A Process Development Study on Reducing the Anisotropy while Maintaining the Strength of Extruded Aluminum Alloy 2195 through Heat Treatment

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A PROCESS DEVELOPMENT STUDY ON REDUCING THE ANISOTROPY WHILE MAINTAINING THE STRENGTH OF EXTRUDED ALUMINUM ALLOY 2195 THROUGH HEAT TREATMENT

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Abstract

The purpose of this study was two-fold: develop an aging curve for extruded 2195 aluminum and test the magnitude of the anisotropy in the extrusion throughout the aging process. Two aging curves were developed, one at 290^{o}F and the other at 320^{o}F, through hardness tests of aged samples. The hardness was found to change, from approximately 72 HRB to 90 HRB, within the first 6 hours and not change more than 2 HRB in the 42 hours following. It was determined that the 320^{o}F temperature was more promising due to faster aging time, and the anisotropy study proceeded with that temperature. Samples were aged at 320^{o}F for 6, 18, 28, and 48 hours and tensile tested. These aging times were chosen due to interesting characteristics found during aging. The researchers measured yield strength to determine the magnitude of the anisotropy throughout the aging time.

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Introduction

Current State of the Aeronautics Industry

A current concern for the passenger airline industry is fuel consumption. This is not entirely an environmental focus; it is about money. The U.S. passenger airline industry's total revenue for the 3rd quarter of 2013 was $43.2 billion. [1] 28% of the total cost, or $10.9 billion USD, was fuel cost (Table I). [1] One way to reduce fuel consumption is to reduce plane weight. The empty weight of a common passenger airplane, the Boeing 737-800, is 91,300 lbs. [2] Three-quarters of this weight, approximately 68,475 lbs., is contributed to the use of either AA 7075 or AA2024 aluminum-copper alloys. [3] Alternatively, aluminum-copper-lithium AA2195 is of similar strength and weighs approximately 90% of either the AA7075 or AA2024 aluminum-copper alloy. [4] If the aluminum-copper alloys within the airplane were replaced with aluminum-copper-lithium AA2195, the new airplane's weight would be approximately 84,452 lbs. This 8% reduction in weight would result in a maximum fuel cost savings of $820 million USD per quarter across the industry.

Table I. North American Airliner Expenditures. [1]

(in Millions of USD)	3Q 2012	4Q 2012	1Q 2013	2Q 2013	3Q 2013	% change [3Q2012 - 3Q2013]
Net Income	1,393.70	-188	-395.2	2,269.00	3,163.30	127
Operating Profit/Loss	2,642.50	556.7	587.2	3,731.50	4,728.10	78.9
Operating Revenue	41,040.90	37,116.70	37,279.70	41,340.70	43,221.20	5.3
Baggage Fee Revenue	906.2	823.3	801	871.1	878.9	-3
Reservation Change Fee Revenue	647.5	613.4	685.3	719.2	734.8	13.5
Operating Expenses	38,398.50	36,559.90	36,692.60	37,609.20	38,493.10	0.2
Fuel Costs	10,975.30	10,715.90	10,609.30	9,883.10	10,895.90	-0.7
Labor Costs	9,505.30	9,038.00	9,261.70	9,499.30	9,777.20	2.9

Extrusion

Extrusion is a primary shaping process in which hot material is pressed through a die to manufacture long, relatively thin pieces of the specific material (Figure 1). This process has many advantages: shapes material quickly with a high material utilization at nearly 93%, relatively cheap capital costs when compared to other deformation processing techniques such as forging, and the end result is a hot-worked material. [5] An extruded material has greater crystallographic texture, which means that the grains are orientated in the same direction. Considering that a single grain, being a single crystal, is anisotropic, this crystallographic texture can have a great effect on the directionality of properties. This texture is particularly prevalent in extruded AA2195, and it is difficult to account for in design because of its variable effect on anisotropy. [6] The disadvantages of extrusion include shape restrictions of the material. The process can only manufacture continuous shapes.

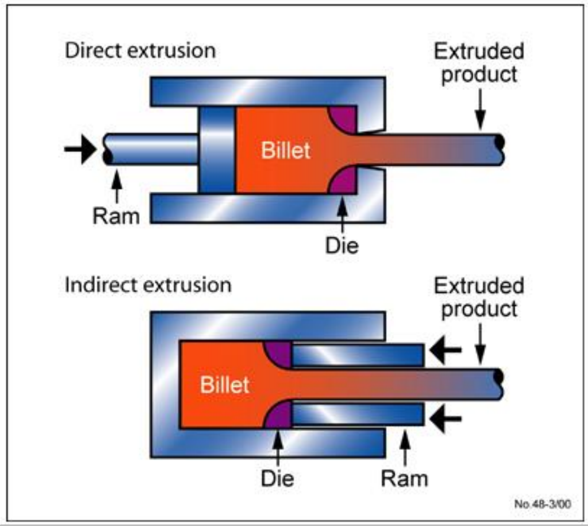

Figure 1. Extrusion can be done in two ways: direct or indirect. In direct extrusion, the ram is pressing the hot material against a die. In indirect extrusion, the ram presses the die against the hot material. [5]

Age (Precipitation) Hardening

One of the significant properties of aluminum alloys is the ability to increase strength through heat treatment. After an age-hardenable aluminum alloy has been quenched, the alloy may be used in the appropriate application. The ambient heat of the environment will continue to allow the alloying elements to diffuse, nucleate and eventually grow into precipitates. These precipitates increase the strength of a material due to forcing dislocations around the precipitates. The extra energy required to move a dislocation around the precipitates is reflected through the increase in strength.

If the ambient temperature is near room temperature [50°F-80°F], this process is called natural aging. If the ambient temperature is artificially high, through the use of a furnace, then this process is called artificial aging. The advantage of natural aging over artificial aging is a higher peak strength, however, natural aging could take years. Artificial aging is faster than natural aging, taking between 15-50 hours; however, artificial aging is prone to overaging. Overaging occurs when the precipitates become too large and too few, allowing the dislocations to easily move through the metal, thus decreasing strength.

Aluminum-copper-lithium

Aluminum-copper-lithium alloys are desirable not only for their low density and high strength, but also for their fatigue strength. [7] The significantly high fatigue strength is attributed to the high crack surface roughness. [7] Although this roughness is significantly decreased during gust simulation, the crack surface roughness is effective in less turbulent, fighter plane simulations (Figure 2). [7]

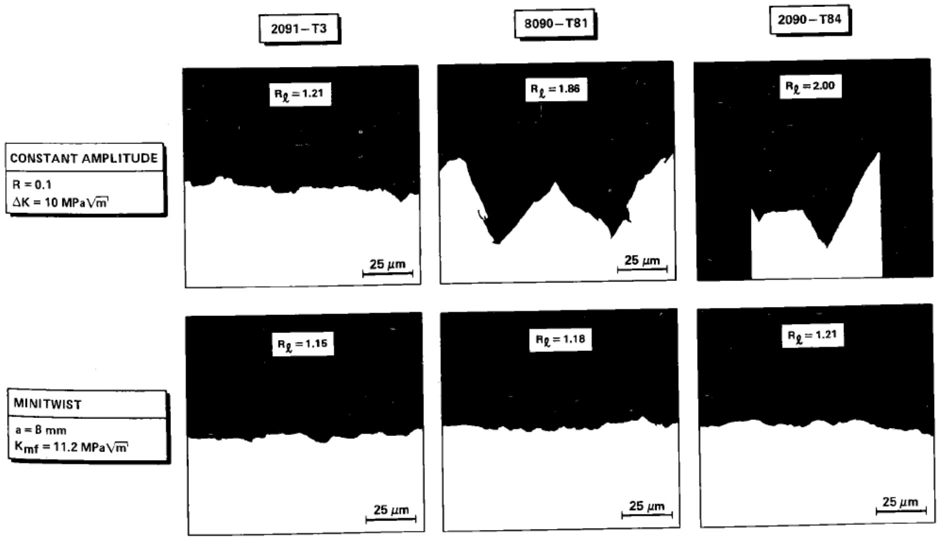

Figure 2. When tested in normal fatigue conditions that simulated a fighter jet, aluminum-copper-lithium alloys retained their fracture surface roughness (8090 and 2090). However, in conditions that simulated a commercial jet with gusts (MINITWIST), the fracture surface roughness was significantly decreased in magnitude. [7]

The aluminum-copper-lithium-magnesium-silver-zirconium series of metals was likely designed to increase weld-ability within the aluminum-lithium alloy system. This development likely occurred starting from aluminum-lithium alloys, the 8xxx series. Considering the cost of aluminum-lithium alloys, due to the cost and relatively large amounts of lithium, alloy developers likely wanted to take advantage of the fatigue strength of aluminum-lithium alloys, but reduce cost. Adding lithium to more common aluminum-copper alloys achieved the desired outcome. Magnesium was likely added for additional strength. [8]

Extruded AA2195 can be manufactured as a nearly isotropic material through the appropriate processing selection and appropriate parameters. [6] There are ways to reduce the magnitude of anisotropy. Reducing the initial wrought deformation would cause the initial straining of the microstructure to be considerably less, resulting in reduction of strength in the dominant direction. After initial extrusion, stretching or cold rolling at an angle from the rolling direction will cause the microstructure to stretch in a non-dominant direction, increasing strength in that direction, but reducing ductility overall. Before aging, heat treating the alloy to recrystallize allows for the strained microstructure to recover some of the

dislocations in the dominant direction, reducing strength in that direction and increasing ductility overall. Overaging the material after putting it through the extrusion process will cause the movement of alloying elements and growth of precipitates, decreasing the strain in the crystal structure, decreasing strength, but increasing ductility. [6]

The aging of AA2195 increases ultimate tensile strength and yield strength (Table II). However, the samples will be pre-deformed due to the forging requirement of forming the samples. This causes the aging time to be of higher importance than the aging temperature. [8] Also, the type of quench has little effect on mechanical properties. [8]

Table II. Effect of Aging Process on Yield Strength and Ultimate Tensile Strength (UTS) on AA2195. [8]

Heat Treatment	Yield Strength (MPa)	UTS (MPa)
T6	452.8	501.8
T8	530.6	570.2

Anisotropy of AA 2195

Tensile testing illustrates various mechanical properties of a material. In this study, aluminum-copper-lithium will likely have an initial 20% difference in yield strength dependent on direction (Figure 3). [6] This difference can be reduced to 2.5% through over-aging, though the specific method was not disclosed.

