KAPL-P-000189
(K97105)

CONF-990980--

MATERIALS PROPERTY TESTING USING A STRESS-STRAIN MICROPROBE

N. F. Panayotou, et. al.

September 1998

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States, nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

KAPL ATOMIC POWER LABORATORY

SCHENECTADY, NEW YORK 10701

Operated for the U. S. Department of Energy
by KAPL, Inc. a Lockheed Martin company

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

u

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Materials Property Testing Using a Stress-Strain Microprobe

NF Panayotou
DG Baldrey

Lockheed Martin
PO Box 1072
Schenectady NY 12301

FM Haggag

Advanced Technology Corporation
Oak Ridge TN 37830

Abstract

The Stress-Strain Microprobe (SSM) uses an automated ball indentation technique to obtain flow data from a localized region of a test specimen or component. This technique is used to rapidly determine the yield strength and microstructural condition of a variety of materials including pressure vessel steels, stainless steels, and nickel-base alloys. The SSM provides an essentially non-destructive technique for the measurement of yield strength data. This technique is especially suitable for the study of complex or highly variable microstructures such as weldments and weld heat affected zones. In this study 119 distinct SSM determinations of the yield strength of eight engineering alloys are discussed and compared to data obtained by conventional tensile tests. The sensitivity of the SSM to the presence of residual stresses is also discussed.

Introduction

A Stress-Strain Microprobe (SSM) system was procured to obtain reliable tensile data from specimens and components where standard tensile tests were not feasible (e.g., the heat affected zone (HAZ) of a weldment) or desirable (e.g., an in-service component).

Test Technique

SSM data were obtained using a portable (Model Number PortaFlow-P1) SSM test system. This system has been described in detail in References 1 - 4. The test method is based on strain controlled, multiple indentations (at a single penetration location) of a polished surface by a spherical indenter. Typical indenter diameters are 62 and 20 mils although other sizes have been used for specific purposes. This test method, also referred to as Automated Ball Indentation, consists of cyclically loading and unloading a spherical indenter into a polished surface under computer control. Loads are increased monotonically in each successive cycle. Applied loads and resulting displacements are measured during both loading and unloading using standard load cell and linear variable differential transformer (LVDT) transducers. A typical load displacement plot is shown in Figure 1 for AISI 304L stainless steel.

A first-degree polynomial fit is used to analyze this load-displacement data. These data are used to derive a true stress-true plastic strain curve, yield strength, and other tensile-type data. A typical true stress-true strain plot including the 0.2 percent offset yield strength for AISI 304L stainless is shown in Figure 2. Determination of yield strength using the SSM does not involve the extrapolation of SSM data, obtained at relatively high strains (Figure 1), back to the onset of yielding. Such extrapolations, Reference 5, result in significant deviations from true yield strengths.

Instead, the yield strength is calculated using a SSM test parameter and empirical correlations for distinct material classes (steels, nickel-base, etc.). This technique allows yield strengths to be reliably obtained for alloys of the same material class which have been subjected to property altering processes such as cold work, hot work, heat treatment, welding, and exposure to neutron radiation.

Tables 1 and 2 provide a summary of the materials, SSM derived yield strengths and, where available, actual tensile yield strength data. These tensile tests utilized several specimen designs and were conducted in accordance with the requirements of ASTM Standard Test Method E8.

Test Results

Tables 1 and 2 summarize yield strength data obtained from both SSM and standard tensile testing of materials with strengths ranging from about 30 to 185 ksi. A total of 119 distinct SSM tests were performed on sections of weldments, cut and mounted for (destructive) metallographic examination, the grip ends of actual tensile specimens, actual lifting and handling components which were returned to service after SSM (non-destructive) testing and tensile specimens subjected to simultaneous axial loading (Table 3). Comparing average values, all SSM yield strength data are within 6 percent and most SSM yield strengths are within 1 to 3 percent of the tensile yield strength data.

SSM profiles across weldments, from base metal through the HAZ and into the weld metal, have demonstrated that the HAZ in the ASTM A508 Class 4 (MIL-S-23194 Composition F) weldments are significantly (20 percent) stronger than the weld and base metal. While some variations in yield strength were noted a similar trend was not observed for the HAZ of the AISI 304L and the nickel-base Alloy 600 and 690 weldments.

Finally, the magnitude of the standard deviation (as indicated by 1σ values in Tables 1 and 2) in SSM yield strength data ranges from 0.6 ksi for AISI 4340 base metal to 6.8 ksi for data obtained in the weld metal of an Alloy 690 plasma arc weldment. In the absence of other sources of variability (e.g., significant microstructural differences) this range in 1σ may be due to residual stress.

