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Elevated Temperature Tensile Tests on DU–10Mo Rolled Foils

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ABSTRACT

Tensile mechanical properties for uranium–10 wt.% molybdenum (U–10Mo) foils are required to support modeling and qualification of new monolithic fuel plate designs. It is expected that depleted uranium–10 wt% Mo (DU–10Mo) mechanical behavior is representative of the low-enriched U–10Mo to be used in the actual fuel plates, therefore DU–10Mo was studied to simplify material processing, handling, and testing requirements. In this report, tensile testing of DU–10Mo fuel foils, prepared using four different thermomechanical processing treatments, were conducted to assess the impact of foil-fabrication history on resultant tensile properties.

The Y–12 National Security Complex at Oak Ridge National Laboratory (Y–12) provided Idaho National Laboratory (INL) with a cast and machined ~4.1 mm-thick, ~127 mm-wide, and ~182 mm-long plate of DU–10Mo. After receipt at INL, the plate (designated alloy 551) was sectioned into four pieces using wire electric discharge machining (wire EDM), and each piece was homogenized at 1000°C for two hours under vacuum of 5×10^{-6} Torr. These pieces were then individually hot-rolled into foil strips of varying thickness. Additional cold-rolling was performed on three of the four foils to bring the final thickness of each cold-rolled foil to a target of 0.38 mm, representative of the final thickness of actual fuel foils. The four foil conditions studied were as follows: Foil 551-2—additional 50% cold-rolling reduction; Foil 551-3—additional 50% cold-rolling reduction followed by stress-relief annealing at 650°C for one hour; Foil 551-4—additional 20% cold-rolling reduction; and Foil 551-5—no further processing, i.e., hot-rolled only. Due to breach of the protective rolling can, hot rolling of foil 551-5 was terminated early, resulting in a final nominal thickness of 0.53 mm. Sub-size flat sheet-type tensile specimens, with dimensions scaled to 50% (i.e., 50 mm nominal overall length) of the normal sub-size specimen, as specified in Figure 1 of ASTM E8/8M-13, were cut from the finished foil sheets using wire EDM machining. Tests were conducted on specimens with both longitudinal and transverse orientation relative to rolling direction, and at various temperatures between room temperature (per ASTM E8/8M-13) and elevated temperatures (per ASTM E21-10) up to 550°C.

This work was conducted under an approve test plan that contained additional requirements and instructions for testing. The following report presents details of the testing system, testing methods, and mechanical properties determined from the test data.

Tensile properties of DU–10Mo at room temperature through approximately 400°C determined from the tests conducted herein suggest the material is stronger and has lower ductility than what has been reported previously in the literature. The explanation for these differences has yet to be determined, but is likely related to differences in grain size and/or impurity content. At the highest temperatures tested (550°C), better agreement between the values reported here and available literature was found. As expected, yield and ultimate tensile strength decreased with increasing test temperature. Generally, the yield stress for all foil processing conditions was found to be in the range of 1100 MPa for room temperature tests, and in the range of 200 MPa for tests conducted at 550°C. Ultimate tensile stress was in the range of 1175 MPa at room temperature, decreasing to approximately 225 MPa at 550°C. Elongation

increased significantly from 0–2% at room temperature, to 50% or more for the tests at 550°C. Additional details on the observed effects of foil processing condition and specimen orientation on tensile properties are summarized below:

- Yield Strength

  No significant effect of fabrication history on yield stress was observed at the lowest temperature (room temperature) and highest temperature (550°C) tested. However, tests indicated yield strength differences exist at the intermediate temperatures tested with the 50% cold-worked and annealed and the hot-rolled-only material producing lower yield stress at the intermediate test temperatures. Significant effects of specimen orientation on yield strength were only observed in a few cases (specifically 20% cold-worked material tested at 200°C resulted in lower yield stress in the transvers orientation, and hot-rolled-only material tested at room temperature and 200°C where the transvers orientation resulted in slightly higher yield stress).

- Ultimate Tensile Strength (UTS)

  Significant differences in the UTS were noted in the longitudinal direction for the four foils at room temperature, with the difference continuing, but converging as the temperature increased. This difference between each of the four foils was also found to exist in the transvers direction. The 50% cold-worked and annealed and the hot-rolled-only material produced lower ultimate tensile stress at room and the intermediate test temperatures, but converged when tested at 550°C.

  Orientation effects for specimens from the same foil were only noted in the following case: 50% cold-worked at 350°C, in which the transvers direction produced lower ultimate tensile stress. All other tests indicated no significant anisotropy due to rolling direction.

- Slope

  Slope of the initial section of the stress-strain curve was calculated for each specimen and then averaged across all specimens tested in each temperature group. The average slope in MPa/% and standard deviation for each test temperature are: 20°C, 884.21±13.15; 200–250°C, 417.63±16.81; 350°C, 422.25±14.75; 400–450°C, 320.43±17.88; 550°C, 199.29±24.41. Room-temperature elastic-modulus values reported in the literature are in the low-to-mid 80s GPa range,[a,b] consistent with our room-temperature test results.

- Ductility

  Room-temperature ductility was determined for all of the foil conditions tested. Of note, the 50% cold worked and annealed foil (foil 551-3) showed increased ductility compared to the 50 and 20% cold-worked foils. The hot-rolled-only foil showed more ductility in the longitudinal direction than any other foil at room temperature, but showed very little ductility in the transverse direction, indicating significant anisotropy at room temperature.

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a. J. E. Gates, et al., "Stress-Strain Properties of Irradiated Uranium–10 w/o Molybdenum," BMI-APDA-638, Battelle Memorial Institute, Columbus, OH, January, 1958.

b. G. Beghi, "Gamma Phase Uranium-Molybdenum Fuel Alloys", EUR-4053e, European Atomic Energy Community, 1968.

Ductility increased continuously for all foil conditions as testing temperature increased and was significant for foils tested at 550°C. At 550°C, the ductility for all foil conditions and orientations increased from ~<10% to as much as ~70% in the 50% cold-worked foil in the longitudinal direction (551-2) and, also, ~70% for the 50% cold-worked and annealed foil (551-3) in both directions. The increase in ductility at 550°C was more pronounced for the 20% cold-worked foil than for other foil-processing conditions.

For a few specimens in both room-temperature and elevated-temperature cases, the 0.2% offset curve did not intersect the stress-strain curve. Theoretically, ductility would be very small in these cases. When combined with the measurement error evaluated in Table 5, and recognizing that it can be difficult to accurately piece specimens back together for post-test elongation measurements due to roughness at the fracture surface; it is likely that actual elongation values reported are less than the reported values of 3% or less. This specifically includes the following specimens tested at room temperature: 551-2-2 L17, T14; 551-5 T1, and T2; and the following specimens tested at elevated temperature: 551-2-2 T11, and T5, but may impact any specimens with reported elongation values of less than 3%.

- Recommendations for Future Work

It is recommended that future work include fractography of selected specimens to determine whether failure mechanisms other than ductile rupture exist and whether fracture initiation sites can be identified. Metallography and microstructural characterization should be completed to characterize grain sizes and other microstructural features that may explain the observed mechanical behavior. Finally, it is recommended that additional testing be conducted on similarly processed material having different impurity content (particularly different carbide distributions) to better understand the range of properties that may be expected in commercially fabricated fuel foils.

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ACRONYMS

DU	depleted uranium
EDM	electric discharge machining
FFC	Fuel Fabrication Capability pillar
INL	Idaho National Laboratory
SC&L	Standards and Calibrations Laboratory (at INL)
UTS	ultimate tensile strength

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Elevated Temperature Tensile Tests on DU–10Mo Rolled Foils

1. BACKGROUND

Tensile properties for rolled uranium–10 wt.% molybdenum (U–10Mo) foils are required to support modeling and qualification of new monolithic fuel plate designs that incorporate these alloy foils as fuel. Limited data exist on the property-processing-structure relationship of U–10Mo fuel foils. Most of the available studies reporting properties for U–Mo alloys were conducted in the 1950s and 1960s. For example, Waldron (1958) reports yield stress, ultimate tensile stress, and modulus for U–Mo alloys, where the wt% of Mo was varied in the alloy and where the heat treatment temperature and time were varied (see Table 1).[1] However, the Waldron report does not provide information relevant to the properties of rolled foils, or the effect of foil-rolling conditions on properties.

Table 1. Summarized mechanical properties from Waldron.[1]

Composition wt % Molybdenum	Prior Heat Treatment Temp (°C)	Prior Heat Treatment Time (Days)	Temp of Testing (°C)	UTS (Tons/sq.in.)	UTS (MPa)[a]	Youngs Modulus (psi x 10^6)	Youngs Modulus (GPa)[a]	Elongation (on 1.2") %
10	900	7	20	44.8	617.8	12.6	86.87	0.35
10	450	14	20	21.3	293.7	17.3	119.3	0.33
10	900	7	200	37	510.2	10.7	73.77	0.5
10			400	26	358.5	7.5	51.71	1
10			600	13	179.3	4.8	33.09	0
10			800	4	55.16	6.0	41.37	3.0
10	450	14	200	22	303.4	13.3	91.7	Nil
10			300	13.3	183.4	15.0	103.4	0.5
10			400	18.6	256.5	15.8	108.9	0.5
10	575	28	400	10.8	148.9	12.2	84.12	2
10			600	9	124.1	8.6	59.29	0.5
10			800	6.3	86.9	8.6	59.29	11

a. These values are calculated conversions from the published data from [11] for the purpose of comparison.

Other previous work by various authors to establish mechanical properties of U–10Mo alloy is summarized by Ozaltun et al. in Table 2.[2] Burkes et al (2009) also summarized previous work reporting mechanical properties of U–Mo alloys. These results are reported based on variation of Mo content in the alloy. Yield stress, ultimate tensile stress, and elongation all increase with increasing Mo content and are attributed to the improved resistance to bulk plastic deformation through increased addition of Mo and associated hardening effect in the γ phase. Burkes et all (2009) compare their results to previously available literature, but note that differences in homogenization treatment, specimen geometry, and strain rates make direct comparison difficult. [3]

The previously reported properties (summarized in both [2] and [3]) are only valid for the specific thermo-mechanical treatments considered, and testing was performed at a limited selection of temperatures. Fabrication history and thermal treatment of the alloy can have a significant impact on the resultant mechanical properties. Thus, an expanded set of mechanical properties for various foil-rolling conditions typical of fuel-foil manufacturing is necessary. This work aims to evaluate the mechanical properties of U–10Mo alloys under various representative rolling conditions to inform modeling efforts, fabrication process development, and ultimately, to support fuel qualification and reactor conversion.

Table 2. U–10Mo properties summarized by Ozaltun.[2]

Fuel Foil (U–10Mo)							
Young's Modulus		Poisson's ratio		Density		Yield Stress	
°C	GPa	°C	(-)	°C	(kg/m^3)	°C	MPa
21	65.00	25	0.35	21	16,750	21	780
				100	16,380	94	760
				200	16,310	205	655
				300	16,230	316	527
				400	16,140	427	474
				500	16,060	539	427
				600	15,980		

2. TEST SPECIMEN AND TEST SYSTEM PREPARATION

2.1 Test Machine

The testing system incorporates a standard Instron 3366 table-top test machine, Instron 5 kN load cell, Instron high-temperature wedge grips, and a C-M 1600-series environmental furnace. The system was developed, calibrated, and verified for performing this series of tests. The system includes an environmental-control furnace that allows elevated-temperature tensile testing in an inert-gas environment with low oxygen concentration, preventing rapid oxidation or oxygen embrittlement of the DU–10Mo test specimens. Room-temperature tests on some of these specimens were performed in air to establish baseline properties for this particular material condition. A strain-estimating algorithm was developed using the room-temperature data to establish correlation between machine crosshead displacement and specimen reduced section strain, allowing elevated-temperature specimen strain to be estimated from test-machine crosshead-displacement data. Other factors unique to the elevated-temperature test configuration were also assessed, and methods to account for factors that are not directly measurable in these tests were developed. Further details of the test-system configuration and performance-verification processes are detailed below.

2.2 Force Transducer (Load Cell)

Load-cell accuracy was verified by the INL Standards and Calibration Laboratory (S&CL) using established procedures. In accordance with ASTM E4-10, the maximum allowable load-cell error is the greater of ±0.50% of any force reading (proportional error) or ±0.25% of load-cell full-scale capacity (fixed error). The load cell was within its calibration time interval for all tests performed. The data sheet from the most recent calibration is replicated as Table 3.

Table 3. Load-cell calibration record data (12 Nov 2013, INL S&CL).

Instron Reading (N) (Accuracy +/-1 digit)	Reference Reading (N)	Indicated Error (N)	Error (% of Instron Reading)
0.0	**0.0**	**0.0**	**NA**
1032±1	**1034.48**	**-2.48**	**-0.14 to -0.34**
1873±1	1877.49	-4.49	-0.19 to -0.29
3262±1	3267.47	-5.47	-0.14 to -0.20
4232±1	4237.43	-5.43	-0.10 to -0.15
0.0	**0.0**	**0.0**	**NA**
988.6±0.1	**991.48**	**-2.88**	**-0.28 to -0.29**
2286±1	2291.53	-5.53	-0.20 to -0.29
3231±1	3236.98	-5.98	-0.15 to -0.22
4208±1	4214.14	-6.14	-0.12 to -0.22

The potential for force-indication error adds to the uncertainty of the calculated stress values. For the majority of tests, the ASTM allowable-error limit of 0.25% of full-scale capacity is the relevant limiting value and corresponds to ±12.5 N. For a nominal specimen cross-section of 1.2 mm², this is a maximum potential stress error of ±10 MPa. However, typical errors within the range of yield strength and UTS measurements during these tests (1000 N) were consistently about 0.30% greater than the machine reading (data obtained from the load-cell-calibration data sheets on file at S&CL). This correlates to errors nominally proportional to the indicated values and smaller than 3 N in the range of interest. For practical purposes, though not assured, the actual applied force appears consistently 0.3% higher than the machine indication. The specimen initial-area error due to initial width and thickness measurement uncertainty is so small (<0.01% of cross-section error) that it is inconsequential.

2.3 Environmental Furnace Preparation and Setup

The furnace's inert-gas plumbing was modified to include an electrical feedthrough to accommodate additional thermocouple leads for specimen- and grip-temperature monitoring. Thermocouples were welded to the exposed end of the upper and lower grip jaws, immediately adjacent to the jaw-to-specimen contact region. Calibration testing with instrumented surrogate test specimens showed that test-specimen temperature was accurately reflected by the instrumented grip-jaw temperature. Based on these tests, test-specimen temperature during all elevated-temperature testing was inferred from thermally equilibrated grip-jaw temperatures, where both grips were holding constant over time and within 5°C of the target test temperature.

A vacuum pump and appropriate isolation valves were also connected to the inert-gas piping system. Cycles of evacuation (with a roughing-type vacuum pump) and argon backfill/purge were completed prior to heating to reduce the oxygen concentration to below 20 ppm, as indicated on an O_2-concentration meter attached to the furnace-outlet gas piping. Typical O_2 concentration values were less than 5 ppm after 4 vacuum/purge cycles. Approximately halfway through the testing, it was determined that the same O_2-concentration values could be obtained after a single cycle of vacuum and argon-gas purge. Argon-gas flow rate through the furnace during heating and testing was 5 l/min (nominal) at a maximum pressure of 10 kPa (gauge pressure inside furnace chamber).

2.4 High-temperature Miniature Wedge Grips

The original jaw inserts provided by Instron Corp. were made from a soft nickel alloy and were intended for use with pin-loaded specimen-end tabs. The serrations of these jaws were too soft to adequately grip the test specimens. Custom grip jaws were fabricated at INL for the Instron-grip bodies to accommodate the tensile specimen-end tabs used in these tests. These replacement jaws were fabricated from H–13 tool steel, and the specimen contact faces received Surfalloy friction coatings to reliably grip the specimen-end tabs over the full range of temperatures and forces that would be used. Approximately halfway through the testing program, the original Instron grip-tightening mechanism failed in one grip. INL designed and fabricated a new mechanism and replaced the mechanisms on both grip bodies. These new mechanisms performed well throughout the remainder of the testing. They facilitated easier specimen installation and removal from the grips as well. The grip-tightening mechanism failure and replacement with new parts did not influence any of the test results.

An alignment collar was fabricated that holds the grip bodies in alignment while the specimen is installed, and the grip jaws, tightened. The design and use of this alignment collar are discussed in [4].

2.5 Strain Measurements and Extensometers

Room-temperature testing was completed using a small 12.7 mm gauge-length extensometer from Epsilon Corp. The extensometer has a measuring range to +20% tensile strain.[4] At intervals not exceeding 24 hours prior to beginning any test, the extensometer was recalibrated (as necessary), and accuracy was verified in accordance with requirements of ASTM E83-10.[5] The extensometer accuracy meets requirements for Class B-2 (the greater value of either ±0.5% of any reading, or 200 $\mu\varepsilon$) as prescribed within ASTM E8/E8M-13.

The test system and environmental-control furnace used for elevated-temperature testing precluded use of specimen-mounted extensometry for strain measurement. In lieu of direct strain measurement, test-system compliance was measured at room temperature, and a quadratic strain-estimating function was developed. Inputs include the quadratic coefficients, the instantaneous applied force, and the effective gauge length of the specimen. The estimated-strain and actual-stress data for each specimen were used to estimate the yield strength and uniform elongation for each test. Equation 1 and Equation 2 make the correlation used to determine approximate specimen strain from system crosshead displacement.

$$XhdCorr = 1.87111 * 10^{-8} * N^2 + 1.10009 * 10^{-4} * N \quad (1)$$

$$SS = \frac{Xhd - XhdCorr}{Gleff} \quad (2)$$

where

SS = approximate specimen strain (%)

Xhd = cross-head displacement (mm)

XhdCorr = correction for cross-head displacement (mm)

N = force (N)

GLeff = effective gauge length (mm/%).

The method used to estimate specimen strain from grip displacement for the elevated-temperature tests works well and provides consistent results from the suite of valid elevated-temperature tests that were completed.

2.6 Test Controls and Data Collection

ASTM E8/8M-13 or ASTM E21-10 guided room-temperature and elevated-temperature testing, respectively. Room-temperature tests occurred in an air environment. Elevated-temperature tests were performed at temperatures varying between 200 and 550°C in an argon-gas environment.

Room-temperature and elevated-temperature tests were run at a constant crosshead speed of 0.2 mm/min, producing a nominal specimen strain rate of 0.5%/min. This rate meets the requirements of both ASTM E8-13 (for room temperature[6] and E21-10 (for elevated-temperature[7]) tensile-testing standards. Elevated-temperature tests were conducted with the test temperature within ±5°C of the target temperature as measured using the calibrated thermocouples attached to the specimen ends of the grip jaws. At the higher temperatures tested, some strain-rate effect may be present in the measured stress (see discussion section for further information).

Tests were controlled and data collected by Instron Bluehill version 3.41 software. Test-method files for control and data acquisition were verified with dummy specimen tests prior to use in running actual tests on the DU–10Mo specimens.

2.7 Source of Material and Foil Preparation

Simulated fuel foils were fabricated using depleted uranium (DU) and molybdenum to simulate actual fuel foils made with low-enriched uranium. Flat, rectangular tensile specimens correspond to a reduced sub-size specimen, as described in Figure 1 of ASTM E8/8M-13,[6] with an additional size reduction of 50%, as shown in Figure 1. The specimens were cut from the foil sheet using wire EDM. Specimens were sectioned from the sheet with the tensile axis both parallel and transverse to the foil-rolling direction. The resultant specimens have a nominal overall length of 50.8 mm, a reduced section width of 3.2 mm, and a reduced section length of 16 mm. The small specimen size is necessary due to size limitations imposed by the furnace's internal dimensions and material availability.

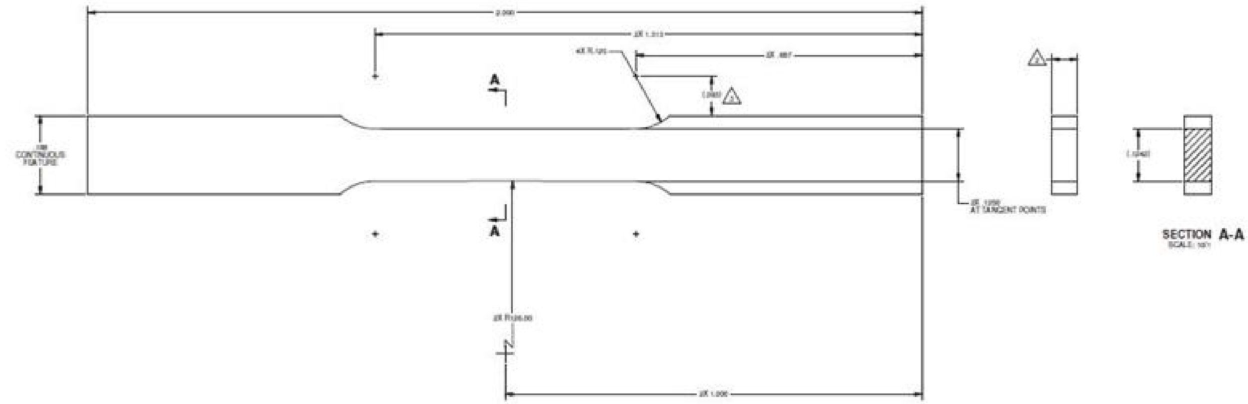

Figure 1. Half-sub-size flat tensile specimen fabrication specification.

The source of DU–10Mo alloy material was coupon #551, provided by the Y–12 National Security Complex at Oak Ridge National Laboratory. This coupon was chosen as it was cast as part of a rolling study being conducted by the Fuel Fabrication Capability (FFC) pillar; thus, it would have similar alloy characteristics to the coupons used by FFC for the rolling studies being conducted.

Once received at INL, the coupon (plate) was quartered using wire EDM, as shown in Figure 2, and homogenized at 1000°C for two hours, while under vacuum at 5×10^{-6} Torr.

Chemistry analysis was performed at Y–12 on a billet sister to the billet from which this coupon was cut and is reported for samples taken near the top, middle, and bottom of the log. The Mo content is 10.4, 10.5, and 10.3% respectively. Carbon impurities are 706, 714, 722 ppm, respectively. Other impurities over 25 ppm are shown in Table A-1. Impurity values less than 25 ppm where provided in the chemistry report from Y–12, but are not reported here.

The resulting four pieces were rolled into simulated fuel foils (Figure 3) using general procedures, except with varying thermo-mechanical processing histories. Several material conditions of potential interest to fabricators, fuel designers, and reactor operators were created by various alterations to the rolling and heat-treating schedules. The results reported here include (1) hot-rolling, followed by 50% cold-rolling (551-2), (2) hot-rolling, followed by 50% cold-rolling and subsequent stress-relief annealing at 650°C for one hour (551-3), (3) hot-rolling, followed by 20% cold-rolling (551-4), and hot-rolling only (551-5).

Figure 2. Machined coupon from Y–12 quartered into sections for rolling. Figure also shows scrap containing a visible casting defect that was cut off during sectioning.

Figure 3. Foil 551-4-1 after hot rolling and cold rolling has been completed.

2.8 Test Specimens and Specimen Dimensional Measurements

Each of the four foils were further subdivided into smaller sections for handling purposes, and small tensile specimens for these tests were cut from the foil sheets using wire EDM (Figure 4, Figure 5, and Figure 6). Flat, rectangular tensile specimens were fabricated, corresponding to a reduced sub-size specimen, as described in Figure 1 in ASTM E8/8M-13,[6] with an additional size reduction of 50%, as shown in the INL Drawing.**Error! Bookmark not defined.** The resultant sheet-type test specimens (flat "dog bone" specimens) had nominal dimensions of overall length, 50.8 mm; reduced section width, 3.2 mm; and, reduced section length, 16 mm. The small specimen size is necessary due to size limitations imposed by the furnace internal dimensions and limited material availability. Specimens were cut with the tensile axis, both parallel and transverse to the rolling direction, to assess potential effects of rolling texture on mechanical properties. Each specimen was labeled, maintaining foil ID, orientation, and location in the foil sheet from which it was removed. The specimens had gauge-mark indents placed on each specimen's lateral centerline, equidistant from the reduced section-length center, with a nominal spacing of 12.70 mm. The marks were made with a carbide indentor that has a small radius tip and conical profile and an alignment and locating fixture. The resultant indents had a surface diameter of less than 0.08 mm and were uniformly circular. Figure 7, Figure 8, and Figure 9 show the marking alignment fixture and a trial specimen with marks applied.

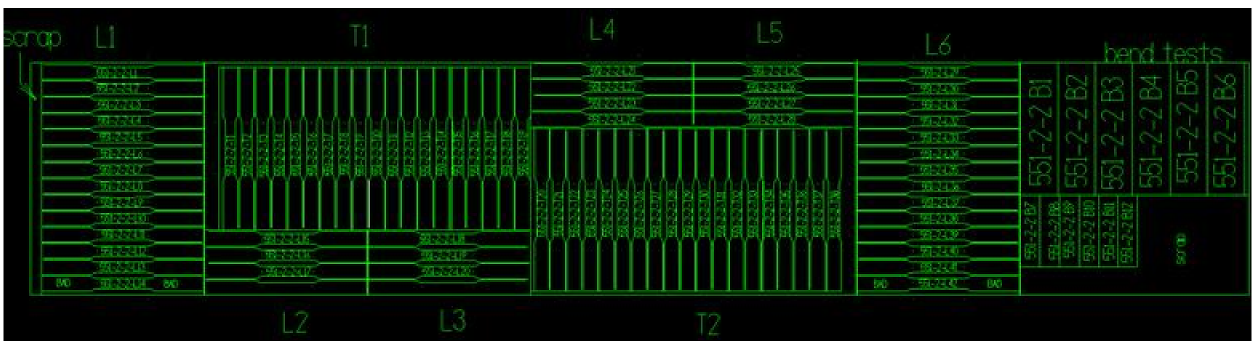

Figure 4. EDM pattern showing the cutting diagram for Foil 551-2-2.

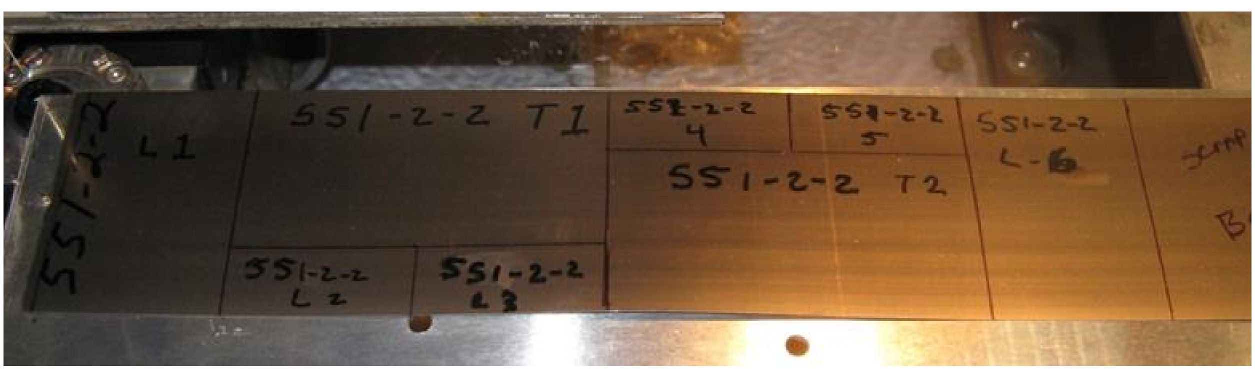

Figure 5. Foil 551-2-2 showing subsection labeling corresponding to the EDM cutting pattern.

