Competitive Academic Agreement Program

Advanced Nondestructive Characterization of Pipeline Materials

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08/19/2015

Outline

- Main objective
- Project team & sponsors
- Conceptual relationships
- Background
  - NDE technologies
- New approach
- **Task 1** reported materials, properties & samples
- **Task 2** microstructure and mechanical properties
- **Task 3** NDE measurements
- **Task 4** Integrated NDE approach ("basis for a properties pig")
- Remaining activity
- Project reporting

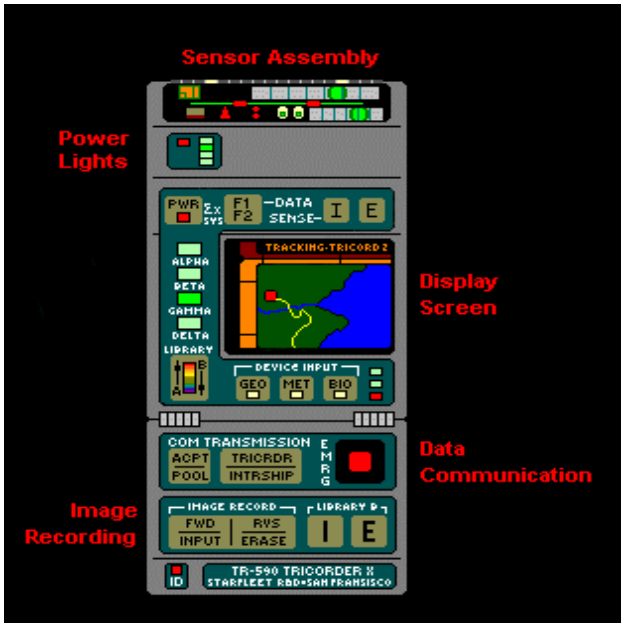
Main Objective

Provide the proof-of-concept for nondestructive measurement capabilities which give data that are sufficient for ensuring safe operation and determining the pressure rating of a pipeline.

What everyone wants a "Tricorder" to measure and map :

- Yield strength
- Tensile strength
- Transition temperature
- Fracture toughness

AKA – **"a properties pig."**



"Tricorder"

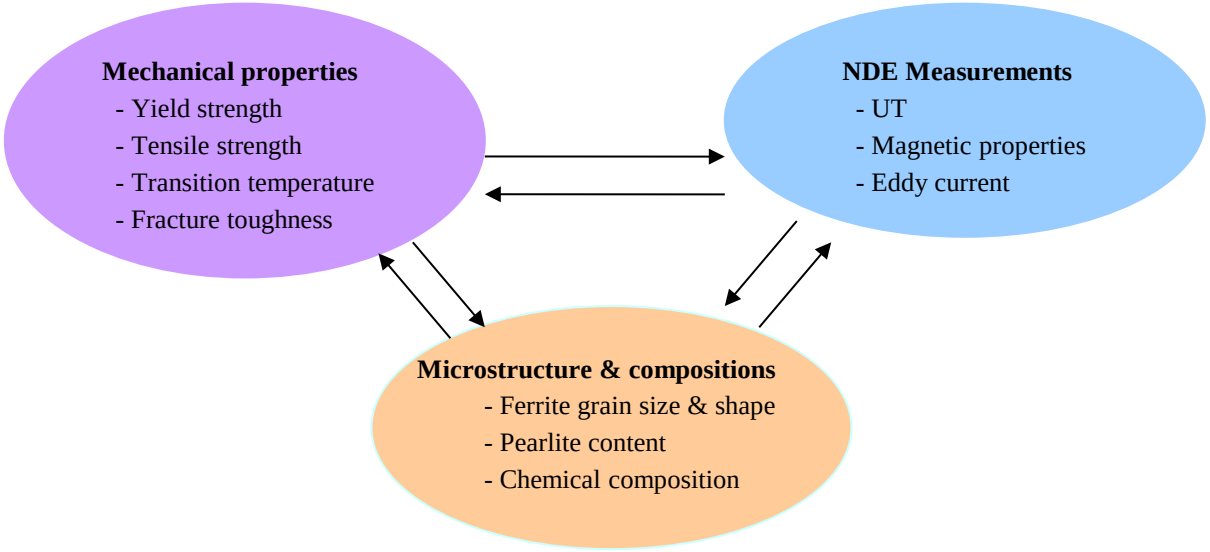
http://psycholee.deviantart.com/art/Star-Trek-Tricorder-162679578

Project Team & Other Sponsors

- Leonard J. Bond (PI)
- Brady Engle (Grad. – Ph.D.),
- Lucinda Smart (Grad. – M.S.)
- Aaron Reyes (Undergraduate)

- Applus RTD
- Pacific Gas and Electric
- Kiefner and Associates, Inc

Conceptual relationship: properties, NDE microstructure and composition



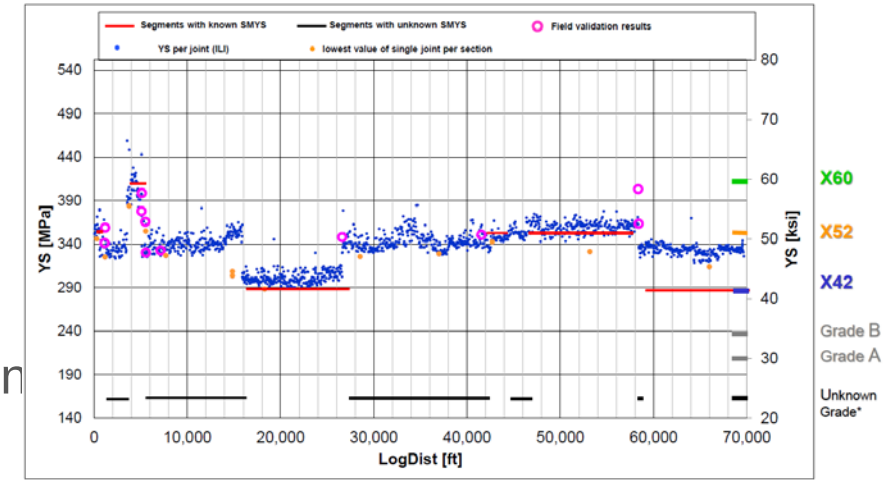
Some of the proposed techniques used on this method are:

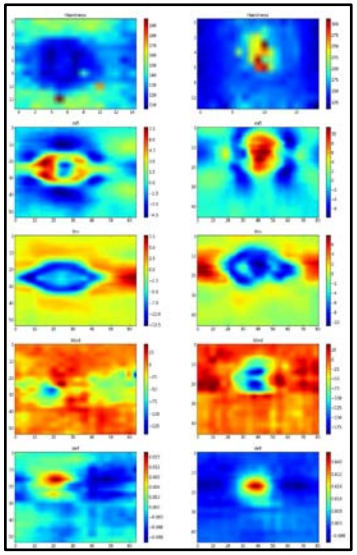
- Ultrasonic backscatter testing to determine grain size
- Determining ultrasonic velocities
- Determining the pearlite content using electromagnetic methods
- Determining the hardness of the steel

Other electromagnetic measurement techniques (Eddy Current, Barkhausen, etc.)

Background: Main NDE Technologies

- Electromagnetic Methods
  - Magnetic relationships have been previously assessed using linear relationships with adequate results*
  - Low- and high-field MFL**
  - Eddy Current with pre-magnetization
- Ultrasonics
  - Measure grain size, attenuation, ferrite percentage, inclusion content, microstructure determination
- Include chemical composition, hardness testing (small indentations), microstructure
- It is likely that a combo of NDE technologies will be implemented to solve this problem





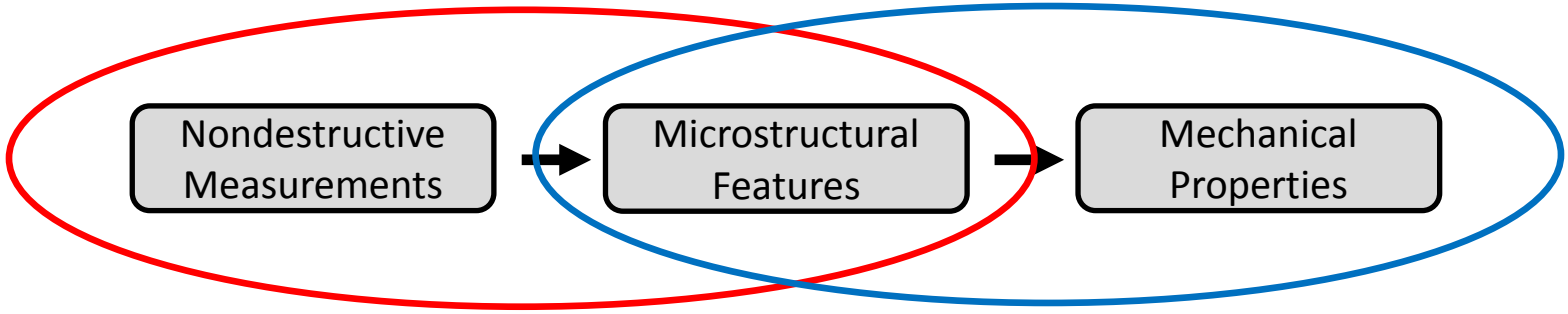
*J. Nestleroth, A. Crouch. 1997, ** A. Belanger, R. Narayanan. 2006.

Use of In-Ditch Assessments

- Limited due to cost, safety, personnel limitations
- A suite of methods may be required to determine all pipe properties
  - Hardness
    - Relationship determined to produce a lower bound YS from Rockwell B Hardness test*
    - Successive loaded hardness determines fit to a power-law stress-strain curve, and potential fracture toughness**
  - Chemical Composition***
    - X-Ray Fluorescence (XRF)
    - Optical Emission Spectroscopy (OES)
  - Metallography****
    - Difficult to perform in-ditch, but under ideal conditions, provides microstructural details

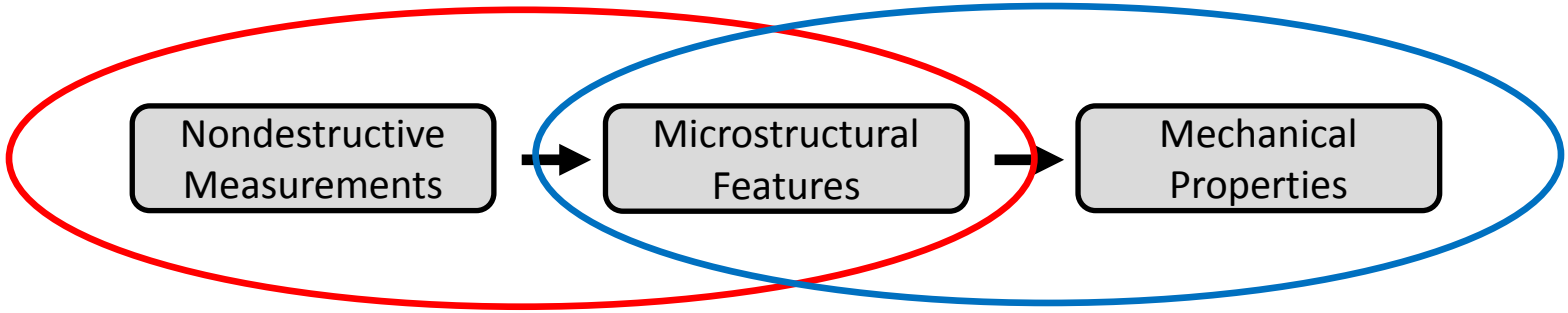
*Burgoon, David A.. 1999, ** Haggag, Fahmy. 1993, *** Pyromation. 2014., **** AZoM.com. 2015.

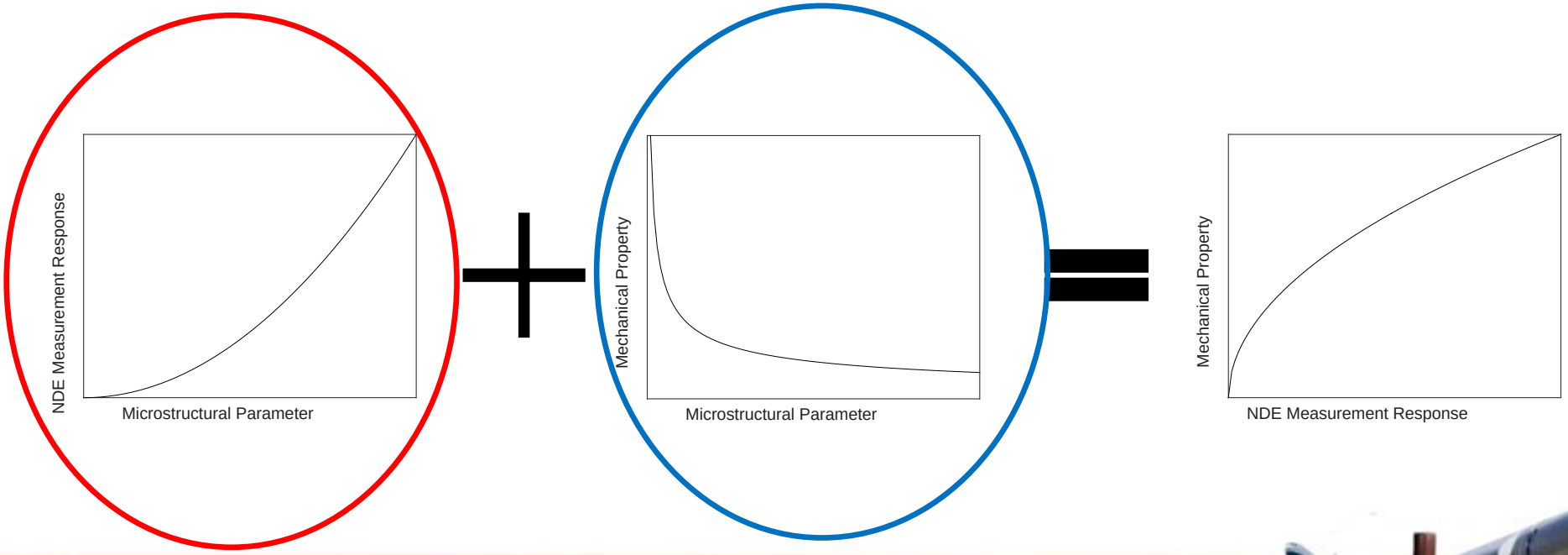
New Approach – Big Picture



- Use NDE to characterize microstructure
- Use relationships between microstructure and mechanical properties
- Combine to get estimate of mechanical property from NDE

