FINAL REPORT

Date of Report: *September 29, 2017*

Contract Number: DTPH5615T00014

Prepared for: *Government Agency: DOT*

Project Title: "Use of Electromagnetic Sensors to Quantify Strength and Toughness in Steel Pipelines In and Out Of Service"

Prepared by: Angelique N. Lasseigne, *Generation 2 Materials Technology LLC (G2MT)*

Contact Information: Joshua E. Jackson, Phone: 303-895-7146, Email: josh@g2mt.com

ABSTRACT

G2MT LLC, proposed a two-year research program to develop a nondestructive testing technology to rapidly evaluate pipeline mechanical properties. The proposal was in response to the PHMSA BAA DTPH5615RA00001 for the topic 'Development of Inspection Tools to Quantify Pipe Strength and Toughness'. G2MT LLC produced a new nondestructive electromagnetic sensor for assessment of bulk strength and toughness of new and vintage steel pipelines operating in any environment. The strength and toughness of the steel pipelines determined from the electromagnetic system will be linked with other inspection and materials characterization testing to provide improved Risk-Based Integrity Management. The proposed sensor development supports the mission of PHMSA to protect people and the environment from the risks inherent in the transportation of hazardous materials by providing an effective method to determine the actual integrity of steel pipelines in or out of service. The technology will enable optimized transport through pipelines by predicting the highest safe operating pressure based on real-world measurements of mechanical properties, including both the strength and toughness.

I. BACKGROUND

The US infrastructure has thousands of miles of unknown and poorly characterized pipelines in service. To safely operate these existing pipelines, the pipeline operators are being forced to dig up representative sections of pipe for material property characterization in laboratories. The cost to analyze these pipelines could easily reach in the billions of dollars just to measure a small fraction of the joints in a line. Because of the enormous costs to characterize the existing pipeline infrastructure, DOT-PHMSA pushed for a more effective and thorough understanding of our pipeline infrastructure utilizing non-destructive tools that can assess real-time bulk material properties to determine the optimum safe operating parameters for aging pipelines.

EXISTING TOOLS FOR ASSESSMENT OF MECHANICAL PROPERTIES OF PIPELINES DURING SERVICE

Over the past century, the pipeline industry has utilized various techniques in the field to estimate the tensile and yield strength of pipelines. These typical techniques include: field hardness measurements and microstructural replication techniques. Unfortunately, these techniques only offer information about the properties of the pipe at the OD pipe surface as opposed to the bulk material properties. Surface measurements are of limited accuracy for many reasons, such as: (1) the hardness and microstructure at the outer diameter (OD) and inner diameter (ID) are often very different than the bulk material properties, (2) scaling, corrosion, pitting, coatings, quenching, and solidification dynamics can all result in different mechanical properties at the OD and ID surface of pipes than in the bulk, and (3) usually the ID has experienced long-term exposure to corrosive media (both stagnant and flowing) while the OD surface may have been insulated (well or poorly) or exposed to the environment. Figure 1 shows an optical micrograph of a cross-section of a high strength pipe steel pipeline that failed in service, showing how the microstructure of the pipeline steel at the OD surface is often completely different than the bulk microstructure and properties.[1]

To remove this layer to test the bulk properties would create a weak point in the pipeline, so surface measurements are a catch-22. And because pipelines are graded by yield strength (X65 must meet or exceed 65 ksi yield strength), they can have a huge variance in fabrication processes, microstructures, and mechanical properties. The reality is that surface properties are not reliably representative of the bulk material properties, so any field technique that produces results based solely on measurements at the OD/ID surface could cause catastrophic consequences for a pipeline company.

Due to the lack of other viable options, the hardness and field metallographic replication techniques remain the most popular choice for most inspection companies because they are easy and cheap, even if the results are of questionable value. At the 2015 Pipeline Pigging Integrity Management Conference in Houston, Texas, two new techniques to measure yield strength in pipelines were presented. The first technique was a combination of metallographic replication with hardness and chemistry testing in the field[2]; this practice is both time consuming and very limited in its application because only the properties of the external pipe surface (OD) are characterized. The second technique is based on eddy current principles to measure changes in the magnetic permeability to correlate to hardness.[3] These techniques are only combining old technologies that have been around for decades.[4-8] In addition, a new system has been developed by a company called Massachusetts Materials Technology and was presented at the Offshore Technology Conference in Houston, Texas. The system is touted as non-destructive, however to perform measurements, a system is attached to the external surface of the pipe and then the pipe is physically scraped (to remove surface) to try to estimate the strength and toughness. This new sensor has the same downfall as all of the other surface techniques being that it only works at the surface, it is not non-destructive, and it is once again only a measurement of the tensile strength. New techniques that continue to focus on surface measurements are not providing any benefits or useful data to the pipeline industry.

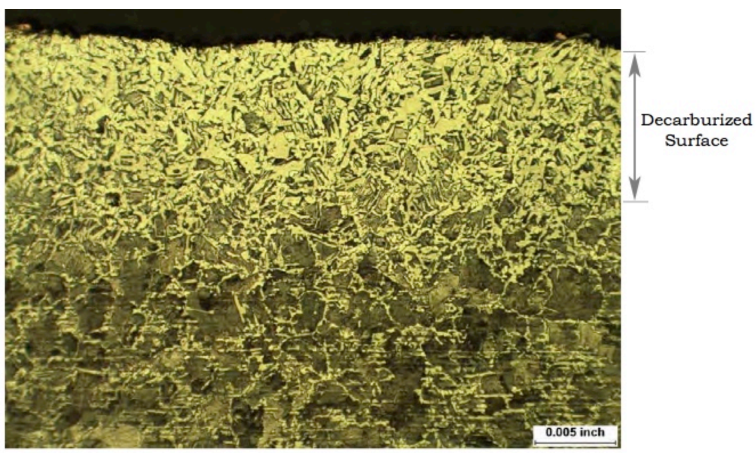


Figure 1: Optical micrograph of pipeline specimen that was in service from 1945 until 2002 showing the differences in microstructure at the OD pipe wall surface.

There are actual non-destructive tools available for characterizing material properties. For example, eddy currents measurements have been directly linked to hardness for so long that nearly every inspection company in the U.S. offers eddy current testing to determine material hardness.[9-17] The problem with using eddy current to determine hardness is: (1) that the actual depth of penetration of eddy currents in steel is on the order of a couple of millimeters (at most), which makes the typical eddy current systems subject to the same problems as surface hardness measurements and (2) hardness is comparable to tensile strength, but not yield strength properties. The huge variance of the microstructures in Figure 1 at the OD surface are common for pipelines; therefore utilizing surface measurements to determine the properties and integrity of pipelines is bound to provide a false sense of integrity, security, and safety.