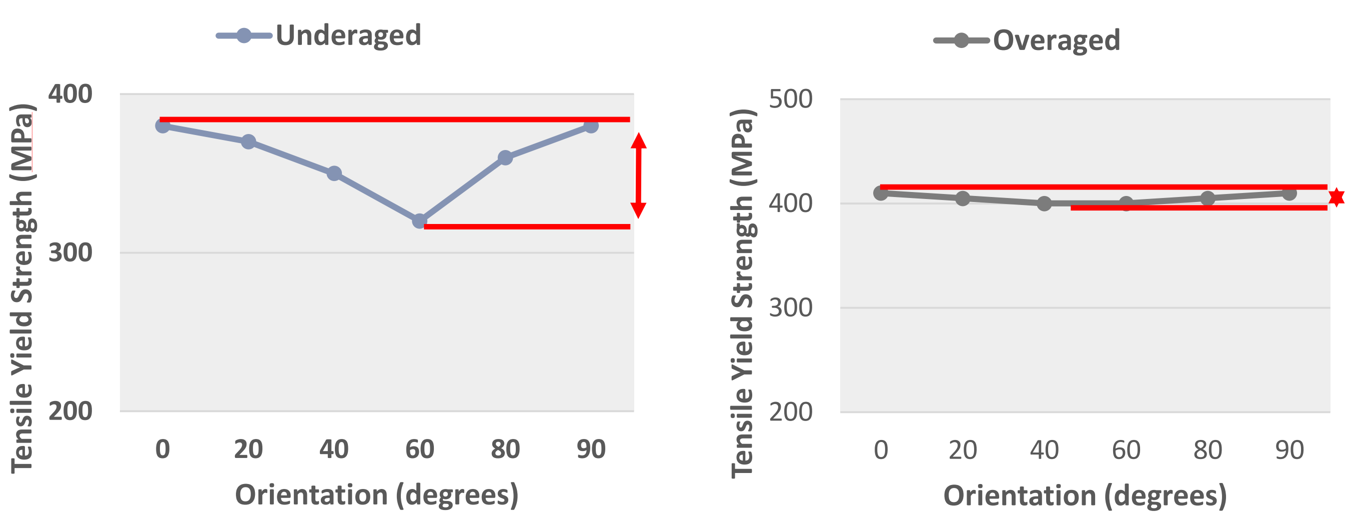

Figure 3. These two graphs display the yield strength of extruded AA2195 based on aging specification and direction with regard to extrusion direction. Over-aging could reduce the anisotropic effect from 20% to 2.5%. [6]

Problem statement

The goal of this project was to determine if reducing the anisotropy of extruded aluminum-copper-lithium alloy 2095 through heat treatment is feasible in an industrial setting. To be feasible, the heat treatment must be shorter than 48 hours and reduce the anisotropy to less than 5%. Cal Poly investigated what temperatures achieve an overaged state through hardness, and upon determining a possible aging temperature, attempted to confirm the over-aged state using tensile testing.

Procedure

Preliminary testing

Some preliminary testing was required to estimate aging times and temperatures. To determine the approximate peak-age, a standard aging procedure was followed: solutionize, quench, and age. The samples were solutionized at 950ºF for 45 minutes. Then, the samples were aged at 290ºF for up to 51 hours. These samples did not reach the peak-age condition according to hardness testing, so the procedure was adjusted: the solutionizing step was removed to preserve the nucleation sites generated by the dislocations produced by the extrusion process and the temperature was increase to 320ºF to promote faster aging. These changes worked as planned, but no over-aging was observed using hardness testing as a measure of strength. We suggested another preliminary run of the material at a higher temperature, however, due to time constraints, the study moved forward and tensile tested samples using the 320ºF heat treatment.

After heat treatment, the flat coupons were hardness tested. Placing the sample on a large anvil, the researcher used a 1/16" steel ball to make an indention. The hardness tester recorded an HRB value according the the depth of the indentation made by the ball. 40 testes were done per sample on the first preliminary test and 10 were done on the second.

Statistical Model

According to Weber Metals, previous tensile tests yielded a range of a 3 ksi. Considering that this study needed to detect a maximum difference of 1.5 ksi between the four directions to be tested, the number of samples could be kept relatively low. An ANOVA test was done to determine the approximate number of samples needed. Assuming that the standard deviation of results was 0.5 ksi and the smallest detectable difference required was 1.5 ksi, 4 replicates were required to achieve an 85% power in this experiment (Figure 4).

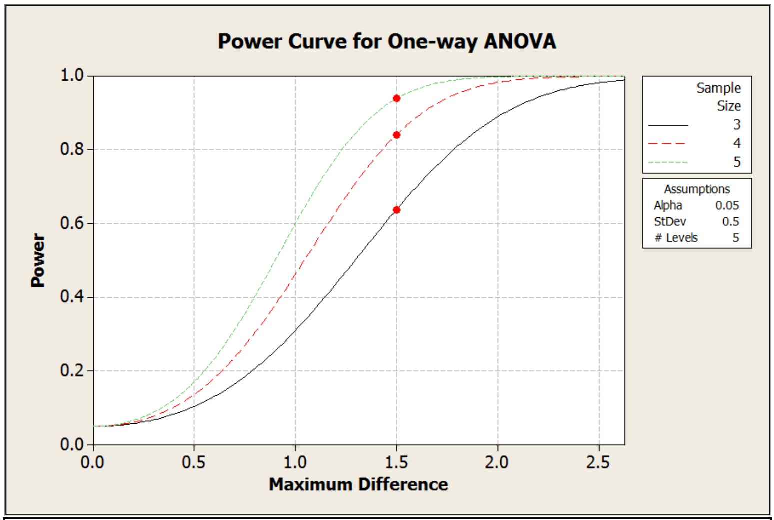

Figure 4. The standard deviation of the tensile tests to be done was based off of the range of 3 ksi given to the study by Weber Metals, while the maximum difference was based literature. [10]

Tensile Testing

Four different directions, relative to extrusion direction, were tested: longitudinal, 45°, 90°, and short transverse. These directions were machined out of the original extruded sample (Figure 5). Due to the expense of this material, tensile samples had to be relatively small in order to attain the 64 samples required to be statistically accurate. Weber Metals usually makes round samples, and so adapters had to be used to fit the samples to the Cal Poly MATE Instron Tensile Tester (Figure 6). Due to the small size of the samples and the series of adapters required to do the testing, some results were discarded due to what has been coined the "Adapter Effect" (Figure 7). This adapter effect did slightly affect

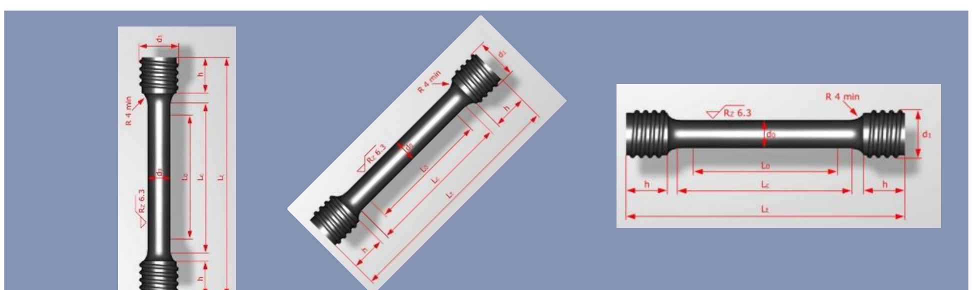

Figure 5. Assume the blue rectangle is the extruded material and the extrusion direction is left to right. The tensile samples were machined so that their primary axis aligned with the direction to be tested. In the illustration above, from left to right, there is a 90° tensile sample, a 45° tensile sample, and a longitudinal tensile sample. A short transverse sample would have its primary axis facing towards the paper.

the number of samples used in the end results, as two to three samples were used to acquire each point rather than the initially prescribed four samples due to the adapter effect. This reduces the power of the experiment to below 65%.

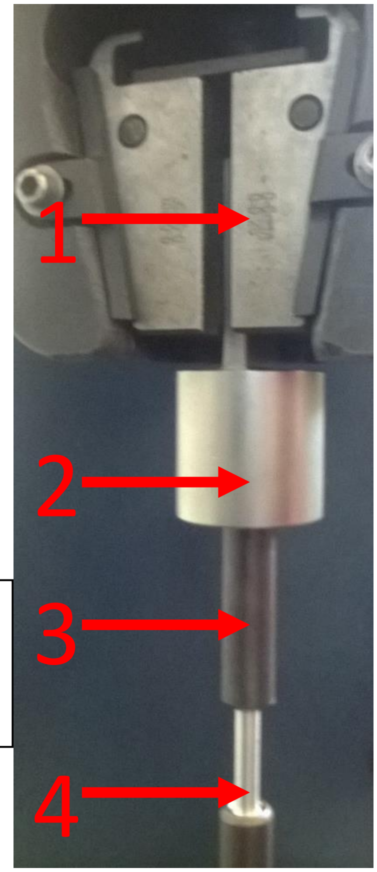

Figure 6. The set-up required to test small, AA2195 samples as follows:
1) Instron Grip
2) Flat-to-round Adapter
3) Large Round to Small Round Adapter
4) Sample — Gauge Length: 1 inch.

