Nondestructive Detection and Assessment of Damage in Aging Aircraft Using a Novel Stress-Strain Microprobe System

F. M. Haggag
Advanced Technology Corp., 115 Clemson Dr., Oak Ridge, TN 37830
Tel: (423) 483-5756 Fax: (423) 481-3473 e-mail: AdvTech@icx.net

J. A. Wang
Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, Tennessee 37831-6370

ABSTRACT

Aging of current commercial and military aircraft has become a major concern as many older aircraft are reaching their original design life. Service failures due to inaccurate characterization of aging responses might result in costly repair, premature component replacement, and loss of human lives. The properties of aluminum alloys, titanium alloys, and nickel-based superalloys used in aircraft structures and engines might degrade with service conditions associated with the operation of the aircraft. Important aspects of environmental conditions encountered in service cannot be accurately simulated. Thus, it will be a great advantage that the in-situ mechanical properties can be obtained nondestructively.

A novel portable/in-situ Stress-Strain Microprobe (SSM) system was developed to use an automated ball indentation (ABI) technique to measure, yield strength, true-stress versus true-plastic-strain curve, strength coefficient, strain-hardening-exponent, and to estimate fracture toughness. Example test results on metallic structural components and samples are given in this paper and a video demonstration will be presented at the Conference. Furthermore, potential applications of the SSM technology to asses the integrity of aging aircraft are briefly discussed.

Key Words: Ball Indentation, Aircraft, Structural Integrity, yield strength, flow properties, metals.

1. INTRODUCTION

Aging of current commercial and military aircraft has become a major concern as many older aircraft are reaching their original design life. The general degradation mechanisms that need to be considered include: microstructure and compositional changes, time-dependent deformation, environmental attack, and the accelerating effects at elevated temperatures.

Service failures due to inaccurate characterization of aging responses might result in costly repair, premature component replacement, and loss of human lives. Fatigue is one of the most common failure mechanisms of gas turbine engine components. High fluctuating loads, high temperature and temperature gradients, frequent starts and stops, stress concentrations resulting from complex geometrical shapes and from surface discontinuities produced by service conditions, all contribute to making the components fatigue-prone. The properties of aluminum alloys, titanium alloys, and nickel-based superalloys used in aircraft structures and engines might degrade with service conditions associated with the operation of the aircraft. Important aspects of environmental conditions encountered in service cannot be accurately simulated. Thus, it will be a great advantage that the in-situ mechanical properties can be obtained nondestructively.

A novel portable/in-situ Stress-Strain Microprobe (SSM) system was developed to use an automated ball indentation (ABI) technique to measure yield strength, true- stress versus true-plastic-strain curve, strength coefficient, strain-hardening-exponent, and to estimate fracture toughness. All SSM localized tests are computer-controlled and conducted in less than 2 minutes per ABI test. Example test results on metallic structural components and samples are given in this paper and a video demonstration will be presented at the Conference. Furthermore, potential applications of the SSM technology to asses the integrity of aging aircraft are briefly discussed. The SSM technology will allow: (1) establishing current key mechanical properties which are needed as input for various damage prediction models (e.g. fatigue, creep, corrosion, etc.) as well as to re-evaluate the operational safety of aging aircraft, and (2) periodic monitoring of aging aircraft to develop correlations between the SSM-measured mechanical properties and the damage accumulation as a function of aircraft service usage.

2. DESCRIPTION OF THE PORTABLE SSM SYSTEM

The portable Stress-Strain Microprobe (SSM) System (Fig. 1), developed and manufactured by Advanced Technology Corporation (ATC), utilizes an electro-mechanical-driven indenter, high resolution displacement transducer and load cell, test controller (16-bit data acquisition and control unit). Also, a personal computer (PC) and comprehensive copyrighted Automated Ball Indentation (ABI) software are used for test control, data acquisition, and data analyses. The ABI test is a new in-situ and substantially nondestructive technique which is being used to determine several key mechanical properties (yield strength, true-stress/true-plastic-strain curve, strain-hardening exponent, and an estimate of the local fracture toughness) of metallic materials [1-9].