Beyond hardness and metallographic replications measurements providing information only about the surface being tested, hardness and surface metallographic replications techniques are incapable of providing an accurate indication of the bulk microstructure, and especially of how that microstructure will fail: **will it fail under brittle cleavage, micro-void coalescence, or both?** This is the reason that the toughness and not only the strength of the vintage pipeline need to be determined. ***Currently there are no existing techniques to measure toughness in the field.***

Because so many new techniques are hardness based, it is important to point out the lack of success in using hardness techniques in other industries like electric power, for example. The electric power industry replaced 2 ¼ Cr-1Mo alloys for a new improved P91/T91 (9Cr-1Mo) steel for pressure vessels, piping, and tubing. The acceptance criteria for these new P91/T91 steels are based on hardness. Within months of installation many of the new P91/T91 components began failing and are still failing at less than one percent of their designed service life. These P91/T91 components began to fail because many of the components were not properly processed so that the microstructure exhibited a ferritic matrix with very large and coarse incoherent carbides as opposed to the fine, coherent carbides that the P91/T91 is designed to have. Hardness measurements are simply not capable of distinguishing between the "good" and "bad" carbides, which dramatically alter the difference in service-life of P91/T91 components. The electric power industry is still reeling from this problem with no major solution still in sight. The pipeline industry is still learning this mistake and is still basing the integrity of our pipeline infrastructure on the type of measurement **systems that cannot differentiate between the good and bad microstructural characteristics** that could result in catastrophic pipeline failures.

The solution for both the pipeline and power industries is to measure the actual mechanical properties, such as strength and toughness, based on the steel's electronic structure, which is a measure of the crystal structure and microstructure (the size, shape, locations of grains and inclusions, etc.). The crystal structure and microstructure predicts the steel properties. The specific crystal structure (body-centered cubic (BCC), face-centered cubic (FCC), hexagonal close-packed (HCP), etc.) of steel, for example, determines the material properties because the 'real' strength and toughness values are inversely related to the mobility of dislocations (linear defects) in the crystal lattice.[19] The number and type of dislocations possible, the magnitude and direction of dislocation slip, and the lattice friction stress (the Peierl's stress) all influence the base strength level and the strength-temperature dependence.[19] The steel's toughness is dependent on the method in which dislocations are generated and impeded in each specific steel crystal structure. Therefore, the ideal solution for the pipeline industry is a non-destructive sensor that measures the actual yield strength and toughness based on the actual microstructural characteristics of the steel.

II. CHALLENGE

The challenge was to accurately develop a pipeline sensor that can provide the actual real-time bulk mechanical properties in a rapid, cost-effective manner to enable improved operation through better understanding of the remaining strength and most likely failure mode (brittle versus ductile) of vintage steel pipelines.

III. CHOSEN APPROACH

G2MT proposed the development of an electromagnetic material property sensor system that measures electronic structure properties to provide real-time quantified bulk strength and toughness values for vintage pipelines. ***How can it be done?*** By evaluating the microstructure (the microscopic arrangement of the atoms in a metal) through electronic property measurements, which determines the strength and cracking resistance (toughness) of steel pipelines. The proposed sensor technology **supports the PHMSA mission** to guarantee the safe operation and security of the vast, aging U.S. pipeline infrastructure by providing optimized operation, safety, and capacity of existing and new pipelines. Once commercialized, this sensor technology should be broadly applicable to improved mechanical integrity, quality assurance, and maintenance practices in many fields (such as drilling, offshore, medical devices, automotive; basically any industry that wants to know "real" quality and integrity of their components).

IV. DISCUSSION AND RESULTS OF THE OBJECTIVES

To develop and implement the electromagnetic strength and toughness sensors in the field, the technical objectives and tasks included:

Objective 1*: Begin calibration procedures to develop the electronic property (to be called the* ***eProperty™*** *system) to quantify strength and toughness on any steel pipeline located in the United States. The pipeline steels can have yield strengths potentially ranging from less than 40 ksi (past) to greater than 120 ksi (future).*

Task 1. Collect vintage pipe samples from cost share partners.

Task 2. Perform measurements on pipes in the field (using various probes) and remove sections of pipe when possible to bring to G2MT for full metallurgical characterization.

Task 3. Fully characterize (chemical analysis, mechanical properties, microstructure, etc.) all vintage pipeline specimens that have not already undergone rigorous characterization.

Task 4. Characterize the strength and toughness of vintage pipe sections in terms of microstructure and fracture characteristics to evaluate brittle & ductile fracture behavior.

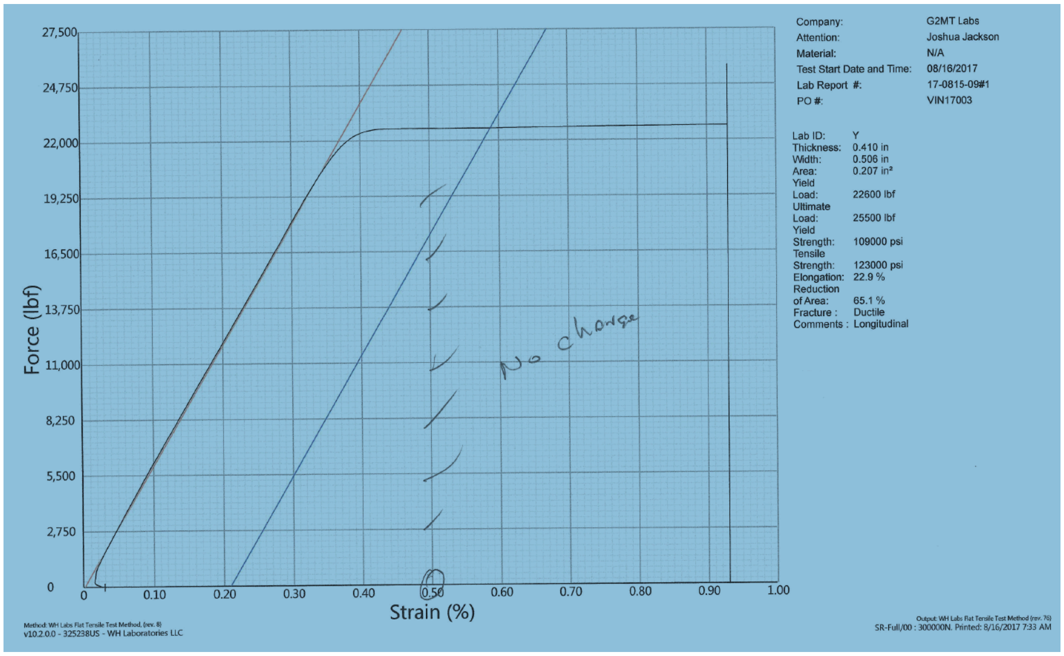
During completion of Objective 1, G2MT collected vintage, new, and used pipe. G2MT fully characterized the microstructure and mechanical properties of all the as-received pipe sections and included the information in a database as seen in Figure 2. The database is used for sensor development and calibration. G2MT also spent time comparing the variation in mechanical properties around the circumference of the pipeline and along the length. G2MT found that the mechanical properties have large variations depending on location of the measurement and the specimen preparation. For example, G2MT performed tensile tests on the same pipe with two samples taken directly adjacent to one another. One sample was a full-sized tensile specimen that is flattened and the other sample is a machined sample without any flattening. These sample preparation methods are both common practices utilized and accepted for tensile testing. The tensile testing results of the same pipe with different sample preparation are shown in Figure 3. The yield strength in the first tensile graph is 109 ksi, while the yield strength in the second tensile graph is 118 ksi. These tests indicate that there is a 9 ksi difference in the yield strength between these two tests. These results are extremely concerning because depending on which method is used, there will be large variations in yield strengths. The difference in the tensile test results is caused by the flattening of the full-size specimens. When the specimens or ends of the specimens are flattened, the material is cold-worked which means that the mechanical properties are being altered.

