SFSA Digital Innovative Design for Reliable Casting Performance (DID)

SAE FD&E Spring Meeting

April 15, 2020 – virtual meeting

Disclaimer

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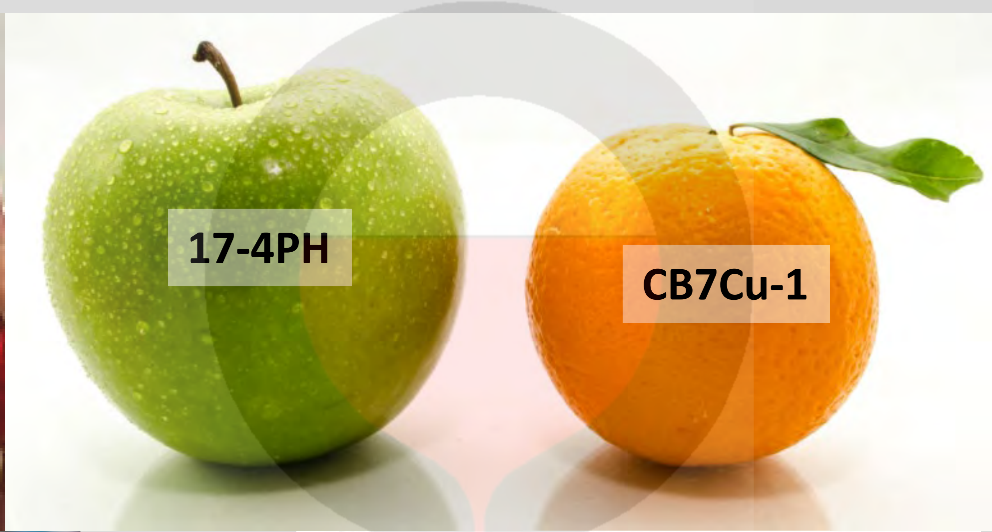
David Poweleit
Steel Founders' Society of America (SFSA)

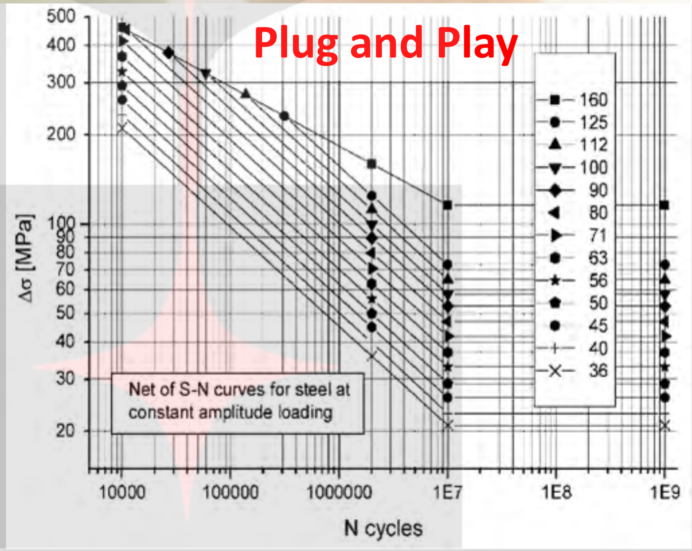
Steel Founders' Society of America (SFSA)

- Our organization
  - Not for profit technical society founded in 1902
  - Goal is advance the steel casting industry
- Our members
  - Are all steel casting producers
  - Have a culture of collaboration and innovation
- Our industry
  - ~1M tons produced
  - About 9M tons worldwide
  - Major markets: railroad, mining, construction, trucks, pumps/valves, oil and gas, energy, industrial equipment, and military

EAF tapping at Bradken-Atchison

Change the way we think!





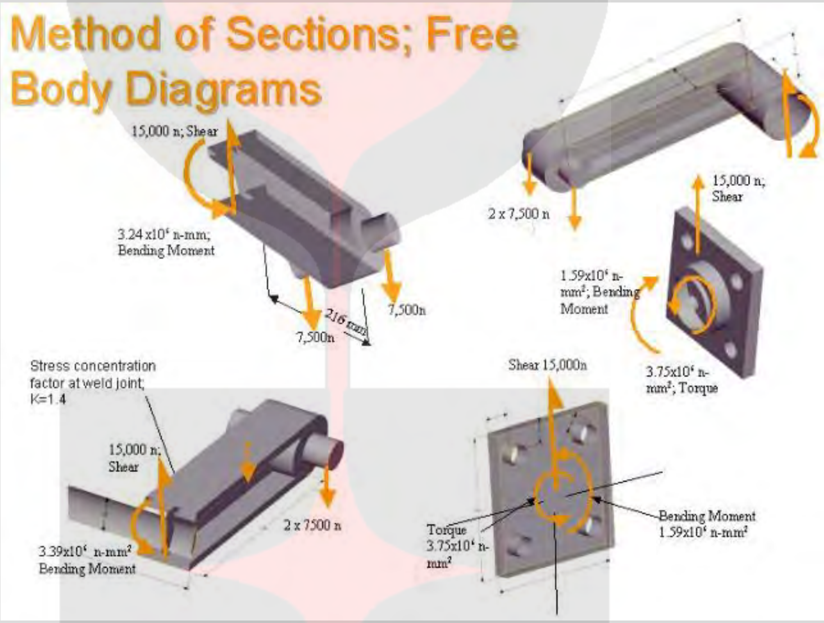
Design, Manufacturability & Reliability

- What is DID?

Not IP

Digital Innovative Design

for Reliable Casting Performance

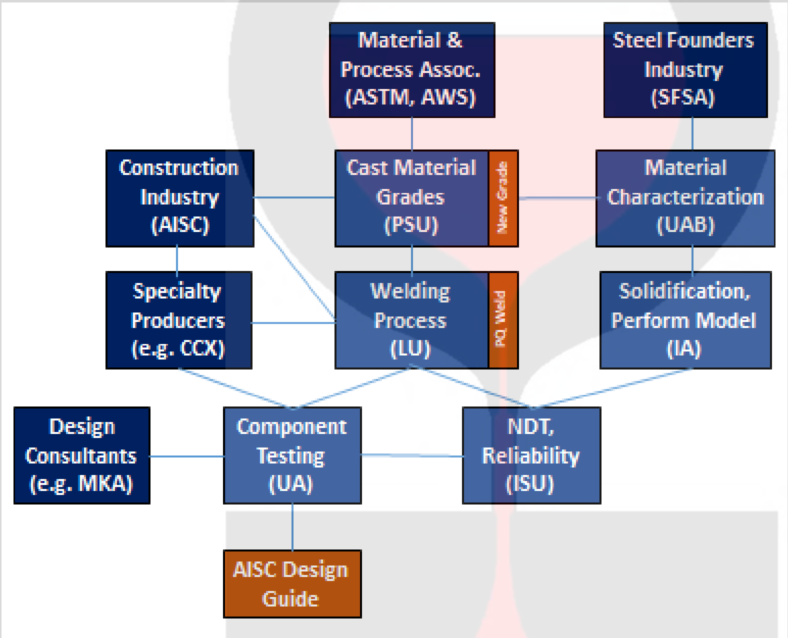


An engineered approach to steel casting performance

For a multitude of partners and purposes

Collaborative Research

Example – castings for building construction



<u>Government</u>

- Defense Logistics Agency (DLA)
- DOD

<u>Industry/Consultants/Other Stakeholders</u>

- SFSA Members
- Darrell Socie – BBM Plus
- OEM's/Partners – GD, Emerson, Magma, AISC, Deere and Cat

<u>Academia</u>

The University of Arizona

Missouri S&T University of Science & Technology

The University of Iowa

Iowa State University

UAB The University of Alabama at Birmingham

Lehigh University

PennState

DID Design Methodology

- Codes based on design allowables
- Model-based Process & Performance Design (MP^{2}D) – lower bound modeling for local properties

NDT strategy for economic and performance design – quantitative for performance NDT

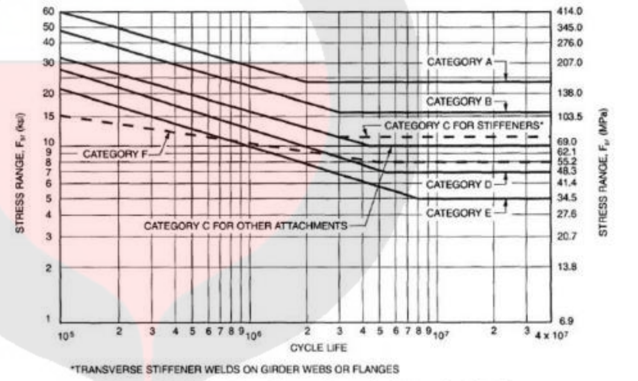
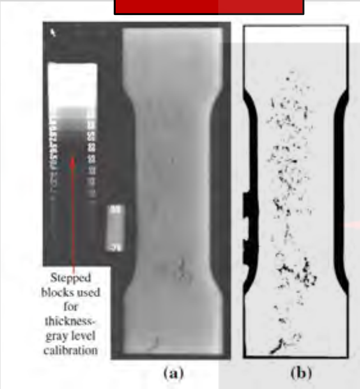
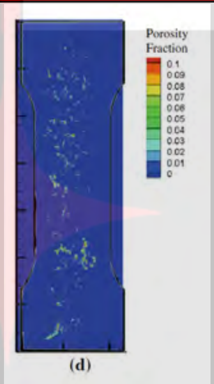


Figure 2.9—Design Stress Range Curves for Categories A to F—Redundant Structures (Nontubular) (see 2.24)

