INL-MIS--18-50074-Revision-0

OSU Flow Test Fuel Plate CladdingMechanical Properties Measurement TEV-2105 R0

Randy R. Lloyd

June 2014

The INL is a U.S. Department of Energy National Laboratory
operated by Battelle Energy Alliance

INL-MIS--18-50074-Revision-0

OSU Flow Test Fuel Plate CladdingMechanical Properties Measurement TEV-2105 R0

Randy R. Lloyd

June 2014

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy

Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

TECHNICAL EVALUATION

Title: OSU Flow Test Fuel Plate Cladding—Mechanical Properties Measurement

TEV No.: 2105 Rev. No.: 0 Project No.: N/A Date: 06/05/14

		Professional Engineer's Stamp
1. Quality Level (QL) No.	2	N/A
2. QL Determination No.	MSA-000186	
3. Engineering Job (EJ) No.	N/A	
4. SSC ID	X	
5. Building	N/A	
6. Site Area	N/A	

7. Introduction:

The properties of the prototype low-enriched uranium (LEU) fuel-plate assembly are required for numerical modeling to simulate fuel plate mechanical response to certain conditions. These fuel plates are similar in form to those used in Idaho National laboratory's (INL's) Advanced Test Reactor (ATR).

The Generic Test Plate Assembly (GTPA) flow-test plates were fabricated using depleted uranium monolithic fuel foil (depleted uranium–10% molybdenum alloy) with 6061 aluminum alloy cladding. Hot isostatic pressing (HIPing) bonds both sheets of cladding to the center fuel layer, and to each other around the perimeter of the fuel. Following bonding, the excess cladding material around the fuel-foil perimeter is removed by mechanical shearing. The resulting trimmings, called "shear drops," are available for various types of characterization testing and consist of only the aluminum-alloy clad material, subjected to processing thermal cycle and pressure.

Tensile test specimens were made from shear drops from three such depleted-uranium fuel plates: CR6064; CS1027; and FP6686. Pieces for test-specimen fabrication originated from each end and along one side of all three plates. Specimen fabrication, testing, and analysis of resulting data are presented.

8. If revision, please state the reason and list sections and/or pages being affected:

N/A

9. Conclusions/Recommendations:

Specimen fabrication and testing was successfully completed. Fifteen of 18 specimens yielded test results meeting validity requirements of ASTM E8/E8M-13a. The data and properties from all specimens tested are included in Appendix A. The suspect test results are segregated from the remaining valid results.

The effects of cladding sheet delaminations observed following testing of some specimens is unknown. Additional testing will be required to provide definitive answers to this question.

CONTENTS

APPENDIXES

Title: OSU Flow Test Fuel Plate Cladding—Mechanical Properties Measurement

TEV No.: 2105 Rev. No.: 0 Project No.: N/A Date: 06/05/14

PROJECT ROLES AND RESPONSIBILITIES

Project Role	Name (Typed)	Organization	Pages covered (if applicable)
Performer	W. R. Lloyd	B120	See eCR 623005
Checker[a]	Michael E. Heighes	C660	See eCR 623005
Independent Reviewer[b]	Barry Rabin	C620	See eCR 623005
CUI Reviewer[c]			
Manager[d]	Timothy J. Roney	B120	See eCR 623005
Requestor[e]			
Nuclear Safety[e]			
Document Owner[e]	Ann Marie Phillips	W120	See eCR 623005

Responsibilities

a. Confirmation of completeness, mathematical accuracy, and correctness of data and appropriateness of assumptions.

b. Concurrence of method or approach. See definition, LWP-10106.

c. Concurrence with the document's markings in accordance with LWP-11202.

d. Concurrence of procedure compliance. Concurrence with method/approach and conclusion.

e. Concurrence with the document's assumptions and input information. See definition of Acceptance, LWP-10200.

NOTE: *Delete or mark "N/A" for project roles not engaged. Include ALL personnel and their roles listed above in the eCR system. The list of the roles above is not all inclusive. If needed, the list can be extended or reduced.*

SUMMARY

Pieces of aluminum cladding from prototype fuel plates made with depleted uranium were tested to determine tensile mechanical properties. The test specimens were removed from the edges of the fabricated plate, and contain only the two clad sheets that are bonded together during the hot isostatic pressing (HIPing) operation. The measured properties are available for input into numerical models to assess mechanical behavior of fuel plates and fuel plate assemblies.

The average property values for longitudinal (“L”, parallel to fuel plate long axis) and transverse (“T”, parallel to plate width direction) orientations varied, but not by large amounts. The average yield strengths (YS = 68.7 MPa) were nearly identical for both orientations. The uniform strain limit (strain at maximum applied force, [ε_u]) was higher by about one standard deviation of the entire data population in the longitudinal direction (18.2% versus 16.5%). The remainder of the properties had higher values in the transverse orientation. The ultimate strength (UTS) was 140.3 MPa (T) versus 136.7 MPa (L). The reduction of area (RA) was 53.9% (T) versus 46.7% (L), and the ductility (ε_f) was 26.9% (T) versus 26.0% (L). Only the reduction of area average was substantially higher in the transverse specimens.

A good portion of the specimens delaminated to some degree during the tests. The effect of these delaminations on the measured properties from those specimens is unknown. It is likely the amount of delamination could affect the reduction of area and ductility values. Delamination could possibly effect the UTS, depending on when the delamination started in a given test and to what extent it progressed during the test. A very slight sawtooth-type shape was noted in many of the stress-strain curves generated from the test data. This could be the result of a relatively slow, intermittent delamination process during the test.

The fact that over half of the specimens tested exhibited some level of delamination between the two clad sheets may be important relative to the process of fuel-plate fabrication.

METHODS

Source Material

Strips of HIP-bonded aluminum alloy cladding to be tested were provided from each of three fuel plates: CR6064; CS1027: and FP6686. The clad material is relatively soft (compared to 6061 aluminum in the T6 temper condition) following its thermal process during HIPing. Some degree of twist, warp, or bow was observed in many of the strips provided. Care was taken not to bend the strips during handling, and no attempt was made to flatten the strips prior to, or following, machining. Such actions have the potential to alter the measured yield strength of the material tested.

Material was provided in six packages, one for each plate and orientation combination. No further identification of multiple pieces within each package was provided. Based upon the length of the individual pieces and certain shapes of pieces, their nominal removal location from each fuel plate was established. The perimeter of each plate was numbered, indicating locations where bend-test proof specimens were removed. A diagram of the plate layout with these markings is shown in Figure 1.