Considering the tensile testing results, G2MT made sure to systematically perform all tensile tests utilizing the machined specimen method. Because of this discovery, G2MT also decided not to accept any pre-performed data from our industrial partners because we could not guarantee the accuracy. The accuracy of the mechanical property data predicts the accuracy of the electromagnetic measurements. Boardwalk Pipeline was actually involved in a large court case that boiled down to the accuracy of the tensile tests. One company reported the failed pipe mechanical properties to be out of specification, while another company performed the same test and found the pipe mechanical properties to be within specification. The experts in court found that the full-size specimens provided inaccurate information by the flattening process that occurred during the specimen preparation.

Vickers	Tensile Strength	Yield Strength	OD	Wall Thickness	ID	Chemistry ID#	Fe	C	Si	Mn	P	S	Cr	Mo	Ni	Cu	V	Nb	Ti	N	Micro	Structure
122.3	72300	50200	8.63	0.25	8.06	16001	98.8500	0.1900	0.2600	0.6400	0.0120	0.0050	0.0100	0.0030	#####	0.0070	0.0040				50x	500x
150.2	82900	54100	23.00	0.40	23.13	16003	98.2400	0.1600	0.3300	1.0400	0.0080	0.0090	0.0700	0.0350	0.0390	0.0360	0.0330				50x	500x
155.0	88700	79600	19.94	1.00	17.88	16004	97.8720	0.0800	0.3600	1.5600	0.0190	0.0050	0.0200	0.0030	0.0080	0.0130	0.0600				50x	500x
157.4	85300	47700	8.25	0.79	6.63	16006	98.4810	0.2000	0.3300	0.8000	0.0220	0.0030	0.0600	0.0120	0.0500	0.0380	0.0040				50x	500x
136.6	68300	42700	10.75	0.83	9.00	16007	98.6450	0.1700	0.4100	0.5000	0.0080	0.0200	0.0600	0.0050	0.0700	0.1100	0.0020				50x	500x
185.1	89600	75500	26.63	0.50	25.56	16008	98.3140	0.0500	0.3200	1.2000	0.0200	0.0050	0.0190	0.0020	0.0090	0.0110	0.0500				50x	500x
153.8	80000	64900	29.88	0.39	29.06	16010	98.3910	0.1000	0.4000	1.0400	0.0130	0.0040	0.0120	0.0080	0.0160	0.0130	0.0030				50x	500x
137.1	69700	57400	4.50	0.19	4.06	16011	98.8760	0.1800	0.0600	0.6400	0.0130	0.0230	0.0330	0.0030	0.1100	0.0600	0.0020				50x	500x
147.3	74300	64600	4.50	0.20	4.06	16012	98.8550	0.0800	0.1600	0.8300	0.0180	0.0070	0.0140	0.0020	0.0140	0.0160	0.0040				50x	500x
190.3	90400	82600	26.63	0.50	25.63	16015	98.3630	0.0500	0.2800	1.2000	0.0160	0.0060	0.0230	0.0020	0.0100	0.0100	0.0400				50x	500x
190.1	93800	61700	30.50	0.32	29.75	16016	98.5620	0.2000	0.0360	0.9500	0.0130	0.0190	0.0250	0.0020	0.1200	0.0700	0.0030				50x	500x
147.1	81700	48500	30.38	0.32	29.63	16017	98.5020	0.2100	0.0900	0.9800	0.0190	0.0210	0.0120	0.0020	0.1000	0.0600	0.0040				50x	500x
147.2	78100	67500	4.50	0.19	4.06	16020	98.8520	0.0700	0.1500	0.8500	0.0180	0.0070	0.0160	0.0020	0.0140	0.0160	0.0050				50x	500x
166.4	87900	60300	8.63	0.32	7.94	16021	98.2590	0.1400	0.3800	1.1300	0.0190	0.0050	0.0150	0.0020	0.0220	0.0240	0.0040				50x	500x
140.1	77200	54100	10.75	0.37	10.00	16022	98.0280	0.1600	0.3900	1.1300	0.0150	0.0040	0.2000	0.0030	0.0270	0.0400	0.0030				50x	500x
120.7	71100	45700	12.75	0.32	12.13	16024	99.2080	0.2000	0.0290	0.4400	0.0120	0.0260	0.0250	0.0080	0.0160	0.0350	0.0010				50x	500x
174.7	95300	61200	16.00	0.25	15.44	16025	98.1500	0.2600	0.0700	1.1900	0.0130	0.0180	0.0280	0.0070	0.0800	0.1800	0.0040				50x	500x
151.1	82200	49100	31.00	0.33	30.38	16026	98.5320	0.2100	0.0800	0.9100	0.0200	0.0240	0.0220	0.0080	0.1200	0.0700	0.0040				50x	500x
147.5	82200	59500	12.75	0.38	12.00	16028	98.7470	0.1400	0.1800	0.8700	0.0240	0.0040	0.0210	0.0020	0.0020	0.0080	0.0020				50x	500x
154.9	86900	69700	10.75	0.37	10.00	16029	98.6600	0.1400	0.1900	0.9200	0.0170	0.0050	0.0220	0.0080	0.0110	0.0250	0.0020				50x	500x
144.5	77600	57400	10.75	0.37	10.00	16030	98.7230	0.1400	0.2000	0.8800	0.0170	0.0050	0.0170	0.0030	0.0020	0.0100	0.0030				50x	500x

Figure 2: Screenshot of the pipe sample database.