New Approach - Concept





Project - Overview

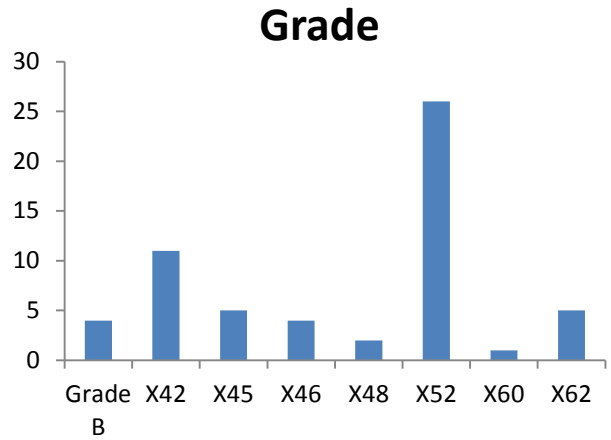
Tasks identified at project start:

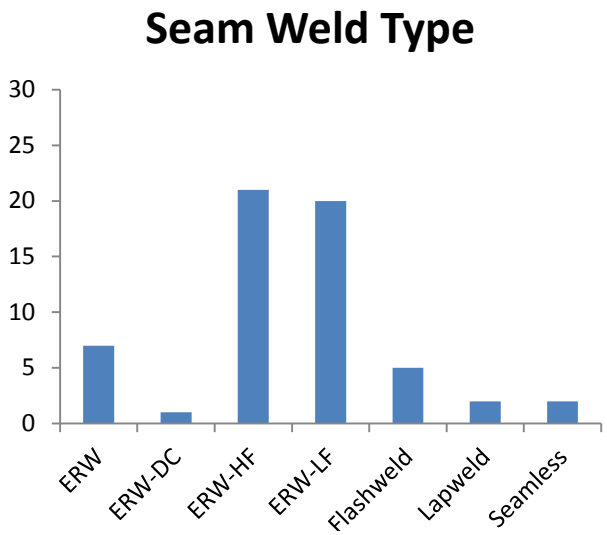
- **Task 1:** Select a class of pipeline steels (e.g. carbon steel such as A53 or A106, or alloy steels such as 4130) for the initial proof-of-concept study (this project).
- **Task 2**: Conduct a literature search for materials data, the state of the art for materials characterization and also any empirical relationships, which can be used to identify the microstructural parameters and alloy elements that are the most important in determining the mechanical properties of the selected class of steels.
- **Task 3**: Select NDE measurement techniques and perform proof-of-concept measurements to evaluate their use to characterize the microstructural and other parameters of interest.
- **Task 4:** Evaluate the NDE approach against direct measurements (tensile tests, impact tests) of the mechanical properties.

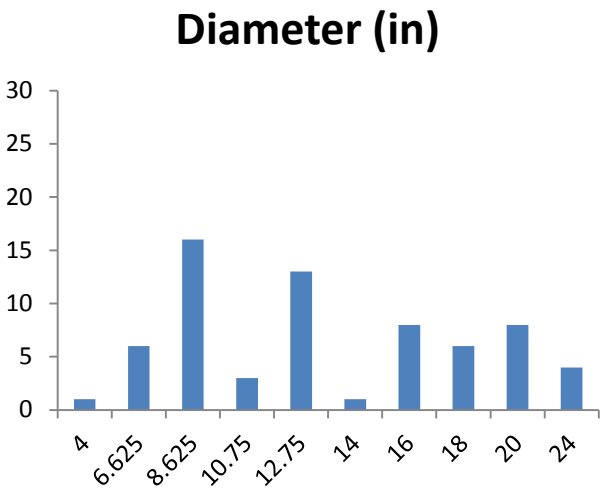
Task 1 – Initial Samples

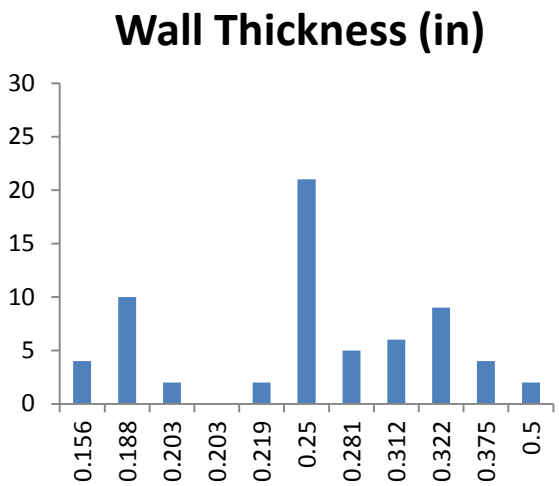
- Two sources of data:
  - on-hand samples
  - sample database
    - no access to actual samples
- Our samples were representative of many pipeline steels, various suppliers, rather than a specific class, or well controlled set.
  - **This caused a large multi-variable problem**

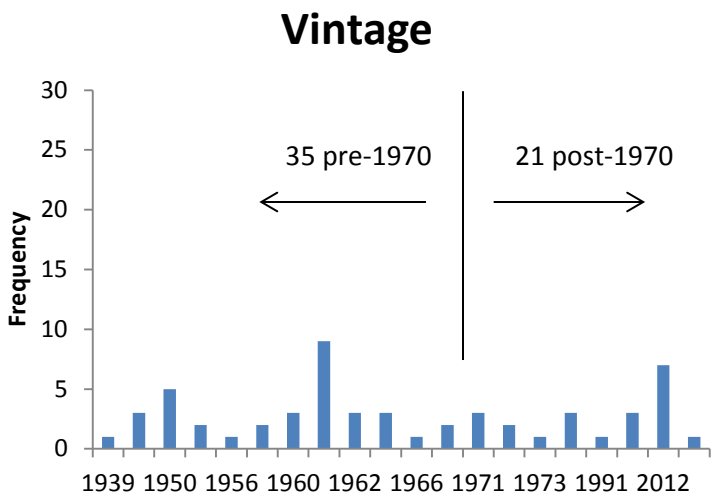
Histograms of Available Data Set





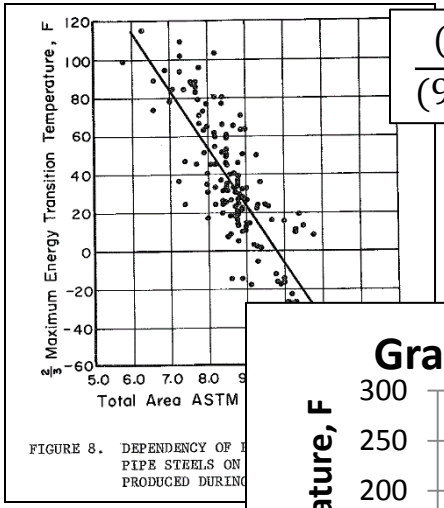




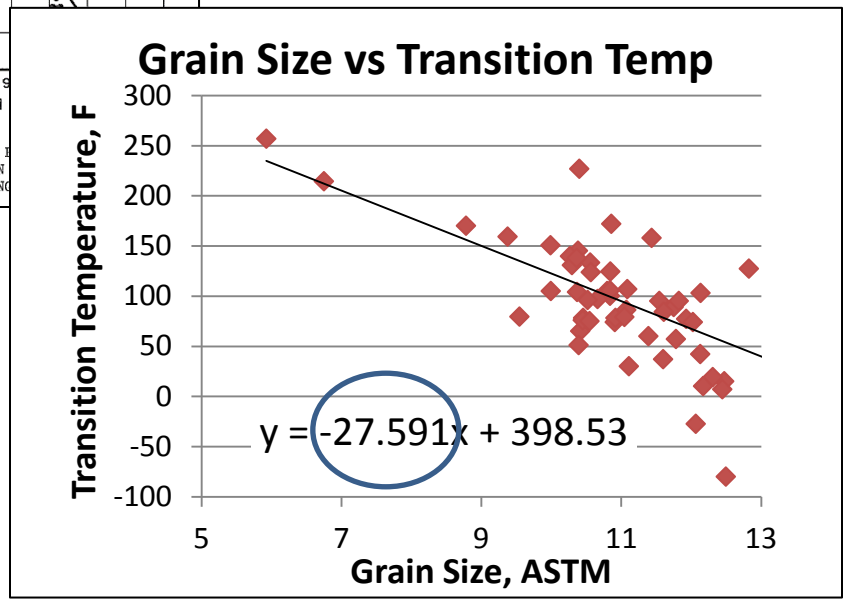


Previous Research Comparison

- Good relationship for grain size vs transition temp

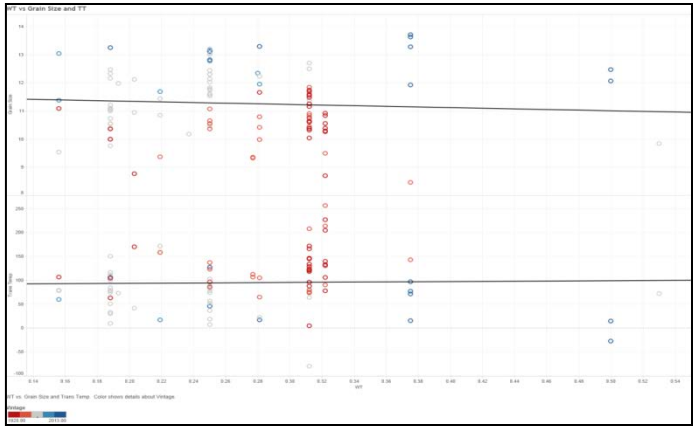


$$\frac{(0-50)}{(9.8-8.0)} = -27.8$$



F.W. Boulgar. 1965.

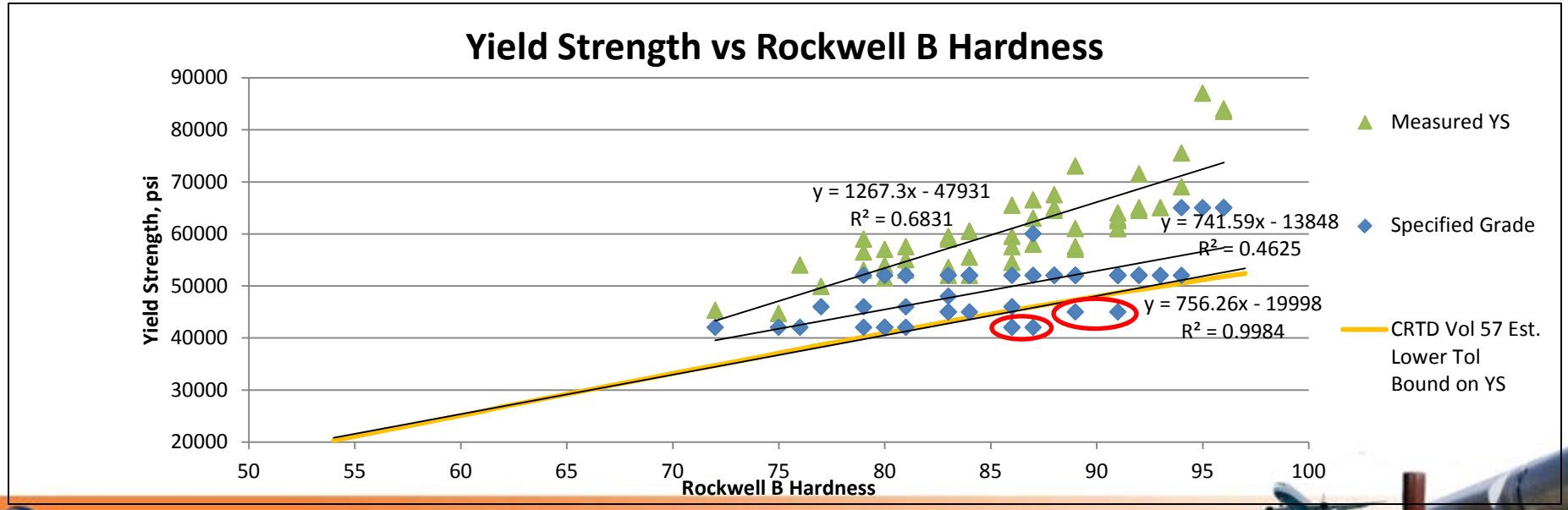
- No noticeable trend in grain size vs WT, may not have enough variability in WTs
- Same effect for transition temp vs WT



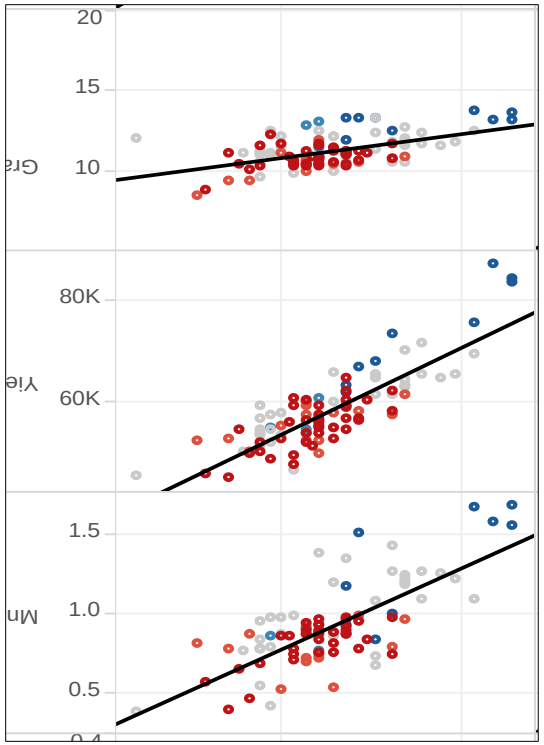
Sample Data compared to ASME CRTD Vol 57 Data

- No samples have Measured YS < Specified Grade
  - Measured YS is non-conservative compared to Specified YS
- 4 samples have Specified Grade non-conservative to Vol 57 relationship
  - Grade X42 (1949) and X45 (1950)
  - Oldest pipe in our sample set
- Vol 57 is conservative compared to all measured YS

(Burgoon, David A. 1999).