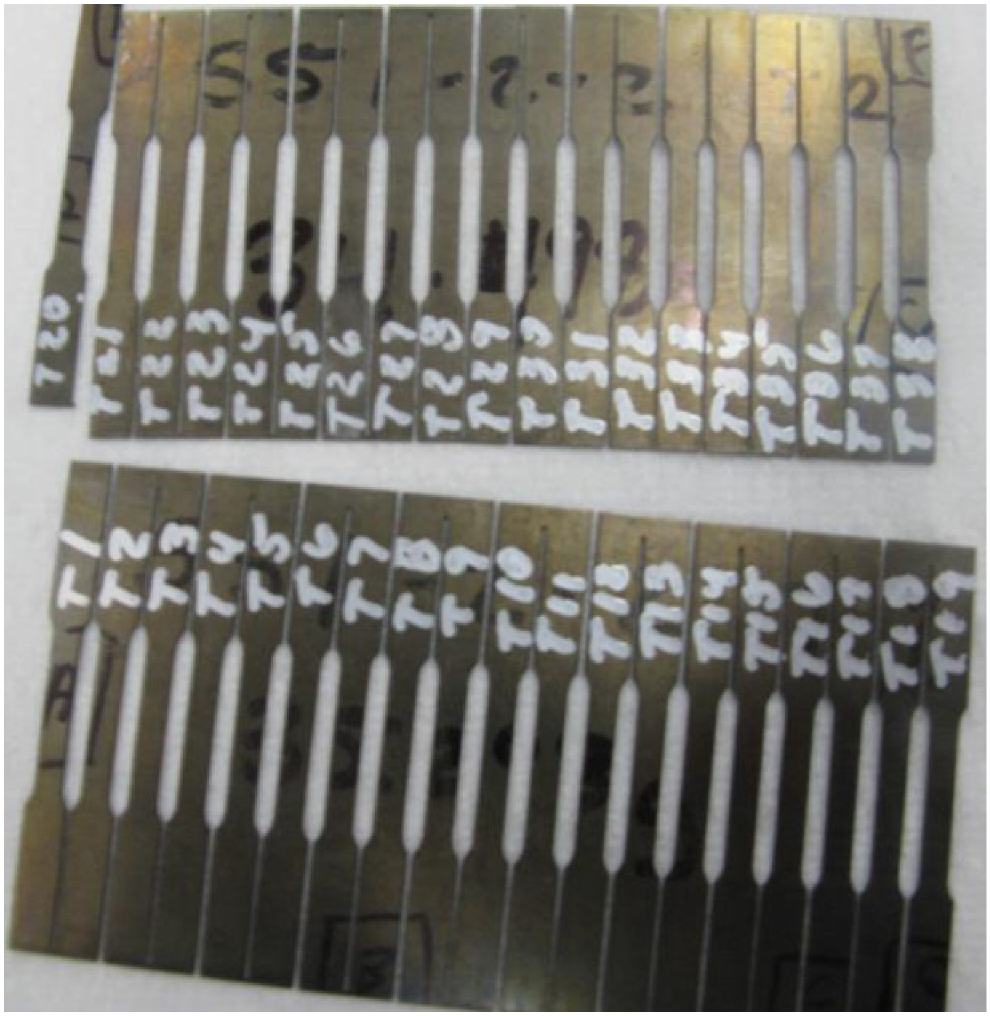

Figure 6. Individually labeled tensile specimens as cut per EDM pattern for Foil 551-2-2.

Figure 7. Gauge-marking specimen-support base.

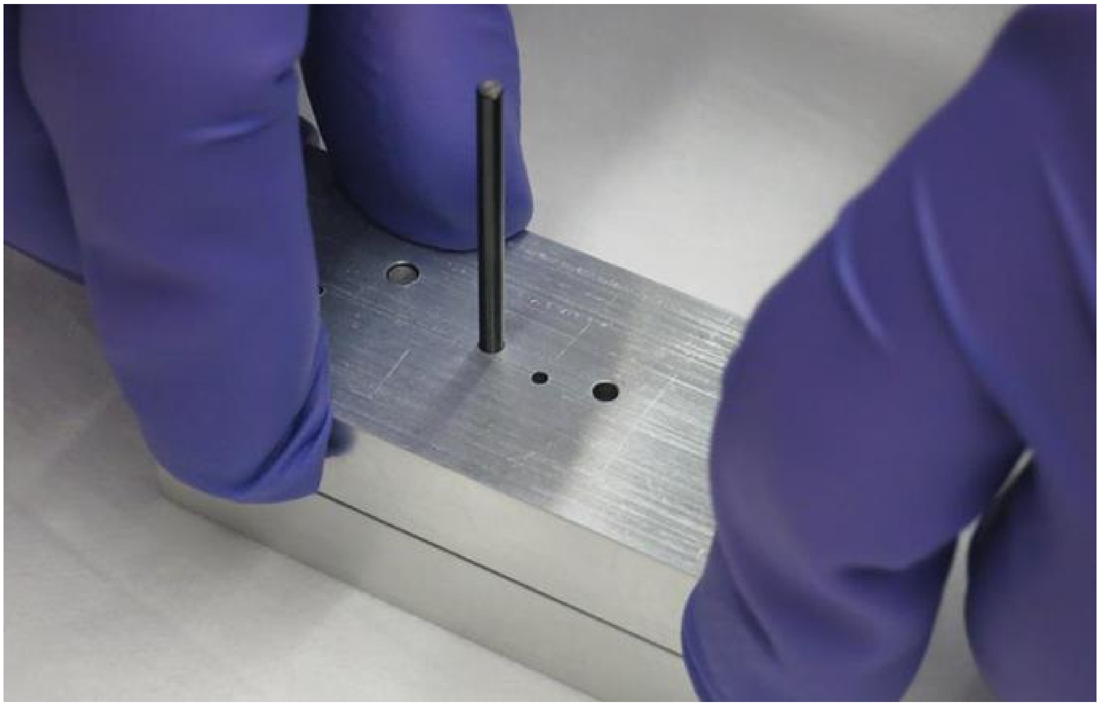

Figure 8. Marking indenter guide plate installed over specimen on support base plate. Punch is placed in one of the guide holes. Finger pressure produces a satisfactory gauge-mark indent.

Figure 9. Stainless steel trial specimen showing gauge-mark indentations produced using the marking fixture. The reduced section width is approximately 3.0 mm. The marks shown appear larger than they actually are due to high contrast and lighting angle.

All specimens were sent to the INL MFC metrology laboratory, where width, thickness, overall length, and gauge-mark spacing were measured and recorded to the nearest 0.001 mm. Overall length for each specimen was measured to the nearest 0.01 mm. All measurements were made with calibrated instruments. Each width and thickness measurement was made twice, and each gauge-mark-spacing measurement was made three times to improve the confidence of the measured dimensions. Locating gauge-mark indentation centers was repeatable to better than 0.005 mm using an optical comparator. The average pre-test dimensions for a sample of specimens from foil 551–2 are provided in Table 4. All dimensional inspections both pre-test and post-test are included in the appendix.

Table 4. Representative average specimen pre-test dimensions from Foil 551–2.

Specimen ID	Thickness (mm)	Width (mm)	Gauge Mark Spacing (mm)	Overall Length (mm)
L-15	0.384	2.969	12.664	50.70
L-16	0.375	2.997	12.703	50.70
L-17	0.371	3.117	12.729	50.70
L-18	0.384	2.973	12.823	50.70
L-19	0.379	2.999	12.720	50.71
L-20	0.371	3.113	12.723	50.71

All specimen dimensions were measured multiple times to ensure accuracy of measurement. Some variability in these replicate specimen dimensional inspections was noted. A brief analysis was conducted to evaluate potential errors that could transfer to the test results, as follows. Measurements from 20 randomly selected test specimens were examined. The variance of each group of replicate measurements was determined. The accumulated variances for each type of measurement were averaged, and the square root, calculated. The result is the sample standard deviation. The standard deviation of measured values from each particular measurement group is provided in Table 5. The standard deviation for post-test thickness, width, and area are not calculated because reporting of reduction of area is not required.

Table 5. Dimensional measurement standard deviations from random sampling of 20 specimens.

Standard Deviation	Gauge Length (µm)	Thickness (µm)	Width (µm)	Area (mm²) (calculated)
Pre-Test Std.Dev.	3.71	0	1.13	1.95E-6
Post-Test Std.Dev.	3.66			

The potential error in the gauge-length measurements leads to an error band for the calculated values of elongation, determined using the pre- and post-test gauge length measurement. The result, 2*std.dev = ~15 µm, is ±0.12% of elongation at the nominal initial gauge length of 12.7 mm.

3. RESULTS

Results from all of the valid tests from both longitudinal and transverse tensile specimens are presented for both room-temperature and elevated-temperature tests (see Table 6 and Table 7).

Representative stress versus strain plots for a room-temperature and a 250°C test are provided in Figure 10. Construction lines for determining 0.2% offset yield strength are also shown.

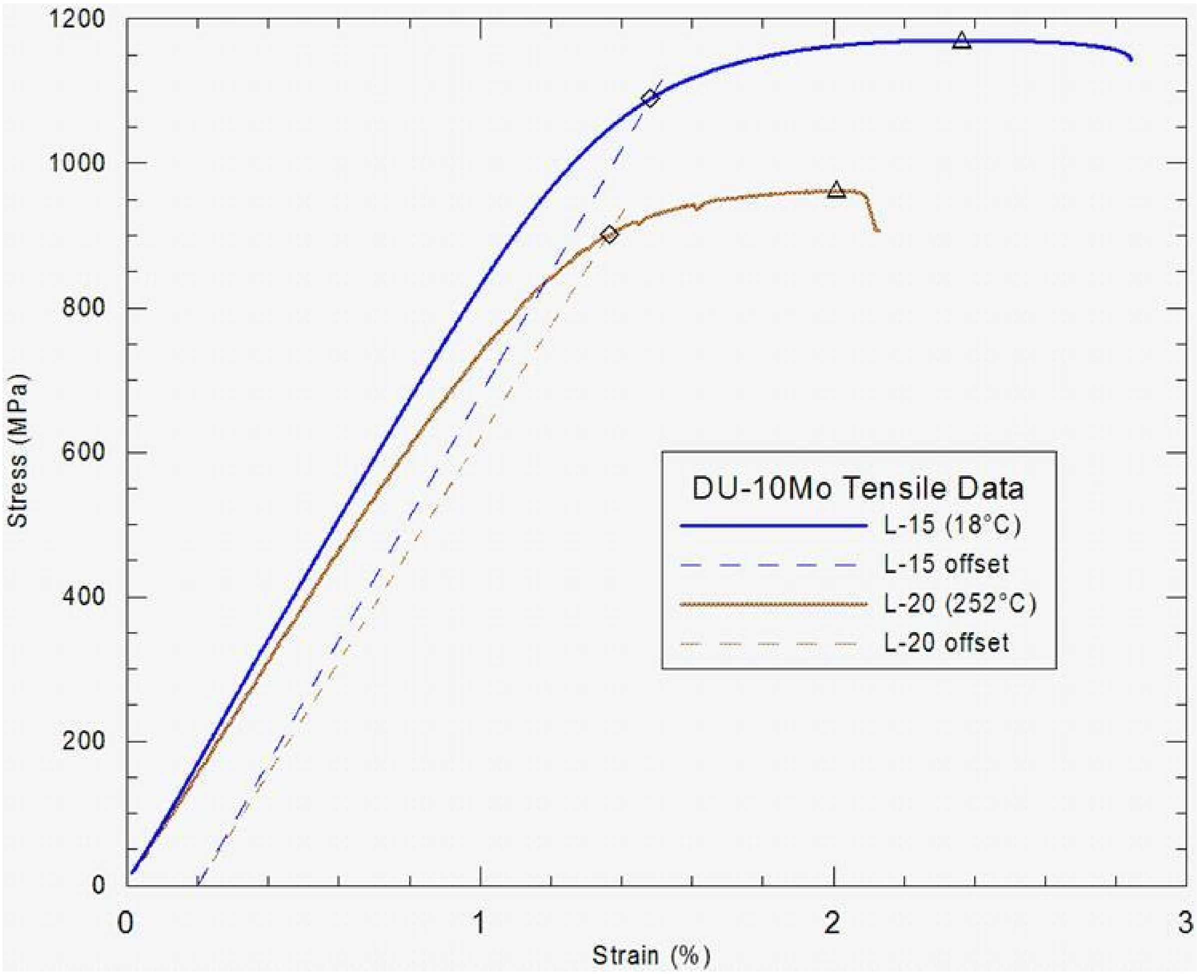

Figure 10. Stress-strain plots for room-temperature and 250°C tensile tests on longitudinal specimens of DU–10Mo foil 551-2 that was prepared by hot-rolling, followed by 50% cold-rolling reduction in thickness. Slope of offset modulus lines (dashed) represents the modulus reduction expected between room temperature and 250°C.

The mechanical properties determined by analysis of the test data, in accordance with ASTM E8/8M-13a (room-temperature) and ASTM E21-10 (elevated-temperature), are shown in Table 6 and Table 7 respectively.

3.1 Summary of Required Reporting Elements

All tests were conducted on DU–10Mo material using half-sub-size sheet-type tensile specimens. Room-temperature tests were conducted in accordance with ASTM E8/8M-13a while elevated-temperatures tests were conducted using ASTM E21–10. In both cases, the 0.2% offset method was used to determine yield strength. Elongation was determined after fracture occurred. A constant crosshead speed of 0.2 mm/min was used producing a nominal specimen strain rate of 0.5%/min. Calculated values were rounded up or down to the nearest digit of the required accuracy (standard rounding method), excepting that, in accordance with the test standard, final specimen elongation values were rounded to the nearest 0.2% deformation interval. All elevated-temperature tests were conducted under argon atmosphere with <20ppm O_2 concentration.

In multiple cases, test results for an individual specimen were invalidated by specimen failure outside of the allowable region or, infrequently, due to other problems with a particular specimen. Replicate specimens under replicate test conditions were tested to obtain the required number of valid tests for that particular material/test condition combination.

Tests that did not fail in the middle 50% of gauge length were considered invalid and not included in results; initial fractography of a few samples of specimens indicate the failure method is ductile rupture. Some specimens failed prior to the stress-strain curve intersecting the 0.2% offset curve; these specimens do not provide a valid yield-strength value and are reported with "NA" for yield strength in the tables.

Testing equipment included the following: Instron 3366 5kN load cell, 12.7 mm gage length extensometer from Epsilon Corp. The extensometer has a measuring range to +20% tensile strain, meeting class B-2 requirements; CM Inc. rapid temp furnace, model 1608 (gas-sealed front loader), SN100400, Eurotherm 2404 temperature controller, thermocouple material, sheathed type-K thermocouple (calibrated) in furnace environment for temperature control, Type K thermocouples (calibrated) welded to the specimen-grip jaw ends for temperature monitoring.

All additional information required for reporting in accordance with the testing standards is provided in Table 6 and Table 7 respectively.

Table 6. Measured mechanical properties of DU–10Mo at room temperature. Tested and reported in accordance with ASTM E8/8M-13. Material: DU–10%Mo from plate #551.

Foil ID	**Specimen ID**	**Foil Condition**	**Yield Strength (MPa)**	**Ultimate Tensile Strength (MPa)**	**Initial Gauge Mark Spacing (mm)**	**Elongation (% increase)**	**Uniform Elongation (%)**	**Note**
551-2-2	L15	50% CW	1100	1170	12.664	1.2	2.36	e.
551-2-2	L16	50% CW	1115	1179	12.703	3.6	2.55	e.
551-2-2	L17	50% CW	NA	1168	12.729	4.0	NA	a., b., c.
551-2-2	T2	50% CW	1098	1199	12.675	2.0	1.97	d.
551-2-2	T3	50% CW	1070	1070	12.685	0.2	1.42	d.
551-2-2	T14	50% CW	NA	1064	12.720	1.6	1.31	b., d.
551-3	L1	50% CW + A	1013	1016	12.738	8.6	1.27	c.
551-3	L2	50% CW + A	1010	1012	12.709	9.0	1.27	c.
551-3	L3	50% CW + A	1013	1016	12.692	9.0	1.26	c.
551-3	T1	50% CW + A	1030	1031	12.678	7.4	1.33	c.
551-3	T2	50% CW + A	1030	1032	12.686	7.6	1.24	c.
551-3	T3	50% CW + A	1028	1028	12.784	7.0	1.35	c.
551-4	L1	20% CW	1091	1139	12.763	6.2	2.30	d.
551-4	L2	20% CW	1099	1148	12.759	5.8	2.27	d.

Foil ID	Specimen ID	Foil Condition	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Initial Gauge Mark Spacing (mm)	Elongation (% increase)	Uniform Elongation (%)	Note
551-4	L3	20% CW	1126	1167	12.758	5.6	2.24	d.
551-4	T1	20% CW	1058	1192	12.756	2.2	2.32	d.
551-4	T2	20% CW	1059	1109	12.769	1.6	1.57	d.
551-4	T3	20% CW	1072	1116	12.756	1.0	1.54	d.
551-5	L1	HR Only	1005	1006	12.730	10.6	1.29	c.
551-5	L2	HR Only	1017	1017	12.715	12.4	1.38	c.
551-5	L3	HR Only	1020	1020	12.696	12.2	1.32	c.
551-5	T1	HR Only	NA	1031	12.745	1.0	0.66	b., c.
551-5	T2	HR Only	NA	1011	12.725	1.2	1.08	b., c.
551-5	T3	HR Only	1025	1026	12.686	1.4	1.41	c.
551-5	T13	HR Only	1061	1063	12.740	8.0	1.61	d.

a. Specimen slipped in wedge grip jaw during early part of test, including through the zone of yielding. In-plane bending of gauge section is suspected to have occurred. Test was suspended, grip re-tightened, and test re-started. Subsequent strain data had to be spliced with initial test data. Due to slip and bending, it was not possible to accurately connect the two data sets, and an accurate 0.2% offset yield strength could not be established.
b. Specimens reached ultimate failure prior to intersection with the 0.2% offset curve; thus, no yield strength could be established.
c. Test operator: Jason Schulthess
d. Test operator: Michael Heighs
e. Test operator: Randy Lloyd

Table 7. Measured mechanical properties of DU–10Mo at elevated temperature.

Foil ID	Specimen ID	Foil Condition	Temperature (C)	Yield Strength (MPa)[a]	Ultimate Tensile Strength (MPa)	Initial Gauge Mark Spacing (mm)	Elongation (% increase)	Time to Attain Temp (min)	Time at Temp before Testing (min)	Other Special Conditions (Temp Overshoots, notes, etc.)
551-2-2	L18	50% CW	250	837	952	12.823	3.0	160	30	e.
551-2-2	L20	50% CW	250	880	962	12.723	3.6	150	5	c.
551-2-2	L22	50% CW	250	887	909	12.721	1.6	120	10	c.
551-2-2	T11	50% CW	250	NA	820	12.700	1.8	275	10	b., c.
551-2-2	T12	50% CW	250	864	872	12.785	1.2	160	5	c.
551-2-2	T13	50% CW	250	856	888	12.727	1.8	120	5	c.
551-2-2	L2	50% CW	350	821	884	12.706	4.5	100	5	c.
551-2-2	L3	50% CW	350	765	876	12.765	3.8	90	5	d.

Foil ID	Specimen ID	Foil Condition	Temperature (C)	Yield Strength (MPa)[a]	Ultimate Tensile Strength (MPa)	Initial Gauge Mark Spacing (mm)	Elongation (% increase)	Time to Attain Temp (min)	Time at Temp before Testing (min)	Other Special Conditions (Temp Overshoots, notes, etc.)
551-2-2	T5	50% CW	350	NA	672	12.746	1.0	90	10	b., c.
551-2-2	T7	50% CW	350	513	513	12.727	0.2	90	30	d.
551-2-2	L4	50% CW	450	539	612	12.691	9.6	90	10	c.
551-2-2	L6	50% CW	450	501	599	12.766	8.4	90	5	c.
551-2-2	L8	50% CW	550	141	175	12.735	73.8	120	10	c.
551-2-2	L9	50% CW	550	136	169	12.741	81.8	90	5	c.
551-2-2	L10	50% CW	550	136	162	12.756	64.2	120	10	c.
551-2-2	T8	50% CW	550	81	108	12.686	51.0	120	40	d., f.
551-2-2	T9	50% CW	550	108	164	12.788	36.4	160	10	d.
551-2-2	T10	50% CW	550	109	159	12.796	39.2	100	5	c.
551-3	L4	50% CW + A	200	673	712	12.756	13.4	180	5	c.
551-3	L5	50% CW + A	200	653	708	12.694	13.0	120	5	c.
551-3	L6	50% CW + A	200	661	710	12.674	14.2	120	5	d.
551-3	T4	50% CW + A	200	677	722	12.714	12.0	105	5	c.
551-3	T5	50% CW + A	200	681	728	12.744	16.0	120	5	c.
551-3	T6	50% CW + A	200	676	724	12.693	12.2	110	5	c.
551-3	L7	50% CW + A	400	491	569	12.736	3.6	90	5	d.
551-3	L13	50% CW + A	400	483	559	12.715	5.8	80	5	d.
551-3	L29	50% CW + A	400	489	561	12.713	5.4	100	5	d.
551-3	T8	50% CW + A	400	493	576	12.640	5.2	90	10	c.
551-3	T9	50% CW + A	400	493	569	12.628	6.2	90	10	c.
551-3	T13	50% CW + A	400	505	578	12.720	6.2	100	5	c.
551-3	L10	50% CW + A	550	161	200	12.730	68.6	80	5	c.
551-3	L11	50% CW + A	550	162	197	12.774	61.4	90	5	d.
551-3	L12	50% CW + A	550	174	202	12.689	77.2	120	5	c.
551-3	T10	50% CW + A	550	161	192	12.856	68.0	100	5	d.
551-3	T11	50% CW + A	550	165	204	12.732	62.4	100	5	d.
551-3	T12	50% CW + A	550	161	195	12.729	66.6	80	5	d.
551-4	L4	20% CW	200	867	911	12.776	3.0	225	5	c., f.
551-4	L5	20% CW	200	875	917	12.851	2.8	210	10	d.
551-4	L6	20% CW	200	866	913	12.729	3.0	185	10	d.

Foil ID	Specimen ID	Foil Condition	Temperature (C)	Yield Strength (MPa)[a]	Ultimate Tensile Strength (MPa)	Initial Gauge Mark Spacing (mm)	Elongation (% increase)	Time to Attain Temp (min)	Time at Temp before Testing (min)	Other Special Conditions (Temp Overshoots, notes, etc.)
551-4	T4	20% CW	200	780	954	12.721	4.0	120	5	c.
551-4	T5	20% CW	200	800	953	12.778	3.6	140	10	c.
551-4	T7	20% CW	200	816	895	12.748	1.6	135	15	c.
551-4	L7	20% CW	400	611	719	12.697	2.8	80	5	c.
551-4	L8	20% CW	400	621	711	12.744	2.4	80	10	c.
551-4	L10	20% CW	550	146	185	12.717	50.6	220	5	d.
551-4	L11	20% CW	550	150	193	12.731	43.8	150	5	d.
551-4	L13	20% CW	550	160	200	12.797	43.4	130	10	c.
551-4	T10	20% CW	550	156	198	12.779	25.4	90	5	d.
551-4	T11	20% CW	550	148	180	12.719	43.0	150	5	c.
551-4	T12	20% CW	550	156	198	12.713	32.8	110	5	c.
551-5	L4	HR Only	200	660	732	12.849	13.0	220	20	d.
551-5	L5	HR Only	200	665	701	12.690	4.8	140	5	d.
551-5	L6	HR Only	200	664	719	12.769	6.4	125	10	c.
551-5	T4	HR Only	200	695	710	12.691	2.0	120	5	d.
551-5	T5	HR Only	200	701	733	12.744	2.9	120	10	c.
551-5	T6	HR Only	200	691	725	12.747	4.8	120	10	c.
551-5	L7	HR Only	400	492	606	12.728	8.6	80	5	d.
551-5	L8	HR Only	400	494	608	12.675	8.6	100	5	c.
551-5	L9	HR Only	400	496	616	12.764	10.6	80	5	d.
551-5	L10	HR Only	550	231	267	12.786	35.2	100	5	c.
551-5	L11	HR Only	550	226	271	12.637	44.4	80	5	c.
551-5	L12	HR Only	550	229	270	12.734	39.6	70	5	c.
551-5	T10	HR Only	550	191	267	12.738	46.0	70	5	c.
551-5	T11	HR Only	550	208	276	12.755	45.2	60	5	c.
551-5	T12	HR Only	550	198	279	12.679	47.4	60	5	c.

a. Yield strengths are approximate because no extensometer was used to measure strain directly; strain values were calculated from crosshead displacement based on test-system-compliance correction and effective specimen-gauge length.
b. Specimens reached ultimate failure prior to intersection with the 0.2% offset curve; thus, no yield strength could be established.
c. Test operator: Jason Schulthess
d. Test operator: Michael Heighs
e. Test operator: Randy Lloyd
f. Temperature overshot by approximately 10°C

Definitions of reported properties are provided in ASTM E8/8M-13.

Given the small size of the test specimens, which tend to increase specimen-to-specimen variation in measured properties, the results are reasonably consistent.

Tensile properties of DU–10Mo at room temperature through approximately 400°C, determined from the tests conducted herein, suggest the material is stronger and has lower ductility than have been reported previously in the literature. The explanation for these differences has yet to be determined, but is likely related to differences in grain size and/or impurity content. At the highest temperatures tested (550°C) better agreement between the values reported here and available literature was found. As expected, yield and UTS decreased with increasing test temperature. Generally, the yield stress for all foil processing conditions was found to be in the range of 1100 MPa for room-temperature tests and in the range of 200 MPa for tests conducted at 550°C. UTS was in the range of 1175 MPa at room temperature, decreasing to approximately 225 MPa at 550°C. Elongation increased significantly from 1–2% at room temperature, to 50% or more for the tests at 550°C. Additional details on the observed effects of foil processing condition and specimen orientation on tensile properties are summarized below.

3.1.1 Yield Strength

No significant effect of fabrication history on yield stress was observed at the lowest (room temperature) and highest temperatures (550°C) tested. However, tests indicated yield strength differences exist at the intermediate temperatures tested with the 50% cold-worked and annealed and the hot-rolled-only material producing lower yield stress at the intermediate test temperatures. Significant effects of specimen orientation on yield strength were only observed in a few cases (specifically 20% cold worked material tested at 200°C resulted in lower yield stress in the transvers orientation, and hot-rolled-only material tested at room temperature and 200°C where the transvers orientation resulted in slightly higher-yield stress).

