

IN-SITU NONDESTRUCTIVE MEASUREMENTS OF KEY MECHANICAL PROPERTIES OF OIL AND GAS PIPELINES

Fahmy M. Haggag
Advanced Technology Corporation
Oak Ridge, Tennessee

ABSTRACT

Thousands of miles of gas and oil transmission pipelines currently in operation in the USA have no documentation of their mechanical properties. Section 49 of the Code of Federal Regulations (CFR) part 192.107 (b) (2) stipulates that for the pipe which is not tensile tested, a yield strength of 165 MPa (24,000 psi) must be used in the equation that determines the design pressure of the pipe section. The Automated Ball Indentation (ABI) test is an in-situ nondestructive technique which measures several key mechanical properties of metallic materials. Furthermore, ABI tests provide the actual yield strength values of base metal, welds, and heat-affected-zones which, most of the time, are higher than the conservative CFR value of 165 MPa; thus natural gas or oil up-rating (increasing transmission throughput) can be accomplished safely. Hence, ABI testing of pipelines is a better alternative to the destructive and expensive mechanical tests as demonstrated by this work. This paper summarizes the flow (stress-strain) properties measured by the innovative ABI test technique on seven pipeline materials.

INTRODUCTION AND BACKGROUND

The laboratory version of the patented Stress-Strain Microprobe (SSM) system (Haggag, 1989a) has been in commercial use since 1991 in three continents, and the portable SSM version received a 1996 R&D 100 Award. Furthermore, a new miniature SSM system was introduced in 1999 to provide even greater portability. Equipped with a small, portable battery pack and manual magnetic mounts, this system was proven to be a valuable test instrument for the pipeline industry. The accuracy, reliability, and easy field applicability of the SSM system to test pipeline materials with unknown properties have been demonstrated in this work on samples and a pipe section obtained from two major natural gas operators.

technique which is described in detail in many publications (Byun, et al., 1997; Druce, et al, 1993; Haggag, et al, 1989b; Haggag, 1993b; and Haggag, et al., 1997). The ABI technique is nondestructive and localized, and is a sophisticated mechanical test technique which can be applied to small samples as well as to metallic components (such as natural gas and oil pipelines) in the field. These capabilities of the ABI technique and the SSM technology are advantageous and desirable for testing aged components and for structural integrity evaluation. One example of such applications is the problem caused by the lack of documentation on some natural gas and oil pipelines. Section 49 of the Code of Federal Regulations (CFR) part 192.107 (b) (2) stipulates that for the pipe which is not tensile tested, a yield strength of 165 MPa (24,000 psi) must be used in the equation that determines the design pressure of the pipe section. Application of the SSM system to test these pipes will allow the determination of their safe operating pressure, and in many cases can allow up-rating (increasing the transmission pressure) for those pipelines when their SSM-measured yield strength is higher than the low/conservative value of 165 MPa (24 ksi). Furthermore, in addition to the ABI stress-strain curve measurements, the nondestructive and localized ABI technique of the SSM system can provide fracture toughness properties which can not be obtained from the destructive (and costly for operating pipelines) tensile test. The determination of fracture properties from ABI tests are described elsewhere (Byun, et al., 1998 and Haggag, 1999a).

The ABI test is based on progressive indentation with intermediate partial unloadings until the desired maximum depth (maximum strain) is reached and then the indenter is fully unloaded. The indentation load-depth data are collected continuously during the test using a 16-bit data acquisition system. The nonlinear spherical geometry of the tungsten carbide indenter allows increasing strain as the indentation penetration depth is increased. Hence, the incremental values of load and plastic depth (associated with each partial unloading cycle) are converted to