To assess the sensitivity of SSM tests to residual stress, tests were performed on Composition F, base metal specimens with and without the application of known tensile stresses. A ring fixture, Figure 3, was used to maintain the applied load during SSM testing. The specimen gage section was rigidly supported during the test to minimize the effect of bending.

Measurements were taken at applied stresses of 0, 20, 34.9 and 57.5 ksi or, 0, 20, 35 and 58 percent of the reported uniaxial yield strength for this material. As listed in Table 1 SSM testing determined that Composition F yield strength was $99.6 \text{ ksi} \pm 1.9 \text{ ksi}$, in excellent agreement with the material certification data.

SSM test results as a function of applied stress are listed in Table 3. Baseline data (zero applied load) were obtained on two distinct specimens. These results, 91.6 and 92.7 ksi, are about 7 ksi less than the value reported in Table 3. In order to ensure that the SSM equipment was operating properly, calibration tests were performed on a certified test block. This calibration testing produced acceptable values. Accordingly, the basis for this difference in the baseline (zero applied load) yield strength of Composition F is not apparent at this time. Two SSM tests were conducted at each of the applied load levels.

Discussion

Comparison with Tensile Data

Excellent agreement between SSM derived and tensile-type 0.2 percent offset yield strengths for a wide range of materials demonstrates that reliable flow-type data can be obtained from test specimens and actual components. The localized nature of this test method allows the determination of strength profiles in complex structures such as weldments.

In some weldments, significant increases in yield strength have been noted in the HAZ. For a given finite strain, this gradient in yield strength indicates that the HAZ would sustain a higher stress than either the base or weld metal. Therefore, based just on stress, the HAZ of a Composition F weldment is potentially more susceptible to, say, environmental effects than either the base or weld metal. Clearly, the microstructure of the HAZ may also play a role in the susceptibility of the weldment to environmental effects.

Sensitivity to Residual Stresses

Residual stresses may affect the SSM derived yield strength. Flow properties measured by the SSM should include contributions due to all types of stresses. This concept is illustrated, Figure 4, using a typical load-deflection curve. From the origin - point A, (zero applied load and zero displacement) the uniaxial loading of a member results in an initial linear deflection - point B, until sufficient load has been applied to cause a permanent or plastic deviation from linear behavior - point X. At an offset displacement of 0.2 percent, the load at point X corresponds to the material's 0.2 percent offset yield strength.

Now, consider a specimen with an applied load, point B - Figure 4, to simulate a residual stress, and subject that specimen to SSM testing. From point B a reduced load and a reduced displacement is required to reach point X - the offset yield strength - as compared to the unstressed condition. Accordingly, a specimen with an applied load should appear to have a reduced yield strength. Conversely, the presence of an initial compressive load, point C, should

result in an apparent increase in the yield strength as measured by the SSM.

In this discussion it is assumed that the stress states caused by the SSM test and the applied stress are identical (and therefore additive) and that the material is homogeneous and isotropic. In reality, while the bulk stresses due to an applied load in a tensile specimen are largely uniaxial, the SSM spherical indenter produces a complex, tri-axial stress state. Furthermore, typical engineering materials are neither completely homogeneous nor isotropic. Accordingly, some deviation from this idealized view would be expected.

Yield strength data are plotted as a function of applied stress in Figure 5. Interestingly, the trend from zero to the maximum applied stress for SSM measured yield strength is a monotonically decreasing function if the 99.6 ksi (Table 1) value for the baseline (zero applied stress) is used. If the 92 ksi (Table 3) baseline yield strength is used then the apparent yield strength increases before decreasing as the applied stress is increased. However, in either case and based on this data it appears that the SSM is sensitive to the presence of applied stresses.

Conclusions

The SSM has been used to obtain reliable flow-type data from a wide range of engineering materials. The localized nature of the method allows strength gradients, which may exist in complex structures such as weldments, to be resolved. For example, a significant difference in the yield strength of the HAZ (as compared to either the base or weld metal) was noted for a Composition F, low alloy steel weldment. Finally, the technique appears to be sensitive to the presence of residual stresses. Accordingly, the SSM potentially can be used to probe a test sample or component of known yield strength to estimate the residual stress level. However, residual stress sensitivity must also be considered as a possible source of error when flow data are obtained using the SSM.

References

1. FM Haggag, 'In-Situ Measurements of Mechanical Properties Using Novel Automated Ball Indentation System', ASTM STP 1204, p. 27, 1993
2. United States Patent, Number 4,852,397, 'Field Indentation Microprobe for Structural Integrity Evaluation', 8/1/89
3. FM Haggag et al., 'The Use of Field Indentation Microprobe in Measuring Mechanical Properties of Welds', in Proceedings of the 2nd International Conference on Trends in Welding Research, (edited by SA David and JM Vitek), p. 843. ASM International, Metals Park, OH (1989).
4. FM Haggag et al., 'Use of Automated Ball Indentation Testing to Measure Flow Properties and Estimate Fracture Toughness in Metallic Materials', Applications of Automation Technology to Fatigue and Fracture Testing, ASTM STP 1092, (edited by AA Braun, NE Ashbaugh, FM Smith), p. 188. ASTM, Philadelphia, PA (1990).

