Characterization of Modern High-Toughness Steels for Fracture Propagation and Arrest Assessment – Phase II Closeout Meeting

Dash Weeks

December 17, 2019

AGENDA

2:00 PM	**Join Virtual Meeting – Introduction – Project Overview**
2:30 PM	Phase II Objectives and Research Approach
3:00 PM	Experimental Details and Results
3:30 PM	Material and Failure Modelling
4:00 PM	Discussion and Conclusions
4:30 PM	Future Work
5:00 PM	Close

Name	Affiliation - Role
Frank Del Rio	NIST – Group Leader
Dash Weeks	NIST – Project Lead
Robert Amaro	NIST/UA – Modelling/Data Analysis
Nik Hrabe	NIST - Metallography
May Martin	NIST – Metallography/SEM
Enrico Lucon	NIST - Charpy
Ross Rentz	NIST – Testing
Robert Smith	DOT/PHMSA – Sponsor
James Merritt	DOT/PHMSA – Technical Manager (retired)
Brian Leis	BN Leis Consultant - TAC
David Johnson	Paragon Industries – TAC
Su Xu	CanmetMATERIALS - TAC
Brian Rothwell	PRCI – TAC
Kip Findley	Colorado School of Mines – TAC
Matthew Merwin	U.S. Steel – TAC
David Taylor	Technical Consultant - TAC

Modern high-strength high-toughness steels and their use in pipeline designs have confounded the available predictive models.

Test methods used to validate predictions do not adequately characterize high-strength high-toughness steels.

The ductile running failure is preceded by a process zone whereby the material undergoes plastic deformation.

Determining arrest-ability based on as-received properties presents the first-order problem for this project.

As-received material has a strain history that is significantly different than that of the material in the plastic process zone, therefore, the crack propagates through material with different mechanical properties.

NIST Proposed

1. To identify the stress/strain/crack velocity conditions for unstable high-rate ductile crack propagation in a full-scale burst test and duplicate those conditions in a medium-scale test.
2. Modelling to validate the conditions and assumptions used in reducing the scale of the tests.
3. To develop the medium-scale test to parametrically determine material properties necessary to qualify high-strength high-toughness steels for pipeline use based on the ductile failure resistance and arrest-ability.
4. To determine the relevant and effective small-scale test or tests that provides necessary information for material selection, design, reliability as well as integrity and risk assessment.

Intentional full-scale burst tests and unintentional full-scale ductile running failures are phenomenologically complex. Separation of the variables controlling an event and then duplicating them in the laboratory is the planned path.

PHASED APPROACH

A phased approach is underway where the complimentary research in successive phases comes from determining knowledge gaps.

This phase determined the most appropriate and controlled way of simulating the process zone of a unstable ductile failure.

This phase conducted metallurgical evaluations on the as-received and “damaged” steel.

This phase informed and calibrated a predictive material failure model to be used in a structural model.

MILESTONES

1. Design, fabrication and testing of a wide-plate specimen for simulating the process zone and associated strain histories.

2. Small-scale test matrix design, sectioning plan and pre-strained wide-plate sectioning.

3. Small-scale specimen machining and test method development.

4. Small-scale testing and material model calibration.

API 5L X70 (UOE Pipe - Plate)

Plates removed and cut from production

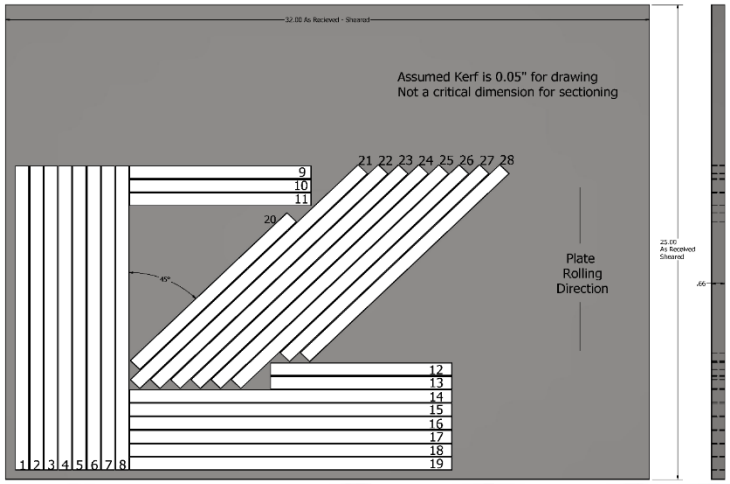
Enough material for as-received characterization and several wide-plate specimens.

Plates are approximately 32” X 25” (rolling direction) and are 0.66” thick.

Small-scale specimens were machined:

- round tensile
- mini-tensile (rectangular cross section)
- cylinders
- notched bar impact (Charpy V-Notch).

Flat Strap Tensile Specimens were not part of the test program.

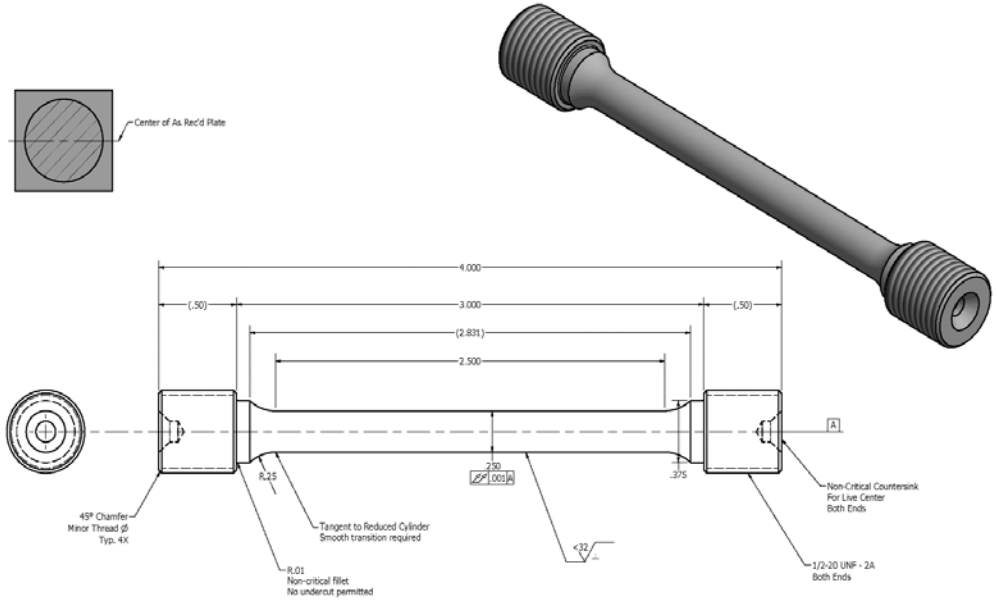


As-Received Sectioning Plan

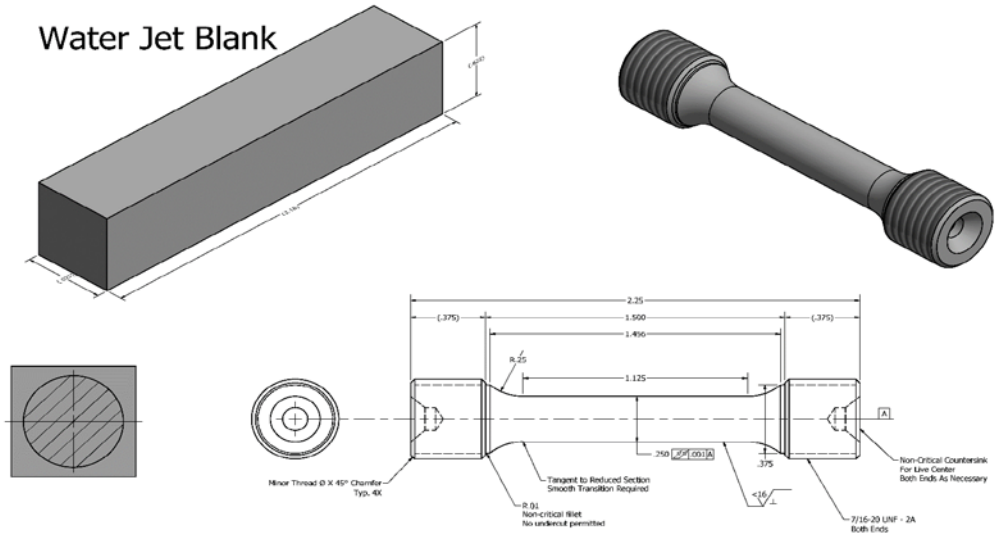
Chemical Analysis of as-received X70 plate

Element	Specified Maximum (%)	Actual (%)
B	0.001	<0.001
C	0.28	0.05
Cr	0.50	0.04
Cu	0.5	0.03
Mn	1.40	1.60*
Mo	0.15	0.01
Nb	--	0.057
Nb + V + Ti	0.15	0.07
Ni	0.5	0.04
P	0.03	0.009
S	0.03	0.006
Ti	--	0.012
V	--	0.003

