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Many pipeline operators own infrastructure that spans a wide range of vintages including pipelines that were built from the 1950s to the 2000s. Some of the pipelines have changed hands, and in some cases resulted in a loss of the operating history and of pertinent pipeline data relating to the grade or mechanical properties and the type of seam welds. Furthermore, the international transportation networks of oil and gas pipelines are aging and their structural integrity must be monitored periodically, particularly those installed in high-consequence areas. Concerns over pipeline rehabilitation are coupled with meeting the current and future energy demands through safely increasing the transmission throughput. For undocumented pipelines with unknown grades, increasing the transmission pressure could result in catastrophic accidents with loss of human lives, infrastructure, and environmental damage.

This article describes applications of an innovative Stress-Strain Microprobe® (SSM) system that utilizes an in-situ, nondestructive Automated Ball Indentation (ABI) test technique to measure the yield strength (YS), the stress-strain curve, and fracture toughness (K_{Jc}) properties of in-service steel pipelines (thus determining the pipe grade and its resistance to failure by growth of a critical crack size). The ABI tests provide the actual/current values of these mechanical properties for base metal, girth welds, seam welds, and heat-affected-zones. The SSM-measured tensile and fracture toughness properties are used with other nondestructive measurements such as crack size (determined from either in-line/smart-pig runs or off-line ultrasound devices) or corrosion pits to determine the safe operating pressure of the pipeline or to necessitate certain actions of rehabilitation. In addition to fitness-for-service assessment of aging pipelines, the ABI tests are also applicable for the quality assurance/control of girth welds of newly constructed pipelines, including high strength steels such as grades X80 to X120.

Advanced Technology Corporation (Oak Ridge, Tennessee, USA), the developer of the patented SSM system, has been offering the commercial equipment worldwide since 1991, and in-situ SSM/ABI pipeline testing services (in favor with several pipeline operators in USA and Europe) since 1999. The large amounts of data produced from the nondestructive ABI tests and the destructive tensile and fracture toughness tests provide adequate statistical data sets to establish the validity and accuracy of the ABI technique which produces both tensile and fracture toughness properties from each single test. The ABI test (accomplished in less than two minutes) is now proven to replace both the tensile and fracture toughness tests without specimen machining or service interruption, and it requires only localized surface polishing of in-service pipelines

Innovative approach for pipeline integrity assessment (integration of SSM and conventional NDE technologies)

The in-situ SSM system (US Patent 4,852,397) of Advanced Technology Corporation (ATC) of Oak Ridge, Tennessee, USA, allows nondestructive field measurements of local key mechanical properties of pipeline base materials and welds.¹⁻⁵ These properties include the yield strength (which determines the grade of the pipeline steel material and the maximum safe operating pressure⁴), true-stress versus true-

plastic-strain curve, strain hardening exponent (uniform ductility), strength coefficient, ultimate tensile strength, and initiation fracture toughness⁵ (which determines the critical size of service-induced sharp cracks). The SSM technology has been reviewed by the US Office of Pipeline Safety (OPS) of the Department of Transportation (DOT) and is recommended for use by the pipeline industry.

The SSM system utilizes an ABI technique that is nondestructive, fast (less than two minutes per test), and very accurate. The ABI test requires a reasonable localized polishing (approximately 63 rms) of the test area for indentation testing. The spherical indentations produced on the pipeline surface are shallow, smooth depressions (i.e., no sharp edges and, hence, no stress concentration sites). Furthermore, the ABI test leaves a compressive surface residual stress that retards crack initiation (similar to the shot peening process used routinely in the aerospace industry). Therefore the ABI test, although a true/robust mechanical test, is considered for practical purposes nondestructive. Thousands of ABI tests have been conducted on ferritic steel samples, including grades from B to X100 of pipeline steels, at various test temperatures. Also, numerous ABI tests have been conducted in the field (at ambient temperatures) on pipelines in the USA, Europe, Africa, and Asia (Fig. 1). The integration of the SSM-measured key mechanical properties with the crack sizes and/or the maximum depth and spacing of corrosion pits, measured using ultrasonic and other techniques, allows a deterministic structural integrity assessment (DSIA), the calculation of the maximum safe transmission pressure for these pipelines, and will allow safe up-rating (increased transmission throughput).

Several large sets of pipeline test results are shown in ATC's reports to the US DOT, the Pipeline Research Council International (PRCI), and to the Gas Technology Institute (GTI). These reports are available for downloading from: <http://www.atc-ssm.com/library.html>. Further reference materials, including numerous downloadable publications and a 5-minute video demonstration are available on ATC's website: <http://www.atc-ssm.com>. The ABI technology, although relatively new to pipeline applications, is a mature technology that has been in commercial use in the nuclear, defense, transportation, aerospace, and other industries for more than 20 years.

SSM/ABI Technology Background and Accomplishments

The laboratory version of the patented SSM system has been in commercial use worldwide since 1991, and the portable/in-situ SSM version received a 1996 R&D 100 Award. In 1999, a miniature SSM system was introduced to provide even greater portability. Equipped with a small load frame, portable electronic control cabinet, and DC electric-magnet mounts, this system has 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 on samples and pipe sections from several pipeline companies and on many pipelines and their welds worldwide. The SSM system received the Pipeline Advanced Technology Award at the International Pipeline Exhibit in 2008.

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 (Fig. 2a). 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 (at the end of each progressive loading cycle) and plastic depth (associated with each partial unloading cycle and the upper part of the final full unloading data) are converted to incremental values of true-stress and true-plastic-strain values (Fig. 2b) according to established elasticity and plasticity theories (Equations 1-5 of Table 1, References 1-3).

