRESS CAT 2, CLASS E IN ZONE B PER AMSXXXX.
   RESIDUAL STRESS TO BE CAT 2, CLASS B IN ZONE A PER AS7045

By calling out Category 2 Class B for Zone A, specifier will only accept part with RS<0.25*Fty in zone A

Example problem 3 – residual stress at Cx hole



Suggested drawing notes:

NOTES:
1. INSTALL COLDWORK HOLE AND INSPECT PER XXX-XXXX, 4PL.
   STARTING HOLE SIZE ø.161-.171
   FINAL HOLE SIZE TO BE ø.190-.193
2. DEBURR AFTER FINAL REAM.
3. SURFACE RESIDUAL STRESS TO BE CAT 3, CLASS A IN ZONE A PER AS7045.
   RESIDUAL STRESS TO BE DETERMINED BY NON-DESTRUCTIVE MEANS, XRD OR NEUTRON

Assuming Fty=60 ksi, the drawing callout indicates that specifier will accept part provided RS_{asses} is no larger than -48 ksi.

Summary

- An RS management standard (measurement/QA/reporting) was developed:
  - *Regarded essential and best path forward,*
  - *AMS standard (rather than MIL STD) considered preferred path,*
  - *Broadly applicable – addresses use of RS modeling, RS measurement, and any structural alloy and form,*
  - *Addresses multiple types (categories) of RS.*
- **The purpose of the AMS standard is to provide uniform methods for defining, quantifying and classifying the residual stress in metallic structural alloy products and finished parts.**
- Such quantification and classification may be required:
  - *When residual stresses within components can impact further in-process distortion during machining or other methods, and/or*
  - *When residual stresses within components can impact final component mechanical properties and performance.*

Summary

- Proposal to convert the initial draft to an AMS Standard was made to the AMEC in April 2019:
  - *AMEC endorsed development of RS standard,*
  - *AMEC received draft from sponsor and converted from MIL format to SAE format, assigned AMEC19AB.*
- No further activity until March 2020, at which time ASM Technical Committee on RS agreed to resume development of the standard.
- The draft AMS standard was extensively revised over the next 15 months.
- AMEC19AB first ballot – Jul. 2021
- AMEC19AB second ballot – Sep. 2022
- SAE Committee B ballot – Jan. 2023
- **SAE Aerospace Standard AS7045 released – May 2023**

AEROSPACE STANDARD	AS7045™	
	Issued 2023-05	

Residual Stress Measurement and Classification,
Metallic Structural Alloy Products and Finished Parts

RATIONALE

AS7045 standardizes methods for defining, quantifying, and classifying residual stress in metallic structural alloy products and finished parts.

1. SCOPE

1.1 Purpose

The purpose of this standard is to provide uniform methods for defining, quantifying, and classifying the residual stress in metallic structural alloy products and finished parts. These stresses may exist within a single element, or they may be the result of a joining process. Such quantification and classification may be required when residual stresses within mill stock or preforms can impact further in-process distortion during machining or other processes, and when residual stresses within finished components can impact final mechanical properties and performance (especially strength, durability, and fracture performance).

1.2 Application

The methods for residual stress assessment in this standard are applicable in the prediction and measurement of fabrication process induced residual stresses, joining process induced residual stresses, and engineered residual stresses. Application of the methods in this standard is limited to metallic structural alloy products and finished parts made from structural alloy products (see 2.9.9), such as alloys of aluminum, titanium, nickel, and steel.

1.3 Classification

Structural alloy products and finished parts made from such products shall be classified with respect to the category and general magnitude of residual stress found to exist in such products or parts.

1.3.1 Categories

Category 1: Bulk Residual Stress (Near-Zero Controlled Residual Stress)

Bulk residual stresses are typically material production, process, or forming stresses and are generally bulk in nature (i.e., distributed over the part volume). Category 1 residual stresses can be managed first by applying post-production processes, such as mechanically cold working or thermally stress relieving to reduce or eliminate them; and second, by assessing the value of residual stress at one or more critical locations and demonstrating by analysis or testing that if the assessed residual stress is within a known range (Class), then the product or part will meet its design performance requirements. While the objective is to identify and limit the presence of detrimental tensile residual stresses, there are scenarios in which the objective could be to control compressive residual stress because compression at one location is an indicator of equilibrating tension at another location.

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