(a)



(b)

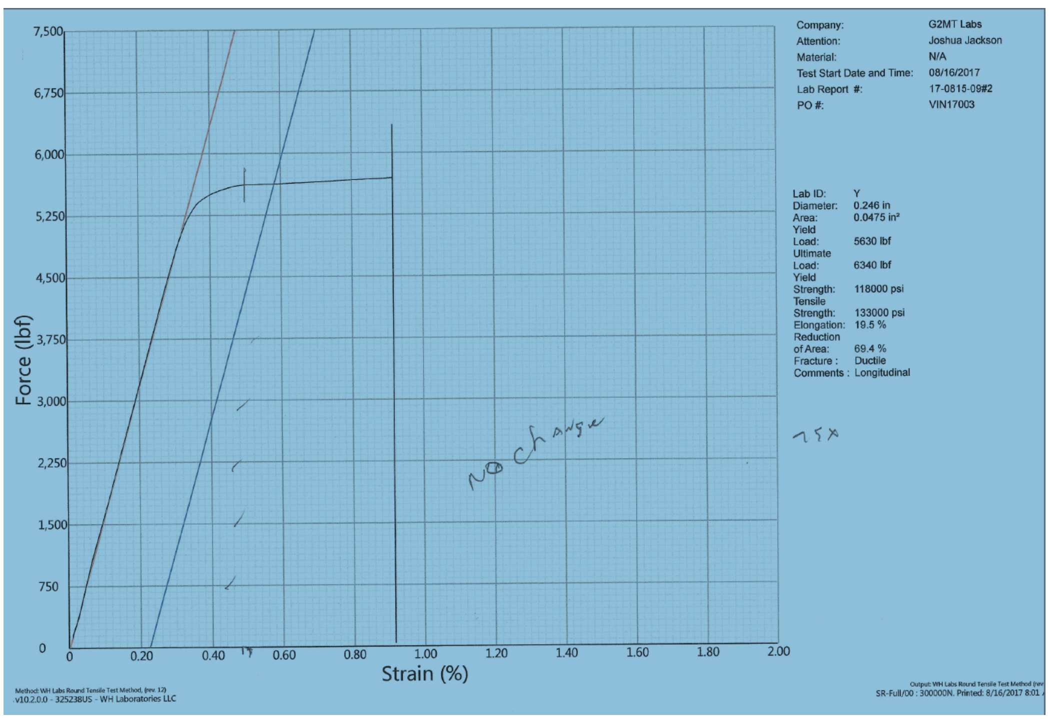


Figure 3: Tensile tests performed on the same section of pipe (adjacent to one another) with (a) the full size specimen that was flattened and therefore cold-worked and (b) the specimen machined to size. The difference in yield between the two is caused by the cold-working of the full-sized specimen which provides erroneous results.

Objective 2:* *Calibrate ePropertyTM system to quantify the strength and toughness measurements.

Task 5. Compare and analyze electromagnetic results and pipe metallurgical characterization results, and determine the relationships between microstructure and mechanical properties.

Task 6. Determine the sensitivity of the electromagnetic sensors to small and large variations in strength and toughness.

Task 7. Determine which probe design is optimum for maximum sensitivity, repeatability, and ease of use for an in-ditch sensor. The same probes that are used for the in-ditch sensor can be installed onto existing "smart" pig system to gather information at rapid speeds along much longer sections of a pipeline. Note that G2MT has already developed their sensor to gather data quickly for rapid inspection of heat exchanger tubes.

Task 8. Develop algorithm to quantify strength and toughness in vintage pipelines.

G2MT worked on calibrating and improving the calibrations throughout the entire length of the project. G2MT worked on establishing relationships between electromagnetic properties such as impedance and yield strength as shown in the graph in Figure 4. The graph in Figure 4 shows the change in impedance with increasing yield from 40 to 50 ksi. Notice that the impedance decreases with increasing yield strength. G2MT established relationships between electromagnetic measurements and mechanical properties up to 120 ksi yield strengths (thus far). G2MT will always continue to characterize additional steel pipes to add to the database to increase the intelligence of the sensors. These relationships established between electromagnetic properties and mechanical properties are not valuable without proper variable separation as discussion in Objective 3.

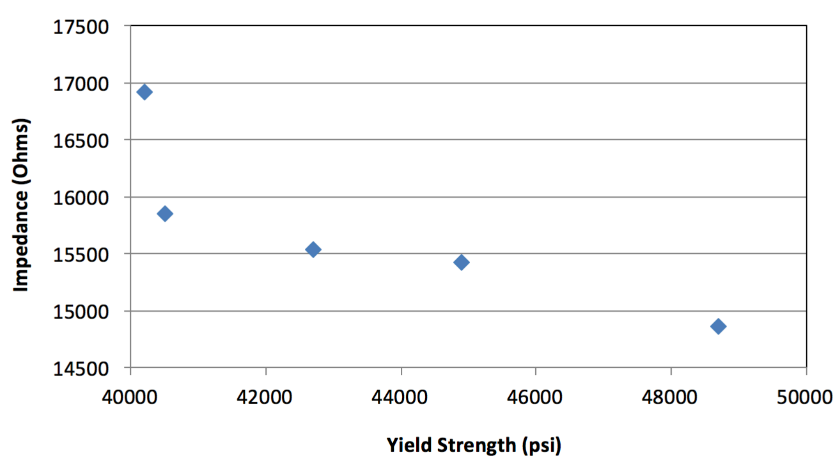


Figure 4: Impedance as a function of yield strength on steel pipe specimens with yield strength ranging from approximately 40 to 49 ksi.

Objective 3: Calibrate ***eProperty***™ system for all other variables associated with steel pipelines to increase accuracy of ***eProperty***™ system.

Task 9. Perform calibrations to account for variations in pipeline temperature, operating pressures, magnetic remanence (e.g. from "smart pigging"), and other variables.

Task 10. Develop the calibration code to account for all of variables in Task 9.