The SSM system utilizes an Automated Ball Indentation (ABI) test

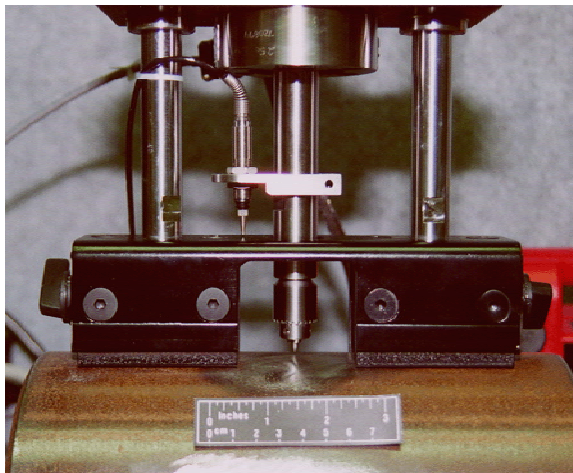


Fig. 1 The testing head of the miniature SSM system is mounted on a 152-mm (6-inch) diameter steel pipe using manual magnets (see detail photo).

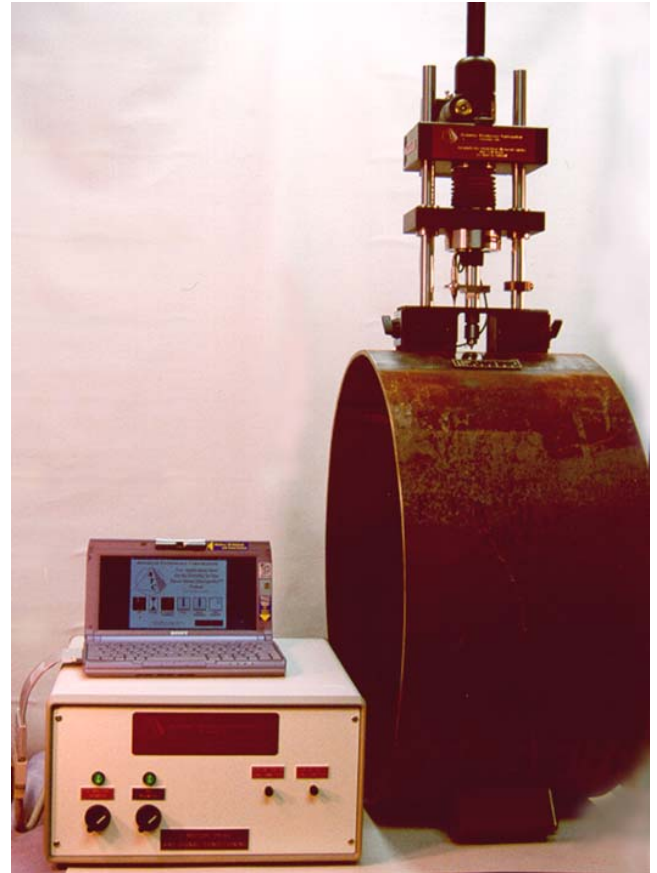


Fig. 2 The testing head of the miniature SSM system is mounted on a 610-mm (24-inch) diameter X-52 steel pipe.

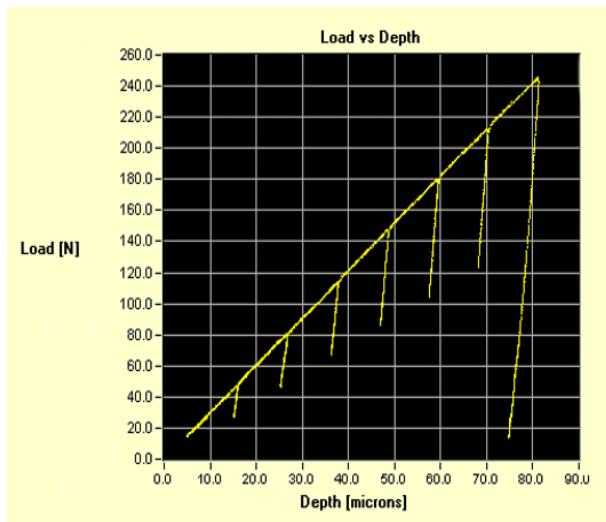
incremental values of true-stress and true-plastic-strain according to elasticity and plasticity theories (Haggag, 1993b and Haggag, et al., 1997). The ABI test is fully automated (using a notebook computer, data acquisition system, and a servo motor) and a single test is completed in one to two minutes depending on the desired strain rate.