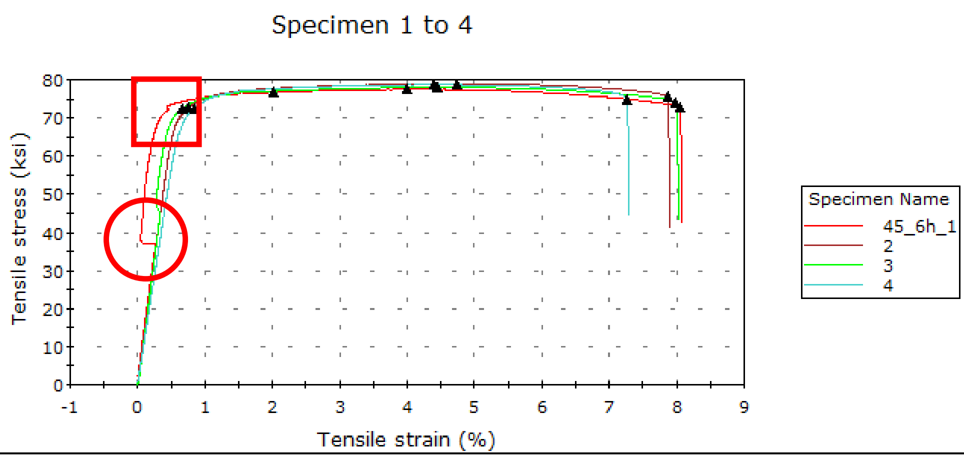

Figure 7. The above graph is a tensile test graph, as seen from the Instron. The adapter effect, highlighted by the red shapes, manifests in two ways. The first, denoted by the circle is a settling effect, is where the adapter moves to accommodate the large strain. The second, denoted by the square, is where the small threads of the sample plastically deforms.

Results

Preliminary Testing

The first preliminary test, in which we solutinized at 950ºF, quenched and aged at 290ºF, resulted in a minimum hardness of 56.1 HRB and a maximum hardness of 82.7 HRB in the 48-hour restriction that the study set. This test's heat treatment was a traditional aging process: solutinize, quench, age at a relatively low temperature. The second preliminary test resulted in a minimum hardness of 70.7 HRB and a maximum hardness of 92.7 HRB (Figure 8). This test's heat treatment only aged the as-received material.

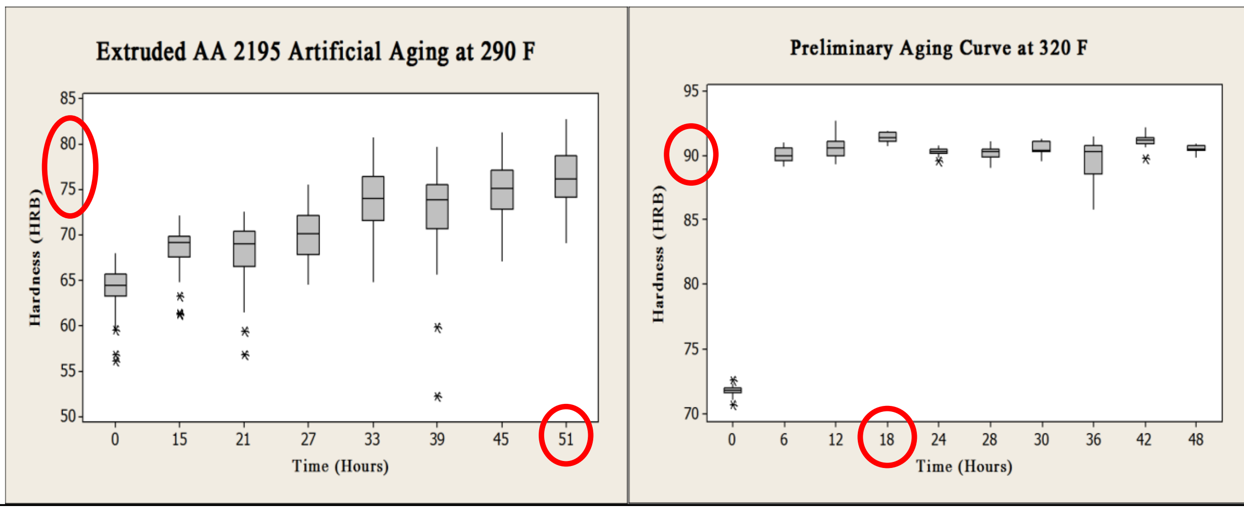

Figure 8. The 290ºF samples had a long aging time and did not reach peak age condition. The 320ºF samples aged quickly and did not overage, according to the preliminary test. The study continued with tensile testing to determine the nature of this aging.

Tensile Testing

The tensile tests were affected by the adapter effect, however many tests ran their full course. Generally, 1 to 2 samples per test were either not tested due to too few threads or poor alignment (Figure 9).

After testing each of the four directions; Longitudinal, 45º, 90º, and Short Transverse; at least three times at each aging time, the results were compiled in a table (Appendix 1). Yield strength was used as the measuring property because it was the least affected by the adapter effect and the most different across samples (Table III).

Table III. Average Yield Strength of AA2195 based on direction and aging time.

	6	18	28	48
Longitudinal	87.46	88.84	86.48	88.12
45	73.64	76.09	75.41	75.71
90	75.14	77.91	74.9	81.02
Short Transverse	74.08	77.35	79.12	72.69

The only direction that stayed constant was longitudinal, staying within a 1 ksi range of 87ksi. The 45° direction aged somewhat slower, but also leveled off around 18 hours, though at a much lower strength of 75 ksi. The 90° direction continued to rise throughout the 48 hours, while the short transverse direction exhibited an almost parabolic shape through the 48 hours. (Figure 9).

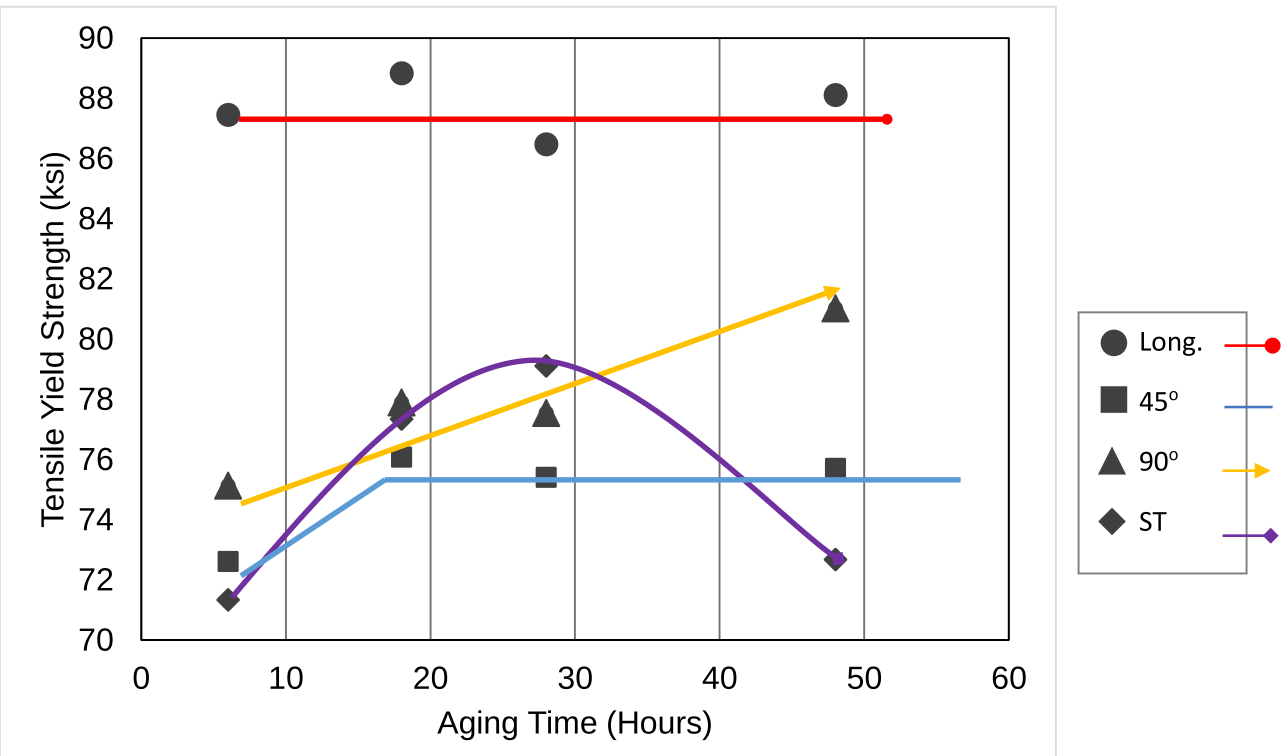

Figure 9. The samples tested in the longitudinal direction had consistently the highest yield strength, while the 45°samples and the ST samples switched between being the lowest. The general trends are displayed by the colored lines drawn on the graph.

Discussion

It does not appear that the samples over-aged with this heat-treatment, as supported by the longitudinal direction's flat aging curve. The 45° and 90° yield strengths also support this assertion. However, the short transverse direction's erratic aging curve can likely be attributed to crystal randomization. Considering that a single crystal of aluminum is anisotropic, the orientation of the crystals would have a drastic effect on yield strength.