The ABI test is fully automated (using a computer, data acquisition system, and a servo motor), and a single test is completed in less than two minutes depending on the desired strain rate. The ABI test is applicable to all materials regardless of the amount of material pile-up around the indentation (the pile-up volume depends on the thermo-mechanical treatment and/or Lüders strain behavior of the test material). Haggag's earlier work⁶ used mechanical profilometry and optical interferometry to quantify the pile-up and/or Lüders strain in order to accurately determine yield strength and stress-strain values from ball indentation. Since these methods are cumbersome and not suitable for field applications, in 1989, Haggag¹ invented the progressive ABI test with its novel intermediate partial unloadings to make the test easier, automated, faster, more accurate, and applicable for field/in-situ test applications. Linear regression is performed on the load-depth data of each elastic/linear partial unloading and on only the upper part of the full unloading at the end of the test, and then the data are extrapolated to the X-axis to determine the plastic depth associated with maximum load of each loading cycle of the entire ABI test. Use of full unloading is incorrect for determining the plastic depth because of non-linearity of the last/lowest 20-30% of the full unloading data (experimental non-linearity results in lower plastic depth and consequently incorrect plastic-strain value).

The plastic indentation depth and its associated cycle maximum load, the indenter diameter, and the elastic moduli of the test material and the indenter are used to calculate the plastic indentation diameter and consequently the true-plastic-strain.¹⁻³ Fig. 3 shows a final indentation produced using a 1.57-mm diameter tungsten carbide indenter on a 4142 steel sample. Despite pronounced pile-up shown in Fig. 3, the average plastic indentation diameter of 945 μm (from optical measurements of 0.943 mm and 0.947 mm) is within 1.1% of the calculated diameter of 935 μm using the innovative partial unloading technique. The precision of the ABI test method has been determined from a round robin study with participation of six organizations and is given in Table 2. The materials used in the round robin study are two aluminum alloys (6061 and 7075) and two steel alloys (1018 and 4142) with a wide range of flow properties. Other ball indenters (e.g., 0.25-mm, 0.51-mm, and 0.76-mm diameters) can be used to interrogate small volumes (e.g., spot or laser-beam welds); however, the choice of indenter diameter must consider the grain size of the test material in order to measure macroscopic tensile and/or fracture toughness properties.

Table 3 provides summary results from 5 field ABI tests conducted on a 24-inch diameter steel pipeline with unknown grade. The standard deviation of every ABI-measured property shows excellent field test repeatability and good homogeneity of the pipeline steel. The ABI-measured tensile results indicate that the pipeline steel meets Grade X52.

Determination of Fracture Toughness Master Curve from ABI Tests

Indentation with a 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 tip; albeit the indentation stress fields are mostly compressive. The high value of the stress under the ball indenter is an example of *plastic constraint* where the rigid material surrounding the indentation volume 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 will prevent cracks from developing during ball indentation of ductile metallic materials. Therefore, only initiation fracture toughness, not tearing modulus, can be determined from ball indentation (Equations 6-12 of Table 1). The initiation fracture toughness is calculated from the integration of the indentation deformation energy (*IDE*) up to the critical depth (when the maximum pressure underneath the ball indenter equals the critical fracture stress of the steel material at the test temperature or reaches a critical strain value of 0.12,

whichever occurs first). An example of the ABI-measured fracture toughness results on pipeline steel is shown in Fig. 4.

Haggag Toughness Method (HTM)

The Haggag Toughness Method (HTM) determines the fracture toughness (K_{Jc}) value from the ABI test on ferritic steel materials by integrating the indentation deformation energy (compression of the two surfaces of the ball indenter and the test material instead of pulling two surfaces in a destructive fracture toughness test) from the beginning of the test up to a critical indentation depth. The latter is calculated using either the critical fracture stress model or the critical fracture strain model; depending on the flow properties of the material at the test temperature. The analysis first checks the attainment of the critical fracture stress (using the mean pressure plot as a function of normalized indentation depth) before a strain value of 12% or a normalized depth of 0.6. If this occurs then the test is analyzed according to this model, and all ABI test results can be further analyzed using the fracture toughness master curve concept. A reference temperature is determined in order to evaluate the brittle behavior of the test material at low temperatures. If the critical fracture stress is not attained prior to a normalized depth of 0.6, then the specimen is analyzed according to the critical fracture strain model and further analysis using the fracture toughness master curve becomes invalid (or if used it will produce a very conservative reference temperature since the test material is in the ductile temperature region instead of the transition region).

The ABI-measured fracture toughness capability is material-thickness independent since different size indenters can be used for all pipelines and pressure vessels to achieve valid results. Furthermore, its localized nature allows testing heat-affected-zones that cannot be tested destructively because of their irregular shapes and small volumes (Fig. 5). The determination of tensile and fracture toughness properties from **in-situ**, nondestructive ABI tests allows the deterministic structural integrity assessment or fitness-for-service evaluation based on robust fracture mechanics analysis. The innovative SSM technology and its nondestructive ABI test technique are superior to using hot-tapping to extract pipe discs in order to machine destructive tensile and Charpy impact specimens. The in-situ ABI test provides instantaneous tensile and fracture toughness properties without cutting any piece of the pipeline and without any need to reduce transmission pressure.

Comparison of ABI-measured tensile and fracture toughness properties with destructive test results

Reference 7 (PRCI Report L52280, April 2007) includes very large amount of nondestructive/in-situ ABI tests and destructive tensile and fracture toughness tests on five pipeline materials (Grade B through Grade X65), a thin sheet steel (A366 with low very yield strength) and a thick steel from a BP storage tank. Figure 7 shows the ABI load-depth data and its stress-strain curves while Figure 8 shows the comparisons of yield and ultimate tensile strength values from both ABI and tensile tests of the seven steel materials. Figure 8 shows excellent comparison of the reference temperatures determined from six each destructive fracture toughness tests (0.5-inch thick CT) and ABI tests on the same specimens.

