Material property relationships for pipeline steels and the potential for application of NDE

Cite as: AIP Conference Proceedings **1706**, 160003 (2016); https://doi.org/10.1063/1.4940620
Published Online: 10 February 2016

Lucinda Smart, and Leonard J. Bond

Material Property Relationships for Pipeline Steels and the Potential for Application of NDE

Lucinda Smart[1, 2a] and Leonard J. Bond[2b]

[1]*Kiefner and Associates, Inc., 1608 S Duff Ave, Ames, IA*
[2]*Center for Nondestructive Evaluation, Iowa State University, Ames, IA*

Corresponding authors: [a]Lucinda.Smart@kiefner.com, [b]BondLJ@iastate.edu

Abstract. The oil and gas industry in the USA has an extensive infrastructure of pipelines, 70% of which were installed prior to 1980, and almost half were installed during the 1950s and 1960s. Ideally the mechanical properties (i.e. yield strength, tensile strength, transition temperature, and fracture toughness) of a steel pipe must be known in order to respond to detected defects in an appropriate manner. Neither current in-ditch methods nor the ILI inspection data have yet determined and map the desired mechanical properties with adequate confidence. In the quest to obtain the mechanical properties of a steel pipe using a nondestructive method, it is important to understand that there are many inter-related variables. This paper reports a literature review and an analysis of a sample set of data. There is promise for correlating the results of NDE measurement modalities to the information required to develop relationships between those measurements and the mechanical measurements desired for pipelines to ensure proper response to defects which are of significant threat.

INTRODUCTION

The oil and gas industry in the USA has an extensive infrastructure of pipelines, 70% of which were installed prior to 1980, and almost half were installed during the 1950s and 1960s (see Fig. 1) [1]. As a result, these lines do not have the benefit of properties resulting from modern manufacturing and construction practices. As this system ages, there is growing interest in maintaining safety and providing knowledge of pipe properties, so that a safe operating pressure can be determined. Therefore, the US Department of Transportation Pipeline and Hazardous Materials Safety Administration (US DOT PHMSA) is developing new regulations regarding their integrity verification processes (IVP). PHMSA describes their IVP as a multidisciplinary engineering approach to verify the gas transmission pipeline properties [2]. Using NDE of the pipe material would be preferred to the traditional destructive methods. For in-service pipe requiring verification of properties, cut-outs may be performed to obtain a sample of the material for use in destructive tests in a laboratory. However, this is not practical or even feasible to do for the entire length of a pipeline. Therefore, more insights are needed around what properties are currently being measured, what properties may be able to be measured with advances in science and technology, and the practical application of the current or future technology.

42nd Annual Review of Progress in Quantitative Nondestructive Evaluation
AIP Conf. Proc. 1706, 160003-1–160003-12; doi: 10.1063/1.4940620

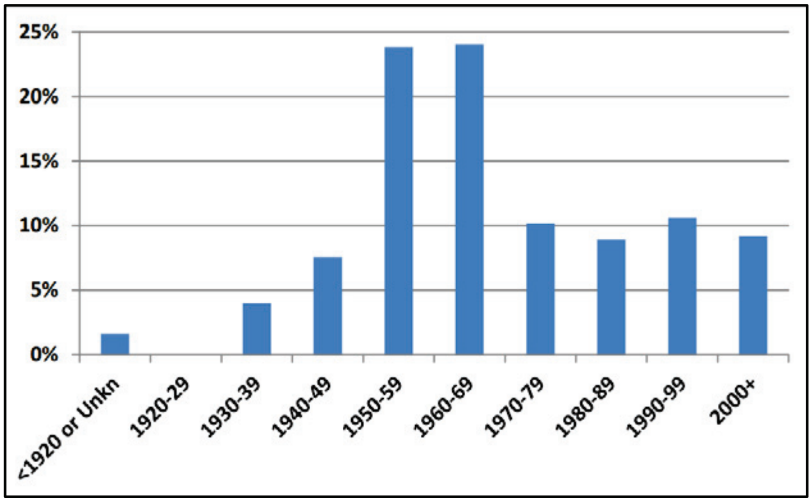


FIGURE 1. Percentage of Pipe Mileage Installed by Decade [1]

Current in-line inspection (ILI) technologies focus on defect detection and characterization for corrosion and cracking, and also the performance of inspection measured with a probability of detection (POD). As a part of the assessment process it is necessary to know the pipe properties and to determine failure limits based on the significance of defects. Ideally the mechanical properties (i.e. yield strength, tensile strength, transition temperature, and fracture toughness) of a steel pipe must be known in order to respond to detected defects in an appropriate manner. Material property measurements such as hardness, chemical content, grain size, and microstructure may be important in determining the mechanical properties of steel pipe, and ideally are needed without the need for performing cut-outs from pipes to give samples for destructive tests. Current nondestructive methods of inspection do not fully determine the necessary properties, so destructive testing must be performed, which is costly, time-consuming, and in many cases is not practical for pipe that is in-service. There are in-ditch methods of inspection that can determine many material properties, and there is potential for determination of some mechanical properties. Neither current in-ditch methods nor the ILI inspection data have yet determined the desired mechanical properties with adequate confidence. In the quest to obtain the mechanical properties of a steel pipe using a nondestructive method, it is important to understand that there are many inter-related variables. Manufacturing processes have changed significantly over the past century, resulting in significant differences in pipe with nominally the same properties, particularly noticeable with the alloying elements present in more modern pipe. Advances in inspection technologies and the data able to be obtained by current technologies is now being explored by several interested parties [3]. ILI companies are specifically focusing on the magnetic data from eddy current and magnetic flux leakage measurements to relate those to mechanical properties [4]. ILI also regularly uses ultrasound measurements for wall thickness determination, and the potential application of advances in ultrasound measurements for grain size and other properties are being explored. This paper reports a literature review and an analysis of a sample set of data. There is promise for correlating the results of NDE measurement modalities to the information required to develop relationships between those measurements and the mechanical measurements desired for pipelines to ensure proper response to defects which are of significant threat.