Hardness



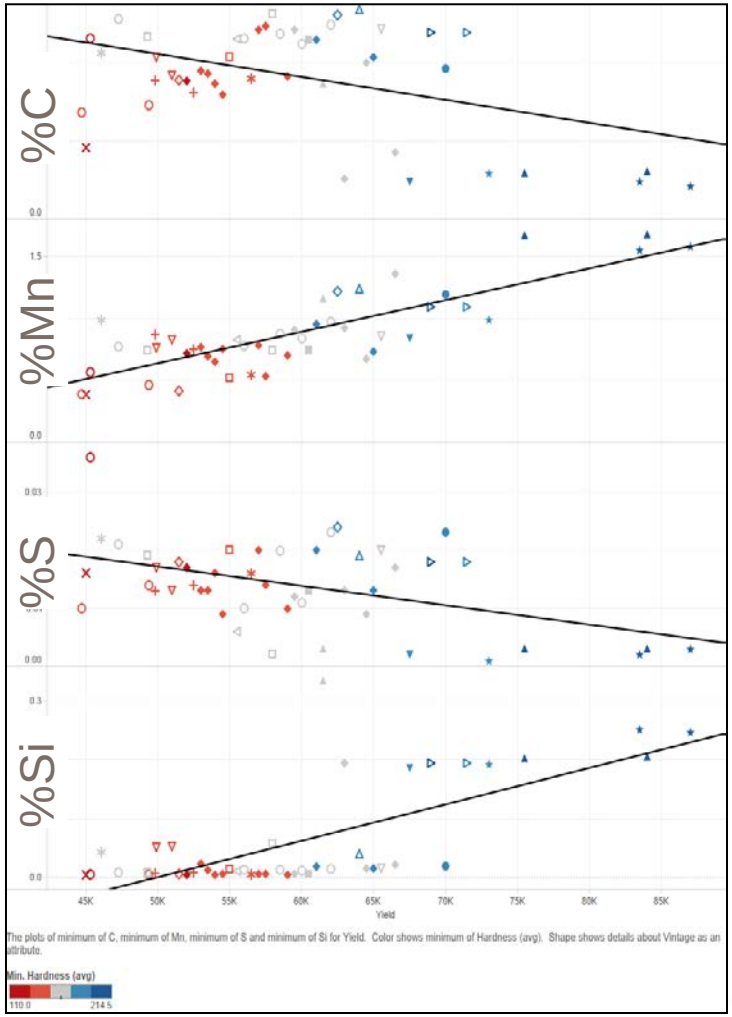
R^2=0.735

R^2=0.851

R^2=0.532

- Relationships are not completely convincing
- Multivariate analysis is likely required

Yield



R^2=0.688

R^2=0.388

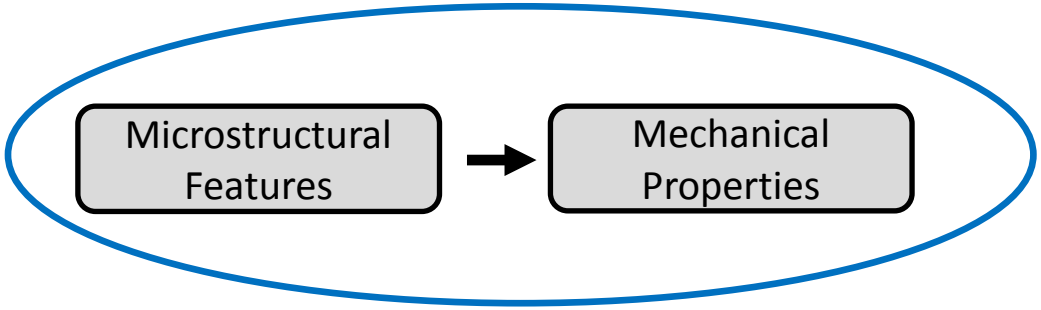
R^2=0.705

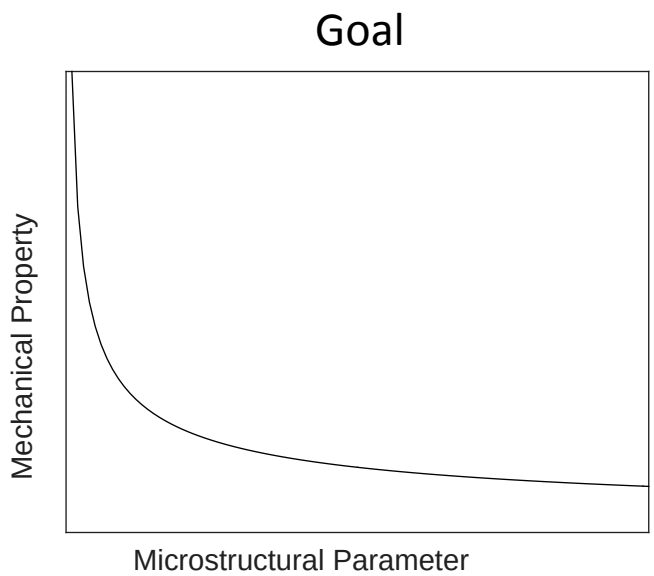
R^2=0.416

Task 2 – Relationships between Microstructure and Mechanical Properties

- **Relationships found in the literature were often poorly reflected or not seen** in the sample database we had access to (~75 samples)
  - We had a sample set of ~10 samples on-hand
- Methods were demonstrated to develop empirical relationships between microstructure/chemistry and mechanical properties

Task 2: Material Properties





Mechanical Properties
Yield Strength
Tensile Strength
Toughness
Ductile-to-Brittle Transition Temperature

Microstructural Features
Grain Size
Secondary Phases and Associated Properties
Inclusions
Heat Treatment History
Chemistry

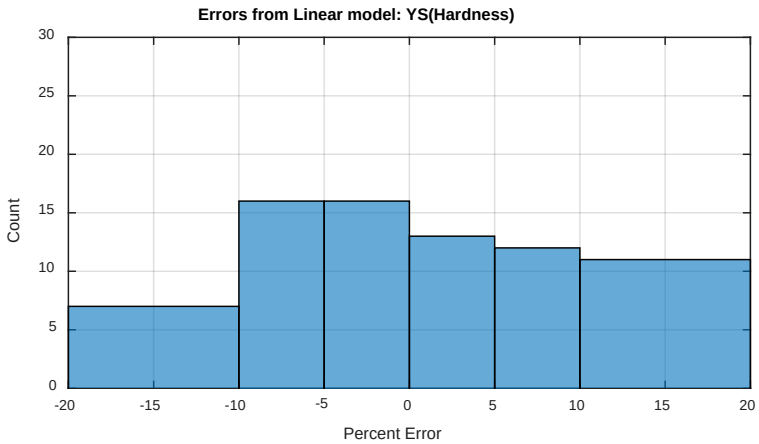
Example: Yield Strength Prediction with linear model (API)

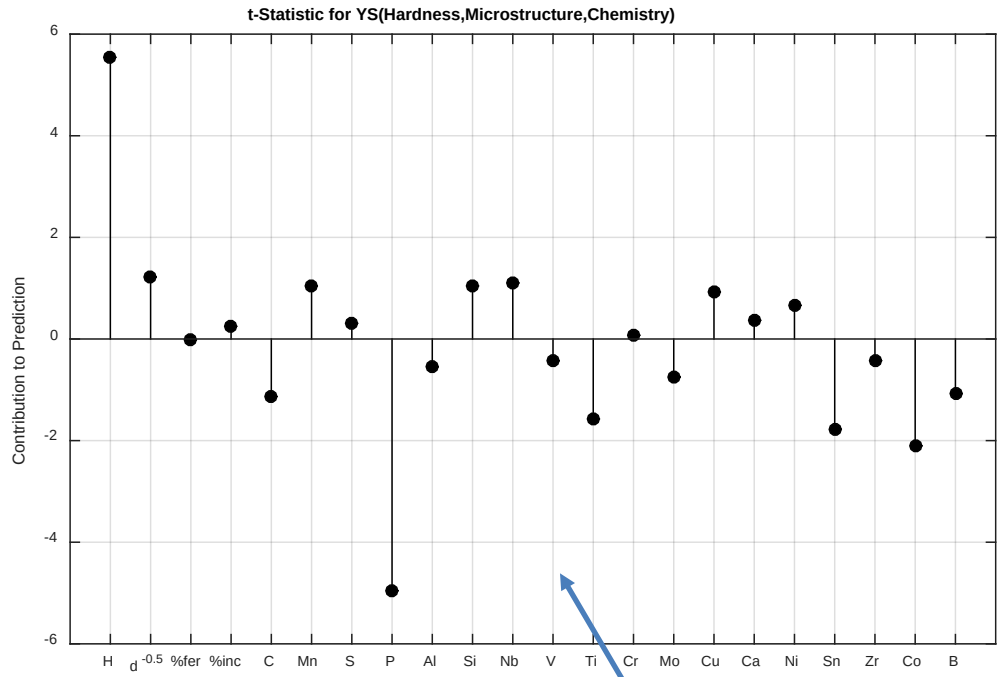
- Hardness commonly used, linearly related
- Including more variables (microstructure, chemistry) increases model accuracy
- Four linear models were made using the sample database:
  - Just hardness
  - Hardness and microstructure
  - Hardness, microstructure, and "carbon equivalent"
  - Hardness, microstructure, and individual chemical elements

$$CE(C \le 0.12\%) = C + \frac{Si}{30} + \frac{(Mn + Cu + Cr)}{20} + \frac{Ni}{60} + \frac{Mo}{15} + \frac{V}{10} + 5B$$

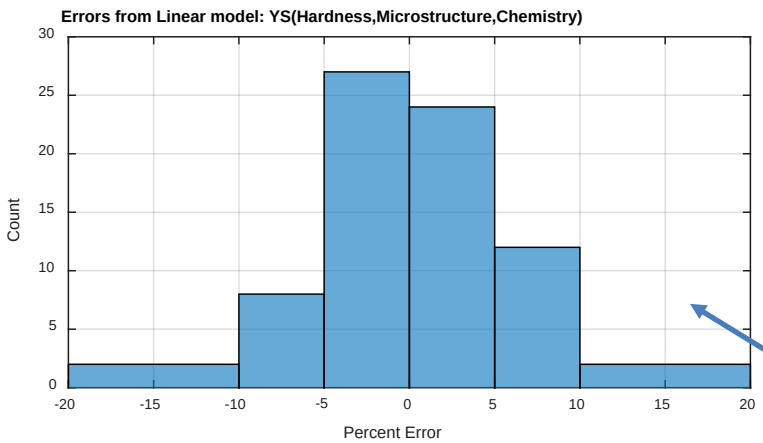
$$CE(C > 0.12\%) = C + \frac{Mn}{6} + \frac{(Cr + Mo + V)}{5} + \frac{Ni + Cu}{15}$$

Example: Yield Strength Prediction with linear model





Contributions to prediction are shown here.



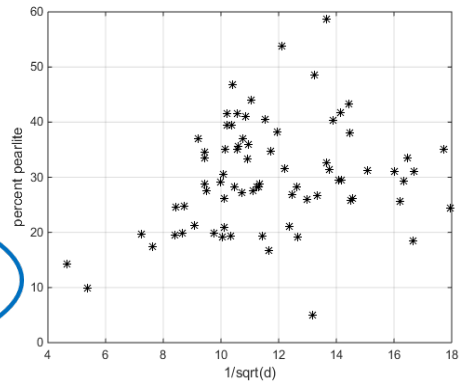
More variables gives better prediction of yield

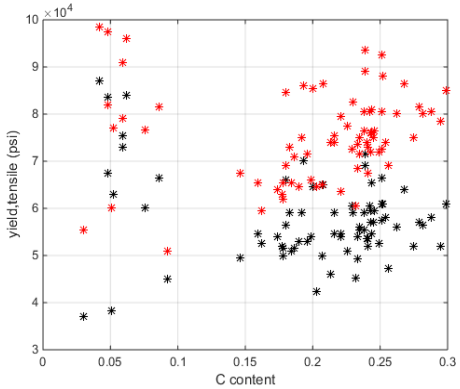
A model that has each element as an independent variable and includes hardness and microstructure predicts yield strength much better than hardness alone.

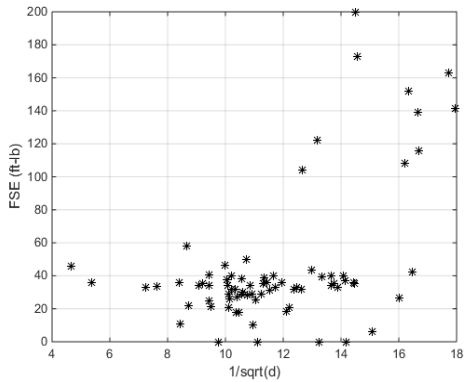
Note that DECREASE in carbon content increases yield, going against what is generally accepted

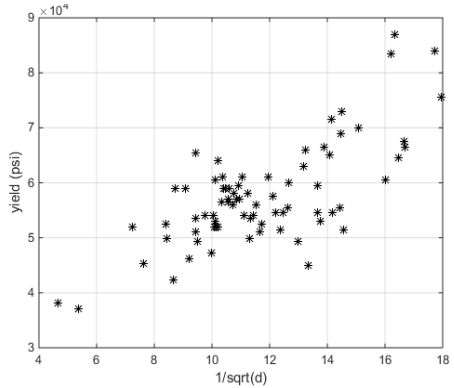
Relationships should be seen in each plot according to the literature

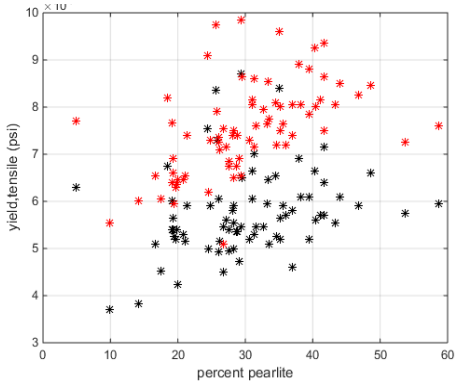
Microstructural Features → Mechanical Properties



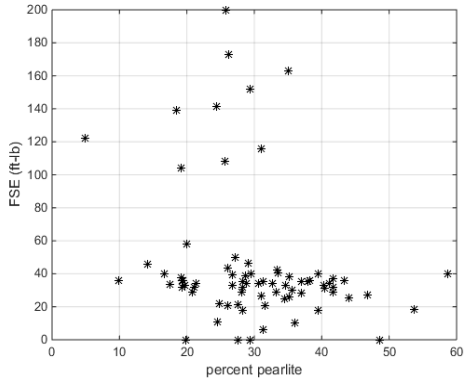


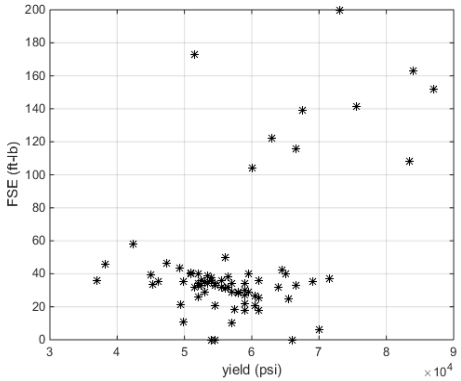






Black: yield, red: tensile





Samuels, Leonard Ernest. *Light Microscopy of Carbon Steels*. ASM International, 1999.

