Evaluation of an Alternate Method for Determining Yield Strength Offset Values for Selective Laser Sintered Polymeric Materials

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ABSTRACT

Due to the unique characteristics of Additively Manufactured (AM) polymeric materials, typical mechanical strength characterization methods such as those commonly used for traditionally-processed polymers or composite materials can produce results that do not accurately represent material capabilities. In order to characterize mechanical properties of these materials, new test and analysis methods are required. As part of the National Aeronautics and Space Administration (NASA) Advanced Composites Project (ACP), Boeing has evaluated true yield testing as an alternative or complimentary test to 0.2% offset yield testing for determining appropriate yield strength values of polymer materials. Previous testing has shown high strain, low modulus polymer materials such as selective laser sintered (SLS) Nylon 11 at elevated temperatures produce large variations in yield strength. The true yield test method was successful in finding the applied strain level when yield commences and appears to offer an increase in data robustness.

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1. INTRODUCTION

As part of the Advanced Composites Project (ACP), NASA is partnering with the aerospace industry to significantly reduce the timeline to certify composite structure for commercial and military aeronautic vehicles. One of the objectives under this program is to develop cost and time efficient test methods to accurately evaluate mechanical properties (e.g., tensile, shear and compression strength) of Polyamide and Polyetherketoneketone materials that are fabricated with additive manufacturing (AM) processes. The effort described in the paper was a portion of the overall effort and initiated to investigate alternate yield strength determination methods and criteria for polymer materials. Specifically of interest was neat, thermoplastic additive manufactured materials and appropriate methods for their yield point determination.

The standard yield point determination method currently employed for aerospace materials is colloquially referred to as the offset yield. The offset yield strength approach determines the material modulus in the linear or elastic portion of the curve and calculates the yield strength from where a specified offset parallel to the slope intercepts the stress-strain curve. While the ASTM standards (ASTM D638 and ASTM D695) do not define the exact strain levels used to calculate the linear modulus or the specified offset, industry standard practice is to use 0.1 and 0.3% strain, and 0.2% strain as the specified offset for determining yield strength. It is acknowledged that ASTM D638 does refer to other methods and offers corrections such as the toe-in correction and secant modulus method but the standard approach is to pre-program the 0.1 and 0.3% chord points and utilize the 0.2% offset.

Using the industry standard values and practice in historical testing led to excessively conservative yield strength determinations in polymer materials at elevated temperature in particular. Nylon 11 tensile testing at temperature is an excellent example of this issue with Figure 1 being a typical historical tensile curve with 0.2% offset yield indicated.

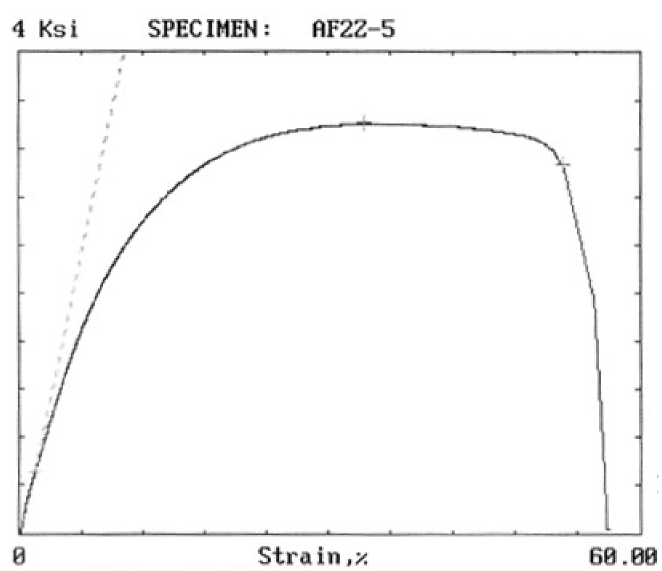

Figure 1: Historical Nylon 11 SLS 165°F/Ambient Tension Test

The specific testing being employed in this paper is the true yield point test method; the intent of which is to determine the actual plastic deformation experienced by a test specimen after it is returned to a zero stress-state and permitted to relax. Previous testing and literature has demonstrated thermoplastics will exhibit a dimensional recovery stage that continues for a period of time after all stress has been removed.

The true yield point of plastics test method was documented in a Datapoint Labs article [1] and references two earlier successful uses of this technique in application to polymethylmethacrylate, polystyrene and polycarbonate materials. The purpose of the true yield point test is to determine the location of the actual yield point on the stress-strain curve (Figure 2). The general idea of the procedure is to load the specimen, unload the specimen, measure the residual deformation after a fixed period of recovery time and then repeat the above steps at progressively higher loaded strain levels. The residual strains measured after each unloading and recovery time are then plotted as a function of the applied strains at each step (Figure 3). When the initial deformation exceeds the plastic limit of the material, a dramatic increase of residual strain is observed.