BACKGROUND

Manufacturing Processes and Destructive Tests

Manufacturing processes have a large impact on the final outcome of a steel pipeline material in terms of its material properties. The degree of variability in material properties within finished pipe has been observed as a function of rolling practices and the new compositions which are incorporated into the process [5]. Hypothetically, two pipes could have been produced from the same heat of steel, but the heat treatment sequence and finishing rolling temperature of the plate could have enough differences so that the grain size or microstructure differs, thus affecting mechanical properties. To highlight the issues further, the testing carried out to measure the final mechanical properties also have inherent variabilities. The traditional destructive testing methods used to determine yield and tensile strength include strap tests or round bar tests, in which the sample of pipe is flattened using either a 3 or 4 point bending method, and a load is applied. Studies have shown that the standard deviation of the measure for yield strength is as high as 26.2 MPa (3800 psi) for a one-step flattening method [6]. Understanding these variabilities in manufacturing processes and destructive tests is important for the implementation of NDT. If materials are not consistently manufactured, this will have an effect on how relationships between material and mechanical properties may be considered, particularly when performing tests on a set of samples. If destructive tests are not carried out consistently, so as to achieve repeatable results, it is difficult to use these data as a reference to verify nondestructive test results with smaller error bounds.

In-Line Inspection Technology

In-line inspections (ILI) are a commonly used form of nondestructive test currently performed on pipelines. This is due in part to their relative ease of use, feasibility to inspect many miles of pipeline within a manageable time frame, and the improvements seen in technology over the years [7]. Magnetic flux leakage (MFL) is used most commonly for determining metal loss and other similar defects in the pipelines, and ultrasonic inspections are useful in assessing crack-like indications as well as wall thickness changes, or metal losses. Therefore, it is reasonable to primarily explore these technologies and how recent advances may determine pipe properties.

Magnetic Flux Leakage (Low-Field)

A low-field magnetization (LFM) technique is currently being used instead of, or in addition to, the now traditional high resolution MFL tools to locate hard spots in older pipe and areas of mechanical equipment damage in all pipe as these are both potentially serious threats to integrity [4]. The catalyst to using this mode of measurement was determining a relationship shown between the Gauss measurements and the wall thicknesses. The first inspections using this technology utilized one tool to magnetize the pipe and one to measure the residual magnetization. [8] There is a relationship between the Gauss measurements for the high-field MFL tool and the hardness based on the reduction of a dependence on material properties, and the lower resolution MFL is able to detect this based on its higher saturation level.

More recent advances in the tools now apply a magnetization at a level near the maximum permeability region to identify material property differences using a single tool. [9] The results of a study of the effectiveness of these tools shows that the tool is currently able to detect differences in the hardness and is approaching a method to quantify the hardness results. There are also distinguishable differences between the method by which the material was hardened, either by heat treatments or quenching of the material. [4] Using these concepts, this tool could detect differences in the hardness of pipe and relate this to the yield strength. If able to determine distinct differences, fewer verification digs would need to be performed to determine the properties of the pipe overall. Improvements in this technology may lead to more precise measurements, which in turn could lead to a better understanding of the relationship between these material measurements and mechanical measurements. However, more work needs to be done to fully understand how hardness, permeability, remanance, and coercivity relate to yield strength, tensile strength, fracture toughness, and transition temperature.

Eddy Current

It has recently been shown that eddy current principles can be used, with certain mathematical models, to obtain mechanical materials properties for sheet metal to an accuracy of with +/-2% for tensile strength and +/-4% for breaking elongation. [10] Eddy current systems have a high sensitivity to changes in the microstructure of a material, and are therefore a valuable measurement method for evaluating the mechanical properties, if a correlation between these properties exists. [11] [12]

One ILI vendor has recently developed an approach to determining pipe grade through eddy current testing with pre-magnetization which is claimed to increase the penetration depth of the eddy currents, minimize possible fluctuations, and result in a more stable response from the measurement system. [13] By applying an appropriate excitation frequency, the depth penetration is small enough that the effects of wall thickness are negligible down to wall thicknesses of 3 to 4 mm. Once decent levels of excitation frequency and pre-magnetization levels were applied, a good correlation is shown from the measurements taken and the yield strength and tensile strength. The final result of various pull tests showed that this technique provides a good prediction of yield strength, as is shown in Figure 2.

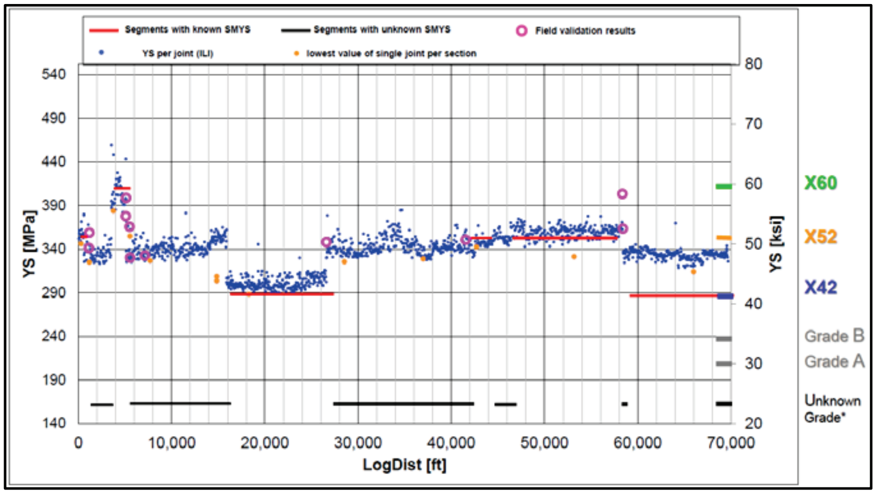


FIGURE 2. Results of the data evaluation for pipe grade determination using Rosen ILI technology. [14]

Ultrasound

While methods of ultrasonic inspection are being applied and developed for managing current integrity threats, there has not been as much work done in advancing ultrasonic technology for the determination of pipeline properties specifically. However, the ground work for understanding and applying the knowledge base shows that opportunities exist for development.

