TECH SPOTLIGHT

An in-situ nondestructive ABI test technique has been developed to measure the stress-strain curves and fracture toughness properties of in-service metallic structures.

Fig. 1 — In-situ SSM system is shown testing the base metal at the 9 O'clock position of a gas pipeline.

Microprobe system measures strength and toughness

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An innovative Stress-Strain Microprobe (SSM) system based on an in-situ nondestructive Automated Ball Indentation (ABI) test technique has been developed to measure the stress-strain curves and fracture toughness properties of in-service metallic structures such as pressure vessels, ships, and other welded structures. The ABI tests provide the actual/current values of these mechanical properties for base metal, welds, and heat-affected-zones. An application for steel pipelines is shown here (Fig.1). Test results are combined with other nondestructive measurements of flaws such as crack size or corrosion pits to determine the safe operating pressure of the pipeline, or to make a decision about repair or rehabilitation. In addition to fitness-for-service assessment, the ABI tests are applicable to the quality assurance/control of girth welds of newly constructed pipelines, including high-strength steels such as grades X80 to X120.

How ABI works

The ABI test is based on progressive indentation with intermediate partial unloadings until the required 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 by 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 are converted to incremental values of true-stress and true-plastic-strain values (Fig. 2b) according to established elasticity and plasticity theories.

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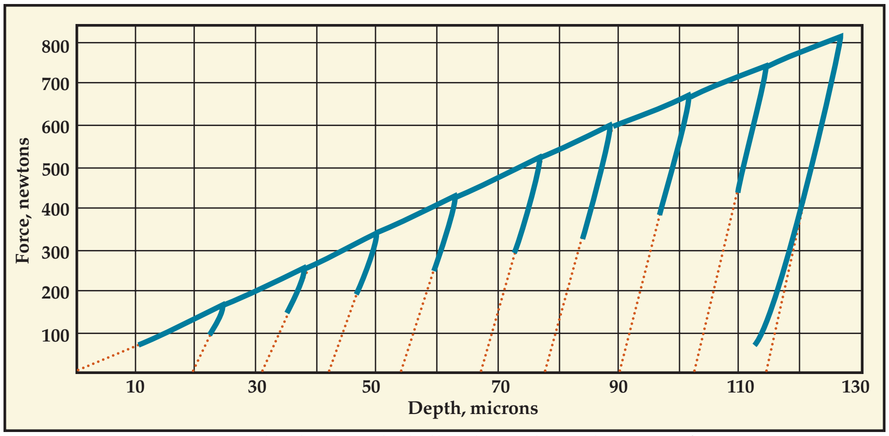

Fig. 2a — Force versus depth when the ball indenter has a diameter of 0.76 mm.

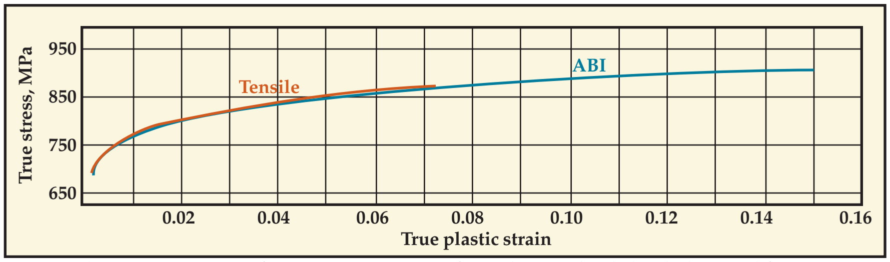

Fig. 2b — Comparison of stress-strain curves from the ABI load-depth data and from a miniature tensile test.