As part of this work, miniature tensile tests were fabricated from the pipeline materials with their axes in the circumferential direction. The ABI tests were conducted on the undeformed end tabs of the miniature tensile specimens using the SSM system. Comparisons of the yield strength values and the stress-strain curves from the ABI and the miniature tensile tests show excellent agreement.

Furthermore, a field demonstration of ABI testing was conducted on a 152-mm (6-inch) diameter section of a steel pipe using the new miniature SSM system where the testing head was temporarily mounted to the pipe using two manual magnets having on/off switches (Fig. 1). The yield strength and the stress-strain curves from the ABI tests on the pipe are in excellent agreement with those from miniature and large tensile tests of specimens manufactured from the steel pipe. Another successful demonstration of the SSM system was made on a 610-mm (24-inch) diameter X52 steel pipe (Fig. 2). Field testing was also successful on a 914-mm (36-inch) diameter pipe in a refinery in Europe as well as on a 1168-mm (46-inch) diameter natural gas pipeline in Azerbaijan. This work demonstrates the major advantages of the SSM technology to the petroleum industry, namely, its nondestructive, localized, and in-situ capabilities. These features make the use of the SSM system, to nondestructively test pipelines with unknown properties, highly desirable to determine the safe operating pressure for the transmission and distribution of natural gas or oil without the need to cut test coupons and repair the test areas. Since this work was completed, commercial use of the SSM system has produced hundreds of successful ABI tests on gas pipelines in Europe and Asia.

RESULTS

Automated Ball Indentation (ABI) and miniature tensile tests were conducted at room temperature on seven materials obtained from two major natural gas operators, namely, ANR Pipeline Company and Columbia Gas Transmission Corporation. The ABI tests were conducted using 0.51-mm and 0.76-mm (0.020-inch and 0.030-inch) diameter tungsten carbide indenters on the end tabs of the miniature tensile specimens, fabricated with their axes in the circumferential direction. The ABI and miniature tensile tests were conducted using the laboratory bench-top configuration of the SSM system. Also as part of this work, the first field demonstration was conducted using the SSM-M1000 system outdoors where it was operated using a small booster battery pack and the testing head was temporarily attached to a 152-mm (6-inch) diameter pipe with two small manual magnets having on/off switches. A field configuration of the SSM system Model SSM-M1000 is shown in Figs. 1 and 2. An example of the indentation load-depth curve (using a 0.51-mm diameter indenter) and a typical comparison of the true-stress versus true-plastic-strain curves from ABI and tensile tests are shown in Fig. 3.



(a)

Fig. 3 (a) Indentation load versus depth in an ABI test using a 0.51-mm (0.02-inch) diameter tungsten carbide indenter on X42 ferritic steel material.

Detailed summary tables and figures of all ABI and tensile tests for all seven pipeline steel materials (Grade B, X42, X52, X60, X42, X52, and X65) are given in Haggag (1999b) (available for downloading from ATC's website: www.atc-ssm.com).

The design of the miniature tensile test specimen was selected to allow manufacturing of specimens with their axes in the circumferential direction for all small and large diameters of the seven pipeline materials.