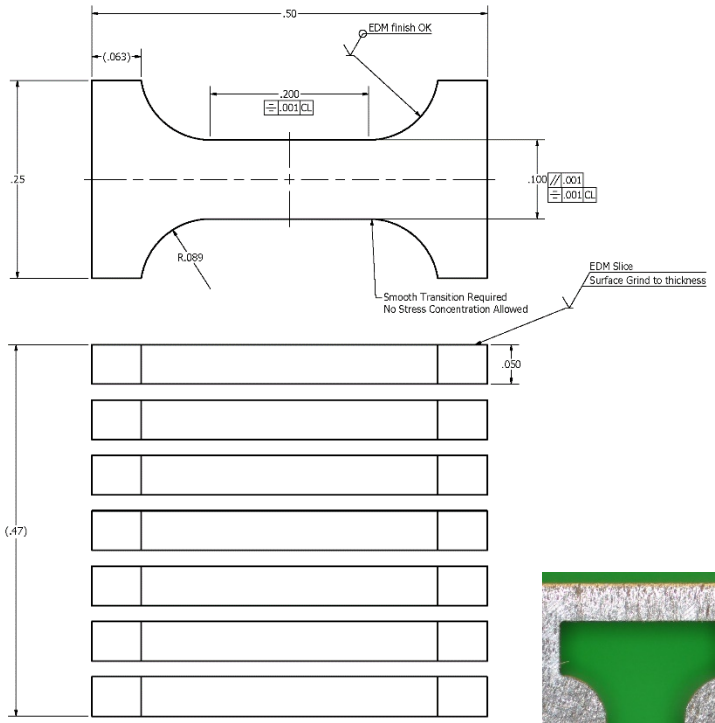
ROUND TENSILE



Used for As-received and Pre-Strained



MINI-TENSILE



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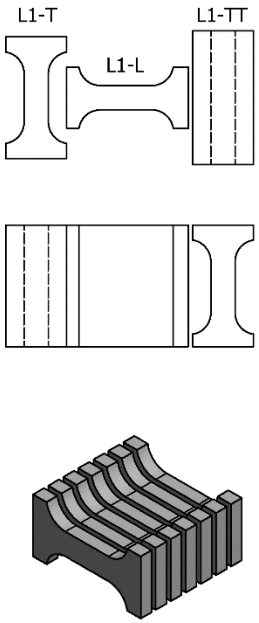
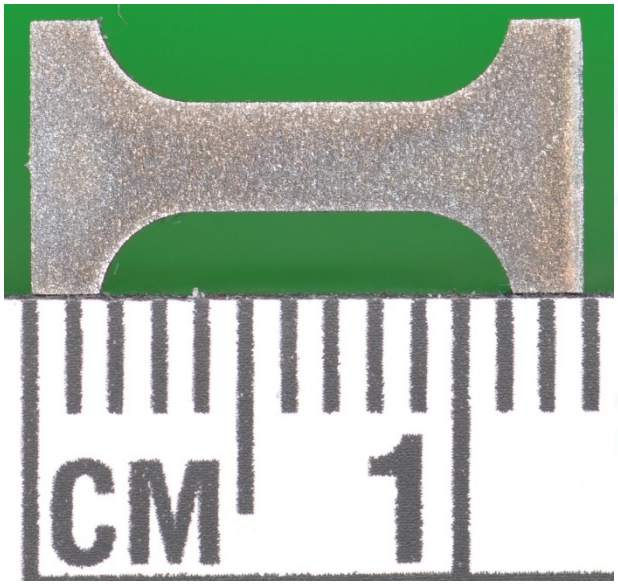
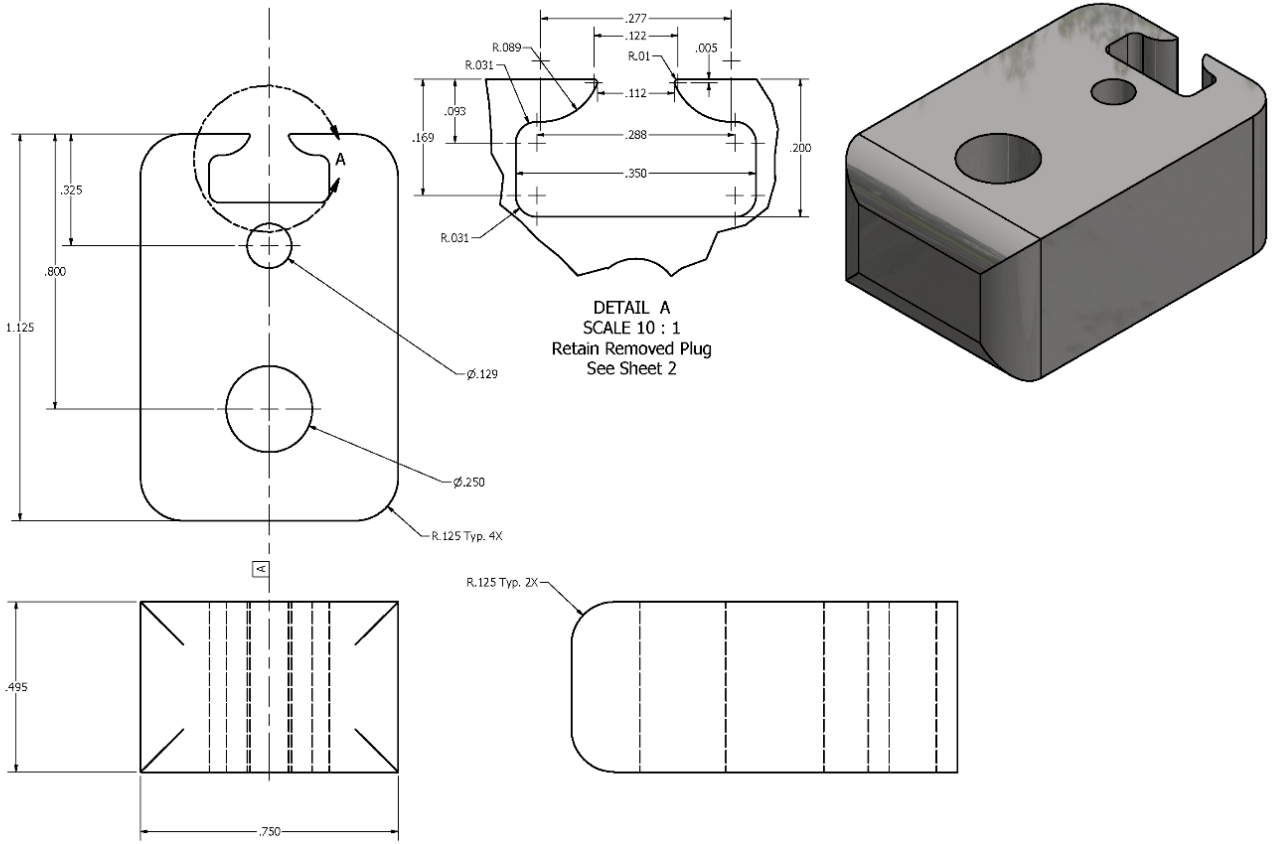
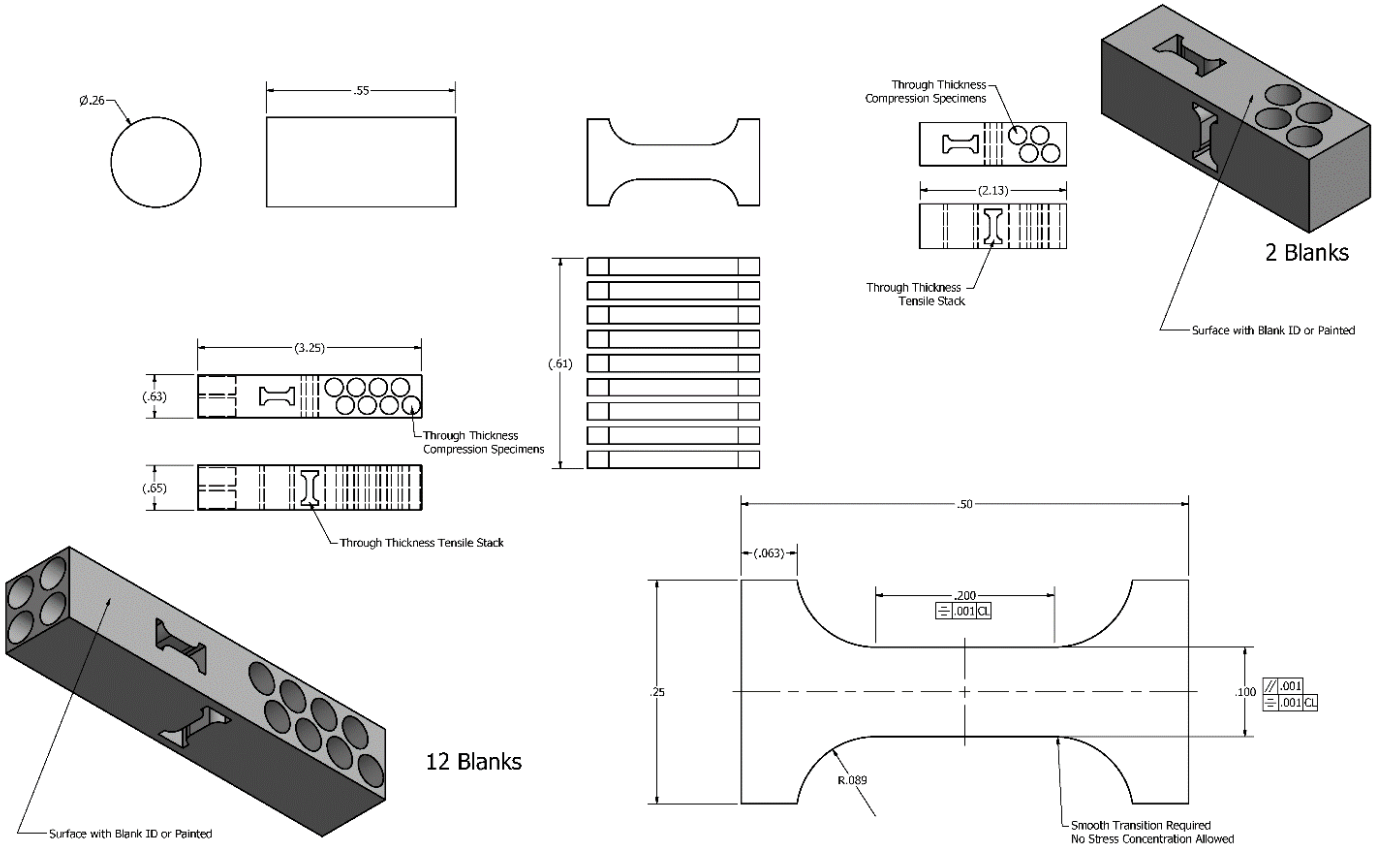