A project was recently initiated with one task involving determining the viability of using ultrasonic measurements for determining grain size on pipeline in order to verify pipeline properties. [15] The longitudinal velocity, attenuation, and backscattered grain noise were all measured for the preliminary measurements. The samples provided for the study included grain size measurements obtained by traditional metallographic techniques to correlate with the grain size results obtained through the use of ultrasonic technology. The results were minimal due to a small sample set, but showed application of the technology may allow for better understanding of properties in the future.

In-Ditch Measurement Techniques

Chemical Composition

Typical methods for determining the chemical composition of a carbon steel material are based on positive material identification (PMI), and may include x-ray fluorescence (XRF) or optical emission spectroscopy (OES). XRF emits a beam of x-rays into the material, the atoms of the material absorb the x-rays, and each element emits x-rays in return at a unique energy. This is then translated into characteristic energies to determine the chemical make-up of that material. OES uses a spark to excite atoms of a material, which then emits a spectrum of light which is measured to determine the chemical make-up. Each method independently reveals valuable information chemical make-ups, since the XRF cannot measure lighter elements such as carbon, and OES probes are able to measure more of these lighter elements.

Hardness

Hardness testing is performed in the ditch, commonly using a Vickers hardness test, shown by the Ernst Handy Esatest in Figure 3. The test may be carried out at temperatures between 5°C and 39°C, and ideally would be performed on a surface that is flat with a minimum 400 grit finish. A calibration procedure is carried out and multiple indentations are performed at intervals with at least 3mm separation. Hardness measurements have been studied in great detail for predicting yield and tensile strength, as will be discussed in a later section of this document.

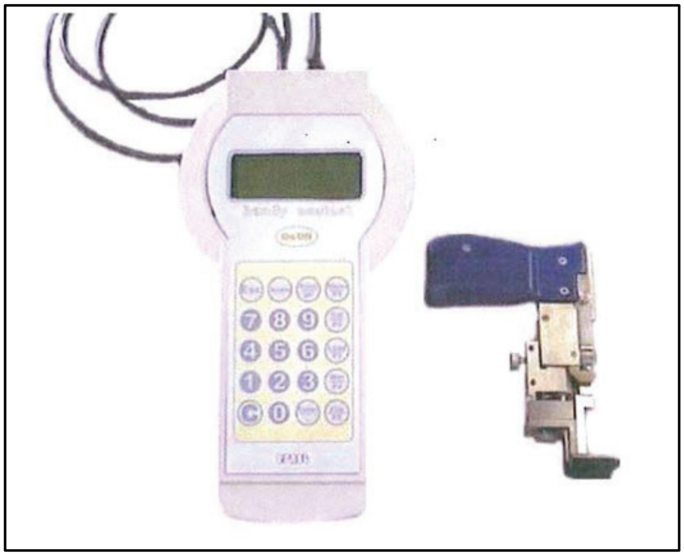


FIGURE 3. Image of the Ernst Handy Esatest. Provided by ApplusRTD Norway.

Grain Size and Microstructure

Grain size is typically measured using microscopy, after polishing is performed to obtain a dent metallographic section of pipe. ASTM E112 is the standard most widely used to carry out this procedure to analyze the grain size and structure. Performing this in the ditch, while possible, can also be quite tedious and at times, impossible, depending on ditch conditions. Lighting plays a huge aspect, as well as positioning on the pipe, to get a decent image of the grain structure and size.

There are several developed and emerging innovative nondestructive techniques for determining microstructure within a material, beyond the simple optical methods most commonly used. Ramuhalli described ultrasonic methods to determine the microstructure, using ultrasonic velocity ratios to correlate with various microstructural parameters. [16]

Magnetic methods have been used to characterize the microstructure; in particular, the testing method using Barkhausen noise (BN) can provide very useful information about the microstructure. One study presents the potential that barkhausen noise can identify microstructural changes and microcracking, and that these changes can be correlated with the mechanical behavior and modification of the microstructure. [17]

Property Relationships

Magnetic Measurements

A detailed study shows that hardness is strongly correlated to the magnetic coercivity of pipeline steel; it has a linear correlation coefficient of 0.83. [18] Furthermore, the relationship between hardness is shown to have a correlation coefficient of 0.86 with yield strength, and 0.96 with ultimate tensile strength. [18] Analytical models were later developed to determine the best-fit relationship to determine hardness given the applied magnetic field and the magnetic induction. [19] More recent advancements in the tools themselves allow the application of a magnetization level near the maximum permeability region to differentiate material properties, and ultimately detect difference in its hardness. [9] A recent study shows that it may be possible to determine the method by which a material was hardened, either by heat treatments or quenching of the material. [4] By using a low-field magnetic flux leakage (MFL), the higher saturation allows for these material property measurements.

Eddy current measurements use pre-magnetization to increase penetration depth, minimizing possible fluctuations, and result in a more stable response from the measurement system. [13] Preliminary pull tests from this measurement system show accuracies of +/- 40 MPa (5801 psi) for this method of electromagnetic determinations of yield strength.

