

**MATERIAL CHARACTERIZATION OF PIPELINE STEELS: INSPECTION  
TECHNIQUES REVIEW AND POTENTIAL PROPERTY RELATIONSHIPS**

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**ABSTRACT**

The oil and gas industry in North America operates an aging infrastructure of pipelines, 70% of which were installed prior to 1980 and almost half of which were installed during the 1950s and 1960s. There is growing interest in having knowledge of pipe properties so that a safe operating pressure can be determined, yet there are a significant number of cases where records are incomplete. Current in-line inspection (ILI) technologies focus on defect detection and characterization, such as corrosion, cracking, and the achieved probability of detection (POD). As a part of the process in assessing defect significance it is necessary to know the pipe properties, so as to determine potential failure limits. The mechanical properties (yield strength, tensile strength and fracture toughness) of steel pipe must be known or conservatively estimated in order to safely respond to the presence of detected defects in an appropriate manner and to set the operating pressure. Material property measurements such as hardness, chemical content, grain size, and microstructure can likely be used to estimate the mechanical properties of steel pipe without requiring cut-outs to be taken from pipes for destructive tests.

There are in-ditch methods of inspection available or being developed that can potentially be used to determine many of the material characteristics and at least some mechanical properties. Furthermore, there is also potential ILI data to be used for obtaining some information. Advances in ILI technologies for this purpose are currently being explored by several interested parties. ILI companies are specifically focusing on relating magnetic measurements from eddy current

and magnetic flux leakage measurements to mechanical properties. ILI also regularly uses ultrasound measurements for wall thickness determination. Potential application of advances in ultrasound measurements for grain size and other properties are being explored. However, nondestructive methods of inspection in common use today usually do not enable determination of either the material or mechanical properties, leaving the only alternative to be destructive testing. This is costly, time-consuming, and often not practical for pipe that is in-service.

ILI and in-situ techniques are reviewed in this paper and provide an analysis of a sample set of data is presented. The paper explores the possibility of obtaining mechanical property data from data potentially measurable by ILI and in-situ measurements. Ideally, results would allow mechanical property measurements desired to assess pipelines so as to ensure that at a specific operating pressure there is the proper response to anomalies that might pose a significant threat. The use of a multivariate regression analysis showed better results than the traditional two-variable regression plots, and may be key to determining which properties are necessary to provide the best results for reliably estimating the mechanical properties of pipe. However, there is still much work to be done in understanding and accounting for the many sources of variability within the pipe material, and how that relates to the resultant relationships between the mechanical and material properties.

## **BACKGROUND**

### **In-Line Inspection Technologies**

ILIs are a commonly used form of nondestructive testing 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. A low-field magnetization (LFM) technique is currently being used instead of, or in addition to, the now traditional high resolution Magnetic Flux Leakage (MFL) tools to locate hard spots in older pipe and areas of mechanically induced damage in all pipe, as these are both potentially serious threats to integrity [1]. The catalyst to using this mode of measurement was the development of a relationship between the Gauss measurements and wall thicknesses. The first inspections using this technology utilized one tool module to magnetize the pipe and one to measure the residual magnetization [2]. More recent advances in the MFL tools now apply magnetization at a level near the maximum permeability of the steel to identify material property differences using a single tool [3]. The results of a study of the effectiveness of these tools showed that they are currently able to detect qualitative differences in hardness and are approaching the point where they can provide a method to quantify hardness measurements.

There are also distinguishable differences in response seen between samples that reflect the method by which the material was hardened, either by heat treatments or quenching of the material [1]. Using these concepts, this type of tool could detect differences in the hardness of pipe which can be related to the yield strength. If ILI tools were able to directly measure hardness, fewer verification digs would need to be performed to determine the properties of the pipe overall because hardness relates to yield. Improvements in this technology may lead to more precise measurements, which in turn could lead to a better understanding of the relationship between these MFL material measurements and mechanical hardness measurements. However, more work needs to be performed to fully understand how hardness, permeability, remanance, and coercivity relate to yield strength, tensile strength, fracture toughness, and transition temperature.

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 within  $\pm 2\%$  for tensile strength and  $\pm 4\%$  for breaking elongation [4]. Eddy current systems have a high sensitivity and respond to changes in the microstructure of a material, and is therefore a valuable measurement method for evaluating mechanical properties, if a correlation between these properties exists [5,6].

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 provide a more stable response from the measurement system [7]. By applying an appropriate excitation frequency, the field depth penetration is small enough that the effects of wall thickness are negligible, for pipe of wall thicknesses as low as 3

to 4 mm. Once an optimized excitation frequency and pre-magnetization levels were applied, reasonable depth penetration could be achieved, and a good correlation was shown between features in the data to determine the yield and tensile strength of the pipe. The final result of various pull tests showed that this technique provided a good prediction of yield strength. [7]

While methods of ultrasonic inspection are being developed and applied for managing current integrity threats, not much work has been performed that seeks to advance ultrasonic technology specifically for determination of pipeline properties. However, the ground work for understanding and applying the knowledge base shows that opportunities exist for such developments. A project was recently initiated with one task involving determining the viability of using ultrasonic measurements for determining grain size on pipe in order to verify its mechanical properties [8]. The longitudinal velocity, attenuation, and backscattered grain noise were all measured. With the samples provided for the study, grain size measurements obtained by traditional metallographic techniques were used to correlate with the grain size results obtained through ultrasonic technology. The results were inconclusive, in large part due to multi-parameter variability in pipe properties and there being only a small sample set. However, this work did demonstrate that the use of such measurements, when used in combination with other NDE tools, may enable measurements that give a better understanding of pipe properties.