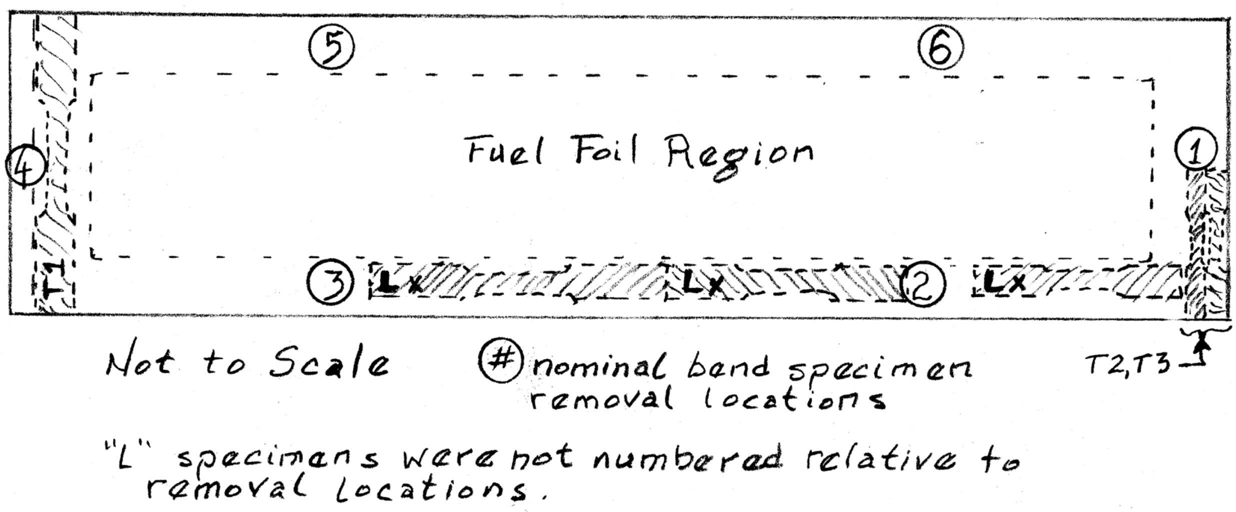


Figure 1. Schematic of GPTA Plate showing bend and tensile specimen relative removal locations.

Material at location 1 was removed and bend-tested prior to being sent for tensile testing. Un-bent material is necessary to measure yield strength, so the bent area in the center was not usable. Two half-subsize specimens (see Specimen Preparation, below) were removed from this piece as indicated to avoid re-testing bent material. The piece provided for tensile testing from the opposing end (location 4) was split prior to bend testing, and the remaining flat piece was used to make one normal subsize specimen. The longitudinal specimen material was provided from the long edge from which bend specimens 2 and 3 were removed, and relative specimen locations are shown in Figure 1.

Packaging segregated the provided material after removal from the plate-edge material prior to machining. Only one piece of material was removed at any given time, and the specimen(s) cut from it were immediately returned to the same marked packaging. This preserved the plate ID and orientation for each specimen produced. Individual specimen numbers were assigned and engraved on specimen end tabs as specimens were subsequently removed from the original packaging when being prepared for testing.

The location of the individual Lx specimens relative to the two provided strips from each plate were not maintained because there was no instruction to do so. Two individual test results from "L" specimens from a common edge did not satisfy test validity requirements. Only in this one instance would the specific removal locations possibly be of significance. This circumstance will be discussed later.

Specimen Preparation

Material provided from each of three fuel plates yielded six specimens from each plate (18 total specimens). Due to material size limitations, all longitudinal specimens and one transverse specimen conformed to the geometry specification of "Rectangular Tension Test Specimens, Subsize Specimen" as shown in Figure 1 in *Standard Test Methods for Tension Testing of Metallic Materials*[1] (**ASTM-E8/E8M-13a**, referred to hereafter as E8). The two remaining transverse specimens removed from the "bend tested" piece of material were fabricated using half-scale sizing of the subsize specimens, or "half-subsize" specimens. The ratio of dimensions of the half-subsize specimens conforms to the requirements of E8. Specimens denoted with "T2" or "T3" use the half-subsize geometry. Specimens labeled L1, L2, L3, and T1 use the standard subsize specimen geometry.

As mentioned above, the provided material is very soft. This material will not tolerate conventional machining techniques without the possibility of deformation during machining. This, in turn, can create uncertainties in the measured properties. As such, specimens were removed from the strips using wire-type electric discharge machining (wire EDM). The Model Shop in REC-603 fabricated the specimens using wire EDM. This method is a “zero-force” material-removal process that prevents deformation of the specimen material during removal from the provided material strips, and only generates a microscopically-thin layer on the cut surface that is thermally affected by the process.

Once the specimen forms were produced from the strips, the specimens received hand-finishing that smoothed the edges of the reduced section, removed the EDM heat-affected layer, and tapered the width very slightly towards the center to ensure the specimens failed in the center portion of the reduced section (required for test results validity). The four edge corners of the reduced section in each specimen were very lightly de-burred where necessary to allow making accurate dimensional measurements. In some specimens, the thickness in the reduced section was not uniform. Where necessary, the surface of the reduced section was scraped with a single-edge razor blade to make the thickness more uniform. Each subsize specimen had ductility gage marks placed with a gage-marking punch. This punch has two conical-point punches located precisely 25.40 mm (1.000 in) apart (this is the standard spacing for the subsize rectangular specimen fabricated using the E8 U.S. customary dimensions). The half-subsize specimens require 0.50 in. nominal mark spacing. These marks were placed by hand with a carbide-tipped scribe. The material is so soft that hand pressure on the body of the scribe tool created suitable conical indents. The initial mark spacing on each half-subsize specimen was measured with a calibrated optical comparator prior to testing.

Specimen Dimensional Measurements

Dimensional measurements of all specimens were made using Standards and Calibration Laboratories (S&CL) calibrated measurement instruments. Appendix A, Individual Specimen Dimensions and Mechanical Properties provides the test specimen dimensions. Appendix A, Individual Specimen Dimensions and Mechanical Properties provides measuring instrument calibration information. For each specimen, thickness and width were measured at the center and near each end of the reduced section. All specimens had minimum width and thickness near the center of the gage section as desired, and width variation was within allowable range in accordance with E8.