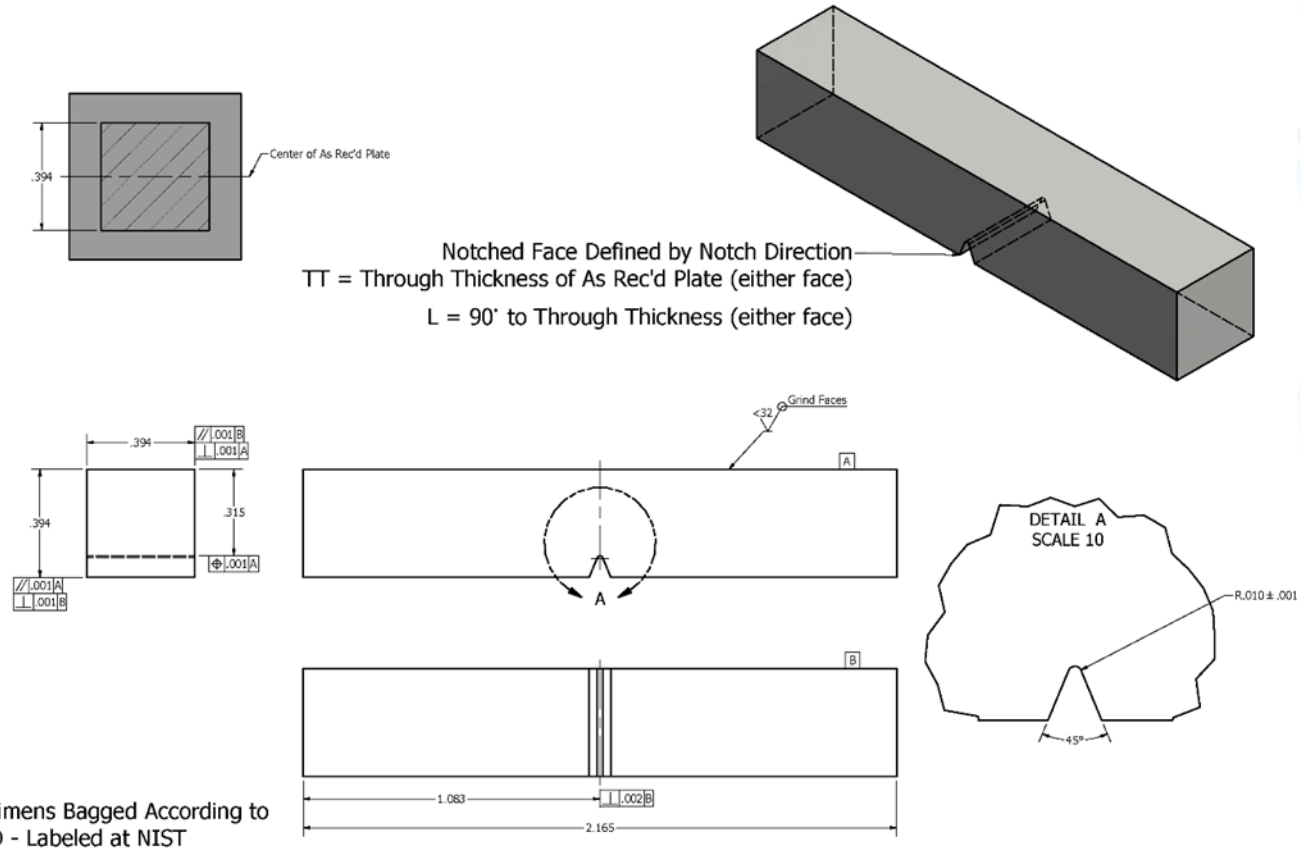
MINI-TENSILE GRIPS



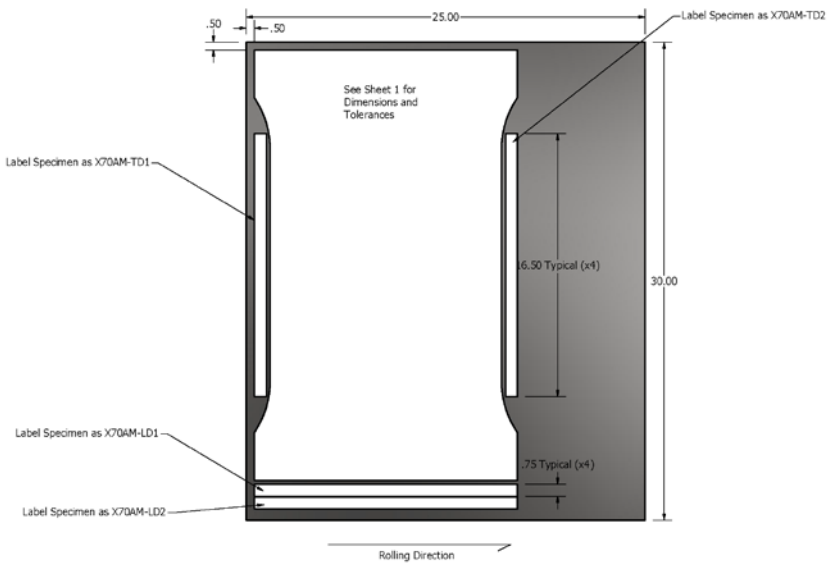
MINI-TENSILE AND CYLINDER SECTIONING

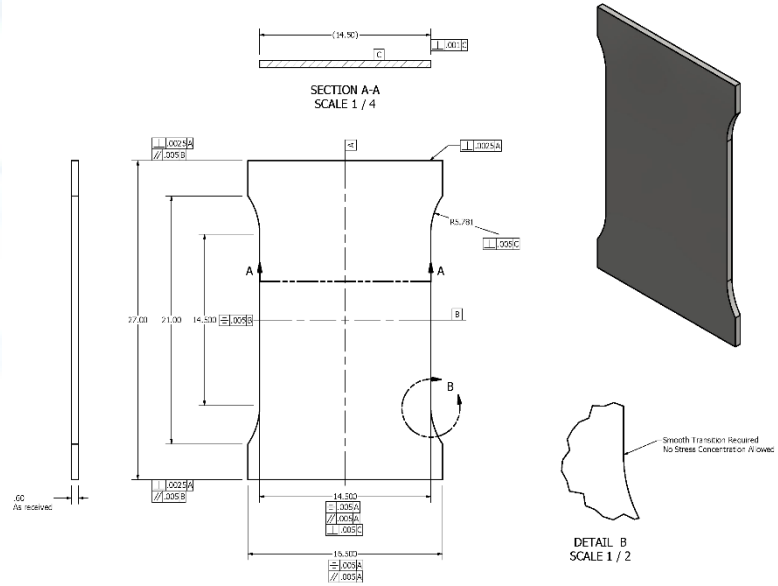


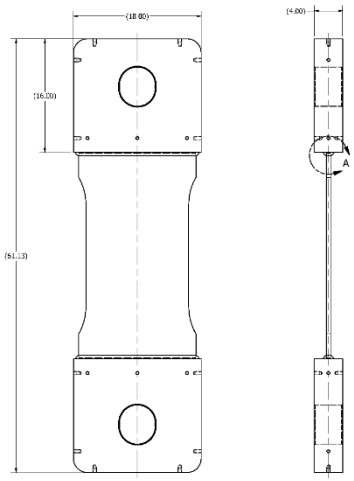
CHARPY

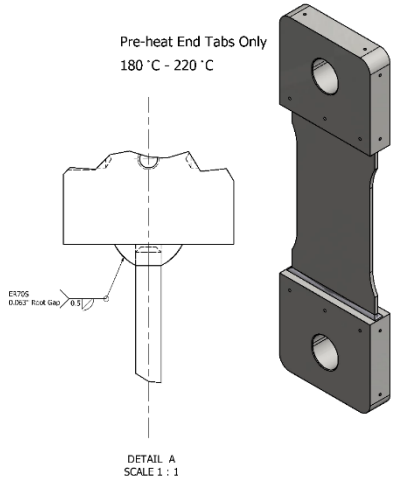

Center of As Rec'd Plate
.394
Notched Face Defined by Notch Direction
TT = Through Thickness of As Rec'd Plate (either face)
L = 90˚ to Through Thickness (either face)
Grind Faces
<32
.394
.001 B
.001 A
.315
.001 A
.001 A
.001 B
A
A
B
DETAIL A
SCALE 10
R.010 ± .001
45°
1.083
.002 B
2.165
All Specimens Bagged According to
Blank ID - Labeled at NIST

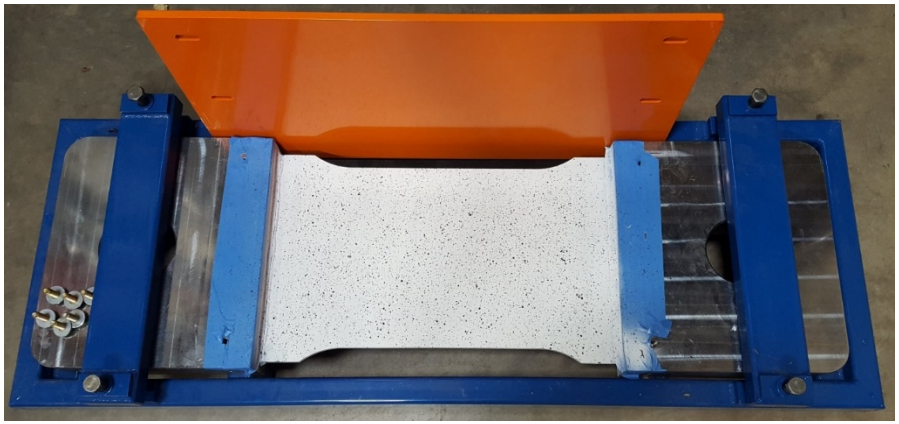
WIDE-PLATE DESIGN











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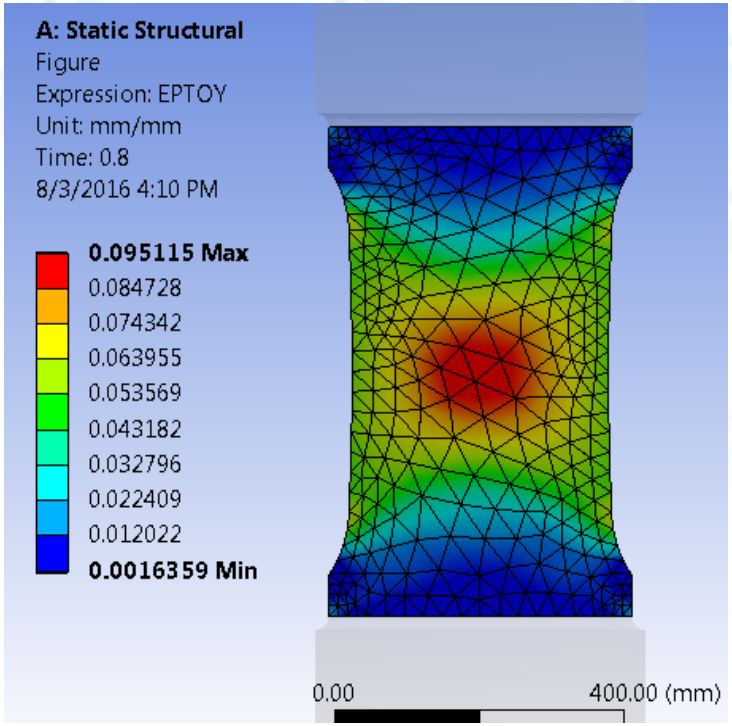
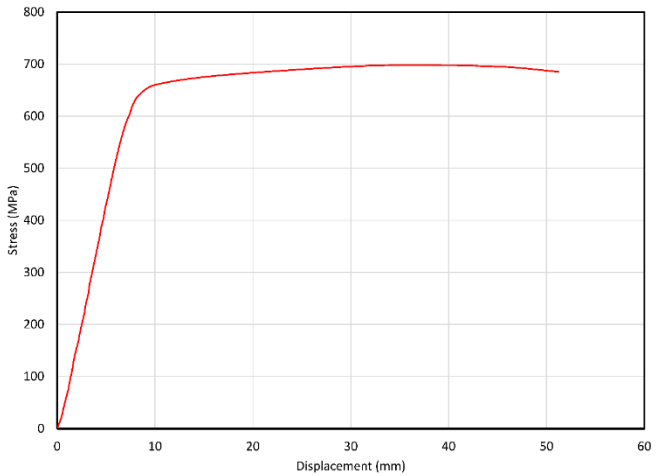
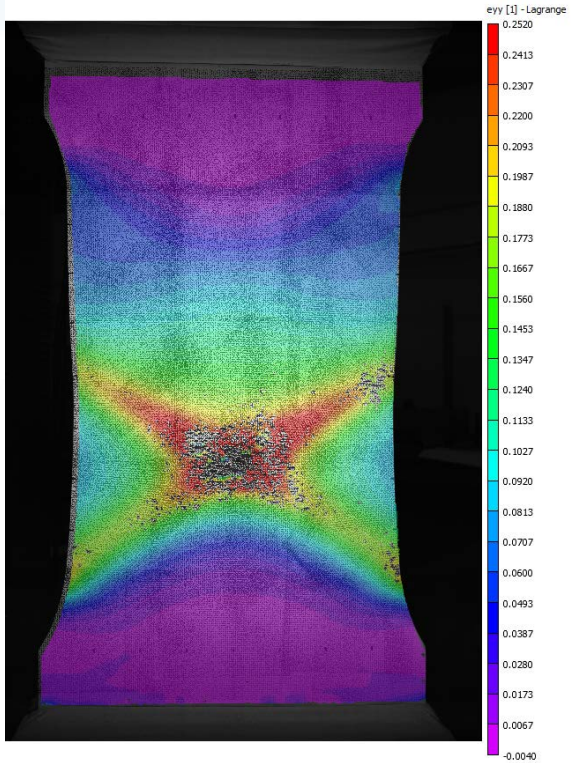
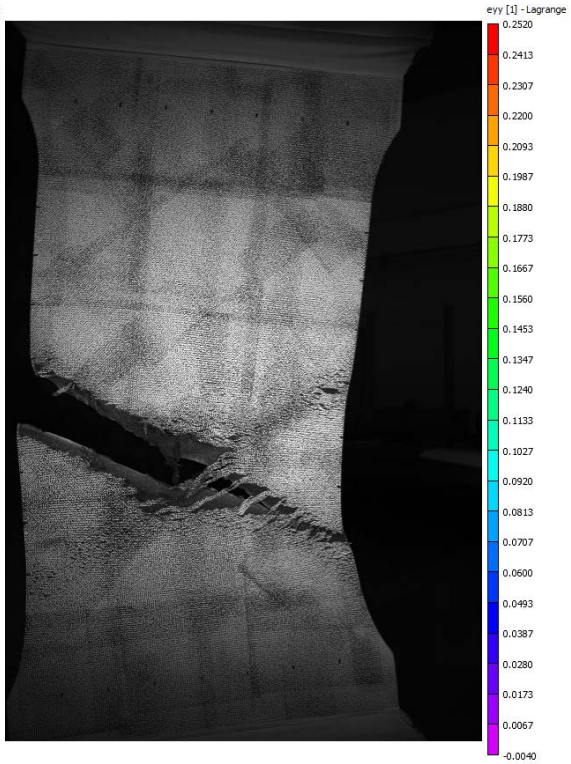
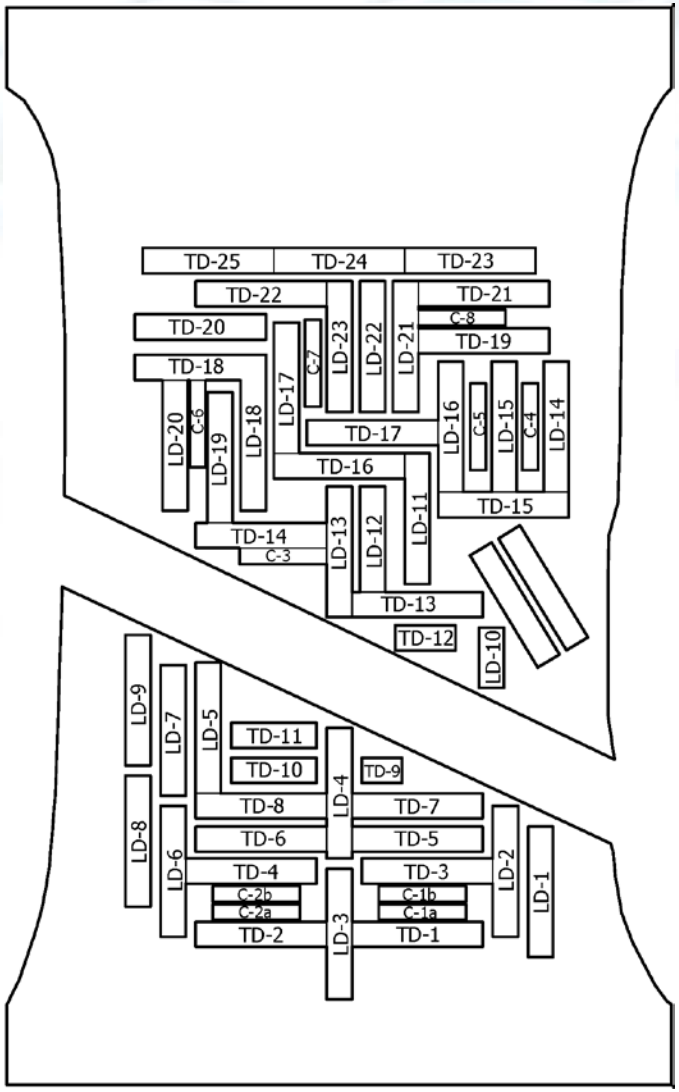