Comparison of Pipe Grade Determination from in-situ ABI tests and from destructive tensile tests

Table 4 shows perfect agreement of the pipe grade determinations from in-situ ABI tests and from destructive tensile tests on various pipe sections obtained from the Gas Technology Institute (GTI). The grade determination is based on the minimum YS and UTS values specified in the API 5L Specification for each pipe grade. If a measured YS value meets a specific pipe grade while the measured UTS value does not meet the minimum UTS value then the pipe grade is downgraded until the test values meet the minimum API 5L values for both the YS and UTS (Table 5).

Conclusions

The SSM System provides the key mechanical properties (tensile and fracture toughness) from each single ABI test in a nondestructive and localized fashion without any interruption to the pipeline transmission service. The in-situ ABI-measured yield and ultimate tensile strength values are used to determine the Grade of the pipeline based on the minimum requirements of the API 5L Specification for the YS and UTS values of each pipe grade.

The integration of the SSM measurements with conventional, non-destructive inspection results (crack/ flaw size and/or corrosion pitting profile⁴ measurements) allows calculating the maximum safe operating pressure and the determination of replacement or repair of older pipelines. In addition, the quality of seam welds and girth welds in repair jobs or in new pipeline construction (particularly for high strength grades such as X80 through X120) can be quantified thoroughly from their ABI-measured fracture toughness values and tensile properties (required for a true verification of weld over-match that is mandated for the strain-based design of arctic or earthquake-prone pipeline applications).

The ABI-measured fracture toughness values are material-thickness independent for pipelines and pressure vessels with thickness greater than 5-mm. Moreover, the use of the ABI-determined reference temperature (from field ABI tests at ambient temperature) and the fracture toughness master curve concept allows the calculation of critical flaw size for any operating temperature.

References

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Author's Biographical Sketch:

Fahmy M. Haggag (Fahmy.Haggag@atc-ssm.com) is president and founder of Advanced Technology Corporation (ATC), Oak Ridge, Tennessee. He has more than 39 years R&D experience in various aspects of structural integrity assessment and fracture mechanics, and has 80+ publications. Prior to ATC, he worked for Oak Ridge National Laboratory, Battelle Columbus Laboratories, and Idaho National Engineering Laboratory. He holds two MS degrees in Nuclear and Materials Engineering from the University of California, Santa Barbara (1980) and the University of Alexandria, Egypt (1976). Haggag is a member of ASME, ASM, ISO, NACE, and ASTM.



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Table 1a - Equations

$$\epsilon_p = \frac{0.2d_p}{D} \quad (1)$$

$$\sigma_i = \frac{4P}{\pi d_p^2 \delta} \quad (2)$$

$$d_i = 2\sqrt{h_i D - h_i^2} \quad (3)$$

$$\frac{P}{d_i^2} = A \left(\frac{d_i}{D} \right)^{m-2} \quad (4)$$

$$\sigma_y = \beta_m * A + B \quad (5)$$

$$IDE = \int_0^{h_i} P_m(h) dh \quad (6)$$

$$P_m = \frac{4P}{\pi d_i^2} \quad (7)$$

$$W = W_0 + W_T \quad (8)$$

$$(K_{Jc})^{ABI} = 30 + \sqrt{2E(W_T)} \quad (9)$$

$$K_{Jc}(med) = 30 + 70e^{0.019(T-T_0)} \quad \text{MPa}\sqrt{\text{m}} \quad (10)$$

$$K_{Id}(med) = 30 + 70e^{0.019(T-T_0+T_{shift})} \quad \text{MPa}\sqrt{\text{m}} \quad (11)$$

$$T_{shift} (^{\circ}F) = 215 - 1.5\sigma_y (ksi) \quad (12)$$

for 36 ksi < σ_y < 140 ksi

Table 1b – Definitions	
ϵ_p	= true plastic strain,
d_p	= plastic indentation diameter,
D	= diameter of the ball indenter.
σ_t	= true stress,
P	= applied indentation load,
δ	= a parameter whose value depends on the stage of development of the plastic zone beneath the indenter.
h_t and d_t	are the total indentation depth and total indentation diameter while the load is being applied, respectively.
A	is the material yield parameter and m is Meyer's index.
σ_y	is the ABI-determined yield strength, β_m is the material yield slope, and B is the yield-strength offset-constant.
The Indentation Deformation Energy (IDE)	is a function of depth (h) and mean pressure (P_m)
The critical indentation depth (h_c)	is the depth when the maximum stress equals the critical fracture stress of the ferritic steel at the low-test temperature.
The static fracture toughness, K_{Jc} ,	has a non-zero lower shelf even at very low-test temperatures.
The fracture toughness energy in J-Integral units	is W .
W_o	is the lower shelf energy per unit area ($30 \text{ MPa}\sqrt{\text{m}}$).
W_T	is the temperature-dependent energy ($W_T = IDE$).
T	is the test temperature in °C and T_0 is the reference temperature when $K_{Jc} = 100 \text{ MPa}\sqrt{\text{m}}$
K_{Id}	is the median dynamic fracture toughness

Table 2 Precision of the ABI Test Methods

	ABI-Yield Strength	ABI-Estimated Ultimate Strength	Strength Coefficient	Strain-Hardening Exponent	Uniform Ductility
CV % _r	1.4	1.5	2.6	5.8	6.9
CV % _R	1.7	2.3	3.4	6.7	7.8

CV %_r = repeatability coefficient of variation in percent within a laboratory

CV %_R = repeatability coefficient of variation in percent between laboratories

Table 3 Summary of ABI-measured tensile, ABI-Hardness, and fracture toughness properties from five (5) ABI tests conducted on a 24-inch diameter steel pipeline using a 0.030-inch (0.76-mm) diameter tungsten carbide indenter.

