Application of Flow Properties Microprobe to Evaluate Gradients in Weldment Properties

F. M. Haggag
Advanced Technology Corporation
Oak Ridge, TN


ABSTRACT

Determination of the integrity of any metallic structure is required either to ensure that failure will not occur during the service life of the components (particularly following any weld repair) or to evaluate the lifetime extension of the structure. A flow properties microprobe (FPM) was developed (and patented) to evaluate, nondestructively in situ, the integrity of metallic components [including base metal, welds, and heat-affected-zones (HAZs)]. The microprobe system utilizes an innovative automated ball indentation (ABI) technique to determine several key mechanical properties (yield strength, true-stress/true-plastic-strain curve, strain-hardening exponent, Lüders strain, elastic modulus, and an estimate of the local fracture toughness). This paper describes in detail ABI test results, from several welds and their HAZs, using the patented microprobe system developed recently at Advanced Technology Corporation, Oak Ridge, Tennessee. A portable/in-situ stress-strain microprobe (Model - PortaFlow-P1) was used successfully to test a circumferentially welded type 347 stainless steel pipe. Four V-blocks were used to mount the testing head of the flow properties microprobe.

INTRODUCTION

The ABI test is based on strain-controlled multiple indentations (at the same penetration location) of a polished surface by a spherical indenter (0.25 to 1.57 mm diameter). The patented PortaFlow microprobe turn-key system and test method (1) are based on well demonstrated and accepted physical and mathematical relationships which govern metal behavior under multiaxial indentation loading. A summary of the ABI test technique is presented here, and more details are given elsewhere (1-6). The PortaFlow microprobe system currently utilizes an electro-mechanically-driven indenter, high resolution penetration transducer and load cell, a personal computer (PC), a 16-bit data acquisition/control unit, and a comprehensive copyrighted ABI software. Automation of the test, where a 386 PC and test controller were used in innovative ways to control the test (including a real-time graphic and digital display of load-depth test data) as well as to analyze test data (including tabulated summary and macrogenerated plots), made it simple, rapid (less than ten minutes for a complete ABI test), accurate, economical, and highly reproducible. Results of ABI tests (at several strain rates) on various base metals, welds, and HAZs, at different metallurgical conditions are presented and discussed in this paper. Excellent agreement (less than 5%) was obtained between ABI-derived data and those from conventional ASTM methods.

A bench-top configuration of the microprobe (Figs. 1 and 2) was used to test laboratory weld specimens (Fig. 3) and resistance spot welds and their HAZs in 1020 carbon steel and 2219 aluminum sheets. Gradients in the yield strength and flow properties and correlations to the material microstructure in the weld and HAZ areas are discussed in another paper.
Fig. 1 The ABI microprobe system configured for laboratory bench-top testing.

Fig. 2 Details of the ball indenter and the LVDT.

Fig. 3 Example of weld samples used in laboratory Automated Ball Indentation (ABI) tests.

Fig. 4 The microprobe testing head is mounted on circumferentially welded 347 SS pipe (114 mm in diameter) using four V-blocks.
by Haggag and Bell in the proceedings of this conference (7). A 347 stainless steel (SS) flat specimen was also tested and the ABI results compared to its material certification. The in-situ configuration (Fig. 4) was used successfully to test a 114-mm outer diameter 347 SS pipe containing a circumferential weld.

PORTABLE / IN-SITU STRESS-STRAIN MICROPROBE SYSTEM AND ABI TEST

The PortaFlow microprobe system currently utilizes an electro-mechanically-driven indenter, high resolution penetration transducer and load cell, a 386 personal computer (PC), a multi-channel 16-bit data acquisition/control unit, and a comprehensive ABI software. Figures 1 and 4 show the different components of Model PortaFlow-P1 used in this work. These include: 1) a compact testing head (Fig. 1 is the bench-top configuration with a support platen for laboratory specimen testing, and Fig. 4 shows the in-situ configuration where the testing head is mounted on a stainless steel pipe), 2) a small electronics cabinet which contains the data acquisition/control board, other boards for signal conditioning and control, and the driver of the electric servo motor, and 3) a portable 386 personal computer. Other testing head mounts such as magnetic holders (either permanent or electric) can be used when appropriate.