3.1.2 Ultimate Tensile Strength

Significant differences in the UTS were noted in the longitudinal direction for the four foils at room temperature, with the difference continuing, but converging as the temperature increased. This difference between each of the four foils was also found to exist in the transvers direction. The 50% cold-worked and annealed and the hot-rolled-only material produced lower ultimate tensile stress at both room temperature and the intermediate test temperatures, but these stresses converged when specimens were tested at 550°C.

Orientation effects for specimens from the same foil were only noted in the following case: 50% cold-worked at 350°C, in which the transvers direction produced lower ultimate tensile stress. All other tests indicated no significant anisotropy due to rolling direction.

3.1.3 Slope

Slope of the initial section of the stress-strain curve was calculated for each specimen and then averaged across all specimens tested in each temperature group. The average slope in MPa/% and standard deviation for each test temperature are 20°C, 884.21±13.15; 200–250°C, 417.63±16.81; 350°C, 422.25±14.75; 400–450°C, 320.43±17.88; and 550°C, 199.29±24.41. Room-temperature elastic-modulus values reported in the literature are in the low-to-mid 80s GPa range[8,9]—consistent with our room-temperature test results.

3.1.4 Ductility

Room-temperature ductility was determined for all of the foil conditions tested. Of note, the 50% cold worked and annealed foil (foil 551-3) showed increased ductility compared to the 50 and 20% cold-worked foils. The hot-rolled-only foil showed more ductility in the longitudinal direction than any other foil at room temperature, but showed very little ductility in the transverse direction, indicating significant anisotropy at room temperature.

Ductility increased continuously for all foil conditions as testing temperature increased and was significant for foils tested at 550°C. At 550°C, the ductility for all foil conditions and orientations increased from ~<10% to as much as ~70% in the 50% cold-worked foil in the longitudinal direction (551-2) and also ~70% for the 50% cold-worked and annealed foil (551-3) in both directions. The increase in ductility at 550°C was more pronounced for the 20% cold-worked foil than for other foil processing conditions.

For a few specimens in both room-temperature and elevated-temperature cases, the 0.2% offset curve did not intersect the stress strain curve. Theoretically, ductility would be very small in these cases. When combined with the measurement error evaluated in Table 5, and recognizing that it can be difficult to accurately piece specimens back together for post-test elongation measurements due to roughness at the fracture surface; it is likely that actual elongation values are less than the reported values of 3% or less. This specifically includes the following specimens tested at room temperature: 551-2-2 L17 and T14, 551-5 T1 and T2, and the following specimens tested at elevated temperature: 551-2-2 T11 and T5. Further, this may impact any specimens with reported elongation values of less than 3%.

3.1.5 Recommendations for Future Work

It is recommended that future work include fractography of selected specimens to determine whether failure mechanisms other than ductile rupture exist and whether fracture initiation sites can be identified. Metallography and microstructural characterization should be completed to characterize grain sizes and other microstructural features that may explain the observed mechanical behavior. Finally, it is recommended that additional testing be conducted on similarly processed material, having different impurity content (particularly different carbide distributions), to better understand the range of properties that may be expected in commercially fabricated fuel foils.

The room-temperature properties appear different from the expected ranges based upon historical data according to [1], [2], and [3], but it is noted that both source-material chemistry and thermo-mechanical processing history of the test specimens can result in significant microstructural differences that may explain these results.[10] Further, characterization work is needed to better understand the differences in reported properties.

4. DISCUSSION

Test-system compliance (including test-frame components, pull rods (long), and high-temperature wedge grips) was assessed prior to commencing this series of tests. Machine crosshead displacement was converted to effective grip displacement using a quadratic compliance-correction function for the elevated-temperature tests. This assessment is discussed in [**Error! Bookmark not defined.**]. The compliance-corrected grip displacement was used to estimate reduced section strain in the specimen. Slope of the initial section of the stress-strain curve was calculated for each specimen and then averaged across all specimens tested in each temperature group. Thus, the average slope in MPa/% and standard deviation by test temperature group are: 20°C, 884.21±13.15; 200–250°C, 417.63± 16.81; 350°C, 422.25±14.75; 400–450°C, 320.43±17.88; and 550°C, 199.29±24.41. Since tension testing per ASTM E111-04 was not conducted, and the tests do not meet the requirements of ASTM E111-04[11]; the slope values reported here are only instructive to provide a comparison to reported elastic modulus values. Historically, room-temperature elastic-modulus values were reported to be in the low-to-mid 80s GPa range[9,12]—consistent with our room-temperature test results for slope of the initial section of the stress-strain curve. Additional modulus data for various temperatures were found in [1] and are summarized in Table 1. Since some non-linearity was noted in the very early stages of the stress-strain curves (particularly at higher temperatures), it is recommended, if a more accurate measurement is desired, that moduli be evaluated using ASTM E494-10.[13]

4.1 Calculated Strength Uncertainties

The overall uncertainty in specimen-strength calculations is a function of accuracy of specimen pre-test dimensional measurement (inconsequential in these tests) and measured force errors (described above). Additionally, linearity of strain transducer response and, to a lesser degree, the absolute accuracy of the measured strain values influences the yield-strength determinations.

Standard deviation for yield stress and UTS for each group of specimens was calculated. The standard deviation of calculated strength values for replicate specimen groups are reported in Table 8. Standard deviations are typically 8–14 MPa, with a low value of zero (perfect specimen-to-specimen agreement); two UTS groups were approximately 65–80 MPa. In essence, replicate specimen-to-specimen variability seemed to be larger than combined errors introduced by force-measurement inaccuracies.

The test results show good specimen-to-specimen consistency, with the exception of transverse tests of foil 551–5 at room temperature. In this case, the results of one specimen were further than one standard deviation below the other tests. One additional test was performed for this condition, which agreed with the primary cluster of results and implies that the one test with low-strength results may have had an uncharacteristic failure mechanism causing premature failure.

Tests were conducted using a constant crosshead displacement rate of 0.2 mm/min, resulting in a strain rate of approximately 0.5%/min. At the higher temperatures tested, some strain-rate effect may be present. The lack of linearity in the early portion of the test data for the high-temperature tests (550°C), suggests that the rate of stress relaxation and is close to the stress induction rate at the tested strain rate.

A summary of the test results is presented in Table 8. Mechanical properties as a function of temperature within the range of room temperature to 550°C are shown graphically in Figure 11 through Figure 22. Figure 11 through Figure 22 indicate little to no fabrication effect on yield stress on the lowest temperature (room temperature) and highest temperature (550°C) tested. Figure 11 through Figure 14 do indicate divergence in the intermediate temperatures tested, based on fabrication effects. Effects of orientation (anisotropy due to rolling) only seem to appear in the following yield-stress cases (50% cold-worked at 250°C and 350°C, 20% cold-worked at 200°C, and hot-rolled-only at room temperature and 200°C) (see Figure 15 through Figure 22). However, these orientation effects are not large in magnitude. Similar orientation effects are noted in the UTS results as shown in Figure 15 through Figure 22. Reviewing the data in Table 8, we note that post cold rolling annealing heat treatment on Foil 551-3 produces results (yield stress, ultimate tensile stress) very similar to the hot-rolled-only foil (551-5), suggesting this post-cold-rolling thermal treatment is effective at substantially recovering tensile properties comparable to hot-rolled-only material.

Table 8. Summary of mechanical properties from the current work.

Group Identifier	Orientation	Nominal T (°C)	Avg YS (MPa)	Std.Dev. YS (MPa)	Avg. UTS (MPa)	Std.Dev. UTS (MPa)	Avg Elongation (%)	Std. dev. Elongation (%)
551-2-2-L-20	L	20	1108	8	1172	5	2.9	1.2%
551-2-2-T-20	T	20	1084	14	1111	62	1.2	0.8%
551-3-L-20	L	20	1012	1	1015	1	8.9	0.2%
551-3-T-20	T	20	1029	1	1030	2	7.3	0.3%
551-4-L-20	L	20	1105	15	1151	12	5.9	0.2%
551-4-T-20	T	20	1063	6	1139	38	1.6	0.5%
551-5-L-20	L	20	1043	18	1014	6	11.7	0.8%
551-5-T-20	T	20	1025	0	1033	19	2.9	2.9%
551-3-L-200	L	200	662	8	710	2	13.5	0.5%
551-3-T-200	T	200	678	2	725	2	13.4	1.8%
551-4-L-200	L	200	869	4	914	2	2.9	0.1%
551-4-T-200	T	200	799	15	934	28	3.1	1.0%
551-5-L-200	L	200	663	2	717	13	8.1	3.6%
551-5-T-200	T	200	696	4	723	10	3.2	1.2%
551-2-2-L-250	L	250	868	22	941	23	2.7	0.8%
551-2-2-T-250	T	250	860	4	860	29	1.6	0.3%
551-2-2-L-350	L	350	793	28	880	4	4.1	0.3%
551-2-2-T-350	T	350	NA	NA	593	80	0.6	0.4%
551-3-L-400	L	400	487	4	564	5	4.9	1.0%
551-3-T-400	T	400	497	6	574	4	5.8	0.5%
551-4-L-400	L	400	616	5	715	4	2.6	0.2%
551-5-L-400	L	400	494	2	610	4	9.3	0.9%
551-2-2-L-450	L	450	520	19	606	7	9.0	0.6%
551-2-2-L-550	L	550	137	2	169	5	73.3	7.2%
551-2-2-T-550	T	550	99	13	144	25	42.2	6.3%
551-3-L-550	L	550	165	6	200	2	69.1	6.5%
551-3-T-550	T	550	162	2	197	5	65.6	2.4%
551-4-L-550	L	550	152	6	193	6	45.9	3.3%

Group Identifier	Orientation	Nominal T (°C)	Avg YS (MPa)	Std.Dev. YS (MPa)	Avg. UTS (MPa)	Std.Dev. UTS (MPa)	Avg Elongation (%)	Std. dev. Elongation (%)
551-4-T-550	T	550	153	4	192	8	33.7	7.2%
551-5-L-550	L	550	229	2	269	2	39.7	3.7%
551-5-T-550	T	550	199	7	274	5	46.2	0.9%

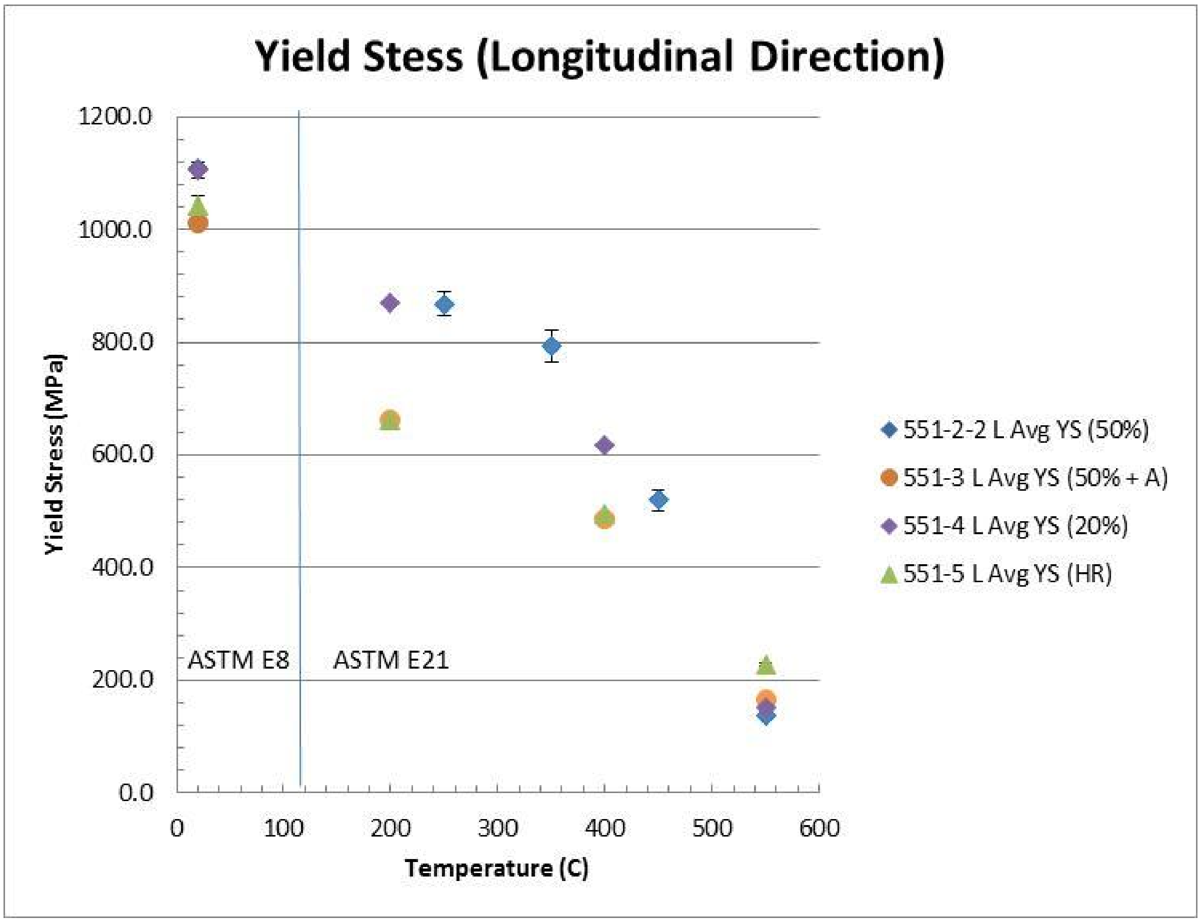

Figure 11. Yield stress in the longitudinal direction for each of the four foil-fabrication conditions. The figure shows the cluster of yield stress at room temperature and at 550°C while there is a divergence in the fabrication conditions in the intermediate values. The annealed and hot-rolled-only foils indicate lower yield-stress values in the intermediate temperatures.

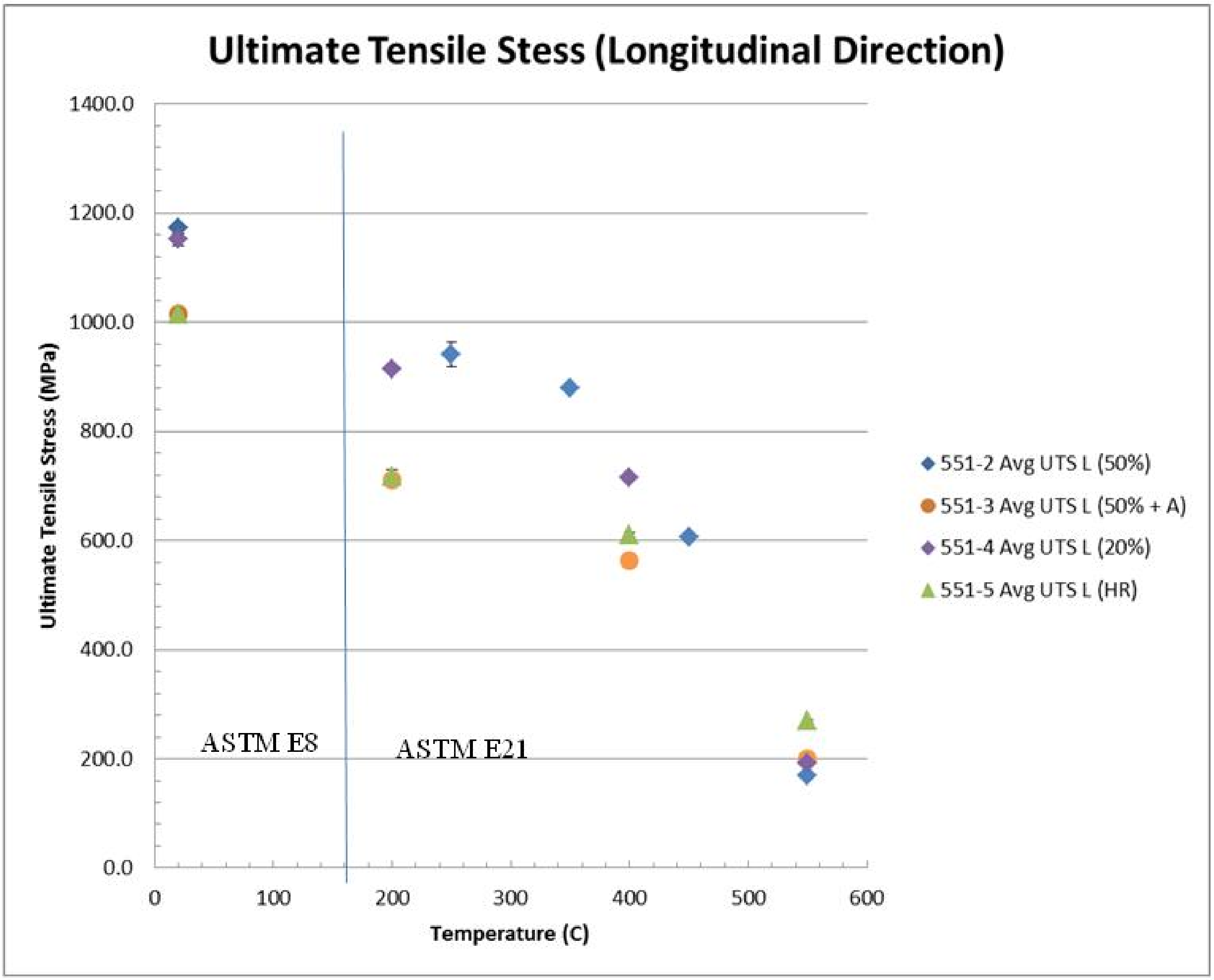

Figure 12. Ultimate tensile stress in the longitudinal direction for each of the four foil-fabrication conditions. The figure shows the cluster of UTS at 550°C while there is a divergence in the fabrication conditions in the room-temperature and intermediate values. The annealed and hot-rolled-only foils indicate lower UTS values in the room and intermediate temperatures.

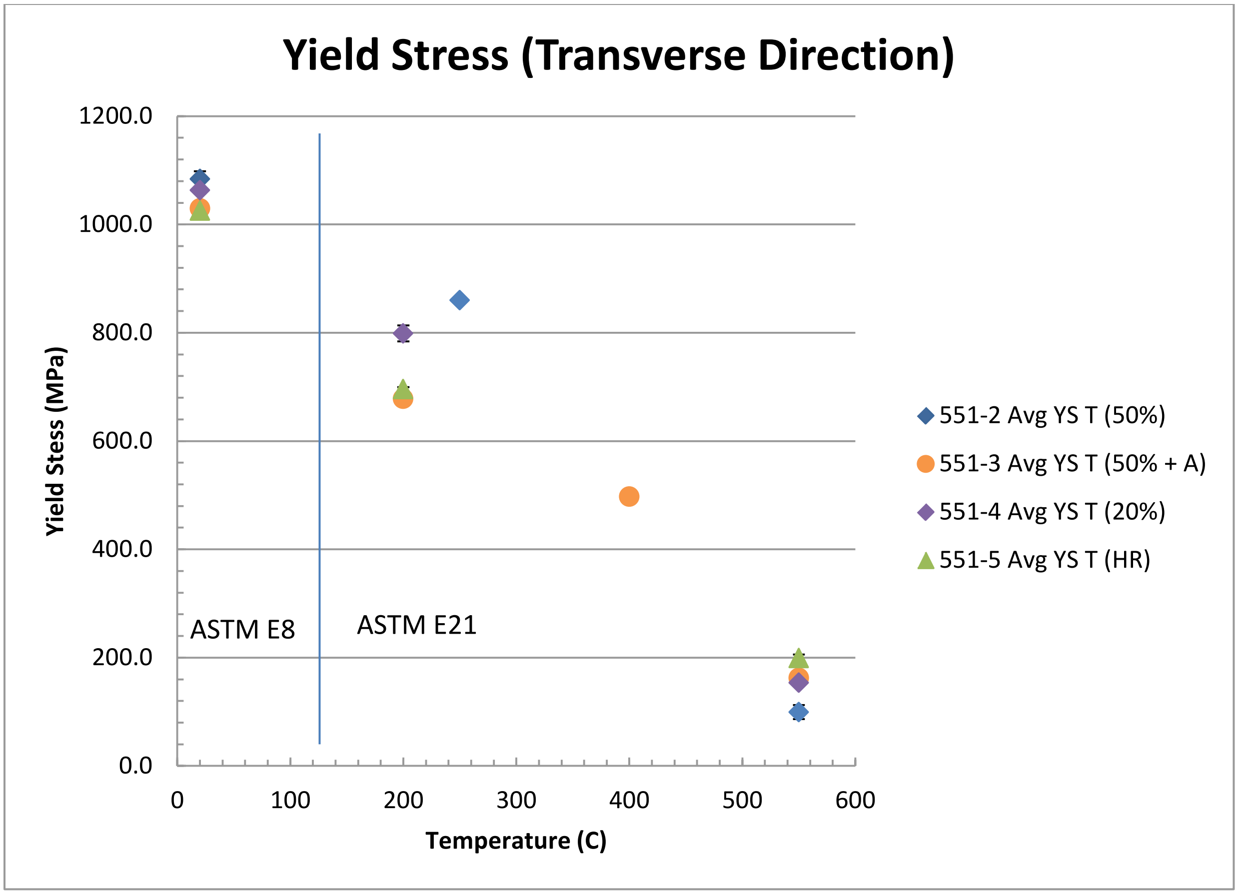

Figure 13. Yield stress in the transverse direction for each of the four foil-fabrication conditions. The figure shows the cluster of yield stress at room temperature and at 550°C while there is a divergence in the fabrication conditions in the intermediate values. The annealed and hot-rolled-only foils indicate lower yield-stress values in the intermediate temperatures. Note that data are not available for foils 551-4 and 551-5 in the transverse direction at 400°C.

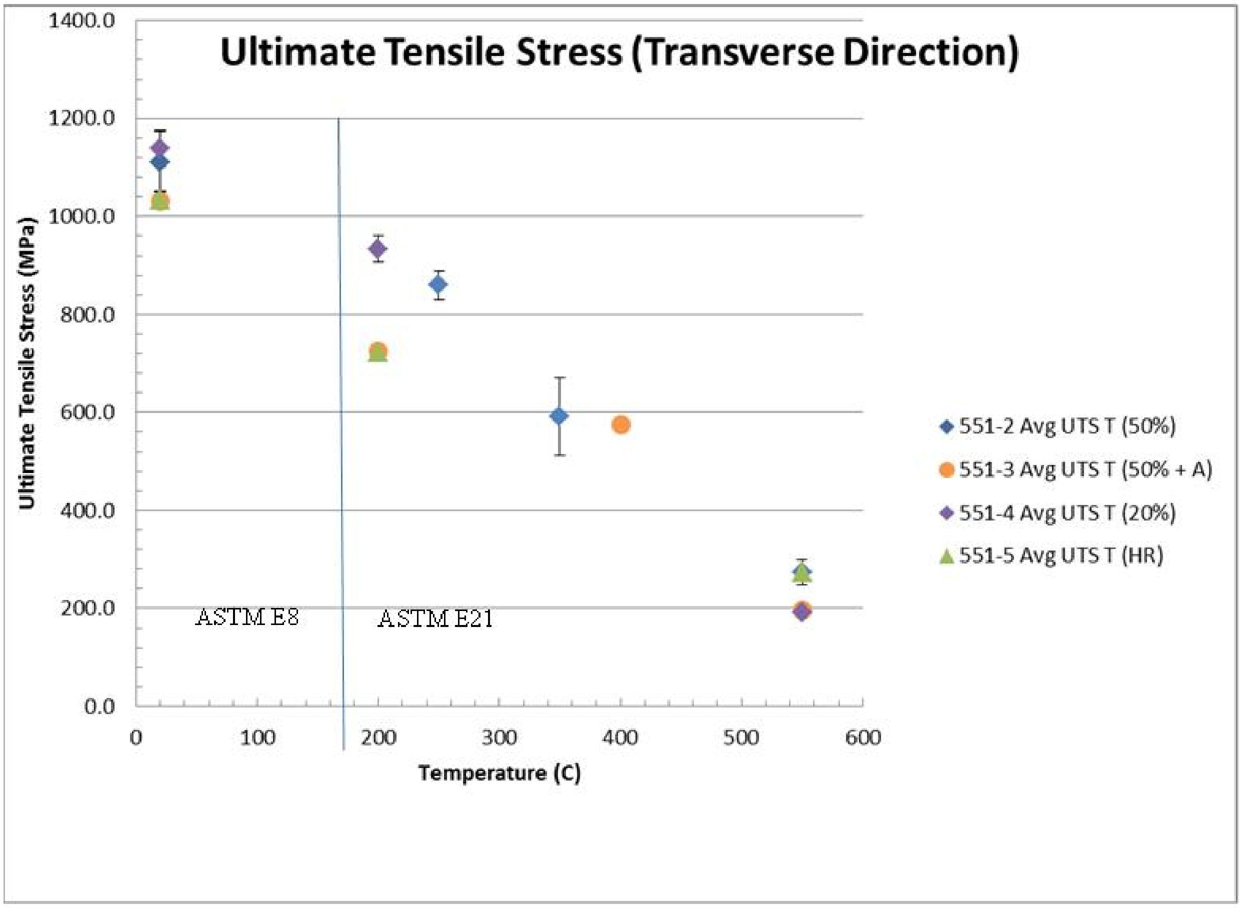

Figure 14. Ultimate tensile stress in the transverse direction for each of the four foil-fabrication conditions. The figure shows the cluster of yield stress at room temperature and at 550°C while there is a divergence in the fabrication conditions in the intermediate values. The annealed and hot-rolled-only foils indicate lower yield-stress values in the intermediate temperatures (200°C), but this seems to reconverge at 400°C. Note that data are not available for foils 551-4 and 551-5 in the transverse direction at 400°C.

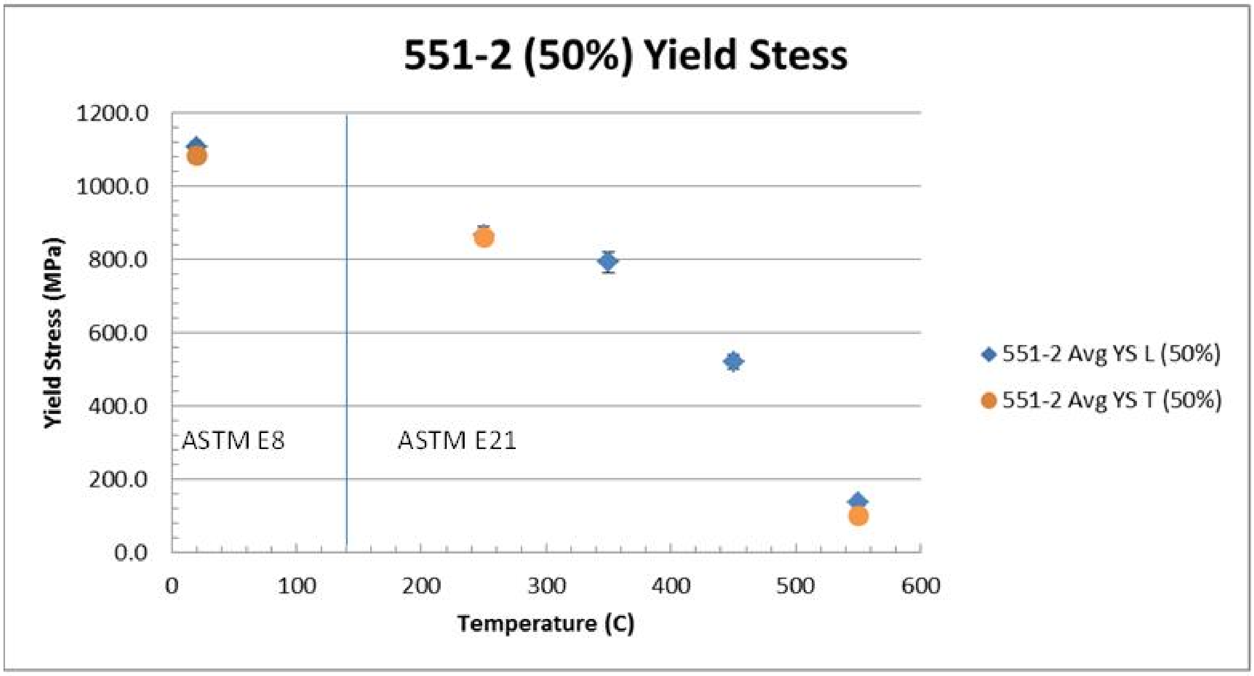

Figure 15. Yield stress for foils cold-rolled to 50% reduction. Note no significant difference in yield-stress values based on rolling direction. No data are available for yield stress in the transvers direction for 350 and 450°C.