Material - mechanical property relationships

The relationships in the literature are generally not reflected in **our data. Literature data generally based on well controlled samples (e.g. from a single process)**

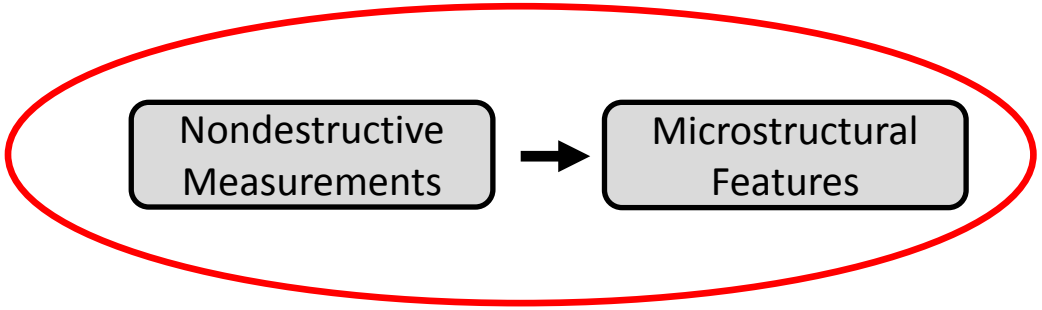
The general problem is that fracture toughness in conventional steels decreases roughly linearly as yield strength is raised, although the relationship between the two is significantly different for different types of steel. The principal factor affecting tensile and yield strengths is carbon content, which influences tensile strength mainly through increasing the amount of pearlite present. Increasing the volume of pearlite also has the direct effect of causing a significant deterioration in fracture toughness. The direct effect of pearlite on yield strength, however, is negligible, but there is an indirect effect in that increasing the volume of pearlite tends to reduce ferritic grain size by blocking growth of the ferrite grains. Reducing ferritic grain size by this or any other means increases yield strength, which varies approximately linearly with the reciprocal of the square root of the grain diameter of the ferrite. Reducing the ferritic grain size also beneficially affects fracture toughness; it is the one factor that improves yield strength and toughness simultaneously. Alloying elements other than carbon have only small direct effects on strength due to solid-solution hardening; they may produce indirect effects by influencing the volume of pearlite present, by affecting the ferrite grain size or, as we shall see later, by introducing precipitation effects.

Samuels, Leonard Ernest. *Light Microscopy of Carbon Steels*. ASM International, 1999.

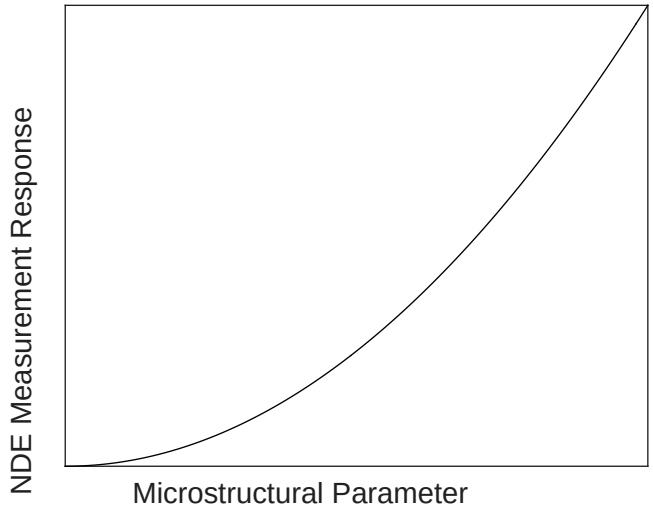
Task 3 – NDE Measurements

- Methodologies for ultrasonic velocity, attenuation and backscatter measurements were demonstrated on ISU samples
  - **Difficult to separate effects of contributions to measurement response from property variables in samples (no calibration set available – CSM now engaged to provide material)**
- Magnetic Barkhausen measurements were demonstrated with commercial system
  - Custom system is near completion

NDE Measurements



Goal



NDE Measurements
Ultrasonic Velocity
Ultrasonic Attenuation
Ultrasonic Grain Noise
Magnetic Barkhausen Noise

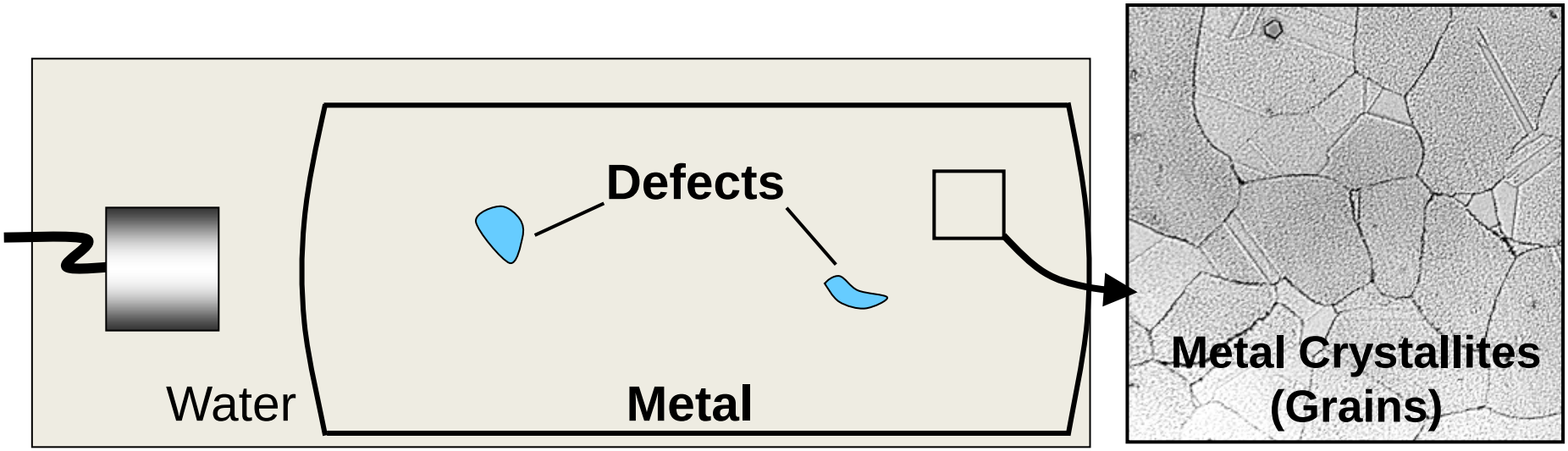
Microstructural Features
Grain Size
Secondary Phases and Associated Properties
Inclusions
Heat Treatment History

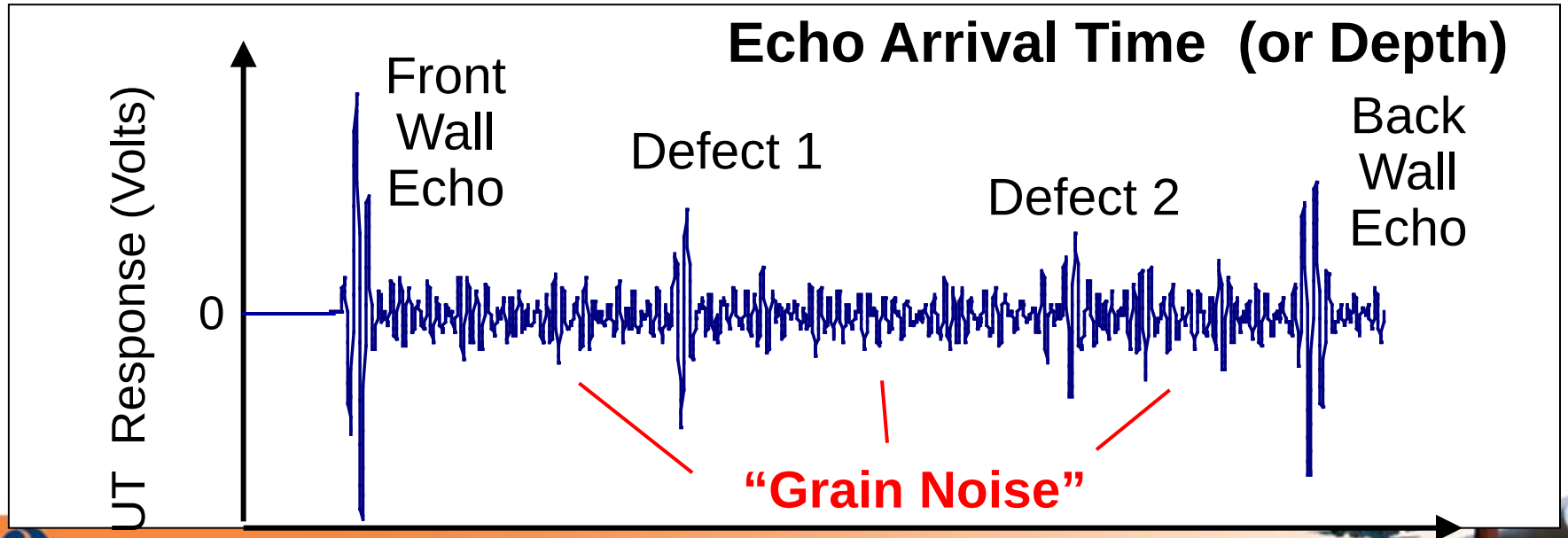
Ultrasonic Measurements: Background

- Previous work provides the basis for using ultrasound as a characterization tool
- Characterization work in nuclear and aerospace industries
- Methods performed on different materials adapted for pipeline steels
  - Nickel and Titanium alloys
  - Cast Iron

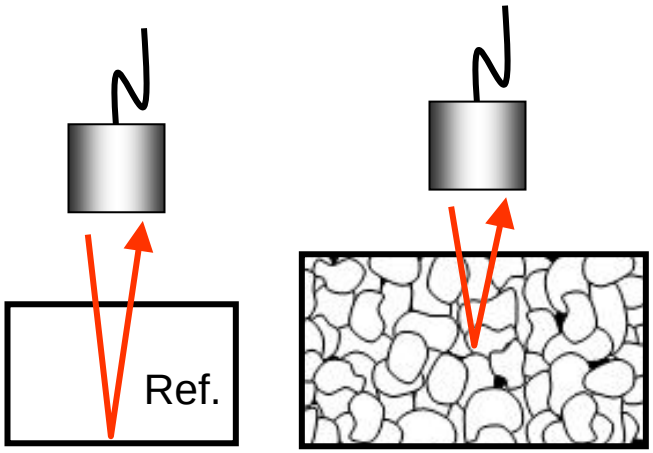
De Moura, E. P., et al. "Characterization of cast iron microstructure through fluctuation and fractal analyses of ultrasonic backscattered signals combined with classification techniques." Journal of Nondestructive Evaluation 31.1 (2012): 90-98.