System Calibration

All requirements for test system calibrations as specified in E8 were met prior to initiation of testing. The force transducer (load cell) used is verified (and calibrated, if necessary) annually by Idaho National Laboratory (INL) S&CL, in accordance with **ASTM E4-10**, *Standard Practices for Force Verification of Testing Machines*[2] (hereafter, E4), and was within its valid calibration period. The data and official record of calibration for force transducers are maintained by the INL S&CL and available at any time for examination. The extensometer (engineering strain transducer) used for strain measurement in the early portion of each test is calibrated and verified by a qualified person in accordance with **ASTM E83-13a**, *Standard Practice for Verification and Classification of Extensometer Systems*[03] (hereafter E83). The extensometer calibration is verified prior to commencement of testing, and at least every 24 hours thereafter if testing continues past the 24-hour period of validity. The extensometer calibration data is included in Appendix D, Extensometer Calibration Data, and meets the requirements of accuracy Class B2 as specified in E83. All reference standards used for calibrations and verification are traceable to NIST primary standards through the INL S&CL.

Tension Testing

An Instron Bluehill 3 automated test control procedure tested each subsize specimen. An equivalent procedure, with test speed adjusted for the geometry change of the half-subsize specimens, was used for those specimens. Bluehill 3 software is user-configurable commercial software, exempted from the INL software quality assurance process.

The specimens were prepared, measured, and tested according to E8. The tests were performed at room temperature using an Instron 5984 universal test machine and Instron Bluehill 3 control software. Force was measured with a calibrated 5 kN Instron load cell (S&CL #708278). Strain in the subsize specimens was measured with a calibrated extensometer with a 25.4 mm (1.00 in.) gage length, and 20% strain measuring range. Strain in the half-subsize specimens was measured with an extensometer with 12.7 mm (0.50 in.) gage length and 30% strain measuring range. Both extensometers met requirements for accuracy Class B-2, as shown in Appendix D, Extensometer Calibration Data.

The subsize specimens were tested at a constant displacement rate of 1.0 mm/min. The half-subsize specimens were tested at a constant 0.7 mm/min. These rates result in an elastic stress rate within the specified range. Data from all transducers were automatically logged by the Bluehill 3 software. If specimen strain exceeded the extensometer measuring range during the test (all of the subsize specimen tests), the controller automatically paused the test for extensometer removal to prevent damaging the transducer. The test is continued once the operator indicates extensometer removal is complete.

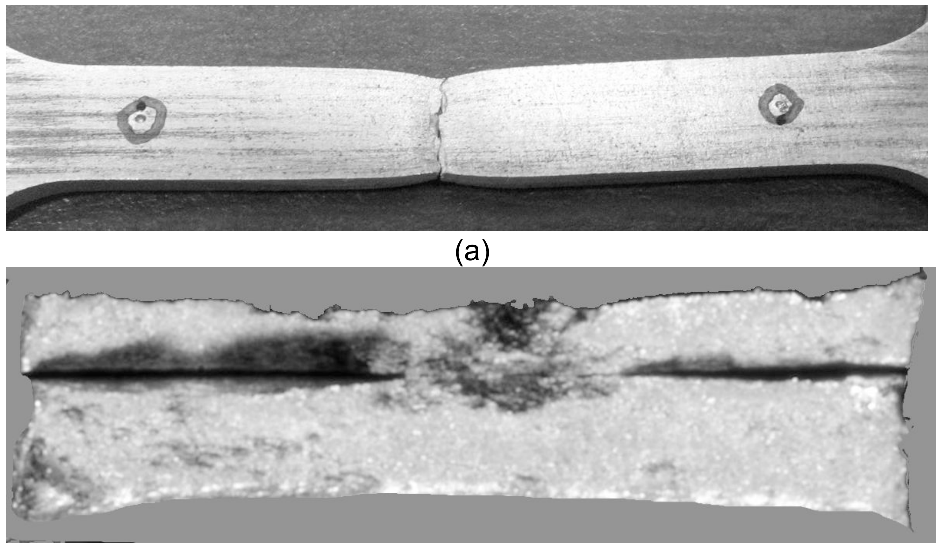
Post-Test Dimensional Measurements

Following each test, the broken specimens were removed from the machine grips, and gage-mark spacing and final cross-section areas were measured. Gage-mark spacing is measured by fitting the two broken halves together where they separated. A calibrated digital caliper (calibrated through INL's Standards and Calibration Laboratory [S&CL] # 730758) was used to measure the ending spacing between the two gage-length punch marks on the specimen surface. A representative broken specimen is shown in Figure 2.

The thin, rectangular cross-section sheet specimens do not deform to create a uniform rectangular cross-section at the break location. To estimate the reduction of area (RA) the thickness of the broken surface area was measured at each end and at its thinnest position, and an average thickness was determined. The final cross-section area was calculated using the average thickness and width. The ratio of area change to initial area provides the reduction of area value for each specimen.

Data Correction and Analysis

Strain Estimation Following Extensometer Removal



(a)

(b)

Figure 2. Broken tensile specimen with (a) gage marks for ductility determination, and (b) broken surface for area calculation.

During tests of the standard subsize specimens, the 20% measuring range of the extensometer is reached prior to specimen failure. In these cases, the extensometer is removed during the test. For a typical tensile test, the specimen strain data ends at that point in the test. In instances where continued specimen strain data are desired (with reduced accuracy) the test machine crosshead displacement can be used to approximate specimen strain. There are several methods for doing this. Some are more accurate than others, but require more analysis and calculation to perform. A method in which a portion of extensometer data near the end of extensometer measurement is correlated to the crosshead displacement data was used when required. By applying offsets and effective gage-length factors, the specimen strain for the latter portion of each test is estimated. This process is detailed in Appendix E.

Initial Slope to Determine Yield Strength

Three of the 18 specimens tested, CR6064-L1, CR6064-L3, and FP6686-L2, had significant non-linearity in the first portion of the stress-strain curve. The two CR6064 specimen responses became non-linear at very low stress levels (<20 MPa). The FP6686-L2 specimen response had a high initial slope with a continuous negative curvature, not showing any significant linear response region. Specimen bending or extensometer mounting irregularities can cause the appearance of the continuous negative curvature (or more commonly an “S”-shaped curve) seen with FP6686-L2. This type of observed behavior is expected when testing small specimens made of very ductile material. The unusual response of the two CR6064 specimens defies explanation at this time.

An assessment of the remaining 15 test data sets resulted in an average initial slope of 66.7 GPa, and a standard deviation of 12.2 GPa. The variability in modulus slope using a larger-range extensometer and small specimens is not unusual, and the average is in the correct range for 6061 aluminum (68.9 GPa[04]). A variability of 10% in the initial slope is usually accepted when using similar measuring equipment and “full-size” specimens. The smaller specimens tend to exacerbate the deviations in the fitted slope.