This heat treatment reduced the magnitude of the anisotropic effect, although not to the degree predicted by literature (Figure 10). The main possible reason that this occurred is too low of temperature. A greater temperature would give the crystals greater energy to randomize. Since the literature, did not state

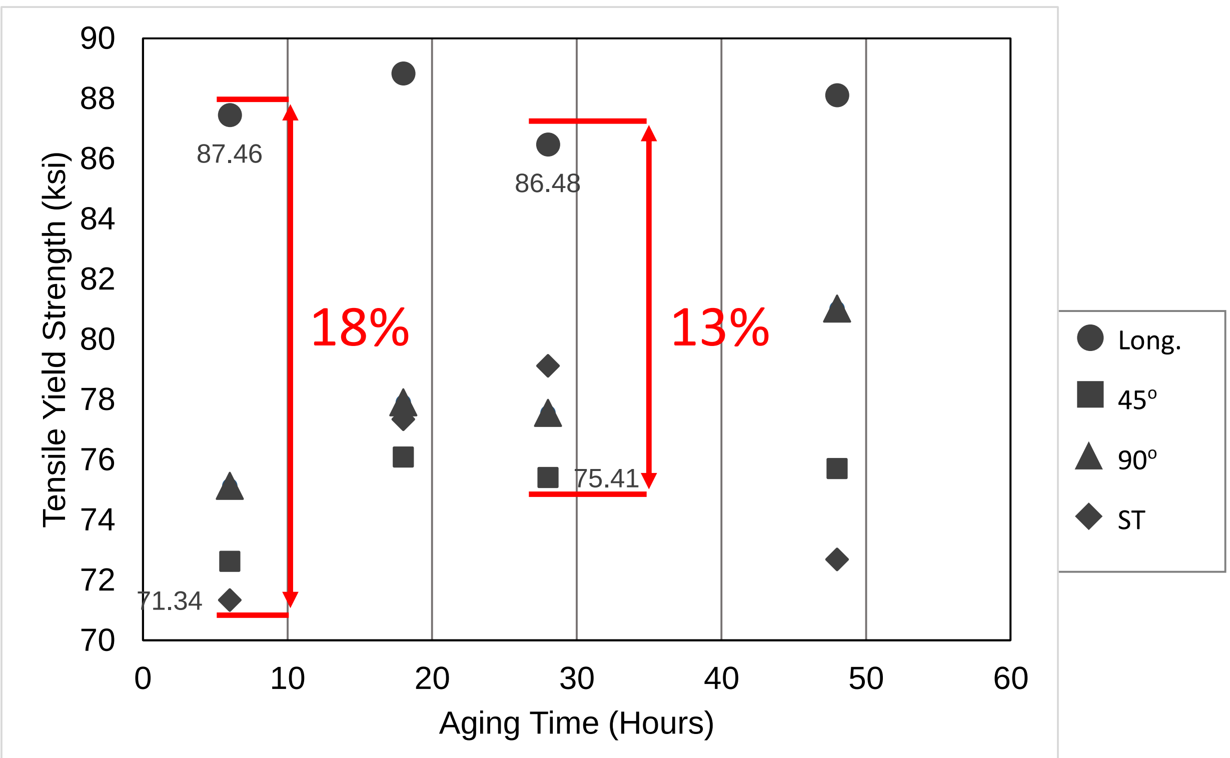

Figure 10. The heat treatment tested in this study produced a decrease in anisotropy, though not to the degree that was projected.

anything about the specifics about the heat treatment, it is possible that the heat treatment used is not industrial practical.

Investigating the results further, we found that ultimate tensile strength has some inconsitencies (Figure 11). The two points that were most suspect were short transverse at 48 hours and 90° at 28 hours.

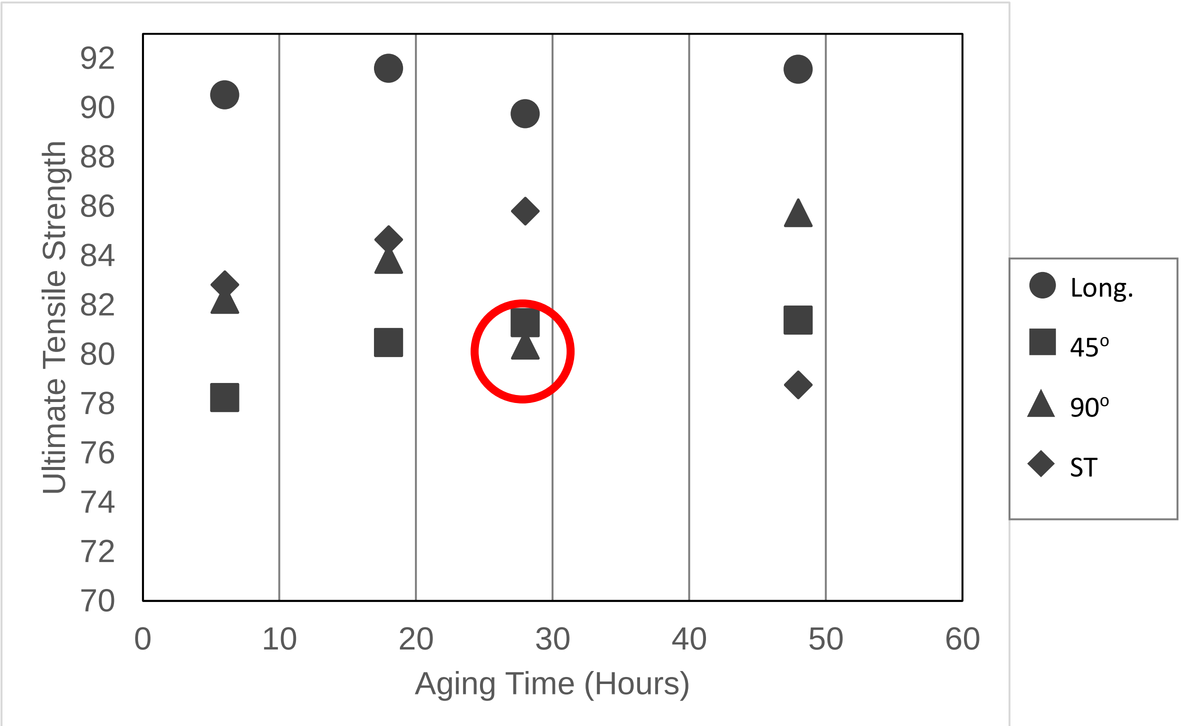

Figure 11. The above graph is of the ultimate tensile strengths of AA2195 based on aging time and direction. The data point that seemed particularly out of place was the 90° test at 28 hours, for it did not follow a similar trend to its yield strength.

The short transverse point matched the yield strength in uncharacteristic trending, but the 90° point did not match its yield strength trend. Looking at the stress-strain curve generated by the Instron for that test, we noticed that three of the tests failed early, one imparticular failed before it yielded (Appendix 2). This was due to alignment of the grip with the sample. If the adapters were not perfect in their alignment, the sample broke early and tended to affect results. We, then, removed all data results that were affected by the alignment, which greatly changed some results (Table IV , Figure 12).

Table IV. Adjusted Yield Strengths of AA21995

	6	18	28	48
Longitudinal	88.21	88.84	86.48	87.8
45	72.62	75.82	75.41	75.71
90	74	76	80	81
Short Transverse	71.34	78.49	81.27	--

Although this elimnated the short transverse data point at 48 hours, the overall effect the heat treatment had on anisotropy is effectively the same. The under-aged condition is instead a spread of 19%, but the 28 hour samples were still approximately 13% anisotropic.

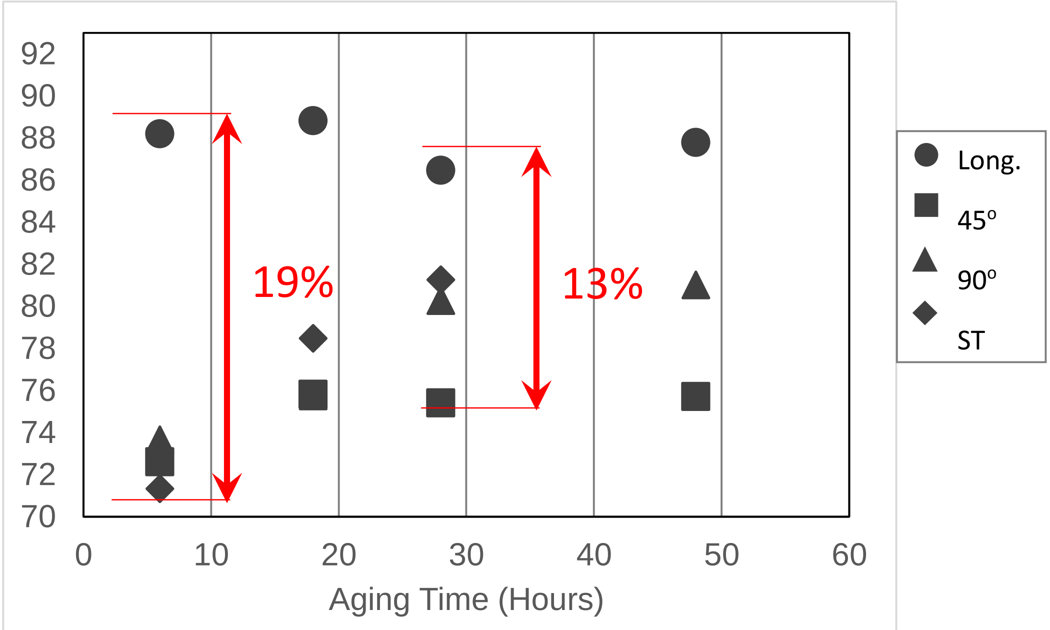

Figure 12. Adjusting the data did not change the yield strength results by much: the under aged percentage went from 18% to 19% while the most isotropic treatment stayed at 13%.