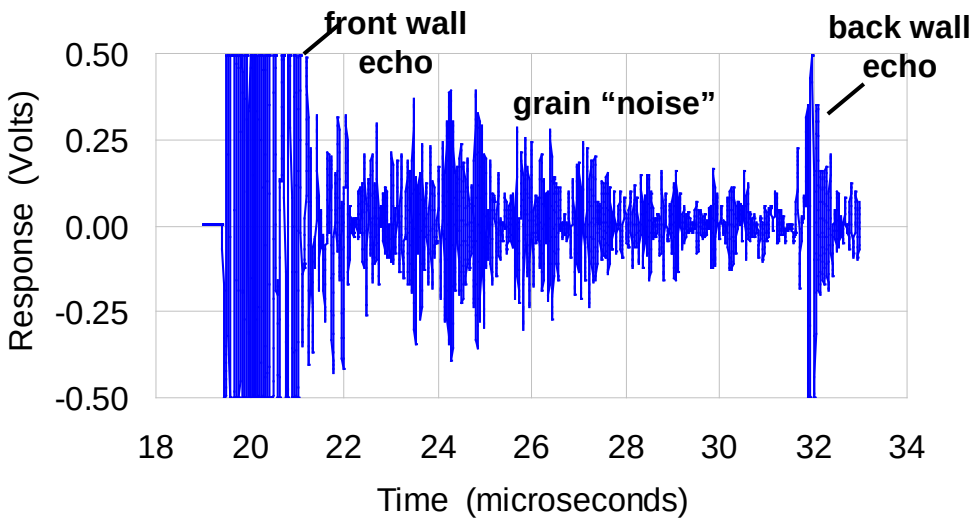
Ultrasonic Pulse-Echo Inspection in the Real World



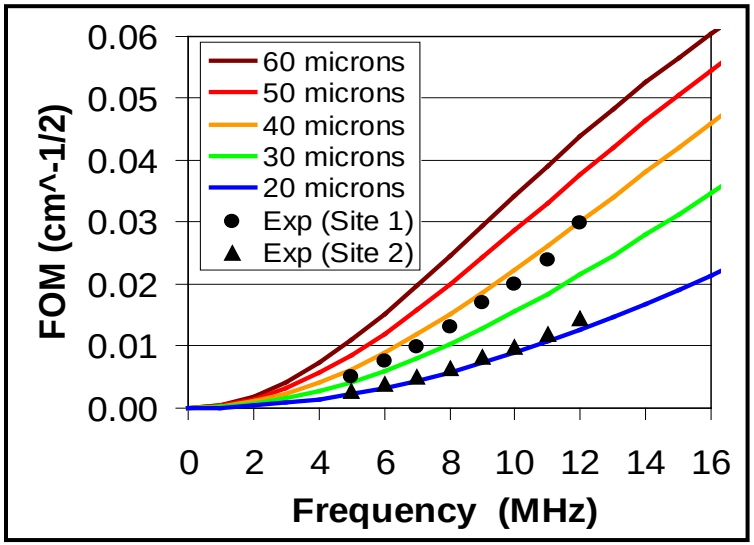


Ultrasonic backscatter

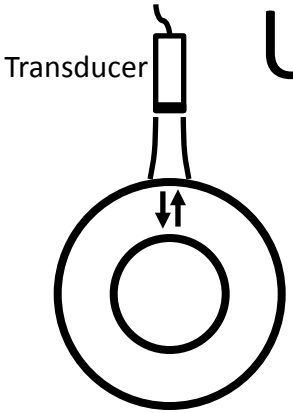




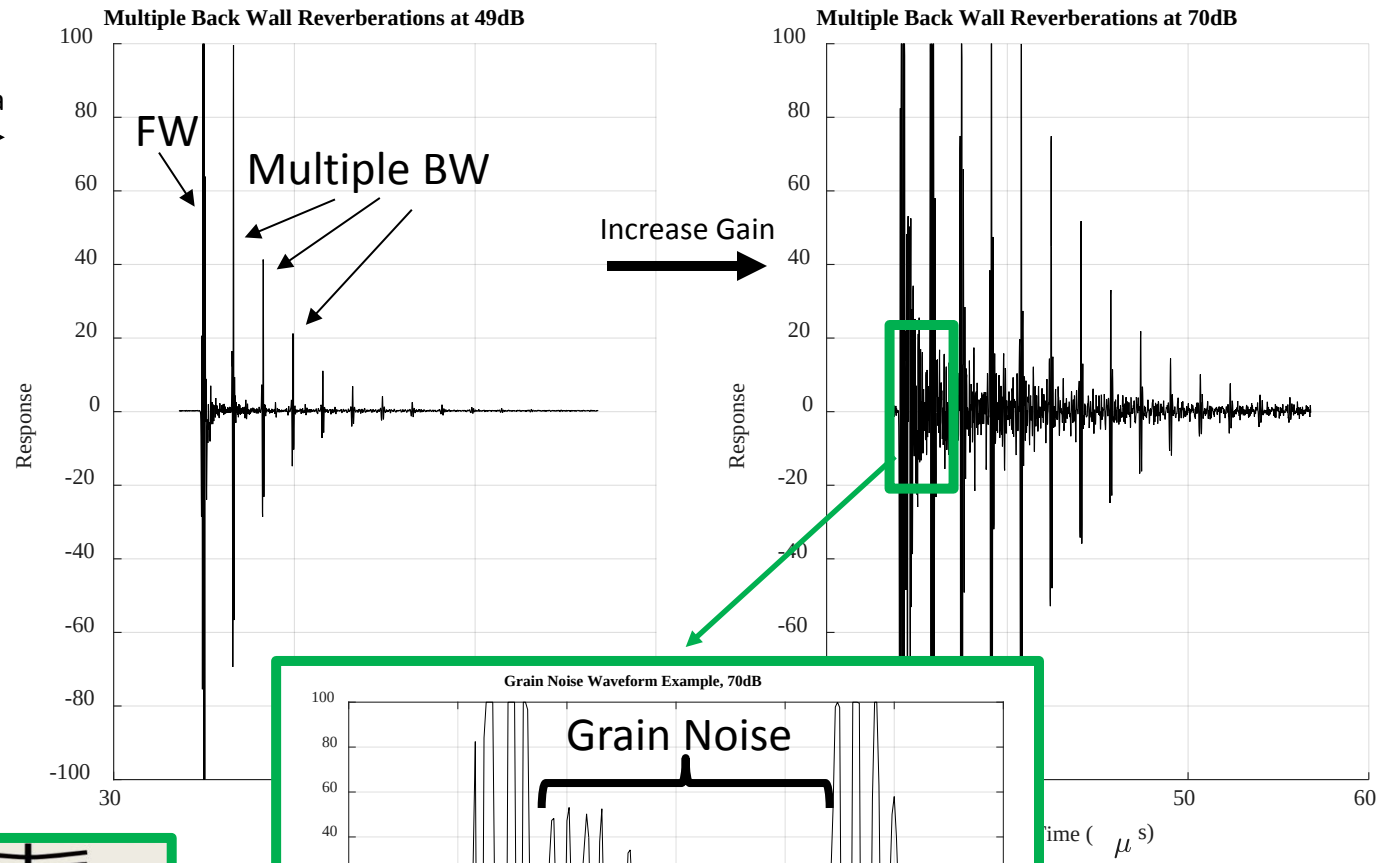
Model predicted curves of backscatter capacity for five Inconel microstructures



Ultrasonic Measurements - pipe



Acquire Data

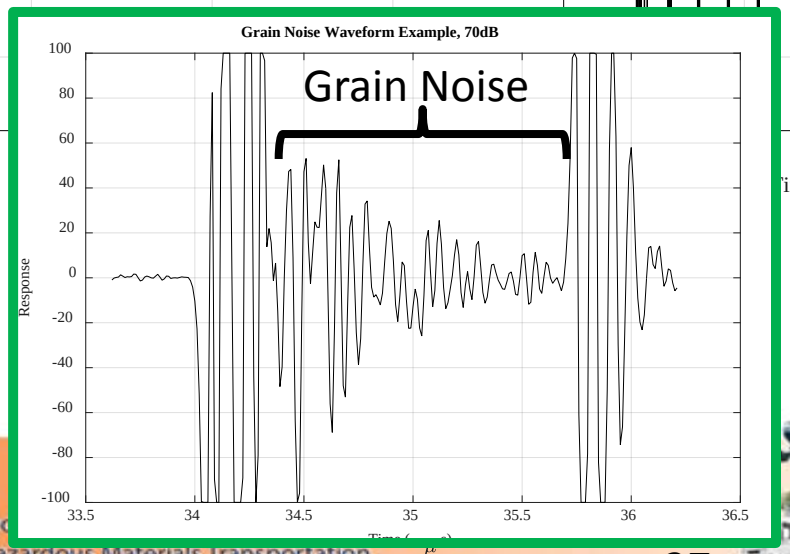


Sound energy reflects between interfaces (FW=Front Wall, BW=Back Wall).

Rate of decay of BW is attenuation.

Arrival time of BW gives velocity.

Backscattered grain noise is signal scattered from individual grains.



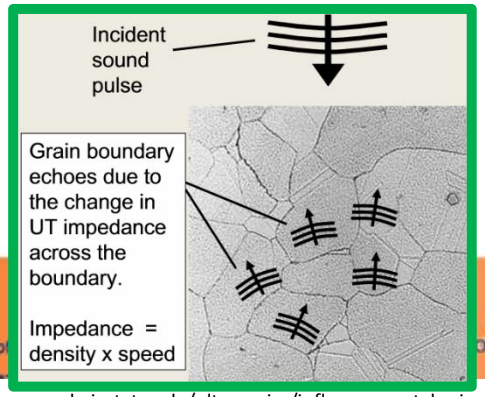
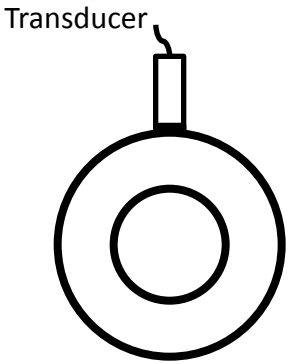
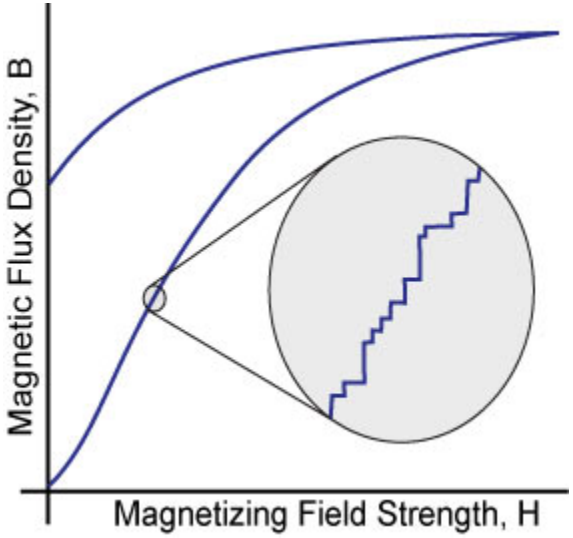


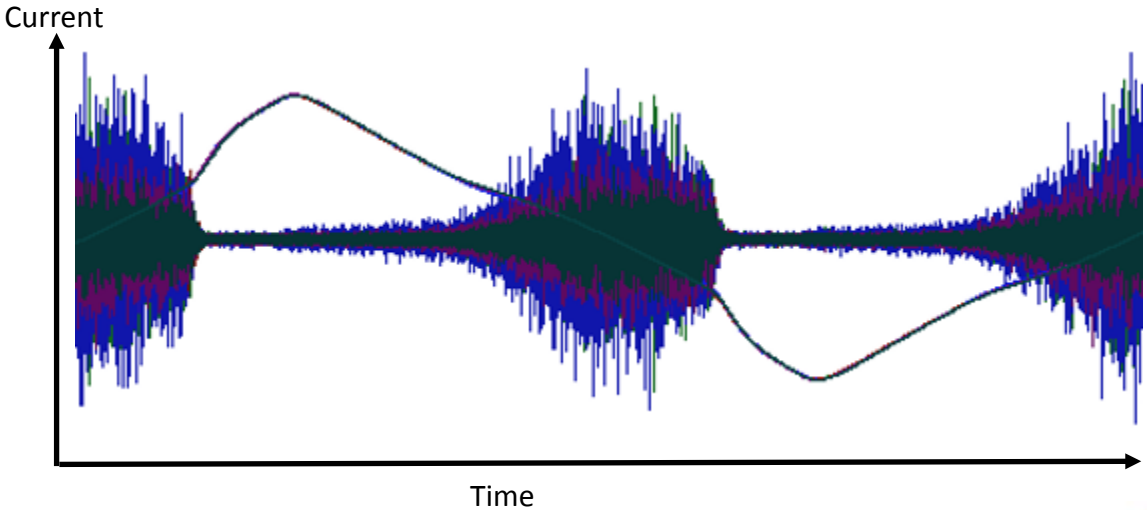
Image from: http://www.cnde.iastate.edu/ultrasonics/influence-metal-microstructure

Magnetic Barkhausen Emission



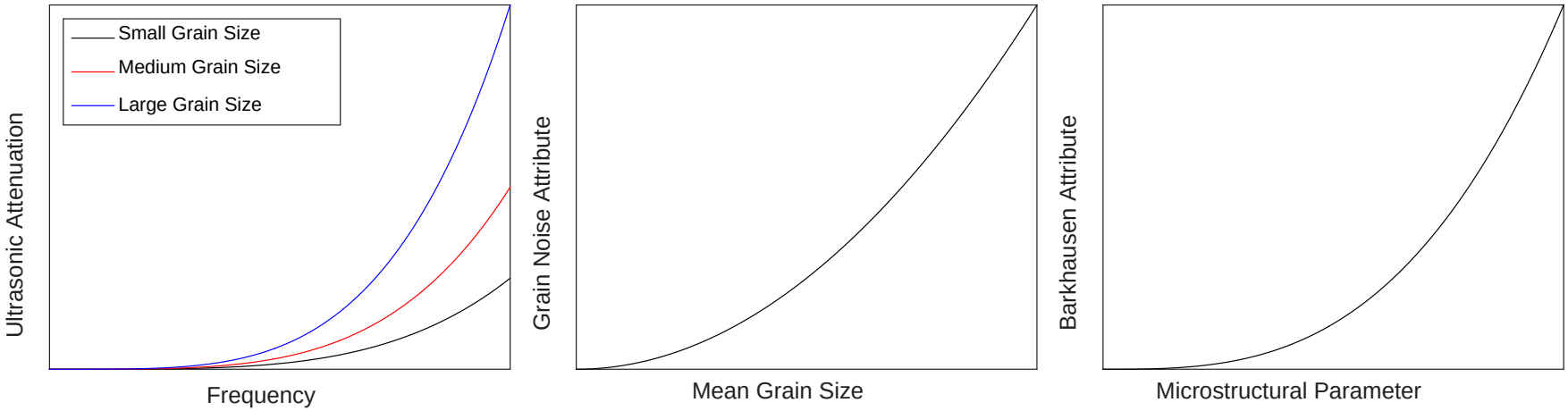
Signals from discrete magnetic domain motion during magnetization





Images from: https://www.nde-ed.org/EducationResources/CommunityCollege/Other%20Methods/AE/AE_BarkhausenTechniques.htm
http://www.stresstechgroup.com/files/jpeg_product/56507/testing_isntruments.jpeg

NDE Measurements: Conceptual Results



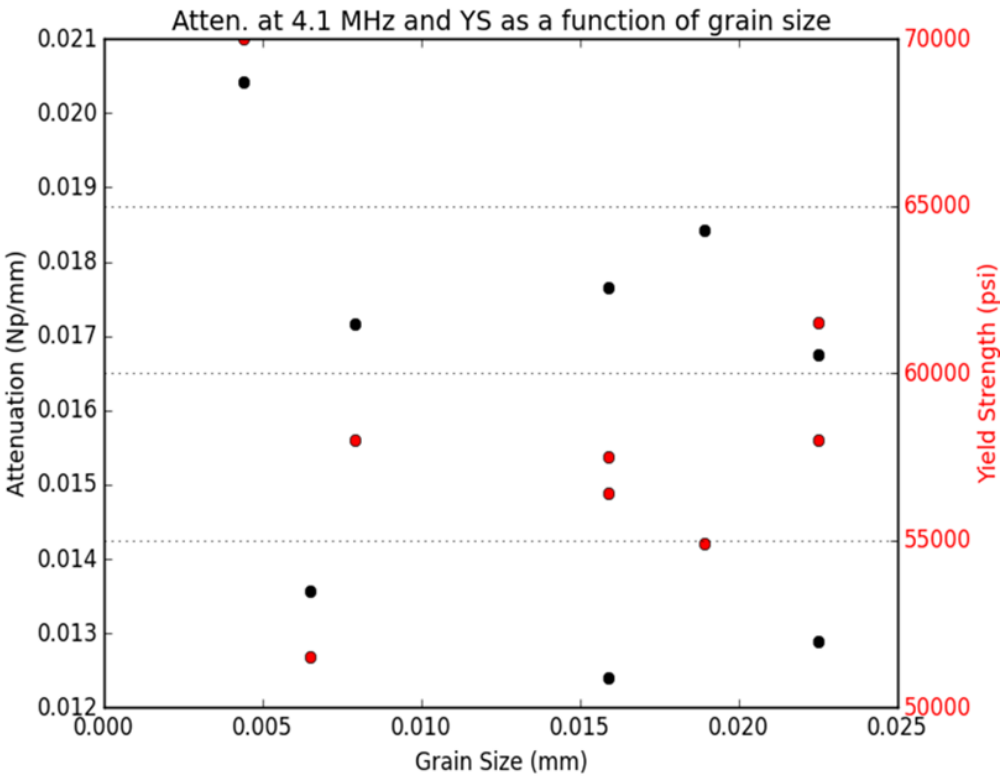
Different measurements allow us to learn about the microstructure. Conceptual results for ultrasonic attenuation, grain noise, and magnetic Barkhausen shown above.