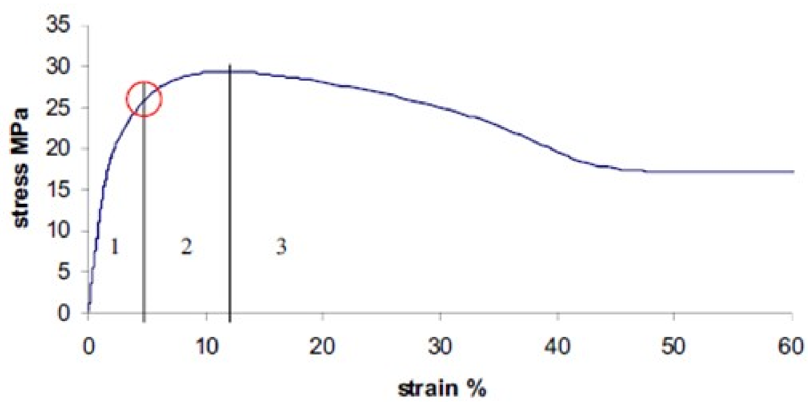

Figure 2: Stress strain curve showing the 3 different regions. The true yield point is circled [1]

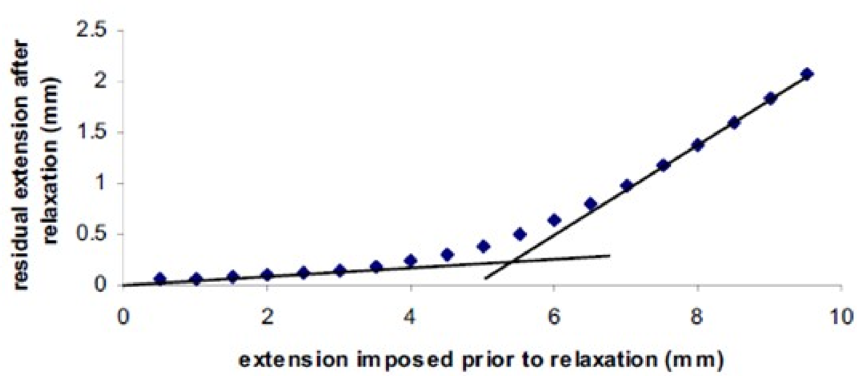

Figure 3: Plot of residual extension versus initial applied extension [1]

The residual strains after the initial few cycles are low and linearly increasing. These residual strains correspond to residual viscoelastic strains. For larger imposed extensions (around 4-5 mm), the residual deformations become much larger, as plastic residual strains are also accumulated. To measure the true yield point from the curve, an onset or an intercept type construction may be applied. Of these, the onset construction presents a more conservative picture of this phenomenon. In this testing, it was decided to utilize onset of creep to define yield instead of the higher intercept of the linear and plastic portions of the response curve. It has been shown in the referenced Datapoint Labs article that this limit definition approach, and the subsequent yield strain, is independent of the time allowed for the material to recover.

2. EXPERIMENTATION

2.1 Material Definition and Specimen Fabrication

The Nylon 11 material used for testing was Rilsan D80 Natural ES from Advanced Laser Materials (ALM). Rilsan D80 was chosen due to a substantial amount of historical data present for this material.

Standard ASTM D638 Type 1 tensile specimens were selected for this testing, with the modification that a label tab was extended from the side of the grip (Figure 4). This label tab has been shown to eliminate failures in the grip region associated with the commonly used labeling technique of engraving in the grip area directly. While this type of grip failure is not common in high elongation materials such as Nylon 11, it has been observed occasionally.

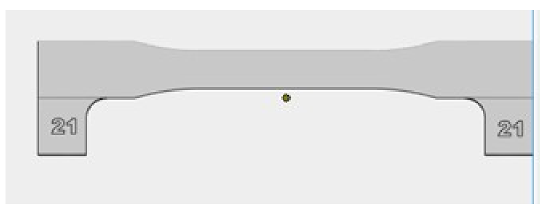

Figure 4: Tensile specimen geometry used

The test specimens were fabricated via the SLS process utilizing Vanguard equipment. Two forms of the specimens were printed, as-built net-shape specimen and rectangular blanks which were then machined using conventional methods to produce the ASTMD638 Type 1 specimen geometry. These two forms were used to evaluate the impact of surface roughness known to be associated with SLS processing on test results.

Relative to the equipment axis, a ZY-orientation (Figure 5) was selected for all test specimens, with a slight rotation around the Z-axis off of true ZY-orientation as a nod to SLS build considerations. Three builds were utilized to produce all the specimens. The first build consisted of rectangular blanks to be utilized in producing the machined specimens, and the second and third builds produced the as-built specimens. The specimens were located in a non-serial fashion in the build as part of a randomization effort to prevent an entire test grouping from coming from one particular build area and possibly influencing the results. Testing was also conducted in a random, non-sequential fashion in this test plan, resulting in further randomization.