Although this procedure did not reduce anisotropy, this material should still be considered for high strength aircraft application. Comparing the yield strengths of this alloy to the current high strength aircraft alloy, AA7075-T6, AA2195 has greater strength even in its weakest direction (Figure 13). This may not be enough to persuade Boeign or other airplane manufacturers to change alloys now, but to dismiss this alloy based on anisotropy alone would be unwise.

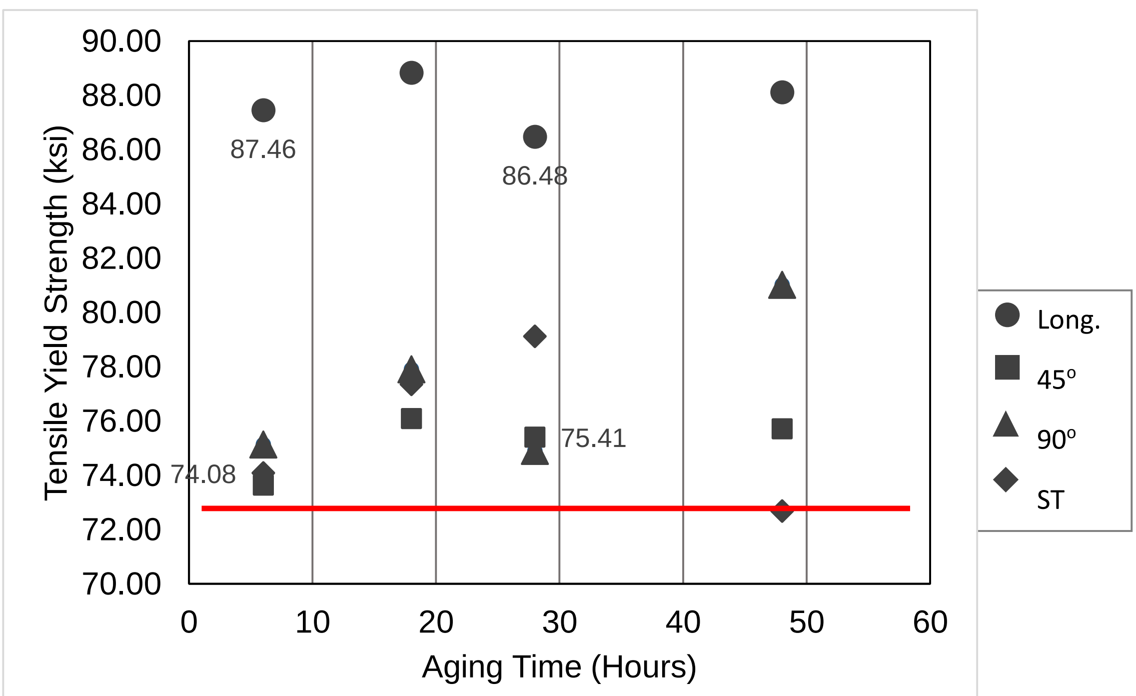

Figure 13. The line on this graph represents the yield strength of AA7075-T6, 73 ksi.

Conclusions

1) The 320ºF age with no solutionization heat treatment does in fact reduce the magnitude of the anisotropy.
2) This study did not achieve over-aging. This is supported by the flat aging curve exhibited by the longitudinal samples. Also, the other directions are exhibiting continuing aging behavior, further indicating lack of peak-aging.

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Appendix 1

Blank samples lines were not tested due to poor sample fabrication. Samples with (*) were not used in the tensile test data due to procedure errors. All units are US customary. Young's Modulus: Mpsi; UTS and Yield Stress: ksi; and Max Load in lbs.

	Young's Modulus	YIELD STRESS	MAX LOAD	UTS	% elong. to fail
ST_6hr_1	12.6	71.56	3.96	81.42	2.22
ST_6hr_2	12.7	70.7	4	82.04	3.14
ST_6h_3	12.1	71.76	4.02	82.49	2.38
ST_6h_4	13.2	82.3	4.22	85.31	4.83
per_6h_1	12.1	75	4	81.4	5.43
per_6h_2	12.4	73.67	4.06	82.79	3.43
per_6h_3	11.9	75.02	3.94	81.56	5.7
per_6h_4	12.3	76.86	4.02	83.16	5.24
L_6h_1					
L_6h_2	11.3	88.21	4.53	90.92	8
L_6h_3	13.1	86.7	4.35	90.1	7.98
L_6h_4					
45_6h_1	3.06	76.68	3.83	77.46	8.05
45_6h_2	13.1	72.76	3.91	78.93	7.87
45_6h_3	17	72.51	3.89	77.95	8
45_6h_4	11.3	72.59	3.89	78.64	7.26

	Young's Modulus	YIELD STRESS	MAX LOAD	UTS	% elong. to fail
ST_18h_1	12.4	73.99	4.11	84.37	2.24
ST_18H_2	12.5	81.19	4.2	85.62	3.71
ST_18h_3	12.1	73.91	4.04	83.65	-0.92
ST_18H_4	11.1	80.3	4.17	84.95	3.03
per_18h_1	12.5	76.48	4.12	84.56	2.2
per_18h_2	12.1	79.35	4.11	81.79	1.52
per_18h_3	12.3	80.76	4.16	85.37	3.16
per_18h_4	13.7	75.03	4.14	83.66	1.99
L_18h_1	12.7	89.2	4.55	91.92	6.83
L_18h_2	12.4	89.19	4.54	91.76	8.31
L_18h_3	11.8	88.51	4.52	91.27	8.41
L_18h_4	12.9	88.46	4.45	91.4	7.62
45_18h_1	13	75.08	3.82	81	6.03
45_18h_2	12.3	75.88	3.94	81.59	4.8
45_18h_3	11.3	76.5	4.07	81.64	6.96
45_18h_4	13	76.89	3.81	77.65	0.83

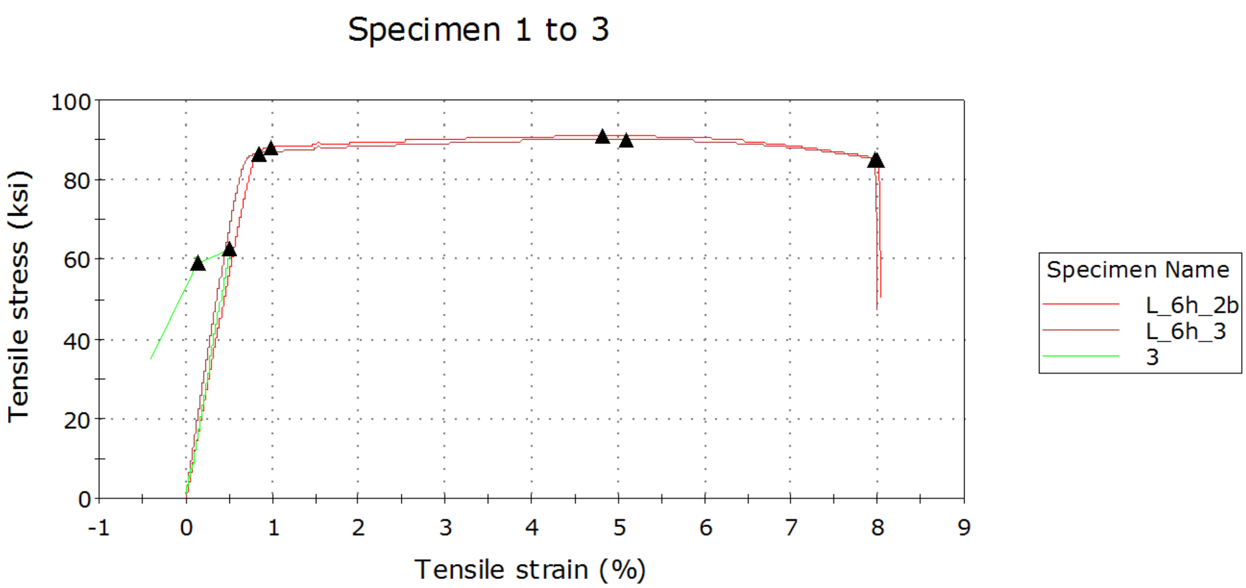
	Young's Modulus	YIELD STRESS	MAX LOAD	UTS	% elong. to fail
ST_28h_1	11.5	74.81	4.1	84.8	1.99
ST_28h_2	10.4	81.77	4.3	86.2	3.49
ST_28h_3	10.5	80.77	4.2	86.3	3.53
ST_28h_4					
per_28h_1	13.3	77.21	4.11	83.8	1.53
per_28h_2	12.6	80.29	4.18	85.2	3.59
per_28h_3	11.5	75.16	4.07	81.6	1.56
per_28h_4	14	66.92	3.51	70.9	0.59
L_28h_1	10.9	89.37	4.56	92.1	8.63
L_28h_2	10.3	86.1	4.39	89.5	7.57
L_28h_3	12.1	83.96	4.3	87.6	6.47
L_28h_4					
45_28h_1	12.1	74.88	3.96	80.6	6.06
45_28h_2	11.3	74.98	3.94	80.9	6.33
45_28h_3	11.8	76.37	4.1	82.3	6
45_28h_4					

	Young's Modulus	YIELD STRESS	MAX LOAD	UTS	% elong. to fail
ST_48h_1	11.8	72.46	3.83	78.1	1.15
ST_48h_2	10.2	72.91	3.9	79.4	1.34
ST_48h_3					
ST_48h_4					
per_48h_1	11.2	81.69	4.22	86.6	3.01
per_48h_2	11.3	81.56	4.19	86.1	3.32
per_48h_3	13.1	79.82	4.12	84.5	3.13
per_48h_4					
L_48h_1	10.7	85.81	4.39	89.4	6.66
L_48h_2	11.5	90.15	4.51	93.4	8.59
L_48H_3*	11.2	89.06	4.5	92.4	5.69
L_48h_4	12.5	87.45	4.43	91	6.95
45_48h_1	11.9	75.18	3.91	80.9	5.2
45_48h_2	11.8	76.42	3.96	81.9	3.66
45_48h_3	11.5	75.54	3.93	81.3	4.57
45_48h_4					