The ABI test is based on controlled sequential indentation cycles on a polished metallic surface by a spherical indenter. The ABI cycles are performed at the same penetration location and each cycle consists of indentation, partial-unload, and reload sequences. The indentation load and its associated penetration depth increase from one cycle to the next until a user-specified depth is reached; then the load is completely removed. The test is fully automated where the computer and test controller are used in innovative ways to control the test as well as to analyze test data. The applied loads and associated displacements are measured using a load cell and a sprig-loaded linear variable differential transducer (LVDT). This novel indentation system operates in a closed loop mode with operator-determined software limits on both the applied indentation load and penetration depth. These limits are continuously checked during the indentation test and the indenter motion is stopped if any of the operator-selected limits is reached and the specimen is then automatically unloaded.

The sophisticated software also provides a real-time graphic display of indentation load versus depth signal, as well as digital display of both load and depth test data in engineering units. The SSM system uses several interchangeable indenters (0.13 to 0.76 mm radius) according to the thickness of the test component and the specific dimensions of the test area.

FIG. 1--A portable Stress-Strain Microprobe (SSM) system is used here for *in-situ* testing of circumferentially welded type 347 stainless steel pipe (100 mm outer diameter and 5 mm thick). The pipe is held in a wooden stand to demonstrate this field application of the SSM system. Four aluminum V-blocks were used to temporarily attach the testing head (two column load frame) of the microprobe system to the pipe, allowing a 360° inspection of the stress-strain curve gradients in the weld and its HAZ. The inset photo is an enlargement of the 100 mm pipe, chuck (20 mm diameter) holding a 1.57 mm spherical tip indenter, and a displacement transducer mounted in a horizontal bracket. (The bench-top system, which is not shown here, has a support platen for laboratory specimen testing.)

The Portable/In-Situ Stress-Strain Microprobe (SSM) system can be used in measuring key mechanical properties of existing and new materials (e.g. metallic, ceramic, and composites) and in assessing the integrity of aging components and structures in the field (e.g. aircraft, pressure vessels, etc.). Results of ABI tests (at several strain rates) on various base metals at different metallurgical conditions are presented and discussed in this paper. Excellent agreement was obtained between ABI-derived data and those from conventional ASTM methods. Gradients in the yield strength and flow properties and correlations to the material microstructure in the weld and heat-affected-zone (HAZ) areas are discussed in Ref. 8. In-situ SSM configuration (Fig. 1) was used successfully to test a 100-mm outer diameter 347 SS pipe containing a circumferential weld.

3. ABI TESTING AND DATA ANALYSIS

3.1 ABI testing

The indentation load-depth data from each partial elastic-unloading sequence are fitted to a first degree polynomial and then extrapolated to obtain the plastic depth corresponding to zero load. The plastic depth, the maximum cycle load, and the total depth (elastic + plastic) 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 the fracture toughness. The ABI analyses are based primarily on elasticity and plasticity theories and few empirical correlations. While the ABI test data are presented as real-time graphics and digital displays, the results are given as tabulated summaries and macro-generated plots. Example of an ABI test on a sample of aluminum 7075 is shown in Figure 2. The ABI test technique is considered nondestructive because no material is removed from the test surface and only a smooth shallow (as small as 0.002 inch deep) spherical indentation is left at the end of the test. This remaining spherical depression is harmless to the tested structure because it has no sharp edges, hence it does not introduce any stress concentration sites. Furthermore, the ball indentation leaves a compressive residual stress in the tested surface which will retard fatigue initiation at the ABI test site (analogous to shot peening). Hence, ABI tests will permit routine in-situ tests of aircraft components without adversely affecting their structural integrity.