5. P Au, et al., 'Flow Property Measurements From Instrumented Hardness Tests', in Non-Destructive Evaluation in the Nuclear Industry, p. 597. ASM, Metals Park, OH (1980).

TABLE 1: WELD/WELDMENT 0.2 PERCENT OFFSET YIELD STRENGTH (KSI)

BASE METAL		HAZ (1)	WELD METAL	
SSM (2)	TENSILE TEST	SSM (2)	SSM (2)	TENSILE TEST
COMPOSITION F - GAS TUNGSTEN ARC				
102.4, 102, 95.4, 100.3, 97.6, 103.2, 99.2, 99.1, 97.6, 99.5	100.5	123.9, 116.7, 116.6, 126.0	105.8, 97.8, 100.6, 100.3	103
99.6±2.4 (3)		120.8±4.9	101.1±3.4	
AISI 304L STAINLESS STEEL - TUNGSTEN INERT GAS				
27.4, 29.9, 29.3, 31.1, 29.6, 32, 29	31.4	33.1, 32.8, 32.2, 33, 36.9, 37, 37.8, 36.2	31.9, 30, 34.2, 36.1	
29.8±1.5		34.9±2.3	33.1±2.7	
ALLOY 600 - TUNGSTEN INERT GAS				
40.3, 48.7, 46.2, 54.1		42.4, 42.4, 40.6, 45.9, 41.2, 44.8, 40.2, 45.2	41, 35.3, 38, 42.8	
47.3±5.7		42.8±2.2	39.3±3.3	
49.2, 51.3, 51, 51, 58		42.1, 47, 55.1, 56.1, 47.7, 45, 54.2, 54.4, 44.7, 48.5	47.9, 44.2, 53.3, 53.6	
52.1±3.4		49.5±5.1	49.8±4.5	
ALLOY 600 - SUBMERGED ARC				
N/A	N/A	N/A	57.8, 57.2, 56, 57.5, 57.9, 56.3	56.0
			57.1±0.9	
ALLOY 690 - PLASMA ARC WELD				
51.4, 54.1, 51.1		51.8, 53.3, 47.9, 51.9	37.6, 38, 51.7, 46.3	
52.2±1.7		51.2±2.3	43.4±6.8	

Table Notes: (1) Heat Affected Zone
 (2) Stress-Strain Microprobe
 (3) Average $\pm 1\sigma$ for data listed above

TABLE 2: BASE METAL 0.2 PERCENT OFFSET YIELD STRENGTH (KSI)

PM 690 (1)		17-4 PH (2)		AISI 4340					
SSM (3)	TENSILE TEST	SSM (3)	TENSILE TEST	HEAT 1		HEAT 2	LIFTING & HANDLING COMPONENTS (SSM)		
				SSM (3)	TENSILE TEST	SSM (3)			
59.4	60.5	186.2	185	135.8	138.4	8.9	LOC. 1	LOC. 2	LOC. 3
61.4		184.9		136.4		100.0	124.2	125.8	128.1
63.8		182.2		133.2		99.3	123.8	124.2	124.1
63.1		†					123.2	126.3	123.3
64.5									
62.5±2.1(4)		184.4±2.0		135.1±1.7		99.4±0.6	123.7±0.5	125.4±1.1	125.2±2.6

Table Notes: (1) Powder Metallurgy
 (2) Precipitation Hardened
 (3) Stress-Strain Microprobe
 (4) Average $\pm 1\sigma$ for data listed above

**TABLE 3: SSM DERIVED, APPARENT YIELD STRENGTH
COMPOSITION F
WITH APPLIED TENSILE STRESS**

Applied Stress (ksi)	Apparent Yield Strength (ksi)
0	91.6, 92.7 (1)
20	98.8, 96.7
34.9	90.2, 92.4
57.5	86.8, 83.5

(1) Based on SSM tests of tensile specimens subsequently loaded in tension. Yield is about 7 ksi less than previous SSM average for the same material

Figure 1. Typical Load vs. Depth of Penetration Plot
(A1S1 304L Stainless Steel)

Figure 2. True Stress-True Strain plot
(A1S1 304L Stainless Steel)

Figure 3. Specimen in place in the ring loading fixture

Figure 4. Typical Load - Deflection (Displacement) Curve

Figure 5. SSM Apparent Yield Strength as a Function of Applied Stress for Composition F Pressure Vessel Steel