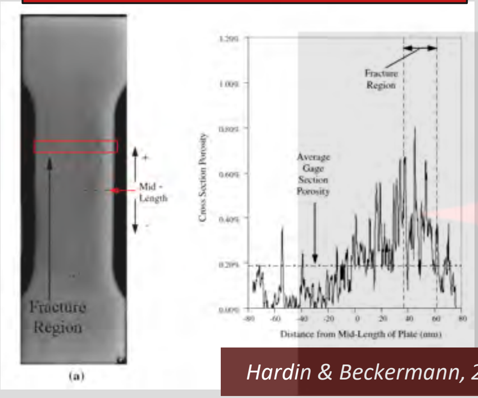
NDT Level



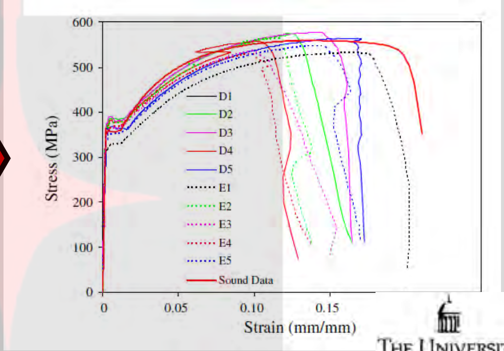
"Quality" Index



Key Quantitative Measures



Structural Performance



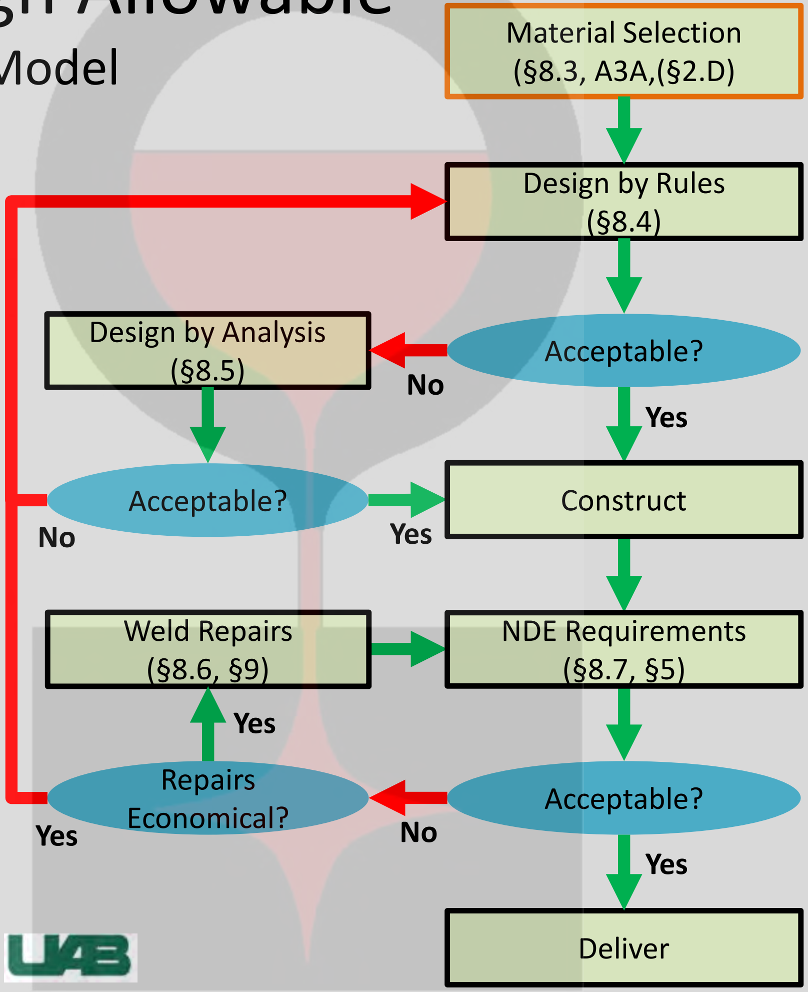
Hardin & Beckermann, 2013

THE UNIVERSITY OF IOWA

Code-based Design Allowable

ASME BPVC Model

- Section II for design allowables plus adopted ASTM standards, e.g. SA216
  - “ASME allowable” with NDT
    - ASTM A216 WCB 36 ksi min YS has allowable design stress of 20 ksi
  - 0.8 “ASME allowable” without NDT
    - ASTM A216 WCB 36 ksi min YS has allowable design stress of 16 ksi
- Section V Volumetric Methods SG
- Section VIII Div-1 & 2 for examination requirements/NDT
  - RT per ASTM E446 in critical sections - limits on porosity and shrinkage
  - MT per ASTM E125 - limits on linear indications, shrink, porosity, inclusions, etc.
  - PT - limits no linear indications > 1/4 in, no non-linear indications > 3/16 in
- Section IX for welding



Fracture Toughness Ratio Effect on Limiting Load Brittle Failure (LEFM) v. Plastic Collapse

Performance controls: material, indication size, indication location (local loading)

$c_{crit} = K_{1c}^2 / \pi \sigma_y^2$

Traditional ½ YS
Non-life critical
Economical

Ratio of K_{Ic}^2/YS^2
>1 plastic cross-section effect
<1 not plastic toughness/length effect

LEFM
Life critical
Performance & cost

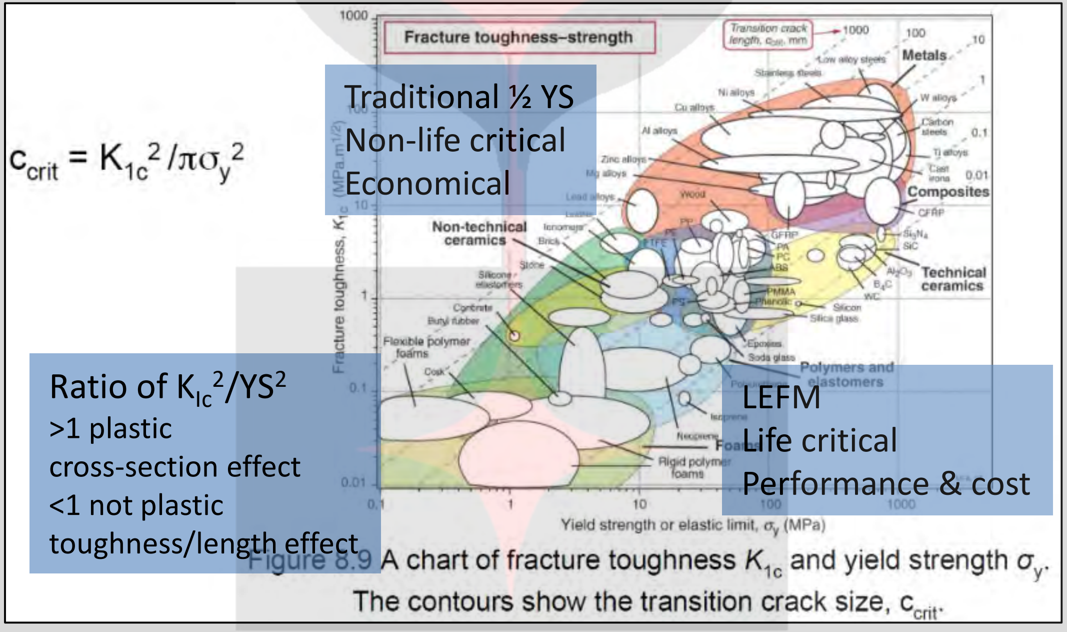
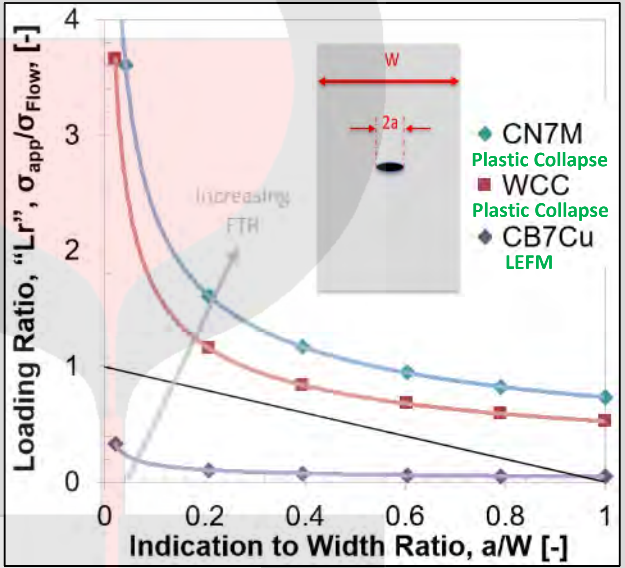
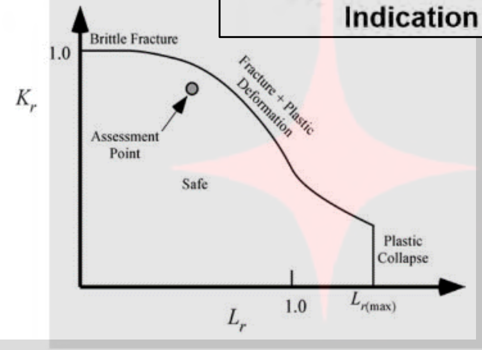
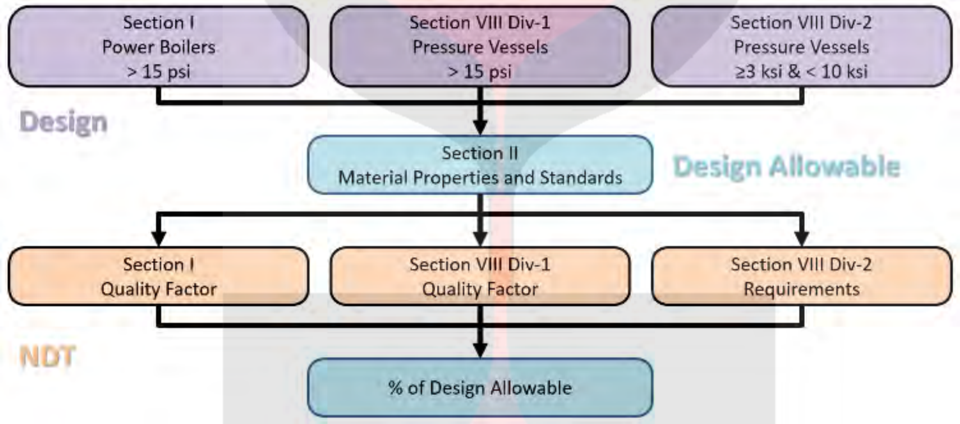