Among the significant features of the ABI test technique are:

(1) it is nondestructive and can be used on fatigued aerospace components without adversely affecting their integrity,
(2) it can be used to determine spatial variations in flow properties (stress-strain curve) which may be of particular interest, for instance, in the characterization of weldments and their heat-affected zones (HAZs) where large gradients may occur,
(3) it avoids the need to manufacture test specimens,
(4) it provides in-situ automated testing which facilitates periodic inspection of components for structural integrity evaluation and lifetime extension,
(5) it is relatively rapid, and
(6) it can be used to determine true stress-true strain data over a wider strain range than that measured in tensile tests for materials which exhibit low tensile ductility.

Since 1991, the ABI test technique has been used by Harwell Laboratory of the United Kingdom, Oak Ridge National Laboratory, Knolls Atomic Power Laboratory, Sandia National Laboratory (Livermore, California), Korea Atomic Energy Research Institute, and ATC (the developer and manufacturer of SSM testing systems). Samples of test results obtained by Harwell Laboratory and ATC show excellent agreement between the ABI-measured stress-strain data and tensile data for reactor pressure vessel steels. A large amount of ABI test results have been generated by these laboratories on nuclear reactor materials (ferritic steels, austenitic and duplex stainless steels) but limited ABI tests were conducted on aerospace materials. In September 1996, ATC was granted a two-year Navy Small Business Inovation Research (SBIR) project, where one task is dedicated to develop a test matrix of fatigue and ABI tests, and to apply it to several aircraft structural materials (coupon specimens) to develop new correlations between incremental fatigue damage and changes in ABI-measured mechanical properties (e.g. yield strength, strain-hardening exponent, etc.). The developed correlations will allow the in-situ nondestructive

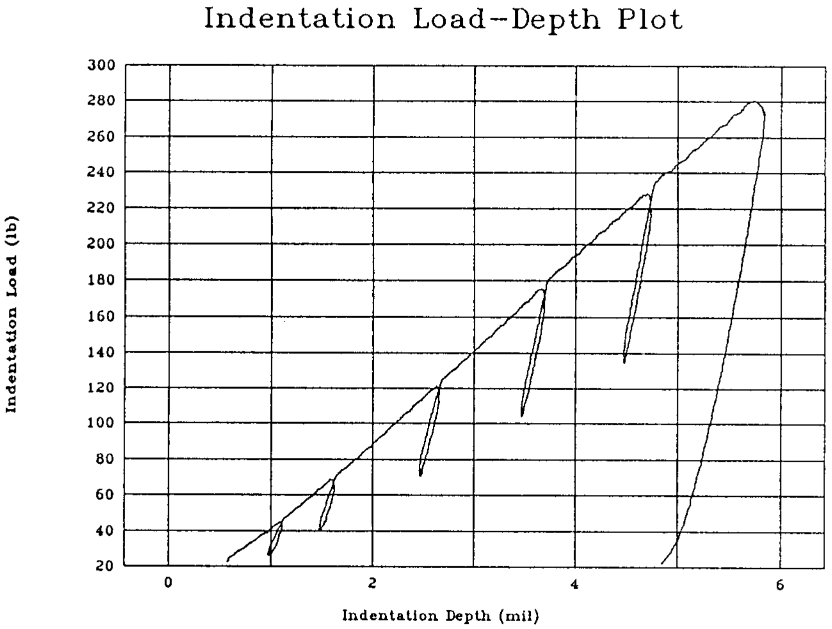

Figure 2 (a) ABI data of 7075 aluminum.