### **In-Situ Measurement Techniques**

Typical methods for determining the chemical composition of a carbon steel material include use of x-ray fluorescence (XRF) or optical emission spectroscopy (OES) chemical analysis. XRF sends a beam of x-rays into the material, the atoms of the material absorb the x-rays, and each element re-emits x-rays with a unique energy/spectral signature. The identification of characteristic energies (spectral lines) is used to determine the chemical make-up of that material. OES uses a spark to excite atoms of a material, which then emits pulses of light. The analysis of the spectrum is then used to identify the chemical composition. Each method independently reveals valuable information about the chemical composition. OES probes are able to measure more of the lighter elements, such as carbon, than XRF.

Hardness testing performed in the ditch commonly produce hardness results in Vickers. Such measurements have been shown to give good correlation to yield strength, and may be used to determine a lower bound yield strength for in-service pipe of grade X52 or lower, manufactured prior to 1980 and with a diameter greater than 4 inches [9]. Work is currently in progress in the industry to improve this method, making it more reliable for in-ditch applications. [10] Linear relationships between hardness and tensile and yield strengths have been studied and found to be valid for steels with yield strengths between 325 MPa and 1,700 MPa (47 ksi and 246 ksi) and tensile strengths between 450 MPa and 2350 MPa (65 ksi to 340 ksi). [10] Additional studies provided similar linear

relationships, with some variations in the correlation relationships that appear to be due to differences in sample microstructure and compositions. [11]

A detailed study showed that hardness is strongly correlated to the magnetic coercivity of pipeline steel; it had a linear correlation coefficient of 0.83 [12]. Furthermore, the relationship between hardness was shown to have a correlation coefficient of 0.86 with yield strength, and 0.96 with ultimate tensile strength [12].

### Statistics

When performing a linear regression analysis, understanding the outputs is important to gaining useful information. A regression line is the predicted or fitted  $\hat{Y}$  value – the mean of Y given X, as shown by Equation (1), where  $b_o$  is the intercept of the model and  $b_1$  is the model coefficient. [13]

$$\hat{Y} = \hat{\mu}_{Y|X} = b_o + b_1X \quad (1)$$

The residual errors are the differences between the observed value and the predicted value shown in Equation 2.

$$e(\text{error}) = Y(\text{observed value}) - \hat{Y}(\text{predicted value}) \quad (2)$$

The standard deviation of these errors is called the residual standard error and this gives an estimate for the average, or typical error of the model.

A few assumptions are made when fitting a linear regression model.

- 1) The Y-values (or the errors, “e”) are independent.
- 2) The Y-values can be expressed as a linear function of the X variable.
- 3) Variation of observations around the regression line (the residual SE) is constant
- 4) For given value of X, Y values (or the error) are normally distributed

The first assumption requires knowledge of data collection to determine the validity of the system. The remaining three assumptions can be checked by examining the residuals of the errors. If the linearity assumption is met, there would be no pattern in the “Residual vs Fitted” plot – the data points will appear to be a cloud of data, and the red fit line would be expected to be straight at 0. The Normal Q-Q (Quantile-Quantile) plot would be expected to appear as a diagonal line if the data is normally distributed. With a multiple linear regression model with multiple x-variables, it is necessary to make the same set of assumptions as a simple linear regression model, but it is not possible to produce a scatterplot of data with more than three variables. The regression diagnostic plots described above allow the user to test the validity of the assumptions required for performing multivariable regression

model statistics, with the general model equation sample shown in Equation 3.

$$\hat{Y} = b_o + b_1X_1 + b_2X_2 + \dots + b_KX_K \quad (3)$$

The p-value is used to test the null hypothesis that all the model coefficients are zero. Calculating Pearson’s correlation between variables gives an indication as to whether or not the variables are dependent upon each other, e.g., the collinearity between % Mn, Hardness, and Grain Size means that one should not directly interpret slopes seen in data as the effect of parameters on the Yield Strength adjusting for each other. A high correlation between variables suggests that the two effects are bounded together.

### ANALYSIS AND RESULTS

The Kiefner and Associates, Inc. laboratory evaluated 94 test coupons and these are used here for preliminary evaluation of potential correlations between material and mechanical properties, or to observe any other significant trends which may become apparent. Information obtained from the test coupons included grain size, percent (%) ferrite, % inclusion content, yield strength, tensile strength, elongation, hardness, full size equivalent (FSE) upper-shelf Charpy vee-notch (CVN) impact energy (toughness), 85% shear-area transition temperatures, and composition (% Mn, S, P, Al, V, Ti, Cr, Mo, Cu, Ca, Ni, Sn, Zr, Co, B). Carbon equivalent (IIW) was not investigated for this study, but may be useful to determine better understanding and will be used for future studies. Information such as pipe diameter, wall thickness, specified grade, seam weld type, and vintage was also provided where available. However, not all samples have a complete set of data from measurements and the related sample source description information 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 1 indicate the frequency with which each specified grade, seam type, diameter, wall thickness, or vintage are present in the samples. Grade X52, ERW seam welds and a wall thickness of 0.25-inch are the most common metrics, 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.