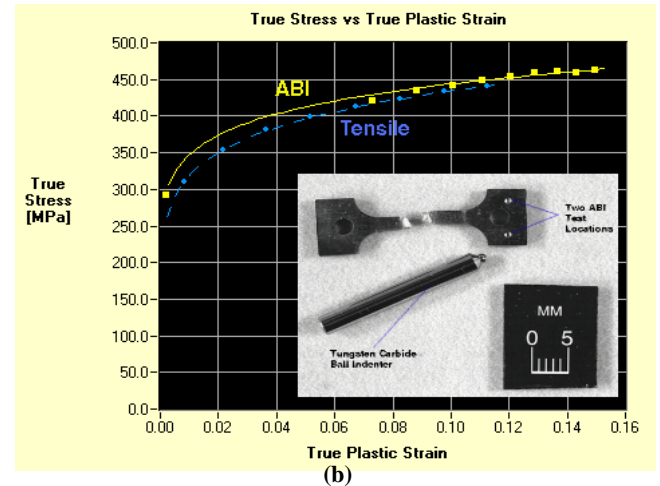


Fig. 3 (b) True-Stress versus True-Plastic Strain curves from ABI and tensile tests on X42 pipeline steel. A miniature tensile specimen is shown with two indentations made with a 1.57-mm indenter.

This design was verified earlier at Oak Ridge National Laboratory (ORNL) where the yield strength and ultimate tensile strength values compared very well with those from large tensile specimens (Haggag, 1993a).

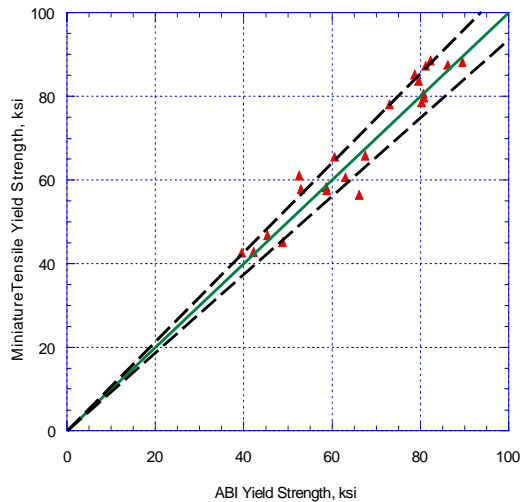
ABI tests were conducted at room temperature on the end tabs of the miniature tensile specimens, and the stress-strain curves from both techniques were overlaid for comparison. All ABI tests were conducted using 0.51-mm and 0.76-mm (0.020-inch and 0.030-inch) diameter tungsten carbide indenters at indentation speed of 0.0076 mm/s (0.0003 inch/s). The two indenter sizes produced excellent results; however, the smaller size of 0.51-mm (0.020-inch) diameter is more advantageous for use in the field with small, manual magnetic mounts since the maximum indentation load will be less than 400N (90 pounds).

The true-stress and true-plastic-strain values were calculated from the ABI load-depth data using Equations Number 2 through 9 (Haggag, 1993b) where the constraint value " α_m " was taken as 1.3 and 1.2 for the 0.51-mm and 0.76-mm (0.020-inch and 0.030-inch) diameter indenters, respectively. The yield strength value was calculated according to Equations 10, 11, and 14 of Haggag (1993b). The values of the yield-strength offset-constant and the yield strength slope (Equation 14 in Haggag, 1993b) were determined as -238.6 MPa and 0.3585 (-34.6 ksi and 0.3585) for the 0.51-mm (0.020-inch) diameter indenter while these values were -284.8 MPa and 0.4273 (-41.3 ksi and 0.4273) for the 0.76-mm (0.030-inch) diameter indenter. The true-stress and true-plastic-strain results (including the yield strength point) were fitted to the power law form of Equation 1 of Haggag (1993b) in order to determine the strain-hardening exponent (equivalent to uniform ductility) and the strength coefficient.

Comparisons of the yield strength from ABI tests, using the 0.51-mm and 0.76-mm (0.020-inch and 0.030-inch) diameter indenters, with those from the miniature tensile specimens are shown in Fig. 4. As