For the three atypical specimens mentioned, a slope line of 68.9 GPa was aligned with the stress strain curve to have a smooth transition into the yielding region. Figure 3 shows data from the three specimens with irregular initial stress-strain relationships, and one typical response curve for comparison. Useful properties data can be extracted from such test results in some instances; however, the shape of the response curves for the two CR6064 specimens is so far from the expected, any yield strength results from them are suspect.

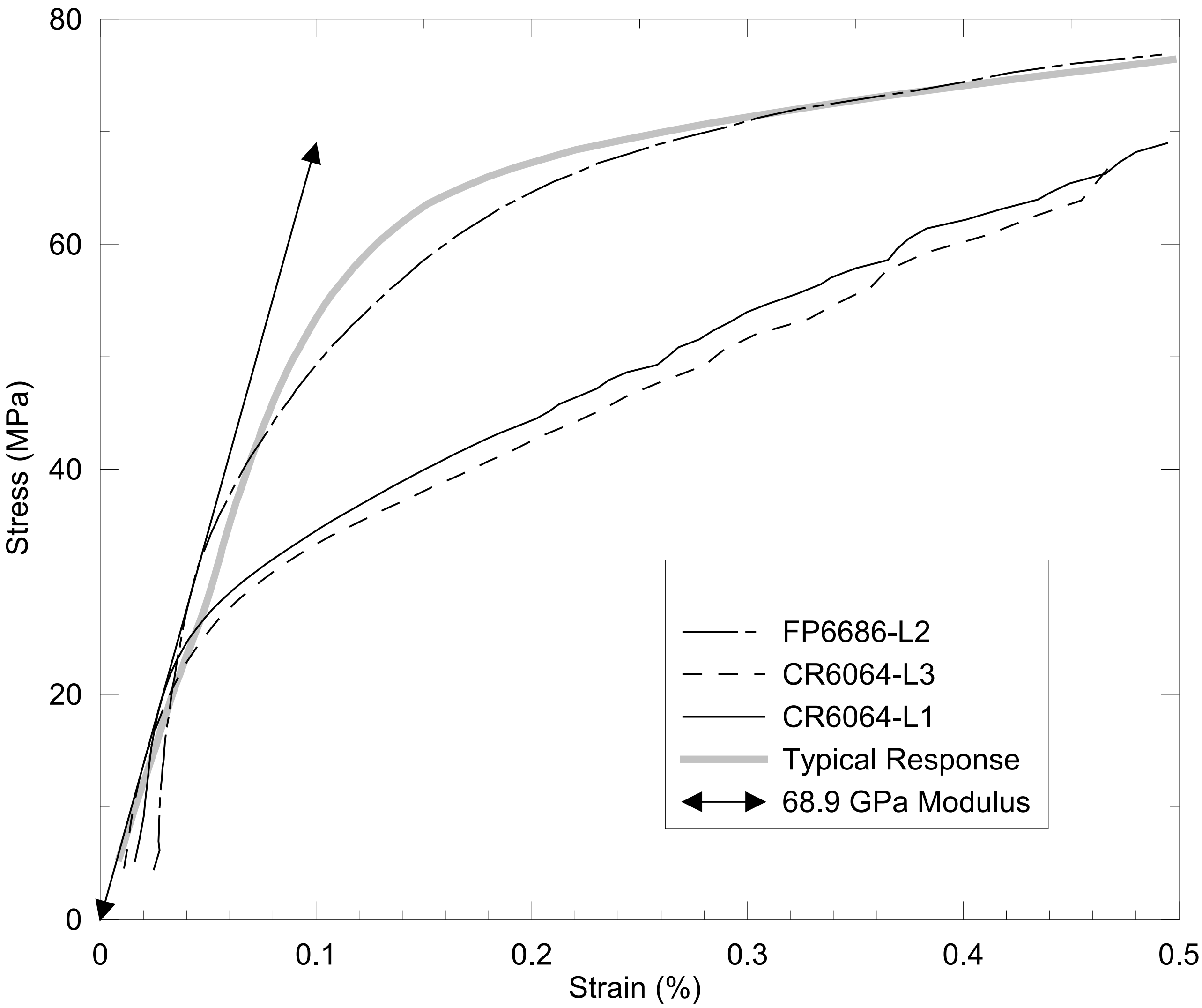


Figure 3. Comparison between three atypical specimen response curves with a typical response curve (thick grey curve).

For the remaining specimens, the normal procedure is to use the fit-slope line for the construction-line basis and report the yield strength at the intersection of the stress-strain curve and the 0.2% offset construction line. In some cases, where the early stress-strain response does not include a well-delineated linear portion, the published modulus for the material being tested is used as the basis for the construction line. This is allowable if the modulus construction line can be reasonably merged with the actual data. This adjustment is noted along with the reported yield strength so determined.

In many instances a substantial change in the construction-line slope, when properly aligned with the "good" data, causes only minor changes in the yield strength. Figure 4 demonstrates the difference in yield strength determination for CR6064-L2 (a "good" set of test data to begin with) when the construction-line slope is changed from 88.4 GPa (data fit) to 68.9 GPa (published material modulus). The yield strength value only changed from 67.3 to 67.9 MPa. Similarly, FP6686-T3 (another "good" data set) had an initial data fit slope of 51.8 GPa. Using this slope resulted in a yield intercept at 72.6 MPa, while using the published material modulus resulted in a yield strength of 71.7 MPa—again a small difference.