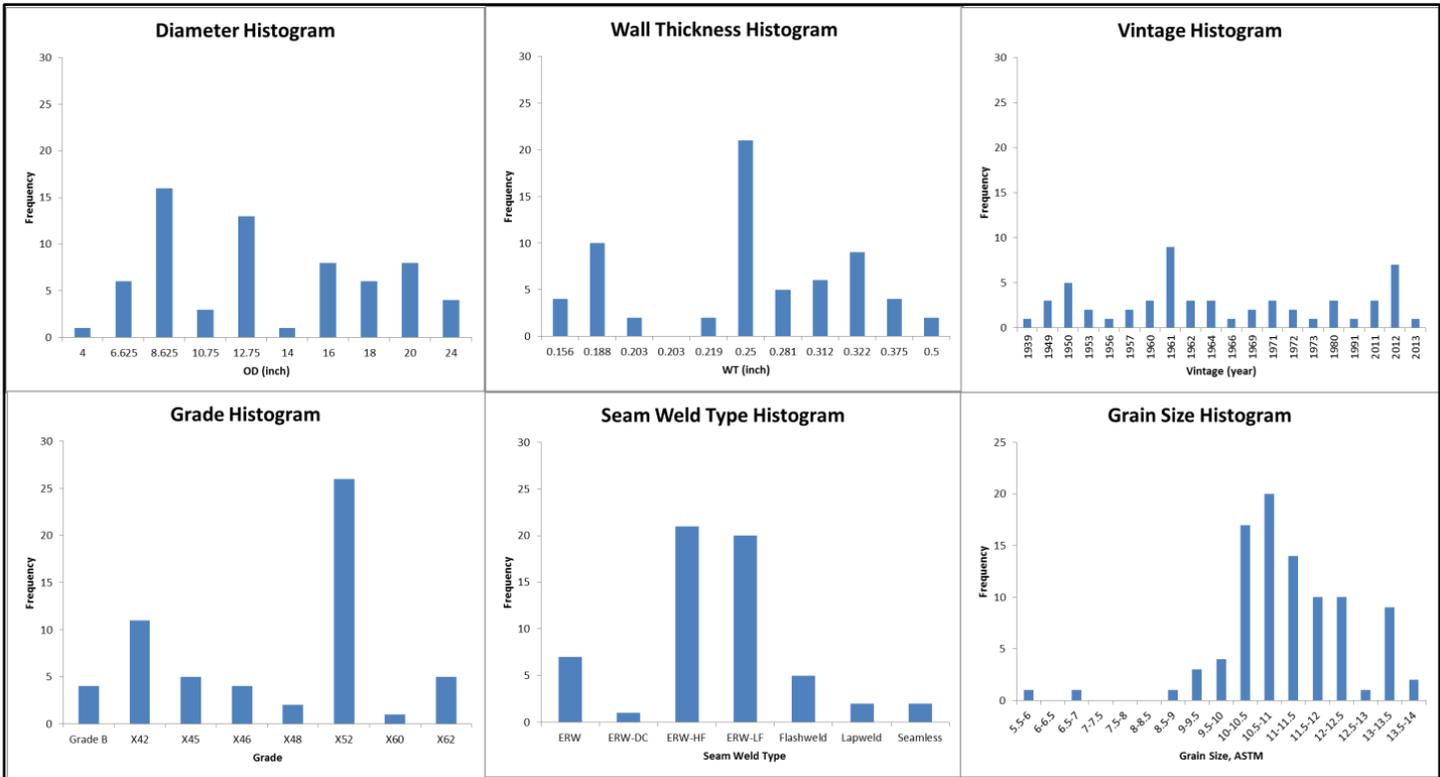


Figure 1. Frequency of pipe properties available from Kiefner sample data set.

The data for all variables were plotted on a simple linear regression plot, and the correlation coefficients were determined to be as shown in Table 1. Note that the empty cells in the table correspond to a perfect correlation of 1. The brighter red highlighted cells indicate a stronger correlation, for example, hardness is more strongly correlated to tensile strength.

The four plots shown in Figure 2 and Figure 3 are simple linear regression plots of two chemical components, hardness, and ASTM grain size number showing how they relate to the

yield strength. The plot of % C to yield shows that there is a strong difference between the relationship of % C to yield between the pre-1980 pipe and post-1980 pipe. This is most likely a result of improved manufacturing processes now being used to produce higher strength, lower carbon steels and should be noted when attempting to correlate pipe yield strengths with chemical content information. Figure 4 shows the effect of vintage in relation to the fracture toughness, but also shows that fracture toughness is not strongly correlated individually to the effects of hardness, ASTM grain size number, % C or % Mn.

Table 1. Linear correlation coefficients for the variables measured for various pipeline steel samples.