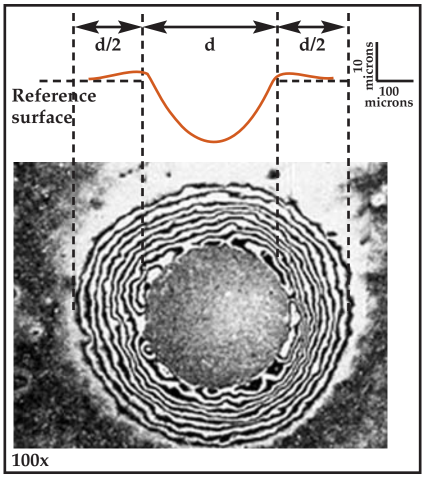

Fig. 3 — Quantification of pile-up from ball indentation compares optical interferometry and mechanical profilometry.

The ABI test is fully automated, and includes a computer, data acquisition system, and a servo motor. A single test is completed in less than two minutes, depending on the 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 material.

In earlier work, mechanical profilometry and optical interferometry served to quantify the pile-up and/or Lüders strain (Fig. 3) to accurately determine yield strength and stress-strain values from ball indentation. However, these methods are cumbersome and not suitable for field applications. Therefore, in 1989, the author 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. The precision of the ABI method was determined from round-robin testing of two steel and two aluminum alloys at eight laboratories, as shown in the table.

In 1999, a miniature SSM system was introduced to provide even greater portability. Equipped with a small, portable battery pack 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.

Fracture toughness

The ball indenter generates concentrated stress (and strain) fields near and ahead of the contact area of the indenter with the surface. These fields are similar to concentrated stress fields ahead of a crack tip, although the indentation stress fields are mostly compressive. The high value of the stress under the ball indenter is an example of *plastic constraint* when the rigid material surrounding the indentation volume does the constraining. Hence, at a certain critical depth, a high state of transverse and lateral stress is generated, similar to that in front of a sharp notch in an elastic material. Although the conditions for crack initiation might be present, the high degree of plastic constraint prevents cracks from developing during ball indentation of ductile metallic materials.

As a result, only initiation fracture toughness, not tearing modulus, can be determined from ball indentation. The initiation fracture toughness is calculated from the integration of the indentation deformation energy up to the critical depth.

The critical depth is defined as the depth at which 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. ABI-measured fracture toughness results on a pressure vessel steel weld are shown in Fig. 4.

The ABI-measured fracture toughness is independent of material thickness, because indenters of different sizes achieve valid results. Furthermore, the technique's localized nature allows testing heat-affected-zones that cannot be tested destructively because of their irregular shapes and small volumes.

The measurement of tensile and

Precision of the ABI test methods

Coeff. of variation	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

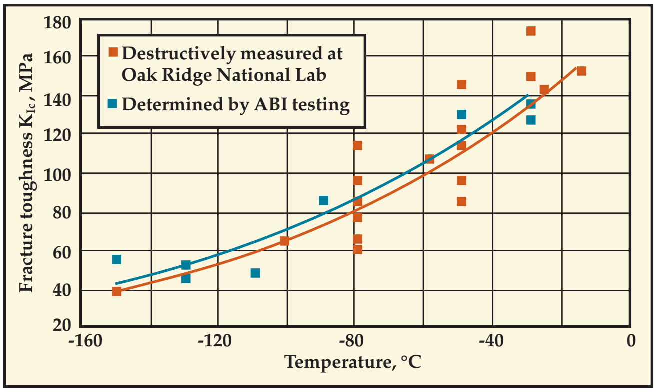

Fig. 4 — Comparison of ABI-determined fracture toughness results with results from destructive 1T CT specimens.

fracture toughness properties from in-situ nondestructive ABI tests allows the deterministic structural integrity assessment of fitness-for-service evaluation based on robust fracture-mechanics analysis. The innovative SSM technology and its ABI test technique are superior to destructive tensile and fracture toughness, as well as hot-tapping and Charpy impact tests.