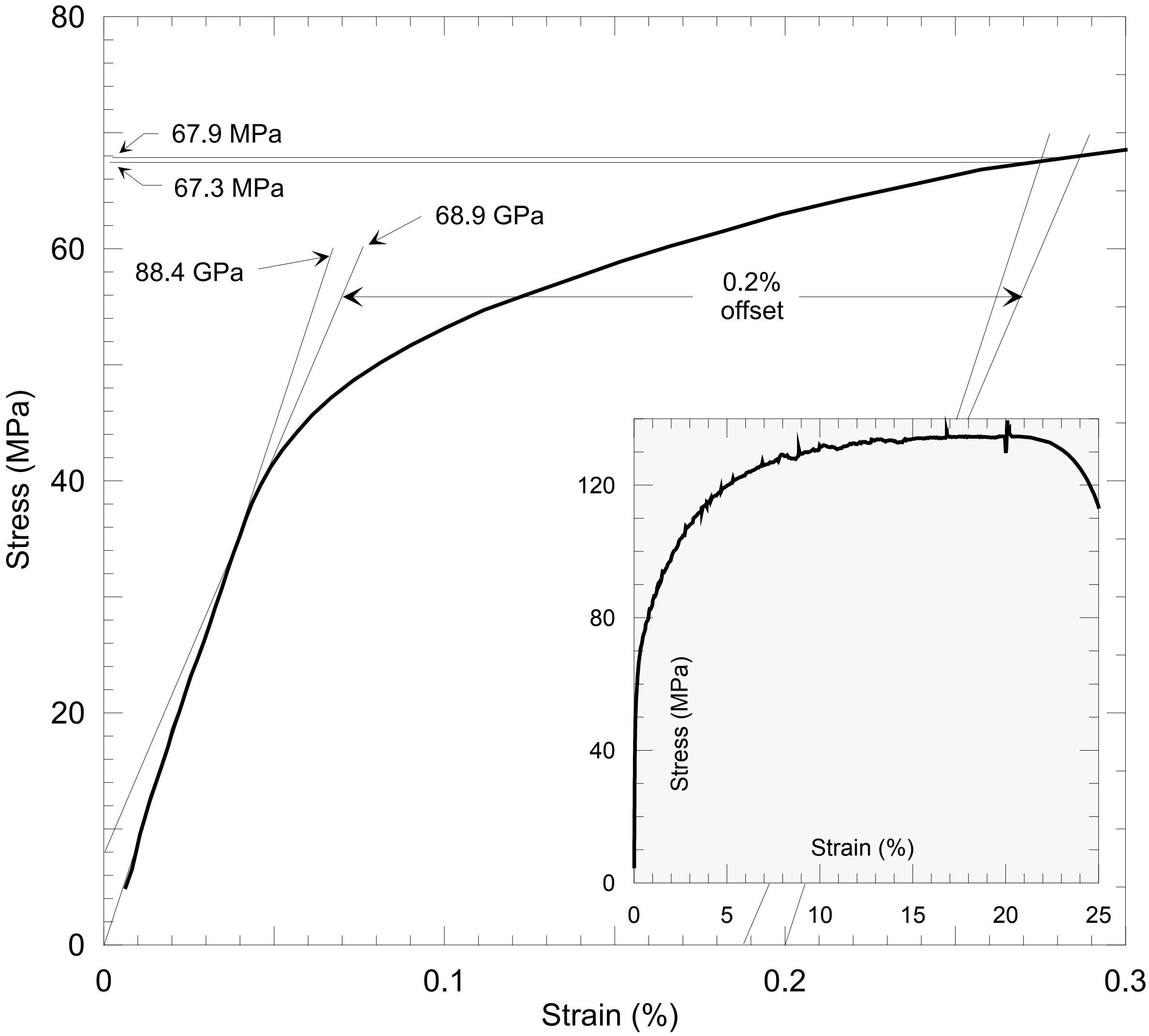


Figure 4. Effect of construction line slope on resulting yield strength determination (minimal).

Test Results

The test results provided are Quality Level 3 because there was not a formalized test plan provided for this task. However, instruments used to collect data during the tests were calibrated and meet the traceability requirements of NQA-1. ASTM E8/E8M-13a and sublevel ASTM standards and procedures guided testing and analysis of the test data.

All specimens broke in the central part of the reduced section; one requirement for the test to be valid. Specimen failure in the middle half of the reduced section (away from the gage marks) allows valid[1] ductility measurement, too. With the exception of three specimens mentioned earlier, mechanical properties measurements from the data analysis are reliable. Analysis of each specimen data set determined the required mechanical properties, tabulated in Appendix A, Individual Specimen Dimensions and Mechanical Properties.

All of the test specimens made from the fuel clad “shear drops” contain the HIPing interface. This interface is not generally located at the mid-plane of the specimen, but is nearer one surface in most cases, as shown in Figure 2(b). In many of the tests, the bond layer delaminates to some degree in the region where the specimen breaks, while some specimens show no sign of delamination. Figure 5 shows representative portions of stress-strain plots from specimens with no delamination, partial delamination, and complete delamination. Many of the stress-strain curves exhibit some level of saw-tooth characteristic during the increasing plastic strain part of the test, as shown. This may be the result of small increments of delamination during the test. These delaminations create some uncertainty in the reduction of area calculations. They also have an unknown effect on the ductility measurement because the delamination reduces lateral constraint in the specimen to some degree.

The figure shows some interesting differences between the specimens. The specimen that had no apparent delamination does not have the number of sharp load-drop events that the other two have. This specimen had a lower UTS value, but the processing parameters might have influenced the UTS value for that particular plate. The specimen with partial delamination shows a number of load -rop events, about the same as the full delamination specimen. However, they are less in magnitude than the specimen that fully delaminated in the break region. The specimen that completely delaminated at the break region exhibited a lower strain at failure than the other two specimens. This phenomenon may be related to the full delamination prior to failure.

Appendix A, Individual Specimen Dimensions and Mechanical Properties provides a summary of test results. The average property values for longitudinal and transverse orientations varied, but not by large amounts. The average yield strengths (YSs) were nearly identical for both orientations (L = 69.0 MPa and T = 68.5 MPa). The uniform strain limit (strain at maximum applied force, (ε_u) was higher by about one standard deviation in the longitudinal direction (18.2% versus 16.5%). The remainder of the properties had higher values in the transverse orientation. The ultimate strength (UTS) was 140.3 MPa (T) versus 136.7 MPa (L). The ductility (ε_f) was 26.9% (T) versus 26.0% (L). Only the reduction of area (RA) average was substantially higher in the transverse specimens: 53.9% (T) versus 46.7% (L).