Ultrasonic velocity allows for estimation of elastic moduli as well as being indicative of microstructural anisotropy

$$ultrasonic\ velocity = \sqrt{\frac{elastic\ modulus}{density}}$$

Task 4: NDE Approach - results

Even if the NDE resulted in a perfectly characterized microstructure, there would still be challenges in estimating the mechanical properties since the expected relationships reported in the literature are not observed with our "mixed" source sample set



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Task 4: NDE Approach - issues

The expected relationships between NDE and microstructure were not seen.

The expected relationships between microstructure and mechanical properties were not seen.

Remaining challenge: How to validate potential for demonstrated measurement approaches to give relationships with strength properties?

Fundamental issues being addressed

- There was a fundamental difference in understanding of the meaning of terms relating to "samples."
- To validate the demonstrated methodologies there is a need for calibration samples, i.e. samples with well characterized produced with a well controlled process.
- In addition to industry partners, NIST, Battelle, TDW all engaged: Now being address with CSM.

- Industry provided samples quite simply had too many unknowns and variables:
  - Vintage of pipe
  - Manufacturing processes
  - Mill test practices
  - Consistency and reliability of destructive tests
- Chemical Composition
- Seam Weld Type

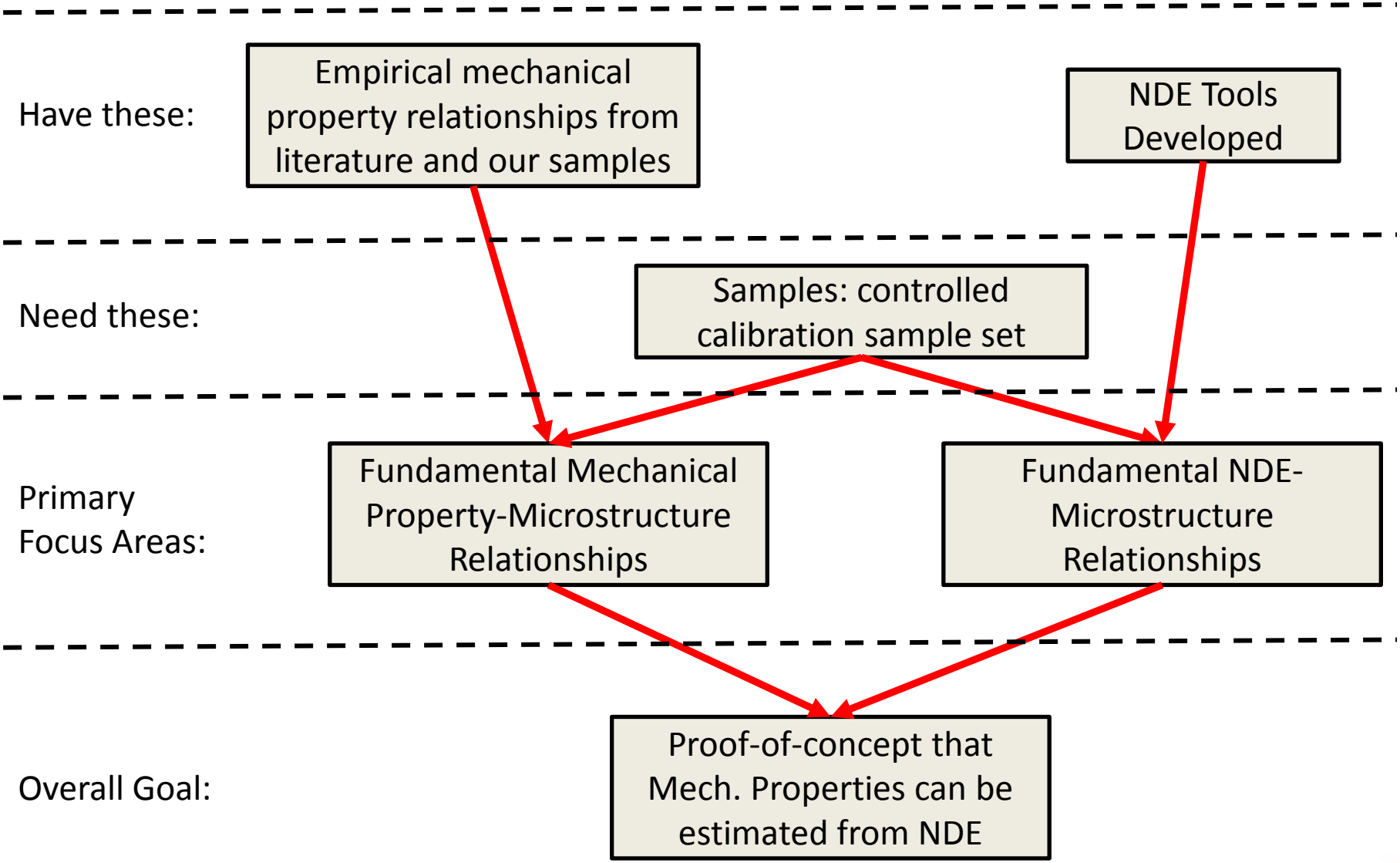
Accomplishments

- Property and mechanical property relationships reviewed
  - Limited samples available
  - Too much variation in samples to calibrate measurements

- Unexpected observation : Relationships between mechanical properties and microstructure – what is seen does not mirror what is reported in the literature
  - Data with trends – these results in the literature tend to be from much more controlled sample sets – i.e. single melt and process

- NDE framework developed
  - Methodologies, analysis software in place for ultrasonic measurements
  - Custom Barkhausen noise system assembled and in final testing (Commercial system available as reference)

Path to completion with needed samples now identified and being followed, working with Colorado School of Mines.


Have these:
Empirical mechanical property relationships from literature and our samples
NDE Tools Developed
Need these:
Samples: controlled calibration sample set
Primary Focus Areas:
Fundamental Mechanical Property-Microstructure Relationships
Fundamental NDE-Microstructure Relationships
Overall Goal:
Proof-of-concept that Mech. Properties can be estimated from NDE

Collaboration with Colorado School of Mines

- X52 Steel Plate
- Can process such that grain size and volume fraction of pearlite are controlled
- All processing parameters will be known
- Allows for fundamental demonstration of NDE measurement response on known, controlled samples
  - Provides crucial information for analysis on existing samples

Summary -- Moving project to completion

- Measurement framework in place
- Demonstrated ability to model mechanical properties as function of variables (microstructure/chemistry)
- <u>Addressing need calibration sample set</u>
  - Colorado School of Mines willing to collaborate
    - Ability to create samples with necessary variable control
- MS student graduates Fall '15, PhD Fall '16.
- Additional publication will be submitted in 2016
- Proposals with CSM being developed

Bibliography

- Engle, B.J., Smart, L.J. and Bond L.J. ((2015) Nondestructive characterization of pipe materials. Proceedings 41st Annual Review of Progress in QNDE, Ed. D.E. Chimenti and L.J. Bond, AIP (New York) AIP Proceedings # 1650, pp 943-951

- Bond, L.J. (2015) Needs and opportunities: nondestructive evaluation for energy systems (Keynote Presentation), Proc. SPIE 9439, Smart Materials and Nondestructive Evaluation for Energy Systems 2015, 943902 (March 27, 2015); doi:10.1117/12.2086279
-
- Engle, B.J., Smart, L.J., Bond L.J. (2015) Ultrasonic and magnetic Barkhausen emission measurements for characterizing pipeline steels, Nondestructive characterization of pipe materials. Proceedings 42st Annual Review of Progress in QNDE, Ed. D.E. Chimenti and L.J. Bond, AIP (New York) AIP Proceedings [In Preparation]

- Smart, L & Bond, L.J. (2015) Material Property Relationships for Pipeline Steels and the Potential for Application of NDE, Proceedings 42st Annual Review of Progress in QNDE, Ed. D.E. Chimenti and L.J. Bond, AIP (New York) AIP Proceedings [In Preparation].

- Smart, L (2015) Literature study for nondestructive characterization of pipeline materials (working title). Draft MS Thesis, Mechanical Engineering Department, Iowa State University (In final draft – submission and oral Fall 2015)

- Engle, B.J. (2016) nondestructive determination of material properties (working title) PhD thesis, Iowa State University (in preparation – expected submission Fall 2016)

Project Reporting

- Final Reporting and any student poster papers will be available from:
- Prof. L.J. Bond, Center for NDE, Iowa State University, Ames, Iowa, 50010
  - bondlj@iastate.edu
- Materials and theses will be posted
  - (a) PHMSA web site
  - (b) the ISU digital repository

    http://lib.dr.iastate.edu/cnde/

Other Project Results

- Insert number of involved students by Student type*
  - 1 PhD, 1 MS, 1 U/G
- Insert number of Published Papers*
  - 4 papers to date - (additional journal papers in preparation)
- Insert number of applied for or issued U.S. Patents*
  - none
- Number of resulting internships* - [MS student working for industrial sponsor]
- Number of full employments * {MS – working, PhD graduates 2016}
- Describe Project handoffs to PHMSA's core R&D Program
  - Working with CSM on developing follow on proposal

* R&D Program performance metrics reported to Congress

Future Program Improvements

- Indicate how DOT/PHMSA can improve/change future CAAP efforts to better meet University needs

Examples:

- Two years is not adequate time for a student to complete a PhD. – 3 or 4 year duration projects needed. Projects need to be larger in $ value.
- Complete award notifications by spring (May at latest) to m*aximize incoming student exposure for Fall project starts*
- Is your university open toward future CAAP awards? yes

THANK YOU!

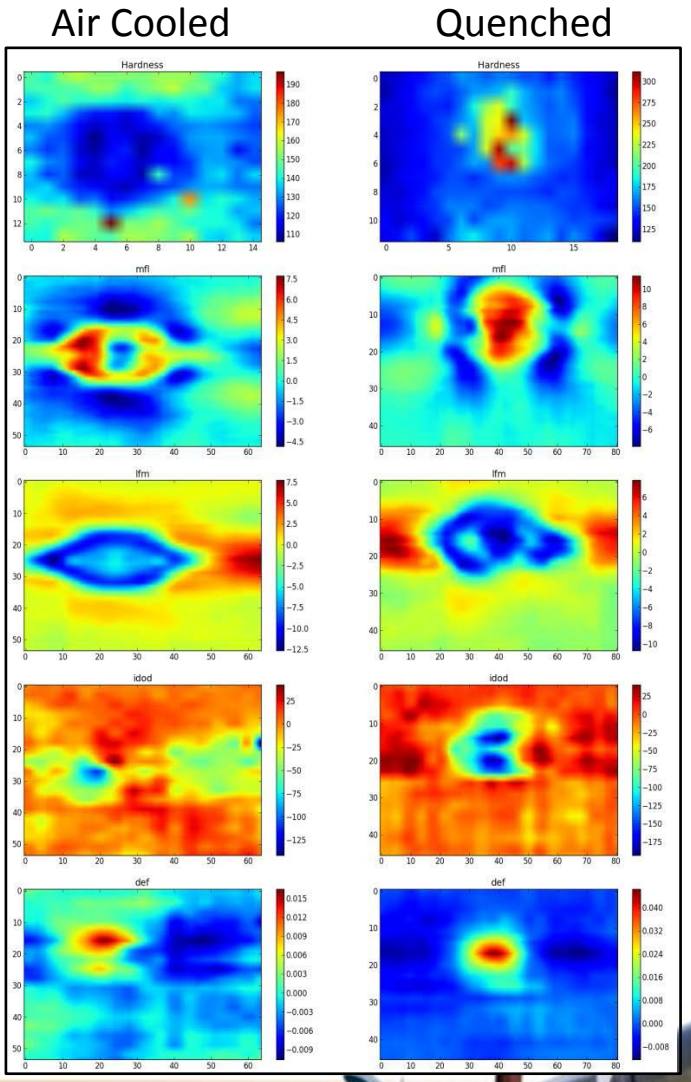
Addendum Slides for Additional Discussion

Some Recent Advancements in ILI

- Magnetic Flux Leakage*
  - Using comparison methods to observe hard spots in the steel
- Relationship between Gauss measurement and hardness of steel
- Results are differential observations, not strictly quantified results