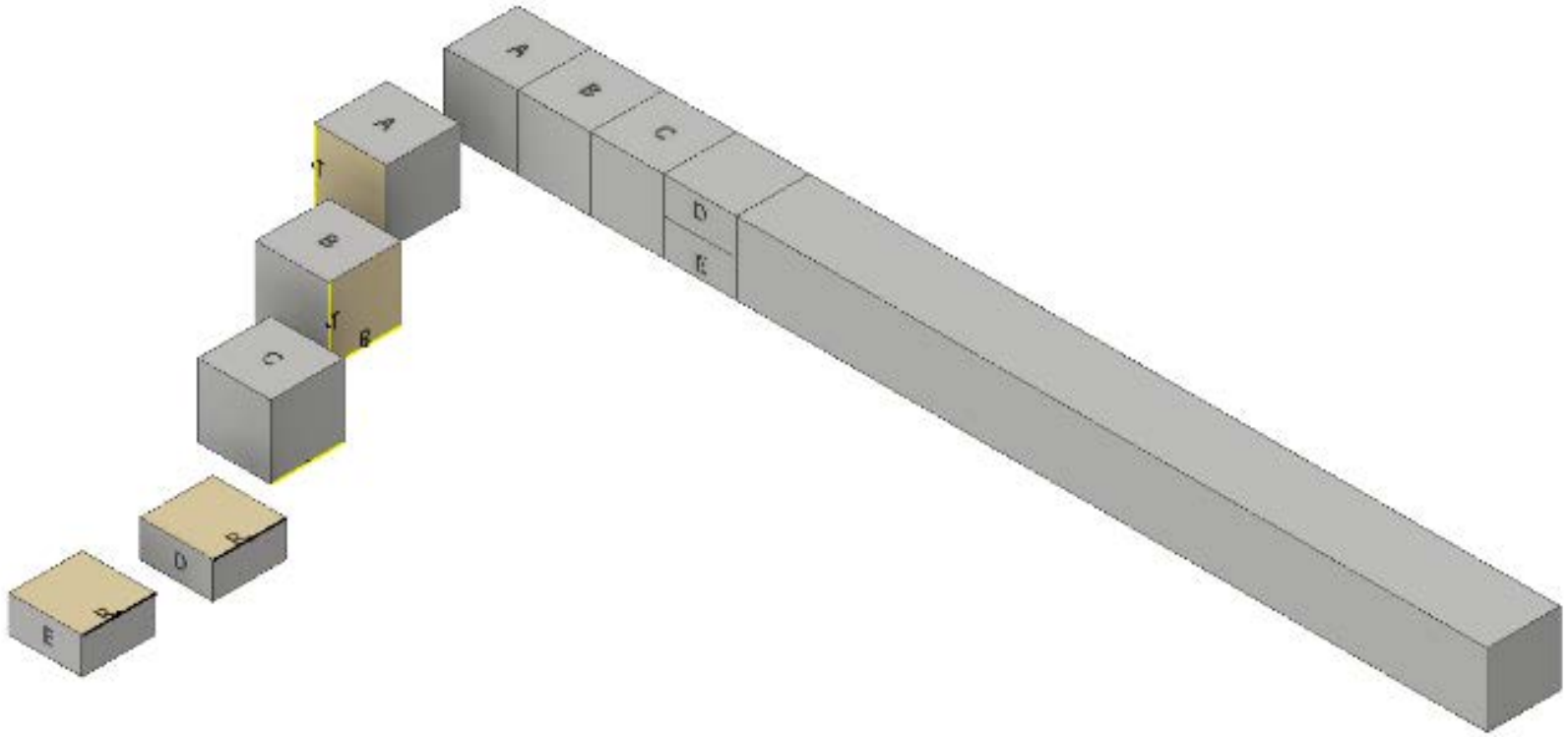




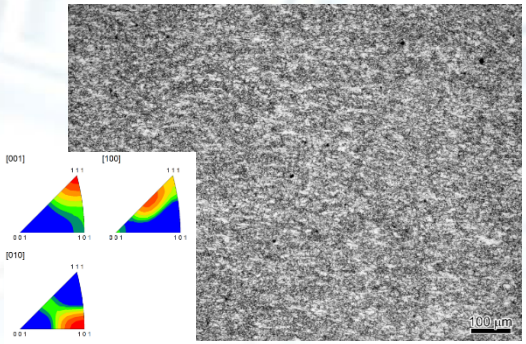


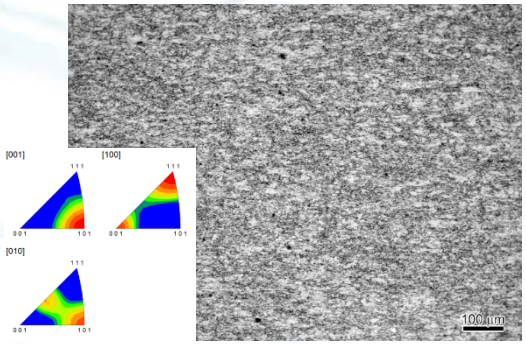


Pre-Strained Blanks 2 % - 21 %

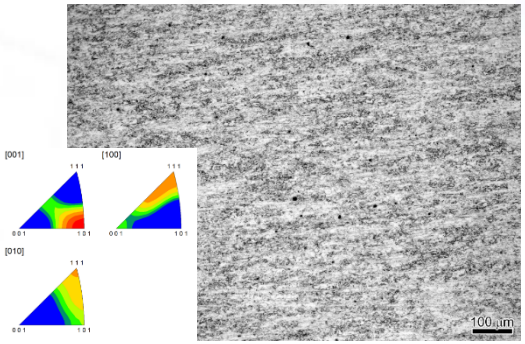

A
B
C
D
E

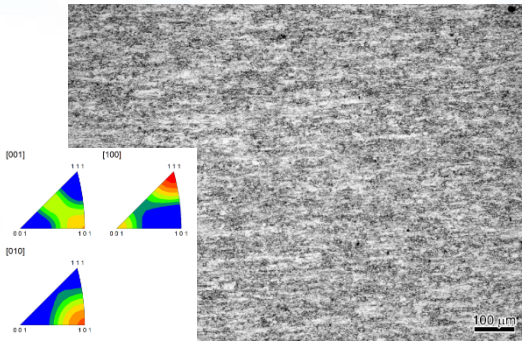
METALLOGRAPHY AND TEXTURE



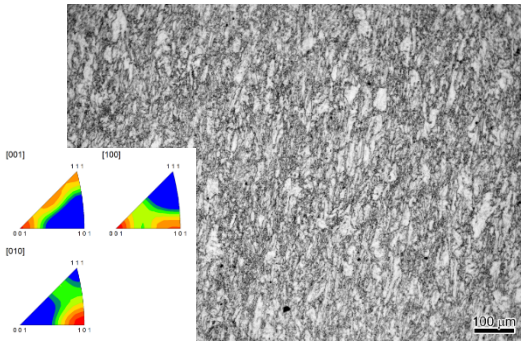


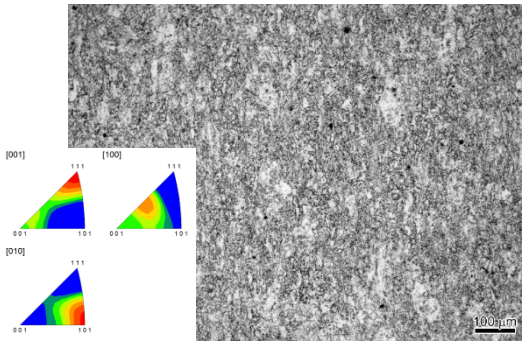
Grain size = 5.23 µm to 4.07 µm





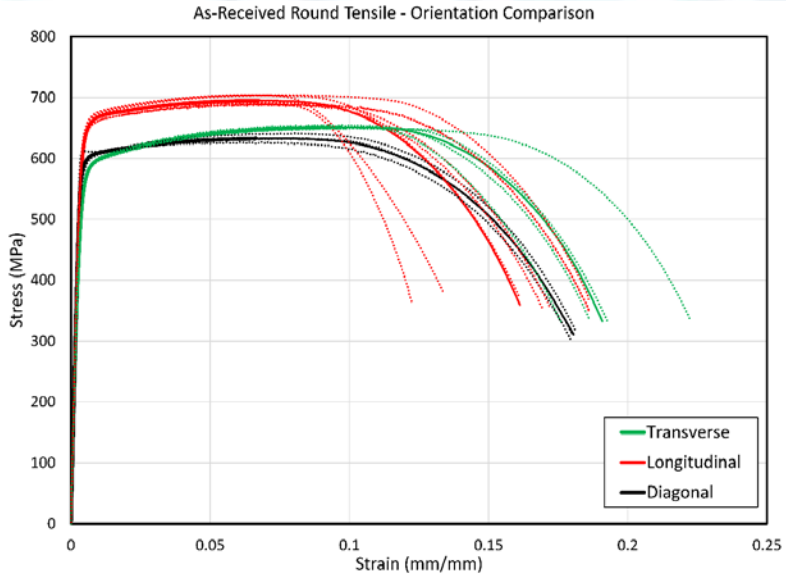
Grain size = 8.84 µm to 5.94 µm