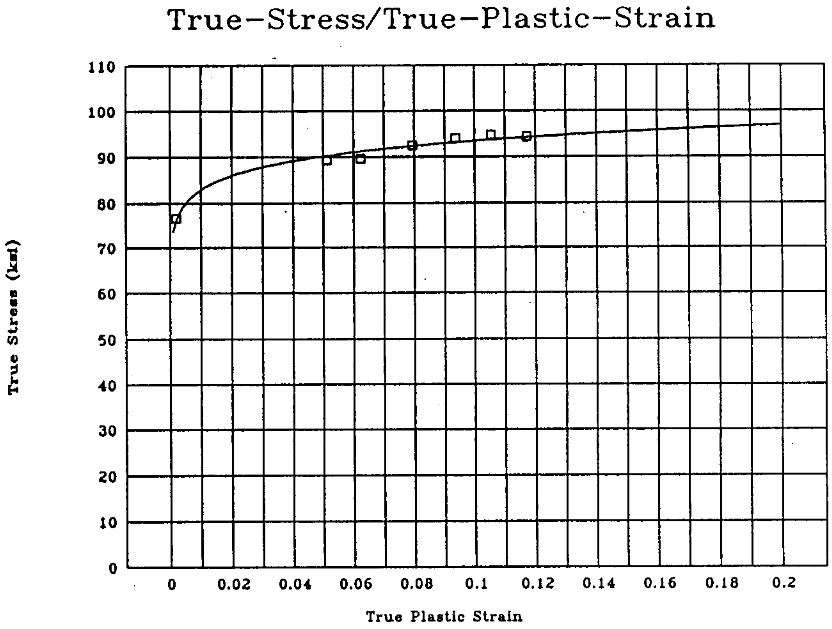

Fig. 2 (b). ABI-measured true-stress/ true-plastic-strain data

Figure 2. Example of ABI test data and results on Aluminum 7075.

periodic application of the ABI technique to monitor the status of fatigued aircraft systems and evaluate their structural integrity. Microstructural examination will be carried out to determine fatigue damage mechanisms. The proposed integrated ABI-testing/fatigue-damage-correlation approach is expected improve the safety, increase the reliability, and avoid the premature decommissioning of Navy aircraft components.

3.2 Yield strength determination from an ABI test

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 chordal diameter (d_t) using the following equation:

$$d_t = 2\,(h_t D - h_t^2)^{0.5} \tag{1}$$

where D is the indenter diameter. Data points from all loading cycles up to $d_t/D = 1.0$ are fit by linear regression analysis to the following relationship:

$$P/d_t^2 = A\,(d_t/D)^{m-2} \tag{2}$$

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 (σ_y) of the material using the following equation:

$$\sigma_y = ß_m A \tag{3}$$

where $ß_m$ is a material-type constant (e.g., a single value of $ß_m = 0.2285$ [2,3] is applicable to all carbon steels whether cold rolled, hot rolled, etc.). The value of $ß_m$ 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 3 above, the units of A and σ_y should be the same.

3.3 Flow properties

The homogeneous plastic flow portion of the true-stress (σ_t)/true-plastic-strain (ϵ_p) curve can be represented by the familiar power law equation:

$$\sigma_t = K\,\epsilon_p^n \tag{4}$$

where n = strain-hardening exponent and K = strength coefficient. It should be noted that this representation is not a necessary requirement for determining the indentation-derived σ_t-ϵ_p data as will be shown later (equations 5 and 6) but it can be used to determine the strain-hardening exponent over the ϵ_p range of interest. Furthermore, a single power curve may not fit the entire σ_t-ϵ_p curve as noted in ASTM Test Method for Tensile Strain-Hardening Exponent (n-Values) of Metallic Sheet Materials (E 646-78).

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

$$\epsilon_p = 0.2\, d_p/D \tag{5}$$

$$\sigma_t = 4P/\pi d_p^2 \delta \tag{6}$$

where

$$d_p = \{0.5\, CD\, [h_p^2+(d_p/2)^2]/[h_p^2+(d_p/2)^2-h_pD]\}^{1/3} \tag{7}$$

$$C = 5.47P(1/E_1 + 1/E_2) \tag{8}$$

In the above equations, σ_t is the true stress, ϵ_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, δ is a parameter whose value depends on the stage of development of the plastic zone beneath the indenter.