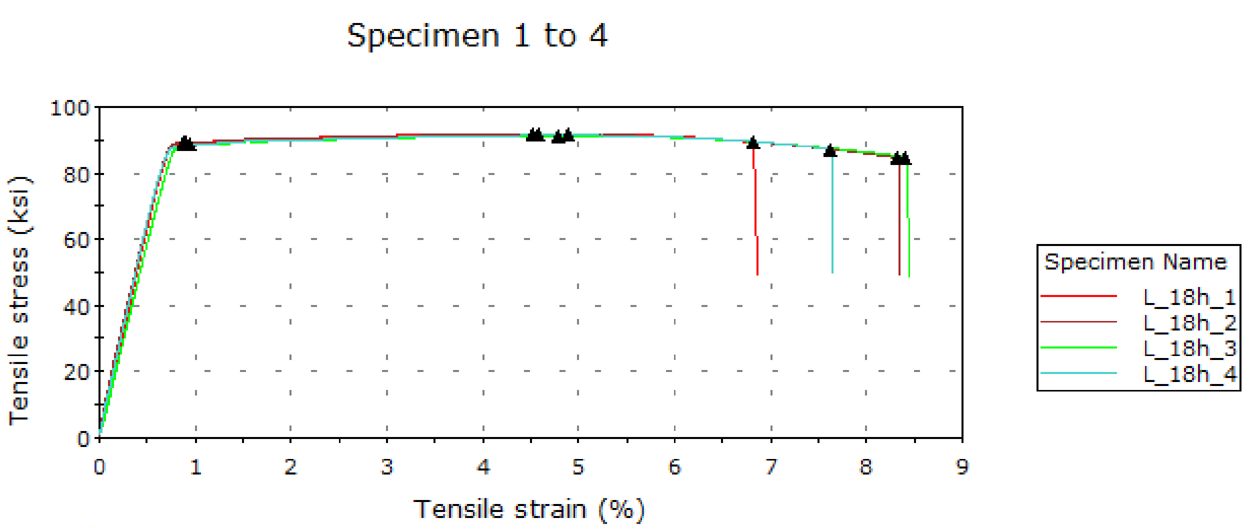
Appendix 2

The following stress strain curves are those produces by the Instron, in their entirety. Some tests were splits amongst multiple graphs due to equipment issues that did not allow all tests of a single parameter to occur on a single graph. The graphs are organized first by direction, then by aging time.