	% 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	0.855	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

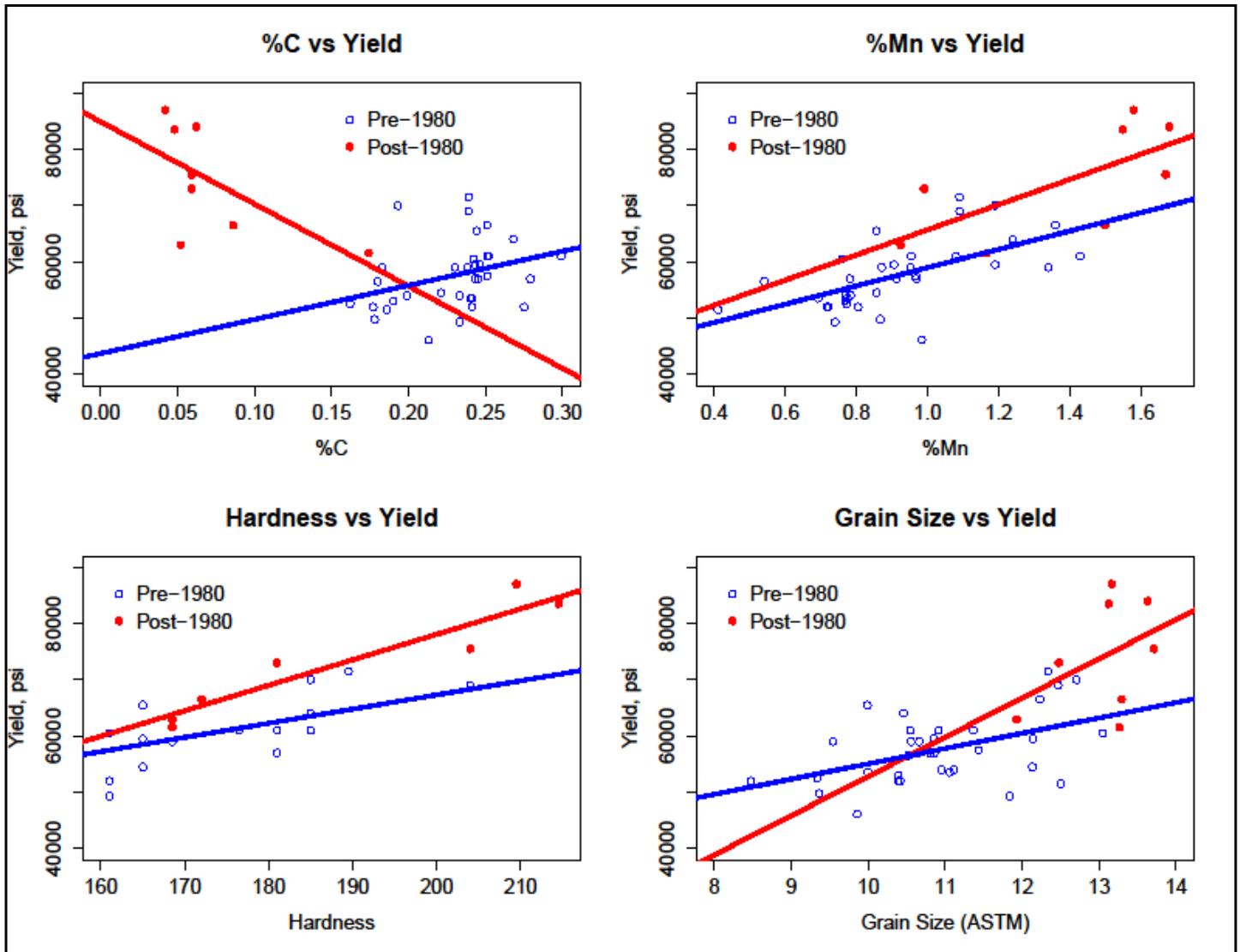


Figure 2. Linear regression plots for yield strength observing the effect of vintage