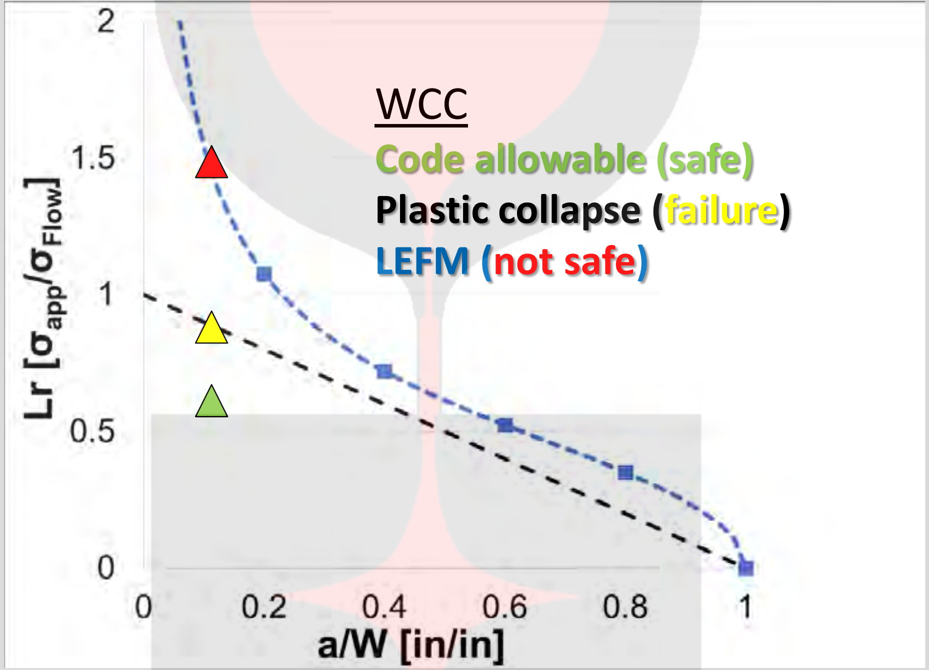
Figure 8.9 A chart of fracture toughness K_{1c} and yield strength σ_y. The contours show the transition crack size, c_{crit}.





Relationship to BPVC





Parametric Design Model and Sensitivity Analysis

Load Type	Component Design	Largest Notch	Failure Criteria
static impact low-low fatigue (1,000) low fatigue (100,000) high fatigue (1,000,000)	Shape: bar, tube, "L" Size Load	Location: surface, internal Geometry: crack/notch, size, quantity/proximity, linear v. non-linear	YS ¼ YS ½ YS ¾ YS ASME allowable 0.8 ASME allowable

Analytical failure analysis with strain controlled fracture mechanics and LEFM.
Not developing crack growth or propagation theory.

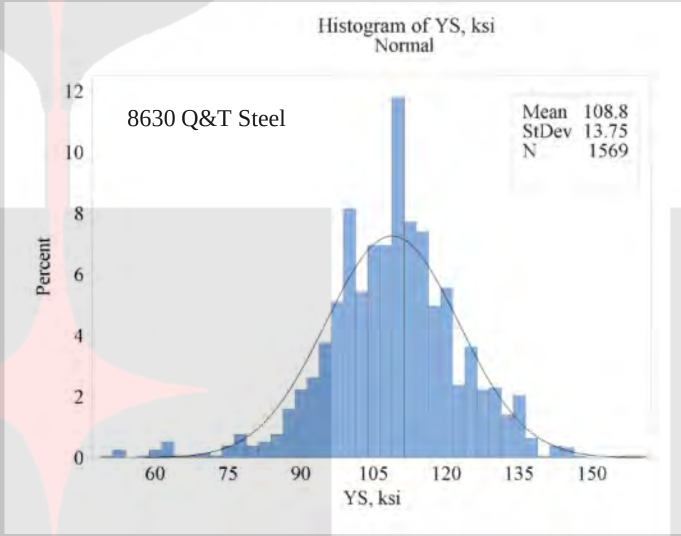
Program will not be pursuing MMPDS but will leverage a similar statistical analysis

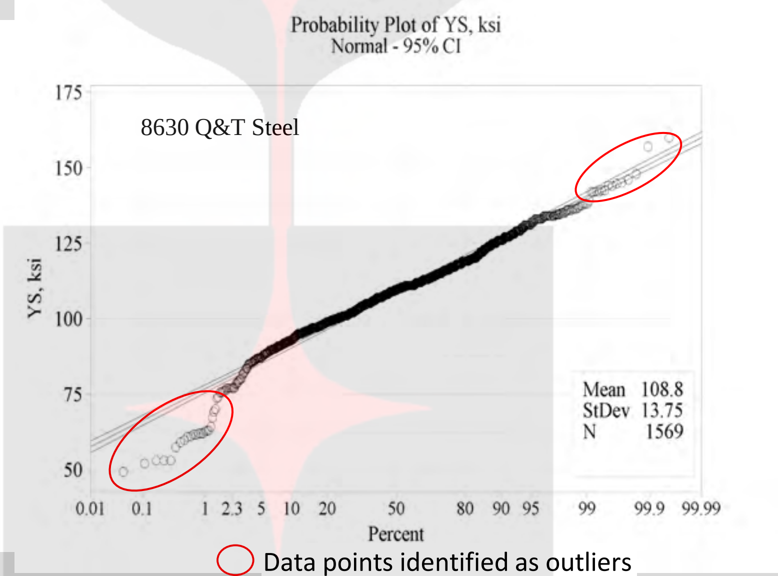
Lower Bound Mechanical Properties (8630)

Determined from SFSA Data

- Mechanical test data for yield and ultimate strengths, elongation and reduction of area have been analyzed for 10 alloys in ASTM A958 and A487.
- Data set contains over 7000 tensile test results.

Example Data for Normal Distribution, Histogram and Probability Plots of Yield Stress Data for 8630 Quenched and Tempered Cast Steel Data Collected from SFSA Members



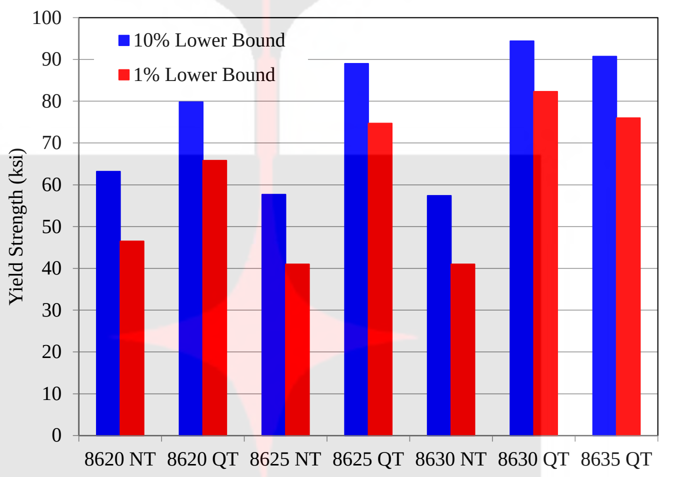


Example Lower Bound Properties (8630)

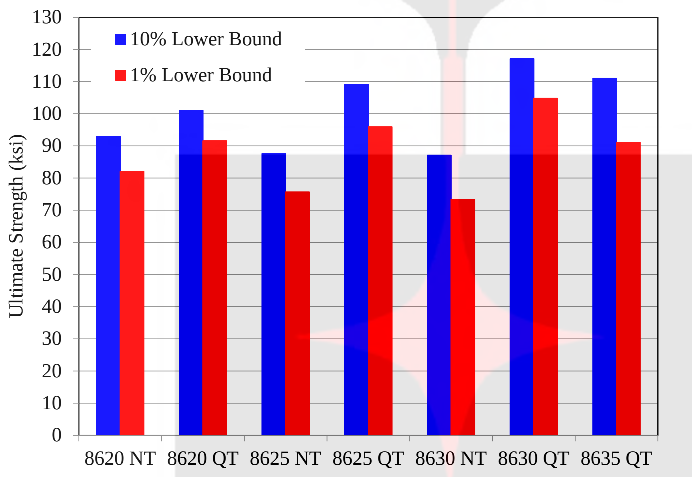
Calculated from SFSA Data

- Calculations made at the 1% and 10% levels, “A” and “B” allowables by MMPDS approach
- Data below is organized by ASTM A958 for seven 86xx alloys
- Results have also been analyzed for data organized by ASTM A487 for three alloys