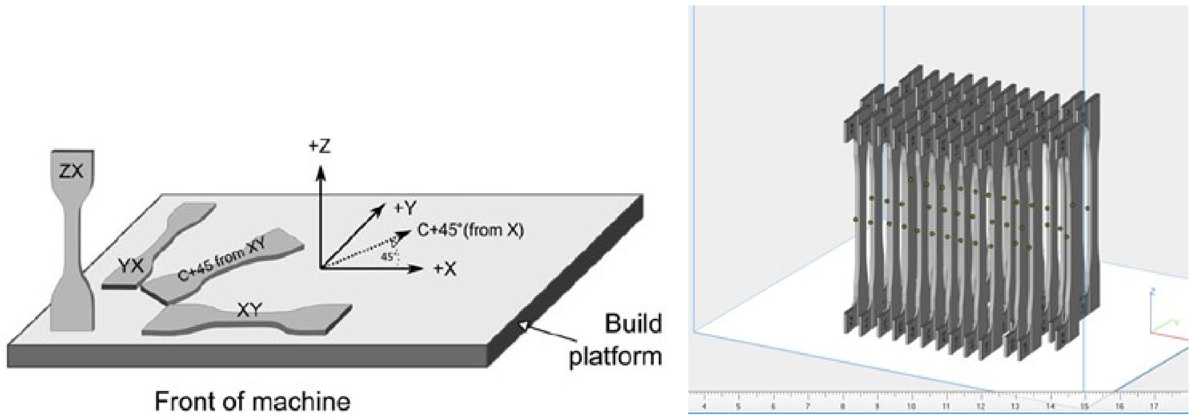

Figure 5: Build orientation and 3D view of build

The machined specimens were machined with a standard ¼" diameter end mill at 25 ipm and 12,000 rpm utilizing air as coolant. During testing of the machined specimens, particularly at -65°F, it was noticed the machined specimens were not of uniform thickness resulting in non-uniform load applications. At other temperatures, it appears the material was soft enough that non-uniform thickness was not a hindrance to load introduction and test results.

Specimen roughness was measured for both as-built and machined specimens. The as-built specimens had an Ra of approximately 700 micro-inches and the machined specimens had an Ra of 16-60 micro-inches.

2.2 Testing Procedure

Two moisture preconditioning levels were selected for this testing to be consistent with previous testing efforts.

1. Ambient – 40 hours @ Room Temperature (RT) / 50% Room Humidity (RH) (ASTM D318 Procedure A and internal Boeing testing)
2. Wet – 7 weeks @ 120°F / 95% RH

Specimen weight gain at the ambient and wet conditions was calculated by weighing extra specimens at the end of testing and then drying them in an oven at 215°F for 6 days. As-built and machined specimens exhibited similar moisture gain under both ambient and wet conditions. The wet conditioning resulted in 1.4% weight gain while the ambient conditioning resulted in 1.0% weight gain.

The true yield test method was evaluated in this work with three individual tensile test methods; a baseline tensile test, the multi-load tensile test and yield point check. The multi-load test is the heart of the true yield test method. The baseline tensile test results were intended to provide a reference data set. The yield point check test results were used to verify that the use of multiple loading cycles did not alter yield behavior relative to a single cycle of loading to the strain level being evaluated.

2.2.1 *Baseline Tensile Test*

The baseline tensile tests were conducted with both the as-built and machined configurations but with only a single replicate of each as it was not the focus of this effort given the availability of the historical data. Baseline specimens were loaded at typical ASTM D638 loading rates of 0.2 inches/min for all RT and above test conditions and 0.1 inches/min for the -65°F test condition with data collected at 10 Hz with an extensometer. Ambient conditioned specimens were temperature stabilized in the chamber for 10 minutes prior to test and wet specimens were temperature stabilized for 3 minutes prior to test to limit moisture loss at temperature.

2.2.2 *Multi-load Tensile Test*

The multi-load tensile tests were the primary data collection mechanism of this effort. The intent was to clearly indicate by sequentially loading and unloading the specimens to progressively higher strain levels where20 plastic deformation begins to occur and to what degree plastic deformation was occurring at higher strain levels. Loading rates, data collection rates and temperature stabilization holds matched those used for the baseline tests. The three minute thermal stabilization period of the wet specimens did lead to data interpretation issues and a greater temperature stabilization time is recommend in future testing with the multi-load method. The planned strain load stopping levels are shown in Table 1.

Table 1: Planned multi-load strain data collection points

Test Region	Cold	RT	Hot/amb	Hot/wet
Elastic	0.5%	0.5%	0.25%	
			0.5%	
			0.75%	
	0.75%	1.0%	1.0%	1.0%
			1.5%	
	1.0%	1.5%	2.0%	2.0%
Transition	1.25%	2.0%	3.0%	
	1.5%	2.25%	4.0%	4.0%
	1.75%	2.5%	5.0%	5.0%
	2.0%	2.75%	6.0%	6.0%
	2.25%	3.0%	7.0%	7.0%
	2.5%	3.25%	8.0%	8.0%
		3.5%	9.0%	
		4%	10.0%	10.0%
		5%	11.0%	
Plastic	2.75%	6.0%	12.0%	12.0%
		7.0%		
	3.0%	9.0%	15.0%	15.0%
	3.5%	11.0%		

The intent was to have several data points collected in each of the regions of the material response load curve; the elastic region, the transition region and the fully plastic region. In future testing, it is recommend greater emphasis be placed on the elastic region and the beginning of the transition region (below 4% applied strain) as data analysis has migrated to focus closely on the initiation of plastic deformation and not on the degree of plastic deformation at higher strain levels. Multi-load specimens were loaded to each strain level and then immediately (<2 seconds) unloaded to reduce creep behavior interactions with the yield point determination. The specimen unloaded state was held at a constant strain state by holding cross head position when the specimen was unloaded to 5 pounds of tension. The unloaded strain state was held for two minutes. The hold was intended to allow for relaxation behavior to be observed. The climbing stress during the low strain holds did manifest as expected and reached a near steady state stress level at the end of the timed hold which allowed the projected zero stress state to be calculated from a reasonably stable unloaded stress state.