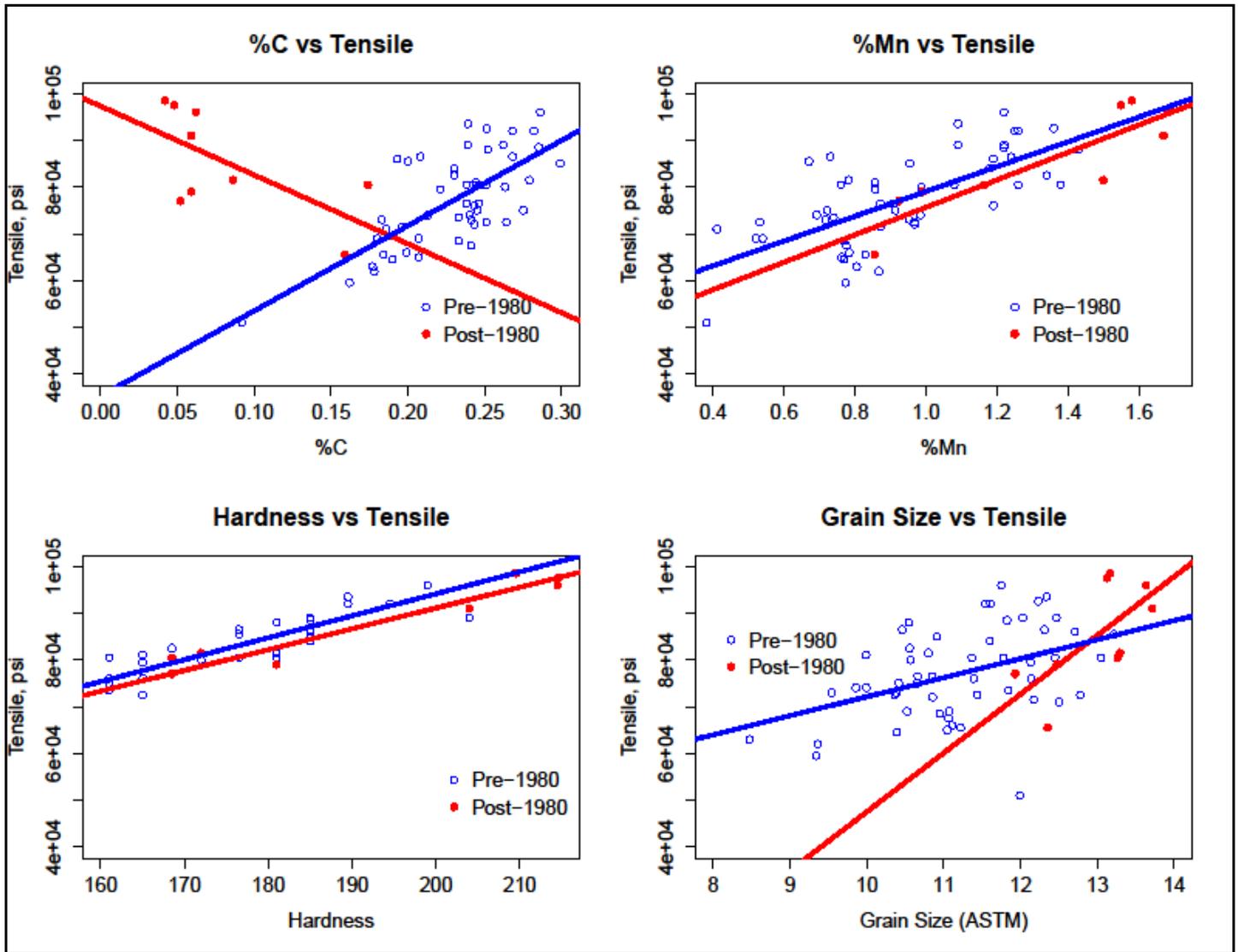


Figure 3. Linear regression plots for tensile strength observing the effect of vintage

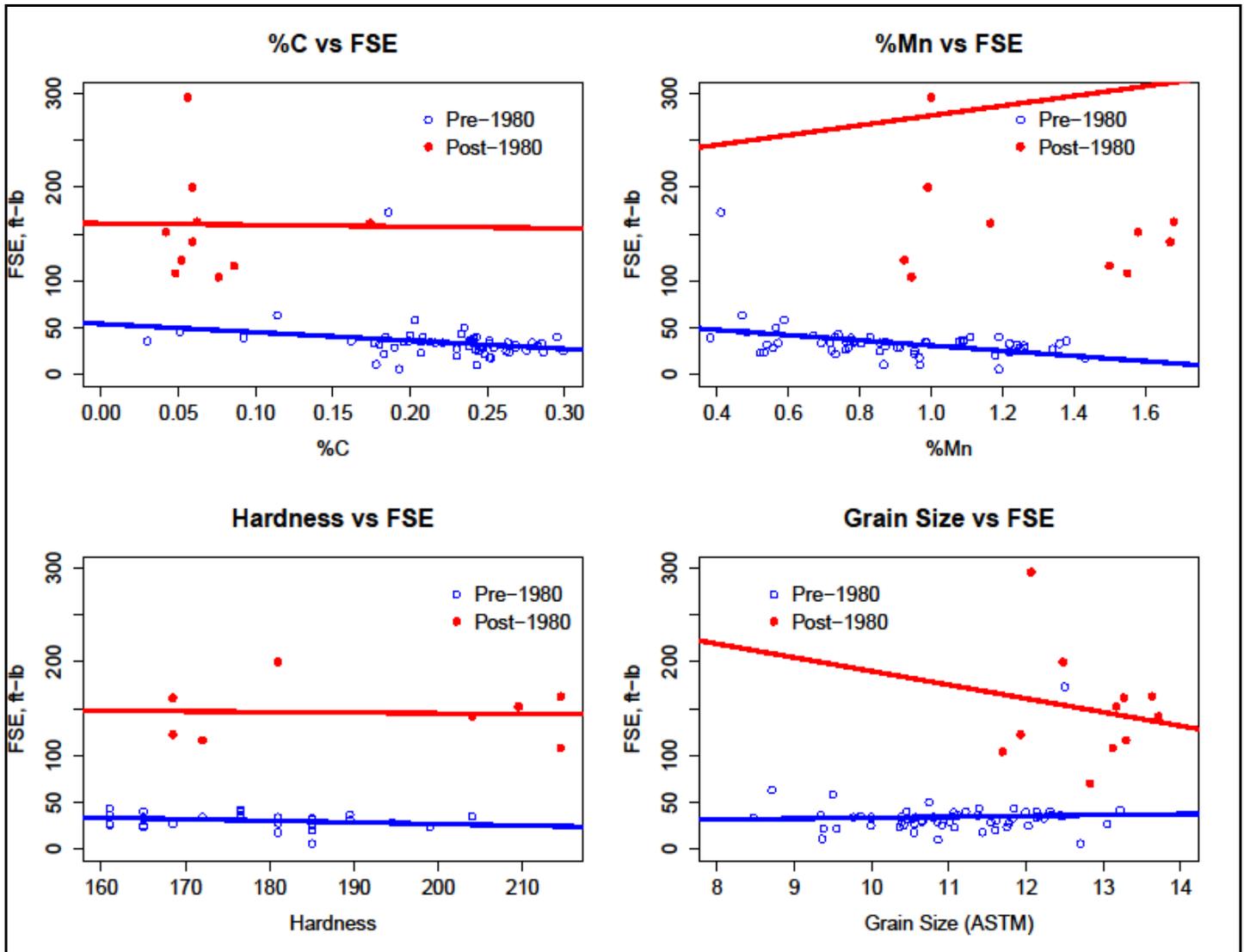
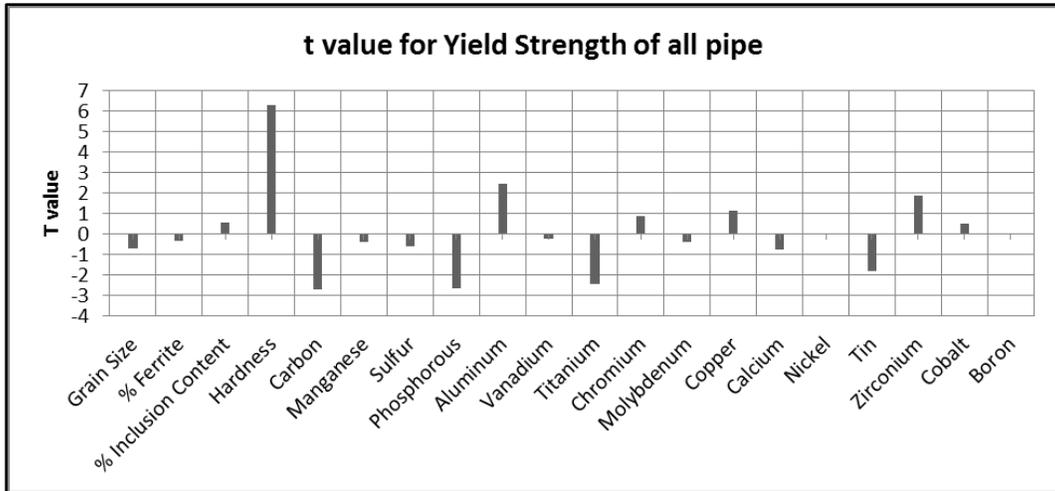