Earlier literature shows that the potential of accuracies of +/-9 MPa (1305 psi) may be considered for tensile strength, and +/-14 MPa (2030 psi) may be considered for yield strength. [20]

Ultrasonic Measurements

Ultrasound measurements have shown the capability for determining grain size by looking at the backscattered grain noise to determine a backscatter coefficient, providing information about the grain size and orientation within the overall microstructure. [21] Preliminary studies show promising results for the application on pipelines. [15] The velocity measurements showed a positive correlation between that and the yield strength, as well as the tensile strength and velocity. An inverse relationship was found between the percent ferrite content and the velocity measurement.

Hardness Measurements

Hardness measurements have been shown to give a good relationship with yield strength, and may be used to determine a lower bound yield strength of in-service pipe, grade X52 or lower, manufactured prior to 1980 and with a diameter greater than 4 inches. [22] Work is currently being done in the industry to improve this method, making it more usable for in-ditch applications. [23] Linear relationships between hardness and tensile and yield strengths have been studied to be true for steels with yield strengths of 325 MPa to over 1700 MPa (47 ksi and 246 ksi) and tensile strengths between 450 MPa and 2350 MPa (65 ksi to 340 ksi). Additional studies provide similar linear relationships, only varying in the coefficients due to differences in microstructure and compositions. [24]

SAMPLE DATA

A set of 94 sample data test coupons were evaluated at the Kiefner and Associates, Inc. lab and are used here for preliminary evaluation of potential relationships between material and mechanical properties. Measurements taken on the test coupons included grain size, percent ferrite, percent inclusion content, yield strength, tensile strength, elongation, hardness, transition temperatures, and available chemical content. Information such as pipe diameter, wall thickness, grade, seam weld type, and vintage was also provided where available. However, not all samples have a complete set of measurements and information available for comparison. The samples currently encompass the following range of pipeline steels:

- Vintage: 1939 to 2013
- Diameter: 4-inch to 24-inch
- Wall Thickness: 0.156-inch to 0.500-inch
- Grade: Grade B to X65
- Seam Types: ERW -DC, -LF, -HF; Flashweld; Lapweld; Seamless
- Grain Size: ASTM 5.9 to ASTM 13.7

It should be noted that approximately half of the samples available have unknown original specified properties as described above. The bar charts in Figure 4 indicate at what frequency each specific grade, seam weld, diameter, wall thickness, or vintage is present in the samples. Grade X52 is most common, ERW seam welds is the dominant type, wall thickness of 0.25-inch, with the rest of the properties fairly evenly distributed among the samples. Grain sizes range from 5.9 to 13.7 ASTM, with sizes predominantly between 10 and 12.5 ASTM.

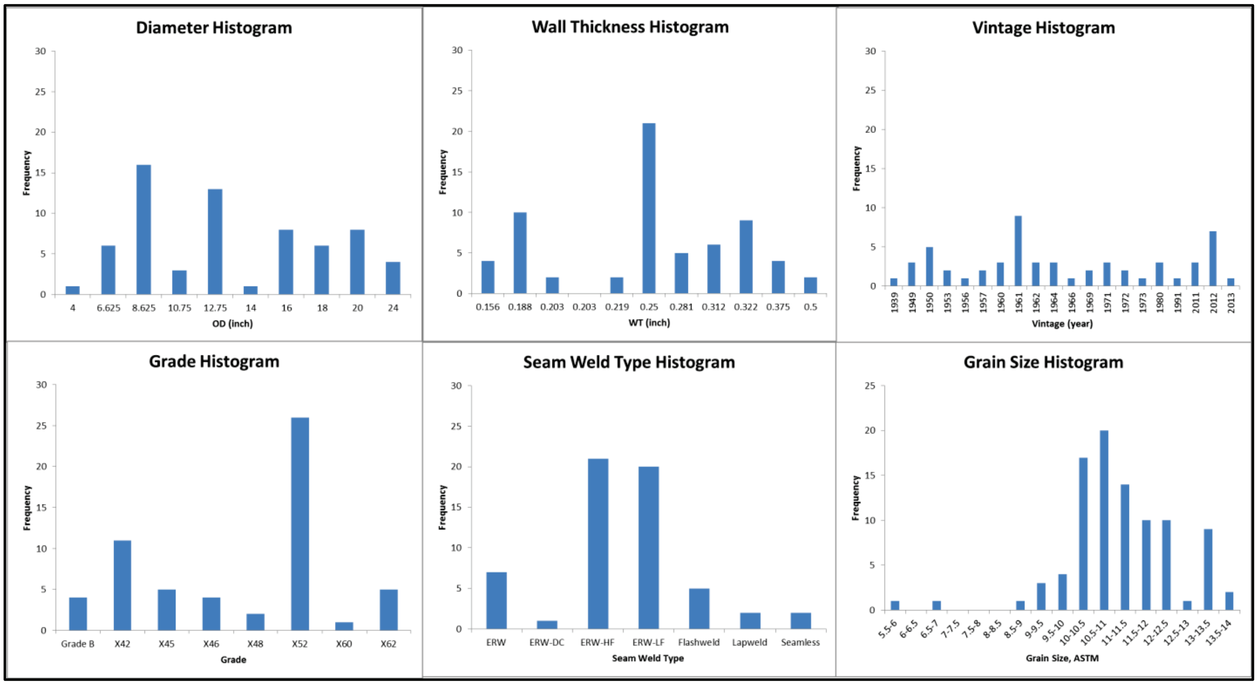


FIGURE 4. Frequency of pipe properties available from Kiefner sample data set.