The engineering ultimate strength (UTS) can be calculated from the ABI test results (if the material stress-strain curve follows a power law) as follows:

$$UTS = K\,.\,(n/e)^n \tag{9}$$

3.4 Brinell hardness

The Brinell hardness number (HB) can also be determined from the ABI test using the maximum indentation load (P_{max} in Kgf) and the final impression diameter (d_f in mm) and the indenter diameter (D in mm) using the following equation (Standard Test Method for Brinell Hardness of Metallic Materials, ASTM E 10-84):

$$HB = 2P_{max}/[\pi D(D - (D^2 - d_f^2)^{0.5})] \tag{10}$$

4. FATIGUE DAMAGE ASSESSMENT

4.1 Low cycle fatigue damage detection and assessment

The assessment of fatigue damage in aircraft is a key step in structural safety evaluations. Low-cycle fatigue damage changes the material flow properties (e.g. cyclic hardening and cyclic softening) and generates cracks leading to failure. The development of new, practical, and reliable nondestructive techniques and methodologies to both qualitatively and quantitatively assess the state of structural fatigue damage accrued and stored in the material itself is very desirable. Hence, there is a considerable benefit to verify the feasibility of using the SSM methodology to quantitatively assess the state of fatigue damage in metallic aircraft materials. The SSM utilizes an automated ball indentation (ABI) technique to nondestructively measure stress-strain behavior at very small surface areas of a component or a specimen. Although the ABI technique is nonintrusive/nondestructive, it is a state-of-the-art mechanical test which directly measures the current/local stress-strain behavior of a specimen or a component quickly and economically. These features of the ABI methodology demonstrate its capability to directly/reliably detect and assess the fatigue damage accrued and stored in the material itself because the damage alters the stress-strain behavior of the fatigued material. Hence, a combined approach of SSM testing and newly-developed fatigue correlations will enable the detection and assessment of fatigue damage accumulated in the material, even before the initiation of cracks.

Some of the fatigue damage assessment studies include the dissection of decommissioned aircraft systems and machining of several fatigue specimens. Although the fatigue tests are very advantageous, they are destructive and expensive. Furthermore, the specimens from dissected components may not represent the status of other fatigued aircraft systems currently in service because they do not experience the same service conditions (different fatigue cycling mechanisms) over their lifetime. Moreover, local property gradients may exist due to component design or the use of welding and joining techniques. Since, the destructive tests represent only the bulk changes in the mechanical properties of the tested material, the local changes (property gradients) may be missed out. Hence, new testing techniques and damage-assessment correlations should be developed to overcome these shortcomings. The ATC's DoD fund SBIR research will address these objectives and will provide innovative capabilities to evaluate fatigued aircraft components.

4.2 Technical background of using SSM to assess fatigue damage

The following discussion provides the technical evidence for the feasibility of the proposed innovative approach. Most metallic alloys will either cyclically strain harden or cyclically strain soften. Hence, the ABI test technique will provide an excellent tool to measure the degree of cyclic-hardening or cyclic-softening of test materials. This will be accomplished by ABI testing of the materials in the as-received (virgin) condition as well as following different stages of their fatigue damage. An example of monotonic and cyclic stress-strain curves for several alloys is shown in Figure 3 [10]. The monotonic/cyclic yield strength values (in ksi) for aluminum 2024-T4, aluminum 7075-T6, and Waspaloy are 44/64, 68/76, and 79/102, respectively [10]. The monotonic/cyclic strain-hardening exponent values (n/n') for these three alloys are 0.20/0.08, 0.113/0.146, and 0.11/0.17, respectively [10]. The aluminum and Waspaloy alloys, shown in Figure 3, have cyclically hardened (e.g., the increase in yield strength ranged from 12% to 45%). However, an example of cyclic strain-softening of SAE 4340 steel is also shown in Figure 3 for comparison with the other three alloys of aluminum and Waspaloy. The ABI technique can accurately monitor the strain-hardening or strain-softening of fatigued components at different intervals of their service life.