Figure 4. Linear regression plots for fracture toughness observing the effect of vintage.

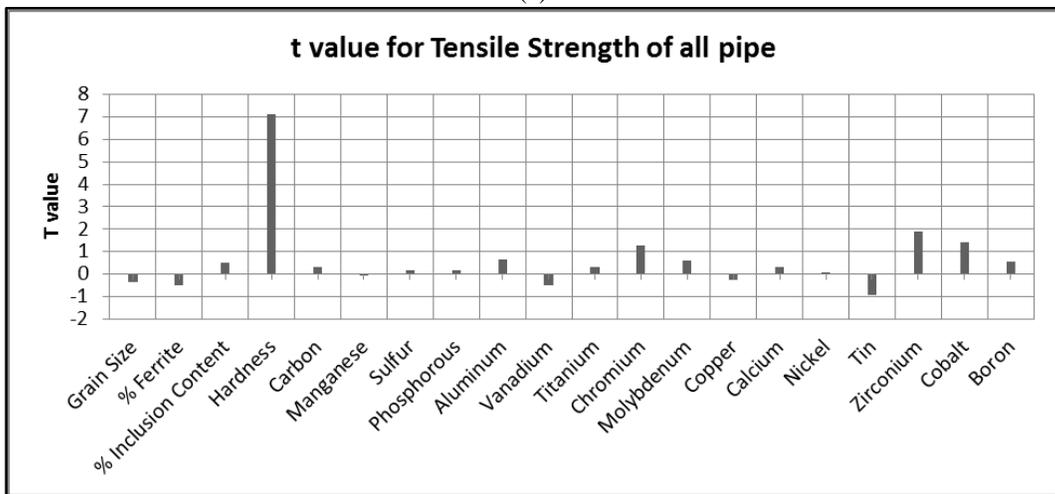
Multivariate regression models can be developed using the knowledge that the results are dependent upon the vintage. Integrating all the available variables and distinguishing the results between all the pipe samples and then again for pipe samples with a year of manufacture prior to 1980, a more accurate model can be developed. In order to determine which variables are more influential in terms of the response of the overall model, t values may be obtained. This t value is an indication as to how strong the relationship is, either negatively or positively, from the individual variable to the overall model. All available input variables were fitted to a single model and analyzed for their significance in determining the three

mechanical properties of interest. The resulting t values are shown in Figure 5.