Yield Strength



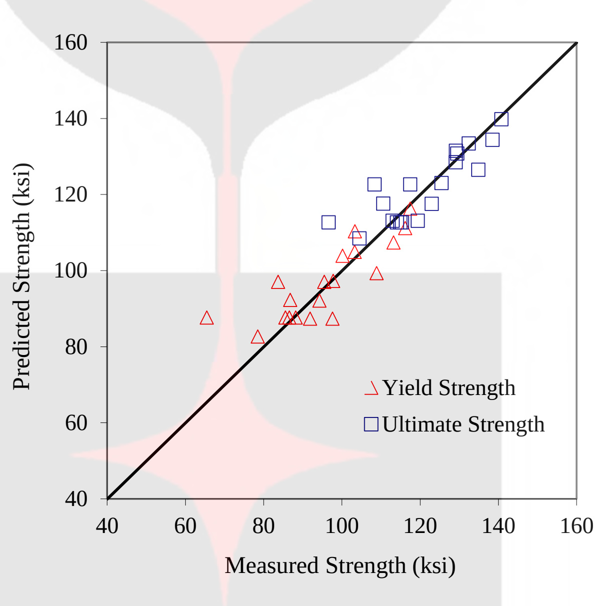
Ultimate Strength



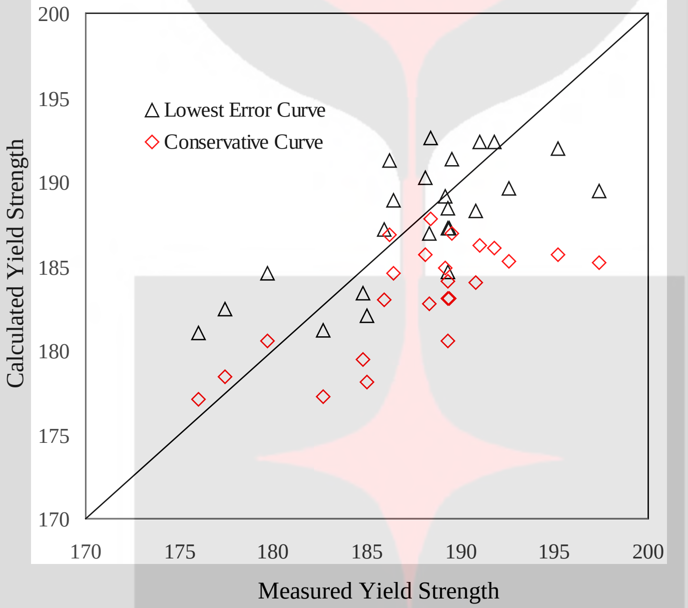
Solidification & MAGMAsteel Property Prediction

YS and UTS

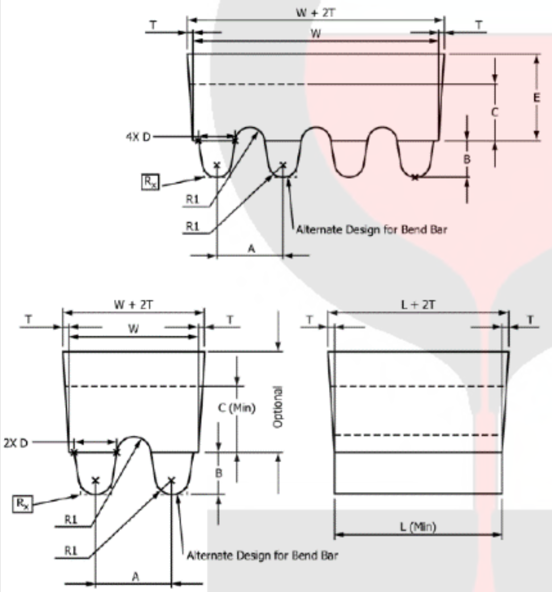
8630 Q&T yield and ultimate strengths predicted from results of *MAGMAsteel* heat treatment model and additional variables such as cooling rates during quench vs. measurements



AF9628 Yield strength predicted from solidification cooling rates, lowest error and conservative lower bound curves vs. measurements

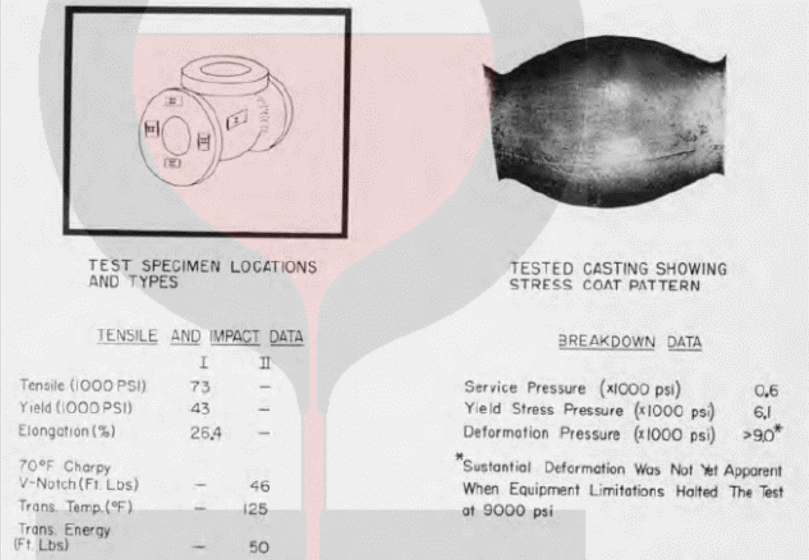


Casting v. Test Coupon Properties



Quality factors

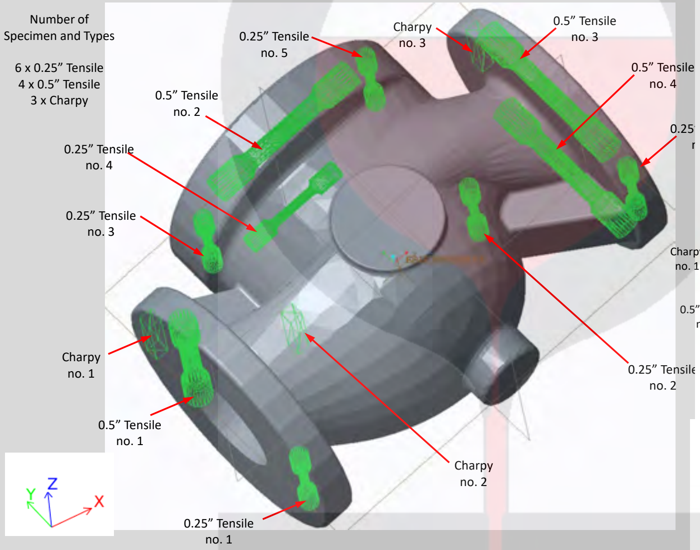
- Porosity
- Segregation
- Welding
- Inclusions
- Cooling rate
- Surface finish
- Others
    - Grain size
    - Embrittlement

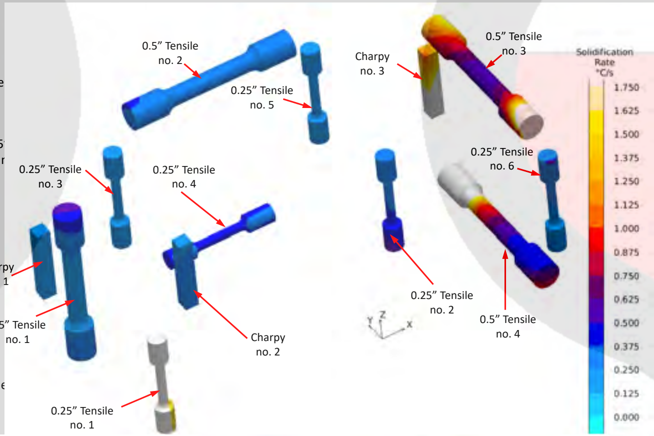


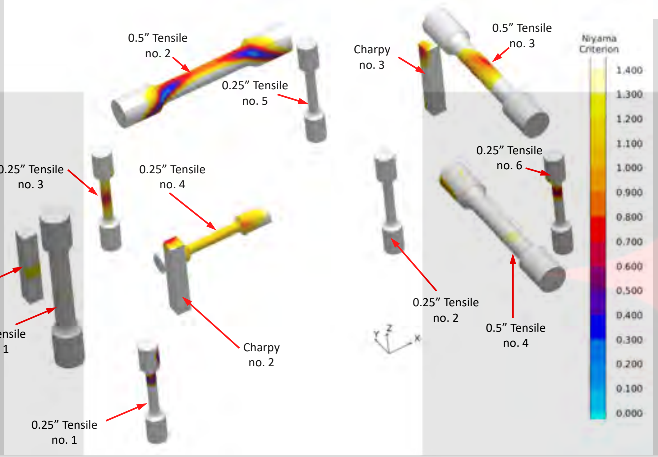
ASTM A781: The tension testing requirements of this specification are intended only to characterize the tensile properties of the heat for determination of conformance to the requirements of the applicable product specification. Such testing procedures are not intended to define the upper or lower limits of tensile properties at all possible test locations within a heat. It is well known and documented that tensile properties will vary within a heat or individual casting as a function of chemical composition, processing, testing procedure, and other factors. It is, therefore, incumbent on designers and engineers to use sound engineering judgement when using tension test results.