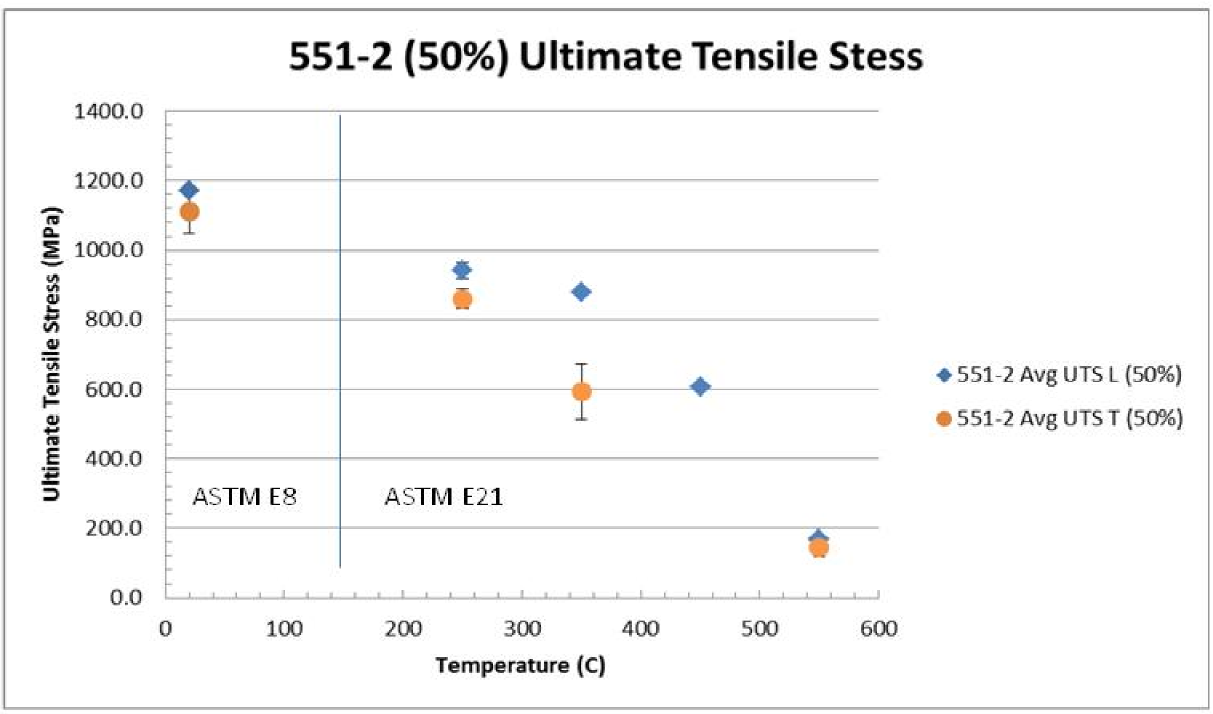

Figure 16. Ultimate tensile stress for foils cold-rolled to 50% reduction and then annealed at 650°C for one hour. Note no significant difference in UTS values based on rolling direction.

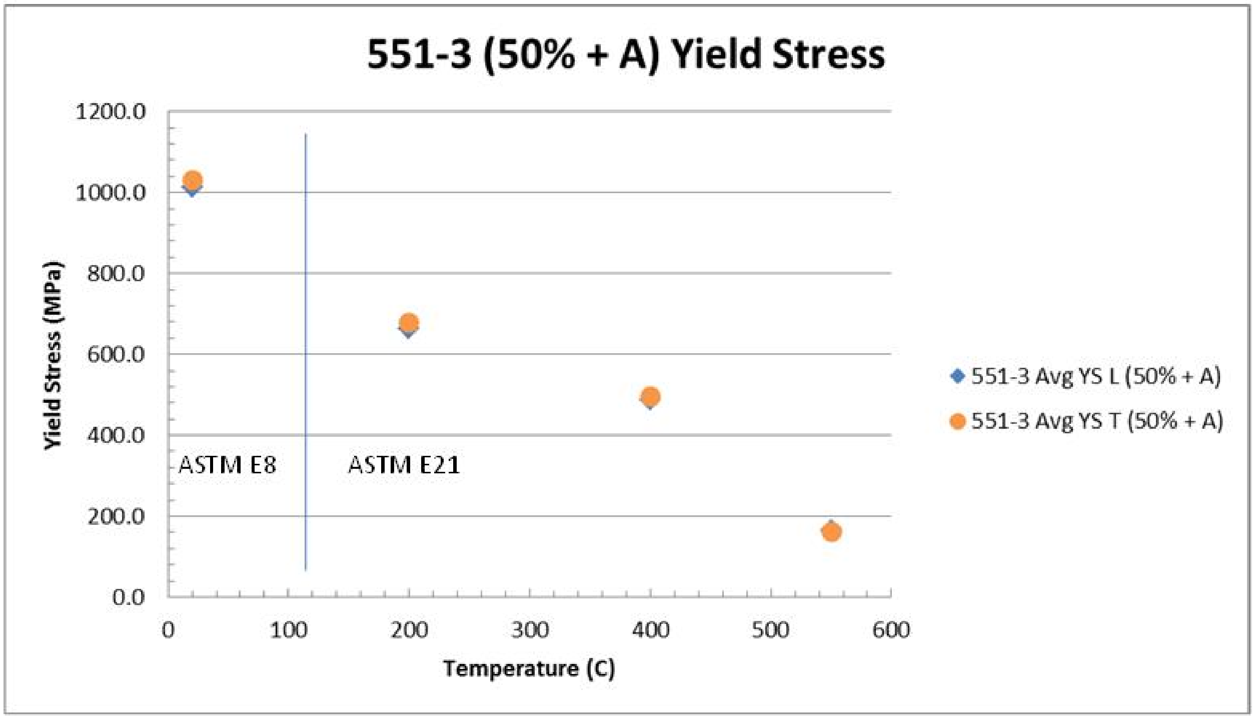

Figure 17. Yield stress for foils cold-rolled to 50% reduction and then annealed at 650°C for one hour. Note no significant difference in yield-stress values based on rolling direction.

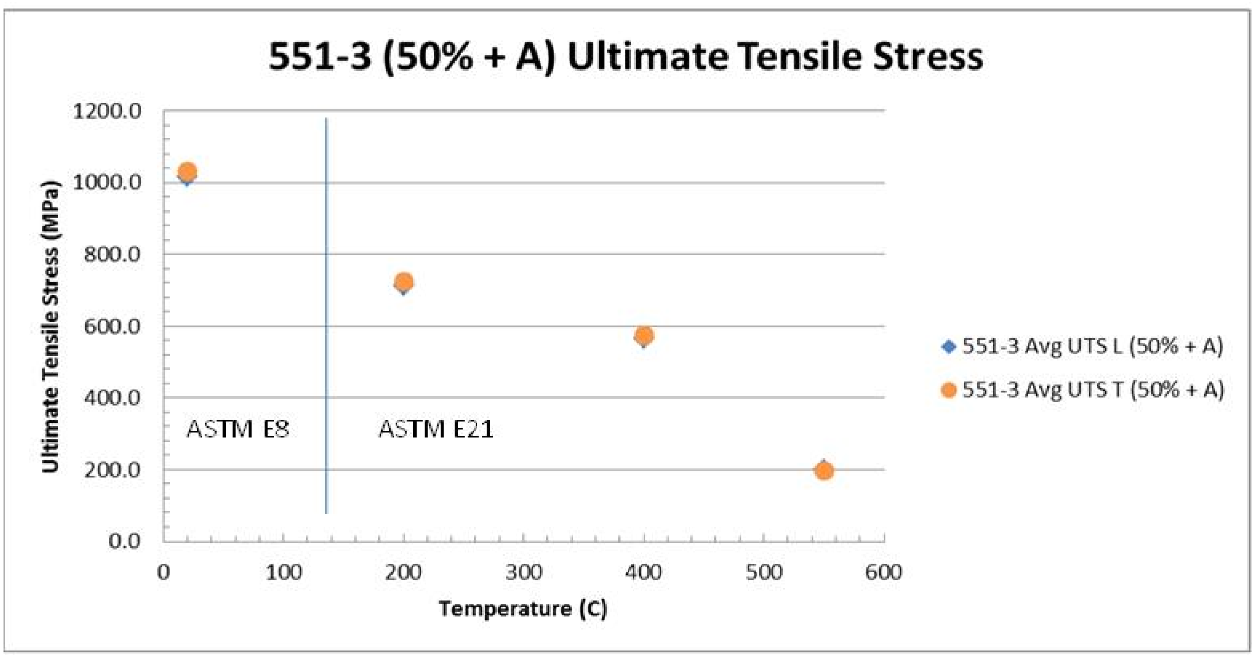

Figure 18. Ultimate tensile stress for foils cold-rolled to 50% reduction and then annealed at 650°C for one hour. Note no significant difference in UTS values based on rolling direction.

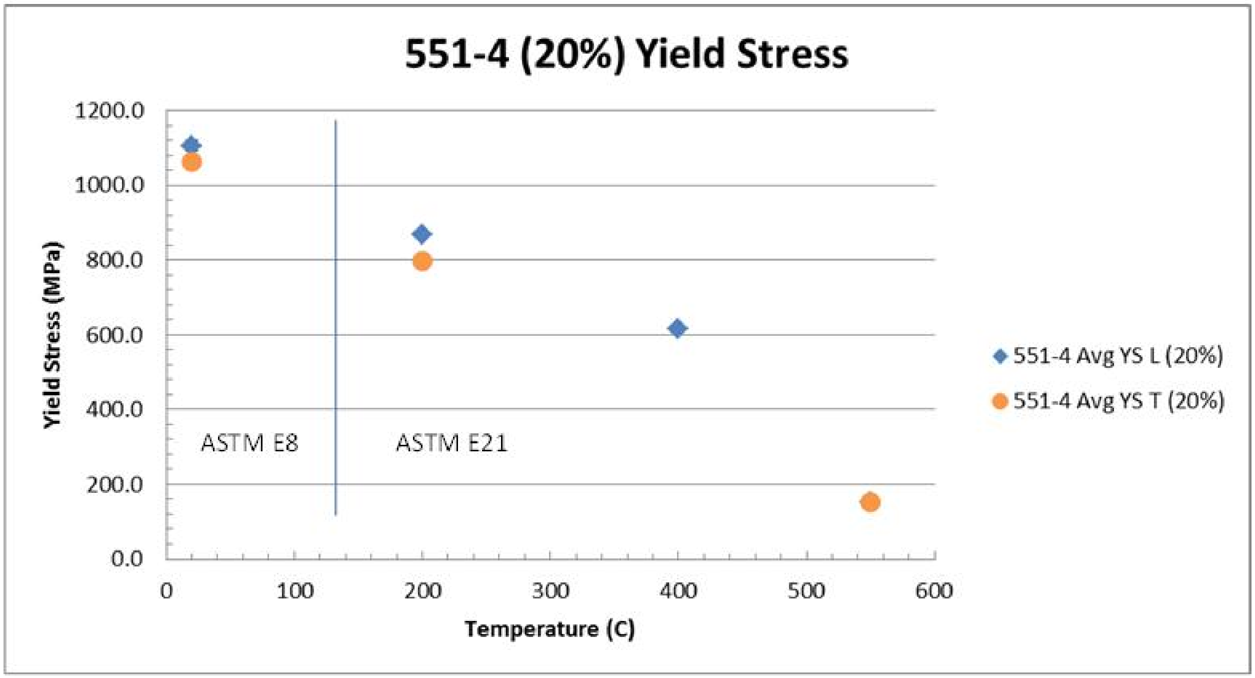

Figure 19. Yield stress for foils cold-rolled to 20% reduction. Note a minor difference in yield-stress values based on rolling direction for 200°C. No transverse data are available for 400°C.

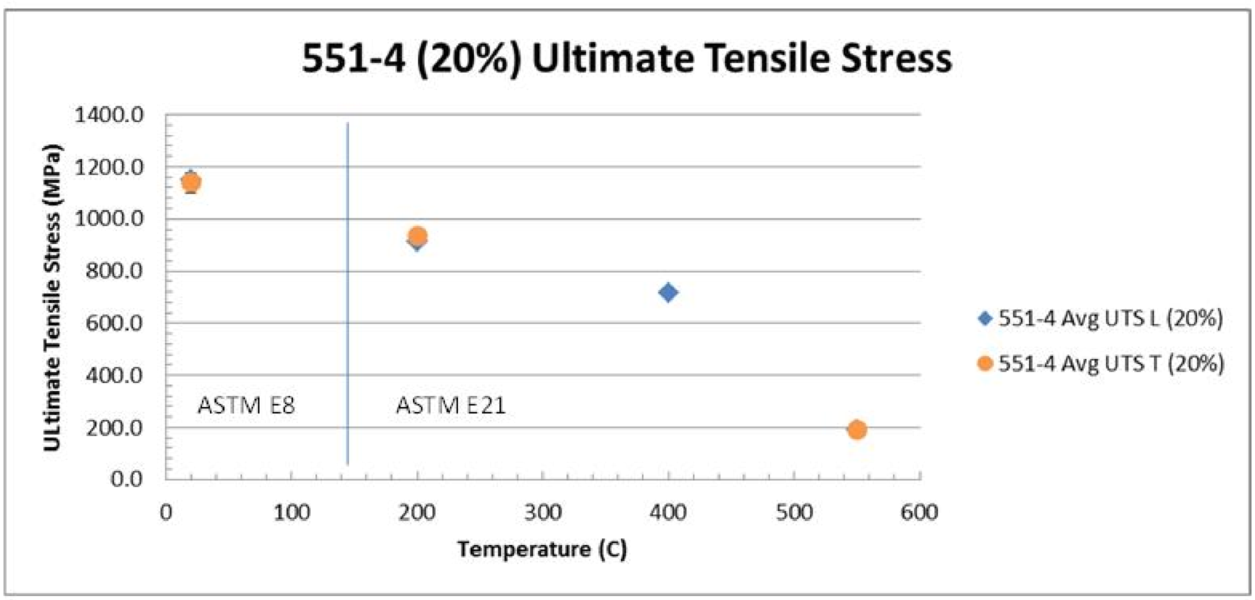

Figure 20. Ultimate tensile stress for foils hot-rolled only with no cold-rolling reduction. Note no significant difference in UTS values based on temperature. No transverse data are available for 400°C.

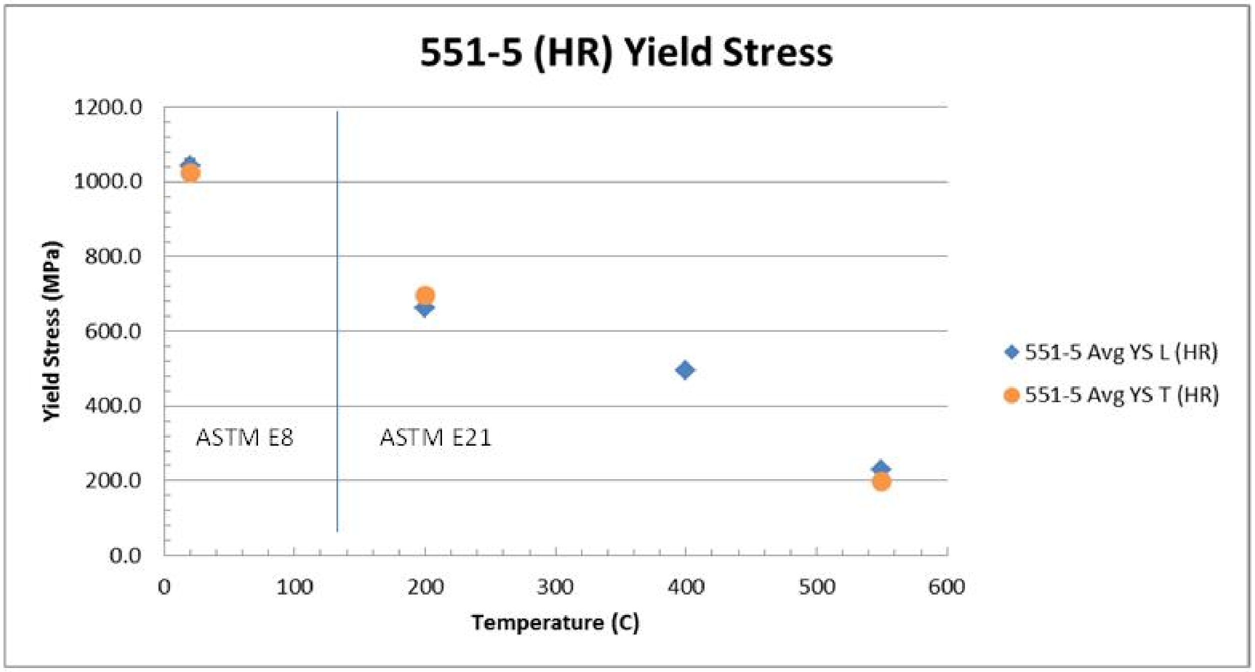

Figure 21. Yield stress for foils hot-rolled only with no cold-rolling reduction. Note no significant difference in yield-stress values based temperature. No transverse data available for 400°C.

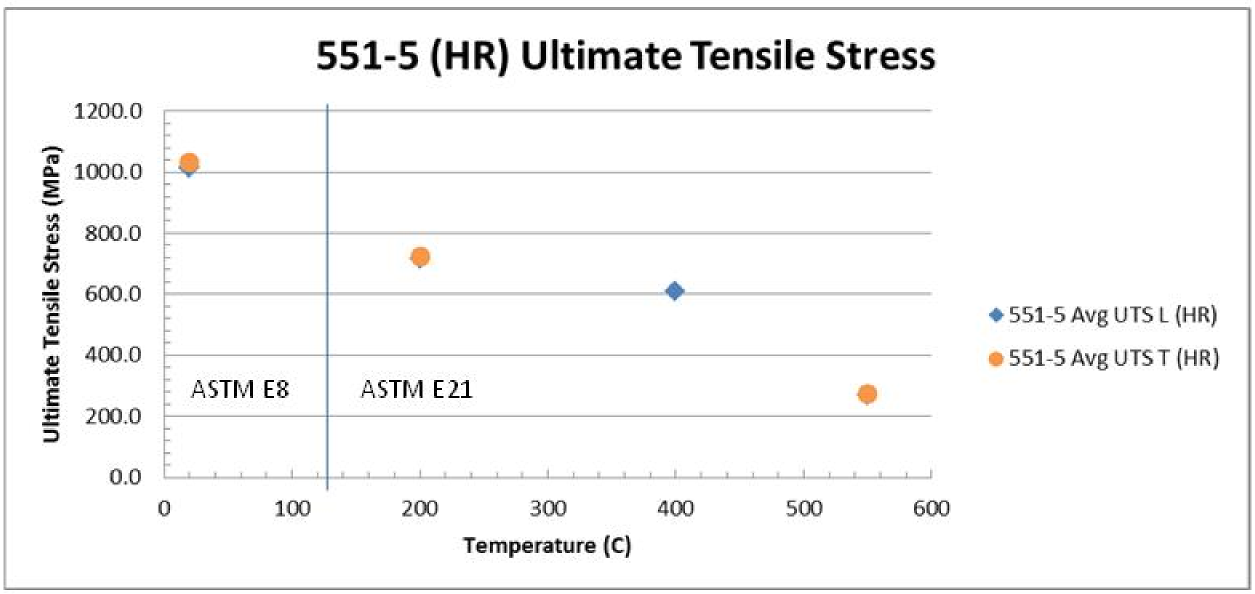

Figure 22. Ultimate tensile stress for foils hot-rolled only with no cold-rolling reduction. Note no significant difference in UTS values based on temperature. No transverse data available for 400°C.

5. REFERENCES

1. M. B. Waldron, R. C. Burnett, S. F. Pugh, *The Mechanical Properties of Uranium–Molybdenum Alloys*, UK Atomic Energy Authority Technical Report, ARE-MB-2554, 1958.
2. Hakan Ozaltun, M-H., Herman Shen, and Pavel Medvedev, "Assessment of residual stresses on U10Mo alloy based monolithic mini-plates during Hot Isostatic Pressing," *Journal of Nuclear Materials* 419.1 (2011), 76–84.
3. D. Burkes at el., *Metall. and Materials Trans. A* 40A (2009), 1069-1079.
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5. *Standard Practice for Verification and Classification of Extensometer Systems*, ASTM E83-10, ASTM International Annual Book of Standards, v.3.01, 2013.
6. *Standard Test Methods for Tension Testing of Metallic Materials*, ASTM E8/8M-13a, ASTM International Annual Book of Standards, v.3.01, 2013.
7. *Standard Test Methods for Elevated Temperature Tension Tests of Metallic Materials*, ASTM E21-09, ASTM International Annual Book of Standards, v.3.01, 2013.
8. J. E. Gates, et al., "Stress-Strain Properties of Irradiated Uranium–10 w/o Molybdenum," BMI-APDA-638, Battelle Memorial Institute, Columbus, OH, January, 1958.
9. G. Beghi, *Gamma Phase Uranium-Molybdenum Fuel Alloys*, EUR-4053e, European Atomic Energy Community, 1968.
10. D. Burkes at el., *Metall. and Materials Trans. A* 40A (2009), 1069-1079.
11. *Standard Test Method for Young's Modulus, Tangent Modulus, and Chord Modulus,* ASTM E111-04, ASTM International Annual Book of Standards, v.3.01, 2013
12. J. E. Gates, et al., *Stress-Strain Properties of Irradiated Uranium–10 w/o Molybdenum*, BMI-APDA-638, Battelle Memorial Institute, Columbus, OH, January, 1958.
13. *Standard Practice for Measuring Ultrasonic Velocity in Materials,* ASTM E494-10, ASTM International Annual Book of Standards, v.3.01, 2013

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Appendix A

Additional Figures

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Appendix A

Additional Figures

Figure A-1. Minimal area inside furnace to install grip alignment collar, install specimen in grips, ensure proper specimen alignment in grips, tighten grip jaws, remove alignment collar, and install extensometer (when used). Care must be used to prevent damage to specimens or fragile Super Kanthal heating elements.

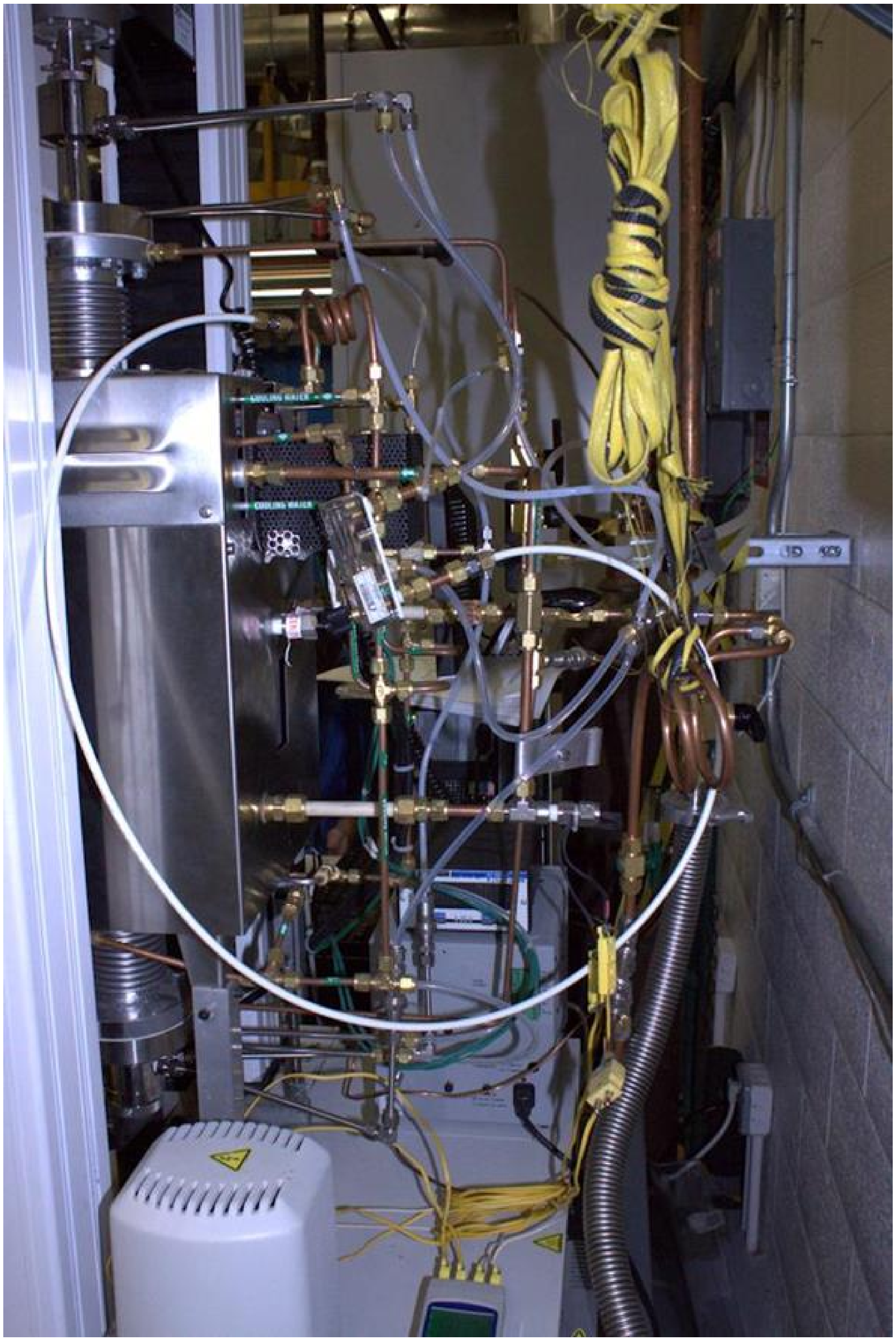


Figure A-2. Inert-gas and cooling-water plumbing at rear of furnace. Metal vacuum hose running down to pump is seen at lower right. Gas piping is all metal or ceramic to prevent oxygen infusion.