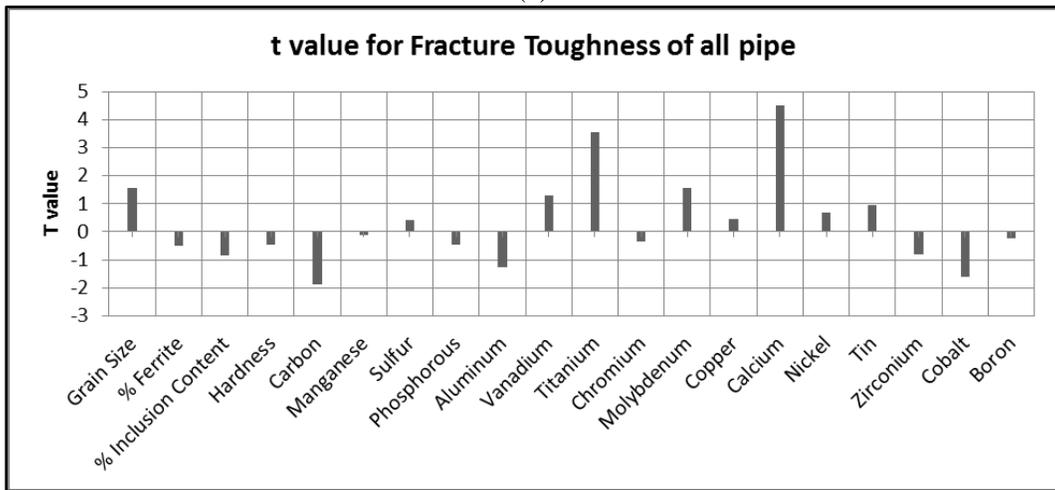
As is expected, hardness is the most significant variable in determining yield and tensile strength, while grain size and various chemical in the composition occurring in the sample were more significant in determining fracture toughness. However, there is not one single variable that stands out as a predictor for fracture toughness in the way that hardness does for yield and tensile strength models. This is likely due to the fact that Charpy energy is a measurement of ductility rather than a direct toughness indicator, and also contains more variability in general.



(a)



(b)



(c)

Figure 5. t values for the variables included in the multivariate regression model for (a) Yield Strength (b) Tensile Strength and (c) Fracture Toughness.

The data for multivariate models cannot be plotted on simple regression plots as shown in Figure 2 through Figure 4, therefore the statistical outputs themselves must be analyzed. The summarized information can be found in Table 2. This table provides the results for a model which includes grain size, %-ferrite, %-inclusion content, hardness, and %-chemical content. The data is also provided for all vintage pipe and into a pre-1980 bin to show the differences present. The “Residual Standard Error” value gives an idea of how far the observed yield values are from the predicted or fitted values for the variable that is being examined based on the overall model; a lower value indicating less error in the model. The “Multiple R-Squared” is an approximation of how much of the variation in the yield, tensile, or fracture toughness output can be accommodated by the model with a higher percentage indicating a better model. The p-value is used to test the null hypothesis that all the model coefficients are zero. In other words, it is an indication of the significance of the model. Lower p-values suggest that the samples available provide enough data to reject the null hypothesis for the entire population. Thus, the pre-1980 data has slightly higher p-values due to there being a smaller sample size available. All of the p-values in this case are quite low, indicating the sample data is significant for use in the model.

**Table 2. Statistical outputs for the multivariate regression analysis divided by vintage.**

		Residual Standard Error	Multiple R-Squared	P-Value
All Data	Yield Strength (psi)	3070	0.89	<2.2E-16
	Tensile Strength (psi)	3175	0.89	<2.2E-16
	Toughness (ft-lb)	21.68	0.87	7.01E-10
Pre-1980 Data	Yield Strength (psi)	2164	0.95	9.20E-05
	Tensile Strength (psi)	2356	0.97	7.70E-06
	Toughness (ft-lb)	12.03	0.94	1.38E-03

Using the t-values shown in Figure 4, the most significant variables were analyzed in a similar statistical fashion as is provided in Table 2. Table 3 shows the difference seen when

using only hardness as a model variable for determining yield and tensile strengths, and only grain size in the model for predicting fracture toughness. Hardness provides a reasonable prediction, but obtaining additional information is beneficial in estimating a value with less variation. The estimation of fracture toughness appears to be a more complex problem, as grain size alone does not give a good model basis for predicting fracture toughness. There was no clear single variable that gave strong relationships for prediction of fracture toughness; therefore the use of a multivariate analysis would appear to be beneficial in the prediction of this property, such as by incorporating both chemical composition and microstructure data. It may be of interest to look at microstructure as it relates to fracture toughness for the pre-1980 pipe. The residual error for toughness is quite high, even for the case of using all variables, unless the data is segmented by vintage.

Going back to the t value plots as obtained previously, the data shown in Figure 6 represents the t values for fracture toughness based on pre-1980 pipe segments. With this plot, there is still not a clear picture of which variables contribute more strongly to predicting the fracture toughness. Consequently, this is the reason that all the variables are required to be included within the multivariate regression model in order to obtain a residual error for fracture toughness of less than 20 ft-lbs, which is implied by in the data in Table 2 and Table 3.