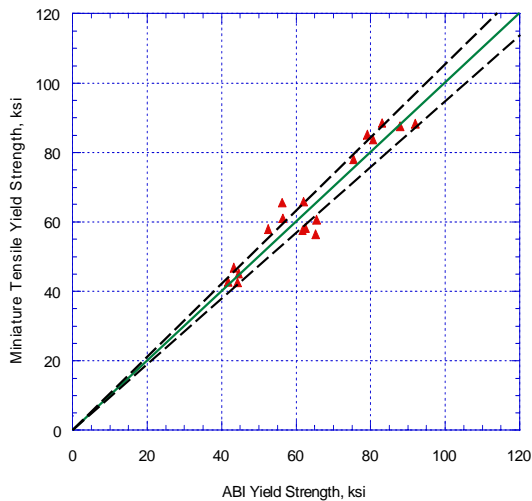
shown in this figure, the yield strength from ABI tests (using both indenter sizes) and from tensile tests are in excellent agreement where most of the data fell between the $\pm 5\%$ dashed lines bounding the perfect agreement line. A similar agreement was obtained for the ultimate strength values from ABI tests with those from the miniature tensile specimens. Hence, Figs. 3 and 4 demonstrate the reliability and the accuracy of the ABI test technique for testing pipelines.

Columbia Gas and ANR pipeline materials tested with a 0.020 inch diameter tungsten carbide indenter.



(a)

Columbia Gas and ANR pipeline material tested with a 0.030 inch diameter tungsten carbide indenter.



(b)

Fig. 4 Comparison between yield strength from ABI tests and miniature tensile tests: (a) using a 0.51-mm diameter indenter, (b) using a 0.76-mm diameter indenter. The dashed lines represent the $\pm 5\%$ variation from perfect agreement (45 degree line). (1 ksi = 6.895 MPa).

DEMONSTRATION OF SSM FIELD TESTING OF PIPELINES

The initial ABI testing of a 152-mm (6-inch) diameter carbon steel

pipe with a nominal thickness of 7-mm (0.27 inch) was conducted using three sizes of tungsten carbide indenters: 1.57-mm, 0.76-mm, and 0.51-mm (0.062-inch, 0.030-inch, and 0.020-inch) diameter. The testing head of the SSM system was mounted on the pipe using four aluminum V-blocks (Haggag, 1999b). Test results on smoothly machined areas were in very good agreement with those from locally polished areas. All ABI tests were carried out up to a maximum indentation depth of 30% of the indenter radius. The true-stress/true-plastic-strain curves from all three indenter sizes produced the same stress-strain curves despite the various test volumes sampled for each ABI test.

A field demonstration was conducted using the miniature Portable/In-Situ Stress-Strain Microprobe system (Model SSM-M1000) outdoors where it was operated using a small booster battery pack and the testing head (weighing 10 kg) was temporarily attached to a 152-mm diameter carbon steel pipe (obtained from Columbia Gas Transmission Corporation) with two small manual magnets having on/off switches. Both the 0.51-mm and 0.76-mm (0.020-inch and 0.030-inch) diameter indenters produced successful ABI test results using the magnetic mounts. The yield strength and stress strain curves from ABI tests on the pipe section and on the end tabs of miniature tensile specimens (fabricated from the pipe section) were in very good agreement with those from the test results of miniature tensile specimens. Another successful SSM field demonstration was conducted on a 610-mm (24-inch) diameter X52 pipeline.

DETERMINATION OF FRACTURE TOUGHNESS MASTER CURVE FROM ABI TESTS

Indentation with a small ball indenter generates concentrated stress (and strain) fields near and ahead of the contact of the indenter and the test surface, similar to concentrated stress fields ahead of a crack albeit the indentation stress fields are mostly compressive. The high value of the stress under the ball indenter is sometimes called an example of *plastic constraint* where it is the rigid material surrounding the indentation volume that does the constraining. Hence, at a certain critical ball indentation depth there is a high state of transverse and lateral stresses similar to those in front of a sharp notch in an elastic material. Although, the conditions for crack initiation might be attained, the high degree of plastic constraint is the reason that cracks do not develop during ball indentation of ductile metallic materials. This explains that only initiation fracture toughness and no tearing modulus can be determined from ball indentation. The initiation fracture toughness is calculated from the integration of indentation deformation energy up to the critical depth (when the maximum pressure underneath the ball indenter equals the critical fracture stress of the steel material) as described in detail elsewhere (Byun, et al., 1998 and Haggag, 1999a). Examples of the ABI-measured fracture toughness results on plate and weld steel materials are shown in Figs. 5 and 6. The new ABI-measured fracture toughness capability is, in practical terms, material thickness independent (since small indenters can be used for all pipelines and

pressure vessels). Furthermore, its localized nature allows testing heat-affected-zones that can not be tested destructively because of their irregular shape and small volumes.