2.2.3 Yield Point Check Test

A yield point check test was designed to validate that the multiple loading and unloading cycles were not causing differences from a direct loading to a higher strain level. To achieve this, yield point specimens were directly loaded to a strain level in the middle of the projected transition between an elastic response and the fully plastic response so that the resultant plastic deformation could be compared against the plastic deformation results from the multipoint test at the equivalent strain loadings. The levels were selected to be near the intersection of the upper and lower linear response curves as shown in Figure 3. In retrospect it would have been wiser to conduct the check at applied strain levels nearer to where the response departs from the initial, elastic response as that has become the area of interest. After loading to the desired applied strain level and unloading to 5 pounds applied load, specimens were held for two minutes at a constraint cross head position in the same manner as the multi-load specimens while recording applied load and the extensometer response.

3. RESULTS

3.1 Baseline Tensile Test Data Reduction & Results

The baseline tensile test data reduction included establishing a modulus and an offset yield point as well as serving as baseline data to determine the yield stress from the yield strain level determined from the multi-load test results. Selection of the chord points for the modulus was one of the critical issues with reducing the baseline test data. Figure 6 shows the stress strain plot of one of the RTA as-built test specimens with the 0.2% offset intercept and one of the 165°F/wet specimens. Both plots have an expanded view of the low strain region without the offset yield intercept. Several issues can be discerned from examining the RT plot.

1. There is a significant toe region invalidating the use of the standard 0.1% and 0.3% chord modulus points
2. The curve is not linear above the toe region indicating a changing modulus
3. The 0.2% strain offset is small in proportion to the overall material strain response

The higher temperature data produced additional issues in the low strain region contributing to the difficulty in selecting the chord modulus points. The 165°F/wet specimens exhibited an excessively low modulus region of the curve between 0.4 and 0.7% strain leading to selection of chord modulus points above that region.

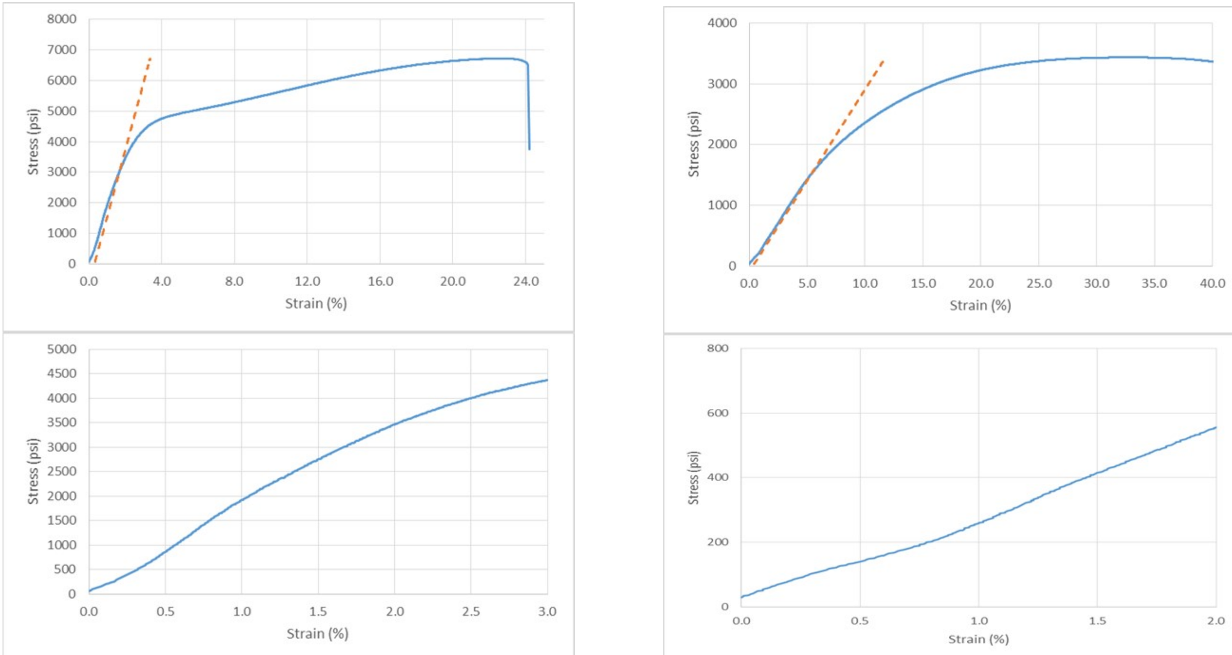

Figure 6: Modulus irregularities at low strain levels - RTA specimen (left); - 165°F/wet specimen (right)