Test	Yield	Strength	Strain	Estimated	Ratio:	Calculated	ABI-	Fracture
Number	Strength	Coefficient,	Hardening	UTS	(YS / UTS)	Uniform	Hardness	Toughness
	(YS)	(K)	Exponent			Ductility	(030G)	[ksi.in ^{0.5}]
	[ksi]	[ksi]	(n)	[ksi]		[%]		
BM-24-1	57.2	115.1	0.114	80.2	0.71	11.5	187	192.5
BM-24-2	57.0	114.5	0.114	79.8	0.71	11.5	186	191.5
BM-24-3	57.4	112.2	0.109	78.9	0.73	11.4	187	189.7
BM-24-4	57.0	114.1	0.113	79.6	0.72	11.5	186	191.6
BM-24-5	57.6	113.2	0.111	79.5	0.72	11.4	187	191.7
Average	57.2	113.8	0.112	79.6	0.72	11.5	187	191.4
S.D.	0.2	1.0	0.002	0.4	0.01	0.05	0.5	0.9

S.D. = Standard Deviation

Table 4 Sample of the Grade determination of GTI pipeline sections from in-situ ABI tests and from destructive tensile tests (pipe Grades ranging from Grade A to Grade X56) using the minimum requirements of the YS and UTS values specified in the API 5L Specification

GTI Pipe Number	Grade From ABI	Grade From GTI Full-Size Tensile
02	X56	X56
12	X52	X52
20	X56	X56
21	X56	X56
22	X46	X46
30	X52	X52
34	Grade A	Grade A
38	X46	X46

Table 5 Minimum yield and tensile strength requirements of API 5L Specification

Grade	Yield Strength, Minimum		Ultimate Tensile Strength, Minimum	
	PSI	MPa	PSI	MPa
A25	25,000	(172)	45,000	(310)
A	30,000	(207)	48000	(331)
B	35,000	(241)	60,000	(413)
X42	42,000	(289)	60,000	(413)
X46	46,000	(317)	63,000	(434)
X52	52,000	(358)	66,000	(455)
X56	56,000	(386)	71,000	(489)
X60	60,000	(413)	75,000	(517)
X65	65,000	(448)	77,000	(530)
X70	70,000	(482)	82,000	(565)
X80	80,000	(551)	90,000	(620)



Fig. 1a In-Situ SSM system being used to test base metal of undocumented gas pipeline in order to determine its Grade. The DC electric magnets have excellent performance even at the toughest 3 O'clock and 9 O'clock positions.



Fig. 1b In-Situ SSM system being used to test base metal of a new construction oil pipeline in order to verify the Grade of the pipeline and its actual yield strength (YS).

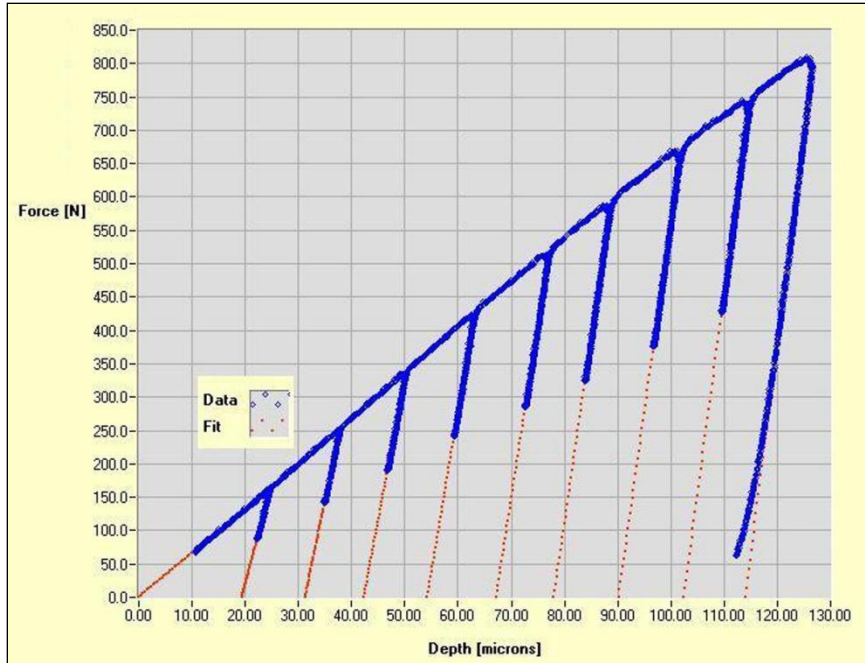


Fig. 2a Force versus depth using a 0.76-mm indenter.