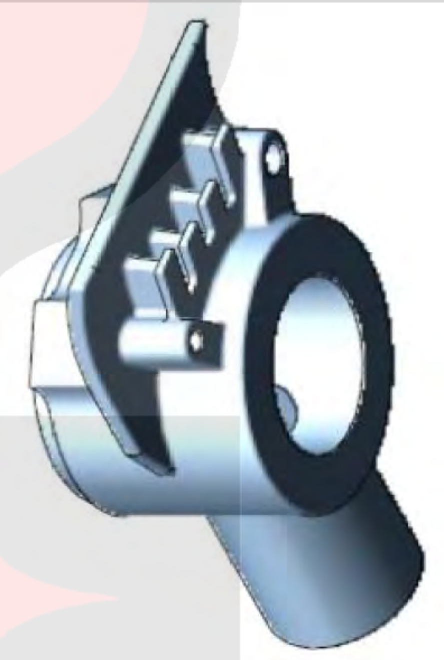
Commercial Casting Properties

Fitness for service







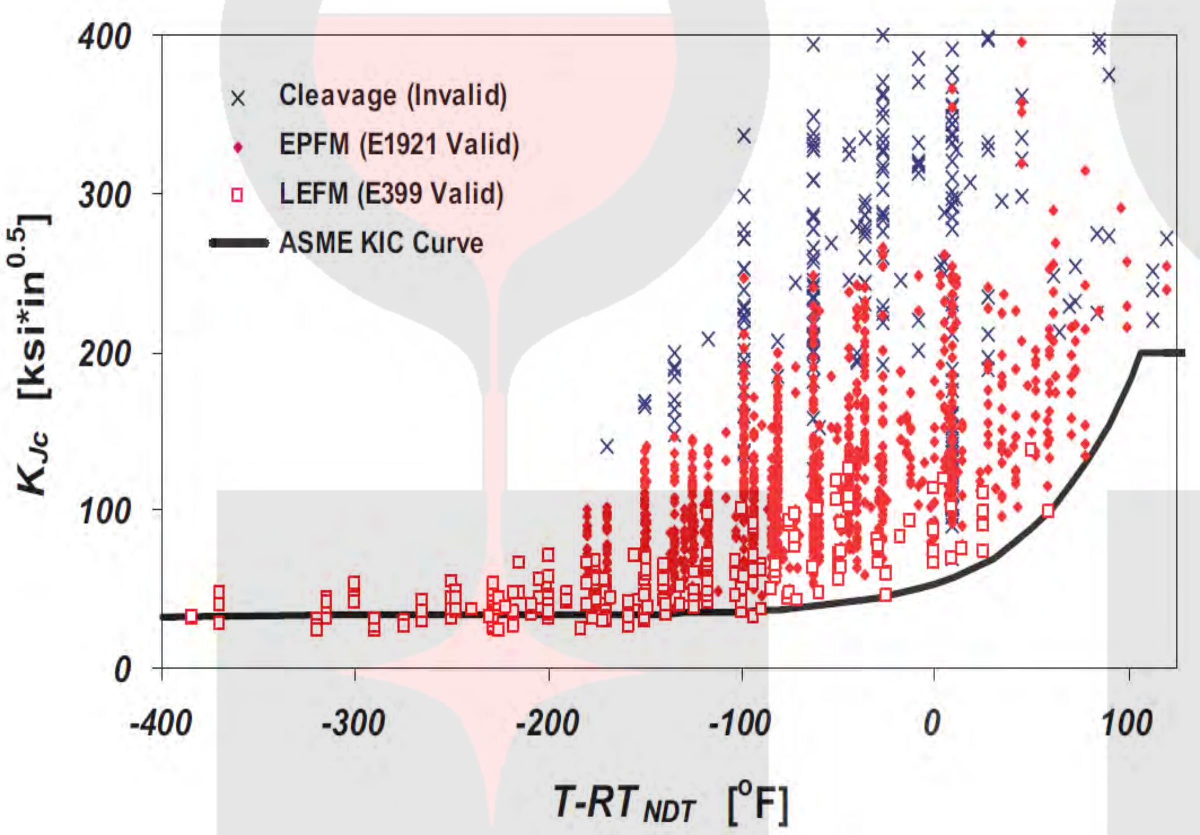


Modeling indicators

- Porosity
- Solidification rate (range and time)
- Niyama criterion
- Carbon segregation ratio
- Predicted properties
- Phase fractions of microstructures

The University of Iowa

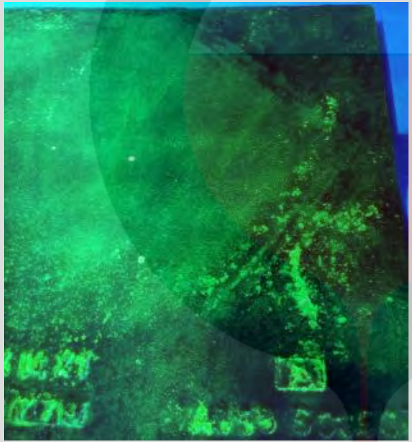
Steel Master Curve

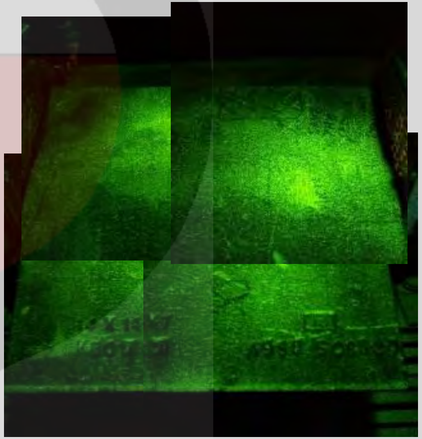


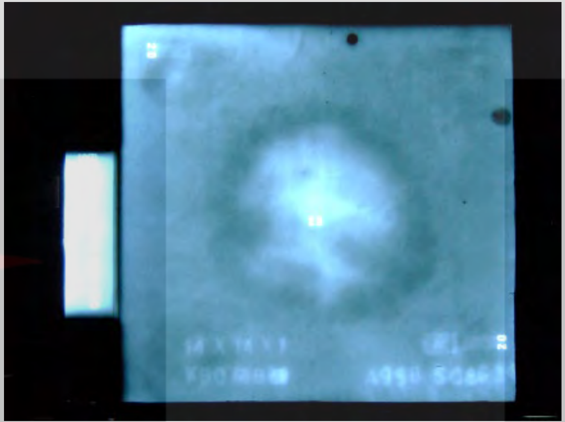
- Fracture toughness
- Based on Nil Ductility Temperature from CVN
- Conservative
- Cost-effective

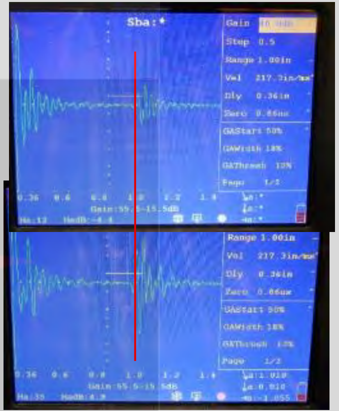
NDT Test Methods

- Visual
- Liquid penetrant
- Magnetic particle
- Radiographic
- Ultrasonic









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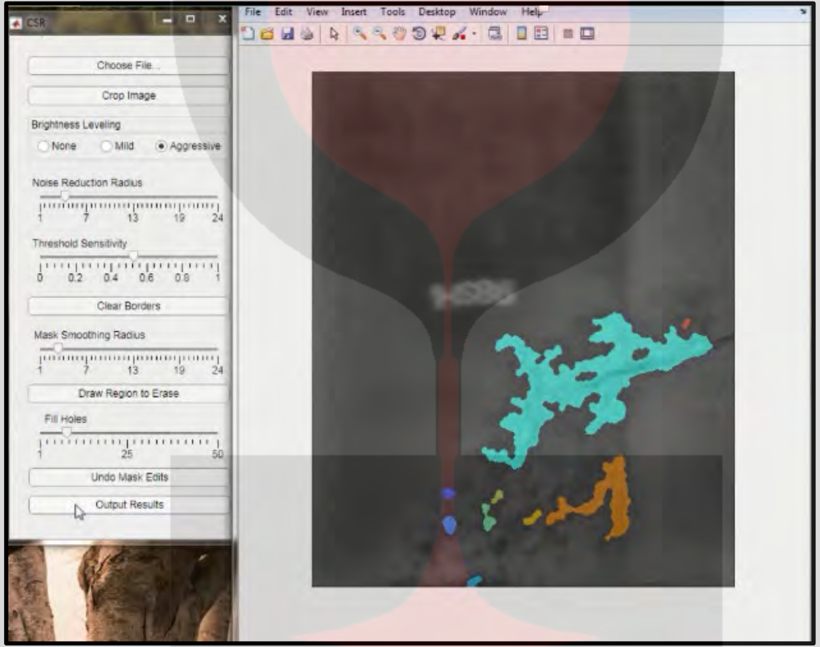
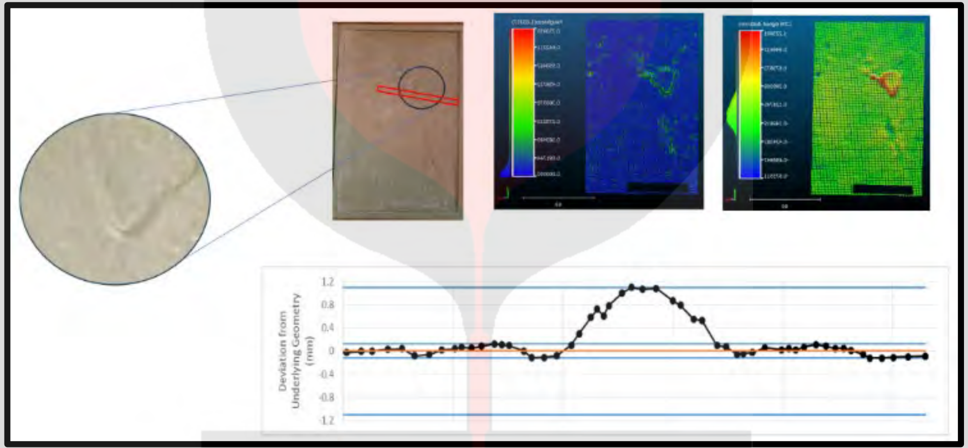
Quantitative NDT