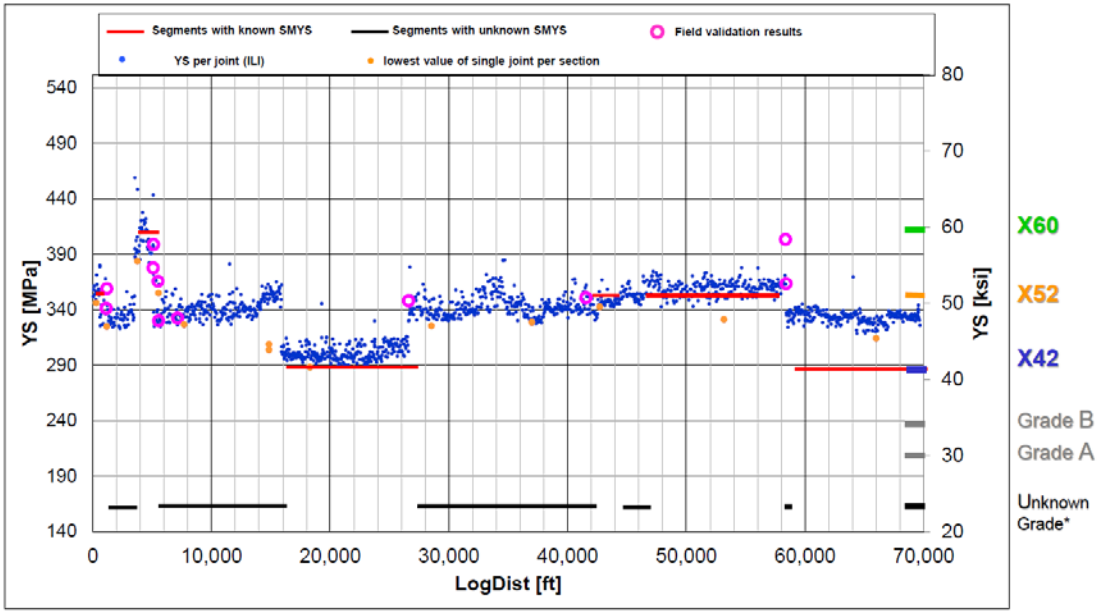
* Belanger, A., and T. Barker. 2014.

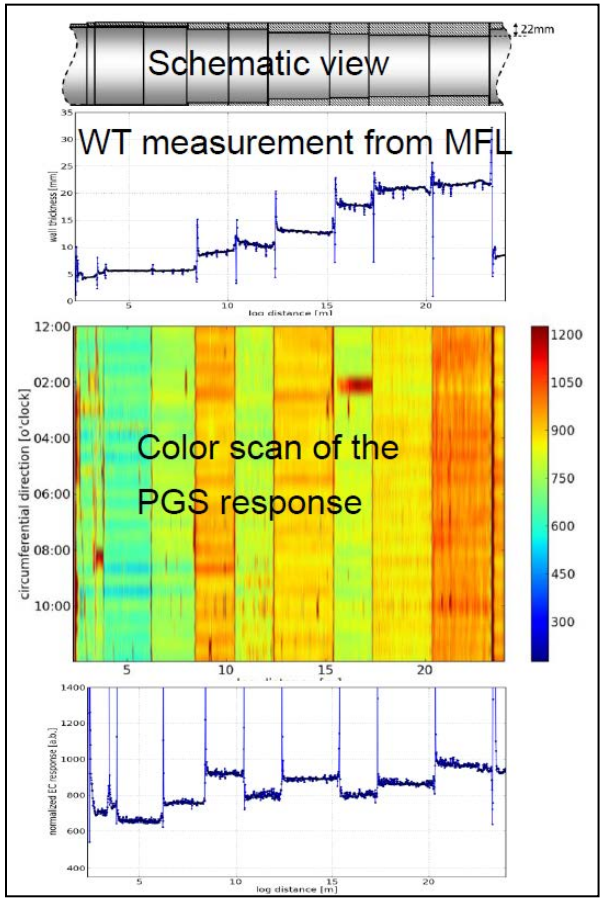
- Hardness
- High-Field MFL
- Low-Field MFL
- IDOD
- Int Def Geo



Recent Advancements in ILI (2)

- Eddy Current*
  - Use pre-magnetization to increase penetration depth of current, minimize fluctuations and produce a more stable response
  - Ability to determine grade for previously unknown pipe grades





*Molenda, D., and W. Thale. 2014.

Recent Advancements in NDE

- Ultrasound*
  - Within ILI tools, this is regarded as the standard for measuring wall loss, making it ideal to use as a direct measurement technique
  - Velocity and backscattered grain noise are valuable in determining yield strength, tensile strength, and percent ferrite
  - More testing and analysis is underway to determine better relationships and application techniques

* Engle, Brady E. Et al 2014.

Previous Research Comparison

- No noticeable trend in grain size vs WT, may not have enough variability in WTs
- Same effect for transition temp vs WT

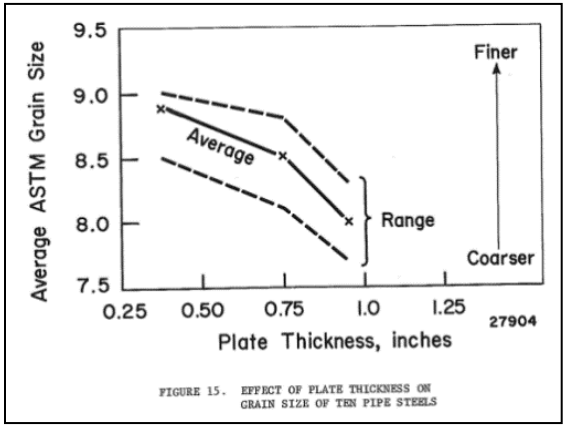
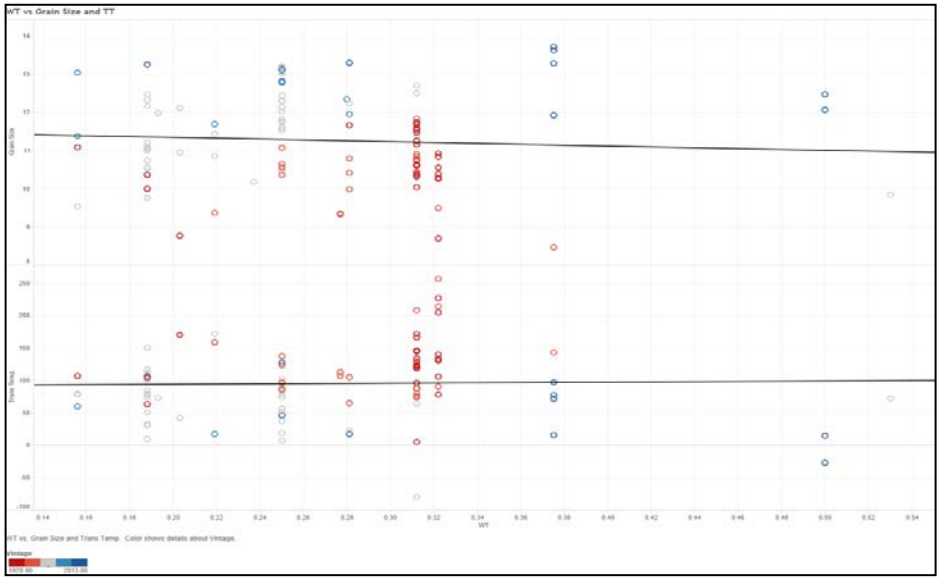


FIGURE 15. EFFECT OF PLATE THICKNESS ON GRAIN SIZE OF TEN PIPE STEELS



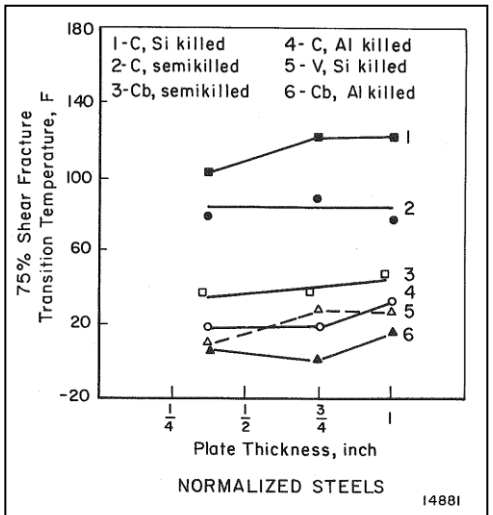
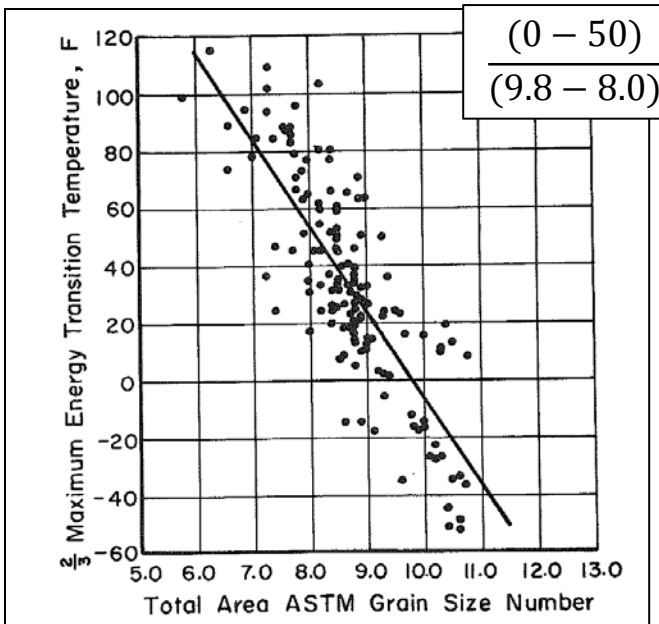


FIGURE 16. EFFECT OF PLATE THICKNESS ON THE NOTCH TOUGHNESS OF NORMALIZED PIPE STEELS

F.W. Boulgar. 1965.

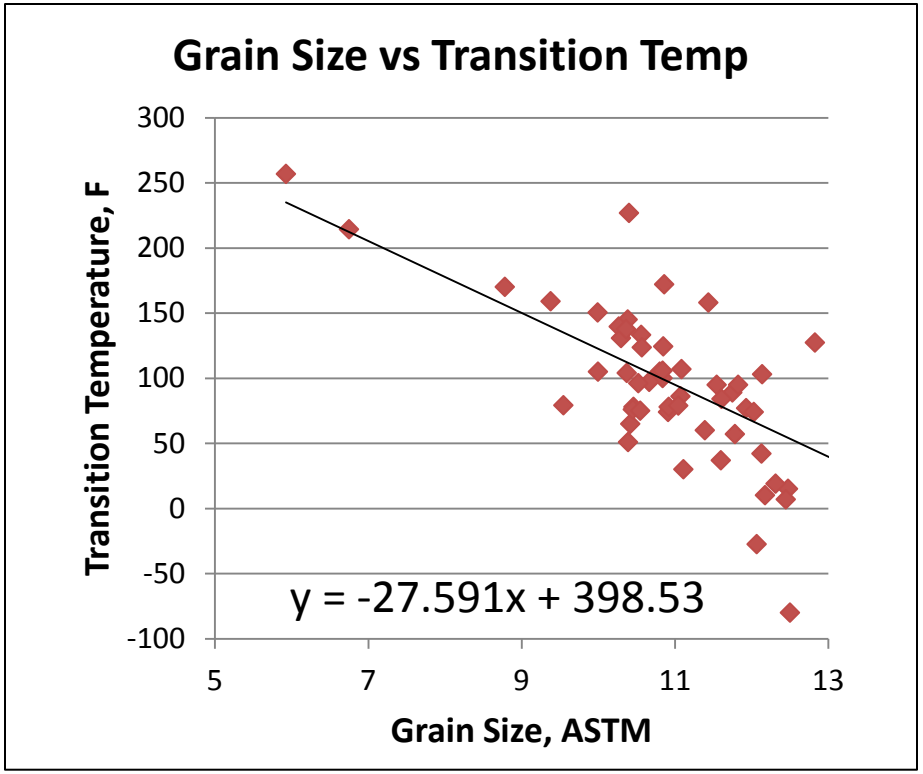
Transition Temp vs. Grain Size

- Our data results reflect standard expectations from previous research



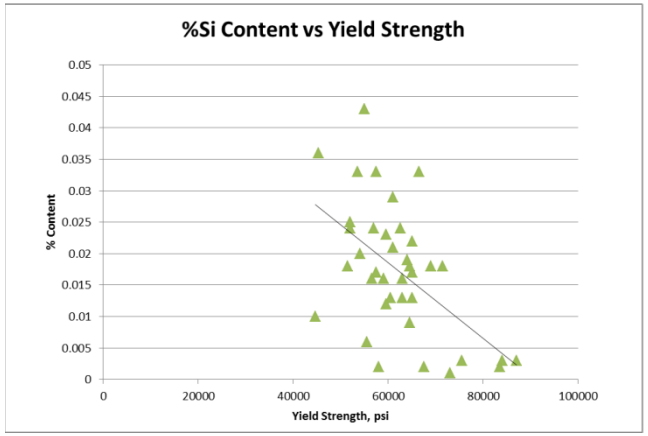
$$\frac{(0-50)}{(9.8-8.0)} = -27.8$$

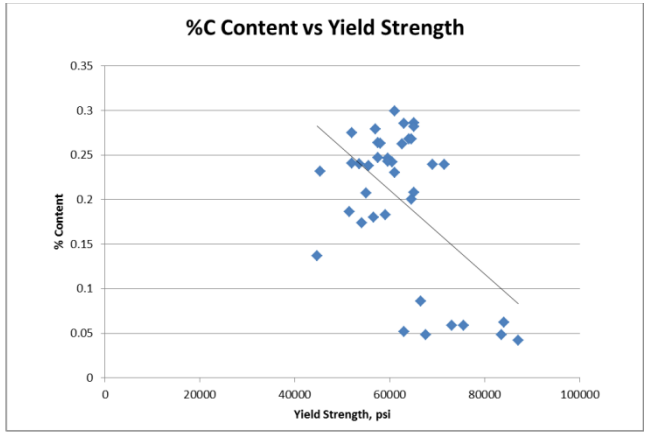
FIGURE 8. DEPENDENCY OF FRACTURE TOUGHNESS OF PIPE STEELS ON THE GRAIN SIZE PRODUCED DURING FABRICATION

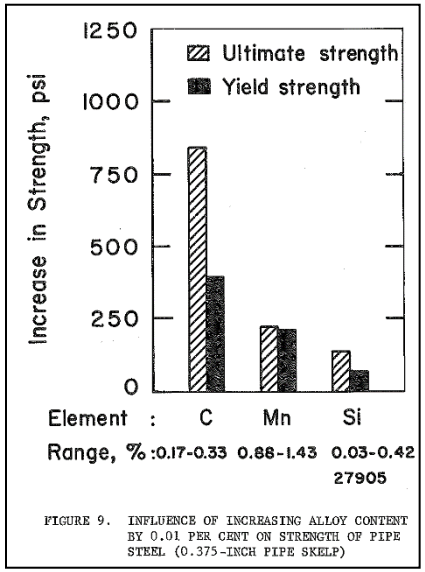


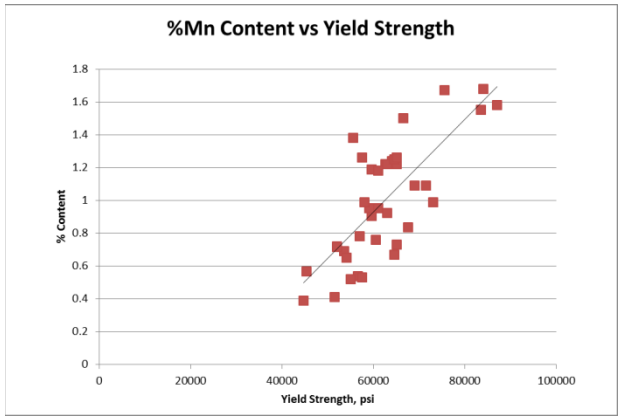
F.W. Boulgar. 1965.