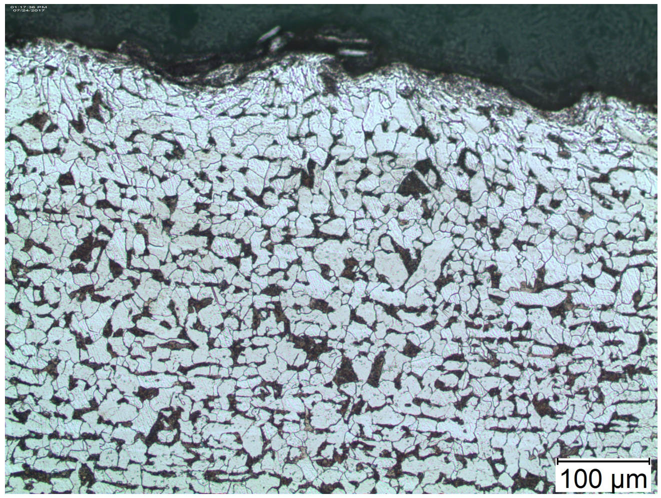
Task 11. Perform analyses with the ***eProperty***™ system in the field on multiple operating steel pipelines of various grades in different climates (to test for temperature sensitivity) and periods of time where there are variations in operating pressures to make sure algorithms properly account for the internal and external variables.

Task 12. Make any modifications to the algorithms as necessary to improve accuracy.

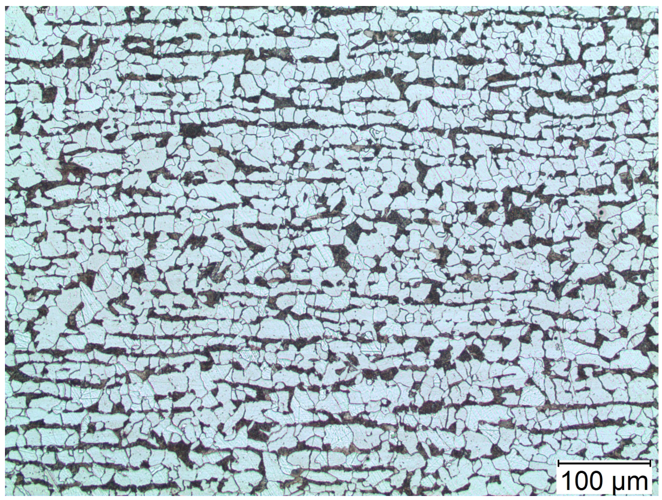
G2MT utilized electromagnetic measurements to measure material properties. Unfortunately, electromagnetic measurements are sensitive to variables such as temperature and microstructure. G2MT has developed algorithms to account for the internal and external variables associated with operating pipelines. Some of the largest variables that G2MT encountered during calibration are the variations in microstructure from the OD to the ID surface. The optical micrographs of a cross-section of pipe steel at 500X magnification are shown at the OD surface, midwall, and ID surface in Figure 5. Notice that there are variations in the microstructure at both the OD and ID surfaces. The OD surface of the steel exhibits a small decarburization region, while the ID surface of the steel exhibits banding (black lines seen in the microstructure in Figure 5 (c)). The difference in microstructure is caused by not having a sufficient heat treat process, however this is the reality of pipelines in America.

Optical micrographs of the transverse cross-sections of various steels pipe are shown in Figure 6. Notice that two different sections of pipe may have similar tensile strengths, but still have very different yield strengths or microstructures. Many of the steel pipeline microstructures exhibit severe banding caused by segregation during steel processing. G2MT Laboratories, a subsidiary of G2MT, LLC has received hundreds of accelerated corrosion failures of pipelines caused by segregated steel. The black lines of pearlite are anodic compared to the white regions surrounding it. When the ID surface of the steel for example has a banded microstructure and the black lines of pearlite are exposed to the corrosive environment, the pearlite is preferentially corroded. Corrosion of the pearlite results in holes in pipes in a matter of weeks. G2MT Laboratories had customers that had hundreds of miles of pipe that exhibited through-wall holes within months of construction. G2MT realized the value of also understanding and knowing when a pipe exhibits segregation or not. Pipe that does not have segregation has either been normalized or did not exhibit segregation in the first place. Note that a segregated microstructure does not mean that the steel will not meet specifications, but it does mean that the steel will not perform the same as a steel that is normalized or does not exhibit banding.

(a)



(b)



(c)

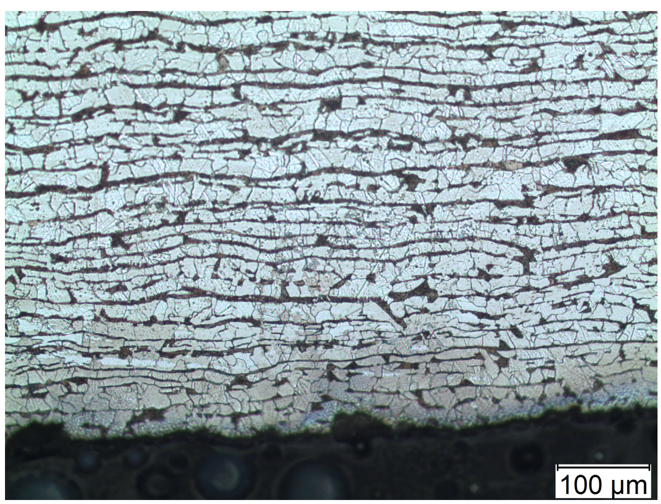
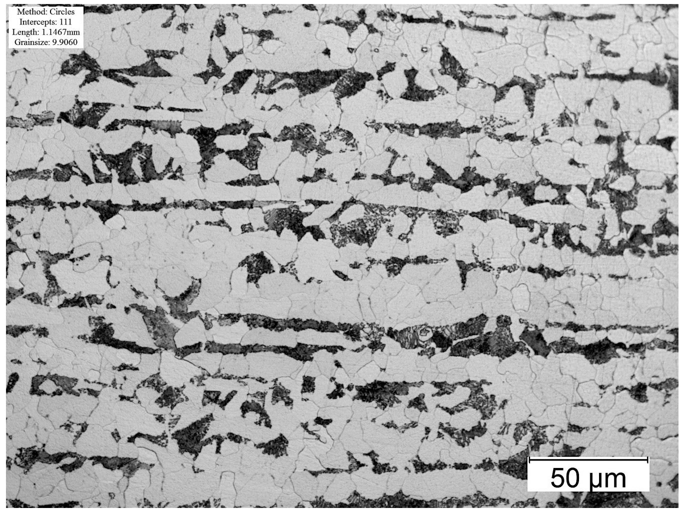
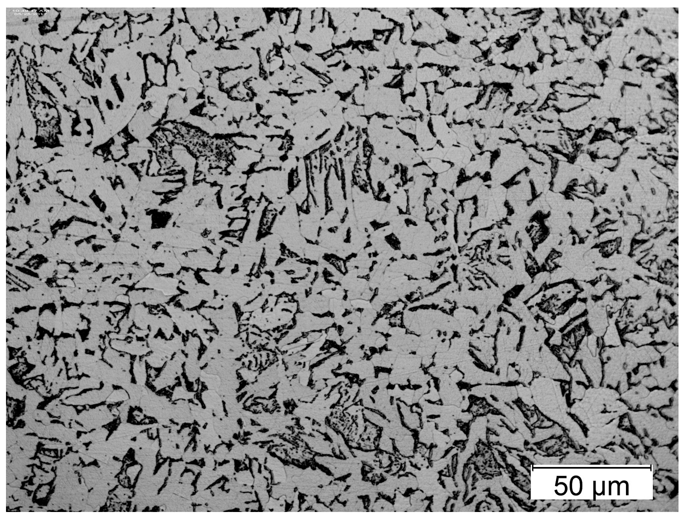
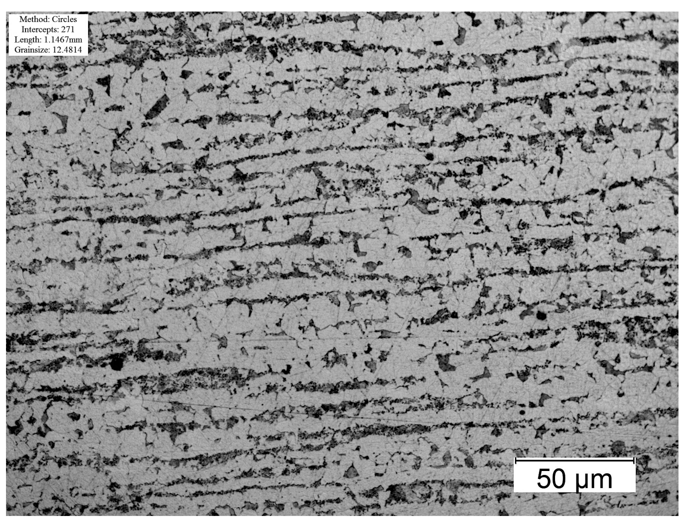