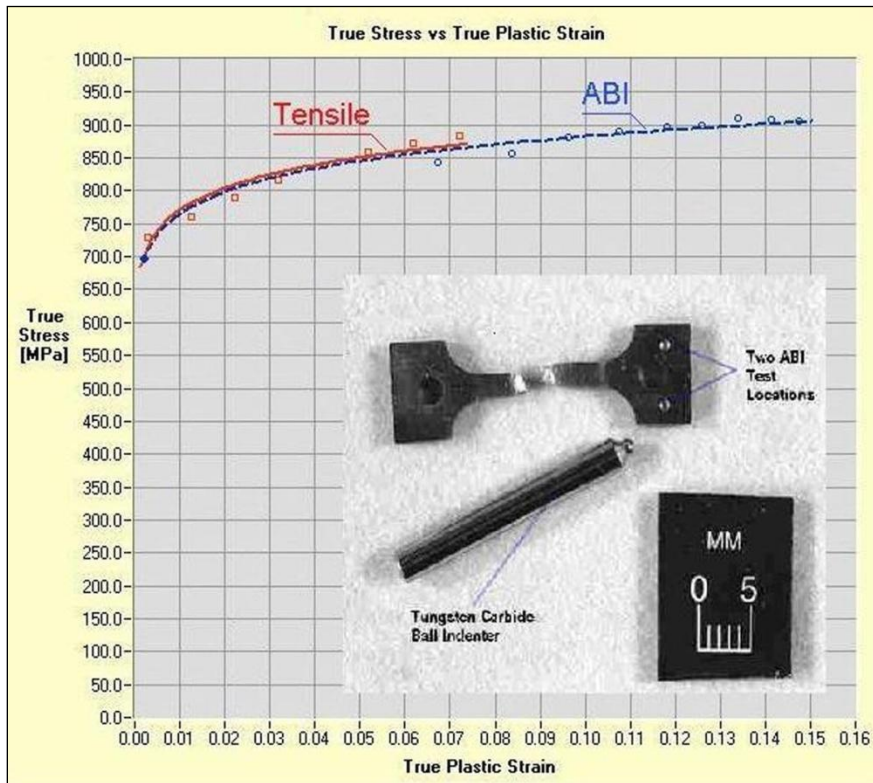


Fig. 2b Comparison of stress-strain curves from the ABI load-depth data and from a miniature tensile test.

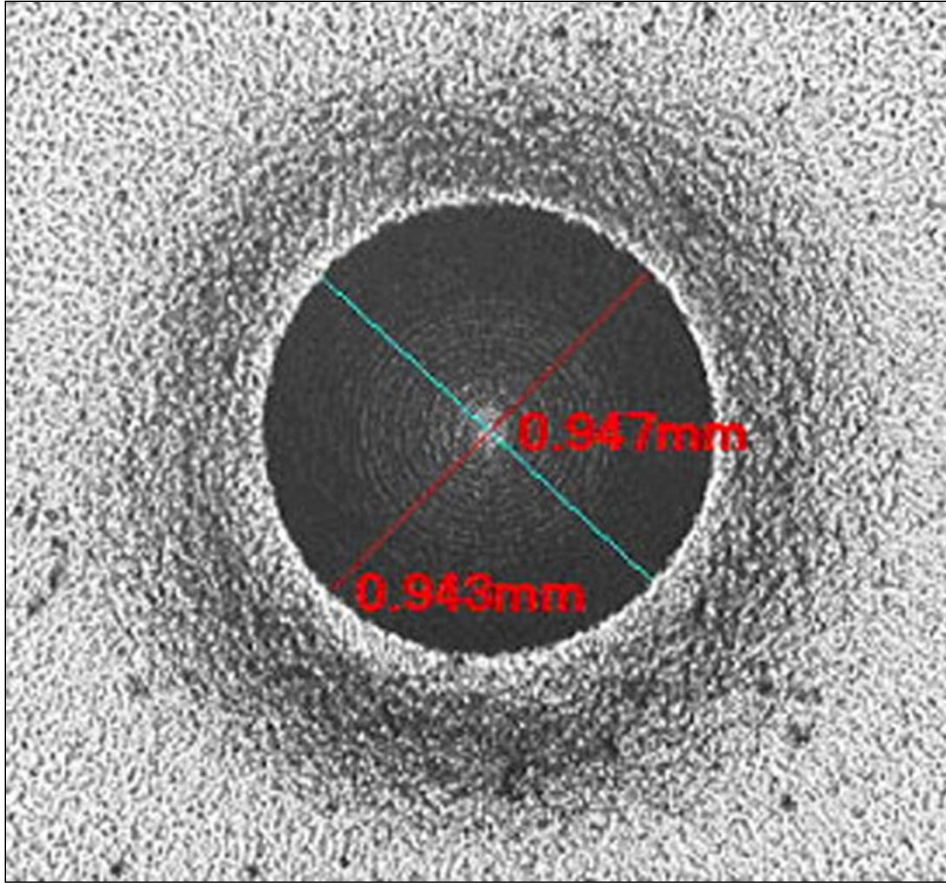


Fig. 3 Pile-up from an ABI test on 4142 steel.