The ABI test is based on multiple indentation cycles (at the same penetration location) on a polished metallic surface by a spherical indenter. Each cycle consists of indentation, unload, and reload sequences. Values of indentation penetration speed (strain rate), data acquisition rate, indentation target delta displacement (penetration depth for each cycle), unload target delta load, indentation maximum (final) load and indentation maximum (final) displacement (penetration depth) are input before the test starts. The computer program checks all test values against limits to detect operator error. Once the test is started, operation is automatic until either maximum load or maximum displacement is reached, but the operator can abort the test at any time if system malfunction is detected. Current test values for indentation load and depth are displayed on the computer monitor in engineering units as well as in real-time graphics (penetration depth as X-axis versus indentation load as Y-axis), so the operator can monitor the test progress. The ABI test data is saved in memory during the test and then stored on the computer hard disc following test completion. The applied loads and associated displacements (depth of penetration of the indenter into the test specimen) are measured using a load cell and a spring-loaded linear variable differential transducer (LVDT). The test set-up of the current work used tungsten carbide ball indenters varying in size from 0.25-mm to 1.57-mm diameter. Appropriate capacity load cells were used for the selected indenter size. Details of the ball indenter and the LVDT are shown in Fig. 2. The load-displacement data from each unloading sequence are fitted with a first degree polynomial and the fit extrapolated to get the displacement corresponding to zero load. These displacements and the maximum cycle load and displacement values from each indentation sequence are used to determine the yield strength, produce the ABI-derived true-stress/true-plastic-strain curve, and to estimate fracture toughness. The ABI analyses are based primarily on elasticity and plasticity theories and some empirical correlations as described in Refs. 1 through 6. The primary equations used in these analyses are given in the next section.

ABI DATA ANALYSIS

The main problem in determining yield strength from ball indentation tests is due to the inhomogeneous or Lüders strain behavior. In a uniaxial tensile test the Lüders strain is the inhomogeneous plateau (horizontal portion) of the stress-strain curve where it is confined mostly to a defined volume of the specimen gage section. Hence, the inhomogeneous (Lüders) and homogeneous (work hardening) behaviors in a tensile test are well defined and separated from each other. In contrast, in an ABI test the material has less constraint at the surface around the indentation. With increasing indentation loads an increasing volume of material is forced to flow under multiaxial compression caused by the indenter and more material pile-up and Lüders strain occur around the indentation. Thus, in an ABI test both inhomogeneous and homogeneous material behavior occur simultaneously during the entire test. Consequently, an accurate determination of yield strength should be based on the entire load-
It should be noted that this representation is not a necessary requirement for determining the indentation-derived $\sigma_t\varepsilon_p$ data as will be shown later (equations 2 and 3) but it can be used to determine the strain-hardening exponent over the $\varepsilon_p$ range of interest. Furthermore, a single power curve may not fit the entire $\sigma_t\varepsilon_p$ curve as noted in ASTM Standard E-646-78.

The computer program is used to solve the following equations and to thereby determine the flow curve from the ABI data.

\[
\varepsilon_p = 0.2 d_p/D \quad \text{(2)}
\]

\[
\sigma_t = 4P / \pi d_p^2 \delta \quad \text{(3)}
\]

where

\[
d_p = \begin{cases} 0.5 & \text{if } \Phi \leq 1 \\ \left( h_p^2 + \left( d_p/2 \right)^2 \right)^{1/3} & \text{if } 1 < \Phi < 27 \\ \Phi \delta_{\text{max}} & \text{if } \Phi > 27 \end{cases} \quad \text{(4)}
\]

\[
\delta_{\text{max}} = 2.87 \alpha_m \quad \text{(8)}
\]

\[
\tau = (\delta_{\text{max}} - 1.12)/\ln(27) \quad \text{(9)}
\]