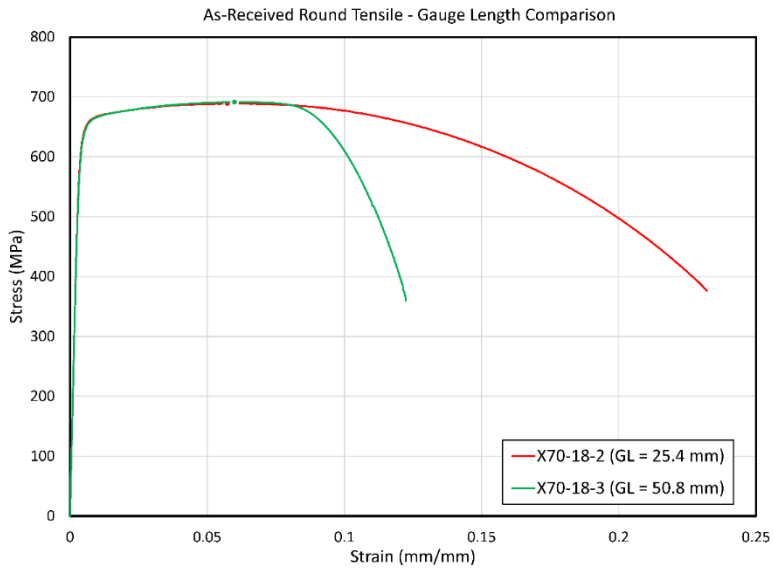


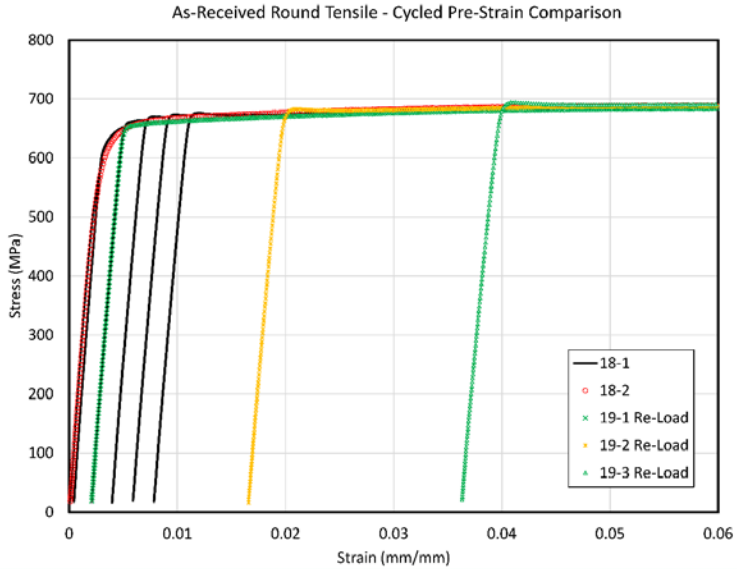


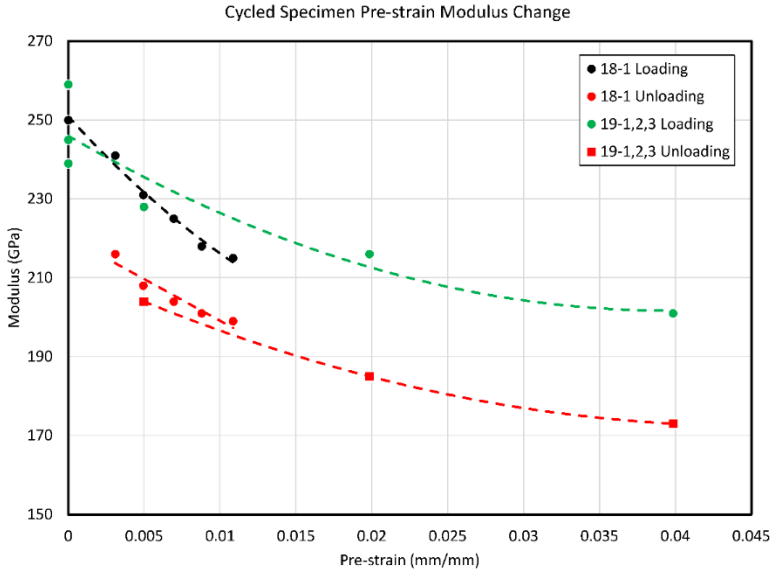
Grain size = 6.05 µm to 5.36 µm

AS-RECEIVED ROUND TENSILE RESULTS

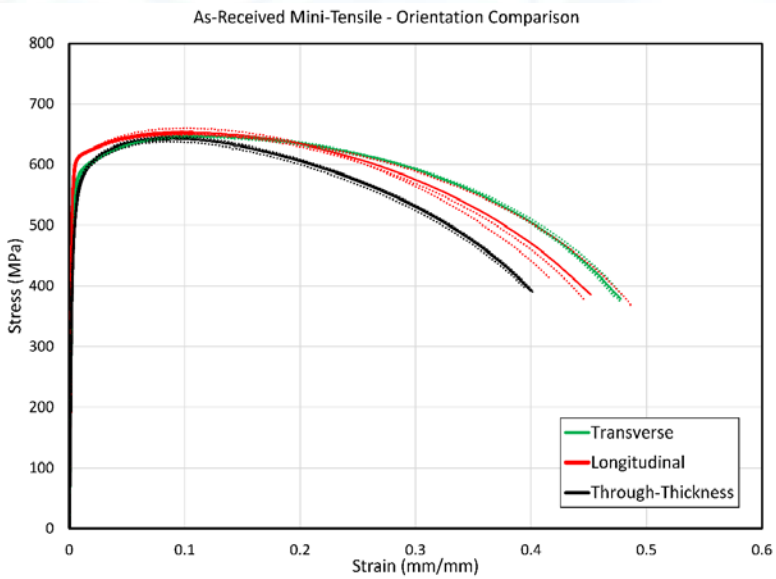


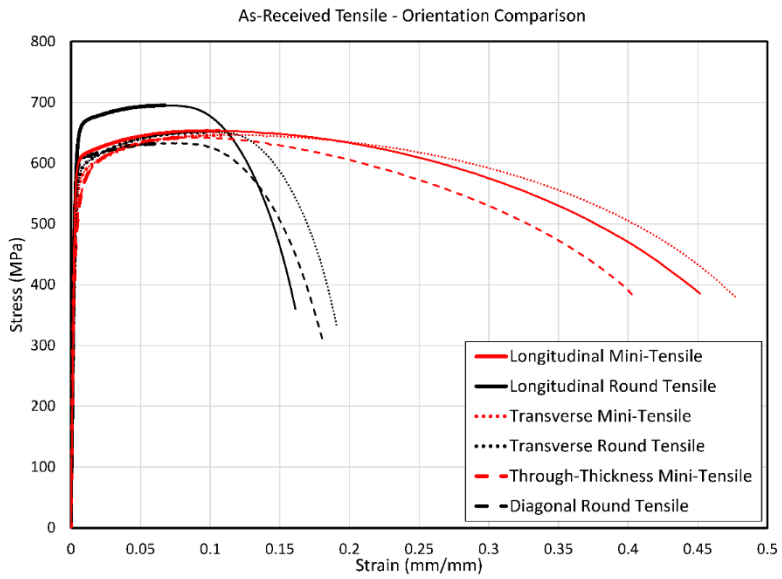




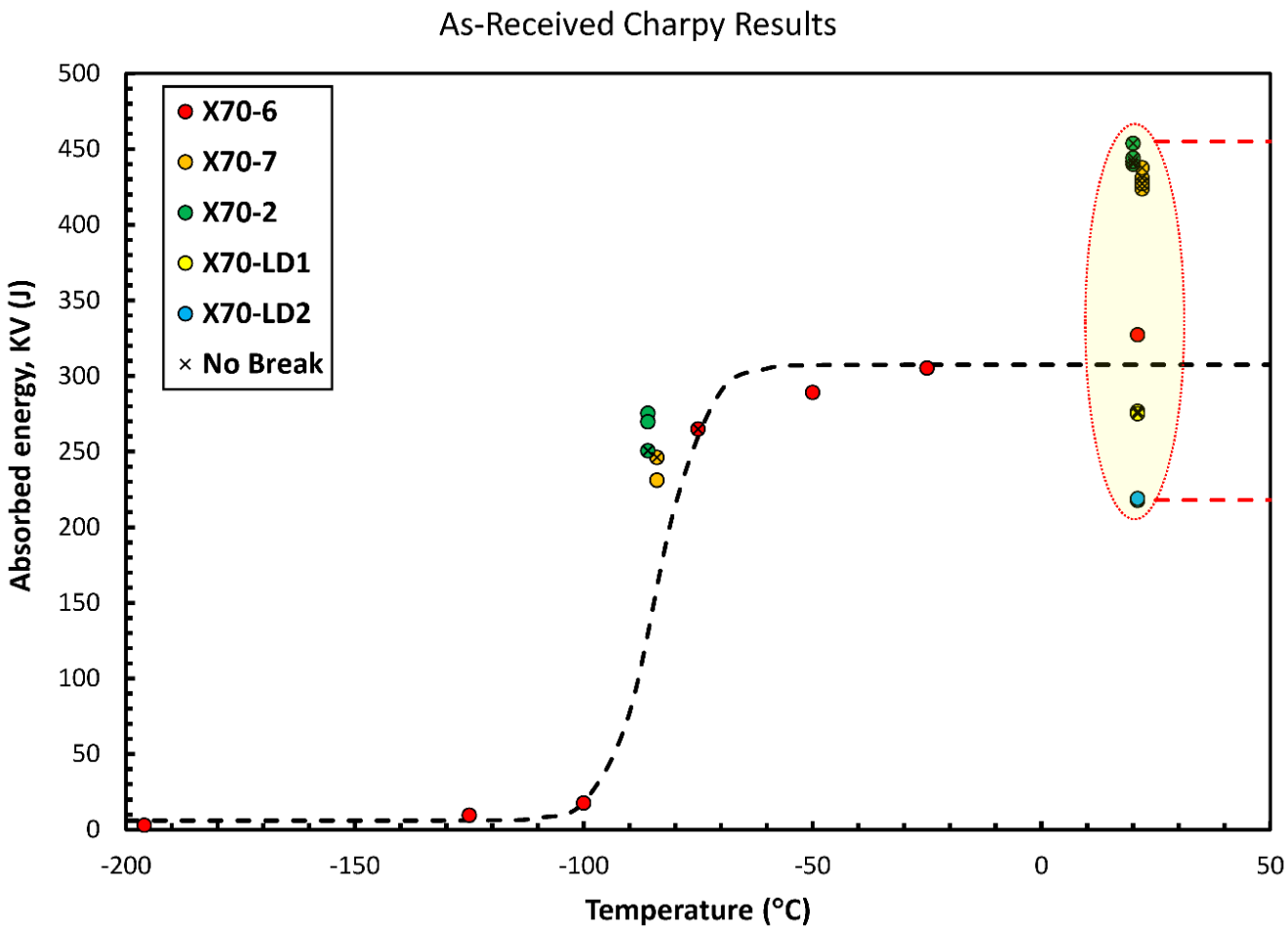


AS-RECEIVED MINI-TENSILE RESULTS

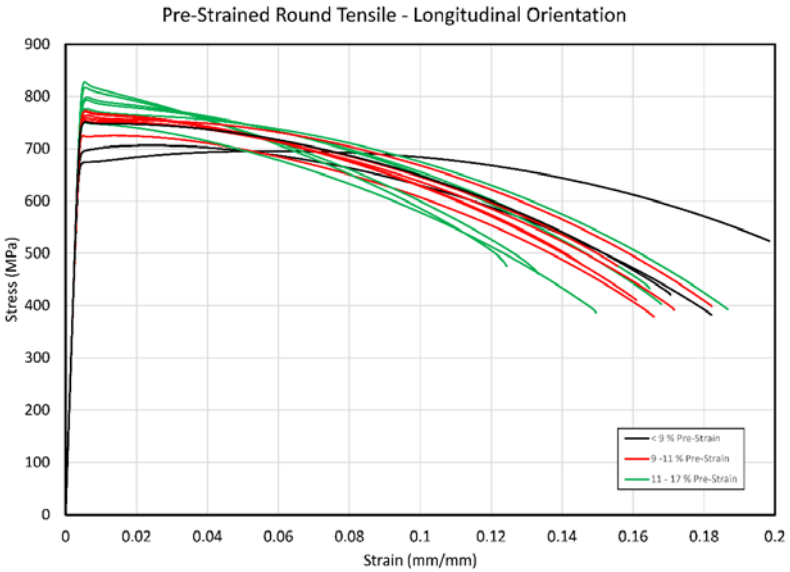


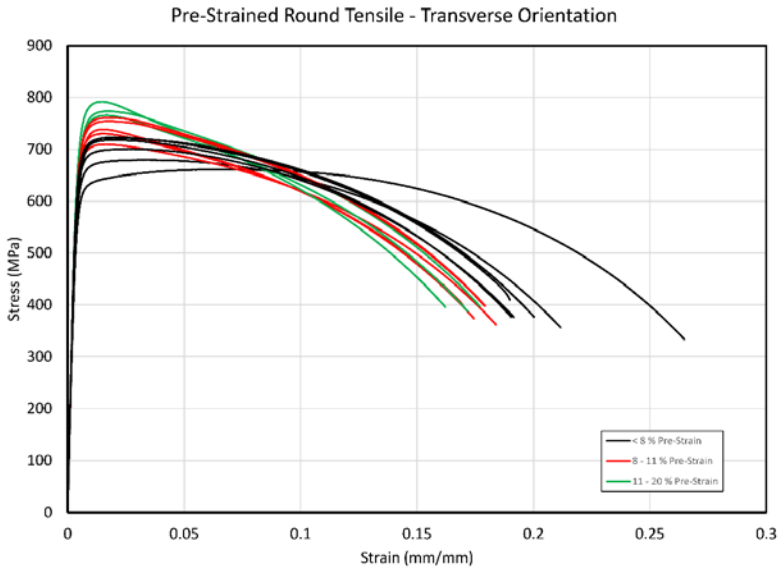


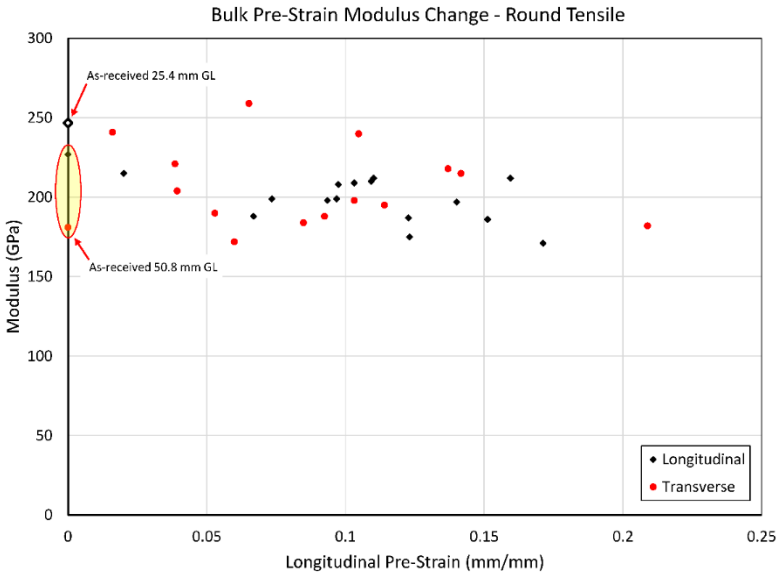