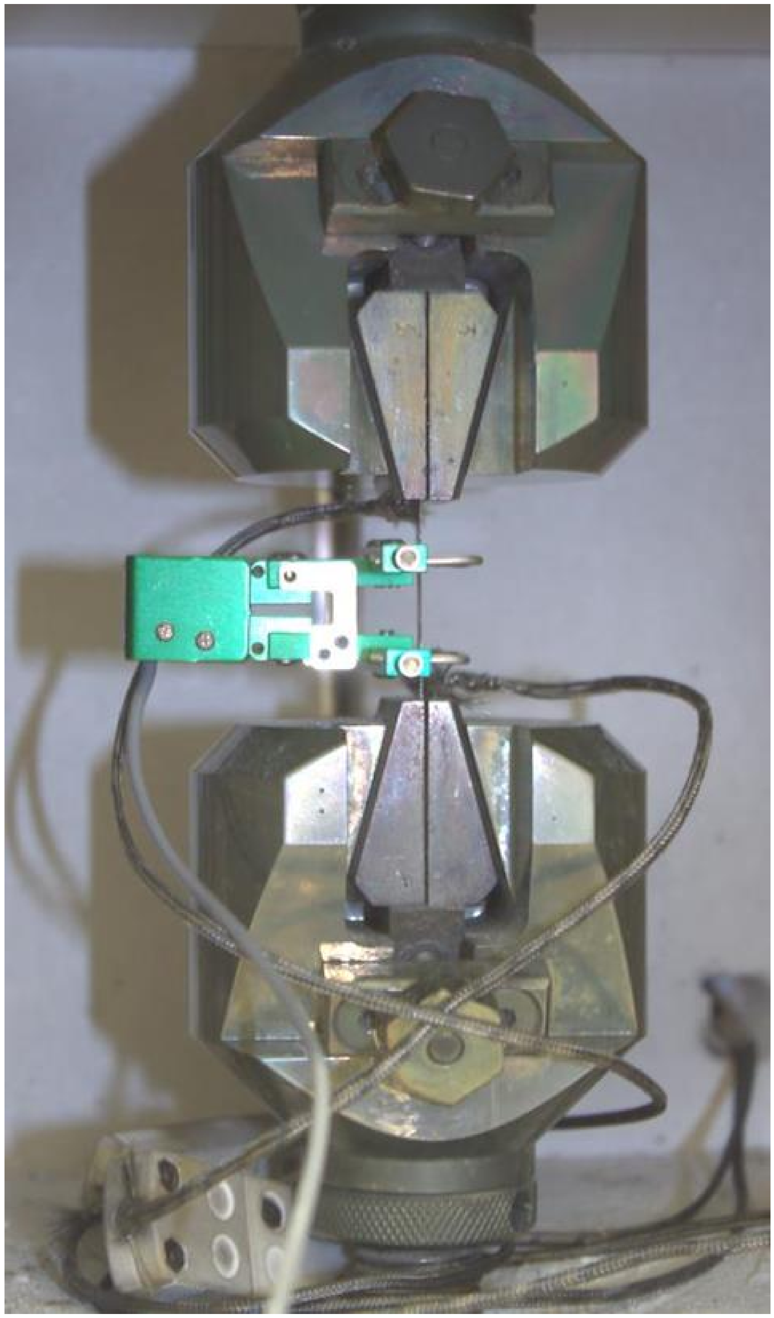
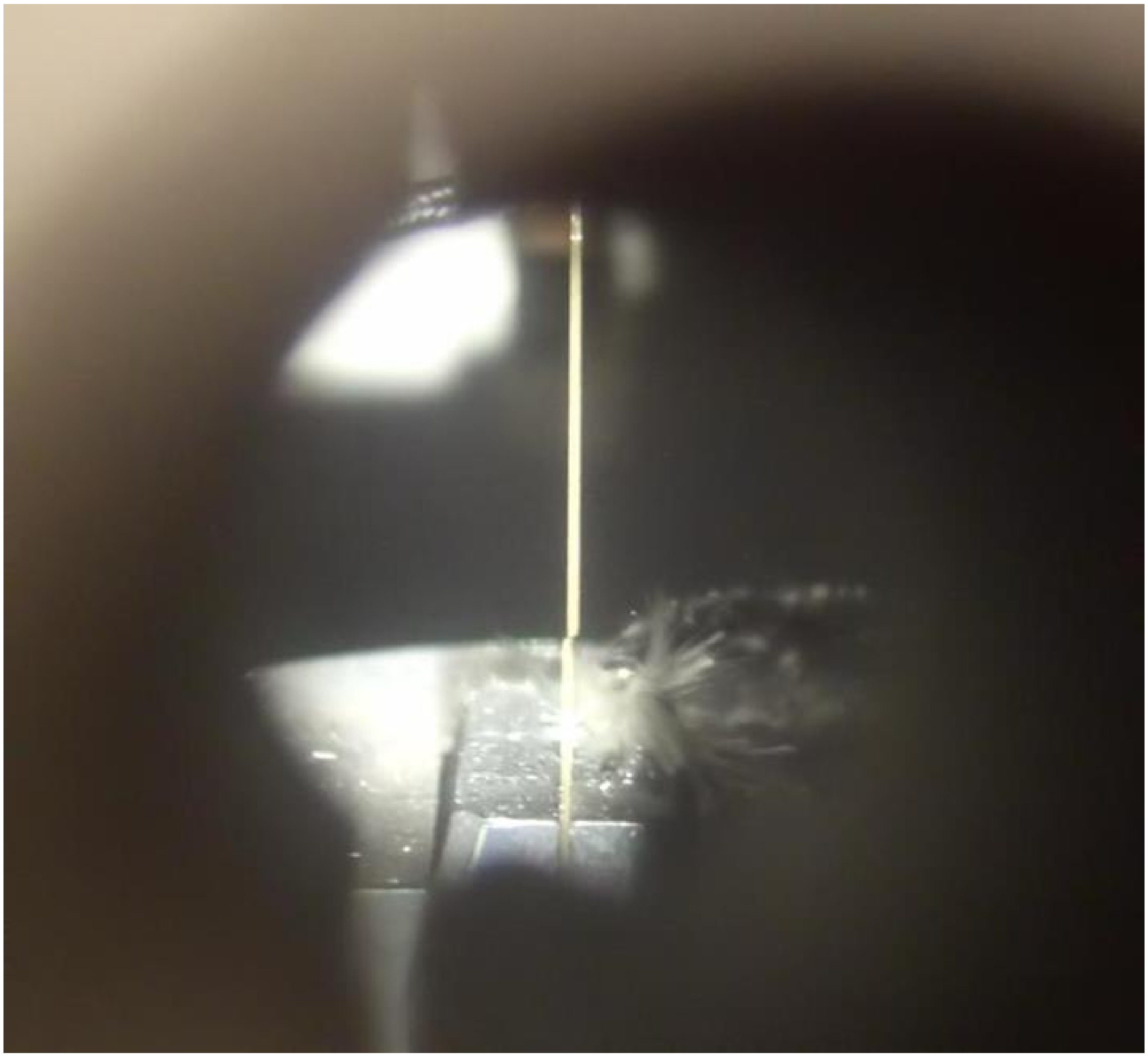


Figure A-3. Specimen installed in grips inside of furnace chamber, with extensometer installed, ready to begin a room-temperature test. Wires from thermocouples welded to grip jaws are seen above and below extensometer. For size reference, the hex grip-tightening bolt-heads are 16 mm. Grip alignment collar has been removed.



FigureA-4. Broken elevated-temperature test specimen as seen through magnifying viewport in furnace door. Lighting is through a narrow window in the door below the viewport. Break is visible at lower portion of reduced section.

Table A-1. Chemistry report provided by Y–12 for log 3C32-WP-TRN0. Impurity levels over 25 ppm reported. Impurity values less than 25 ppm where provided in the chemistry report from Y–12 but are not reported here.

3C32-WP-TRNO	%Mo	ppm C	ppm Al	ppm Cu	ppm Er	ppm Fe	ppm K	ppm Mn	Ppm Ni	ppm P	ppm Si	ppm W
Top	10.40	706	60	13	5.9	160	32	28	37	<20	250	28
Middle	10.50	714	60	13	28	160	<16	29	39	<20	250	25
Bottom	10.30	722	61	12	3.0	160	21	29	38	<20	240	25

ORIGINAL

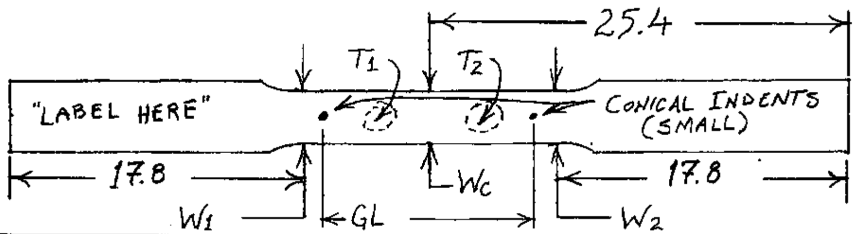
551-2-2 Pre Test Dimensions

Tensile Specimen Dimensional Record Sheet

Date: 9-12-13

Measurement Operator	Name: James Reseigh	Signature: James Reseigh	
GL measurement instrument	ID: A678	Expiration Date: 4-11-14	
W measurement instrument	ID: A687	Expiration Date: 4-11-14	
T measurement instrument	ID: A609	Expiration Date: 4-11-14	
Temperature instrument	ID: A52394	Expiration Date: 8-12-14	

1. Locations to measure are indicated in the diagram. All dimensions in mm. Record measurements to 0.001 mm.
2. Conical indent marks for GL are small, less than 0.1 mm typical. Measure indents center-to-center three times with optical comparator. Reset reference zero for each measurement (three independent measurements).
3. Measure W_1, W_2, and W_C two times. Reset reference zero for each measurement (two independent measurements).
4. Measure two thicknesses at each of two locations inside of gage mark indents as indicated. Measuring device contact surface should not cover the indent. Ball tip micrometer use is suggested for small contact area on indent face of specimen. Use minimum pressure needed to achieve consistent measurements.
5. Record room temperature before starting and after completion of each group of measurements.



Start of Measurements: 18.9 °C

End of Measurements: 19.0 °C

Notes:

Specimen ID	W1 (mm)		W2 (mm)		Wc (mm)		GL (mm)			T1 (mm)		T2 (mm)	
	#1	#2	#1	#2	#1	#2	#1	#2	#3	#1	#2	#1	#2
L-15	2.997	2.998	2.975	2.975	2.969	2.970	12.665	12.663	12.663	.384	.385	.382	.382
L-16	3.012	3.012	3.012	3.012	2.997	2.997	12.701	12.703	12.705	.376	.375	.375	.374
L-17	3.131	3.131	3.134	3.135	3.118	3.115	12.728	12.730	12.728	.371	.370	.371	.371
L-18	2.978	2.978	2.984	2.984	2.973	2.972	12.824	12.821	12.824	.384	.384	.384	.384
L-19	3.014	3.013	3.014	3.014	2.999	2.999	12.721	12.718	12.721	.378	.378	.379	.380
L-20	3.129	3.127	3.133	3.131	3.114	3.112	12.724	12.725	12.721	.371	.371	.371	.372
L-21	2.974	2.974	2.983	2.983	2.967	2.966	12.712	12.718	12.721	.381	.382	.381	.381
L-22	3.008	3.007	3.016	3.015	2.992	2.995	12.721	12.722	12.720	.382	.382	.382	.382
L-23	3.133	3.131	3.130	3.131	3.115	3.113	12.951	12.945	12.947	.387	.387	.387	.388
L-24	3.124	3.123	3.131	3.131	3.104	3.101	12.713	12.720	12.723	.388	.389	.389	.389

Test Type (dimensions in mm)

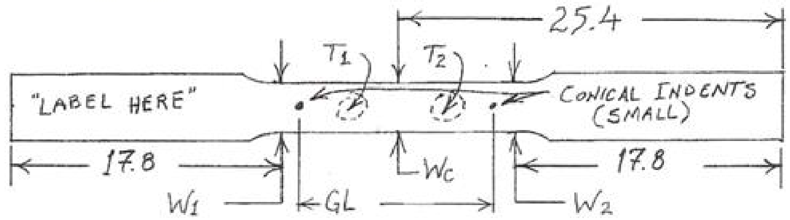
Test Type	Specimen	(initial) Specimen OAL_o	Specimen OAL_F	ΔOAL	$\frac{\Delta OAL}{OAL_o}$ (%)
RT	L-15	not measured (use 50.70 as reference)	51.12 / 51.09	.41	
RT	L-16	"	51.45 / 51.44	.75	
RT	L-17	"	51.00 / 50.98	.29	
250	L-18	"	51.11 / 51.10	0.41	0.0081
250	L-19	50.71 / 50.70	50.84 / 50.83	0.13	0.0026
250	L-20	50.70 / 50.71	51.07 / 51.06	0.36	0.0071
250	L-21	50.72 / 50.72			
250	L-22	50.71 / 50.71			
	L-23	50.70 / 50.70			
	L-24	50.71 / 50.68			
	L-25	50.26 / 50.26			
	L-26	50.24 / 50.24			
	—	(no L-27)			
	L-28	50.23 / 50.23			
	~~L-29~~ L-27 JLS 16OCT2013	50.20 / 50.21			

Measurement by calipers 730710, Exp: 04 Sep 2014

ORIGINAL

Date: 12 Sept 2013 **Tensile Specimen Dimensional Record Sheet (continuation)**

Measurement Operator Name: James Reseigh Signature: see sheet 1



Specimen ID	W1 (mm)		W2 (mm)		Wc (mm)		GL (mm)			T1 (mm)		T2 (mm)	
	#1	#2	#1	#2	#1	#2	#1	#2	#3	#1	#2	#1	#2
L-25	2.982	2.980	2.977	2.976	2.962	2.960	12.738	12.740	12.748	.373	.374	.373	.373
L-26	3.008	3.008	3.014	3.013	2.998	2.996	12.699	12.684	12.678	.381	.381	.381	.381
										~~.385~~	~~.386~~	~~.387~~	~~.387~~
L-28	3.131	3.131	3.128	3.130	3.116	3.114	12.837	12.831	12.834	.385	.386	.387	.387
~~L-29~~ L-27 JCS [illegible]	3.121	3.118	3.132	3.131	3.105	3.102	12.723	12.722	12.725	.389	.389	.389	.390

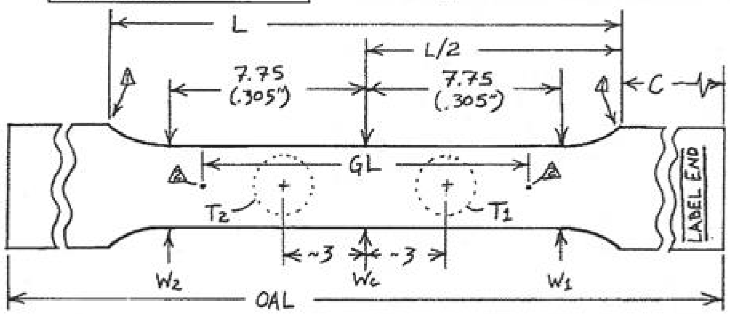
Notes:

Foil: 551-2-2 Pre test Dimensions New

Date: 11-7-13

Tensile Specimen Dimensional Record Sheet (continuation)

Sheet 1 of 3



Measurement Operator Name: James Reseigh Signature: [signature]

OAL measurement instrument ID: A678 Expiration Date: 4-11-14

GL measurement instrument ID: A678 Expiration Date: 4-11-14

W measurement instrument ID: A678 Expiration Date: 4-11-14

T measurement instrument ID: A31801 Expiration Date: 10-28-14

Temperature instrument ID: 730725 Expiration Date: 10-1-14

Start of Measurements: 19.6 °C End of Measurements: 20.2 °C

Delta 1. Reference positions for reduced section locations – corner at intersection of end tab and fillet. Locate center between corners (L/2) as zero position reference. It is not necessary to record dimension L.

Delta 2. Conical indent marks for GL measurement are small, less than 0.1 mm typical. Measure indents center-to-center three times with optical comparator. Reset reference zero for each measurement (three independent measurements).

1. Locations to measure are indicated in the diagram. All dimensions in mm except as indicated by (in.). Record measurements to 0.001 mm excepting "C" and "OAL."
2. Record dimension "C" to 0.01 mm resolution.
3. Record dimension "OAL" to 0.01 mm resolution. This can be measured with a caliper.
4. Measure W_1, W_2, and W_C two times. Reset width reference zero for each measurement (make two independent measurements at each location).
5. Measure thicknesses T_1 and T_2, twice at each location, approximately 3 mm either side of centerline. Measuring device contact surface should not cover the gage mark indent. Ball tip micrometer use is suggested for small contact area on indent face of specimen. Use minimum pressure needed to achieve consistent measurements.
6. Record room temperature before starting and after completion of each group of measurements.

Specimen ID	OAL (mm)	C (mm)	W_1 (mm)		W_2 (mm)		W_C (mm)		GL (mm)			T_1 (mm)		T_2 (mm)	
			#1	#2	#1	#2	#1	#2	#1	#2	#3	#1	#2	#1	#2
T1	52.340	16.827	3.136	3.136	3.135	3.136	3.122	3.121	12.732	12.722	12.721	.387	.387	.386	.386
T2	52.383	16.871	3.140	3.140	3.141	3.141	3.124	3.124	12.675	12.667	12.685	.388	.388	.391	.391
T3	52.410	16.916	3.143	3.144	3.140	3.140	3.112	3.111	12.687	12.683	12.685	.389	.389	.389	.389
T4	52.442	16.925	3.151	3.152	3.144	3.144	3.117	3.117	12.676	12.675	12.680	.389	.389	.391	.391
T5	52.474	17.010	3.217	3.218	3.184	3.184	3.179	3.179	12.756	12.740	12.741	.389	.389	.389	.389
T6	52.498	17.018	3.135	3.134	3.149	3.149	3.115	3.115	12.754	12.756	12.757	.389	.389	.390	.390
T7	52.523	17.095	3.137	3.137	3.138	3.138	3.112	3.112	12.728	12.723	12.730	.390	.390	.390	.390
T8	52.544	17.079	3.133	3.133	3.139	3.139	3.113	3.114	12.682	12.688	12.687	.390	.390	.390	.390

Date: 11-7-13

Tensile Specimen Dimensional Record Sheet (continuation)

Sheet 2 of 3

Measurement Operator Name: James Reseigh   Signature: James Reseigh

Specimen ID	OAL (mm)	C (mm)	W₁ (mm)		W₂ (mm)		W_C (mm)		GL (mm)			T₁ (mm)		T₂ (mm)	
			#1	#2	#1	#2	#1	#2	#1	#2	#3	#1	#2	#1	#2
T9	52.568	17.106	3.131	3.131	3.135	3.135	3.109	3.109	12.788	12.791	12.786	.389	.389	.389	.389
T10	52.599	17.121	3.132	3.132	3.136	3.136	3.110	3.109	12.795	12.801	12.794	.391	.391	.391	.391
T11	52.637	17.180	3.133	3.134	3.132	3.132	3.115	3.115	12.695	12.706	12.700	.389	.389	.391	.391
T12	52.264	17.176	3.139	3.139	3.139	3.140	3.112	3.111	12.786	12.780	12.789	.391	.391	.390	.389
T13	52.663	17.200	3.132	3.132	3.133	3.133	3.112	3.113	12.727	12.730	12.725	.386	.386	.389	.389
T14	52.677	17.211	3.142	3.141	3.138	3.138	3.107	3.106	12.723	12.714	12.724	.386	.386	.386	.386
T15	52.678	17.123	3.069	3.068	3.090	3.090	3.049	3.050	12.717	12.710	12.722	.386	.387	.388	.388
T16	52.689	17.077	3.143	3.143	3.146	3.147	3.133	3.134	12.688	12.684	12.690	.386	.386	.386	.386
T17	52.699	17.091	3.134	3.133	3.130	3.131	3.117	3.116	12.813	12.814	12.802	.386	.386	.388	.387
T18	52.706	17.111	3.110	3.110	3.104	3.105	3.092	3.091	12.746	12.743	12.740	.385	.385	.386	.386
T19	52.706	17.109	3.101	3.101	3.107	3.107	3.053	3.052	12.736	12.740	12.738	.387	.387	.389	.389
T20	51.360	15.315	3.136	3.136	3.131	3.131	3.119	3.119	12.682	12.681	12.681	.389	.389	.389	.389
T21	51.361	15.302	3.136	3.137	3.140	3.140	3.129	3.128	12.780	12.782	12.782	.386	.386	.386	.386
T22	51.352	15.316	3.133	3.134	3.134	3.134	3.114	3.114	12.783	12.785	12.788	.386	.386	.389	.389
T23	51.348	15.326	3.145	3.145	3.142	3.142	3.118	3.118	12.763	12.747	12.744	.386	.386	.388	.388
T24	51.355	15.333	3.188	3.188	3.208	3.208	3.172	3.172	12.720	12.725	12.725	.389	.389	.389	.389
T25	51.357	15.303	3.136	3.136	3.128	3.127	3.117	3.116	12.839	12.838	12.840	.389	.389	.389	.389
T26	51.352	15.287	3.137	3.137	3.131	3.130	3.112	3.112	12.802	12.797	12.790	.386	.386	.389	.389
T27	51.354	15.266	3.138	3.138	3.129	3.128	3.109	3.109	12.703	12.705	12.701	.386	.386	.389	.389
T28	51.363	15.278	3.133	3.132	3.125	3.125	3.109	3.109	12.796	12.780	12.776	.387	.387	.386	.386

Measurement Notes (use back of sheet if needed):

T18 - 2 Conical indents on end opposite the Lable end. GL measurement is on the furthest indents apart

Date: 11-7-13

Tensile Specimen Dimensional Record Sheet (continuation)

Measurement Operator Name: James Reseigh

Signature: James Reseigh

Specimen ID	OAL (mm)	C (mm)	W_1 (mm)		W_2 (mm)		W_C (mm)		GL (mm)			T_1 (mm)		T_2 (mm)	
			#1	#2	#1	#2	#1	#2	#1	#2	#3	#1	#2	#1	#2
T29	51.358	15.280	3.135	3.134	3.135	3.136	3.105	3.105	12.733	12.739	12.740	.386	.386	.386	.386
T30	51.631	15.303	3.135	3.135	3.137	3.137	3.123	3.123	12.745	12.745	12.752	.387	.387	.389	.389
T31	51.635	15.303	3.134	3.133	3.130	3.131	3.110	3.111	12.751	12.756	12.754	.386	.386	.389	.389
T32	51.635	15.301	3.135	3.135	3.131	3.131	3.114	3.114	12.740	12.741	12.738	.387	.387	.388	.388
T33	51.647	15.290	3.136	3.135	3.122	3.122	3.104	3.104	12.807	12.813	12.806	.386	.386	.387	.387
T34	51.650	15.341	3.090	3.089	3.073	3.073	3.047	3.047	12.810	12.796	12.795	.386	.386	.387	.387
T35	51.668	15.460	3.145	3.144	3.148	3.148	3.123	3.123	12.689	12.697	12.692	.389	.389	.390	.390
T36	51.682	15.479	3.127	3.127	3.132	3.131	3.104	3.105	12.667	12.668	12.681	.388	.388	.391	.391
T37	51.698	15.484	3.120	3.120	3.115	3.114	3.097	3.097	12.760	12.740	12.738	.387	.387	.388	.388
T38	51.700	15.542	3.106	3.105	3.112	3.113	3.051	3.052	12.729	12.723	12.721	.386	.386	.388	.388

Measurement Notes (use back of sheet if needed):

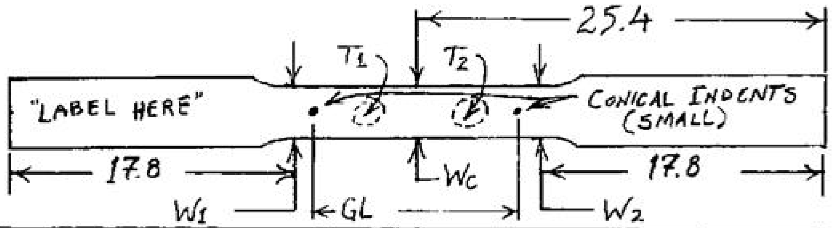
Foil SS1-2-2 Pretest Dimensions Old

Date: 10-15-13

Tensile Specimen Dimensional Record Sheet

Measurement Operator	Name: James Roseigh	Signature: James Roseigh
GL measurement instrument	ID: A678	Expiration Date: 4-11-14
W measurement instrument	ID: A678	Expiration Date: 4-11-14
T measurement instrument	ID: A609	Expiration Date: 11-12-13
Temperature instrument	ID: 730725	Expiration Date: 10-1-14

1. Locations to measure are indicated in the diagram. All dimensions in mm. Record measurements to 0.001 mm.
2. Conical indent marks for GL are small, less than 0.1 mm typical. Measure indents center-to-center three times with optical comparator. Reset reference zero for each measurement (three independent measurements).
3. Measure W_1, W_2, and W_C two times. Reset reference zero for each measurement (two independent measurements).
4. Measure two thicknesses at each of two locations inside of gage mark indents as indicated. Measuring device contact surface should not cover the indent. Ball tip micrometer use is suggested for small contact area on indent face of specimen. Use minimum pressure needed to achieve consistent measurements.
5. Record room temperature before starting and after completion of each group of measurements.