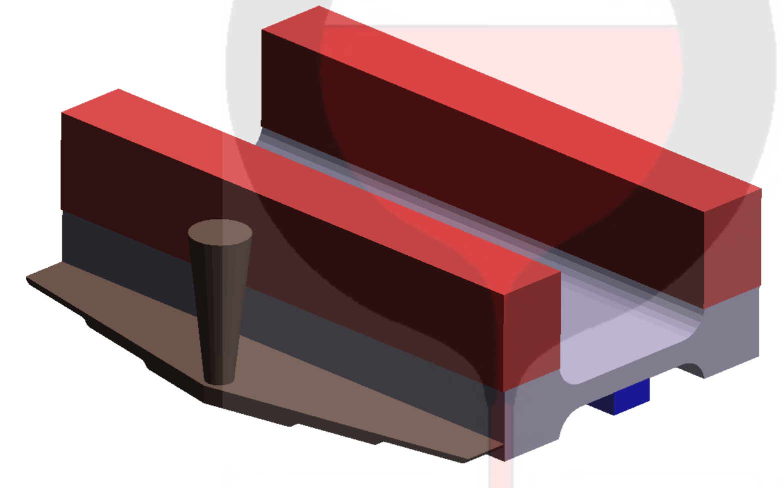


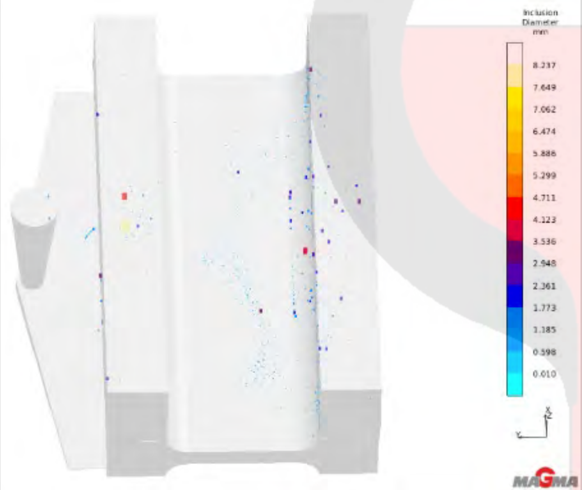
Automated image analysis (RT)

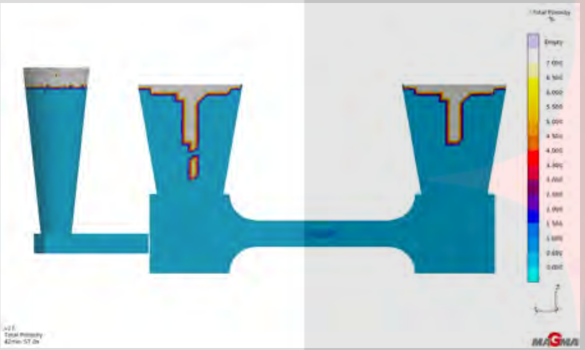


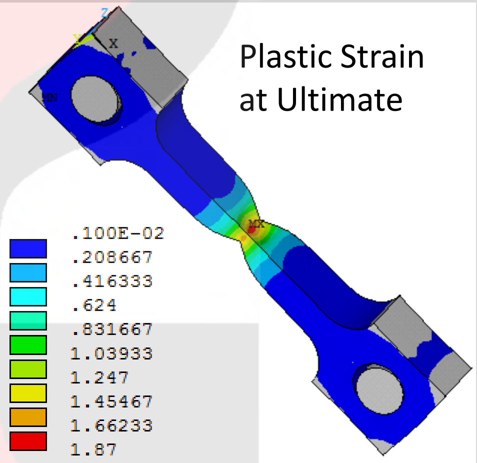
Digital surface inspection (visual)

“Real” Test Specimens







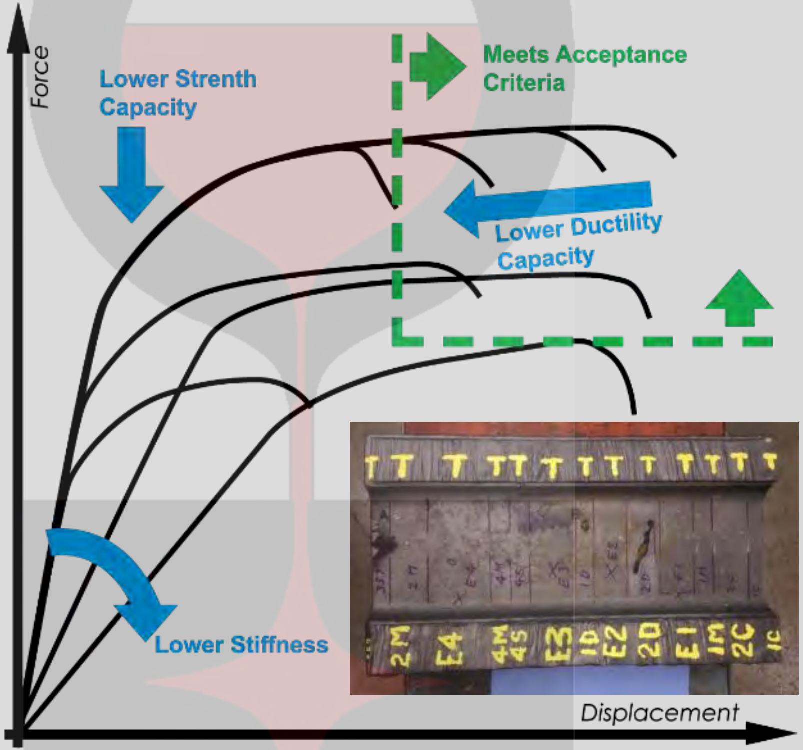


Full Size Casting Test Demonstration

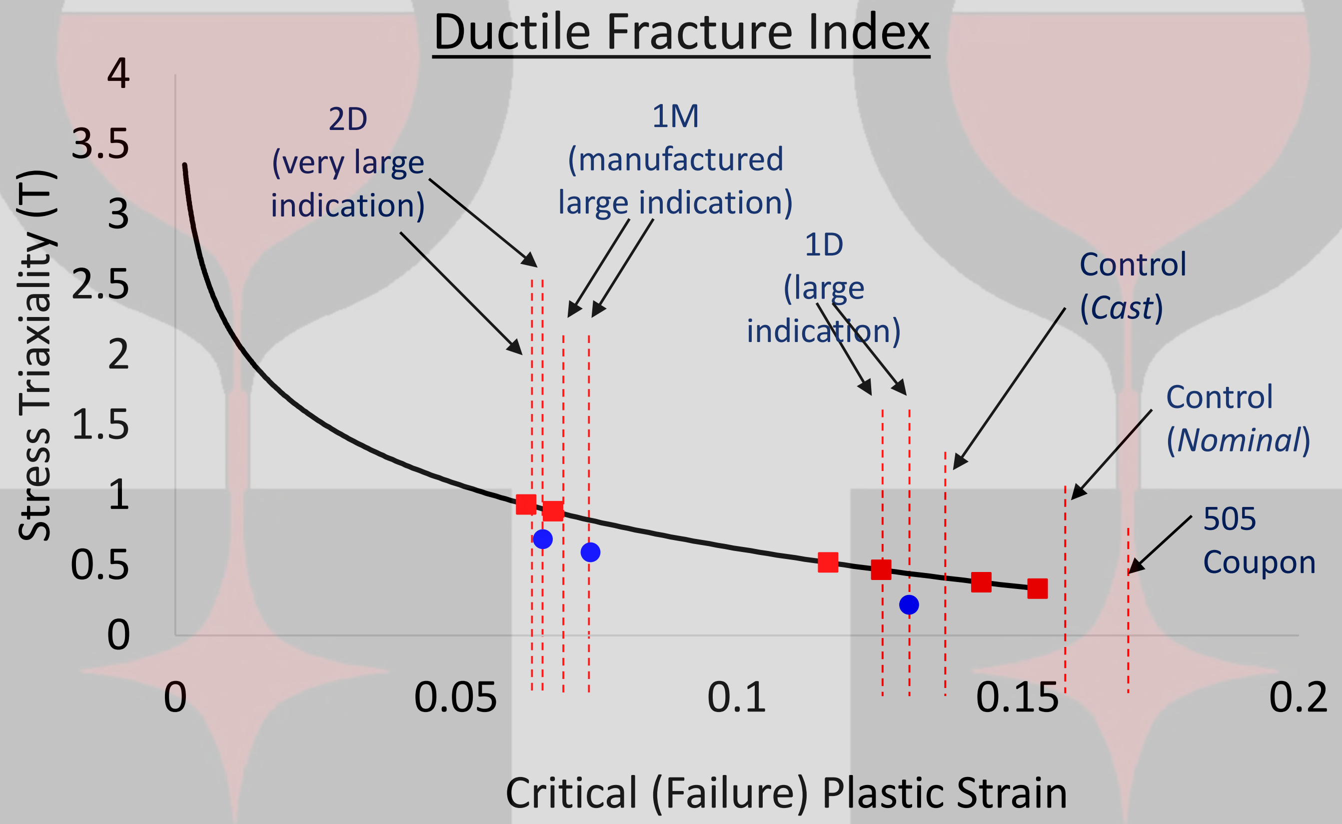
Casting Quality Effect on Performance:

- Surface finish
- Shrink Porosity
- Gas Porosity
- Inclusions

“Real” Test Specimens



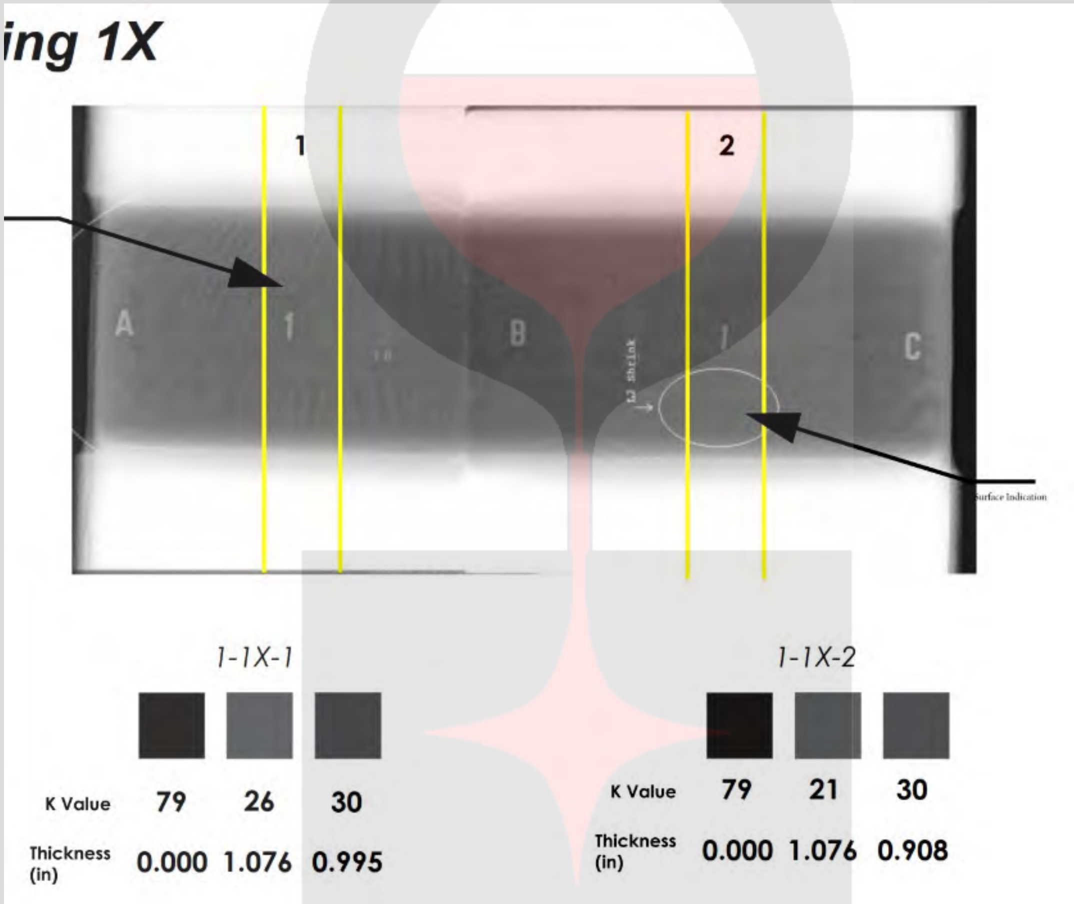
“Real” Test Specimens



Phase I Castings: Internal Indications

Procedure

- Import radiograph into digital imaging software
- Convert Image into CMYK colors
- Establish baseline K value for grayscale intensity of solid regions
- Estimate location, size and depth of indications based on lower K values relative to baseline
- To ensure best possible modeling, average K value over the pixels in a given region were used for each indication

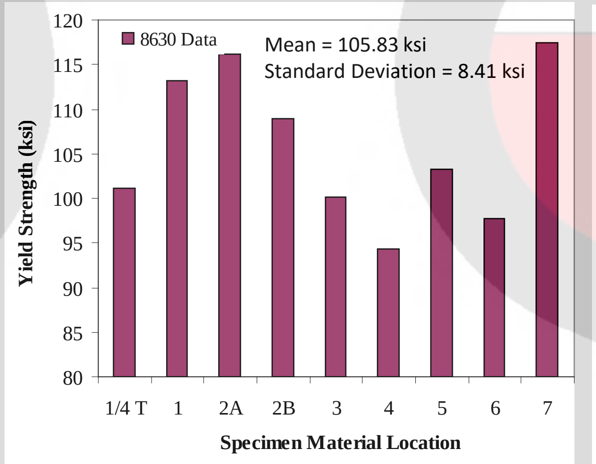


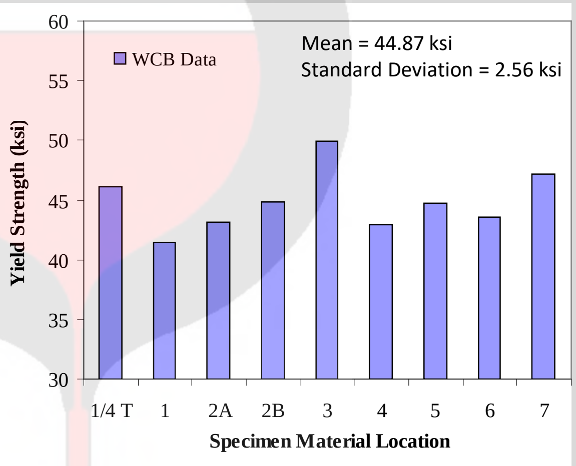
Heavy Section Mechanical Properties

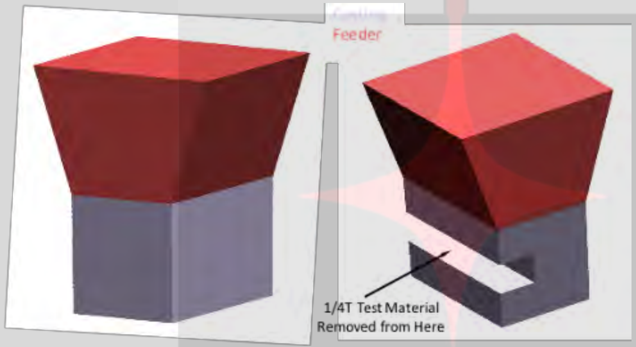
Characterize mechanical properties and microstructure of heavy section castings

Preliminary analysis on:

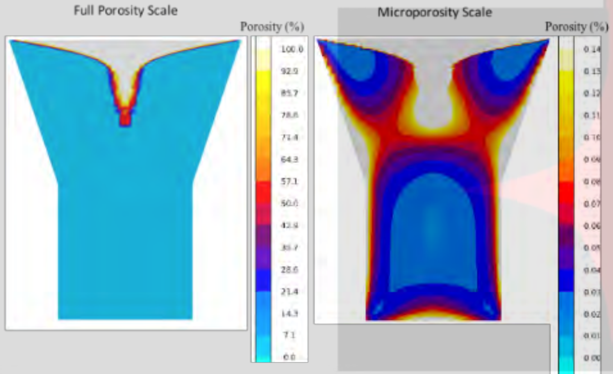
- WCB and 8630
- 4” Y-blocks sectioned for tensile testing



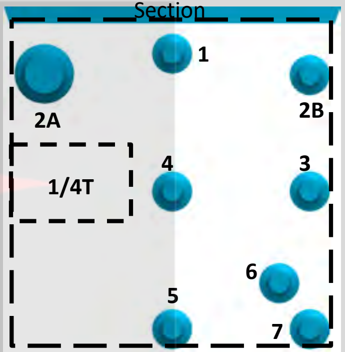




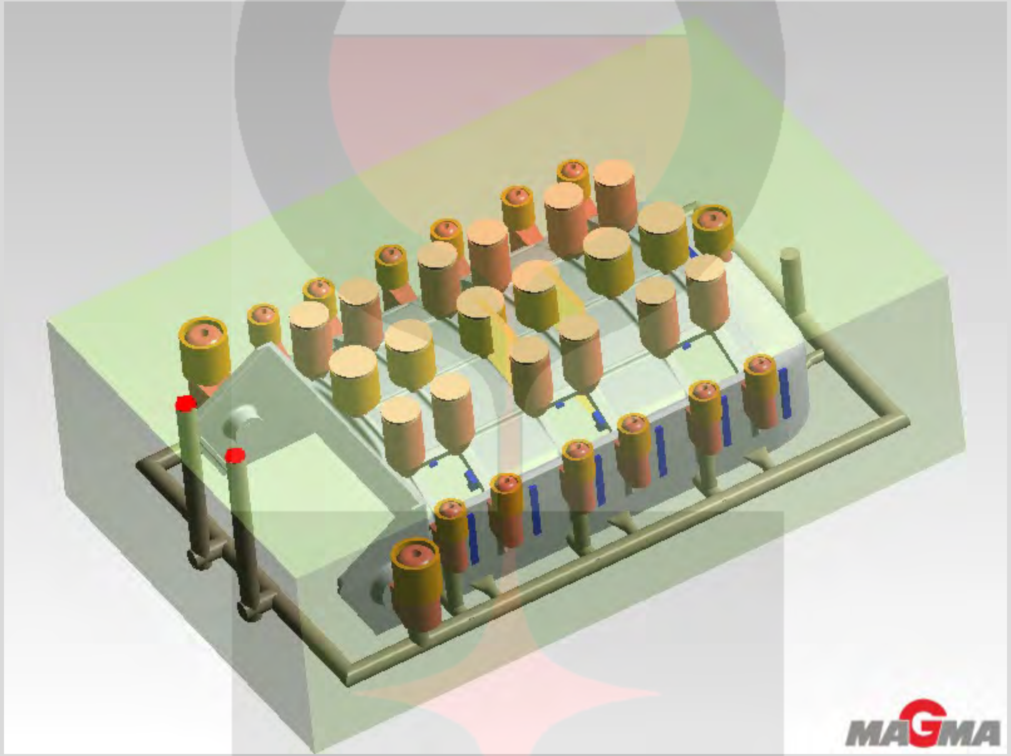
Default Boundary Condition Assumes Hot Topping and Good Feeding