AS-RECEIVED CHARPY RESULTS

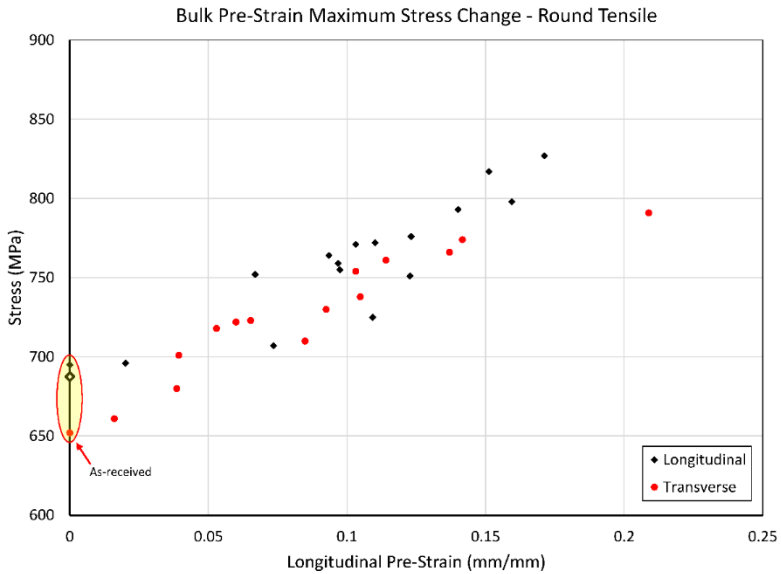


PRE-STRAINED ROUND TENSILE RESULTS

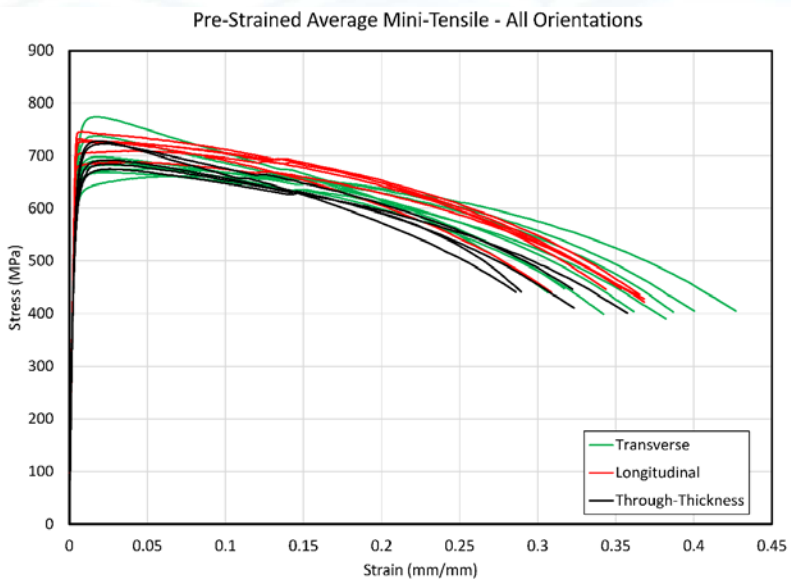


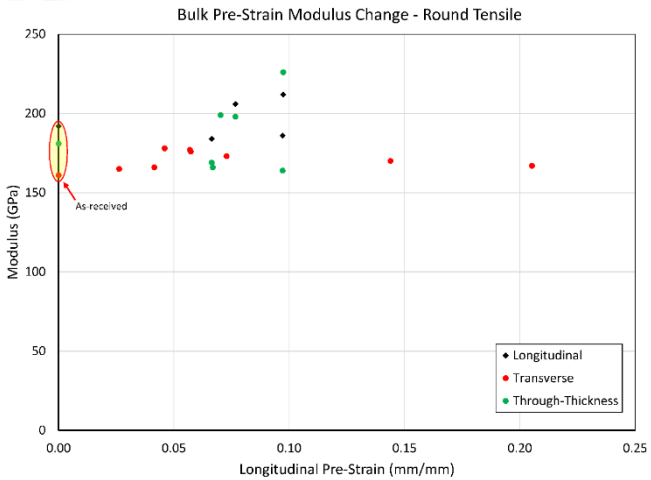


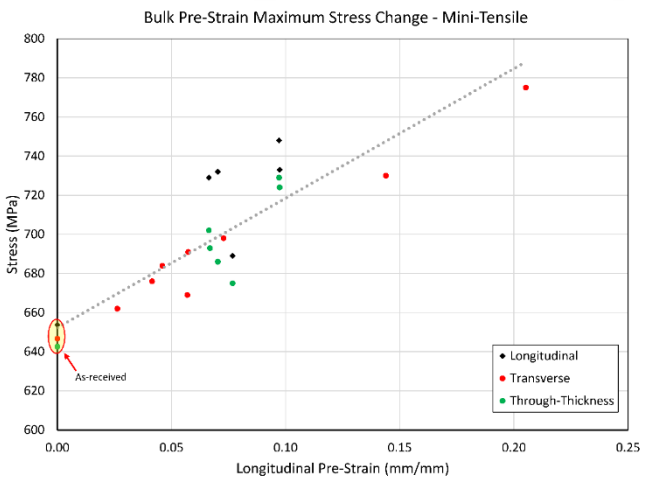




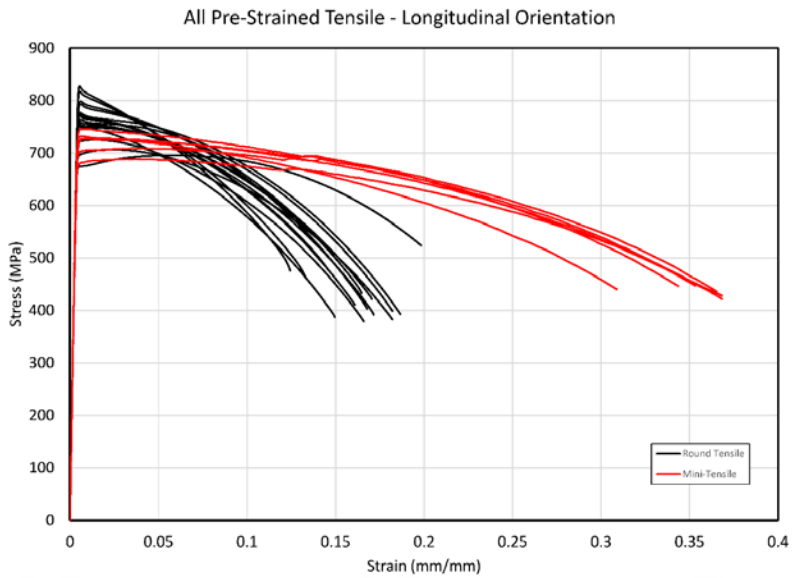
PRE-STRAINED MINI-TENSILE RESULTS

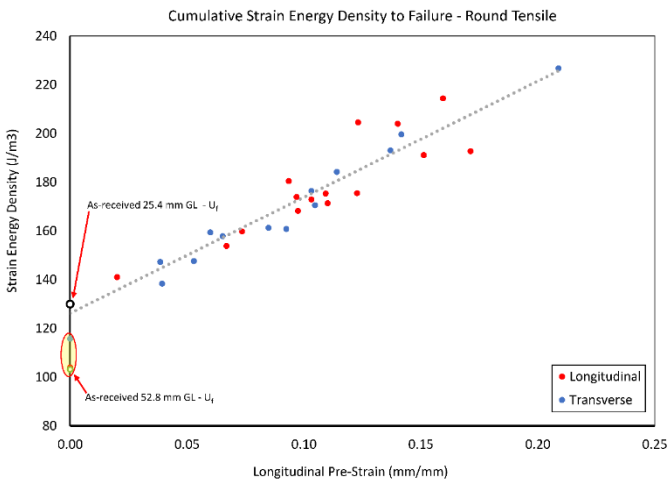


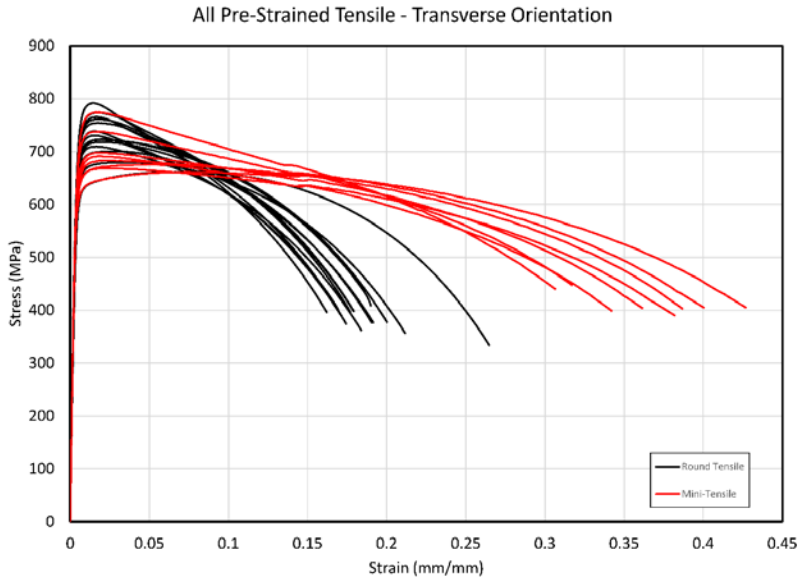


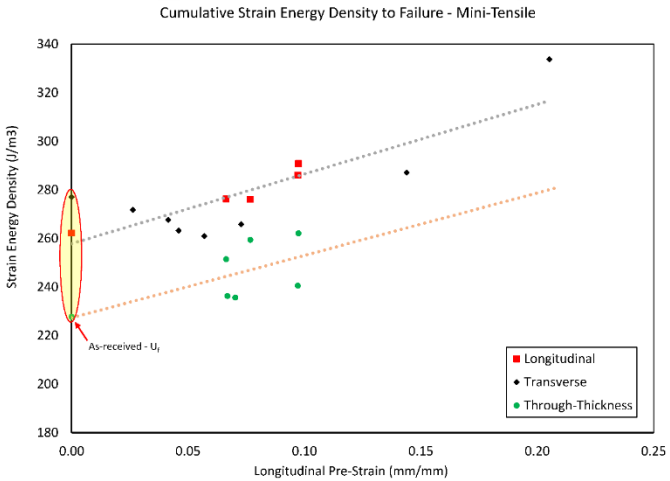


ROUND AND MINI COMPARISON