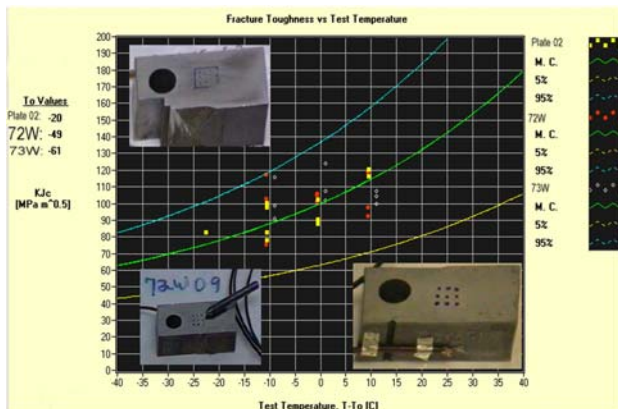


Fig. 5 Fracture toughness Master Curve obtained from ABI tests on three reactor pressure vessel steels. A 0.51-mm (0.020-inch) diameter tungsten carbide indenter was used to perform 11 ABI tests on Plate 02 (the specimen on the top left of the figure), and 9 ABI tests each on the 72W and 73W weld samples (shown on the left and right lower part of the figure, respectively). The ABI-determined reference temperatures of the three materials were within 5°C of the values from the pedigreed destructive fracture toughness tests.

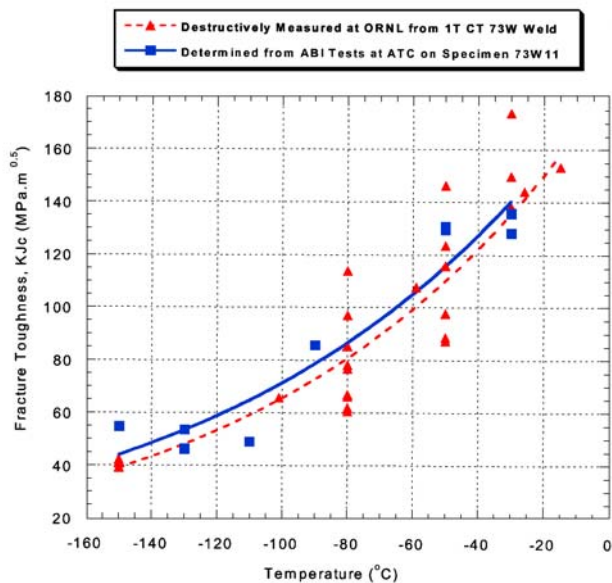


Fig. 6 Comparison between nondestructively ABI-measured $(K_{Ic})^{ABI}$ performed at ATC (using a 1.57-mm indenter) and destructive 1T CT fracture toughness test results of 73W weld of ORNL.

SUMMARY AND CONCLUSIONS

The results presented briefly in this paper and in detail in Haggag (1999b) demonstrate the capabilities of ATC’s patented Portable/In-Situ Stress-Strain Microprobe (SSM) system and its Automated Ball Indentation (ABI) test technique to nondestructively measure the yield strength and the stress-strain curve of carbon steel materials, from various natural gas pipeline manufacturers, in a reliable and accurate manner on samples and components.