General Correlations

The available data was investigated to look for any trends present between various mechanical and material properties. Correlation plots were created to relate the most likely property relationships as understood by the background information collected. The linear correlation coefficients for properties measured are given in Table 1. Using this table, prioritization was given to variables based on their strength of linear relationship. Hardness is a primary material property to obtain, which is known by the industry in that current studies are being centered on determining a more precise relationship between hardness and YS and UTS. Interestingly, the correlation coefficients for %Mn to YS, UTS, and hardness are also quite high. The other alloying elements which show a slightly higher correlation to YS, UTS, and hardness include %Si, %Nb, %V, and %Zr. However, %Nb, %V, and %Zr are relatively recent additions to the alloying process and therefore are likely simply indicate the result of recent vintage pipe being manufactured using a process that leads to higher a YS and UTS, and consequently, a higher hardness. It is likely, therefore, that a relationship between three or more variables would be required for a multi-variate model approach to obtaining a more accurate YS and UTS. By incorporating the %Mn and the hardness measurements, it may be possible to obtain a higher correlation coefficient, and a model which relates these two measurements to the desired mechanical property of YS and UTS. It should also be noted at this time, that this sample set is likely not ideal for performing preliminary tests on due to the wide variability of properties. There are too many variables to consider, thus leading to difficulties in obtaining strong relationships that are independently related.

The yield, hardness, grain size, %Mn, %Si, %C, and %S were plotted against one another in Figure 5. Some interesting notes can be made based on a visual assessment of these plots. First of all, there are some apparent linear relationships between grain size and hardness, yield and hardness, and possibly yield and %Mn. Outside of these, there seem to be too many outlying features to gain much more useful information.

TABLE 1. Linear correlation coefficients for the variables measured for various pipeline steel samples. Brighter red highlight indicates stronger linear correlation.

	% Ferrite	% Inclusion	Yield	Tensile	Elongation	Hardness	Grain Size	FSE (ft-lb)	Transition Temp (F)	Vintage	OD	WT
% Ferrite		0.328	0.118	0.441	0.248	0.360	0.047	0.341	0.195	0.310	0.001	0.130
% Inclusion	0.328		0.088	0.101	0.239	0.137	0.181	0.370	0.083	0.311	0.036	0.146
Yield	0.118	0.088		0.826	0.257	0.851	0.581	0.511	0.140	0.679	0.287	0.132
Tensile	0.441	0.101	0.826		0.342	0.960	0.508	0.239	0.147	0.401	0.392	0.096
Elongation	0.248	0.239	0.257	0.342		0.274	0.211	0.400	0.209	0.246	0.315	0.427
Hardness	0.360	0.137	0.855	0.960	0.274		0.532	0.326	0.143	0.458	0.397	0.156
Grain Size	0.047	0.181	0.581	0.508	0.211	0.532		0.589	0.488	0.690	0.269	0.039
FSE (ft-lb)	0.341	0.370	0.511	0.239	0.400	0.326	0.589		0.410	0.808	0.383	0.432
Trans Temp (F)	0.195	0.083	0.140	0.147	0.209	0.143	0.488	0.410		0.298	0.170	0.049
Vintage	0.310	0.311	0.679	0.401	0.246	0.458	0.690	0.808	0.298		0.208	0.241
OD	0.001	0.036	0.287	0.392	0.315	0.397	0.269	0.383	0.170	0.208		0.332
WT	0.130	0.146	0.132	0.096	0.427	0.156	0.039	0.432	0.049	0.241	0.332	
Carbon	0.614	0.381	0.416	0.024	0.364	0.084	0.441	0.761	0.298	0.804	0.190	0.341
Manganese	0.403	0.179	0.705	0.743	0.149	0.735	0.416	0.265	0.109	0.553	0.266	0.119
Sulfur	0.074	0.244	0.388	0.206	0.195	0.235	0.431	0.519	0.198	0.496	0.092	0.118
Phosphorus	0.292	0.384	0.095	0.358	0.227	0.395	0.094	0.163	0.066	0.192	0.156	0.029
Aluminum	0.221	0.340	0.616	0.435	0.151	0.523	0.621	0.646	0.139	0.798	0.276	0.375
Silicon	0.133	0.263	0.688	0.568	0.164	0.676	0.574	0.731	0.156	0.799	0.264	0.264
Niobium	0.200	0.254	0.772	0.617	0.035	0.650	0.646	0.541	0.319	0.677	0.217	0.160
Vanadium	0.089	0.037	0.716	0.557	0.003	0.690	0.440	0.513	0.142	0.653	0.216	0.059
Titanium	0.409	0.357	0.389	0.283	0.491	0.325	0.463	0.655	0.225	0.691	0.345	0.601
Chromium	0.001	0.246	0.242	0.153	0.031	0.147	0.134	0.240	0.106	0.085	0.165	0.037
Molybdenum	0.149	0.135	0.385	0.374	0.013	0.406	0.289	0.409	0.364	0.212	0.084	0.040
Copper	0.146	0.127	0.125	0.207	0.065	0.280	0.059	0.082	0.211	0.152	0.118	0.009
Calcium	0.062	0.299	0.103	0.098	0.104	0.083	0.313	0.415	0.043	0.418	0.155	0.158
Nickel	0.288	0.017	0.088	0.203	0.017	0.255	0.002	0.073	0.246	0.244	0.200	0.017
Tin	0.163	0.070	0.058	0.179	0.001	0.244	0.053	0.117	0.108	0.260	0.216	0.101
Cobalt	0.248	0.154	0.046	0.111	0.109	0.111	0.004	0.198	0.230	0.252	0.054	0.237
Boron	0.073	0.077	0.149	0.204	0.056	0.235	0.044	0.040	0.060	0.024	0.152	0.032
Zirconium	0.249	0.169	0.699	0.634	0.134	0.686	0.360	0.326	0.170	0.485	0.086	0.083

Based on our background knowledge of the advancements in manufacturing processes over the years causing potential for variability in trends, particularly with regards to chemical content, the data was next filtered by vintage as opposed to using this variable as a comparison within the relationships. Figure 5 shows the same plots with vintage listed instead on the color scale so that features can be picked out as to what general timeframe they are within on the correlation plots. It is interesting to find that the differing vintages tend to be clustered in certain locations within the plots. For example, the blue data points (pipe installed post-1980) tend to be clustered, and occasionally isolated from the majority of the red and grey data points (pipe installed pre-1980). The newer pipe (indicated by the blue data points) tends to not fit the trends as often, and appears to show a different trend than the older pipe. This occurs for nearly all the correlations shown in this Figure 5.