In summary, the individual baseline tensile results highlight issues with data quality at the low strain levels with this low strength/high elongation material. As another way of evaluating the low strain data inconsistencies, the as-built and machined stress strain responses at a given test condition were plotted on the same plot with the ratio between their stress responses overlaid on the same plot (Figure 7). Plotting the relative responses in this manner was another way to highlight the data inconsistencies at low strain levels. It is not apparent why there should be a changing ratio between the as-built and machined specimen stress and strain (Figure 7), but this behavior was seen under all test conditions. A difference in modulus, ultimate strain and perhaps yield strain would be expected but not the changing ratio in the lower regions of the elastic curve unless it is due to non-uniform initial loading of the machined specimens due to the non-uniform thickness issue noted in Section 2.1. When the strain levels typical of yield stresses are reached for each environmental condition, the percent difference between the as-built and machined specimens settles to between 90 and 94% as indicated by the plots. At lower strain levels, the relative stresses are much more erratic, with the stresses of the as-built specimens often exceeding that of the machined specimens. This does not correlate with expectations given the rough surface of the as-built specimens and the expected modulus reduction induced by those rough surfaces from essentially missing material.

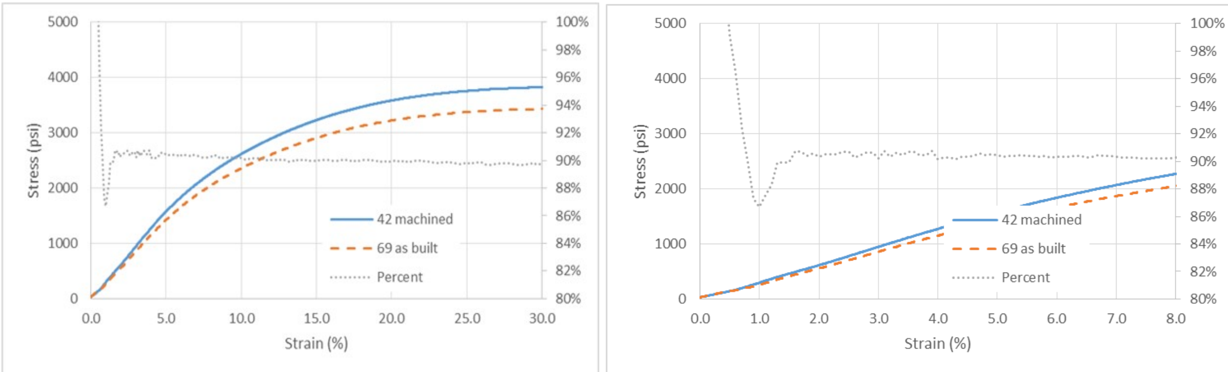

Figure 7: 165°F/wet baseline tensile stress strain curves

Data quality at the lower strain levels (below 1.5%) does not impact ultimate stress calculations but it does add variability to modulus calculations and the subsequent offset yield calculations based on the modulus determination for an individual test.

Examining the expanded baseline tensile data presented in Table 2 and the percentage differences between the as-built and machined modulus and 0.2% offset yield values allows for some correlations to be seen. When the percentage difference in modulus roughly matches the ratio of strengths at higher strains shown in the plots at 90-95%, the yield strengths and strains percentages also maintain that ratio. The 215°F/wet data is an example of this. However, when the ratio of the modulus between as-built and machined specimens was closer to 100%, such as the RT/ambient and 215°F/ambient conditions, the delta in offset yield stress and strain was greater than average due to lower as-built yield strains. The converse was true when the modulus of the as-built specimens was substantially lower than the machined specimen resulting in unexpectedly high as-built yield strains such as occurred at the two 165°F test conditions.

Table 2: Expanded tensile test result summary

Environmental Test Condition	Surface Condition	Spec ID	Modulus				0.2 % Offset Yield			
			1st Chord Strain (%)	2nd Chord Strain (%)	(ksi)	Mod Δ (%)	Strength (ksi)	Strength Δ (%)	Strain (%)	Strain Δ (%)
-65F/amb	as-built	53	0.4%	0.7%	246		7.87		3.3%	
	machined	18			*		*		*	
RT/amb	as-built	3	0.4%	0.7%	220	99%	3.01	86%	1.7%	89%
	machined	37			223		3.50		1.9%	
165F/amb	as-built	21	0.3%	0.6%	37.5	87%	1.09	97%	3.0%	111%
	machined	58			43.1		1.12		2.7%	
165F/wet	as-built	69	0.8%	1.1%	30.0	86%	1.52	116%	5.4%	132%
	machined	42			34.7		1.31		4.1%	
215F/amb	as-built	15	0.5%	0.8%	38	97%	1.16	76%	3.2%	78%
	machined	34			39		1.53		4.1%	
215/wet	as-built	19	1.0%	1.3%	28	93%	1.46	94%	5.4%	100%
	machined	16			30		1.56		5.4%	

* strain data not properly recorded. Extensometer pin likely not released prior to test initialization. Crosshead displacement of spec 18 was 2.26x higher than specimen 53. The issue may have been related to specimen lack of flatness and non-even loading.