Start of Measurements: 19.7 °C

End of Measurements: 19.4 °C

Notes:

Specimen ID	W_1 (mm)		W_2 (mm)		W_C (mm)		GL (mm)			T_1 (mm)		T_2 (mm)	
	#1	#2	#1	#2	#1	#2	#1	#2	#3	#1	#2	#1	#2
L1	3.145	3.147	3.144	3.145	3.119	3.120	12.768	12.771	12.769	.369	.369	.369	.370
L2	3.148	3.148	3.152	3.152	3.130	3.130	12.703	12.712	12.703	.374	.374	.377	.377
L3	3.145	3.146	3.150	3.150	3.125	3.125	12.761	12.768	12.767	.377	.377	.380	.380
L4	3.155	3.156	3.151	3.152	3.130	3.129	12.695	12.693	12.687	.378	.378	.382	.381
L5 Invalid	3.373	3.373	3.505	3.504	3.418	3.418	12.782	12.786	12.783	.384	.383	.384	.384
L6	3.148	3.148	3.145	3.145	3.133	3.132	12.750	12.763	12.764	.386	.387	.388	.387
L7	3.148	3.147	3.146	3.146	3.126	3.125	12.738	12.735	12.734	.388	.387	.388	.390
L8	3.144	3.142	3.145	3.147	3.131	3.131	12.744	12.747	12.737	.389	.389	.389	.389
L9	3.144	3.145	3.138	3.138	3.132	3.132	12.752	12.746	12.745	.389	.389	.389	.388
L10	3.150	3.150	3.164	3.164	3.141	3.140	12.761	12.761	12.771	.386	.386	.388	.388

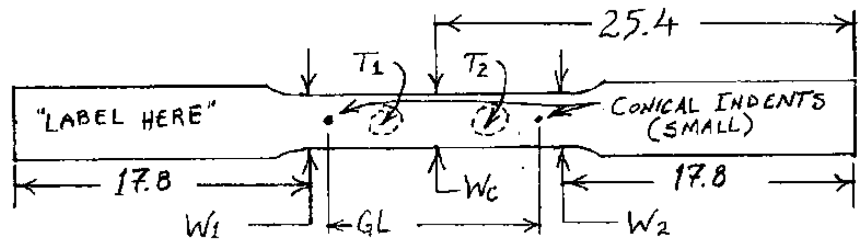
Date: 10-15-13

Tensile Specimen Dimensional Record Sheet (continuation)

Measurement Operator

Name: James Reseigh

Signature: James Reseigh



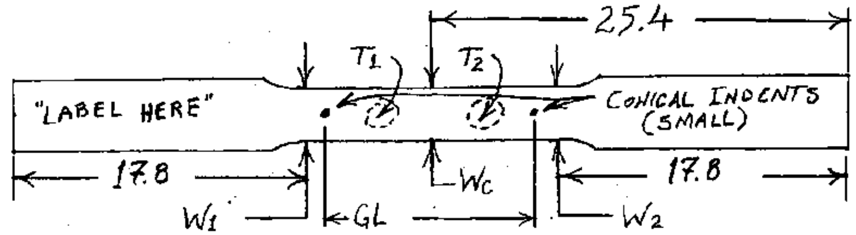
Specimen ID	W_1 (mm)		W_2 (mm)		W_C (mm)		GL (mm)			T_1 (mm)		T_2 (mm)	
	#1	#2	#1	#2	#1	#2	#1	#2	#3	#1	#2	#1	#2
L 11	3.148	3.149	3.144	3.143	3.129	3.129	12.758	12.752	12.755	.382	.382	.384	.384
L 12	3.158	3.158	3.150	3.150	3.138	3.138	12.730	12.725	12.720	.377	.377	.378	.379
L 13	3.154	3.156	3.149	3.149	3.136	3.135	12.760	12.759	12.752	.374	.374	.372	.372
L 29	3.143	3.143	3.141	3.141	3.114	3.114	12.771	12.774	12.770	.376	.377	.375	.375
L 30	3.147	3.146	3.153	3.154	3.127	3.127	12.690	12.686	12.689	.381	.381	.380	.380
L 31	3.140	3.140	3.140	3.141	3.132	3.131	12.725	12.731	12.728	.385	.385	.385	.384
L 32	3.148	3.149	3.149	3.148	3.129	3.129	12.740	12.747	12.740	.388	.388	.388	.390
L 33 Invalid	3.371	3.371	3.513	3.512	3.427	3.427	12.672	12.676	12.670	.392	.392	.389	.389
L 34	3.151	3.152	3.149	3.149	3.129	3.128	12.753	12.742	12.754	.391	.391	.390	.390
L 35	3.146	3.146	3.151	3.150	3.131	3.130	12.629	12.637	12.634	.392	.392	.391	.391
L 36	3.148	3.149	3.147	3.146	3.130	3.131	12.689	12.690	12.685	.395	.395	.394	.394
L 37	3.143	3.143	3.144	3.144	3.122	3.122	12.706	12.700	12.701	.394	.394	.392	.392
L 38	3.146	3.147	3.158	3.158	3.143	3.143	12.729	12.726	12.721	.394	.394	.393	.392
L 39	3.143	3.142	3.142	3.142	3.131	3.131	12.736	12.730	12.738	.388	.388	.387	.388

Notes:

Date: 10-15-13

Tensile Specimen Dimensional Record Sheet (continuation)

Measurement Operator Name: James Ressigh Signature: [signature]



Specimen ID	W_1 (mm)		W_2 (mm)		W_C (mm)		GL (mm)			T_1 (mm)		T_2 (mm)	
	#1	#2	#1	#2	#1	#2	#1	#2	#3	#1	#2	#1	#2
L40	3.154	3.154	3.158	3.157	3.146	3.147	12.756	12.751	12.761	.387	.387	.384	.384
L41	3.155	3.154	3.148	3.148	3.138	3.138	12.761	12.747	12.760	.378	.378	.378	.378

Notes:

Test Type	Specimen	Specimen OAL_o	Specimen OAL_F	ΔOAL	$\frac{\Delta OAL}{OAL_o}$	
350 °C	L1	50.46 / 50.46	50.60 / 50.60			Specimen did not break slipped in grip
	L2	50.44 / 50.44	50.97 / 50.86			
	L3	50.47 / 50.45	50.81 / 50.83			
	L4	50.47 / 50.46	51.98 / 51.96			
	L5	50.45 / 50.45				
	L6	50.43 / 50.44				
	L7	50.45 / 50.44				
	L8	50.45 / 50.44				
	L9	50.43 / 50.44				
	L10	50.45 / 50.44				
	L11	50.43 / 50.44				
	L12	50.45 / 50.44				
	L13	50.46 / 50.45				
	L29	50.78 / 50.78				
	L30	50.78 / 50.77				
	L31	50.80 / 50.79				
	L32	50.75 / 50.75				
	L33	50.75 / 50.76				
	L34	50.76 / 50.76				
	L35	50.76 / 50.76				
	L36	50.76 / 50.77				
	L37	50.77 / 50.76				
	L38	50.79 / 50.78				
	L39	50.79 / 50.79				
	L40	50.81 / 50.81				
	L41	50.83 / 50.83				

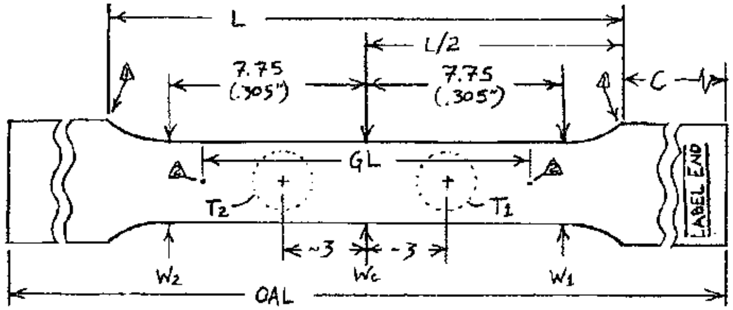
measurement by calipers expiration 3-21-2014
~~726313~~
725117

Foil 551-2-2 Post Test Dimensions

Date: 3/5/14

Tensile Specimen Dimensional Record Sheet (continuation)

Sheet 1 of 3



Measurement Operator Name: James Reseigh Signature:

OAL measurement instrument ID: A678 Expiration Date: 4/11/14

GL measurement instrument ID: A678 Expiration Date: 4/11/14

W measurement instrument ID: A678 Expiration Date: 4/11/14

T measurement instrument ID: A609 Expiration Date: 11/13/14

Temperature instrument ID: A51610 Expiration Date: 10/22/14

Start of Measurements: 18.7°C End of Measurements: 19.1°C

Delta 1. Reference positions for reduced section locations – corner at intersection of end tab and fillet. Locate center between corners (L/2) as zero position reference. It is not necessary to record dimension L.

Delta 2. Conical indent marks for GL measurement are small, less than 0.1 mm typical. Measure indents center-to-center three times with optical comparator. Reset reference zero for each measurement (three independent measurements).

1. Locations to measure are indicated in the diagram. All dimensions in mm except as indicated by (in.). Record measurements to 0.001 mm excepting "C" and "OAL."
2. Record dimension "C" to 0.01 mm resolution.
3. Record dimension "OAL" to 0.01 mm resolution. This can be measured with a caliper.
4. Measure W_1, W_2, and W_C two times. Reset width reference zero for each measurement (make two independent measurements at each location).
5. Measure thicknesses T_1 and T_2, twice at each location, approximately 3 mm either side of centerline. Measuring device contact surface should not cover the gage mark indent. Ball tip micrometer use is suggested for small contact area on indent face of specimen. Use minimum pressure needed to achieve consistent measurements.
6. Record room temperature before starting and after completion of each group of measurements.

Specimen ID	OAL (mm)	C (mm)	W_1 (mm)		W_2 (mm)		W_C (mm)		GL (mm)			T_1 (mm)		T_2 (mm)	
			#1	#2	#1	#2	#1	#2	#1	#2	#3	#1	#2	#1	#2
L2	51.120	15.378	3.134	3.132	3.138	3.137	3.106	3.107	13.277	13.270	13.271	.378	.378	.379	.379
L3	51.036	15.268	3.132	3.133	3.132	3.132	3.109	3.109	13.252	13.255	13.258	.381	.381	.379	.379
L4	52.129	15.406	3.074	3.075	3.062	3.062	3.020	3.021	13.920	13.921	13.918	.363	.363	.365	.365
L6	51.993	15.201	3.105	3.105	3.072	3.072	3.044	3.044	13.836	13.824	13.821	.365	.365	.366	.366
L7	50.709	15.152	3.153	3.154	3.143	3.144	3.129	3.130	12.823	12.821	12.822	.382	.382	.382	.382
*L8	62.484	15.261	3.045	3.047	3.059	3.056	2.618	2.615	22.140	22.127	22.125	.258	.258	.282	.282
*L9	62.535	15.256	3.002	3.003	3.051	3.055	2.509	2.515	23.167	23.135	23.152	.256	.256	.246	.246
*L10	60.445	15.192	3.015	3.014	3.014	3.014	2.744	2.748	20.946	20.928	20.929	.281	.281	.272	.272

Date: 3/5/14

Tensile Specimen Dimensional Record Sheet (continuation)

Sheet 2 of 3

Measurement Operator Name: James Reseigh

Signature: [signature]

Specimen ID	OAL (mm)	C (mm)	W_1 (mm)		W_2 (mm)		W_C (mm)		GL (mm)			T_1 (mm)		T_2 (mm)	
			#1	#2	#1	#2	#1	#2	#1	#2	#3	#1	#2	#1	#2
L15	51.030	14.862	2.961	2.962	2.852	2.853	2.957	2.956	12.812	12.815	12.814	.384	.384	.384	.383
L16	51.565	15.540	2.942	2.943	2.997	2.998	2.953	2.954	13.160	13.167	13.173	.372	.372	.372	.372
L17	51.132	15.169	3.129	3.128	3.111	3.112	3.113	3.113	12.784	12.791	12.788	.372	.372	.372	.372
L18	51.095	15.248	2.990	2.991	2.939	2.940	2.960	2.961	13.221	13.214	13.211	.381	.381	.378	.378
L19	51.126	15.258	3.028	3.027	2.982	2.983	3.003	3.003	12.787	12.788	12.786	.380	.380	.378	.378
L20	51.205	15.188	3.128	3.128	3.127	3.127	3.027	3.027	13.179	13.175	13.170	.372	.372	.371	.370
L21	50.846	15.320	2.962	2.961	2.993	2.993	2.975	2.976	12.704	12.718	12.709	.372	.372	.372	.372
L22	50.951	15.291	3.022	3.022	3.020	3.019	3.005	3.004	12.921	12.938	12.935	.380	.380	.380	.380
T1	52.379	16.843	3.139	3.139	3.138	3.138	3.121	3.121	12.737	12.727	12.738	.388	.388	.387	.387
T2	52.647	16.876	3.136	3.136	3.131	3.131	3.110	3.110	12.925	12.922	12.928	.387	.386	.389	.389
T3	52.615	16.917	3.138	3.139	3.141	3.143	3.117	3.118	12.713	12.711	12.709	.385	.385	.386	.386
T4	52.599	17.044	3.156	3.156	3.144	3.145	3.123	3.123	12.693	12.697	12.706	.388	.390	.390	.389
T5	52.638	16.996	3.217	3.217	3.196	3.196	3.183	3.183	12.877	12.877	12.864	.388	.388	.386	.386
T6	52.839	17.053	3.149	3.150	3.146	3.146	3.120	3.120	12.780	12.771	12.776	.389	.389	.390	.390
T7	52.937	17.040	3.141	3.142	3.148	3.149	3.114	3.114	12.737	12.752	12.746	.388	.388	.389	.389
*T8	61.782	17.304	3.069	3.050	3.047	3.056	3.027	3.027	19.149	19.151	19.182	.258	.258	.246	.245
*T9	58.556	17.234	3.034	3.035	3.099	3.101	2.982	2.983	17.433	17.436	17.436	.311	.311	.320	.320
*T10	59.424	17.237	3.070	3.071	3.039	3.039	2.988	2.988	17.820	17.825	17.812	.300	.300	.296	.296
T11	52.867	17.180	3.137	3.137	3.133	3.133	3.115	3.114	12.935	12.932	12.920	.389	.389	.389	.389

Measurement Notes (use back of sheet if needed):

Note: * Tensile specimens L8, L9, L10, T8, T9, T10, were broke in such a way that it made it very difficult to line the specimens back up for inspection. The Conical indent marks were very faint and difficult to measure.

Date: 3/5/14

Tensile Specimen Dimensional Record Sheet (continuation)

Sheet 3 of 3

Measurement Operator Name: James Reseigh

Signature: [signature]

Specimen ID	OAL (mm)	C (mm)	W_1 (mm)		W_2 (mm)		W_C (mm)		GL (mm)			T_1 (mm)		T_2 (mm)	
			#1	#2	#1	#2	#1	#2	#1	#2	#3	#1	#2	#1	#2
T12	52.865	17.171	3.134	3.134	3.139	3.141	3.116	3.116	12.956	12.942	12.944	.387	.387	.387	.387
T13	52.919	17.214	3.134	3.134	3.129	3.129	3.116	3.116	12.957	12.958	12.948	.388	.388	.389	.389
T14	52.863	17.236	3.138	3.137	3.143	3.144	3.114	3.113	12.914	12.918	12.922	.385	.385	.384	.385

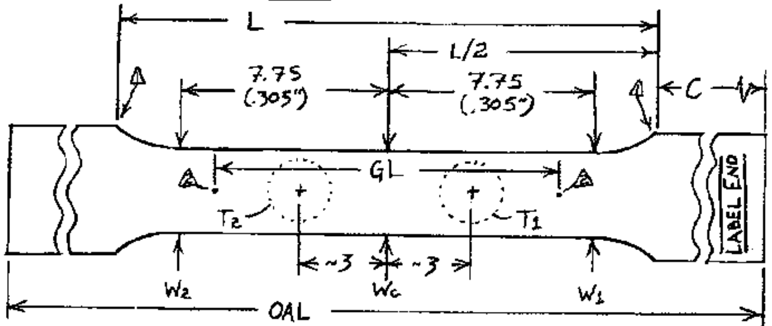
Measurement Notes (use back of sheet if needed):

Foil 551-2-2 Pre test Dimensions

Date: 11-6-13

Tensile Specimen Dimensional Record Sheet (continuation)

Sheet 1 of 2



Measurement Operator Name: James Reseigh Signature: [signature]

OAL measurement instrument ID: A678 Expiration Date: 4-11-14

GL measurement instrument ID: A678 Expiration Date: 4-11-14

W measurement instrument ID: A678 Expiration Date: 4-11-14

T measurement instrument ID: A31801 Expiration Date: 10-28-14

Temperature instrument ID: 730725 Expiration Date: 10-1-14

Start of Measurements: 19.6 °C End of Measurements: 19.6 °C

Delta 1. Reference positions for reduced section locations – corner at intersection of end tab and fillet. Locate center between corners (L/2) as zero position reference. It is not necessary to record dimension L.

Delta 2. Conical indent marks for GL measurement are small, less than 0.1 mm typical. Measure indents center-to-center three times with optical comparator. Reset reference zero for each measurement (three independent measurements).

1. Locations to measure are indicated in the diagram. All dimensions in mm except as indicated by (in.). Record measurements to 0.001 mm excepting "C" and "OAL."
2. Record dimension "C" to 0.01 mm resolution.
3. Record dimension "OAL" to 0.01 mm resolution. This can be measured with a caliper.
4. Measure W_1, W_2, and W_C two times. Reset width reference zero for each measurement (make two independent measurements at each location).
5. Measure thicknesses T_1 and T_2, twice at each location, approximately 3 mm either side of centerline. Measuring device contact surface should not cover the gage mark indent. Ball tip micrometer use is suggested for small contact area on indent face of specimen. Use minimum pressure needed to achieve consistent measurements.
6. Record room temperature before starting and after completion of each group of measurements.

Specimen ID	OAL (mm)	C (mm)	W_1 (mm)		W_2 (mm)		W_C (mm)		GL (mm)			T_1 (mm)		T_2 (mm)	
			#1	#2	#1	#2	#1	#2	#1	#2	#3	#1	#2	#1	#2
L1	50.589	15.381	3.136	3.136	3.139	3.139	3.115	3.116	12.800	12.796	12.798	.368	.368	.370	.370
L2															
L3															
L4															
L5	50.438	15.158	3.367	3.368	3.496	3.496	3.406	3.407	12.776	12.776	12.761	.386	.386	.386	.386
L6	50.438	15.109	3.149	3.148	3.139	3.138	3.121	3.121	12.763	12.767	12.769	.388	.388	.388	.388
L7	50.436	15.074	3.135	3.135	3.142	3.142	3.124	3.124	12.741	12.737	12.731	.390	.390	.391	.391
L8	50.429	15.061	3.144	3.144	3.148	3.148	3.137	3.137	12.734	12.737	12.735	.386	.386	.387	.388

L1 was tested on 16 oct 2013 so these Dimensions are post test values the rest are pre test values

Date: 11-6-13

Tensile Specimen Dimensional Record Sheet (continuation)

Sheet 2 of 2

Measurement Operator Name: James Roseigh   Signature: [signature]

Specimen ID	OAL (mm)	C (mm)	W_1 (mm)		W_2 (mm)		W_C (mm)		GL (mm)			T_1 (mm)		T_2 (mm)	
			#1	#2	#1	#2	#1	#2	#1	#2	#3	#1	#2	#1	#2
L9	50.434	15.009	3.160	3.160	3.137	3.137	3.129	3.129	12.741	12.742	12.739	.386	.386	.388	.388
L10	50.440	14.939	3.146	3.146	3.140	3.140	3.130	3.129	12.749	12.761	12.759	.386	.386	.386	.386
L11	50.437	14.944	3.136	3.136	3.142	3.142	3.121	3.120	12.752	12.748	12.755	.383	.383	.383	.383
L12	50.454	14.857	3.155	3.155	3.153	3.153	3.138	3.139	12.713	12.710	12.709	.378	.378	.378	.378
L13	50.466	14.844	3.154	3.154	3.146	3.145	3.136	3.136	12.743	12.743	12.741	.375	.375	.371	.371
L29	50.797	15.367	3.137	3.137	3.139	3.138	3.111	3.111	12.768	12.757	12.759	.374	.374	.374	.374
L30	50.799	15.408	3.144	3.144	3.150	3.150	3.120	3.119	12.681	12.673	12.676	.381	.381	.381	.381
L31	50.782	15.379	3.135	3.136	3.133	3.133	3.123	3.123	12.725	12.734	12.735	.381	.381	.383	.383
L32	50.775	15.421	3.151	3.151	3.145	3.144	3.124	3.124	12.740	12.747	12.748	.386	.386	.386	.386
L33	50.766	15.185	3.370	3.370	3.503	3.502	3.417	3.416	12.713	12.723	12.721	.391	.391	.391	.391
L34	50.768	15.136	3.151	3.151	3.139	3.140	3.128	3.129	12.744	12.745	12.751	.391	.391	.391	.391
L35	50.767	15.095	3.138	3.138	3.145	3.145	3.128	3.127	12.609	12.612	12.606	.391	.391	.392	.392
L36	50.770	15.081	3.147	3.147	3.144	3.145	3.134	3.135	12.687	12.674	12.679	.393	.393	.391	.391
L37	50.787	15.039	3.144	3.144	3.141	3.140	3.124	3.123	12.716	12.710	12.718	.391	.391	.391	.391
L38	50.789	14.984	3.152	3.152	3.150	3.150	3.139	3.139	12.713	12.718	12.720	.388	.388	.388	.388
L39	50.797	14.978	3.142	3.142	3.139	3.139	3.128	3.127	12.736	12.734	12.738	.387	.387	.386	.386
L40	50.815	14.926	3.161	3.160	3.156	3.156	3.138	3.138	12.731	12.742	12.743	.384	.384	.381	.381
L41	50.839	14.903	3.164	3.164	3.147	3.147	3.133	3.133	12.745	12.735	12.740	.376	.376	.376	.376

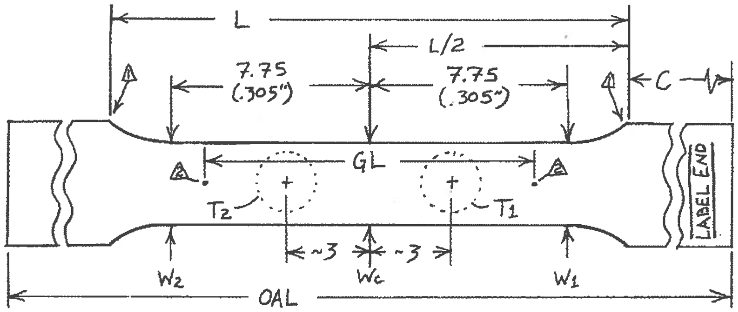
Measurement Notes (use back of sheet if needed):

Foil 551-3 Pre-Test Dimensions

Date: 5/1/14

Tensile Specimen Dimensional Record Sheet (continuation)

Sheet 1 of 2



Measurement Operator Name: James Reseigh Signature:

OAL measurement instrument ID: A678 Expiration Date: 4/9/15
GL measurement instrument ID: A678 Expiration Date: 4/9/15
W measurement instrument ID: A678 Expiration Date: 4/9/15
T measurement instrument ID: A609 Expiration Date: 11/13/14
Temperature instrument ID: A52393 Expiration Date: 6/24/14
Start of Measurements: 18.4C° End of Measurements: 18.3C°

Delta 1. Reference positions for reduced section locations – corner at intersection of end tab and fillet. Locate center between corners (L/2) as zero position reference. It is not necessary to record dimension L.
Delta 2. Conical indent marks for GL measurement are small, less than 0.1 mm typical. Measure indents center-to-center three times with optical comparator. Reset reference zero for each measurement (three independent measurements).

1. Locations to measure are indicated in the diagram. All dimensions in mm except as indicated by (in.). Record measurements to 0.001 mm excepting "C" and "OAL."
2. Record dimension "C" to 0.01 mm resolution.
3. Record dimension "OAL" to 0.01 mm resolution. This can be measured with a caliper.
4. Measure W_1, W_2, and W_C two times. Reset width reference zero for each measurement (make two independent measurements at each location).
5. Measure thicknesses T_1 and T_2, twice at each location, approximately 3 mm either side of centerline. Measuring device contact surface should not cover the gage mark indent. Ball tip micrometer use is suggested for small contact area on indent face of specimen. Use minimum pressure needed to achieve consistent measurements.
6. Record room temperature before starting and after completion of each group of measurements.

Specimen ID	OAL (mm)	C (mm)	W_1 (mm)		W_2 (mm)		W_C (mm)		GL (mm)			T_1 (mm)		T_2 (mm)	
			#1	#2	#1	#2	#1	#2	#1	#2	#3	#1	#2	#1	#2
L29	50.695	15.182	3.194	3.195	3.195	3.195	3.175	3.175	12.705	12.720	12.714	.374	.376	.376	.376
L30	50.690	15.354	3.198	3.198	3.195	3.195	3.174	3.174	12.712	12.710	12.706	.383	.383	.382	.382
L31	50.688	15.377	3.190	3.190	3.189	3.189	3.168	3.168	12.752	12.751	12.748	.384	.384	.383	.383
L32	50.696	15.348	3.192	3.193	3.189	3.189	3.175	3.175	12.709	12.708	12.701	.388	.388	.389	.389
L33	50.692	15.361	3.196	3.195	3.193	3.194	3.166	3.166	12.710	12.706	12.700	.390	.390	.391	.391
L34	50.688	15.329	3.190	3.190	3.190	3.191	3.167	3.167	12.770	12.774	12.780	.390	.390	.390	.391
L35	50.683	15.322	3.191	3.191	3.196	3.195	3.161	3.162	12.666	12.669	12.661	.391	.392	.392	.391
L36	50.682	15.293	3.190	3.190	3.189	3.189	3.173	3.174	12.753	12.754	12.758	.393	.393	.393	.393

Date: 5/1/14

Tensile Specimen Dimensional Record Sheet (continuation)

Measurement Operator Name: James Reseigh

Signature:

Specimen ID	OAL (mm)	C (mm)	W_1 (mm)		W_2 (mm)		W_C (mm)		GL (mm)			T_1 (mm)		T_2 (mm)	
			#1	#2	#1	#2	#1	#2	#1	#2	#3	#1	#2	#1	#2
L37	50.692	15.256	3.190	3.190	3.192	3.192	3.171	3.170	12.769	12.772	12.771	.390	.390	.391	.391
L38	50.698	15.325	3.200	3.200	3.196	3.195	3.167	3.167	12.728	12.730	12.738	.387	.387	.387	.387
L39	50.698	15.298	3.203	3.204	3.194	3.194	3.184	3.183	12.684	12.681	12.687	.387	.386	.387	.387
L40	50.700	15.280	3.184	3.184	3.185	3.186	3.169	3.169	12.720	12.721	12.725	.381	.381	.381	.381
L41	50.705	15.294	3.174	3.174	3.184	3.184	3.165	3.165	12.645	12.641	12.641	.378	378	.377	.378

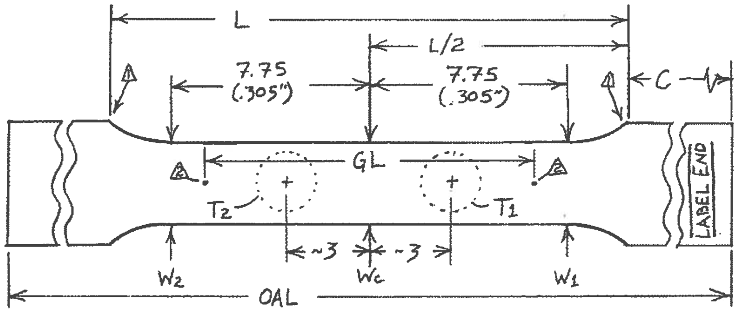
Measurement Notes (use back of sheet if needed):

Foil 551-3 Pre-Test Dimensions

Date: 4/14/14

Tensile Specimen Dimensional Record Sheet (continuation)

Sheet 1 of 3



Measurement Operator Name: James Reseigh Signature: [signature]

OAL measurement instrument ID: A678 Expiration Date: 4/9/15

GL measurement instrument ID: A678 Expiration Date: 4/9/15

W measurement instrument ID: A678 Expiration Date: 4/9/15

T measurement instrument ID: A609 Expiration Date: 11/13/14

Temperature instrument ID: A51610 Expiration Date: 10/22/14

Start of Measurements: 64.3C° End of Measurements: 67.8C°

Delta 1. Reference positions for reduced section locations – corner at intersection of end tab and fillet. Locate center between corners (L/2) as zero position reference. It is not necessary to record dimension L.

Delta 2. Conical indent marks for GL measurement are small, less than 0.1 mm typical. Measure indents center-to-center three times with optical comparator. Reset reference zero for each measurement (three independent measurements).