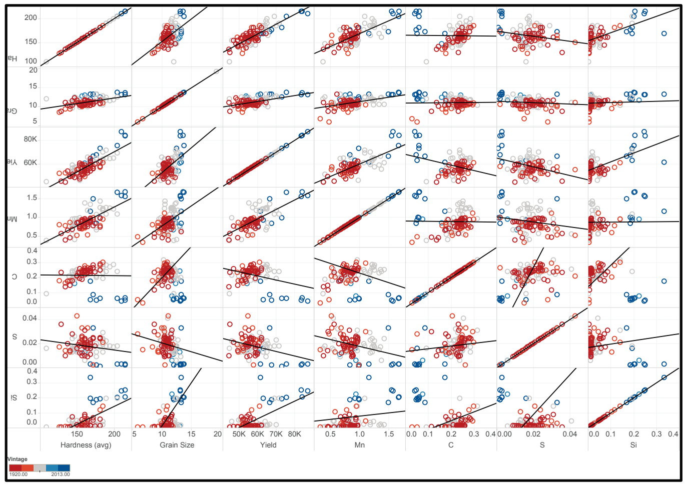
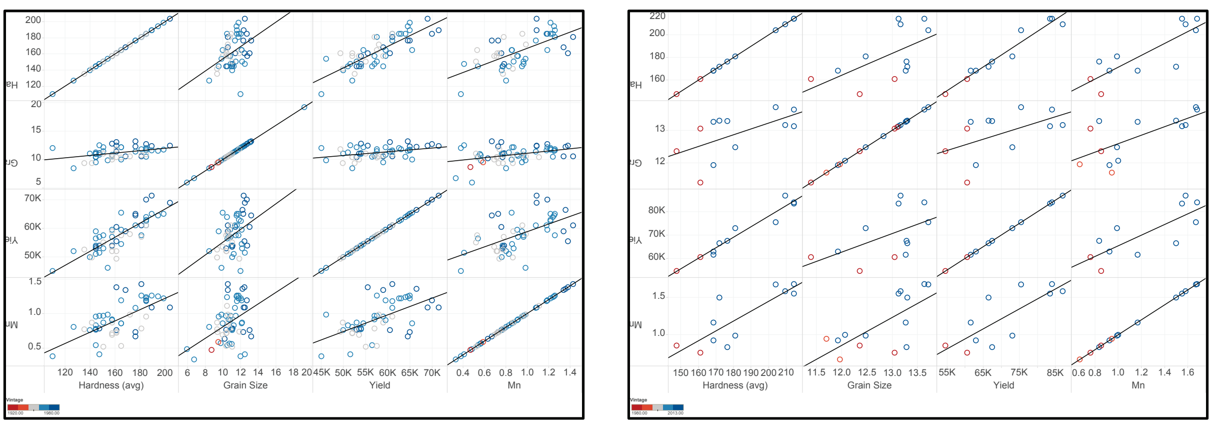


FIGURE 5. Linear regression plot comparisons for Yield, Hardness, Grain Size, %Mn, %Si, %C, %S. Vintage is indicated by the color scale, blue indicates newer vintage, red indicates older.

After filtering the data to remove pipe that is newer than 1980, in Figure 6a we can see that the relationships between hardness, yield, and %Mn, appear to be stronger. We are also seeing quite a bit more scatter in the %Mn to yield relationship than was observed previously, indicating our linear relationship was primarily based on the vintage and secondarily based on the correlation between %Mn and yield alone.

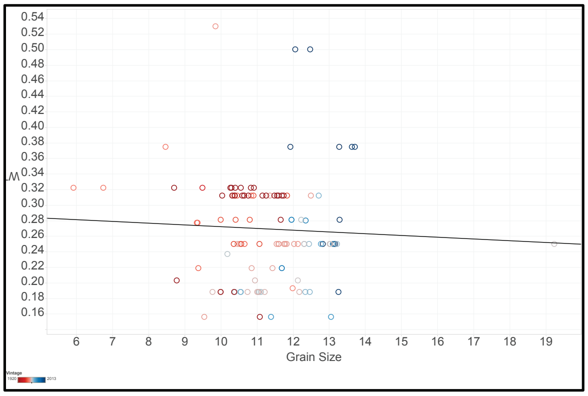


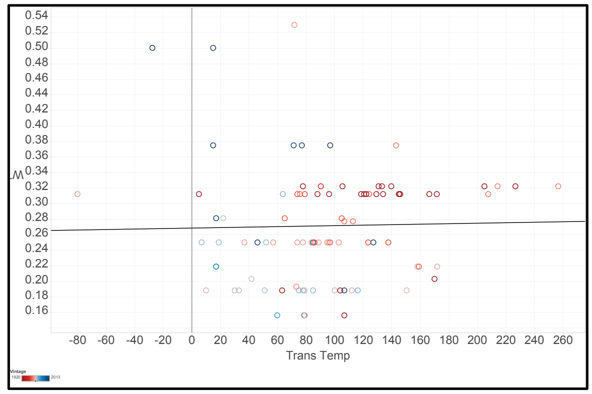
(a) (b)

FIGURE 6. Linear regression plot comparisons for Yield Hardness, Grain Size, %Mn. (a) Pipe vintage from 1920 to 1980. (b) Pipe vintage from 1980 to 2013.