---

1. With the caveat that delaminations of some specimens may influence the properties measured from them.

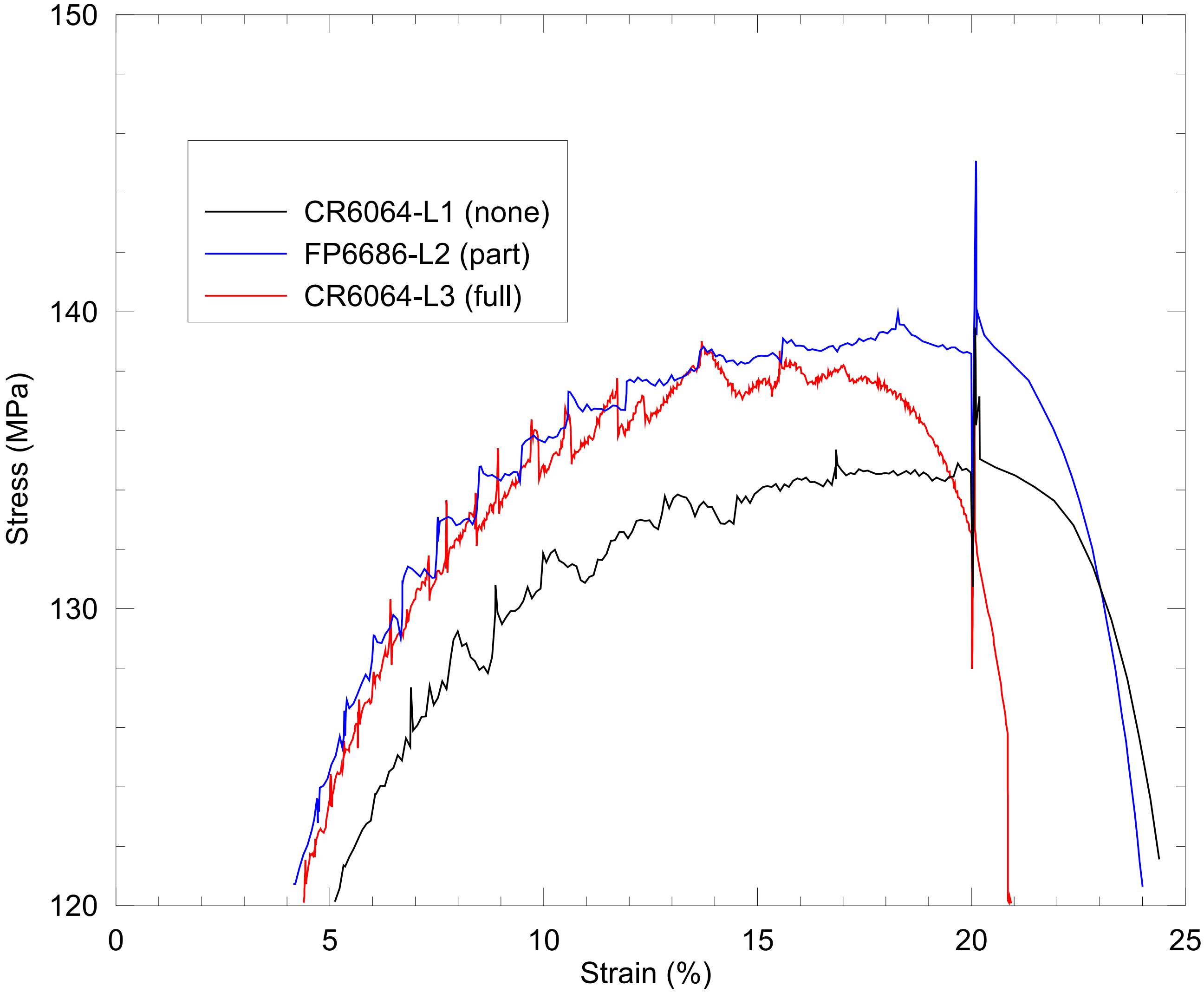


Figure 5 . Plastic strain portions of response from three specimens: no, partial, or full delamination prior to final failure.

DISCUSSION

The stress-strain response for CR6064-L1 and L3 had very distinct slope changes at low stress levels. The slope prior to the change was in agreement with the expected modulus of the material, but, while remaining reasonably linear, dropped to a new slope that was the order of half or less of the original slope (modulus) until the anticipated yield stress range was reached. A few other specimens showed just a hint of this behavior. All aspects of the experimental set-up remained the same throughout testing of the standard subsize specimens, so it is unlikely a test configuration problem caused this. Broken specimen appearance in both cases was similar to the other specimens and provides no clues about the differing response. The material tested does consist of two sheets that are HIPed, and many specimens exhibited delamination at the bond line where the specimen finally broke into separate pieces. The yield strengths from these two specimens—both 59 MPa based on analysis of the initial linear section of each curve—are significantly lower than the average strength of the entire group, including two orientations from three different plates. As discussed earlier, the material provided from plate CR6064 for “longitudinal” orientation specimens came in two pieces – one about 275 mm long from the mid-plate position, and one about 130 mm long that was nearer the position “1” end of the fuel plate. It is possible that specimens CR6064-L1 and L3 were removed from the longer strip, immediately adjacent to one another, and were possibly representative of some localized processing condition. Further assessment of possible processing-related effects is beyond the scope of this report.

REFERENCES

1 “Standard Test Methods for Tension Testing of Metallic Materials,” ASTM E8/E8M-13a, ASTM International, West Conshohocken, PA, 2013.

2 “Standard Practices for Force Verification of Testing Machines,” ASTM E4-10a, ASTM International, West Conshohocken, PA, 2013.

3 “Standard Practice for Verification and classification of Extensometer Systems,” ASTM E83-13a, ASTM International, West Conshohocken, PA, 2013

4 Properties for 6061-0 aluminum alloy, http://www.matweb.com/search/DataSheet.aspx?MatGUID=626ec8cdca604f1994be4fc2bc6f7f63&ckck=1

Title: OSU Flow Test Fuel Plate Cladding—Mechanical Properties Measurement

TEV No.: 2105 Rev. No.: 0 Project No.: N/A Date: 06/05/14

Appendix A

Individual Specimen Dimensions and Mechanical Properties

Table A-1. Suspect Properties—Invalid Tests.

ID	E (GPa)	YS (MPa)	e_{YP} (%)	UTS (MPa)	e_u (%)	RA (%)	e_f (%)	Delam?	GL_0 (mm)	GL_f (mm)	t_0 (mm)	t_f (mm)	W_0 (mm)	W_f (mm)
CR6064-L1	68	51.8	0.28	134.4	17.06	47.7	24.7	no	25.40	31.67	2.064	1.38	6.286	4.92
CR6064-L3	51.9	48.2	0.27	135.1	17.42	47.8	26.9	near full	25.40	32.23	2.075	1.33	6.313	5.14
FP6686-L2	165	69.1	0.24	135.7	16.6	49.4	25.4	near full	25.40	31.84	2.032	1.29	6.311	5.03
Group Avg	95.0	56.37	0.263	135.1	17.03	48.3	25.7							

Table A-2. Valid Tests and Results.