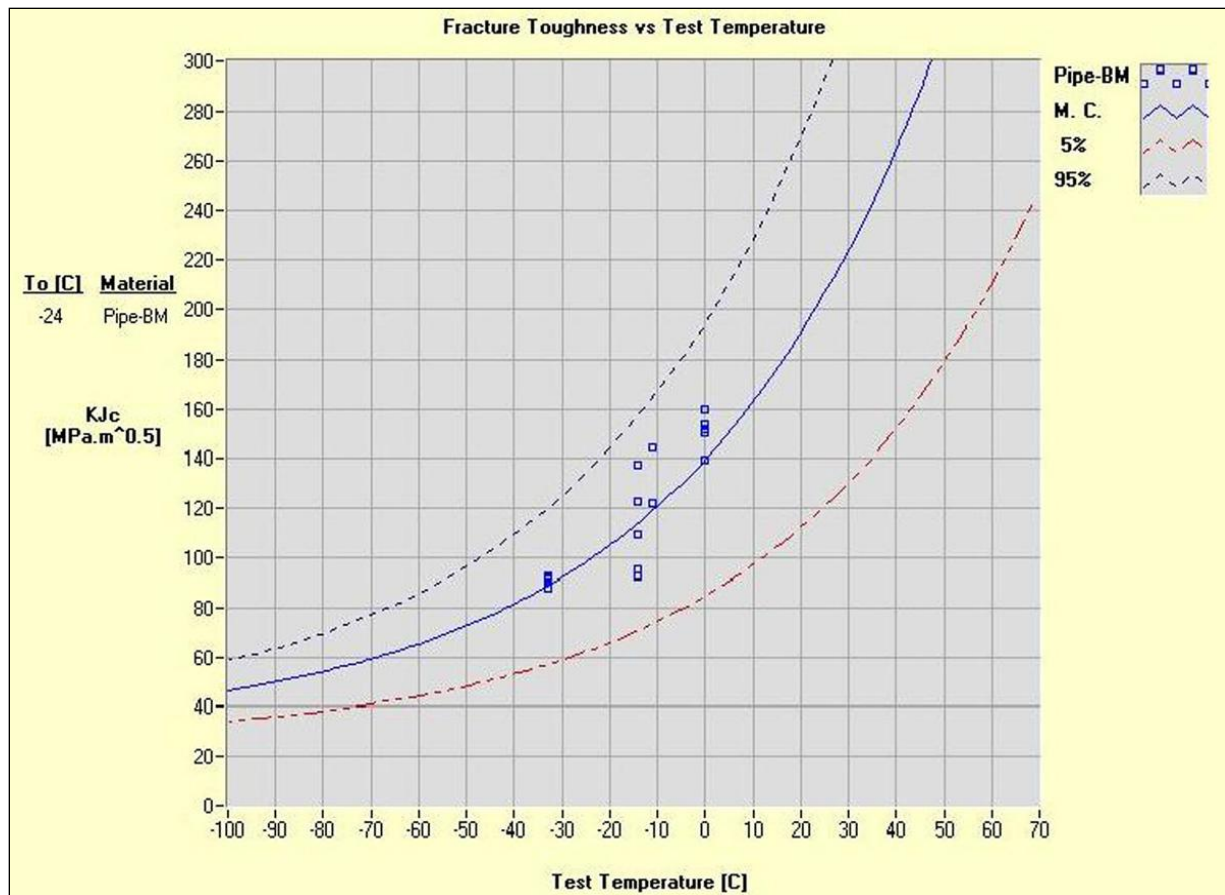


Fig. 4 Fracture toughness test results, their median master curve, and 95% and 5% confidence curves.

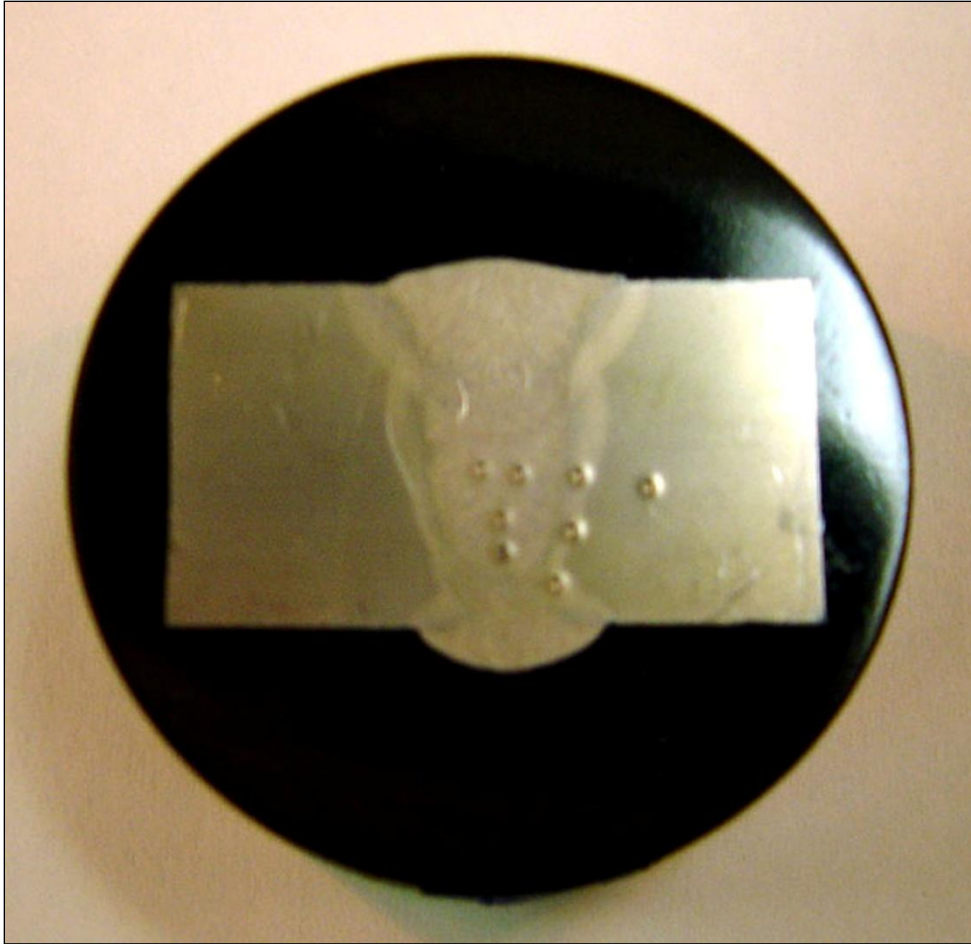


Fig. 5 ABI tests on base metal, girth weld, and HAZ areas of high strength pipeline steel.