In Figure 6b, the filter has been applied to show only pipe newer than 1980. This data set is considerably smaller, making it more difficult to be confident in the trends shown. However, the correlation between hardness and yield appears stronger, as well as the correlation between %Mn and hardness. Looking back at Figure 5, there may also be a decent correlation between %C and hardness or yield, but the amount of data and the current spread of the data does not allow for much confidence in those results.

Another correlation to consider is based on understanding of changes in manufacturing processes over time to look at grain size and wall thickness. As seen in Figure 7a and 7b, there is not any trend between these two characteristics of the pipe. It may be that there is not enough wall thickness variation in the samples to see a difference in grain size, or it may be that the normalization process to obtain consistent grain sizes was sufficient for these samples. The transition temperature was similarly plotted with the wall thickness, and no trend was observed.





(a) (b)

FIGURE 7. Wall thickness versus (a) grain size and (b) transition temperature.

The relationship between grain size and transition temperature presented by [25] was recreated using the sample data shown in Figure 8. The trend is largely the same, with the same slope, so we can be confident grain size and transition temperature are related in this nature. The correlation coefficient for this relationship is 0.488. It should be noted that the majority of the grain sizes lie between 10 and 13 ASTM; it would be helpful to collect more data from newer pipe samples that likely have smaller grain sizes for a better understanding of how the relationship holds for different vintage pipe as well as different grain sizes.

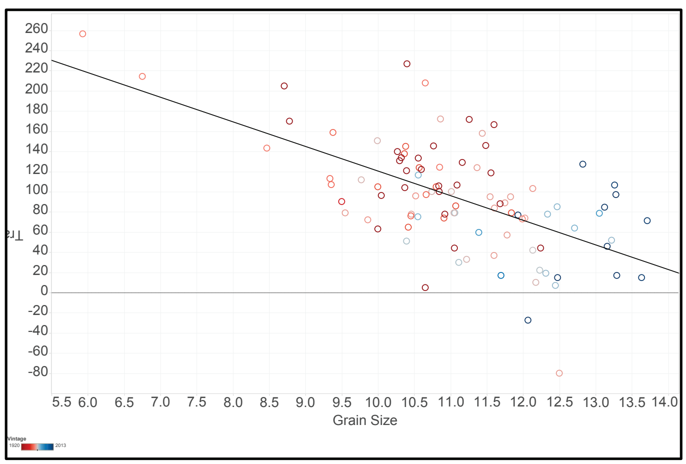


FIGURE 8. Grain size (ASTM) versus transition temperature (°F).

CONCLUSIONS

To understand the properties of a steel pipe, it is important to understand the many inter-related variables simultaneously present. The preceding material is to be used as a foundation of knowledge as to the current practices used to determine material properties, both destructively and nondestructively. The solution of determining material properties of pipe will not be a simple solution using a single measurement or single technology. It will require knowledge and understanding of several different material properties, how those are currently able to be obtained, whether destructively or nondestructively, and how they relate to desired mechanical properties.

There is promise for correlating the results of NDE measurement modalities to the information required to develop relationships between those measurements and the mechanical measurements desired for pipelines to ensure proper response to defects which are of significant threat.

Pipe has been manufactured for over a century, and manufacturing processes have vastly changed over time. Therefore, it is reasonable to expect that the relationships expected from a certain vintage range of pipe would be different from much newer pipe. This is shown by the sample data set, and is most notable in the differences in chemical content. What is not observed due to inadequate information on the sample data set, however, is the difference in manufacturing processes: whether the heat treatments applied, or the basic mechanics of how the plate is rolled, the pipe assembled; formed, spiral welded, seamless, or any of the other practices. It is recommended that more evaluation and research be performed to determine the accuracy and repeatability of destructive tests to determine its measurement error range. Without this knowledge, using nondestructive measurements and justifying their improved accuracy will be difficult, if not impossible.

While magnetic measurements are already being explored and applied by ILI companies, and it would be of use to obtain saturation, permeability, coercivity, and remanence measurements on the available sample data to see if the correlations are similar or better than what is available. More information on more recent vintage pipe would be helpful as well, to better understand the differences of vintage and pipe manufacturing practices. Additionally, creating a chart of the various ultrasound measurements such as velocity, attenuation, and backscatter grain noise could open up more insight as to how effective ultrasonic measurements are in determining the desired mechanical properties. However, measurements first need to be compiled, and then related in a similar manner.

Based on the results of this preliminary literature review and sample data analysis, there is promise for correlating the results of NDE measurement modalities to the information required to develop relationships between those measurements and the mechanical measurements desired of pipelines to ensure proper response to defects which are of significant threat. However, more work needs to be done to look at the multi-variate problem, and relationships that are not solely linear. More testing should be performed for ultrasonic measurements to gain more information about the viability of that technology to pipeline material characterization. Currently, there are too many inter-dependent variables that are either unknown, or unknown in their relationships to one another. Obtaining more samples with known, similar properties would help to isolate the variables, therefore assisting in the likelihood that relationships between other variables may be identified.

ACKNOWLEDGMENTS

This work was supported by the Competitive Academic Agreement Program of the United States Department of Transportation Pipeline and Hazardous Materials Safety Administration in collaboration with Kiefner and Associates Inc, Applus RTD, the Pacific Gas and Electric Company, and the Center for Nondestructive Evaluation.