ID	E (GPa)	YS (MPa)	ε_{YP} (%)	UTS (MPa)	ε_u (%)	RA (%)	ε_f (%)	Delam?	GL_0 (mm)	GL_f (mm)	t_0 (mm)	t_f (mm)	W_0 (mm)	W_f (mm)
CR6064-L2	93.3	67.47	0.273	134.4	19.35	48.2	27.3	no	25.40	32.33	2.084	1.35	6.313	5.05
CR6064-T1	71.1	64.36	0.291	137.2	18.82	48.8	27.4	tiny?	25.40	32.36	1.993	1.31	6.338	4.94
CR6064-T2	60.9	65.46	0.306	143.1	20.13	51.0	29.6	no	12.63	16.37	1.999	1.26	3.112	2.42
CR6064-T3	70.6	67.28	0.295	140.9	16.76	53.5	29.4	no	12.66	16.38	1.967	1.19	3.086	2.37
CR6064 Plate Avg	74.0	66.14	0.291	138.9	18.77	50.4	28.4							

Title: OSU Flow Test Fuel Plate Cladding—Mechanical Properties Measurement

TEV No.: 2105 Rev. No.: 0 Project No.: N/A Date: 06/05/14

ID	E (GPa)	YS (MPa)	ε_{YP} (%)	UTS (MPa)	ε_u (%)	RA (%)	ε_f (%)	Delam?	GL_0 (mm)	GL_f (mm)	t_0 (mm)	t_f (mm)	W_0 (mm)	W_f (mm)
CS1027-L1	65.2	70.35	0.306	136.1	18.24	49.0	26.2	minor	25.40	32.06	2.001	1.29	6.283	4.97
CS1027-L2	56.4	72.07	0.328	136.1	19.32	44.6	26.9	tiny?	25.40	32.24	2.008	1.38	6.244	5.03
CS1027-L3	49.7	67.00	0.335	137.5	15.42	39.8	22.8	full	25.40	31.20	1.998	1.47	6.269	5.13
CS1027-T1	81.2	70.72	0.285	139.9	15.38	44.6	22.8	no	25.40	31.20	1.950	1.35	6.297	5.04
CS1027-T2	64.6	70.50	0.310	142.0	15.49	60.6	30.5	no	12.03	15.70	1.950	1.05	2.996	2.19
CS1027-T3	71.3	65.24	0.292	140.0	16.33	61.1	28.0	minor	12.38	15.85	1.985	1.04	3.101	2.30
CS1027 Plate Avg	64.7	69.31	0.309	138.6	16.70	50.0	26.2							
FP6686-L1	56.1	68.56	0.320	136.1	18.33	48.7	26.6	tiny?	25.40	32.16	2.044	1.32	6.310	5.01
FP6686-L3	66.7	68.67	0.300	140.0	18.27	49.8	26.5	partial	25.40	32.06	2.019	1.28	6.316	5.00
FP6686-T1	86.1	66.12	0.285	138.4	15.57	48.0	23.1	minor	25.40	31.27	1.979	1.29	6.300	5.03
FP6686-T2	55.8	73.80	0.335	140.6	14.66	61.8	25.5	partial	12.72	15.96	1.941	1.00	3.100	2.30
FP6686-T3	51.8	72.60	0.378	140.2	15.73	56.1	26.1	minor	12.85	16.21	1.921	1.17	3.109	2.24
FP6686 Plate Avg	63.3	69.95	0.324	139.1	16.51	52.9	25.6							

Title: OSU Flow Test Fuel Plate Cladding—Mechanical Properties Measurement

TEV No.: 2105 Rev. No.: 0 Project No.: N/A Date: 06/05/14

Definitions

Orientation: L: longitudinal = parallel to fuel plate long axis; T: transverse, parallel to plate width direction; perpendicular to “L” orientation.

Slope: Slope of elastic portion of stress-strain used in yield-strength determination. Value of 100 GPa used as reference when correcting extensometer data for specimen bending, based upon average slope of curves needing correction.

σ_{yp}: 0.2% Offset Yield Strength.

UTS: Ultimate tensile strength: maximum engineering stress supported by specimen.

ε_u: Uniform strain limit: strain at UTS, assumed nominal onset of specimen necking.

RA: Reduction of Area: plastic cross-section area change at end of test.

ε_f: Failure plastic strain, called elongation at failure or ductility: change in separation of reference marks within specimen reduced section at end of test, measured by fitting broken specimen halves back together following test.

Appendix B

Statistical Analysis of Mechanical Properties (Orientation Effects)

	E (GPa)	Yield Strength (MPa)	Strain at Yield, ε_{YP} (%)	UTS (MPa)	Uniform Strain Limit, ε_u (%)	Reduction of Area, RA (%)	Ductility, ε_f (%)
All Valid Results							
Average	66.7	68.68	0.309	138.8	17.2	51.0	26.6
Std.Dev.	12.2	2.79	0.026	2.4	1.7	6.2	2.3
All Valid Longitudinal							
Average	64.57	69.02	0.310	136.7	18.2	46.7	26.1
Std.Dev.	15.1	1.89	0.021	1.7	1.5	3.3	1.7
All Valid Transverse							
Average	68.16	68.45	0.309	140.3	16.5	53.9	26.9
Std.Dev.	10.6	3.30	0.029	1.7	1.7	6.0	2.6

Appendix C

Measurement and Test Equipment Calibration

Name	ID	Cal. Expiration	Measurement Use
Calipers	S&CL 730758	01 Oct 2014	Overall lengths, final gage mark spacing
1” Micrometer	S&CL 713989	12 Aug 2014	Specimen initial width and thickness
50 mm Mic Head	S&CL 723699	15 Apr 2014	“t,” specimen surface thicknesses at “X”
50 mm Mic Head	S&CL 723700	27 Jun 2014	“x,” width location on broken surface, specimen width
Load Cell (5 kN)	S&CL 708278	30 Apr 2014	test force measurement, stress calculation source
Extensometer	Instron 2620-824, S/N: 1027	Cal Before Use	specimen engineering strain
Extensometer	Instron 2630-121, S/N: 26	Cal Before Use	specimen engineering strain
Extensometer Calibration Stand	S&CL 716141	21 Aug 2014	calibration of extensometer(s) prior to use

Appendix D

Extensometer Calibration Data

Definitions

STD	Reference standard values, measures in length, converted to strain based upon extensometer gage length.
UUT	“Unit under test” (readings from the extensometer being verified).
“%”	Strain in percent, equal to mm/mm * 100
“με”	Strain unit of microstrain, equal to mm/mm*1E6, typically used for error measurements
“1” and “2”	Comparison data collection sequence. E83 requires one “run”, then remove and reinstall the extensometer on the calibration stand, and perform a second “run” to assure measurement repeatability on any given mounting to the specimen.
Error	Comparison error at any given calibration stand setting.

ASTM E83-13a requires a minimum of 5 measurements for any given “run,” with a specified range of measurement position difference. Best practice is to use the sequence “1,2,4,7” per decade of measurement, repeating as necessary, and capturing the maximum measurement range value on the final measurement if it does not coincide with a standard measurement increment, e.g., 25%, or 0.30 in. ASTM E83-13a Accuracy Class for these tests: Class B2

Reference Standard: Epsilon Model 3590, S&CL ID#716141, Calibration Expiration: 21 Aug 2014

Title: OSU Flow Test Fuel Plate Cladding—Mechanical Properties Measurement

TEV No.: 2105 Rev. No.: 0 Project No.: N/A Date: 06/05/14

Table D-1. Instron 2620-824, S/N 1027, +20% Strain Full Scale Range, Gage Length = 25.40 mm (1.000 in.).