**Table 3. Statistical outputs for the linear regression analysis divided by vintage.**

		Residual Standard Error	Multiple R-Squared	P-Value
All Data	Yield Strength (psi)	4180	0.69	<2.2E-16
	Tensile Strength (psi)	3073	0.88	<2.2E-16
	Toughness (ft-lb)	43.27	0.17	3.49E-05
Pre-1980 Data	Yield Strength (psi)	3525	0.66	6.28E-13
	Tensile Strength (psi)	2869	0.92	<2.2E-16
	Toughness (ft-lb)	21.18	.0053	0.5872

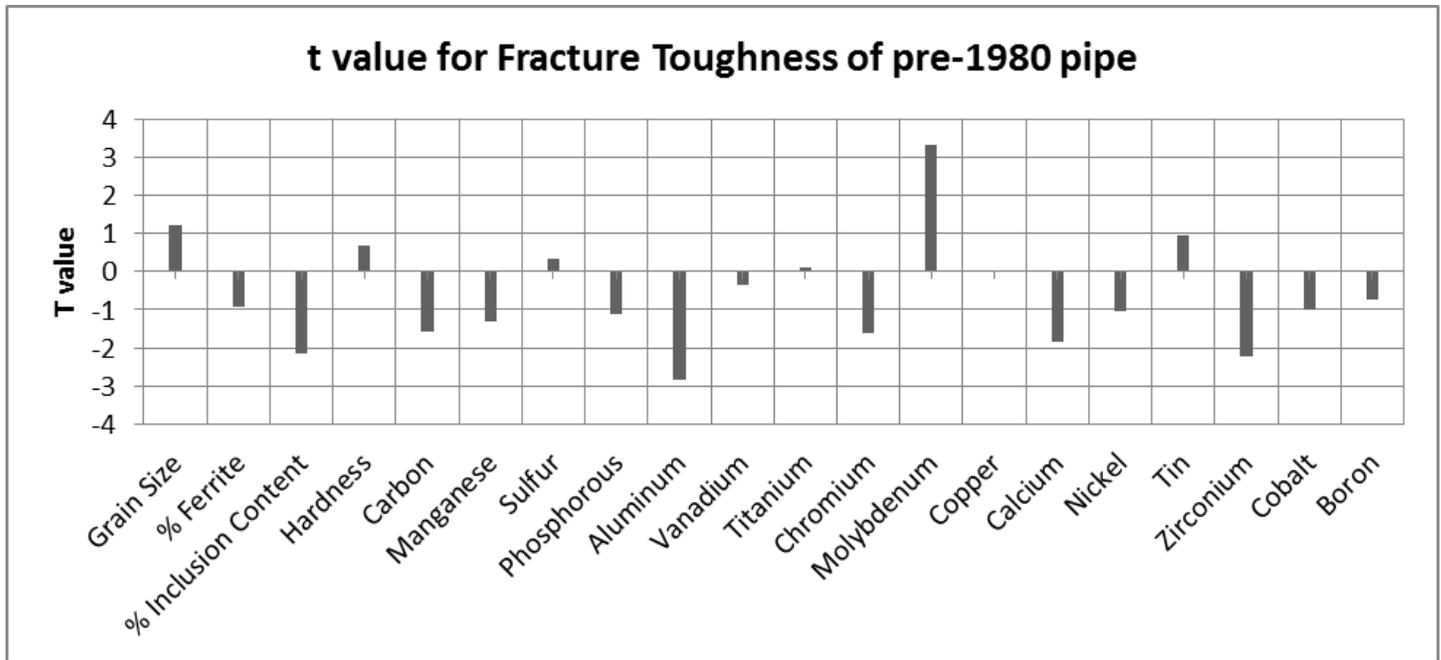


Figure 6. t values for the variables included in the multivariate regression model for Fracture Toughness in pipe older than 1980

## CONCLUSIONS

To understand the relationships between properties of a steel pipe, it is important to understand the effects of many inter-related variables simultaneously. The aim is to use measurements of pipe properties as predictors for desired mechanical properties.

The current study has demonstrated relationships that can potentially be used as the starting point in establishing relationships, as it relates to current practices employed to determine material properties, both destructively and nondestructively.

Developing relationships to predict pipe mechanical properties will not be a simple task and there is clearly not a solution that can be achieved by using a single measurement or single measurement technology. It will require knowledge and understanding of several different material properties, how those property measurements are currently obtained, whether destructively or nondestructively, and how they relate to prediction of the desired pipe mechanical properties.

There is indication that it may be possible to correlate 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.

A major complication is that line pipe has been manufactured for over a century, and manufacturing processes have changed significantly over this time. Therefore, it is reasonable to expect that the relationships from a certain vintage range of pipe would be different from those for much newer pipe. This is shown by the sample data set, and is most

notable in the differences in chemical content. The variables not observed due to inadequate information on the sample data set, however, are the effects of differences in manufacturing processes, such as steel rolling practices, pipe forming methods, welding processes, and heat treatments. It is recommended that more evaluation and research be performed to determine the accuracy and repeatability of destructive tests, so as to determine 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 some ILI companies, it would be of use to obtain saturation, permeability, coercivity, and remanence measurements in MFL 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 effects of differences due to 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 of pipe. However, measurements first need to be performed on a large sample set, data compiled, and then related in a similar manner to the analyses reported here.

Based on the results of a preliminary 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 [14].

However, more work needs to be performed to investigate 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. Additionally, understanding of current measurement techniques (destructive or otherwise) and their measurement errors should be included in future studies to determine the level of accuracy needed in the NDE techniques that are to be investigated during future studies.

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