In the above equations, $\sigma_t$ is the true stress, $\varepsilon_p$ is the true-plastic-strain, $d_p$ is the plastic indentation diameter, $D$ is the diameter of the ball indenter, $P$ is the applied indentation load, $h_p$ is the plastic indentation depth, $E_1$ is the elastic modulus of the indenter, $E_2$ is the elastic modulus of the test material, $\delta$ is a parameter whose value depends on the stage of development of the plastic zone beneath the indenter, $\alpha_m$ is a parameter proportional to the strain rate sensitivity of the test material or specimen (e.g., for low strain-rate-sensitive materials $\alpha_m = 1.0$), and "ln" is the natural logarithm.

It can be seen that $d_p$ appears on both sides of Equation No. 4; the computer program solves this equation by iteration. Equations 3, 6, and 7 also have to be solved by iteration, since $\sigma_t$ depends on $\delta$, which depends on $\Phi$, which depends on $\sigma_t$. This part of the data reduction is almost impossible if attempted manually. The computer program is used also to fit the ABI-derived $\sigma_t\varepsilon_p$ data (calculated using Equations 2 and 3) by linear regression analysis to the relationship of Equation (1), and determine the strain-hardening exponent ($n$) and the strength coefficient ($K$). The previous equations

\[
\sigma_t = K \varepsilon_p^n \quad \text{(1)}
\]

where

- $n =$ strain-hardening exponent
- $K =$ strength coefficient
provide means for predicting the homogeneous portion of the stress/strain curve from indentation data.

**Yield Strength**

For each ABI loading cycle the total penetration depth (h_t) is measured while the load is being applied, then converted to a total indentation diameter (d_t) using the following equation:

\[ d_t = 2(h_t D - h_t^2)^{0.5} \]  

(10)

Data points from all loading cycles up to \( d_t/D = 1.0 \) are fit by linear regression analysis to the following relationship:

\[ P/d_t^2 = A (d_t/D)^{m-2} \]  

(11)

where \( P \) is the applied indentation load, \( m \) is Meyer's coefficient, and \( A \) is a test material (or specimen) parameter obtained from the regression analysis of test data of \( d_t/D \) versus \( P/d_t^2 \). The test material parameter (\( A \)) is then used to calculate the yield strength (\( \sigma_y \)) of the material using the following equation:

\[ \sigma_y = \beta m A \]  

(12)

where \( \beta m \) is a material-type constant (e.g., a single value of \( \beta_m = 0.2285 \) (Ref. 2) is applicable to all carbon steels whether cold rolled, hot rolled, or irradiated). The value of \( \beta_m \) for each class or type of material is determined from regression analysis of various tensile yield-strength values (measured from specimens with different heat treatments and flow properties and machined from different orientations) and their corresponding "A" values as measured from entire ABI curves (up to \( d_t/D = 1.0 \)). In Equation (12) above, the units of \( A \) and \( \sigma_y \) should be the same. The simplified and more accurate approach of this invention to determine yield strength eliminates the determination of material pile-up except for residual stress evaluation and thereby significantly reduces testing time and thus cost. A major reason for the success of the above procedure for determining yield strength from ABI measurements is that the yield strength, strength proportionality constant, Lüders strain (\( \varepsilon_L \)) and strain hardening exponent are governed by the following relationship:

\[ \ln (K/\sigma_y) = \varepsilon_L - n . \ln \varepsilon_L \]  

(13)

**RESULTS AND DISCUSSION**

The bench-top configuration of the flow properties microprobe was used to test laboratory specimens of A533, A537, and A508 nuclear pressure vessel steels obtained from the Electric Power Research Institute (EPRI). The ABI-measured yield strength and strain-hardening exponent were in very good agreement with those from tensile test results. Several resistance spot welds made from 1020 carbon steel and 2219 aluminum sheets were also tested successfully (weld nugget, HAZ, and base metal) at various strain rates. The ABI results and the microstructural evaluation are presented in another paper in this conference. An example of the true-stress/true-plastic-strain curves of these spot welds is shown in Figure 7. This figure shows that the microprobe system is capable of determining the gradients of yield strength and flow properties in very small areas. Such a capability is essential in determining the structural integrity of spot welds and in improving the welding procedures.