Calibration Date: 08 Feb 2014, by: W. R. Lloyd (accuracy of standard is ±50 με)						
STD (in.)	STD (%)	UUT Run 1 (%)	UUT Run 2 (%)	Err1 (με)	Err2 (με)	Allowable Error (+/- με)
0.00100	0.1000	.098	.097	-20	-30	-250
0.00200	0.2000	.200	.201	0	10	-250
0.00400	0.4000	.406	.404	60	40	-250
0.00700	0.7000	.700	.698	0	-20	-250
0.01000	1.0000	.997	.999	-30	-10	-250
0.02000	2.0000	2.003	2.003	30	30	-250
0.04000	4.0000	4.000	3.999	0	-10	-250
0.07000	7.0000	7.000	6.997	0	30	-349
0.10000	10.0000	10.000	9.998	0	-20	-498
0.20000	20.0000	19.989	19.940	-110	-600	-999
Passes ASTM E83, Accuracy Class B-2						

Table D-2. Instron 2630-121, S/N 26, +30% Strain Full Scale Range, gage Length = 12.7 mm (0.500 in.).

Calibration Date: 09 Feb 2014, by: W. R. Lloyd (accuracy of standard is ±100 µe)						
STD (in.)	STD (%)	UUT Run 1 (%)	UUT Run 2 (%)	Err1 (µε)	Err2 (µε)	Allowable Error (+/- µε)
0.00100	0.200	.192	.194	-80	-60	-250
0.00200	0.400	.401	.406	10	60	-250
0.00400	0.800	.798	.808	-20	80	-250
0.00700	1.400	1.404	1.413	40	130	-250
0.01000	2.000	1.996	2.018	-40	180	-250
0.02000	4.000	3.995	4.019	-50	190	-250
0.04000	8.000	7.990	8.011	-100	110	-250
0.07000	14.000	13.987	14.011	-130	110	-349
0.10000	20.000	20.011	20.03	110	300	-498
0.15000	30.000	30.05	30.06	500	600	-999
Passes ASTM E83, Accuracy Class B-2						

Appendix E

Process for Estimating Specimen Strain from Crosshead Displacement

In the present case, this strain estimation from displacement data was not necessary, since all subsize specimens broke very shortly after extensometer removal, and the half-subsize specimens broke before reaching the measuring limit of the extensometer.

The first step in the process makes an approximate correction to the machine crosshead-displacement data to account for the machine and test-train compliance (frame compliance). The frame compliance can be assessed by several methods:

1. Test a very stiff, short, specimen in the same load train and grips (most accurate);

2. Calculate compliance of the load-train components and add to the published test-machine compliance;

3. Estimate compliance based on historical results from similar test set-ups

4. Make no correction (least accurate).

In all instances, the effective compliance is not constant, but is a function of applied load. Contributing factors include grip jaw tightening in the grip bodies as applied force increases, straightening of minor misalignment of the loading components (universal joint, threaded pull rods, threaded couplers, etc.), and other internal test-frame factors. The straightening of the load string occurs in the initial portion of specimen loading, where an extensometer measures strain; this effect is of minimal concern in normal circumstances. Method 1 is costly and time-consuming, and the accuracy improvement is seldom required. The mechanical testing labs at the INL Research Center have considerable historical test data that allows application of method 3 in most cases. The “no correction” method (4) requires no extra steps, is the least accurate but, in some cases, is adequate.

Multiplication of applied force at each data point by the established frame compliance for that load gives the amount of displacement contributed by everything other than the test specimen. The combined frame and load-string displacement is subtracted from the total displacement at that point to give a corrected “specimen displacement.” The accuracy of the resultant specimen displacement is dependent on the method employed to obtain the compliance function (method [1], constant [2] or [3], or zero [4] as shown above).

The specimen end-tab displacement (hereafter “specimen displacement”) determined as a function of machine crosshead displacement (as detailed above) provides the base values for the strain calculation after extensometer removal. Several ways of processing the specimen displacement values allow estimating specimen strain following extensometer removal.

There are several approaches to making strain estimations from remote, i.e. not a directly attached extensometer, displacement values.

Title: OSU Flow Test Fuel Plate Cladding—Mechanical Properties Measurement

TEV No.: 2105 Rev. No.: 0 Project No.: N/A Date: 06/05/14

A simple (but potentially less accurate) method uses a specified effective gage length value to calculate strain, and offsets the strain to match at the last data point prior to extensometer removal. This method relies on a good estimation of the effective gage length by the analyst. Instron Bluehill software uses this approach, applies no compliance correction to the crosshead displacement data, and performs a single point offset adjustment at the last extensometer data point. For the purpose of creating a continuous stress versus strain data plot this is adequate, but experience suggests that use of the crosshead-displacement-based strain data for calculation of, e.g., ductility, is not very reliable.

A strain-estimation method that potentially results in the closest estimation of engineering strain adjusts offset values and effective gage-length values to minimize the error between extensometer strain and the calculated strain over some portion of the extensometer strain data—usually in the range of 75–100% of available extensometer measuring range. The selection of offset and gage-length values to minimize the error between extensometer strain and displacement-based strain is easily done by manual selection of values as follows. The portion of the two data sets to match is plotted on a common graph in a spreadsheet program. The effective gage length and specimen strain offset are then adjusted to align the two plot curves as closely as possible. An accumulated error calculator (integrating absolute value of point-by-point error over the fitting range) could also be included to fine tune the fit if desired. Details of this approach follow below.

A test frame and load string compliance (single value or function as appropriate) is applied to the raw crosshead data and subtracted from total crosshead displacement, resulting in the “specimen end tab displacement.” Experience with testing small specimens requiring low applied forces indicates the actual “frame compliance” is non-linear and includes some load reversal hysteresis. However, for the expected strain measuring accuracy, assuming a linear compliance has proven to be satisfactory for most requirements.

The specimen end tab displacement (hereafter, displacement) data are then offset and divided by the effective gage length (both values determined by the graphical-matching approach described above) to generate the estimated specimen strain for each data point.

It is important to note that once the tensile specimens start to experience strain localization shortly after maximum applied force is exceeded, i.e. at the uniform strain limit, and the actual true strains will be significantly higher than these estimated values.