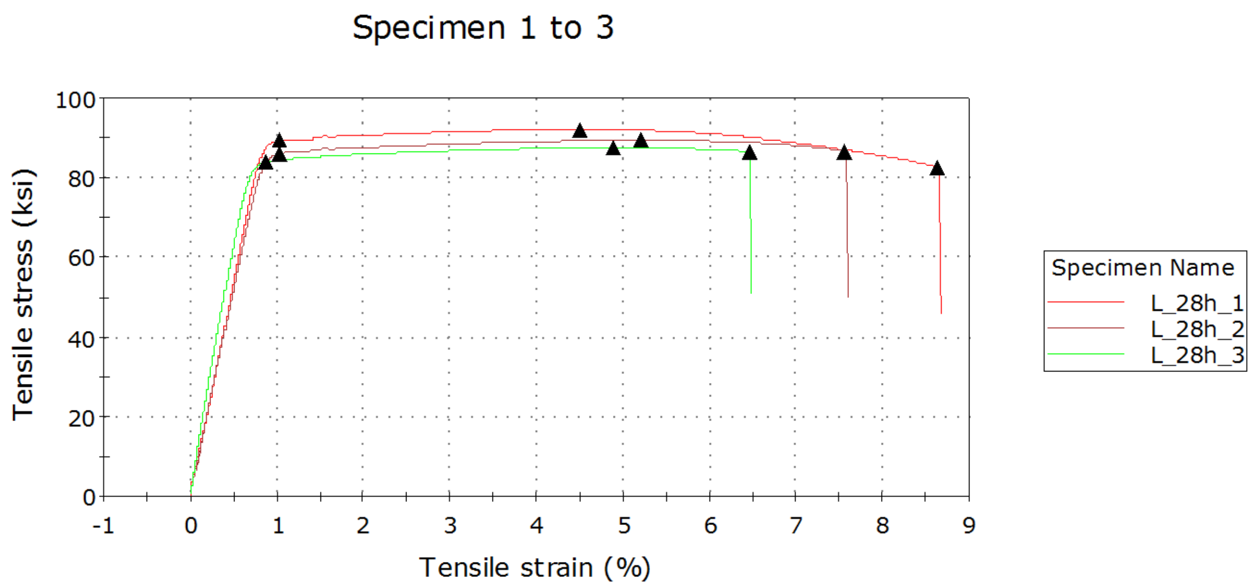
Longitudinal – 6 hour



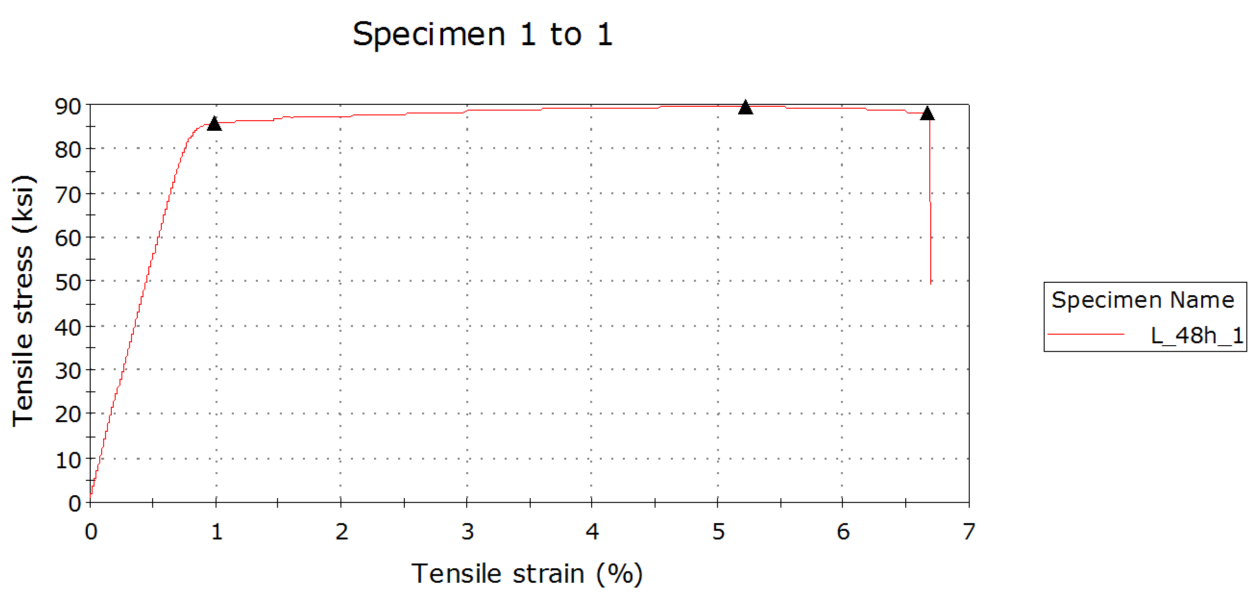
Longitudinal – 18 hour



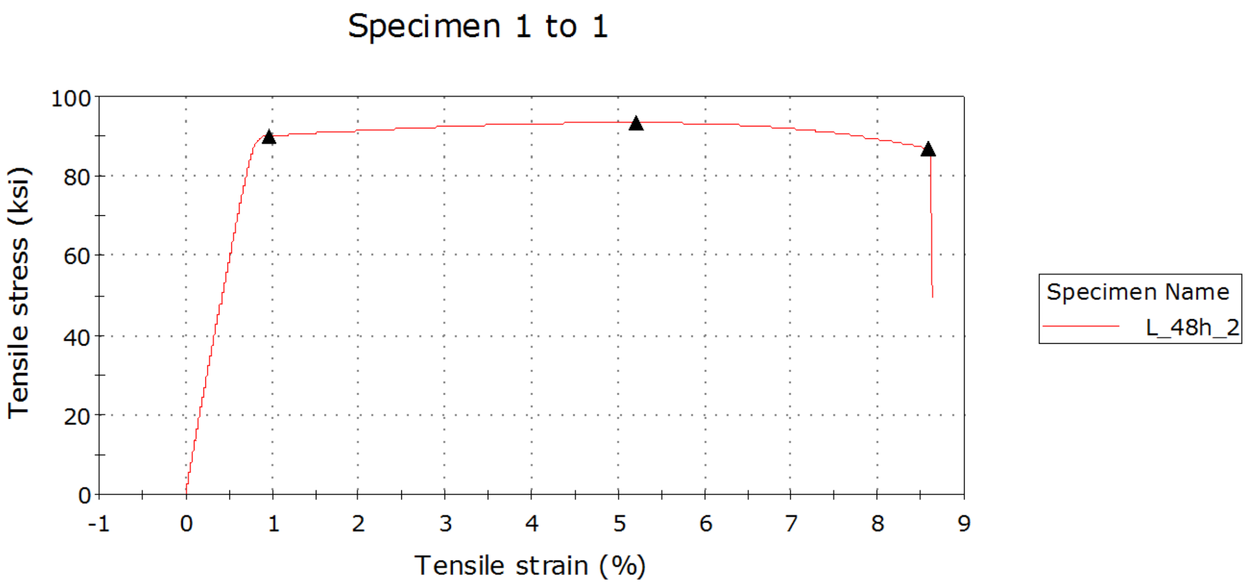
Longitudinal – 28 hour

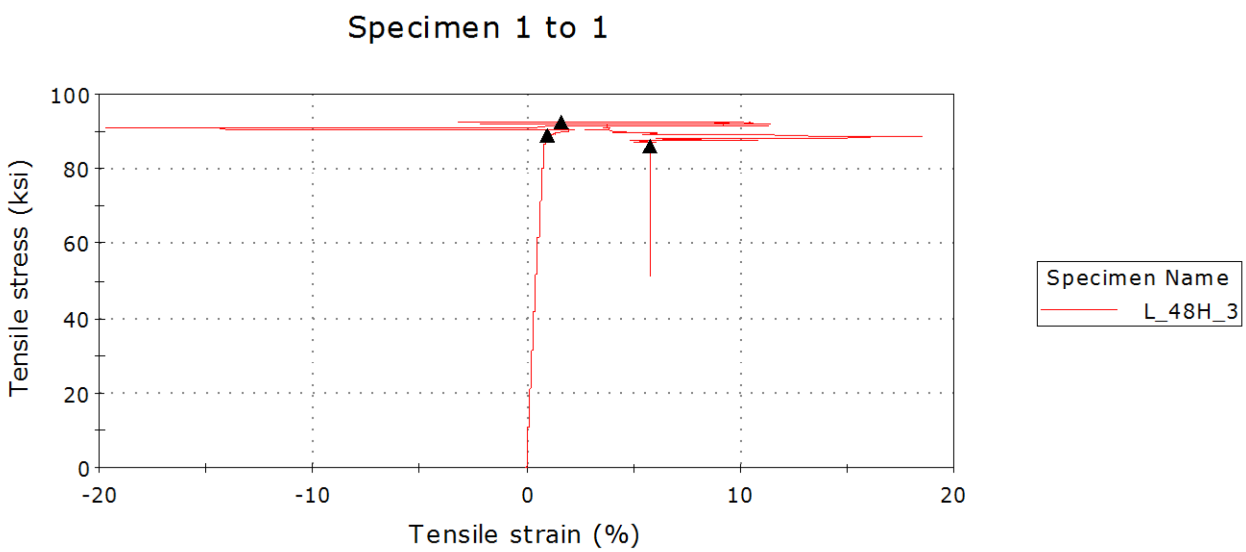


Longitudinal – 48 hour

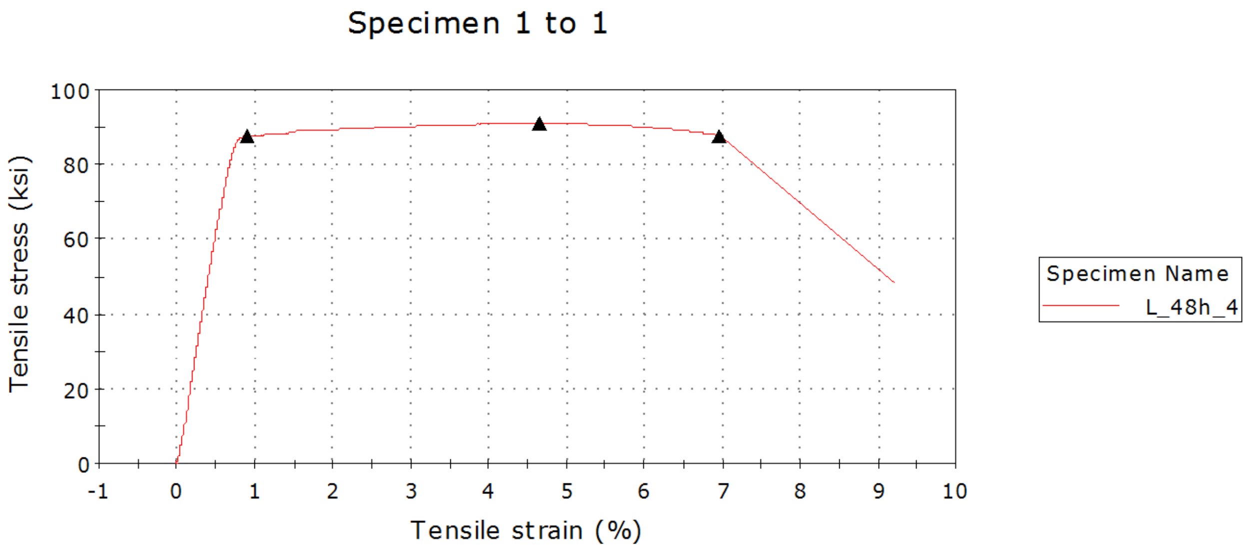


Longitudinal – 48 hour continued