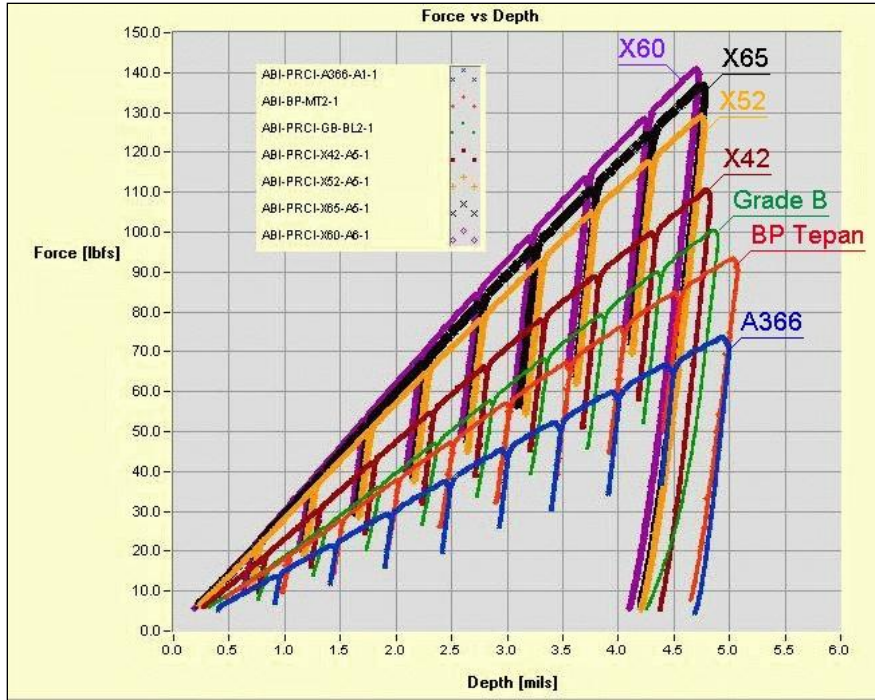


Fig. 6a Sample of ABI force-depth data from ABI tests conducted on the end tabs of seven steel base materials showing distinct differences and a wide range of force-depth data.

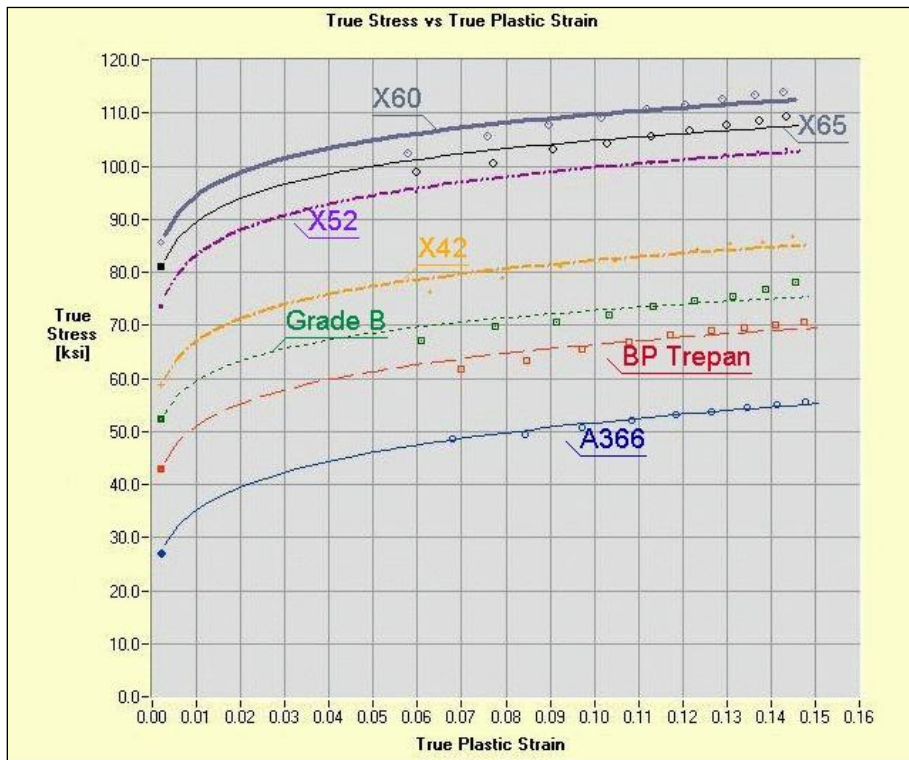


Fig. 6b Sample of ABI-measured true-stress/true-plastic-strain curves from ABI tests conducted on the end tabs of seven steel base materials showing distinct differences and a wide range of stress-strain curves (wide range of yield strength, tensile strength, uniform ductility, etc.).