1. Locations to measure are indicated in the diagram. All dimensions in mm except as indicated by (in.). Record measurements to 0.001 mm excepting "C" and "OAL."
2. Record dimension "C" to 0.01 mm resolution.
3. Record dimension "OAL" to 0.01 mm resolution. This can be measured with a caliper.
4. Measure W_1, W_2, and W_C two times. Reset width reference zero for each measurement (make two independent measurements at each location).
5. Measure thicknesses T_1 and T_2, twice at each location, approximately 3 mm either side of centerline. Measuring device contact surface should not cover the gage mark indent. Ball tip micrometer use is suggested for small contact area on indent face of specimen. Use minimum pressure needed to achieve consistent measurements.
6. Record room temperature before starting and after completion of each group of measurements.

Specimen ID	OAL (mm)	C (mm)	W_1 (mm)		W_2 (mm)		W_C (mm)		GL (mm)			T_1 (mm)		T_2 (mm)	
			#1	#2	#1	#2	#1	#2	#1	#2	#3	#1	#2	#1	#2
L1	50.490	15.154	3.200	3.199	3.196	3.196	3.166	3.165	12.732	12.739	12.742	.366	.366	.365	.365
L2	50.456	15.081	3.196	3.195	3.202	3.202	3.190	3.190	12.713	12.712	12.703	.369	.369	.371	.371
L3	50.452	15.099	3.193	3.193	3.201	3.202	3.171	3.171	12.687	12.690	12.699	.377	.377	.375	.375
L4	50.441	15.086	3.194	3.194	3.186	3.187	3.167	3.166	12.753	12.765	12.750	.379	.379	.381	.381
L5	50.438	15.104	3.189	3.189	3.196	3.197	3.184	3.183	12.697	12.691	12.694	.385	.385	.386	.386
L6	50.440	15.078	3.193	3.192	3.191	3.191	3.166	3.166	12.672	12.672	12.679	.387	.387	.386	.386
L7	50.436	15.083	3.188	3.188	3.197	3.196	3.171	3.169	12.737	12.738	12.732	.386	.386	.385	.385
L8	50.437	15.113	3.204	3.205	3.193	3.193	3.184	3.183	12.747	12.746	12.757	.387	.387	.387	.387

Date: 4/14/14

Tensile Specimen Dimensional Record Sheet (continuation)

Sheet 2 of 3

Measurement Operator Name: James Reseigh

Signature:

Specimen ID	OAL (mm)	C (mm)	W_1 (mm)		W_2 (mm)		W_C (mm)		GL (mm)			T_1 (mm)		T_2 (mm)	
			#1	#2	#1	#2	#1	#2	#1	#2	#3	#1	#2	#1	#2
L9	50.440	15.104	3.191	3.192	3.187	3.188	3.164	3.165	12.688	12.682	12.680	.386	.386	.386	.386
L10	50.432	15.091	3.195	3.194	3.191	3.191	3.174	3.174	12.727	12.731	12.732	.384	.384	.384	.384
L11	50.422	15.093	3.199	3.199	3.186	3.185	3.167	3.167	12.768	12.776	12.778	.382	.382	.382	.382
L12	50.415	15.080	3.187	3.186	3.196	3.196	3.183	3.184	12.690	12.690	12.688	.378	.378	.378	.378
L13	50.416	15.084	3.195	3.195	3.193	3.193	3.186	3.187	12.714	12.713	12.717	.371	.371	.373	.373
T1	50.535	15.075	3.200	3.199	3.186	3.185	3.175	3.175	12.669	12.666	12.670	.387	.387	.388	.388
T2	50.542	15.093	3.199	3.200	3.195	3.195	3.177	3.177	12.686	12.691	12.682	.387	.387	.386	.386
T3	50.536	15.085	3.192	3.192	3.195	3.195	3.164	3.164	12.794	12.776	12.781	.388	.388	.389	.389
T4	50.529	15.051	3.194	3.194	3.189	3.190	3.176	3.176	12.712	12.711	12.718	.388	.388	.389	.389
T5	50.526	15.050	3.186	3.187	3.189	3.189	3.169	3.169	12.741	12.742	12.749	.386	.386	.388	.388
T6	50.529	15.066	3.184	3.184	3.190	3.190	3.162	3.161	12.689	12.696	12.694	.387	.387	.390	.390
T7	50.508	15.030	3.188	3.188	3.186	3.187	3.160	3.159	12.774	12.778	12.771	.387	.387	.390	.390
T8	50.493	15.004	3.191	3.191	3.193	3.192	3.167	3.168	12.643	12.640	12.638	.390	.390	.390	.390
T9	50.493	15.004	3.191	3.191	3.194	3.194	3.167	3.167	12.623	12.633	12.629	.389	.389	.387	.387
T10	50.472	14.988	3.185	3.186	3.189	3.189	3.161	3.161	12.861	12.850	12.856	.389	.389	.388	.388
T11	50.462	14.990	3.192	3.192	3.188	3.188	3.167	3.167	12.729	12.729	12.739	.390	.389	.390	.390
T12	50.456	14.946	3.189	3.189	3.195	3.196	3.169	3.169	12.730	12.728	12.730	.388	.389	.391	.391
T13	50.442	14.916	3.196	3.196	3.194	3.193	3.165	3.165	12.717	12.729	12.716	.390	.390	.390	.390
T14	50.435	14.908	3.180	3.180	3.190	3.190	3.167	3.166	12.749	12.756	12.747	.390	.390	.391	.391

Measurement Notes (use back of sheet if needed):

Date: 4/14/14

Tensile Specimen Dimensional Record Sheet (continuation)

Sheet 3 of 3

Measurement Operator Name: James Reseigh

Signature: [signature]

Specimen ID	OAL (mm)	C (mm)	W_1 (mm)		W_2 (mm)		W_C (mm)		GL (mm)			T_1 (mm)		T_2 (mm)	
			#1	#2	#1	#2	#1	#2	#1	#2	#3	#1	#2	#1	#2
T15	50.467	14.898	3.197	3.198	3.199	3.199	3.186	3.186	12.870	12.868	12.865	.390	.389	.390	.390
T16	50.478	14.920	3.193	3.193	3.185	3.184	3.168	3.169	12.736	12.742	12.752	.389	.389	.390	.391
T17	50.476	14.878	3.183	3.181	3.192	3.193	3.156	3.156	12.721	12.727	12.727	.388	.388	.389	.389
T18	50.478	14.886	3.190	3.190	3.186	3.186	3.165	3.164	12.722	12.726	12.737	.389	.389	.390	.389
T19	50.467	14.862	3.209	3.210	3.194	3.193	3.162	3.163	12.816	12.815	12.812	.389	.390	.390	.388

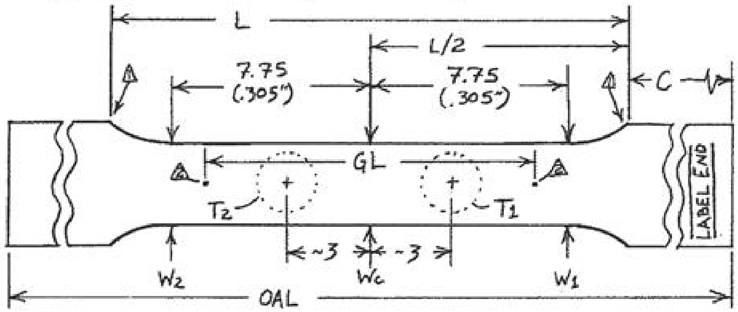
Measurement Notes (use back of sheet if needed):

Foil 551-3 Post Test Dimensions
Foil 551-5 Post Test Dimensions

Date: 7/9/14

Tensile Specimen Dimensional Record Sheet (continuation)

Sheet 1 of 3



Measurement Operator Name: James Reseigh Signature:

OAL measurement instrument ID: A678 Expiration Date: 4/9/15
GL measurement instrument ID: A678 Expiration Date: 4/9/15
W measurement instrument ID: A678 Expiration Date: 4/9/15
T measurement instrument ID: A609 Expiration Date: 11/13/14
Temperature instrument ID: A52393 Expiration Date: 6/23/15
Start of Measurements: 19.3C° End of Measurements: 19.0C°

Delta 1. Reference positions for reduced section locations – corner at intersection of end tab and fillet. Locate center between corners (L/2) as zero position reference. It is not necessary to record dimension L.

Delta 2. Conical indent marks for GL measurement are small, less than 0.1 mm typical. Measure indents center-to-center three times with optical comparator. Reset reference zero for each measurement (three independent measurements).

1. Locations to measure are indicated in the diagram. All dimensions in mm except as indicated by (in.). Record measurements to 0.001 mm excepting "C" and "OAL."
2. Record dimension "C" to 0.01 mm resolution.
3. Record dimension "OAL" to 0.01 mm resolution. This can be measured with a caliper.
4. Measure W_1, W_2, and W_C two times. Reset width reference zero for each measurement (make two independent measurements at each location).
5. Measure thicknesses T_1 and T_2, twice at each location, approximately 3 mm either side of centerline. Measuring device contact surface should not cover the gage mark indent. Ball tip micrometer use is suggested for small contact area on indent face of specimen. Use minimum pressure needed to achieve consistent measurements.
6. Record room temperature before starting and after completion of each group of measurements.

Specimen ID	OAL (mm)	C (mm)	W_1 (mm)		W_2 (mm)		W_C (mm)		GL (mm)			T_1 (mm)		T_2 (mm)	
			#1	#2	#1	#2	#1	#2	#1	#2	#3	#1	#2	#1	#2
551-3 L29	51.552	15.442	3.168	3.168	3.156	3.156	3.123	3.123	13.394	13.397	13.393	.370	.371	.371	.372
551-5 L1	52.211	15.544	3.126	3.126	3.130	3.129	2.879	2.879	14.082	14.084	14.085	.499	.500	.487	.487
L2	52.445	15.387	3.162	3.162	3.120	3.118	1.991	1.992	14.285	14.285	14.281	.518	.518	.506	.506
L3	52.387	15.416	3.148	3.148	3.131	3.132	2.916	2.195	14.239	14.240	14.238	.520	.520	.502	.502
L4	52.655	15.429	3.113	3.113	3.112	3.112	2.112	2.113	14.520	14.527	14.531	.520	.519	.507	.506
L5	51.351	15.417	3.185	3.186	3.190	3.190	3.150	3.149	13.292	13.299	13.293	.498	.498	.504	.504
L6	51.687	15.378	3.166	3.165	3.134	3.134	3.130	3.130	13.592	13.587	13.587	.509	.510	.512	.512
L10	55.825	15.466	3.026	3.025	2.986	2.986	2.768	2.767	17.307	17.293	17.292	.424	.424	.428	.428

Date: 7/9/14

Tensile Specimen Dimensional Record Sheet (continuation)

Sheet 2 of 3

Measurement Operator Name: James Reseigh

Signature:

Specimen ID	OAL (mm)	C (mm)	W_1 (mm)		W_2 (mm)		W_C (mm)		GL (mm)			T_1 (mm)		T_2 (mm)	
			#1	#2	#1	#2	#1	#2	#1	#2	#3	#1	#2	#1	#2
L11	57.060	15.482	2.982	2.982	2.977	2.977	2.737	2.737	18.144	18.452	18.140	.416	.416	.406	.407
L12	56.576	15.432	3.044	3.044	2.907	2.907	2.762	2.762	17.789	17.785	17.776	.430	.430	.409	.409
T1	50.871	15.347	3.217	3.217	3.229	3.229	3.195	3.195	12.863	12.861	12.860	.532	.532	.543	.543
T2	50.909	15.340	3.175	3.174	3.172	3.172	3.156	3.156	12.864	12.865	12.867	.545	.545	.544	.545
T3	50.832	15.383	3.196	3.196	3.182	3.182	3.163	3.162	12.861	12.871	12.863	.547	.547	.544	.544
T4	51.066	15.380	3.184	3.183	3.188	3.189	3.161	3.161	12.946	12.941	12.941	.537	.537	.537	.537
T5	51.202	15.391	3.194	3.194	3.176	3.174	3.159	3.158	13.118	13.115	13.122	.536	.536	.537	.537
T6	51.440	15.375	3.183	3.183	3.181	3.181	3.162	3.161	13.359	13.360	13.359	.537	.537	.530	.530
T10	57.439	15.487	2.955	2.957	3.003	3.003	2.798	2.799	18.597	18.594	18.583	.404	.404	.365	.366
T11	57.278	15.431	2.993	2.992	3.006	3.006	2.882	2.883	18.527	18.523	18.531	.396	.396	.415	.415
T12	57.620	15.448	2.979	2.978	3.036	3.036	2.918	2.918	18.702	18.710	18.691	.400	.400	.430	.430
551-3 L1	51.680	15.138	3.159	3.159	3.158	3.157	2.965	2.966	13.830	13.833	13.835	.358	.358	.357	.357
L2	51.718	15.142	3.144	3.143	3.155	3.155	2.975	2.974	13.862	13.855	13.850	.356	.356	.363	.363
L3	51.710	15.156	3.171	3.171	3.156	3.156	2.990	2.990	13.845	13.842	13.843	.361	.361	.369	.369
L4	52.398	15.232	3.104	3.105	3.104	3.102	3.014	3.014	14.473	14.475	14.484	.363	.363	.361	.361
L5	52.419	15.138	3.049	3.049	3.115	3.115	3.059	3.058	14.343	14.340	14.342	.362	.362	.370	.370
L6	52.351	15.125	3.088	3.088	3.110	3.111	3.012	3.013	14.471	14.483	14.475	.362	.362	.371	.369
L7	51.083	15.100	3.170	3.169	3.163	3.164	3.117	3.117	13.203	13.198	13.206	.380	.380	.384	.384
L8	51.093	15.114	3.129	3.129	3.193	3.193	3.151	3.151	13.145	13.143	13.149	.385	.385	.385	.385
L9	51.409	15.107	3.180	3.179	3.079	3.079	3.129	3.130	13.106	13.110	13.114	.384	.384	.384	.384

Measurement Notes (use back of sheet if needed):

Date: 7/9/14

Tensile Specimen Dimensional Record Sheet (continuation)

Sheet 3 of 3

Measurement Operator Name: James Reseigh

Signature: [signature]

Specimen ID	OAL (mm)	C (mm)	W_1 (mm)		W_2 (mm)		W_C (mm)		GL (mm)			T_1 (mm)		T_2 (mm)	
			#1	#2	#1	#2	#1	#2	#1	#2	#3	#1	#2	#1	#2
L10	60.781	15.424	2.778	2.779	2.980	2.979	2.528	2.528	21.465	21.465	21.474	.251	.251	.278	.278
L11	59.039	15.300	2.834	2.833	2.995	2.993	2.357	2.356	20.294	20.289	20.286	.266	.265	.290	.293
L12	61.740	15.133	2.880	2.879	2.831	2.830	2.111	2.110	22.488	22.486	22.494	.270	.270	.270	.270
L13	51.338	15.105	3.155	3.155	3.156	3.157	3.088	3.089	13.457	13.452	13.456	.373	.373	.375	.375
551-3 T1	51.613	15.078	3.151	3.150	3.148	3.148	3.080	3.079	13.628	13.624	13.626	.376	.375	.385	.384
T2	51.623	15.105	3.134	3.133	3.157	3.157	3.087	3.087	13.650	13.651	13.647	.376	.376	.383	.383
T3	51.568	15.085	3.128	3.128	3.159	3.159	3.089	3.088	13.673	13.673	13.672	.380	.380	.383	.384
T4	52.281	15.073	3.063	3.063	3.086	3.087	3.039	3.039	14.260	14.242	14.237	.378	.378	.372	.372
T5	52.813	15.076	3.099	3.098	3.029	3.029	2.959	2.959	14.778	14.767	14.769	.372	.372	.369	.369
T6	52.367	15.166	3.039	3.038	3.130	3.130	3.037	3.068	14.249	14.241	14.247	.376	.376	.383	.383
*T7	See	Note													
T8	51.337	15.038	3.191	3.191	3.199	3.199	3.116	3.115	13.301	13.314	13.307	.388	.388	.391	.391
T9	51.185	15.029	3.165	3.165	3.172	3.173	3.108	3.107	13.408	13.406	13.409	.389	.389	.394	.394
T10	60.966	15.119	2.952	2.952	2.842	2.843	2.587	2.589	21.592	21.597	21.589	.267	.267	.254	.254
T11	59.841	15.092	2.922	2.922	2.918	2.917	2.447	2.445	20.657	20.672	20.672	.257	.258	.288	.287
T12	60.510	15.070	2.902	2.902	2.922	2.922	2.631	2.631	21.206	21.203	21.195	.254	.254	.291	.291
T13	51.410	14.929	3.151	3.152	3.170	3.169	3.127	3.126	13.506	13.504	13.505	.391	.391	.390	.390

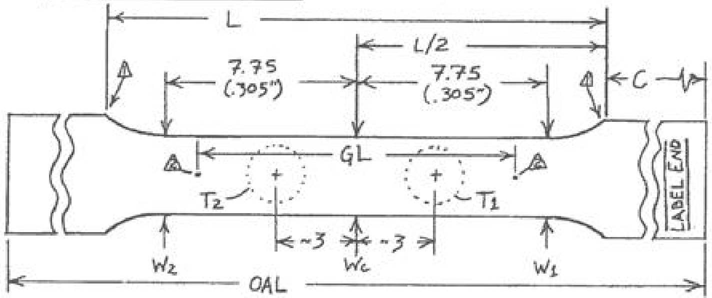
Measurement Notes (use back of sheet if needed): T7 Broke in 3 pieces not able to get accurate measurements without additional fixturing.

Foil 551-4 Pre-Test Dimensions

Date: 2-13-14

Tensile Specimen Dimensional Record Sheet (continuation)

Sheet 1 of 5



Measurement Operator Name: James Reseigh Signature: [signature]

OAL measurement instrument ID: A678 Expiration Date: 4-11-14

GL measurement instrument ID: A678 Expiration Date: 4-11-14

W measurement instrument ID: A678 Expiration Date: 4-11-14

T measurement instrument ID: A609 Expiration Date: 11-13-14

Temperature instrument ID: A51610 Expiration Date: 10-22-14

Start of Measurements: 19.4C End of Measurements: 18.6 C

Delta 1. Reference positions for reduced section locations – corner at intersection of end tab and fillet. Locate center between corners (L/2) as zero position reference. It is not necessary to record dimension L.

Delta 2. Conical indent marks for GL measurement are small, less than 0.1 mm typical. Measure indents center-to-center three times with optical comparator. Reset reference zero for each measurement (three independent measurements).

1. Locations to measure are indicated in the diagram. All dimensions in mm except as indicated by (in.). Record measurements to 0.001 mm excepting "C" and "OAL."
2. Record dimension "C" to 0.01 mm resolution.
3. Record dimension "OAL" to 0.01 mm resolution. This can be measured with a caliper.
4. Measure W_1, W_2, and W_C two times. Reset width reference zero for each measurement (make two independent measurements at each location).
5. Measure thicknesses T_1 and T_2, twice at each location, approximately 3 mm either side of centerline. Measuring device contact surface should not cover the gage mark indent. Ball tip micrometer use is suggested for small contact area on indent face of specimen. Use minimum pressure needed to achieve consistent measurements.
6. Record room temperature before starting and after completion of each group of measurements.

Specimen ID	OAL (mm)	C (mm)	W_1 (mm)		W_2 (mm)		W_C (mm)		GL (mm)			T_1 (mm)		T_2 (mm)	
			#1	#2	#1	#2	#1	#2	#1	#2	#3	#1	#2	#1	#2
T1	50,630	15.260	3.038	3.038	3.045	3.045	3.009	3.008	12.763	12.751	12.754	,389	,389	,388	,388
T2	50.593	15.369	3.198	3.198	3.198	3.197	3.171	3.172	12.766	12.772	12.770	,389	.388	.389	.389
T3	50.621	15.365	3.184	3.184	3.198	3.199	3.165	3.165	12.747	12.760	12.762	.390	,390	.389	.389
T4	50.740	15.362	3.191	3.191	3.200	3.200	3.166	3.166	12.727	12.719	12.717	,389	,389	,388	,388
T5	50.704	15.349	3.192	3.192	3.201	3.201	3.169	3.170	12.780	12.783	12.771	,390	,390	.387	.387
T6	50.741	15.371	3.186	3.186	3.181	3.181	3.166	3.165	12.791	12.793	12.793	.390	.390	.390	.390
T7	50.795	15.368	3.187	3.187	3.195	3.195	3.163	3.164	12.757	12.743	12.744	.390	,390	.388	.388
T8	50.827	15.360	3.196	3.195	3.191	3.191	3.161	3.161	12.758	12.748	12.745	,390	,390	.389	.389

Date: 2-13-14

Tensile Specimen Dimensional Record Sheet (continuation)

Measurement Operator Name: James Reseigh

Signature: [signature]

Specimen ID	OAL (mm)	C (mm)	W_1 (mm)		W_2 (mm)		W_C (mm)		GL (mm)			T_1 (mm)		T_2 (mm)	
			#1	#2	#1	#2	#1	#2	#1	#2	#3	#1	#2	#1	#2
T9	50.870	15.355	3.184	3.184	3.179	3.179	3.154	3.154	12.779	12.781	12.783	.388	.388	.389	.389
T10	50.875	15.336	3.184	3.184	3.192	3.191	3.152	3.152	12.785	12.774	12.777	.391	.391	.390	.391
T11	51.019	15.501	3.173	3.173	3.185	3.185	3.157	3.157	12.722	12.718	12.717	.391	.391	.391	.391
T12	51.060	15.497	3.182	3.183	3.178	3.178	3.151	3.151	12.712	12.711	12.717	.391	.391	.389	.389
T13	51.113	15.497	3.175	3.174	3.175	3.175	3.156	3.156	12.727	12.722	12.710	.391	.391	.391	.391
T14	51.310	15.510	3.198	3.198	3.185	3.186	3.182	3.183	12.715	12.717	12.709	.390	.390	.390	.390
T15	51.152	15.488	3.184	3.183	3.183	3.183	3.160	3.160	12.724	12.715	12.713	.390	.390	.390	.390
T16	51.152	15.494	3.187	3.186	3.186	3.185	3.160	3.161	12.714	12.709	12.705	.392	.391	.391	.390
T17	51.170	15.492	3.182	3.183	3.174	3.174	3.163	3.165	12.650	12.651	12.653	.391	.391	.390	.390
T18	51.169	15.495	3.178	3.178	3.183	3.183	3.164	3.164	12.709	12.718	12.719	.391	.391	.390	.390
T19	51.180	15.522	3.167	3.167	3.155	3.156	3.155	3.156	12.691	12.690	12.694	.390	.390	.389	.389
T20	53.360	15.362	3.186	3.186	3.185	3.185	3.163	3.163	12.700	12.713	12.708	.393	.393	.393	.393
T21	53.340	15.347	3.189	3.190	3.182	3.182	3.156	3.156	12.681	12.689	12.686	.394	.394	.391	.391
T22	53.311	15.334	3.178	3.176	3.173	3.173	3.159	3.159	12.783	12.790	12.785	.392	.393	.391	.393
T23	53.326	15.319	3.170	3.170	3.170	3.171	3.156	3.157	12.682	12.670	12.684	.393	.394	.393	.393
T24	53.240	15.327	3.174	3.174	3.178	3.178	3.162	3.161	12.603	12.597	12.598	.391	.391	.393	.393
T25	53.320	15.308	3.176	3.176	3.174	3.175	3.156	3.155	12.728	12.733	12.735	.394	.393	.393	.393
T26	53.200	15.303	3.168	3.169	3.174	3.174	3.150	3.151	12.737	12.729	12.726	.392	.391	.392	.392
T27	53.235	15.278	3.179	3.179	3.173	3.173	3.158	3.158	12.672	12.678	12.671	.393	.393	.392	.392
T28	53.240	15.283	3.171	3.171	3.178	3.179	3.148	3.148	12.839	12.833	12.831	.393	.393	.391	.391

Measurement Notes (use back of sheet if needed):

Date: 2-13-14

Tensile Specimen Dimensional Record Sheet (continuation)

Sheet 3 of 5

Measurement Operator Name: [illegible]

Signature:

Specimen ID	OAL (mm)	C (mm)	W_1 (mm)		W_2 (mm)		W_C (mm)		GL (mm)			T_1 (mm)		T_2 (mm)	
			#1	#2	#1	#2	#1	#2	#1	#2	#3	#1	#2	#1	#2
T29	53.195	15.278	3.183	3.183	3.174	3.175	3.160	3.160	12.681	12.685	12.679	.394	.393	.392	.392
T30	53.251	15.241	3.169	3.170	3.173	3.173	3.153	3.153	12.677	12.679	12.675	.393	.393	.393	.393
T31	53.147	15.247	3.177	3.176	3.176	3.176	3.149	3.149	12.751	12.742	12.741	.393	.393	.393	.393
T32	53.220	15.235	3.167	3.167	3.173	3.173	3.147	3.146	12.773	12.775	12.782	.392	.392	.390	.390
T33	52.828	15.240	3.177	3.176	3.176	3.174	3.170	3.170	12.741	12.736	12.725	.390	.390	.390	.391
T34	53.059	15.240	3.170	3.169	3.186	3.185	3.159	3.158	12.737	12.729	12.723	.393	.393	.392	.393
T35	53.143	15.217	3.169	3.169	3.182	3.182	3.160	3.160	12.645	12649	12.647	.391	.391	.391	.391
T36	53.057	15.218	3.176	3.175	3.184	3.184	3.144	3.144	12.666	12.670	12.667	.392	.392	.393	.392
T37	53.080	15.206	3.171	3.172	3.186	3.187	3.158	3.158	12.831	12.827	12.822	.392	.392	.391	.392
T38	53.146	15.109	3.150	3.150	3.149	3.149	3.164	3.167	12.731	12.732	12.745	.393	.393	.392	.392
L1	50.244	15.412	3.208	3.207	3.206	3.206	3.168	3.167	12.760	12.769	12.760	.373	.373	.373	.372
L2	50.211	15.398	3.185	3.184	3.186	3.186	3.171	3.171	12.761	12.755	12.762	.377	.377	.378	.378
L3	50.185	15.404	3.181	3.181	3.176	3.176	3.160	3.160	12.756	12.758	12.760	.381	.381	.381	.382
L4	50.183	15.394	3.176	3.177	3.177	3.178	3.151	3.152	12.784	12.770	12.775	.386	.386	.386	.386
L5	50.180	15.417	3.181	3.181	3.191	3.190	3.152	3.151	12.839	12.854	12.859	.386	.386	.387	.386
L6	50.179	15.408	3.180	3.180	3.172	3.172	3.155	3.155	12.738	12.727	12.723	.389	.389	.389	.389
L7	50.180	15.401	3.182	3.182	3.182	3.183	3.154	3.154	12.702	12.696	12.694	.388	.388	.390	.390
L8	50.182	15.399	3.188	3.188	3.185	3.185	3.160	3.159	12.739	12.744	12.749	.388	.388	.390	.390
L9	50.181	15.385	3.180	3.180	3.177	3.177	3.155	3.155	12.712	12.704	12.713	.386	.386	.386	.386

Measurement Notes (use back of sheet if needed):

T38 Has a raised section in the middle of specimen

Date: 2-13-14

Tensile Specimen Dimensional Record Sheet (continuation)

Measurement Operator Name: James Reseigh   Signature: [signature]

Specimen ID	OAL (mm)	C (mm)	W_1 (mm)		W_2 (mm)		W_C (mm)		GL (mm)			T_1 (mm)		T_2 (mm)	
			#1	#2	#1	#2	#1	#2	#1	#2	#3	#1	#2	#1	#2
L10	50.192	15.403	3.191	3.191	3.178	3.178	3.154	3.153	12.716	12.719	12.715	.386	.386	.387	.387
L11	56.195	15.405	3.190	3.190	3.181	3.181	3.159	3.158	12.731	12.729	12.732	.384	.384	.386	.386
L12	50.196	15.403	3.190	3.190	3.181	3.180	3.172	3.172	12.709	12.709	12.714	.383	.383	.382	.382
L13	50.197	15.412	3.186	3.186	3.185	3.185	3.171	3.170	12.794	12.798	12.791	.377	.377	.378	.378
L14	50.201	15.394	3.189	3.189	3.187	3.188	3.161	3.161	12.775	12.764	12.769	.370	.370	.369	.369
L15	50.888	15.385	3.203	3.204	3.193	3.192	3.161	3.161	12.813	12.807	12.797	.387	.387	.387	.387
L16	50.877	15.376	3.148	3.149	3.139	3.140	3.120	3.121	12.700	12.701	12.700	.384	.384	.383	.383
L17	50.877	15.420	3.156	3.156	3.141	3.140	3.125	3.124	12.644	12.651	12.644	.378	.378	.378	.378
L17A	50.857	15.625	3.182	3.181	3.180	3.180	3.161	3.161	12.841	12.834	12.827	.374	.374	.374	.374
L18	50.461	15.417	3.190	3.191	3.707	3.206	3.171	3.172	12.746	12.745	12.736	.386	.386	.386	.386
L19	50.456	15.397	3.189	3.189	3.193	3.193	3.172	3.172	12.718	12.723	12.727	.385	.385	.386	.385
L20	50.465	15.399	3.190	3.190	3.192	3.193	3.158	3.157	12.840	12.848	12.843	.377	.377	.379	.379
L21	50.460	15.382	3.181	3.180	3.197	3.196	3.153	3.153	12.605	12.599	12.598	.372	.372	.373	.373
L22	50.587	15.539	3.201	3.202	3.191	3.191	3.169	3.168	12.676	12.667	12.670	.374	.374	.374	.374
L23	50.578	15.588	3.186	3.186	3.187	3.187	3.159	3.159	12.800	12.788	12.787	.382	.382	.382	.382
L24	50.556	15.578	3.186	3.186	3.181	3.181	3.161	3.161	12.781	12.792	12.781	.385	.384	.386	.385
L25	50.531	15.642	3.174	3.173	3.178	3.179	3.154	3.154	12.729	12.730	12.732	.388	.388	.390	.391
L26	50.729	15.391	3.184	3.184	3.187	3.187	3.163	3.163	12.757	12.751	12.749	.372	.373	.372	.374
L27	50.721	15.404	3.188	3.188	3.184	3.184	3.163	3.163	12.727	12.723	12.739	.383	.384	.384	.384
L28	50.700	15.389	3.192	3.191	3.193	3.193	3.163	3.161	12.735	12.744	12.748	.385	.385	.385	.385

Measurement Notes (use back of sheet if needed):

L25 Has one side that is almost flat, very little cut out.