Figure 5: Optical micrographs of the transverse cross-section of pipe steel showing the variation in microstructure from the (a) OD surface, (b) midwall, and (c) ID surface at 200X magnification.

(a) **Yield: 63.7 ksi** **Tensile: 77.1 ksi**	
(b) **Yield: 55.3 ksi** **Tensile: 83.9 ksi**	
(c) **Yield: 65.0 ksi** **Tensile: 80.7 ksi**	

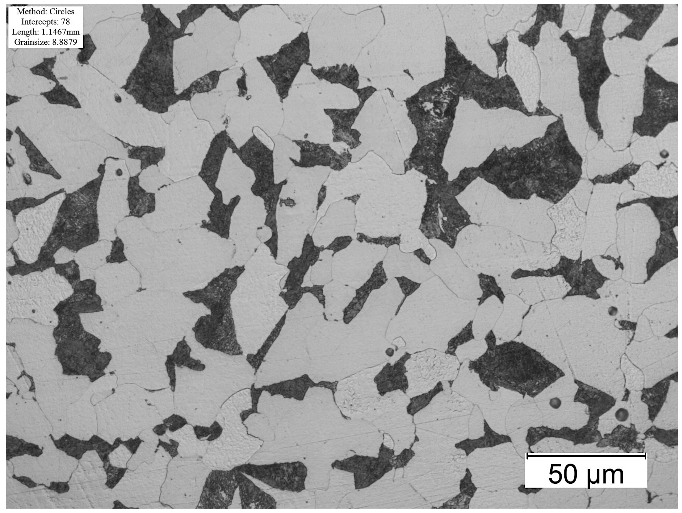
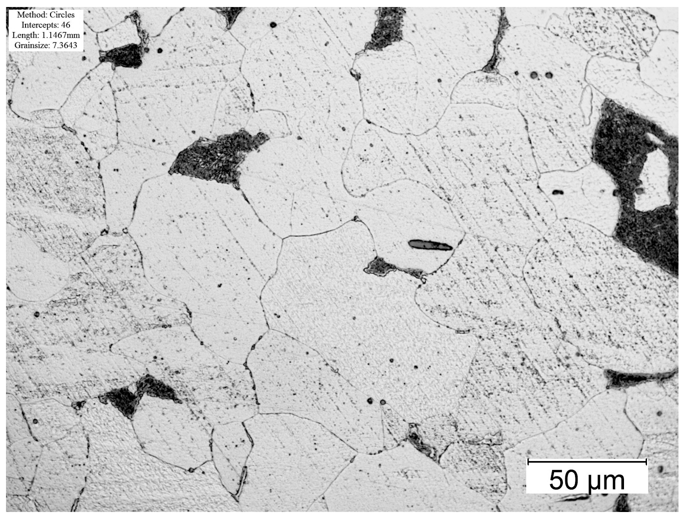
(d) **Yield: 46.1 ksi** **Tensile: 78.5 ksi**	
(e) **Yield: 32.3 ksi** **Tensile: 52.6 ksi**	

Figure 6: Optical micrographs of the transverse cross-section of various sections of pipe steel showing the variation in microstructure and mechanical properties at 500X magnification.

Objective 4: *Calibrate **eProperty™** system for lift-off variations due to coatings, corrosion product, user handling of sensors, etc.*

Task 13. Perform calibrations to account for variations in lift-off (distance between sensor and steel surface) for any reason that could cause the ***eProperty***™ sensor to not be within a specific distance away from the steel surface.

Task 14. Continue to modify the algorithm to account for variations in lift-off so that a specific lift-off is not required, to make equipment more user-friendly and capable.

G2MT designed the probes to intentionally not be sensitive to properties such as lift-off, variations in wall thickness, and pipe diameter. The photograph in Figure 7 shows two examples of probe prototypes that were designed during the development of the strength/toughness sensor. G2MT continued to improve the probes after use in the field so that they were more robust and could be used on any diameter pipeline. G2MT decided it was important to avoid the need of specific probes based on pipe diameter.

Figure 7: Photographs of sample sensors developed during this project to account for temperature, wall thickness, and pipe diameter.

Objective 5: *Determination of optimum data form for integrity management program.*

Task 15. Work with Quest integrity management teams to determine the optimum data type, yield strength, tensile strength, toughness (based on microstructure and fracture mechanics models), and transfer method to incorporate the true strength/toughness values into their integrity management models.

Task 16. Once optimum data form is determined begin processing and sending data to optimize the transportation, retrieval, and analysis processes.