Chemical Content Effects on Yield Strength









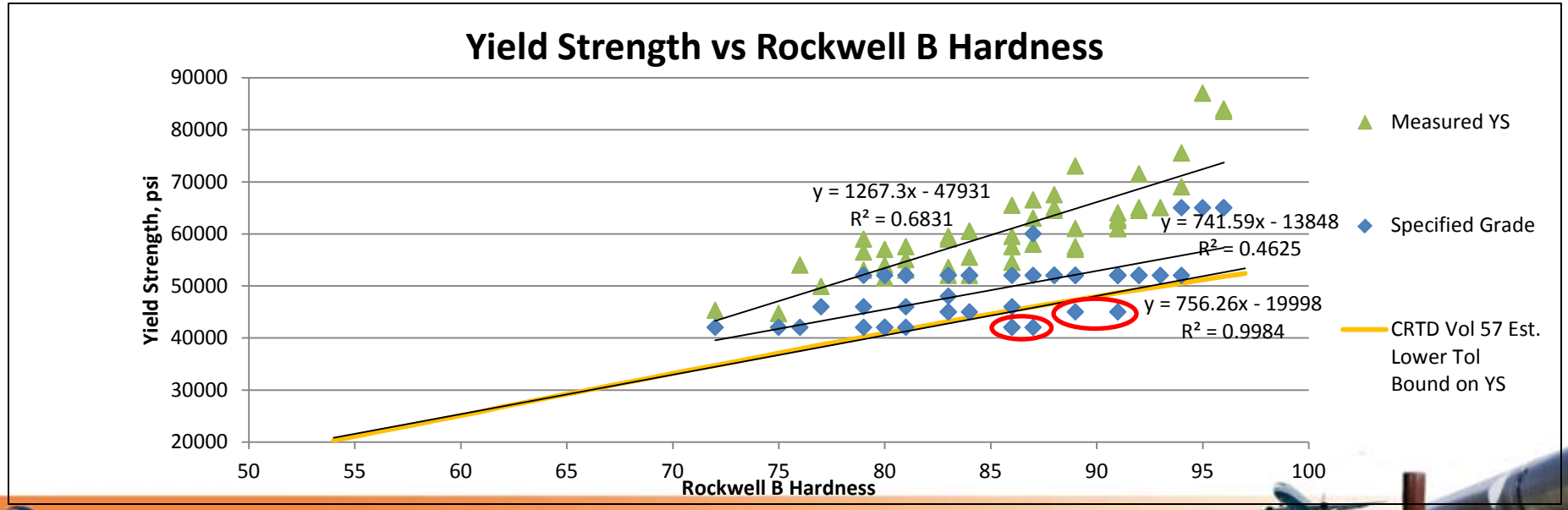
- Correlations between yield strength and chemical content are apparent for Mn, Si, and C

F.W. Boulgar. 1965.

Sample Data compared to ASME CRTD Vol 57 Data

- No samples have Measured YS < Specified Grade
  - Measured YS is non-conservative compared to Specified YS
- 4 samples have Specified Grade non-conservative to Vol 57 relationship
  - Grade X42 (1949) and X45 (1950)
  - Oldest pipe in our sample set
- Vol 57 is conservative compared to all measured YS

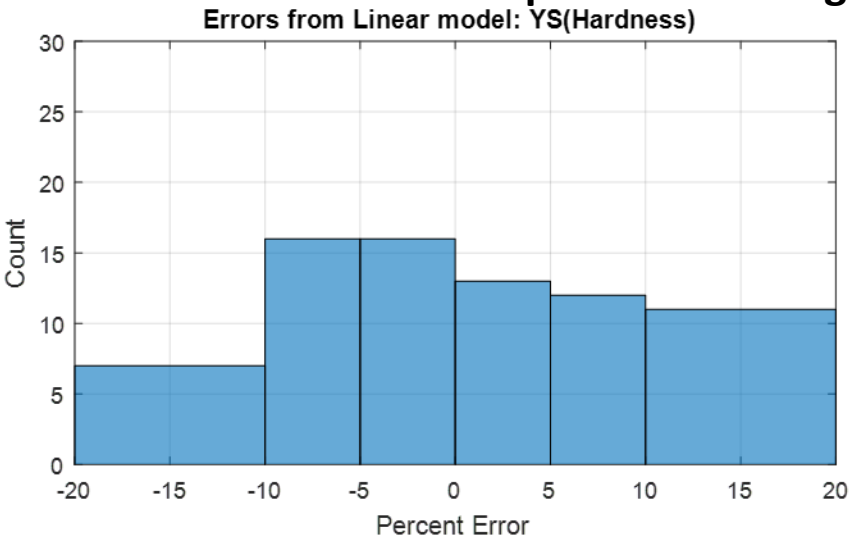
(Burgoon, David A. 1999).

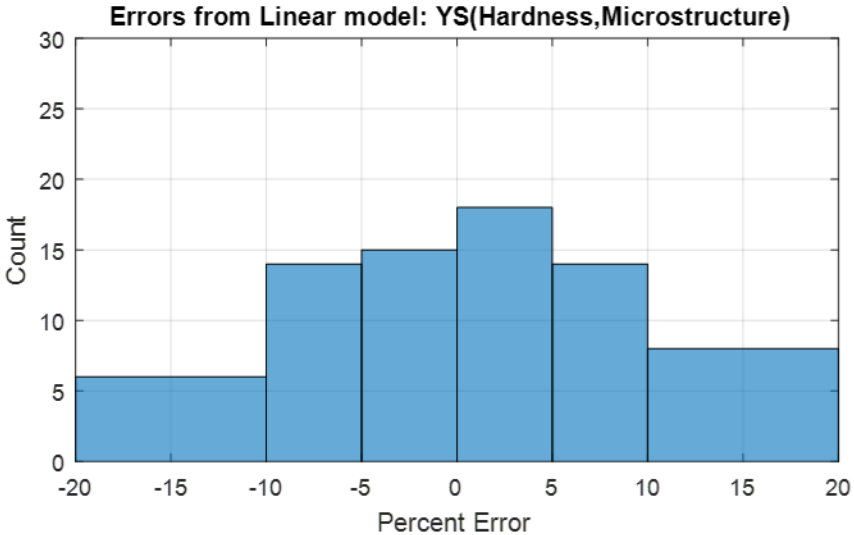


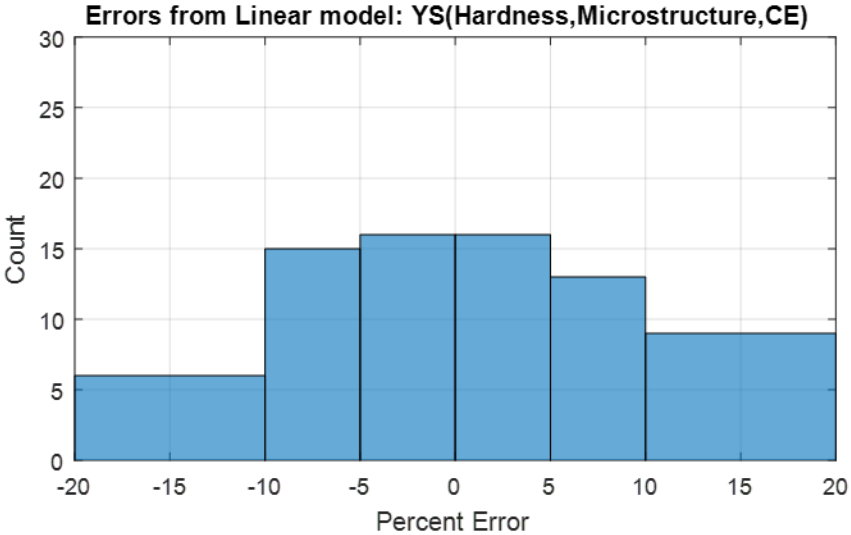
Summary of Linear Correlations

- A strong linear correlation between hardness and tensile strength (R^2=0.96)
  - It follows that hardness and yield strength (R^2=0.85)
- A relationship between grain size and transition temperature may exist (R^2=0.68)
- %Mn correlates well with yield (R^2=0.71) and tensile (R^2=0.74) strengths
- Appear to be relationships between vintage and various chemical contents (%C, %Al, %Si), but may be a result of the limited sample set

Example: Yield Strength Prediction with linear model

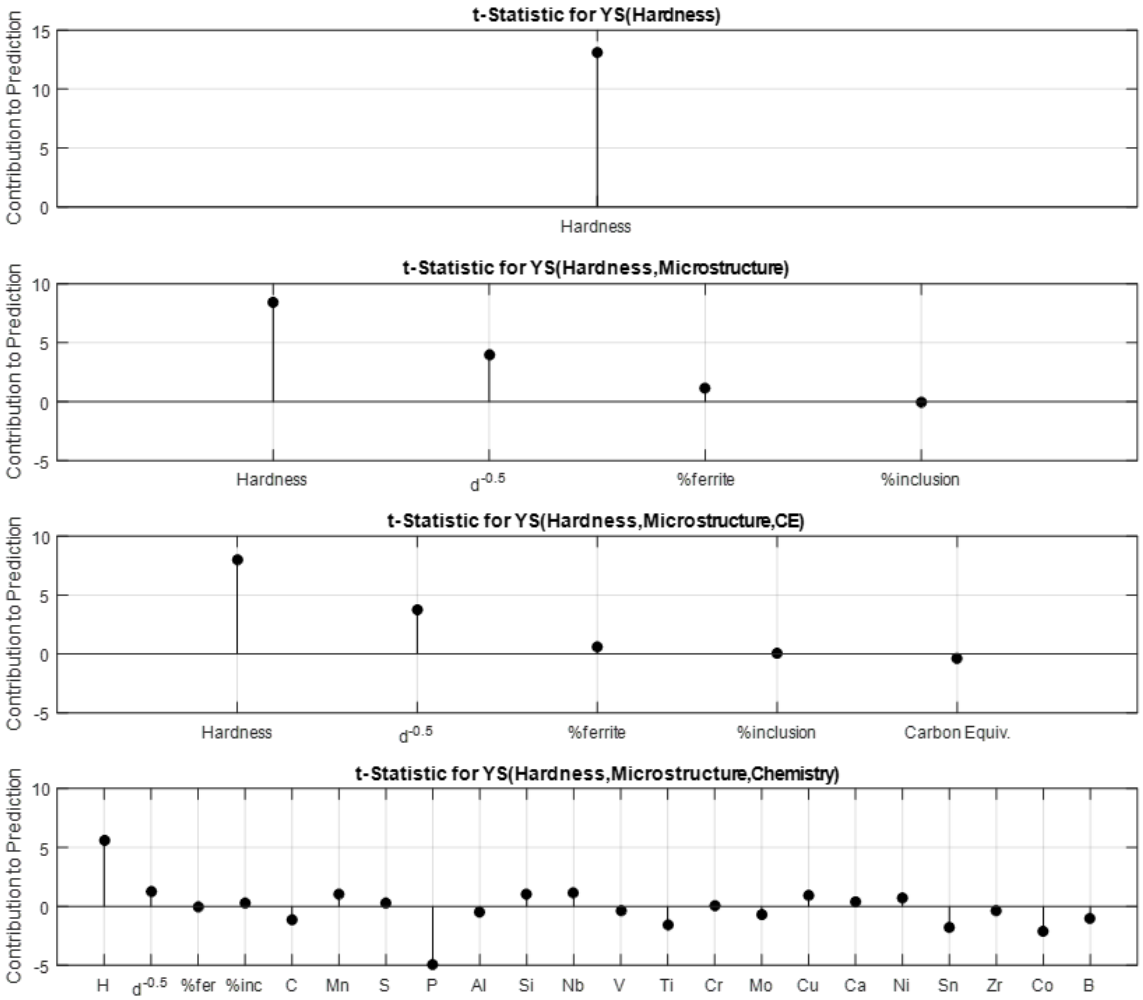






More variables gives better prediction of yield

Example: Yield Strength Prediction with linear model



A model that has each element as an independent variable and includes hardness and microstructure predicts yield strength much better than hardness alone.

Contributions to prediction are shown here.

Note that DECREASE in carbon content increases yield, going against what is generally accepted