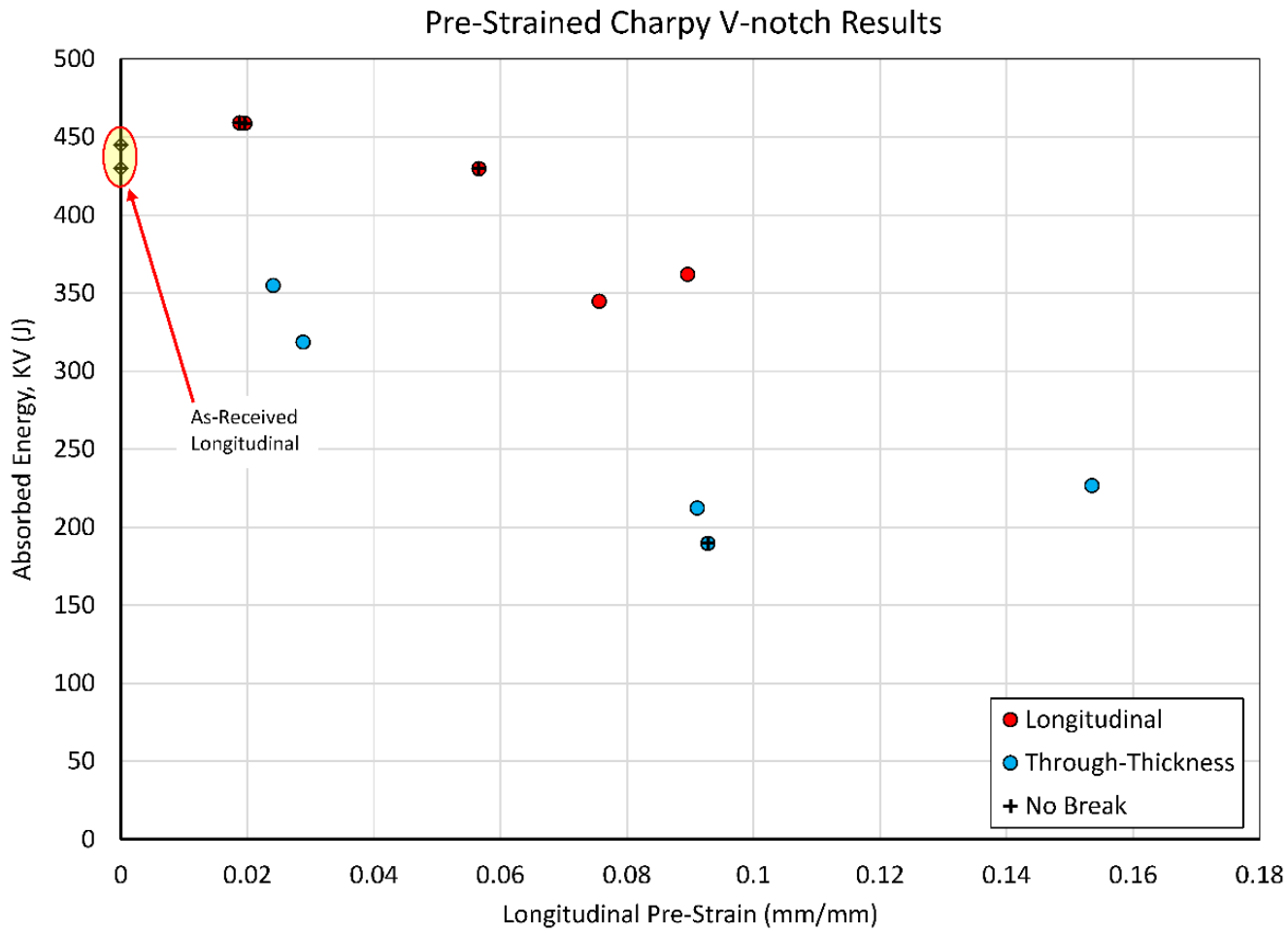




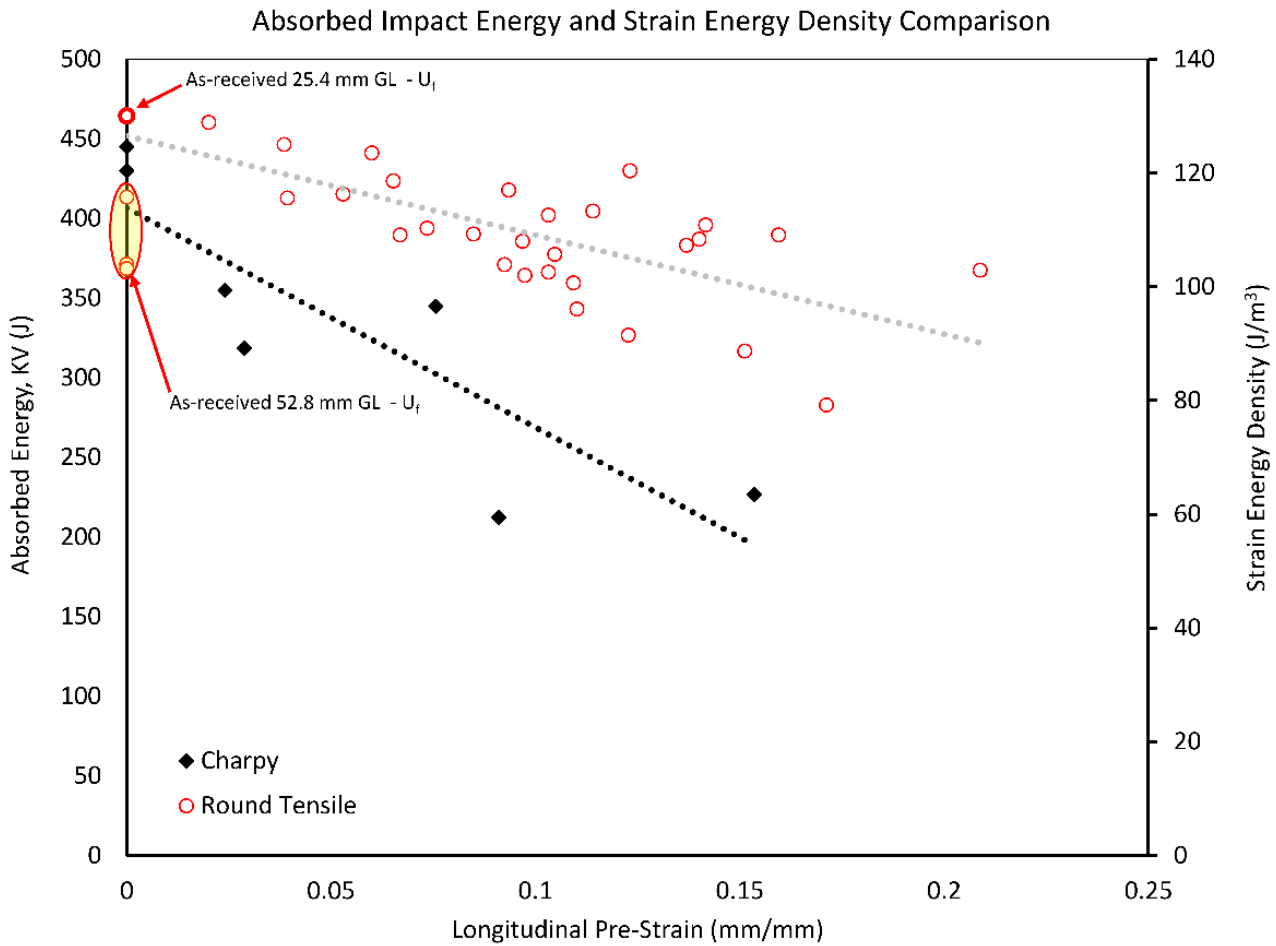


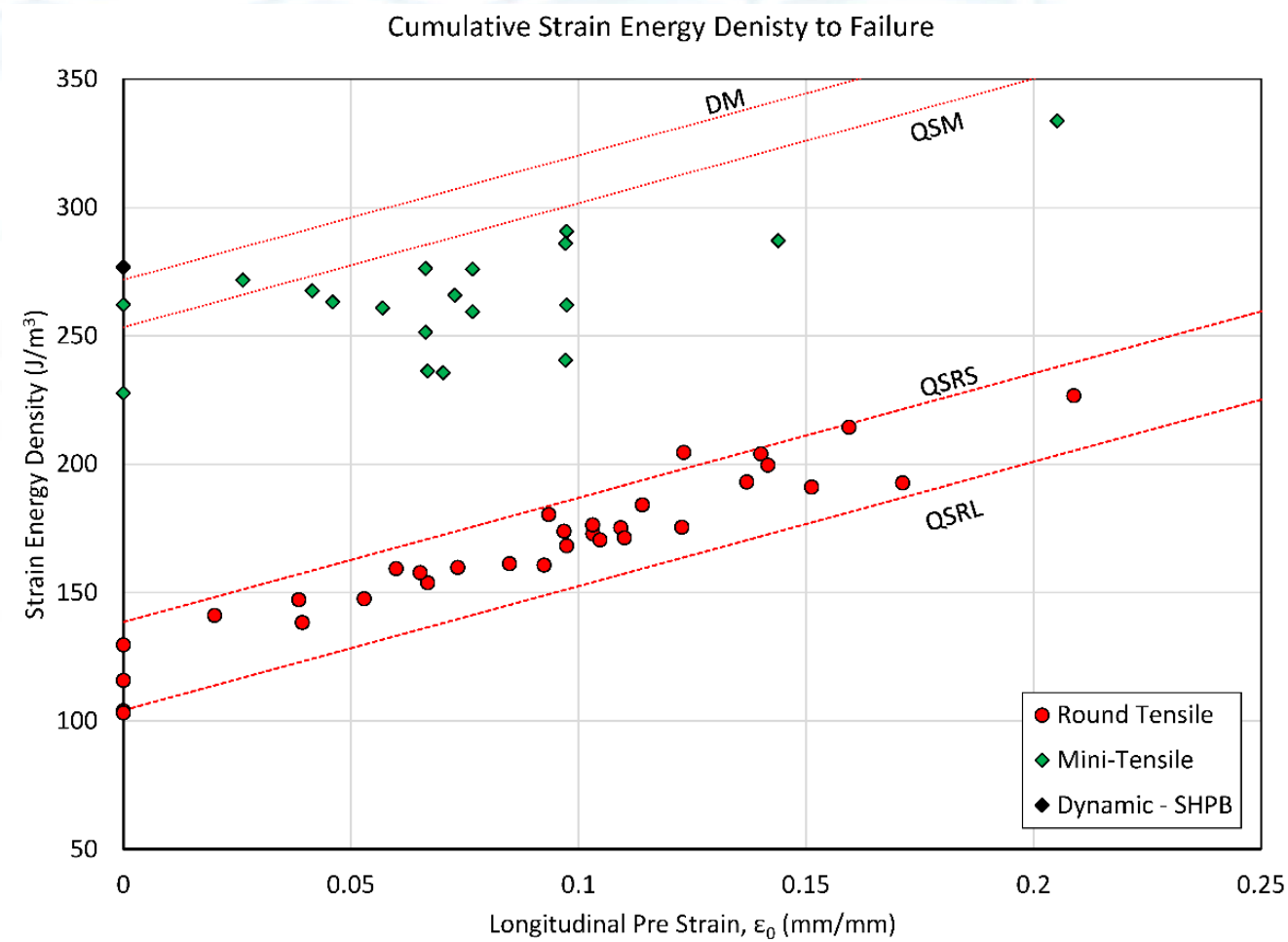


PRE-STRAINED CHARPY RESULTS



STRAIN ENERGY DENSITY COMPARISON





Barba's Law

$$\varepsilon_f = \beta \frac{\sqrt{A_0}}{l_0} + \varepsilon_0$$

$$U_{crit} = \beta \frac{{A_0}^{0.3}}{l_0} + U' + \frac{dU_f}{d\varepsilon_0}\varepsilon_0$$

CONCLUSIONS

Pre-strained wide-plate material to generate strain histories (2 % to 21 %) to calibrate the material failure model.