The suspected cause of these varying ratios between the as-built and machined modulus and offset yield strength values was quality of the modulus values due to test repeatability/stability at the chord modulus strain levels. To understand if this could be smoothed out by adjusting the chord modulus point selections to higher and assumedly more stable levels, the chord modulus and subsequent yield values were recalculated with alternate chord modulus values at 1.5% or above to correlate with the regions where the ratios between the machined and as-built specimen stress response was more stable. The results are plotted in Table 3. Scatter was reduced between the modulus reduction and offset yield strength reductions for as-built versus machined specimens and brought the strain at the offset yield strengths closer to equal. However, a significant amount of variability remained. Utilizing the higher chord modulus points generally reduced the calculated modulus for the tests although this was not universal. The change in modulus was perhaps most obvious in the room temperature modulus. It has been noted in previous testing that Nylon 11 SLS does not have a linear stress strain slope or constant modulus even in the elastic portion of its response behavior. Overall, the strains and stresses at the yield point were increased by utilizing the higher chord modulus points as would be expected by the general trend of lower modulus when utilizing higher chord modulus points.

Table 3: Expanded tensile test result summary with alternate (higher) chord modulus points

Environmental Test Condition	Surface Condition	Spec ID	Modulus				0.2 %			
			1st Chord Strain (%)	2nd Chord Strain (%)	(ksi)	Mod Δ (%)	Strength (ksi)	Strength Δ (%)	Strain (%)	Strain Δ (%)
-65F/amb	as-built	53	1.5%	1.8%	251		6.96		2.7%	
	machined	18			*		*		*	
RT/amb	as-built	3	1.5%	1.8%	148	95%	4.09	94%	2.6%	100%
	machined	37			155		4.35		2.6%	
165F/amb	as-built	21	2.0%	2.3%	34.0	89%	1.69	94%	4.9%	104%
	machined	58			38.0		1.80		4.7%	
165F/wet	as-built	69	2.0%	2.3%	29.0	91%	1.67	88%	6.0%	97%
	machined	42			31.7		1.89		6.2%	
215F/amb	as-built	15	2.0%	2.3%	35.1	85%	1.38	101%	4.0%	111%
	machined	34			41.4		1.36		3.6%	
215/wet	as-built	19	2.0%	2.3%	31.8	98%	1.14	90%	4.0%	98%
	machined	16			32.5		1.26		4.1%	

* strain data not properly recorded. Extensometer pin likely not released prior to test initialization. Crosshead displacement of spec 18 was 2.26x higher than specimen 53. The issue may have been related to specimen lack of flatness and non-even loading.

Achieving only partial success of reducing the yield strength variability was disappointing as one of the goals of this effort was to use the true stress method to establish a yield strain for a given material and test condition and then revert to the standard offset method except with different modulus definition points for generating yield strength data as part of allowables testing. This approach will still be pursued and evaluated but it now does not look as promising.

3.2 Multi-load Tensile Test Data Reduction & Results

Utilizing the measured test specimen width and thickness, load was converted to stress data at each data collection point as per standard practice. The following steps were followed for data reduction:

1. Record residual stress & strain at the end of each unload hold: Residual stress and strain level was manually extracted at the end of each strain hold period and added to a table for subsequent data manipulation

2. Project residual strain at zero stress at the end of each unload hold: Specimen elastic modulus was calculated for each specimen from the first loading cycle and this elastic modulus was utilized to project from the residual strain after each loading level to what the residual strain would have been if the loading was reduced to zero instead of near zero assuming an elastic response. Residual strain versus applied strain was then plotted for both the uncorrected and corrected zero strain states for each specimen with the goal of obtaining the strain response if the specimen was fully unloaded at the end of each progressively higher loading and unloading cycle.
3. Determine slope of residual strain versus applied strain curve in elastic response region: A simple chord slope was found sufficient to establish the linear elastic response with ignoring any visually non-linear behavior which typically included the first loading cycle.
4. Curve fit of the transition region of the residual strain versus applied strain curve: A curve fit is of the residual strain versus applied strain curve is required to calculate a specific amount of plastic strain or amount of departure from the linear response portion of the curve. A better curve fit was obtained without using an excessively high order polynomial by limiting the region of the curve fit to the regions of interest.
5. Calculate yield strain: To calculate the plastic deformation or yield strain, first an acceptable amount of plastic deformation or strain must be selected (typically from 0.05% to 0.5%). The applied strain at which the difference between the actual residual strain response and the projected elastic linear response is equal to the defined acceptable plastic strain at yield is then the yield strain. The yield strain could be determined mathematically by subtracting the equation from each other, setting them equal to the acceptable residual strain and solving them mathematically for the applied strain.

The true yield testing or multi-load tensile tests are each a unique combination of test temperature and pretest moisture conditioning. The yield strain results were determined for each test condition but for the sake of this paper only one condition will be discussed in detail. No conclusion has been reached what would be an appropriate value to utilize for the permitted amount of plastic deformation, although the minimum value of 0.1% is currently favored. The 0.05% strain value was selected as the minimum plastic deformation level used to calculate yield as 0.05% plastic deformation from the linear behavior appeared to be where values repeatedly rose above the noise in the output plot. The maximum strain level of 0.5% of permitted plastic deformation was selected due to being roughly twice the standard 0.2% offset value used in traditional offset yield calculations.

The yield testing results via the true yield method for multi-load tensile testing at 165°F/ambient are summarized in Table 4 with a typical plot shown in Figure 8. There is not a significant difference in strains at yield for the as-built versus machined specimens, a behavior similar to RT/ambient testing. The specimen 66 yield strain did seem a bit on the high side but the average yield strain was representative of the overall group as the specimen 66 result was offset by lower strain of specimen 1.