The accuracy, reliability, and easy field applicability of the SSM technology to test pipeline materials with unknown properties has been demonstrated in this work. This work (Haggag, 1999b) was reviewed favorably by the Office of Pipeline Safety in December 1999. Hence, this work provides the technical basis for: (1) a pipeline operator to submit a waiver to the Department of Transportation (DOT), Office of Pipeline Safety (OPS) to use the ABI test as an alternative to the tensile test, and (2) preparing an Amendment to 49 CFR 192 Appendix B to allow nondestructive ABI testing as an alternative to the destructive and expensive tensile testing to measure the yield strength and the stress-strain curve of steel pipeline with unknown properties. The laboratory version of the SSM system has been in commercial use since 1991 in three continents, and the portable SSM version received a 1996 R&D 100 Award. Furthermore, the miniature SSM-M1000 was introduced in 1999 to provide even greater portability. Equipped with a portable battery pack and manual magnetic mounts, the SSM-M1000 proved to be a valuable test instrument for the pipeline industry. The use of the SSM system to test pipelines in the field will improve their structural integrity evaluation and their operational efficiency (by allowing safe up-rating).

ACKNOWLEDGMENTS

Advanced Technology Corporation (ATC) would like to thank ANR Pipeline Company and Columbia Gas Transmission Corporation for providing several steel pipeline materials (various grades manufactured from 1931 through 1978) to perform the destructive tensile and the nondestructive Automated Ball Indentation (ABI) tests at ATC. The tensile and ABI tests were conducted using ATC’s patented Portable/In-Situ Stress-Strain Microprobe (SSM). We extend our sincere thanks to Mr. Ted Clark (Columbia Gas), Mr. Richard Eckert (ANR Pipeline), and Dr. Jude Foulds (Exponent) for attending the miniature tensile testing, ABI blind testing, and the demonstration of the SSM system to test a full-cylindrical pipe section at ATC on June 22 and 23, 1999. The continued encouragement of Mr. Gopala Vinjamuri (Office of Pipeline Safety, US DOT) and Dr. John H. Smith (Metallurgy Division, National Institute of Standards and Technology, Gaithersburg, MD) during this work is greatly appreciated.

REFERENCES

1. Byun, T. S., et al., 1997, "Measurement of Through-the-Thickness Variations of Mechanical Properties in SA508 Gr.3 Pressure Vessel Steels Using Ball Indentation Test Technique," *International Journal of Pressure Vessels and Piping*, 74, pp. 231-238.
2. Byun, T. S., et al., 1998, "A Theoretical Model for Determination of Fracture Toughness of Reactor Pressure Vessel Steels in the Transition Region from Automated Ball Indentation Test," *Journal of Nuclear Materials*, 252, pp. 187-194.
3. Druce, S. G., et al., 1993, "The Use of Miniature Specimen Techniques for the Assessment of Material Condition," *ASME PVP-Vol. 252*, pp. 58-59.
4. Haggag, F. M., 1989a, "Field Indentation Microprobe for Structural Integrity Evaluation," U.S. Patent No. 4,852,397.
5. Haggag, F. M. et al., 1989b, "Structural Integrity Evaluation Based on an Innovative Field Indentation Microprobe," *ASME PVP-Vol. 170*, pp. 101-107.
6. Haggag, F. M., 1993a, "Effects of Irradiation Temperature on Embrittlement of Nuclear Pressure Vessel Steels," *ASTM STP 1175*, pp. 172-185.
7. Haggag, F. M., 1993b, "In-Situ Measurements of Mechanical Properties Using Novel Automated Ball Indentation System," *ASTM STP 1204*, pp. 27-44.
8. Haggag, F. M., et al., 1997, "Use of Portable/In Situ Stress-Strain Microprobe System to Measure Stress-Strain Behavior and Damage in Metallic Materials and Structures," *ASTM STP 1318*, pp. 85-98.
9. Haggag, F. M., 1999a, "Nondestructive and Localized Measurements of Stress-Strain Curves and Fracture Toughness of Ferritic Steels at Various Temperatures Using Innovative Stress-Strain Microprobe™ Technology," Report No. DOE/ER/82115-2.
10. Haggag, F. M., 1999b, "Nondestructive Determination of Yield Strength and Stress-Strain Curves of In-Service Transmission Pipelines Using Innovative Stress-Strain Microprobe™ Technology," Report No. ATC/DOT/990901.