Completed small-scale tensile testing with multiple geometries

In-situ pre-straining of a round dog-bone does not replicate bulk pre-strained wide-plate material.

As-received round tensile specimens in the longitudinal direction had markedly higher strength than every other geometry and orientation. All other geometries and orientations were similar up to maximum stress. The higher strength is associated with a strong <101> crystallographic orientation that is softened with pre-straining.

Through-thickness mini-tensile properties are different than in-plane properties but as of now they don't appear to be significant.

Mini-tensile tests resulted in unsurprising differences in non-uniform elongation. No fundamental correlations between geometry and non-uniform, post UTS behavior are known from this phase.

Elastic modulus is not a useful damage indicator for this project, while cumulative strain energy density is well behaved and is an excellent energy parameter accounting for damage.

Charpy V-Notch results trend as expected but still remain suspect respective of a failure criteria.

A failure model has been proposed which, when calibrated, can predict the onset of ductile failure for a given material as a function of loading history and component volumetric considerations. Specifically, the model predicts the onset of ductile failure as a function of critical accumulation of energy density within the component and is insensitive to strain rate.

The calibrated model may be employed within a finite element package to predict the onset of failure given known loading conditions and boundary conditions.

FUTURE WORK

1. Material/Failure Model Calibration
2. Model implementation into structural FEA model
3. Medium-Scale Test Development

Questions/Work from this Phase

1. Investigate bulk pre-strain magnitude
    - What is the real strain-state at any location in the wide-plate?
    - What are the strain-state changes due to sectioning blanks and subsequently mini-specimens?
2. Optimize tensile geometries to have the same slimness ratio – small test matrix
3. Test through-thickness mini-tensile specimens with more pre-strain
4. Test compression cylinders
5. Develop mini-round tensile specimen
6. Is there a correlation between strain-history and strain-rate?
7. Does the pre-strained material show a strain-rate sensitivity?
8. Did strain aging affect the results from Phase II?

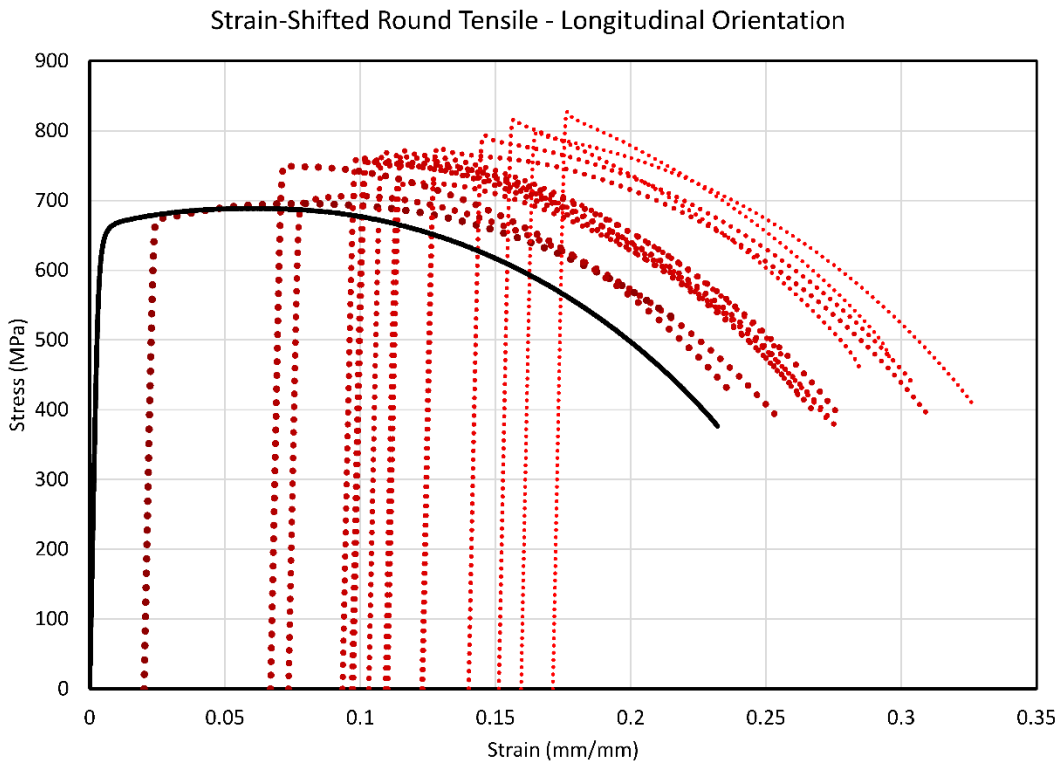


Figure 43. Full stress vs. strain curves from bulk pre-strained X70 round tensile specimens tested in the longitudinal direction – the strain shift corresponds to the bulk pre-strain for the specimen blank. The tensile data for an as-received specimen (X70-18-2) is also shown.

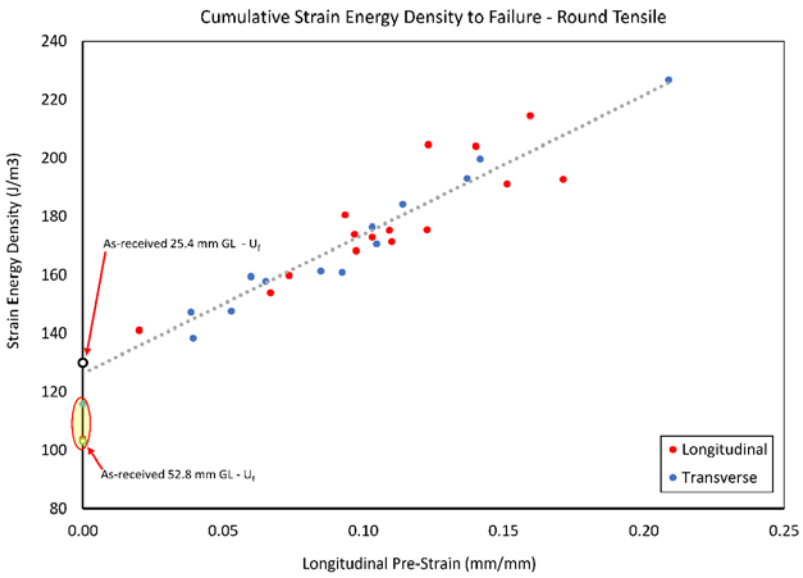


Figure 46. Cumulative strain energy density to failure for pre-strained round tensile specimens tested in longitudinal and transverse orientations.

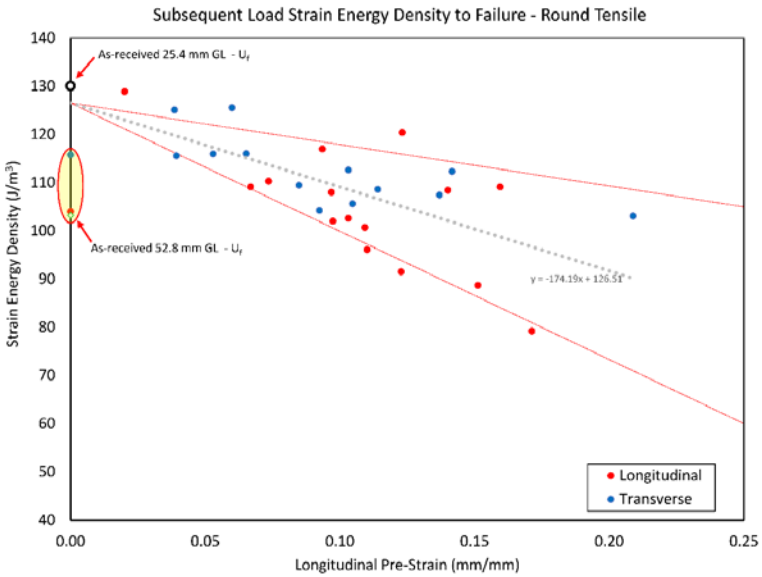


Figure 47. Strain energy density to failure for bulk pre-strained X70 round tensile specimens tested in longitudinal and transverse orientations. Data is provided for final load incursion only and does not include strain energy density accumulated during pre-straining.

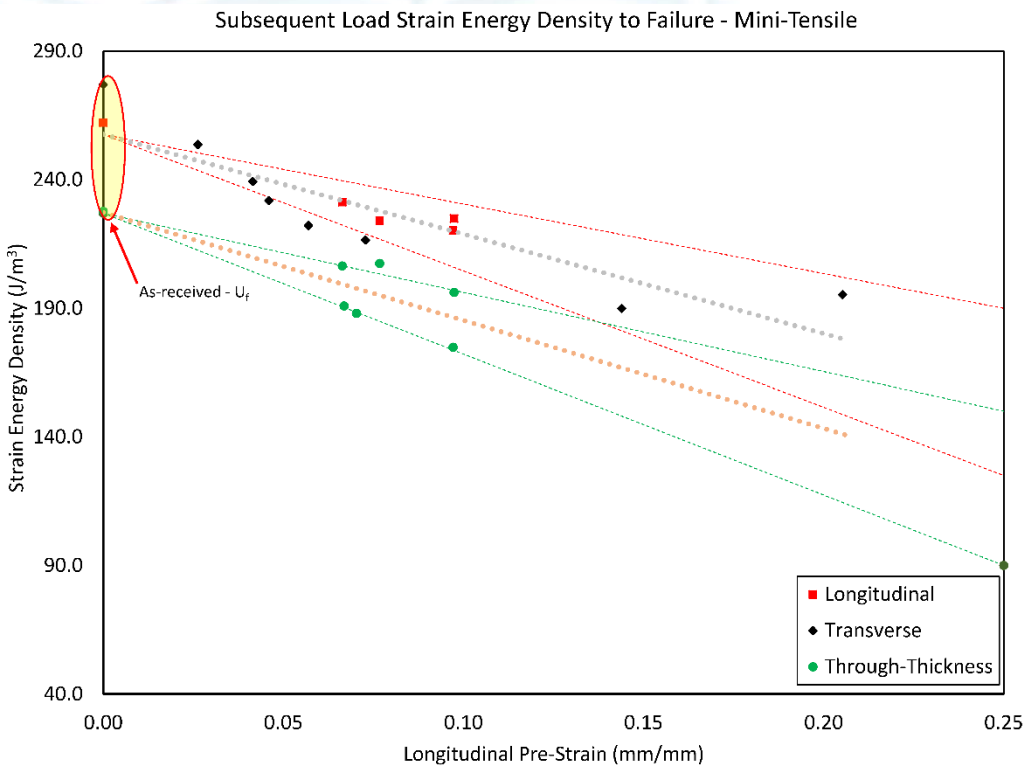


Figure 54. Strain energy density to failure for bulk pre-strained X70 mini-tensile samples tested in longitudinal, transverse and through-thickness orientations. Data is provided for final load incursion only and does not include strain energy density accumulated during pre-straining.