REFERENCES

1. Kiefner, J.F., and M.J. Rosenfeld. The Role of Pipeline Age in Pipeline Safety. INGAA Foundation, Inc, 2012.
2. S. Nanney, “Overview of Integrity Verification Process (IVP) Workshop”, (PHMSA, Arlington, VA, August 7, 2013), Retrieved October 9, 2014, from http://www.phmsa.dot.gov/staticfiles/PHMSA/DownloadableFiles/Pipeline/Technical%20Advisory%20Committees/IVP_Meeting_Update_S_Nanney.pptx.
3. J.B. Nestleroth, and H.H. Haines, “NDE-4A Pipeline Discrepancy Analysis Using an ILI”, (Pipeline Research Council International, Houston, TX, 2013).
4. A. Belanger and T. Barker, “Multiple Data Inspection of Hard Spots and Cracking,” *ASME 2014 10th International Pipeline Conference*, IPC2014-33060, (ASME, Calgary, AB, Canada, 2014).
5. M.J. Gray, R.L. Fazackerley, and W.J. Fazackerley, “Tensile Property Variation in DSAW and ERW Line Pipe,” Final Report PR-187-9602, Line Pipe Supervisory Committee, Microalloying International, Inc., (Pipeline Research Council International, Inc, Houston, 1999).
6. L.E. Collins, M. Rashid, "Best Practices for Yield Stress Determination Using the Flattened Strap Tensile Test," *ASME 2014 10th International Pipeline Conference*, IPC2014-33684, (ASME, Calgary, AB, Canada, 2014).
7. A. Barbian, M. Beller, and U. Schneider, "Advanced Pipeline Inspection Utilizing Ultrasound: Special Applications," *Pipeline Technology Conference 2007*, (Euro Institute for Information and Technology Transfer in Environmental Protection, Hannover, Germany), pp. 1-10 (2007).
8. H.M. Crump, and S. Papenfuss, "Utilization of Magnetic Flux Leakage Inspection Pigs for Hard Spot Detection and Repair," (Corrosion 91), pp 366 (1991).

9. L. Pollard, A. Belanger, and T. Clarke, "Managing HIC Affected Pipelines Utilizing MFL Hard Spot Technology," (Corrosion 2004, New Orleans, LA).
10. J. Heingartner, M. Born, and P. Hora, "Eddy Current Measurement for the Nondestructive Acquisition of the Mechanical Properties of Sheet Metal," (NDT Article Prague 2009 Proceedings. Prague: NDT, 2009).
11. M. Schwind, “Zerstörungsfreie Ermittlung mechanischer Eigenschaften von,” (Meisenback, 1998).
12. M. Maass, “Bestimmung von richtungsabhängigen Werkstoffeigenschaften und,” (VDI Verlag, 2001).
13. D. Molenda, and W. Thale, "A Novel Approach for Pipe Grade Determination Through In-Line Inspection (ILI)," *ASME 2014 10th International Pipeline Conference*, IPC2014- 33441, (ASME, Calgary, AB, Canada, 2014).
14. C. De Leon, “ILI for MAOP & Pipe Grade Validation,” *AGA Operations Conference*, (Rosen, May 21 2015).
15. B. E. Engle, L. J. Smart, and L. J. Bond, “Nondestructive Characterization of Pipeline Materials,” in *Review of Progress in Quantitative Nondestructive Evaluation*, eds. D. E. Chimenti and L. J. Bond, (American Institute of Physics 1650, Melville, NY) **34**, 943-951 (2015).
16. P. Ramuhalli, R. M. Meyer, A. D. Cinson, T. L. Moran, M. Prowant, B. Watson, M. T. Anderson, "In-situ Characterization of Cast Stainless Steel Microstructures," *In Proceedings of the Eighth International Conference on NDE in Relation to Structural Integrity for Nuclear and Pressurized Components*, (Berlin, Germany, 2012).
17. M. Zergoug, A. Haddad, O. Bourdjam, and R. D. D. Ibrahim, “Micro-Structure Characterization by Micro Magnetic Methods,” *Centre de soudage et de contrôle, Laboratoire d'Electronique et d'Electrotechnique*, (ECNDT, Algeria 2006).
18. J. B. Nestleroth, and A. E. Crouch, “Variation of Magnetic Properties in Pipeline Steels,” (U.S. Department of Transportation, Washington, D.C., 1997).
19. A. Belanger, and R. Narayanan, "Calculation of Hardness Using High and Low Magnetic Fields," ECNDT 2006 - Tu.4.1.1, 2006.
20. H. Frenz, "Results of an Interlaboratory Comparison Test with 91 European Testing Laboratories," Material Testing, 40 (1998).
21. F. J. Margetan, B. R. Thompson, and T. P. Lerch, "An Analytical Approximation for a Common Ultrasonic Grain Noise Diffraction Integral," *In Review of Progress in Quantitative Nondestructive Evaluation*, eds. D. O. Thompson and D. E. Chimenti (American Institute of Physics 1650, Melville, NY) **18A**, 45-52 (1999).
22. D. A. Burgoon, O. C. Chang, R. B. Francini, B. N. Leis, and S. W. Rust, “Determining the Yield Strength of In-Service Pipe,” (ASME International CRTD, 1999).
23. B. Amend, "Using Hardness to Estimate Pipe Yield Strength; Field Application of ASME CRTD - Vol. 91," *2012 9th International Pipeline Conference*, (ASME, Calgary, AB, 2012).
24. E. J. Tyne, Pavlina, and C.J. Van, "Correlation of Yield Strength and Tensile Strength with Hardness for Steels," *In Journal of Materials Engineering and Performance* (ASM International), **17** (6), 888-893 (2008).
25. F.W. Boulgar, W.R. Hansen, "Role of Manufacturing Variables on the Properties of Line Pipe," AGA 3rd Line Pipe Symposium, 161-196 (1965).