The yield strain results in Table 4 were calculated between the linear approximation of the elastic portion of the response curve and a fourth order polynomial curve fit of the data between

1% and 5% applied strain. The elastic linear slope was calculated from the 0.5% and 1.0% applied strain levels and was varied from slightly positive to slightly negative slope as can be seen in the appendix plots of the individual results.

Table 4: Yield test result summary at 165°F/ambient

Spec ID	Surface Condition	Yield Strain					
Plastic Strain used to Define Yield Point		0.05%	0.1%	0.2%	0.3%	0.4%	0.5%
1	as-built	2.20	2.95	3.90	4.55	5.00	5.45
55	as-built	2.55	3.25	4.25	4.95	5.45	5.50
66	machined	2.90	3.55	4.35	5.00	5.50	5.50
86	machined	2.55	3.25	4.15	4.80	5.30	5.50
90	machined	2.45	3.10	4.00	4.65	5.25	5.70
average		**2.53**	**3.22**	**4.13**	**4.79**	**5.30**	**5.53**

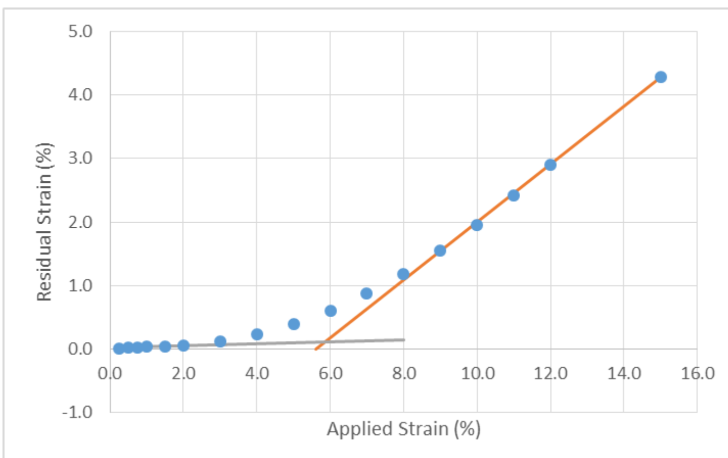

Figure 8: Yield at 165°F/ambient: machined tensile projected residual strain @ 0 load versus applied strain curve (spec 66)

3.3 Yield Point Check Test Results

The 165°F ambient yield point checks consisted of three tests and were loaded to 4% applied strain. The 165°F ambient yield point check results are summarized in Table 5 with an example response shown in Figure 9. The residual strains with the single loading tests produced residual strains similar to the multi-load results at the same applied strain levels indicating the use of multiple loading cycles was not biasing the test results.

Table 5: 165°F/ambient yield point check results

Single Load Check Test Results				Projected residual strain @ 0 lbs from muli-load tests after applied strain (%)						Multi-load applied yield strain @ 0.1% plastic strain
Spec Id	Surface Condition	Applied Strain	Projected residual strain @ 0 lbs	average	as-built		machined			average
25	as-built	4%	**0.34%**	**0.22%**	0.27%	0.28%	0.23%	0.15%	0.17%	3.22%
67	as-built	4%	**0.31%**							
30	machined	4%	**0.17%**							
88	machined	4%	**0.14%**							

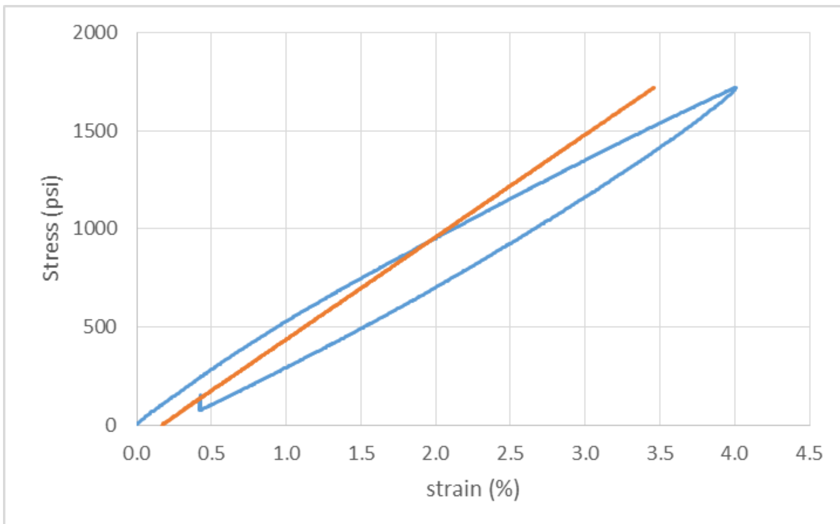

Figure 9: Typical 165°F/ambient yield point check test plot

The residual strains from the check test bracket the multi-load residual strains and the differences between the as-built and machined specimen strains are assumed to be due to test variability and not a difference due to the surface preparation. The four 165°F/ambient check load specimen stress strain plots are plotted on the same plot in Figure 10 to compare curve shape. The stress strain curves all appear very similar in shape with higher stresses recorded with the even numbered machined specimens for any given strain level as would be expected given the rough surface finish and related area loss of the odd numbered as-built specimens. To more carefully compare the as-built and machined curve shapes, the as-built specimens 25 and 67 multiplied by the ratio of the stress at 4% of specimens 30 and 25 and plotted in Figure 11. From Figure 11, it can be observed that the curve shapes overlay very closely during the loading portion of the test cycle while the as-built specimen responses tend to diverge some from the machined specimen responses during the unloading portion of the test cycle. The cause of this divergence was not discovered.