Pipeline integrity

The in-situ SSM system allows nondestructive field measurements of local key mechanical properties of pipeline base materials and welds. The yield strength determines the grade of the pipeline steel material and the maximum safe operating pressure. Initial fracture toughness determines the critical size of service-induced sharp cracks. Other properties include the true-stress versus true-plastic-strain curve, the strain-hardening exponent (uniform ductility), the strength coefficient, and ultimate tensile strength. The U.S. Office of Pipeline Safety of the Department of Transportation has reviewed the SSM technology and recommends its use in the pipeline industry.

The system is nondestructive, fast (less than two minutes per test), and very accurate. The ABI test requires a reasonable, localized polishing of the test area. The spherical indentations are shallow and smooth with no sharp edges, and therefore create no stress concentration sites. Furthermore, the ABI test leaves a compressive surface residual stress that retards crack initiation in a manner similar to that of the shot peening process,

The ABI test, although a true/robust mechanical test, is considered practically 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 United States, Europe, Africa, and Asia.

The integration of the SSM-measured key mechanical properties with the crack sizes and/or the maximum depth and spacing of corrosion pits, allows a deterministic structural integrity assessment and the calculation of the maximum safe transmission pressure for these pipelines. It also allows safe up-rating for increased transmission throughput. ◆

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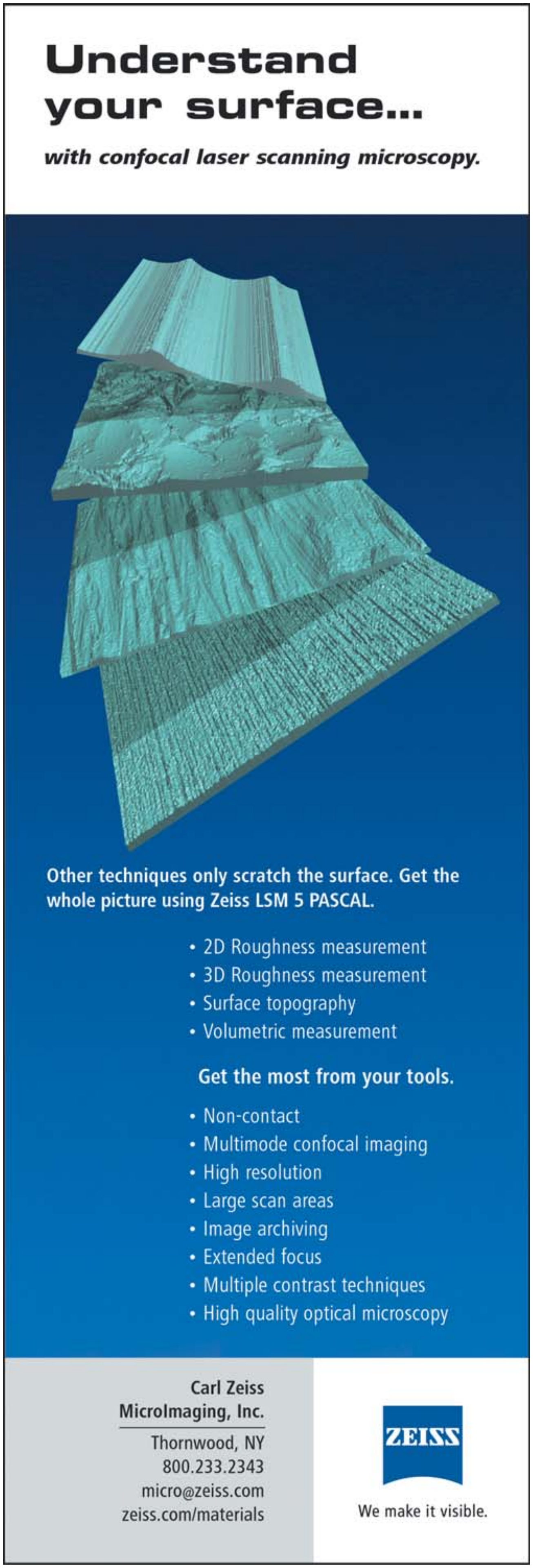
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