G2MT has worked with the cost-share partners, especially Koch Pipeline, in determining the optimum data form. G2MT is providing the values of the yield strength, tensile strength, and upper and lower impact energies. G2MT is currently working with the end-user to optimize the data collection and mechanisms of dispersal.

Objective 6: *Perform field-testing of **eProperty™** to determine performance capabilities.*

Task 17. Using the optimized sensor and algorithms, perform laboratory and field measurements using Quest Integrity inspectors and G2MT researchers on pipelines owned by the cost-share partners.

Task 18. Determine the success of the sensors in characterizing both strength and toughness and providing the data to Quest Integrity for instantaneous data manipulation through the RBI and FFS models.

Task 19. Determine how well the sensors performed in the field and evaluate the ergonomics/proficiency needed for the inspectors to obtain accurate readings. Perform burst testing to validate sensor performance.

G2MT performed the first rounds of field measurements utilizing the G2MT packaged sensor system shown in Figure 8. The device is used in the manner as shown in Figure 9. A single user can operate the system. The system does not require any training of the inspector. The sensor automatically lights up when the sensor is being held appropriately and accurate measurements are being performed. The software was designed to show the inspector the mechanical properties visually on the screen. The mechanical properties are also stored and sent to the end user for integrity models.

G2MT performed field testing and from the pipeline strengths that were known, the sensor yield strength values for example were within five percent of the provided values. G2MT requested that sections of pipe be removed for full characterization utilizing the same mechanical property testing standards utilized by G2MT for a more accurate determination in accuracy. When results are provided by pipeline operators, G2MT cannot verify the test methods that were utilized, so G2MT had to verify the properties. Within the laboratory, the sensors were within 0.5% of the actual yield strengths.

After performing the field measurements, G2MT made slight changes to the sensor probes in terms of ergonomic handling, speed of measurement, and changing the carrying method. With those changes, G2MT completed the packaging of the strength/toughness system as discussed further in the following section.

Figure 8: Photograph of the strength/toughness sensor utilized for field measurements.

Figure 9: Photograph of a G2MT researcher performing trial measurements on a section of steel pipe.

Objective 7: *Complete the packaging of the **eProperty™** system for the field.*

Task 20. Make the ***eProperty™*** system more robust including making all components as wireless as possible. Send inspectors in the field with ***eProperty™*** system to determine improvements or modifications that should be made. G2MT will continue to advance material property sensors along with advancements in computer and electronics technologies. G2MT and Quest Integrity will optimize the sensor output.

Task 21. Make the ***eProperty***™ system a wireless operating unit using satellites or cellular towers to immediately transmit data to appropriate integrity management system.

Objective 8: *Develop training procedures and manuals to use the* ***eProperty***™ *system.*

Task 22. Work with Quest Integrity, who currently service the pipeline industry, to develop the training procedures for the operation of the ***eProperty***™ system to develop an easy, user-friendly manual and training system.

Task 23. Publish the manual and training procedure.

Objective 9: *Deploy the* ***eProperty***™ *system in the field.*

Task 24. Send Quest Integrity inspectors out with the new ***eProperty***™ systems piggybacking the system on the existing NDE inspection capabilities.

Task 25. With success of Objective 7 Task 1, evaluate the use of sensors on smart pigs for inline inspection to determine the potential benefit of the ***eProperty***™ system via pigs.

Objectives 7 through 9 all contribute to one another considering that the packaging and manuals had to be completed before deployment in the field. G2MT finalized the design of the ***eProperty***™ system and produced four different systems that were ready to be deployed in the field. The full system is shown in Figures 10 and 11. The photograph in Figure 11 shows the locations where the ***eProperty***™ system is charged and where the sensor is connected. The ***eProperty***™ is battery powered and has enough power for an entire day of measurements. The results are displayed on the tablet within five seconds of performing the measurement. After deploying the sensor in the field, G2MT has decided to further improve the sensor by eliminating the tablet altogether and designing a screen onto the actual sensor. G2MT will utilize the newest version for commercialization of the ***eProperty***™ system.

Figure 10: Photograph of the G2MT eProperty™ system and handheld sensor.

***Figure 11: Photograph of the inside of the G2MT eProperty*™.**

V. INDUSTRY INTEREST AND DESIRE FOR THE *ePropertyᵀᴹ* SYSTEM

G2MT examined the interest from industry by providing presentations and performing demonstrations of the ***eProperty***™ system. G2MT also set up a booth at the TAG Exhibition hosted by Stress Engineering. The TAG Exhibition consisted mainly of pipeline owners and operators. G2MT received a very warm and welcome response from industry. The industrial parties were ecstatic to get the systems commercialized and into the market. The overwhelming response would be that the pipeline operators would utilize the sensors today if they could get them. Photographs from the TAG Expo are shown in Figures 12 and 13. G2MT set up the computer screen to show what the tablet displays to the customer. In Figure 12, the screen is highlighting the yield strength of the pipe.

Beyond the TAG Expo, G2MT has also been closely negotiating with Koch Industries and Koch Pipeline on investment and partnership opportunities. Koch would like to aid in the expedition process of the commercialization and manufacturing of the ***eProperty***™ system and other future systems as well purely because they see the need for the sensors on their own pipelines and within their facilities. G2MT working with Koch on these sensors is invaluable because G2MT is provided a full-scale test bed for the ***eProperty***™ and other sensors.

In addition, G2MT gained a new and extremely valuable partner during this project. Dr. Ted Anderson, the former CTO of Team Industrial Services decided to leave Team and work with G2MT in developing the sensors of the future! G2MT would not have been able to gain the attention or respect of Dr. Anderson had it not been for the continued support of DOT-PHMSA.

Figure 12: G2MT booth at TAG (Technology Assessment Group) hosted by Chris Alexander formerly with Stress Engineering. This photograph shows the G2MT booth before the exposition started.

Figure 13: G2MT booth at TAG (Technology Assessment Group) hosted by Chris Alexander formerly with Stress Engineering. This photograph shows the G2MT booth during the exposition.

VI. EXPECTED/DESIRED OUTCOMES

Because of the successes in the development of the ***eProperty***™ system, G2MT is in the process of patenting the ***eProperty***™ system. In the past G2MT kept the sensors as trade-secrets, but with the aid of cost share partners advice G2MT will protect the sensors with a combination of a patent and trade secret. G2MT will continue to advance the ***eProperty***™ system because the electronic components are advancing every day, which will continue to make the current systems smarter. G2MT is also researching ideas about applying the ***eProperty***™ to smart pigs. G2MT designed a research device to move sensors at variable speed inside of a section of pipe as shown in Figure 14. G2MT ultimately would also like to combine residual stress sensors with the ***eProperty***™ system on a smart pig to provide more options to the pipeline industry.