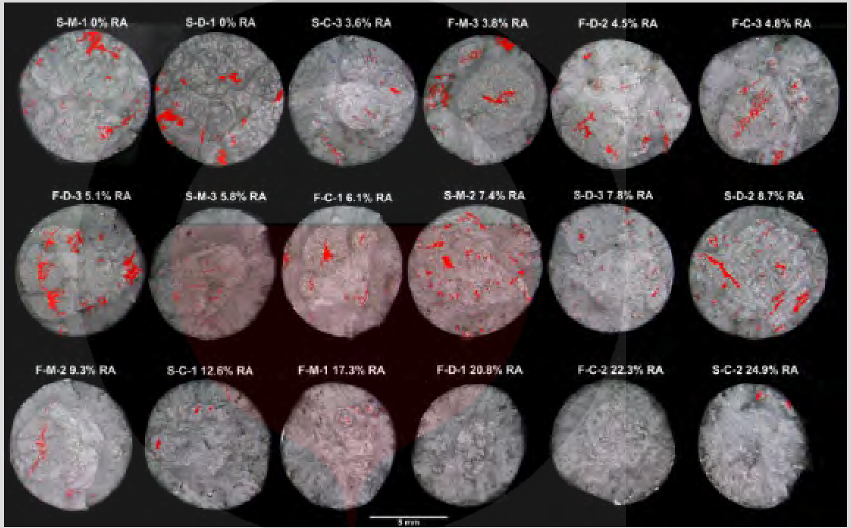


Numbering Scheme in Cross Section



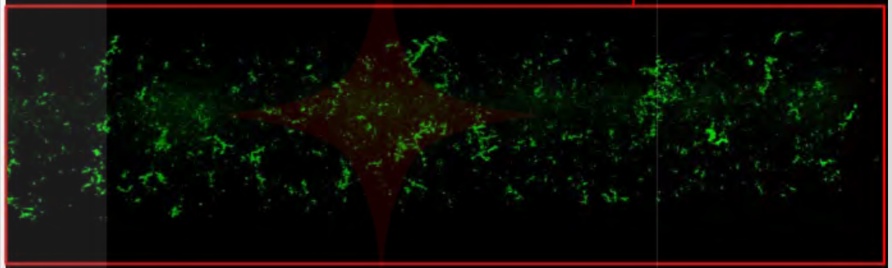
Max Pore Cluster Size





- Specimen diameter is 0.375" (9.53 mm)

Length of images below is about 1.5"



Production and Fabrication Welding

	Alloy 1A	Alloy 1B	Alloy 2A	Alloy 2B
Cast-to-Cast	WCB	WCB	A148 Grade 115/95 (8630)	A148 Grade 115/95 (8630)
Cast-to-Mill	WCB	A516 Grade 70	A148 Grade 115/95 (8630)	4130
Mill-to-Mill	A516 Grade 70	A516 Grade 70	4130	4130

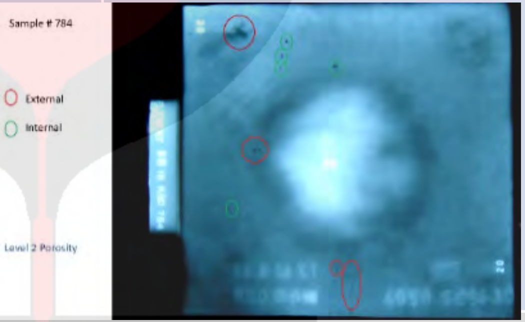
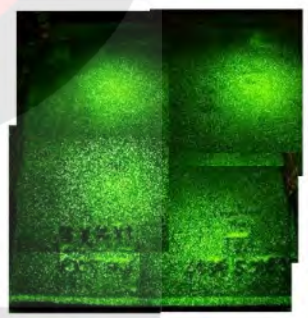
Alloy 1 – carbon steel

Chemistry	C	Mn	Si	Cr	Ni	Mo	P	S	V	Cu
ASTM A216 WCB	0.30	1.00	0.60	0.50	0.50	0.20	0.035	0.035	0.03	0.30
Measured	0.21	0.93	0.4	0.28	0.17	0.05	0.012	0.002	0.02	0.1

	UTS, ksi	YS, ksi	%El	%RA
ASTM A216 WCB	70-95	36 min	22 min	35 min
Measured*	73	46	35	63

**1750F 4hrs, air cooled, 1200F 4hrs, air cooled*

Production and Fabrication Welding

ASME BPVC Section IX (for ¾" ≤ test coupon T < 1.5")[1]	AWS D1.1 (for test coupon T ≥ 1")[2]	Additional [Lehigh] Tests	ASTM A488 [Procedure] (3/4" to 1-1/2" thickness)
4 transverse side bend 2 reduced section tensile 	4 transverse side bend 2 reduced section tensile 	2 longitudinal root bend[3] 2 longitudinal face bend[3] 2 transverse root bend[4] 2 transverse face bend[4] 1 weld metal tensile[5] 1 macroetch[6] 1 macrohardness[7] CVN[8]	4 transverse side bend 2 reduced section tensile 

[1] *Qualifies 3/16" to 2T base metal thickness*

[2] *Qualifies 3/16" and thicker*

[3] *Required in ASME BPVC Section IX and AWS D1.1 only if bending properties between base metals or base metal and weld metal are markedly different (e.g. welding Grade 115 to Grade 60)*

[4] *Required in ASME BPVC Section IX for test coupon T <3/4" and in AWS D1.1 for test coupon T ≤ 3/8"*

[5] *Required in AWS D1.1 to qualify ESW and EGW or to qualify filler metal (consumable)*

[6] *Required in AWS D1.1 for PJP and fillet welds*

[7] *For informational purposes only*

[8] *CVN is not required by the material specification A148 115/95 so CVN test will be done only for informational purposes. CVN test will be @ lower shelf temperature (to be determined from DBTT testing of cast base metal). Lower shelf T is typically used because it is the worst case scenario (provides most conservative value). Test at 2 locations (3 samples each location): weld metal and HAZ (on cast-to-mill, HAZ in both sides will be tested)*

Summary of Results (as per D1.1)

Charpy Impact Testing is underway

Test Type	Direction	Number of Tests	Cast to Cast (A216 WCB to A216 WCB)	Cast to Wrought (A216WCB to A516 Grade70)	Wrought to Wrought (A516 Grade70 to A516 Grade70)
Bend Test	Transverse Root	2	Acceptable	Acceptable (note: 2-retests) (Initial 1 of 2 unacceptable)	Acceptable
	Transverse Face	2	Acceptable	Acceptable	Acceptable
	Longitudinal Face	2	Acceptable	Acceptable (note: 2-retests) (Initial 1 of 2 unacceptable)	Acceptable
	Longitudinal Root	2	Acceptable	Acceptable	Acceptable
	Transverse Side	4	Acceptable	Acceptable	Acceptable
Tensile Test	Transverse	2	Avg. UTS: 73.8 ksi Failure Location: Base Metal	Avg. UTS: 75 ksi Failure Location: Base Metal	Avg. UTS: 79.3 ksi Failure Location: Base Metal
	All Weld	1	YS: 90.5 ksi UTS: 97.6 ksi %Elongation: 24	YS: 87 ksi UTS: 94.8 ksi %Elongation: 24	YS: 75.5 ksi UTS: 86.3 ksi %Elongation: 27
	Base Metal	2	YS: 38.4 ksi UTS: 72.8 ksi %Elongation: 29	none	YS: 47.5 ksi UTS: 78.1 ksi %Elongation: 34

Design Resources

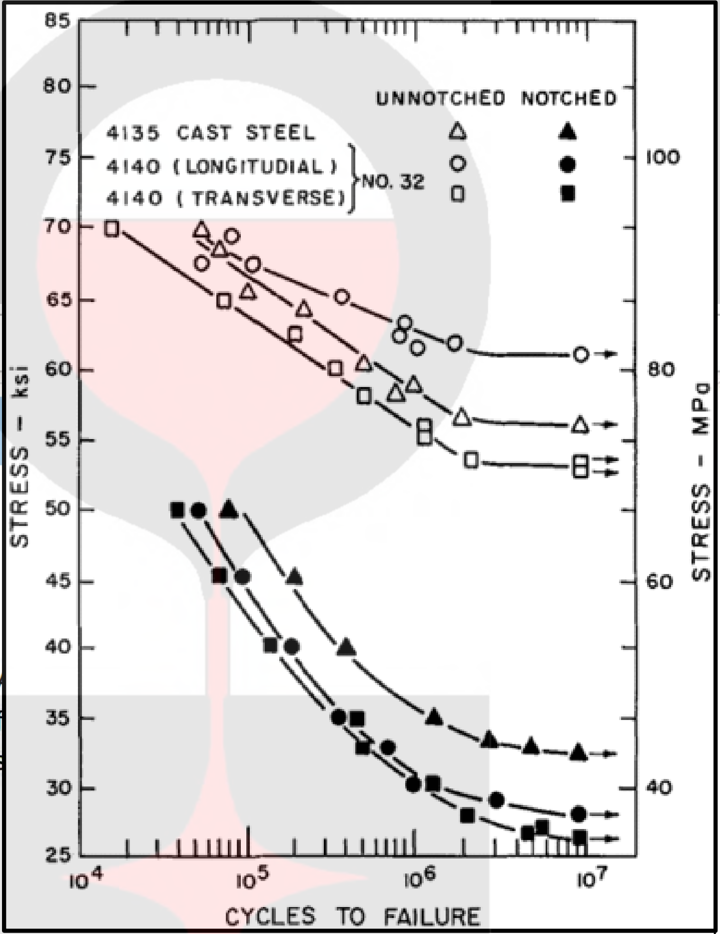
https://www.sfsa.org/publications/

Free publications

Casteel Reporter - SFSA's newsletter

Other free SFSA publications:

- **Supplements to the Steel Castings Handbook**
- **Research Reports 94 A&B** on Fatigue and Fracture Toughness of Five Carbon or Low A
- **SFSA Project A95** on Corrosion, Toughness, Weldability and Metallurgical Evaluation of
- **Test Coupons and Casting Properties** - Information gathered from several publications coupons and the properties of castings
- **Fracture Toughness in Relation to Steel Castings Design and Application**
- **Ultrasonic Testing of Steel Castings**
- **Cast to Shape.** A history of the steel castings industry in the United States
- **Raw Materials Specifications**
- **Sub-size Charpy specimens**



http://user.engineering.uiowa.edu/~becker/documents.dir/SFSA/2003-3.5%20Fatigue%20of%208630.pdf

Questions

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Real casting properties

Test specimens v. real castings

Welding – minor v. major

Design/customers