![Figure 7 Example of ABI test results on spot welds: (a) 1020 steel and (b) 2219 aluminum.](chart)
A flat 347 SS specimen obtained from Aerospace Alloy (Heat No. F846) was tested prior to testing the 347 SS pipe to establish a comparison between ABI and tensile test results. The ABI-measured (from one 7-cycles test) yield strength of 315.8 MPa was in good agreement with the tensile-yield strength of 317.2 MPa (indicated on this material's test report). A total of five ABI tests were then performed on the 114 mm outer diameter 347 SS pipe (5 mm thick) containing a circumferential weld (308 SS). The testing head of the flow properties microprobe was clamped on the pipe using four 90° V-blocks as shown in Fig. 4. This mounting method allowed the head to be rotated 360° and clamped rigidly for ABI testing at any location of the weld, HAZ, or the base metal.

The engineering ultimate strength (UTS) can be calculated from the ABI test results as follows:

\[
UTS = \frac{(K - n^n)}{(1 + n)}
\]  

The Brinell hardness number (HB) can also be determined from the ABI test using the maximum indentation load \((P_{\text{max}} \text{ in Kgf})\) and the final impression diameter \((d_i \text{ in mm})\) and the indenter diameter \((D \text{ in mm})\):

\[
HB = 2P_{\text{max}}/\left[\pi D(D - (D^2 - d_i^2)^{0.5})\right]
\]

An example of the ABI results is shown in Fig. 8 and the results are summarized in below.

**Base Metal (347SS):**
Test No. 5: \(\sigma_y = 325 \text{ MPa}, \ UTS = 666 \text{ MPa}, \ HB = 188, \ \sigma_t (\text{MPa}) = 1097 \varepsilon_{p}^{197}\)

**HAZ:**
Test No. 4: \(\sigma_y = 331 \text{ MPa}, \ UTS = 649 \text{ MPa}, \ HB = 186, \ \sigma_t (\text{MPa}) = 1060 \varepsilon_{p}^{191}\)

**Weld Metal (308SS)**
Test No. 1: \(\sigma_y = 283 \text{ MPa}, \ UTS = 600 \text{ MPa}, \ HB = 169, \ \sigma_t (\text{MPa}) = 990 \varepsilon_{p}^{196}\)
Test No. 2: \(\sigma_y = 283 \text{ MPa}, \ UTS = 564 \text{ MPa}, \ HB = 164, \ \sigma_t (\text{MPa}) = 920 \varepsilon_{p}^{190}\)
Test No. 3: \(\sigma_y = 300 \text{ MPa}, \ UTS = 595 \text{ MPa}, \ HB = 172, \ \sigma_t (\text{MPa}) = 971 \varepsilon_{p}^{190}\)

The above ABI test results show that the flow properties measured by the microprobe at three circumferential weld areas are in good agreement with each other and are consistently slightly lower than those at the base metal and HAZ test locations. The above successful tests also demonstrate the applicability of the flow properties microprobe to nondestructively test welded pipes in the petroleum, fossil and nuclear power plants etc.

Fig. 8 **In-Situ** ABI test results of the HAZ in welded 347 stainless steel pipe.
CONCLUSIONS

(1) The ABI technique was very successful in accurately measuring the yield strength and flow properties of welds in several metallic materials (A533-B-1, A204B, A508, 1020, 1050, 347 SS, 316 SS, and 2219 aluminum).

(2) The gradients in mechanical properties of weld metals and their HAZs were successfully determined from ABI tests conducted on both laboratory specimens as well as on structural components (114 mm outer diameter 347 stainless steel pipe containing a circumferential weld).

(3) The ABI results from tests conducted on curved structures were in excellent agreement with those from tests conducted on similar flat specimens.

(4) Field ABI tests on pipes were proven to be nondestructive, accurate, reproducible, and fast (less than 10 minutes per test).

REFERENCES