Examples of fatigue strength and fatigue ductility properties for SAE 4340 steel are shown in Figure 4 [11,12]. This is an example of the fatigue data to be developed in ATC's work in progress. Morrow[11] determined that fatigue strength exponent b and fatigue ductility exponent c can be obtained from the cyclic strain-hardening exponent (n') from the following two equations:

$$b = (-n') / (1 + n') \qquad (11)$$

$$c = (-1) / (1 + 5n') \qquad (12)$$

Equation 11 shows that low values of cyclic strain-hardening exponent (n') will be desired for better fatigue life for predominantly elastic strains associated with high cycle fatigue (HCF). However, Equation 12 shows that the plastic strain fatigue or low cycle fatigue (LCF) resistance should be greater in more

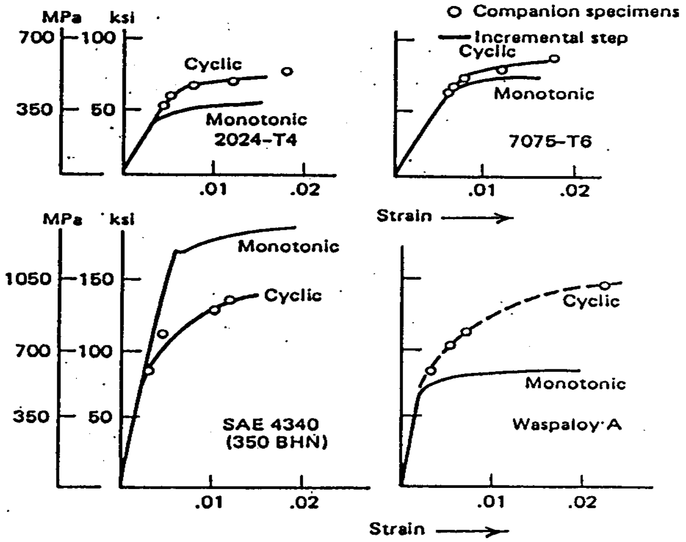

Fig. 3 Example of monotonic and cyclic stress-strain curves of several engineering alloys (Aluminum 2024-T4 and Aluminum 7075-T6, Waspaloy A, and SAE 4340), From Reference 10.

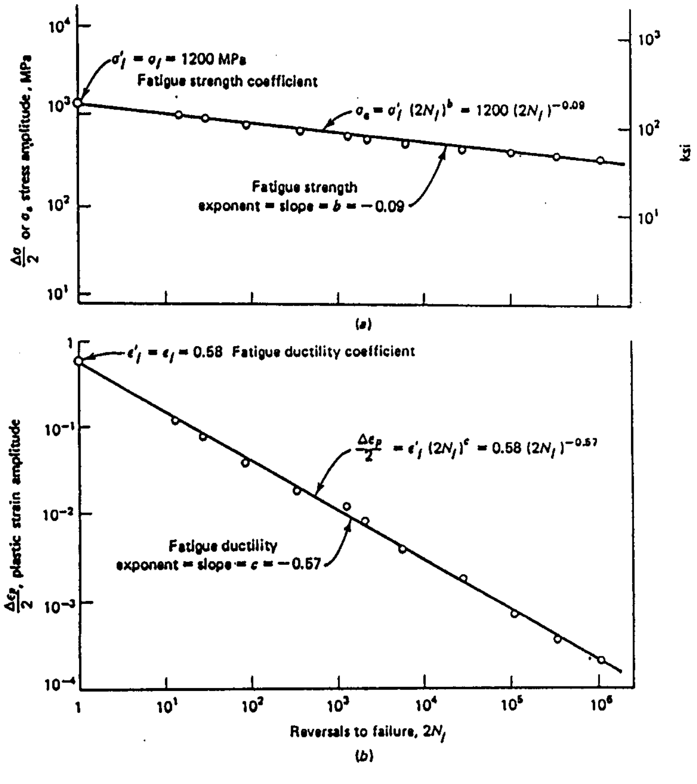

Fig. 4 (a) Fatigue strength properties of SAE 4340 steel, (b) Fatigue ductility properties of SAE 4340 steel, from References 10 and 11.

