Ultrasonic and magnetic Barkhausen emission measurements for characterization of pipeline steels

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Ultrasonic and magnetic Barkhausen emission measurements for characterization of pipeline steels

Abstract
To ensure that the aging pipeline infrastructure in the USA can be safely operated, the mechanical properties of the pipe materials must be verified. It is hypothesized that characterization of the pipeline steels and their microstructures through nondestructive methods will allow for the estimation of the mechanical properties of interest, namely yield strength, tensile strength, toughness, and ductile-to-brittle transition temperature. This work will discuss how material properties, such as microstructure and chemical composition, affect the mechanical properties as well as strategies for measuring the material properties nondestructively using magnetic Barkhausen emission and ultrasonic velocity and attenuation measurements. Preliminary results on a limited sample set will be shown and challenges encountered will be discussed.

Keywords
Materials properties, Ultrasonic phenomena, Magnetism, Mechanical stress, Mechanical properties

Disciplines
Materials Science and Engineering | Mechanics of Materials

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Ultrasonic and Magnetic Barkhausen Emission Measurements for Characterization of Pipeline Steels

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Abstract. To ensure that the aging pipeline infrastructure in the USA can be safely operated, the mechanical properties of the pipe materials must be verified. It is hypothesized that characterization of the pipeline steels and their microstructures through nondestructive methods will allow for the estimation of the mechanical properties of interest, namely yield strength, tensile strength, toughness, and ductile-to-brittle transition temperature. This work will discuss how material properties, such as microstructure and chemical composition, affect the mechanical properties as well as strategies for measuring the material properties nondestructively using magnetic Barkhausen emission and ultrasonic velocity and attenuation measurements. Preliminary results on a limited sample set will be shown and challenges encountered will be discussed.

INTRODUCTION

There is a network of over 300,000 miles of natural gas pipelines in the United States. Much of this infrastructure is from the 1950s/60s/70s. To ensure safe operation of the in-service pipe four parameters of interest have been identified that should be determined: yield strength, tensile strength, toughness, and the ductile-to-brittle transition temperature.

\textbf{FIGURE 1.} Conceptual overview of problem highlighting two focus areas.
Two sources of pipeline sample data were available for this work: 1) a database including several dozen samples with information such as grain size, pearlite content, chemical composition, and destructive test results for mechanical properties, and 2) on-hand samples consisting of eight pipeline samples with known grain size, chemical composition, and destructive test results, and five samples with known chemical composition and destructive test results. Both the on-hand samples and the database were taken from previously in-service pipelines.

**CASE STUDY: PREDICTING YIELD STRENGTH**

One of the mechanical properties of interest, yield strength, has been shown to have relationships with hardness and grain size [1, 2]. The trend between yield and grain size can roughly be seen in the database of samples seen in Fig. 2. The on-hand samples do not exhibit this trend.

![Yield Strength as a Function of Grain Size](image)

**FIGURE 2.** Yield strength as a function of the inverse square root of grain size.

Hardness is commonly used to predict yield strength using a linear model [2]. It is hypothesized that an estimation of yield strength using hardness and grain size would be more accurate than a prediction using just hardness.

To test this hypothesis, four linear models were made using 75 samples from the sample database with known yield strength:

- Only hardness,
- hardness and microstructure (which includes the inverse square root of grain size, ferrite percentage, and inclusion percentage),
- hardness, microstructure, and carbon equivalent, and
- hardness, microstructure, and individual chemical elements.

The carbon equivalent is a weldability parameter defined as

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

\[
CE(C > 0.12\%) = C + \frac{Mn}{6} + \frac{(Cr + Mo + V)}{5} + \frac{(Ni + Cu)}{15}
\]
A linear model between hardness and yield strength gives 57 out of the 75 samples having a predicted yield strength within ±10% of the true value. The model adding in microstructure gives slightly better predictions, with 61 samples having a predicted yield strength within ±10% of the true value. Including the carbon equivalent causes almost no change, giving 60 samples having a predicted yield strength within ±10% of the true value. Allowing each chemical element to be an independent variable, along with hardness and the microstructural parameters, gives 71 out of 75 samples having a predicted yield strength within ±10% of the true value.

Figure 5 shows the t-statistic for each variable in each of the linear models, which is an estimate of the contri-
bution to the prediction of the model. In each model hardness has the largest contribution to the prediction, followed by the inverse square root of grain size for all except the model that has each element as an independent variable. For that model, phosphorus has the second largest contribution to the prediction and the microstructural information has the same contribution as many of the other chemical elements. It is noteworthy that the t-statistic for carbon indicates that a decrease in carbon leads to an increase in yield strength, which goes against the common knowledge seen in the literature [1].

![Graphs showing t-statistics for each independent variable.](image)

**FIGURE 5.** t-statistics for each independent variable. The t-statistic gives the contribution to the prediction from each variable.

## EXPERIMENTAL RESULTS

Ultrasonic and magnetic measurements were performed to see what variation there would between the on-hand samples. A 5 MHz shear-wave contact transducer was used to measure velocity and attenuation in the samples. The attenuation was measured as

$$\alpha(f) = -\frac{1}{2z} \ln \left( \frac{\Gamma_2(f)}{\Gamma_1(f)} \right)$$

where $z$ is the sample thickness and $\Gamma_1$ and $\Gamma_2$ are the spectra of the first and second back wall reverberations, respectively. The attenuation as a function of frequency was largely varying such that comparing attenuation at different
specific frequencies gave very different results. This may be due to using a transducer with too low of center frequency.

**FIGURE 6.** Example of steps in attenuation calculation: top: windowed back wall signals, middle: spectra of back wall signals, bottom: ratio of spectra as given in Eq. 3.

**FIGURE 7.** Attenuation at two frequencies and yield strength as a function of grain size.

The velocity was measured with the shear wave polarity in three directions for each sample: in the axial direction, the hoop direction, and 45 degrees between the two. A directional dependence in velocity can be an indicator of crystallographic texture, which in turn could lead to anisotropy in strength. Figure 8 shows the velocity results, and varying degrees of directional dependence can be seen in the samples, from almost no dependence on direction to almost 5% variation. This may indicate that the samples were processed in different ways.
Preliminary magnetic Barkhausen noise measurements were made on a subset of samples using a commercial Stresstech Rollscan system, but a coating on one sample led to a very small response, and a variation was seen in the Barkhausen response for samples with the same yield strength. This highlights the sensitivity of the measurement technique to the condition of the surface of the sample.

CONCLUSIONS AND FUTURE WORK

- Yield strength prediction using hardness, microstructure, and chemical composition with each element as an independent variable gives a better prediction than using hardness alone.
- Some of the contributions to yield strength prediction are counter to what was expected based on the literature, notably carbon content.
- Our on-hand samples do not exhibit the expected relationship between grain size and yield strength.
- No consistent trend can be seen between ultrasonic attenuation and grain size, though using a higher frequency transducer may address this.
- The on-hand samples show varying degrees of directional dependence for shear wave velocity, which may be an indicator of different manufacturing processes.
- No correlations were seen in the Barkhausen measurements done on a small set of samples, but this was due in part to surface coatings negatively affecting the measurements.

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