The 0.2% offset yield strain intercept (1.8%) is plotted for reference purposes in Figure 9 and it is below the yield strain (3.2%) found by the true point yield method as reported in section 3.2. The slope change or modulus variation in the stress strain plot is also readily apparent and indicative of how selecting various regions to define the modulus will lead to variations in the offset yield strength. In this particular instance, the modulus was determined from chord points of 0.3% and 0.6% strain. The modulus and 0.2% offset differences between the 165°F/ambient and 165°F/wet yield point check plots highlight the difficulties with applying the offset criteria to high elongation materials like Nylon 11 at higher temperature.

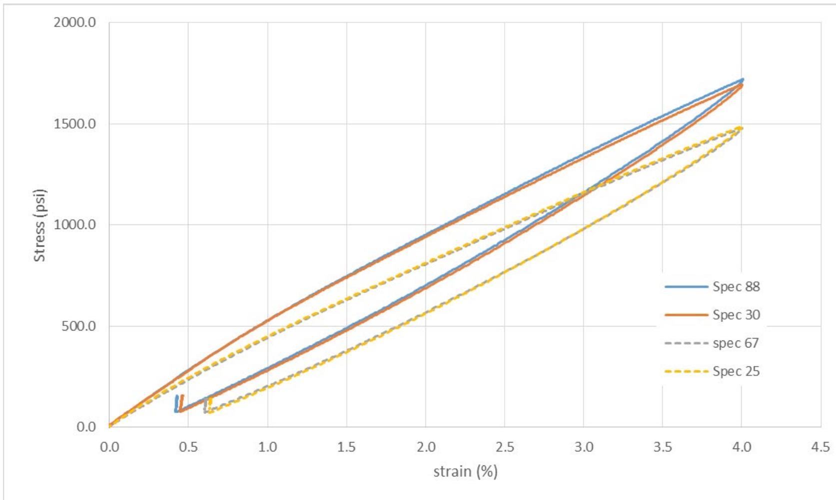

Figure 10: All four 165°F/ambient yield point check test plots

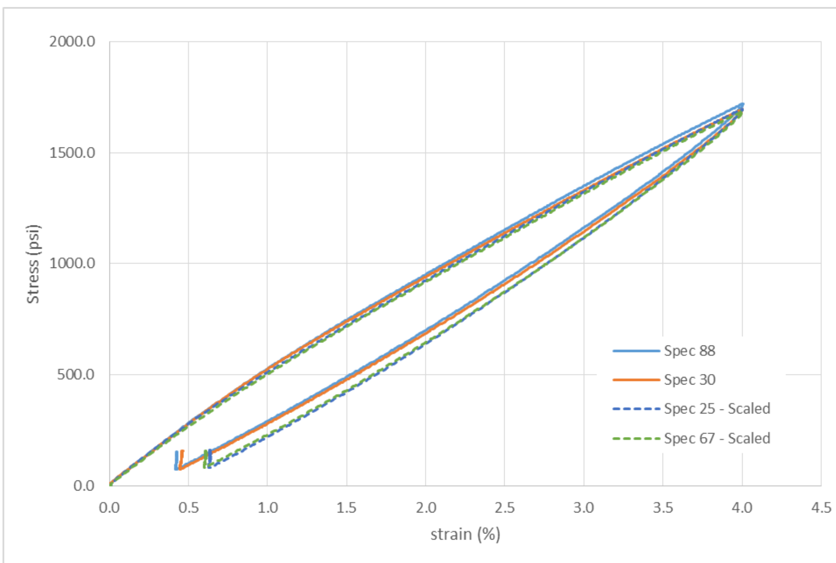

Figure 11: Curve shape comparison of all four 165°F/ambient yield point check test plots with scaling applied.

4. SUMMARY

True yield testing was investigated as an alternative or complimentary test to 0.2% offset yield testing for determining appropriate yield strength values of plastic materials. Previous testing has shown high strain, low modulus plastic materials such as selective laser sintered (SLS) Nylon 11 at elevated temperatures produce large variations in yield strength that may be more due to the test method than the material itself.

The true yield test method was shown to demonstrate finding the applied strain level when yield commences and appears to offer an increase in data robustness compared to the standard offset yield approach for the SLS Nylon 11 material. Use of this test method is envisioned as a limited number of tests (such as six) with the true yield method at a given temperature condition to define the resultant yield strain for the material/temperature. This would then be followed by standard tensile testing in larger quantities across multiple material batches where the yield strain level would be used to determine the yield stresses for the multi-batch testing for subsequent allowable/design guidance stress calculations.

5. ACKNOWLEDGMENTS

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6. REFERENCES

1. *Measuring true yield point of plastics*, Reporting on developments in material properties for engineering design, Francis Barthelat – Datapoint Labs – Winter ’01, Volume 7.1