ductile materials possessing high cyclic strain-hardening exponents. The ABI test technique measures the current flow properties and determines the strain-hardening exponent of any metallic alloy at any fatigue service condition. Hence, the ABI-measured strain-hardening exponent (n′) value, following fatigue service, can be used to determine the number of fatigue cycles to failure (N_f) associated with certain values of alternating stress or strain[14]. Observations have also shown that the fatigue strength coefficient is approximately equal to the monotonic fracture strength[13]. The literature data mentioned above also show that fatigue damage alters the materials flow properties (stress-strain behavior). Hence, similar correlations between fatigue damage or cycles to failure and ABI-measured stress-strain data can be developed for aerospace alloys.

4. RESULTS AND DISCUSSION

4.1 In-situ ABI testing of structural components

A flat 347 stainless steel (SS) specimen obtained from an 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 yield strength of 316 MPa (from one 7-cycles test) was in good agreement with the tensile yield strength of 317 MPa (indicated on this material's test certificate). A total of five ABI tests were then performed on the 100 mm outer diameter 347 SS pipe (5 mm thick) containing a circumferential weld (308 SS). The testing head of the portable/in-situ stress-strain microprobe system was clamped on the pipe using four 90° V-blocks as shown in Fig. 1. This mounting method allowed the testing head to be rotated 360° and clamped rigidly for ABI testing at any location of the weld, HAZ, or the base metal. A value of $ß_m = 0.191$ [2] was used for all ABI tests on stainless steel samples and pipe materials. The results are summarized in Table 1 below. These 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 the HAZ test locations. The above in-situ tests also successfully demonstrate the potential applicability of the microprobe system to nondestructively test welded pipes and pressure vessels in the aerospace industry.

TABLE 1-Summary of In-Situ ABI test results from welded 347 SS pipe.

Test Area	ABI-True Stress/ True-Plastic Strain (Equation)	ABI-Yield Strength (MPa)	Ultimate Strength (MPa)	Brinell Hardness
Weld Metal (308 SS):				
Test No. 1	σ_t (MPa) = $990\,\epsilon_p^{.198}$	283	589	169
Test No. 2	σ_t (MPa) = $920\,\epsilon_p^{.190}$	283	555	164
Test No. 3	σ_t (MPa) = $971\,\epsilon_p^{.190}$	300	586	172
HAZ:				
Test No. 4	σ_t (MPa) = $1060\,\epsilon_p^{.191}$	331	638	186
Base Metal (347 SS):				
Test No. 5	σ_t (MPa) = $1097\,\epsilon_p^{.197}$	325	654	188

The nondestructive aspect of the ABI technique allows testing welded joints without the need to destructively machine miniature specimens which might also release residual stresses (generated from the welding procedure). Furthermore, the localized ABI testing allows testing very narrow and/or irregular geometry HAZ areas. The SSM system can be used to map out gradients in the stress-strain behavior of welded structural components nondestructively in-situ. Hence, structural integrity and/or proper welding procedures and post-weld heat treatments can be evaluated.

6. CONCLUSIONS

Aging of current commercial and military aircraft has become a major concern as many older aircraft are reaching their original design life. A novel portable/in-situ SSM system was developed to use an ABI technique to nondestructively measure the key material properties. The general applications and potentials of the SSM system are summarized as below:

(1) The ABI technique of the SSM system was successful in accurately determining the yield strength and measuring the flow properties of base and weld metals in metallic materials and structural components. 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. Furthermore, welding and repair procedures can be accurately assessed.

(2) The SSM technology will allow: (a) establishing current key mechanical properties which are needed as input for various damage prediction models (e.g. fatigue, creep, corrosion, etc.) as well as to re-evaluate the operational safety of aging aircraft, and (b) periodic monitoring of aging aircraft to develop correlations between the SSM-measured mechanical properties and the damage accumulation as a function of aircraft service usage.

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