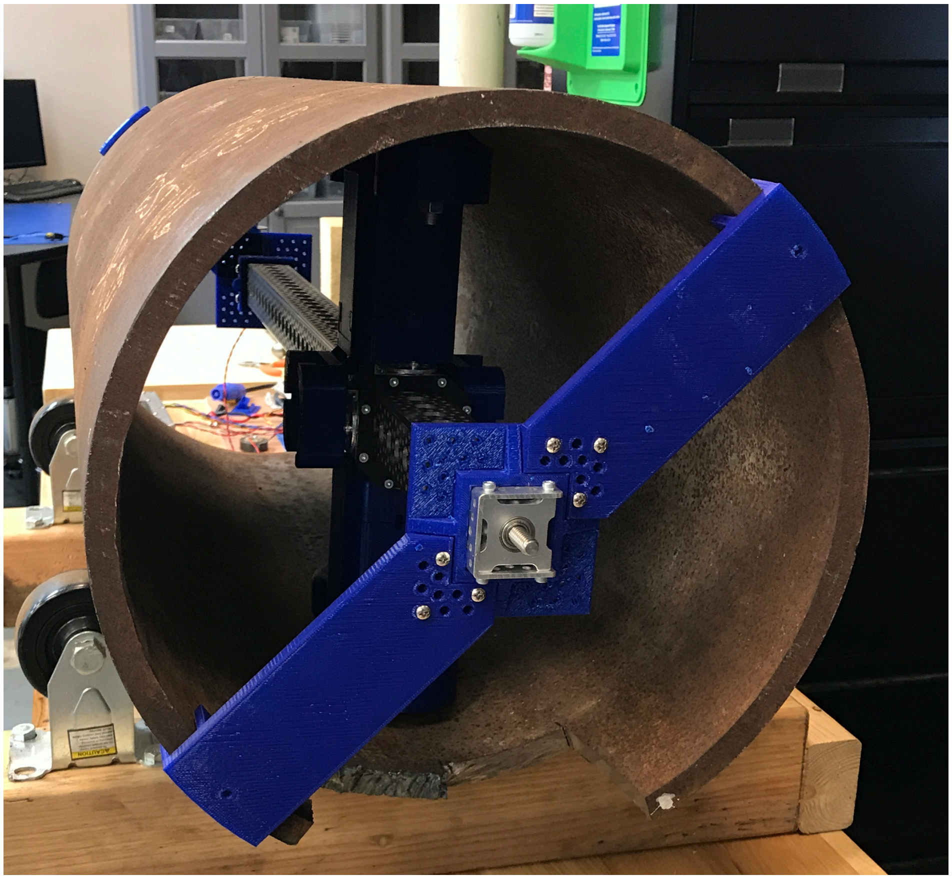


Figure 14: Photograph of research device designed for developing moving sensors that would duplicate the movement of a smart pig inside of a pipeline.

VII. ACKNOWLEDGEMENTS

The authors would like to acknowledge and thank our cost share partners and multiple researchers and institutions for their help and support in G2MT completing this DOT-PHMSA program.

- James Merritt for continued support
- Ted Anderson, formerly with Quest Integrity and Team Industrial Services
- David McColskey at the National Institute of Standards and Technology, Boulder, Colorado

VIII. REFERENCES

1. DOT Report No. 64961, REV. 1, "Metallurgical Investigation of a Fractured Section of the 20" O.D. Pipeline at Milepost 314.77 in the Conway to Corsicana Segment of the Pegasus Crude Oil Pipeline" Prepared for ExxonMobil Pipeline Company and the Pipeline and Hazardous Materials Safety Administration pursuant to Corrective Action Order CPF 4-2013-5006H

2. Donikowski, G. and Belanger, A., Presentation, "Innovative Solution of Integrity Verification Process (VIP), TDW's Positive Materials Identification Program", PPIM 2015, Feb. (2015), Houston, Texas.
3. Rosen, "MAOP Validation and Pipe Grade Determination Using ILI Technologies", PPIM 2015, Feb. (2015), Houston, Texas.
4. Bray, D.E. and Stanley, R.K., Non-Destructive Evaluation: A Tool in Design, Manufacturing, and Service, Rev. Ed., CRC Press, Inc., Boca Raton, FL,(1997).
5. Chandler, H., Hardness Testing, 2nd ed., ASM Intl., Technology and Engineering, Jan, (1999), pg. 170.
6. Amend, B., "In-situ Analyses to Characterize the Properties and Metallurgical Attributes of In-Service Piping", http://www.scribd.com/doc/243914594/InSitu-Analysis-of-Pipeline-Metallurgy-tcm153-574187.
7. Frank, S., "Portable Hardness Testing – Principles and Applications", 8th ECNDT, Barcelona, Vol 7., No. 10, (2002).
8. DNV USA, "Continued Validation of the Procedure for Using Hardness to Estimate Pipe Yield Strength", http://www.dnvusa.com/Binaries/DNV%20Prospectus_Hardness%20vs%20Yield%20Strength%20JIP_tcm153-573890.pdf.
9. Criterion NDT, Heat Treat – Hardness Verification & Hardness Testing with Eddy Current Technology, http://criterionndt.com/solutions/hardness-testing,
10. IBG NDT Systems Corporation, http://www.ibgndt.com/eddynomic-eddy-current-test.php
11. Marposs, http://www.marposs.com/technology.php/eng/eddy_current_nd_testing
12. Law NDT, http://www.law-ndt.de/en/eddy-current-hardness-test-instrument-wgp/
13. Foerster, Eddy Current Testing for Safe Components, http://www.foerstergroup.de/ROTO-PUSH.126.0.html?&no_cache=1&L=1&cid=412&did=1286&sechash=d41f1714
14. LMATS, http://lmats.com.au/services/non-destructive-testing/eddy-current-test-et.html
15. http://www.wilson-hardness.com/Resources/PressandPublications/NondestructiveTesting.aspx
16. Mercier, D., Lesage, J., Decoopman, x., and Chicot, D., "Eddy Currents and Hardness Testing for Evaluation of Steel Decarburizing", NDT&E International, Vol. 39, Issue 8, Dec. (2006), pg. 652-660.
17. Jessop, J., "Evaluating product integrity with eddy current", The Tube and Pipe Journal, Oct/Nov (2010)
18. Dieter, G.E., Mechanical Metallurgy, 3rd Ed., McGraw-Hill, (1986), pgs. 145, 184, 282, 283.
19. Wilkes, P., Solid State Theory in Metallurgy. Cambridge: Cambridge University Press, (1973).