Date: 2-13-14

Tensile Specimen Dimensional Record Sheet (continuation)

Measurement Operator Name: James Reseigh

Signature: [signature]

Specimen ID	OAL (mm)	C (mm)	W_1 (mm)		W_2 (mm)		W_C (mm)		GL (mm)			T_1 (mm)		T_2 (mm)	
			#1	#2	#1	#2	#1	#2	#1	#2	#3	#1	#2	#1	#2
L29	50.677	15.368	3.192	3.193	3.187	3.187	3.158	3.158	12.722	12.727	12.728	.389	.389	.390	.389
*L29	50.477	15.267	3.188	3.187	3.193	3.192	3.166	3.166	12.762	12.757	12.753	.373	.373	.374	.374
L30	50.492	15.271	3.190	3.189	3.184	3.184	3.157	3.157	12.757	12.756	12.750	.382	.382	.383	.383
L31	50.470	15.223	3.177	3.177	3.192	3.191	3.157	3.157	12.738	12.741	12.738	.386	.386	.387	.387
~~L32~~	~~50.463~~	~~15.221~~	~~3.190~~	~~3.189~~	~~3.176~~	~~3.176~~	~~3.156~~	~~3.157~~	~~12.472~~	~~12.472~~	~~12.468~~	~~.390~~	~~.390~~	~~.390~~	~~.390~~ JR
L33	50.486	15.204	3.191	3.190	3.186	3.186	3.159	3.160	12.732	12.723	12.730	.392	.392	.390	.391
L34	50.583	15.186	3.188	3.189	3.184	3.183	3.161	3.161	12.757	12.756	12.754	.392	.392	.392	.392
L35	50.589	15.160	3.187	3.187	3.177	3.178	3.153	3.154	12.764	12.760	12.757	.394	.394	.395	.395
L36	50.592	15.180	3.181	3.182	3.173	3.173	3.160	3.160	12.736	12.738	12.739	.394	.394	.395	.395
L37	50.596	15.167	3.181	3.179	3.182	3.182	3.166	3.165	12.703	12.711	12.710	.394	.394	.394	.394
L38	50.601	15.145	3.187	3.185	3.187	3.187	3.162	3.161	12.888	12.894	12.892	.393	.393	.393	.393
L39	50.596	15.128	3.062	3.061	3.063	3.063	3.037	3.038	12.717	12.718	12.714	.389	.389	.389	.389
L40	50.593	15.115	3.078	3.078	3.067	3.066	3.044	3.045	12.822	12.828	12.820	.387	.387	.387	.387
L41	50.608	15.226	3.082	3.082	3.083	3.084	3.050	3.050	12.736	12.740	12.746	.384	.384	.384	.384
L42	50.672	15.219	3.100	3.100	3.095	3.094	3.084	3.085	12.689	12.690	12.690	.375	.375	.376	.376
L32	50.463	15.221	3.190	3.189	3.176	3.176	3.156	3.157	12.742	12.742	12.768	.390	.390	.390	.390

Measurement Notes (use back of sheet if needed):

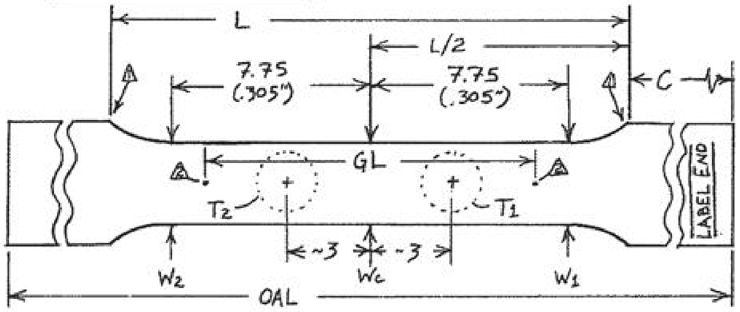
2 L29's * from Bag with unique ID A-551-4-1-L6

551-4 Post Test Dimensions

Date: 3/24/14

Tensile Specimen Dimensional Record Sheet (continuation)

Sheet 1 of 2



Measurement Operator Name: James Reseigh   Signature:

OAL measurement instrument ID: A678   Expiration Date: 4/11/14
GL measurement instrument ID: A678   Expiration Date: 4/11/14
W measurement instrument ID: A678   Expiration Date: 4/11/14
T measurement instrument ID: A609   Expiration Date: 11/13/14
Temperature instrument ID: A51610   Expiration Date: 10/22/14
Start of Measurements: 18.6°C   End of Measurements: 19.5°C

Delta 1. Reference positions for reduced section locations – corner at intersection of end tab and fillet. Locate center between corners (L/2) as zero position reference. It is not necessary to record dimension L.
Delta 2. Conical indent marks for GL measurement are small, less than 0.1 mm typical. Measure indents center-to-center three times with optical comparator. Reset reference zero for each measurement (three independent measurements).

1. Locations to measure are indicated in the diagram. All dimensions in mm except as indicated by (in.). Record measurements to 0.001 mm excepting "C" and "OAL."
2. Record dimension "C" to 0.01 mm resolution.
3. Record dimension "OAL" to 0.01 mm resolution. This can be measured with a caliper.
4. Measure W_1, W_2, and W_C two times. Reset width reference zero for each measurement (make two independent measurements at each location).
5. Measure thicknesses T_1 and T_2, twice at each location, approximately 3 mm either side of centerline. Measuring device contact surface should not cover the gage mark indent. Ball tip micrometer use is suggested for small contact area on indent face of specimen. Use minimum pressure needed to achieve consistent measurements.
6. Record room temperature before starting and after completion of each group of measurements.

Specimen ID	OAL (mm)	C (mm)	W_1 (mm)		W_2 (mm)		W_C (mm)		GL (mm)			T_1 (mm)		T_2 (mm)	
			#1	#2	#1	#2	#1	#2	#1	#2	#3	#1	#2	#1	#2
L1	51.098	15.433	3.172	3.172	3.176	3.176	3.063	3.063	13.560	13.558	13.545	.366	.366	.371	.371
L2	51.049	15.419	3.170	3.171	3.156	3.155	3.091	3.091	13.485	13.489	13.493	.369	.369	.374	.374
L3	50.990	15.411	3.158	3.159	3.160	3.159	3.079	3.078	13.482	13.478	13.479	.375	.375	.381	.381
L4	50.598	15.413	3.172	3.172	3.171	3.172	3.127	3.127	13.151	13.147	13.147	.383	.383	.385	.384
L5	50.582	15.370	3.165	3.165	3.173	3.173	3.099	3.100	13.222	13.217	13.216	.386	.386	.387	.386
L6	50.597	15.417	3.178	3.177	3.165	3.165	3.076	3.077	13.101	13.103	13.112	.388	.388	.387	.387
*L10	57.920	15.684	3.011	3.012	2.963	2.963	2.580	2.581	19.161	19.163	19.159	.281	.281	.283	.283
*L11	57.091	15.627	3.024	3.025	3.004	3.005	2.769	2.769	18.329	18.315	18.300	.304	.304	.293	.293

Date: 3/24/14

Tensile Specimen Dimensional Record Sheet (continuation)

Sheet 2 of 2

Measurement Operator Name: James Reseigh

Signature: [signature]

Specimen ID	OAL (mm)	C (mm)	W1 (mm)		W2 (mm)		Wc (mm)		GL (mm)			T1 (mm)		T2 (mm)	
			#1	#2	#1	#2	#1	#2	#1	#2	#3	#1	#2	#1	#2
*L12	59.436	15.593	3.022	3.020	2.967	2.968	2.608	2.608	20.226	20.257	20.274	.292	.292	.278	.278
*L13	57.023	15.651	2.977	2.978	3.080	3.080	2.644	2.645	18.361	18.338	18.351	.299	.299	.306	.306
T1	50.612	15.312	3.025	3.026	3.035	3.035	2.991	2.991	13.038	13.028	13.038	.386	.386	.385	.384
T2	50.809	15.375	3.189	3.188	3.185	3.185	3.156	3.157	12.972	12.985	12.968	.387	.387	.388	.388
T3	50.767	15.409	3.179	3.179	3.180	3.180	3.155	3.154	12.886	12.879	12.889	.389	.389	.387	.387
T4	51.249	15.368	3.170	3.170	3.156	3.155	3.133	3.134	13.215	13.218	13.225	.387	.387	.385	.385
T5	51.241	15.361	3.160	3.160	3.167	3.167	3.090	3.090	13.247	13.239	13.228	.386	.386	.385	.386
T6	51.322	15.409	3.170	3.170	3.109	3.108	3.132	3.132	12.963	12.972	12.968	.385	.385	.385	.385
T7	51.039	15.353	3.174	3.175	3.175	3.174	3.130	3.129	12.937	12.950	12.946	.389	.390	.386	.388
*T10	55.000	15.522	3.115	3.114	3.145	3.144	2.914	2.915	16.024	16.024	16.034	.308	.309	.326	.327
*T11	57.751	15.656	3.028	3.027	3.047	3.047	2.749	2.749	18.194	18.206	18.198	.289	.290	.301	.301
*T12	56.542	15.647	3.076	3.078	3.014	3.015	2.817	2.817	16.887	16.867	16.861	.317	.317	.333	.333

Measurement Notes (use back of sheet if needed):

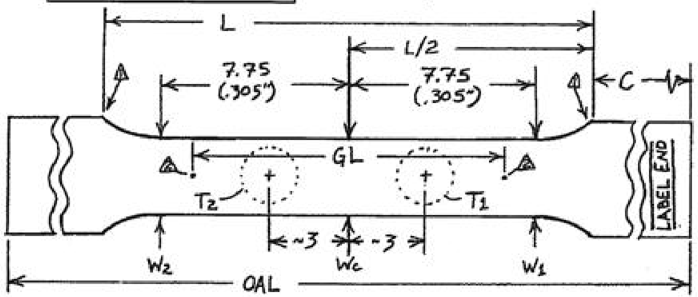
Note: * Tensile specimens L10, L11, L12, L13, T10, T11, T12, were broke in such a way that it made it very difficult to line the specimens back up for inspection. The Conical indent marks were very faint and difficult to measure.

Foil 551-4 Post Test Dimensions
Foil 551-5 Post Test Dimensions

Date: 7/23/14

Tensile Specimen Dimensional Record Sheet (continuation)

Sheet 1 of 1



Measurement Operator Name: James Reseigh Signature:

OAL measurement instrument ID: A678 Expiration Date: 4/9/15
GL measurement instrument ID: A678 Expiration Date: 4/9/15
W measurement instrument ID: A678 Expiration Date: 4/9/15
T measurement instrument ID: A609 Expiration Date: 11/13/14
Temperature instrument ID: A52393 Expiration Date: 6/23/15
Start of Measurements: 20.1C° End of Measurements: 20.1C°

Delta 1. Reference positions for reduced section locations – corner at intersection of end tab and fillet. Locate center between corners (L/2) as zero position reference. It is not necessary to record dimension L.

Delta 2. Conical indent marks for GL measurement are small, less than 0.1 mm typical. Measure indents center-to-center three times with optical comparator. Reset reference zero for each measurement (three independent measurements).

1. Locations to measure are indicated in the diagram. All dimensions in mm except as indicated by (in.). Record measurements to 0.001 mm excepting "C" and "OAL."
2. Record dimension "C" to 0.01 mm resolution.
3. Record dimension "OAL" to 0.01 mm resolution. This can be measured with a caliper.
4. Measure W_1, W_2, and W_C two times. Reset width reference zero for each measurement (make two independent measurements at each location).
5. Measure thicknesses T_1 and T_2, twice at each location, approximately 3 mm either side of centerline. Measuring device contact surface should not cover the gage mark indent. Ball tip micrometer use is suggested for small contact area on indent face of specimen. Use minimum pressure needed to achieve consistent measurements.
6. Record room temperature before starting and after completion of each group of measurements.

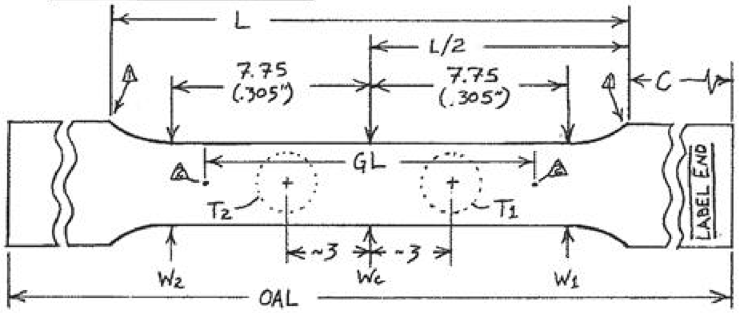
Specimen ID	OAL (mm)	C (mm)	W_1 (mm)		W_2 (mm)		W_C (mm)		GL (mm)			T_1 (mm)		T_2 (mm)	
			#1	#2	#1	#2	#1	#2	#1	#2	#3	#1	#2	#1	#2
551-5 L7	52.039	15.436	3.156	3.155	3.157	3.156	3.099	3.100	13.819	13.824	13.820	.526	.526	.528	.528
L8	52.116	15.468	3.157	3.157	3.138	3.140	3.102	3.103	13.775	13.773	13.778	.527	.527	.525	.525
L9	52.382	15.436	3.141	3.142	3.135	3.136	3.092	3.092	14.119	14.118	14.108	.525	.525	.523	.523
551-5 T13	51.936	15.393	3.159	3.158	3.151	3.151	3.122	3.122	13.764	13.748	13.758	.534	.534	.535	.535
551-4 L7	50.634	15.350	3.181	3.180	3.183	3.183	3.112	3.112	13.051	13.063	13.060	.393	.393	.394	.394
L8	50.575	15.398	3.207	3.206	3.190	3.190	3.178	3.178	13.053	13.045	13.049	.391	.391	.394	.394
*L9	50.549	15.412	3.187	3.187	3.187	3.188	3.168	3.166	12.806	12.790	12.803	.389	.389	.391	.391

Measurement Notes (use back of sheet if needed): * 551-4-L9 Specimen broke at Conical indent mark. GL measurement difficult to align on indent mark.

Foil 551-5 Pre Test Dimensions

Date: 5/12/14

Tensile Specimen Dimensional Record Sheet (continuation)



Measurement Operator Name: James Reseigh Signature:

OAL measurement instrument ID: A678 Expiration Date: 4/9/15
GL measurement instrument ID: A678 Expiration Date: 4/9/15
W measurement instrument ID: A678 Expiration Date: 4/9/15
T measurement instrument ID: A609 Expiration Date: 11/13/14
Temperature instrument ID: A52393 Expiration Date: 6/24/14
Start of Measurements: 22.0C˚ End of Measurements: 19.5C˚

Delta 1. Reference positions for reduced section locations – corner at intersection of end tab and fillet. Locate center between corners (L/2) as zero position reference. It is not necessary to record dimension L.
Delta 2. Conical indent marks for GL measurement are small, less than 0.1 mm typical. Measure indents center-to-center three times with optical comparator. Reset reference zero for each measurement (three independent measurements).

1. Locations to measure are indicated in the diagram. All dimensions in mm except as indicated by (in.). Record measurements to 0.001 mm excepting "C" and "OAL."
2. Record dimension "C" to 0.01 mm resolution.
3. Record dimension "OAL" to 0.01 mm resolution. This can be measured with a caliper.
4. Measure W_1, W_2, and W_C two times. Reset width reference zero for each measurement (make two independent measurements at each location).
5. Measure thicknesses T_1 and T_2, twice at each location, approximately 3 mm either side of centerline. Measuring device contact surface should not cover the gage mark indent. Ball tip micrometer use is suggested for small contact area on indent face of specimen. Use minimum pressure needed to achieve consistent measurements.
6. Record room temperature before starting and after completion of each group of measurements.

Specimen ID	OAL (mm)	C (mm)	W_1 (mm)		W_2 (mm)		W_C (mm)		GL (mm)			T_1 (mm)		T_2 (mm)	
			#1	#2	#1	#2	#1	#2	#1	#2	#3	#1	#2	#1	#2
L1	50.710	15.361	3.192	3.192	3.196	3.196	3.161	3.163	12.726	12.735	12.728	.523	.523	.521	.521
L2	50.707	15.369	3.206	3.206	3.199	3.199	3.174	3.174	12.721	12.710	12.714	.533	.533	.532	.532
L3	50.701	15.377	3.191	3.191	3.196	3.196	3.168	3.168	12.699	12.693	12.695	.540	.540	.535	.535
L4	50.695	15.374	3.192	3.193	3.204	3.203	3.164	3.165	12.835	12.857	12.856	.532	.532	.535	.536
L5	50.694	15.395	3.193	3.193	3.195	3.195	3.175	3.175	12.688	12.691	12.692	.506	.506	.516	.516
L6	50.700	15.365	3.189	3.189	3.208	3.208	3.175	3.174	12.771	12.771	12.766	.520	.520	.520	.521
L7	50.699	15.385	3.194	3.194	3.202	3.202	3.176	3.176	12.726	12.729	12.731	.544	.544	.541	.541
L8	50.706	15.407	3.202	3.202	3.191	3.192	3.179	3.179	12.681	12.673	12.672	.541	.542	.538	.538

Date: 5/12/14

Tensile Specimen Dimensional Record Sheet (continuation)

Measurement Operator Name:

Signature:

Specimen ID	OAL (mm)	C (mm)	W_1 (mm)		W_2 (mm)		W_C (mm)		GL (mm)			T_1 (mm)		T_2 (mm)	
			#1	#2	#1	#2	#1	#2	#1	#2	#3	#1	#2	#1	#2
L9	50.709	15.389	3.201	3.201	3.195	3.197	3.169	3.169	12.767	12.765	12.761	.542	.542	.540	.541
L10	50.709	15.389	3.198	3.198	3.195	3.196	3.180	3.180	12.783	12.787	12.788	.536	.536	.535	.535
L11	50.708	15.406	3.189	3.189	3.187	3.187	3.166	3.165	12.642	12.636	12.632	.533	.533	.534	.534
L12	50.711	15.384	3.197	3.197	3.198	3.198	3.170	3.170	12.744	12.730	12.729	.527	.527	.525	.525
L13	50.710	15.406	3.195	3.196	3.187	3.187	3.173	3.172	12.752	12.748	12.740	.519	.519	.518	.518
L14	50.716	15.384	3.194	3.194	3.198	3.199	3.165	3.163	12.744	12.748	12.753	.505	.50+6	.504	.503
*L29	50.703	15.129	3.190	3.190	3.190	3.190	3.179	3.179	12.720	12.713	12.708	.530	.530	.530	.530
L30	50.704	15.172	3.195	3.194	3.201	3.201	3.179	3.180	12.768	12.770	12.769	.541	.541	.547	.547
L31	50.704	15.189	3.205	3.205	3.213	3.213	3.191	3.191	12.775	12.766	12.770	.550	.550	.550	.550
L32	50.699	15.207	3.201	3.201	3.215	3.214	3.189	3.189	12.732	12.734	12.733	.550	.550	.554	.554
L33	50.698	15.207	3.199	3.199	3.207	3.207	3.186	3.186	12.713	12.716	12.720	.521	.521	.526	.526
L34	50.699	15.244	3.198	3.197	3.217	3.217	3.187	3.187	12.715	12.720	12.718	.550	.551	.555	.555
L35	50.708	15.250	3.193	3.193	3.202	3.202	3.186	3.185	12.780	12.774	12.777	.552	.552	.555	.555
L36	50.697	15.275	3.203	3.203	3.206	3.207	3.183	3.184	12.762	12.769	12.776	.554	.554	.554	.554
L37	50.700	15.288	3.203	3.203	3.201	3.201	3.182	3.182	12.737	12.739	12.742	.546	.546	.546	.546
L38	50.697	15.322	3.200	3.200	3.222	3.221	3.193	3.193	12.761	12.758	12.761	.548	.548	.549	.549
L39	50.698	15.324	3.204	3.204	3.213	3.213	3.191	3.191	12.733	12.725	12.730	.542	.542	.545	.545
L40	50.696	15.346	3.198	3.198	3.218	3.218	3.192	3.192	12.691	12.703	12.702	.541	.541	.541	.542
L41	50.700	15.345	3.199	3.199	3.202	3.202	3.198	3.198	12.713	12.715	12.716	.524	.524	.530	.530

Measurement Notes (use back of sheet if needed): L29 specimen is not full width

Date: 5/12/14

Tensile Specimen Dimensional Record Sheet (continuation)

Measurement Operator Name:

Signature:

Specimen ID	OAL (mm)	C (mm)	W_1 (mm)		W_2 (mm)		W_C (mm)		GL (mm)			T_1 (mm)		T_2 (mm)	
			#1	#2	#1	#2	#1	#2	#1	#2	#3	#1	#2	#1	#2
L42	50.698	15.363	3.194	3.193	3.197	3.197	3.184	3.184	12.754	12.750	12.751	.531	.531	.531	.532
T1	50.755	15.338	3.218	3.217	3.221	3.222	3.192	3.192	12.744	12.748	12.744	.531	.531	.540	.540
T2	50.764	15.341	3.174	3.174	3.173	3.174	3.145	3.146	12.731	12.720	12.724	.543	.543	.539	.539
T3	50.772	15.384	3.202	3.203	3.191	3.191	3.174	3.175	12.684	12.691	12.682	.541	.541	.540	.540
T4	50.785	15.335	3.195	3.195	3.192	3.191	3.173	3.174	12.693	12.690	12.689	.540	.539	.540	.540
T5	50.783	15.382	3.196	3.196	3.198	3.198	3.168	3.167	12.747	12.739	12.746	.539	.539	.531	.531
T6	50.784	15.362	3.213	3.212	3.195	3.195	3.175	3.175	12.749	12.744	12.747	.536	.536	.536	.536
T7	50.788	15.385	3.196	3.196	3.201	3.201	3.172	3.172	12.672	12.671	12.664	.538	.538	.539	.539
T8	50.804	15.386	3.200	3.201	3.192	3.192	3.172	3.172	12.705	12.707	12.710	.538	.538	.540	.539
T9	50.784	15.390	3.201	3.201	3.200	3.198	3.172	3.173	12.807	12.808	12.803	.540	.540	.539	.539
T10	50.787	15.394	3.195	3.194	3.194	3.194	3.171	3.171	12.736	12.743	12.734	.539	.539	.539	.539
T11	50.784	15.379	3.197	3.198	3.197	3.197	3.177	3.177	12.748	12.758	12.758	.538	.538	.538	.538
T12	50.809	15.383	3.203	3.203	3.195	3.196	3.173	3.173	12.678	12.678	12.680	.541	.541	.539	.539
T13	50.779	15.406	3.193	3.194	3.194	3.194	3.176	3.177	12.746	12.738	12.738	.541	.541	.540	.540
T14	50.781	15.397	3.211	3.211	3.191	3.192	3.181	3.181	12.693	12.691	12.691	.539	.539	.537	.537
T15	50.766	15.384	3.187	3.186	3.203	3.203	3.165	3.164	12.695	12.705	12.708	.543	.543	.538	.538
T16	50.748	15.395	3.210	3.211	3.193	3.193	3.172	3.172	12.751	12.755	12.746	.538	.539	.540	.540
T17	50.740	15.397	3.191	3.191	3.202	3.202	3.175	3.175	12.720	12.726	12.724	.546	.546	.543	.543
T18	50.729	15.403	3.213	3.214	3.195	3.196	3.171	3.171	12.672	12.664	12.662	.529	.530	.539	.539

Measurement Notes (use back of sheet if needed):

Date: 5/12/14

Tensile Specimen Dimensional Record Sheet (continuation)

Sheet 4 of 4

Measurement Operator Name:

Signature:

Specimen ID	OAL	C	W_1 (mm)		W_2 (mm)		W_C (mm)		GL (mm)			T_1 (mm)		T_2 (mm)	
	(mm)	(mm)	#1	#2	#1	#2	#1	#2	#1	#2	#3	#1	#2	#1	#2
T19	50.969	15.421	3.198	3.198	3.203	3.204	3.163	3.162	12.800	12.804	12.809	.534	.534	.538	.538

Measurement Notes (use back of sheet if needed):