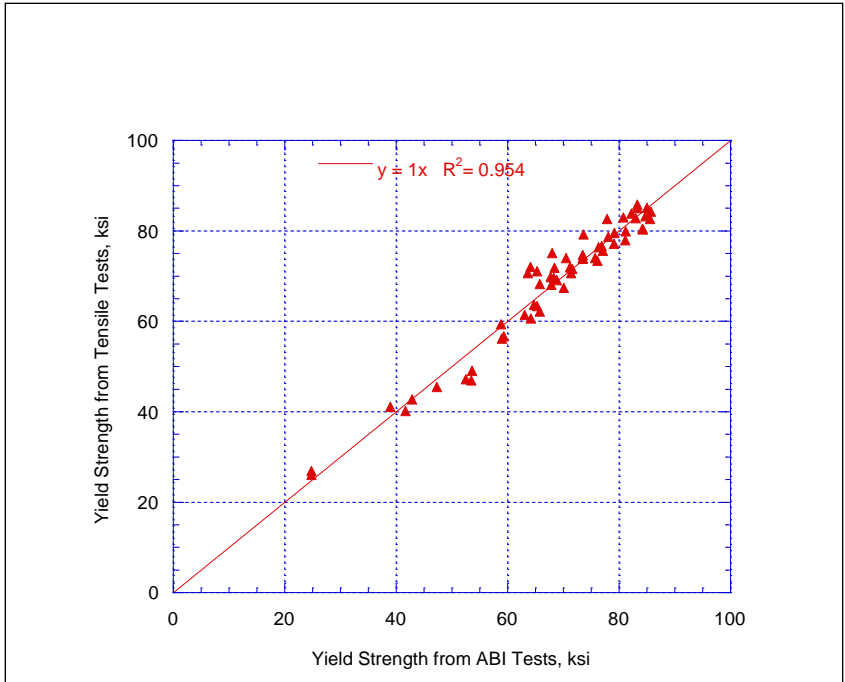


Fig. 7a Yield strength from miniature tensile versus the yield strength from ABI tests conducted on the end tabs of these miniature tensile specimens.

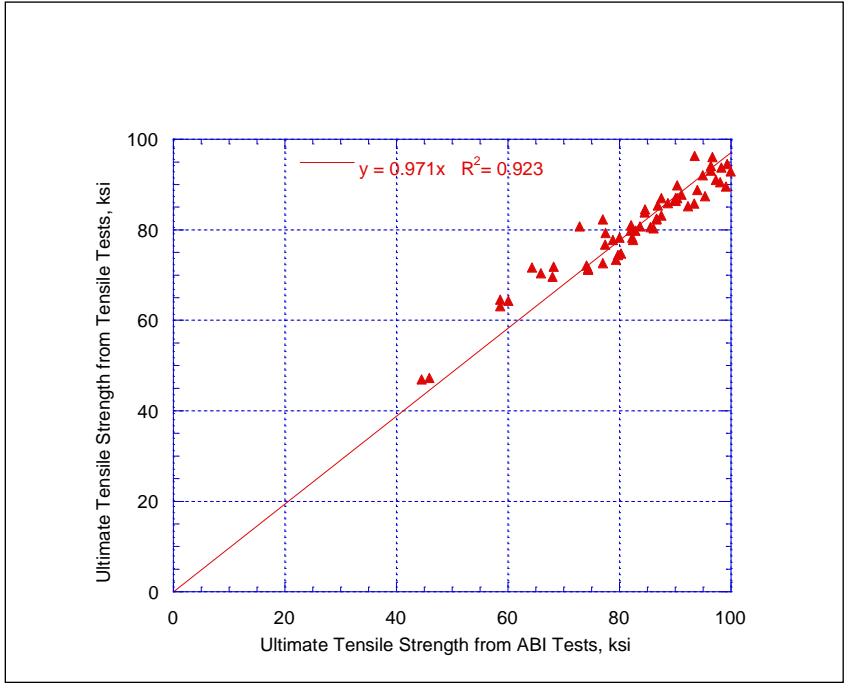


Fig. 7b Comparison of ultimate tensile strength (TS) values from tensile and ABI tests.

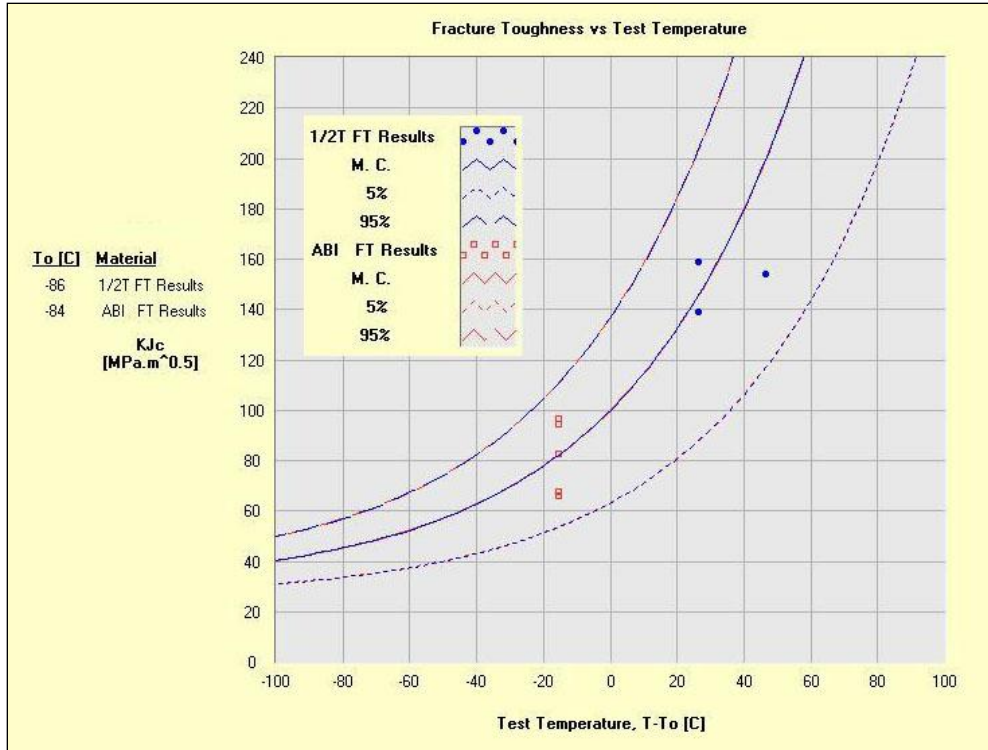


Fig. 8 Fracture toughness plotted versus normalized test temperature ($T - T_0$) showing excellent comparison of reference temperatures from six destructive fracture toughness specimens and from six ABI tests at low-test temperatures.