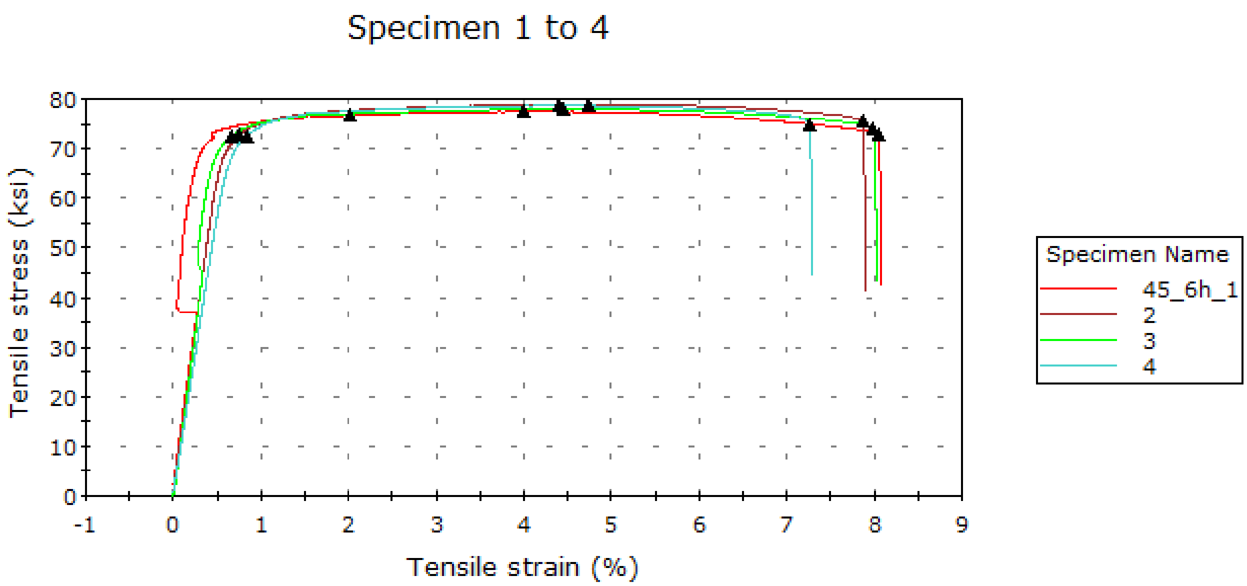




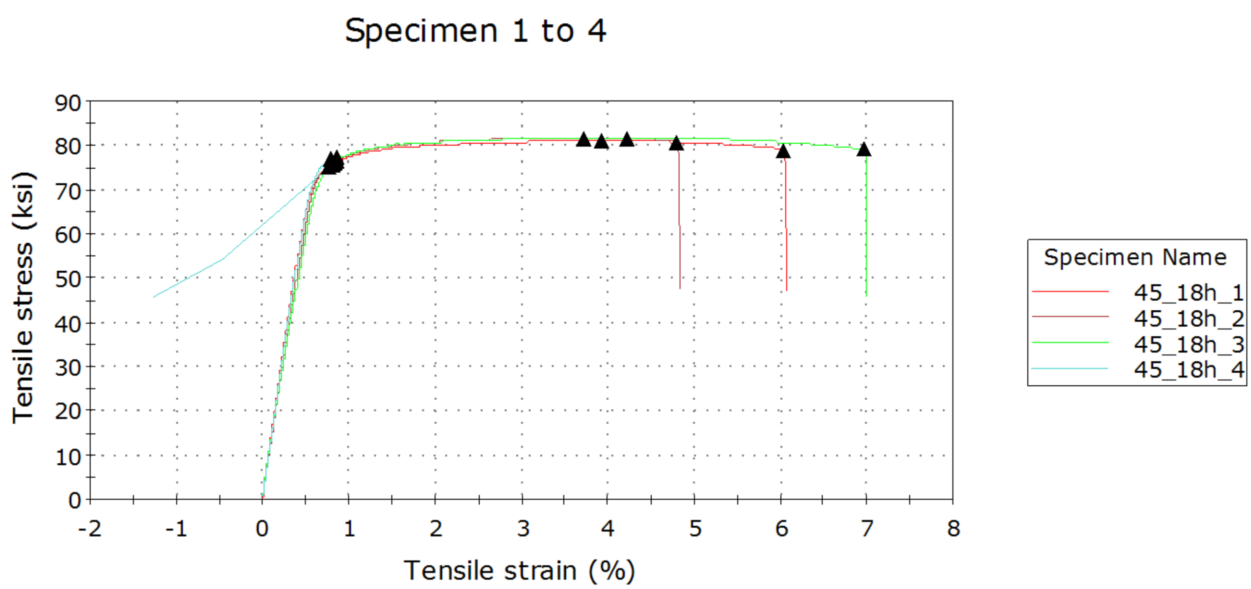
Longitudinal – 48 hour conitnued



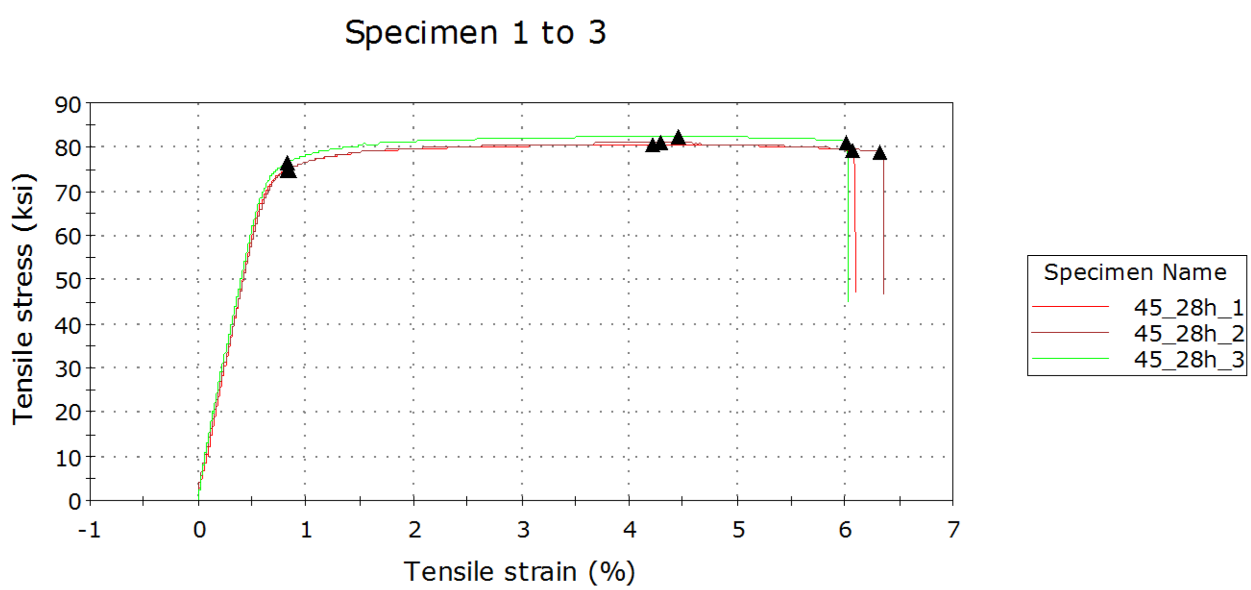
45° – 6 hour



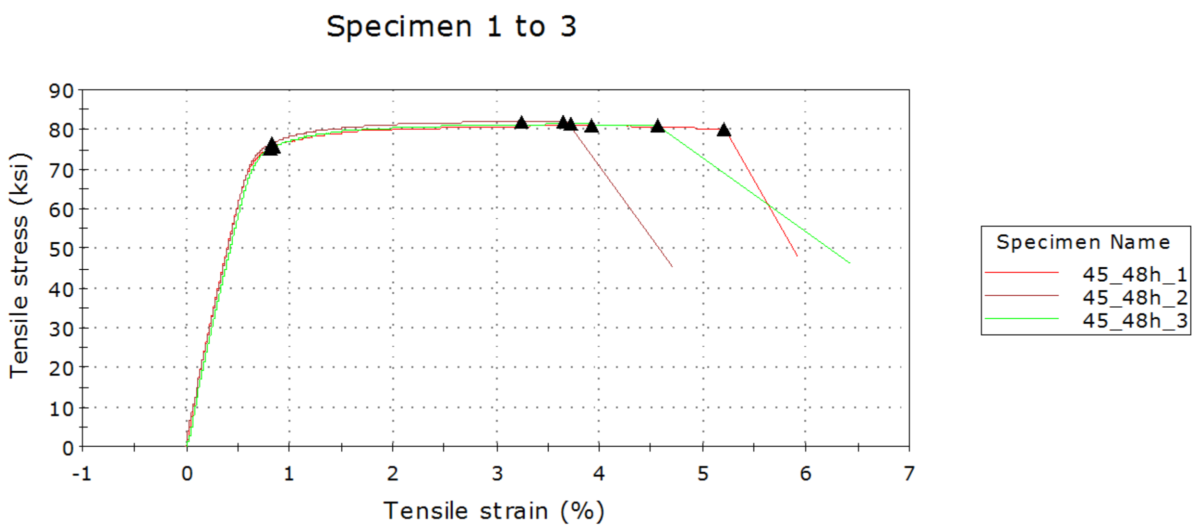
45º – 18 hour



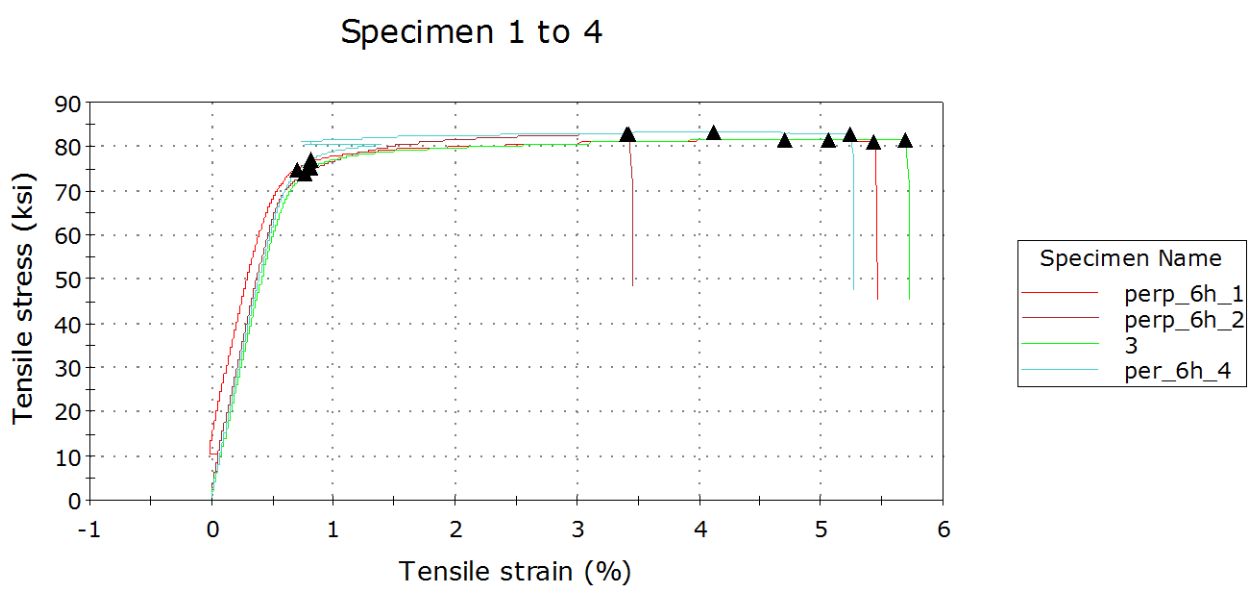
45º – 28 hour



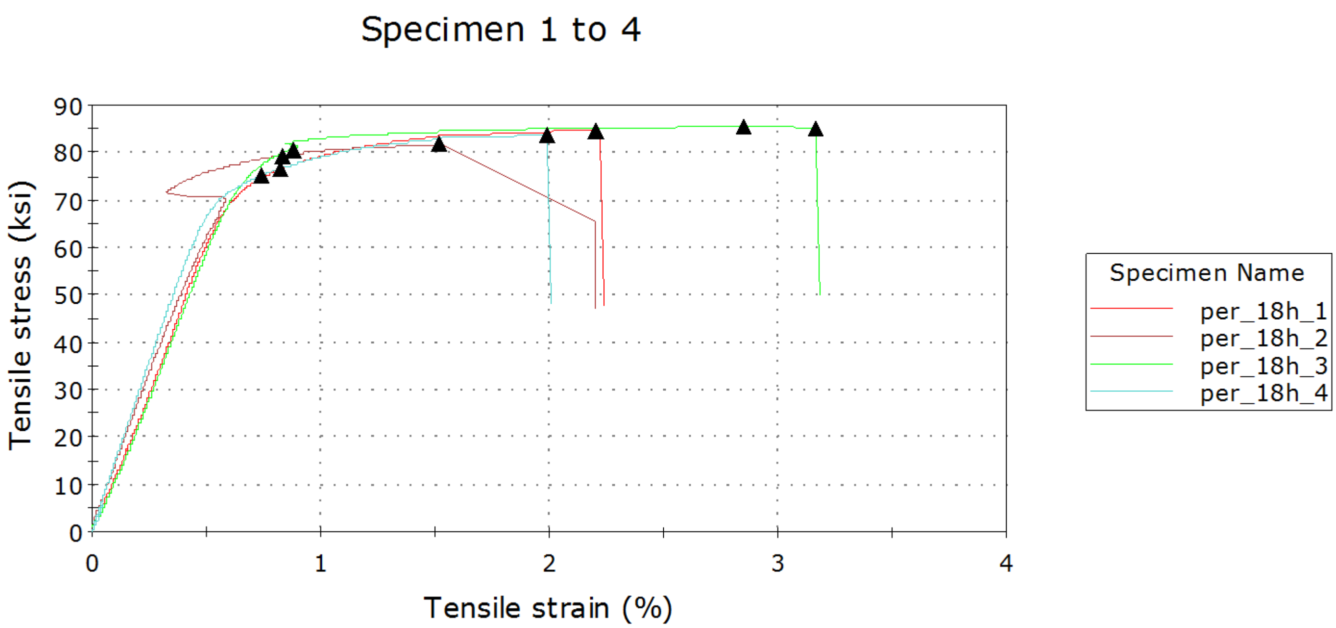
45° – 48 hour



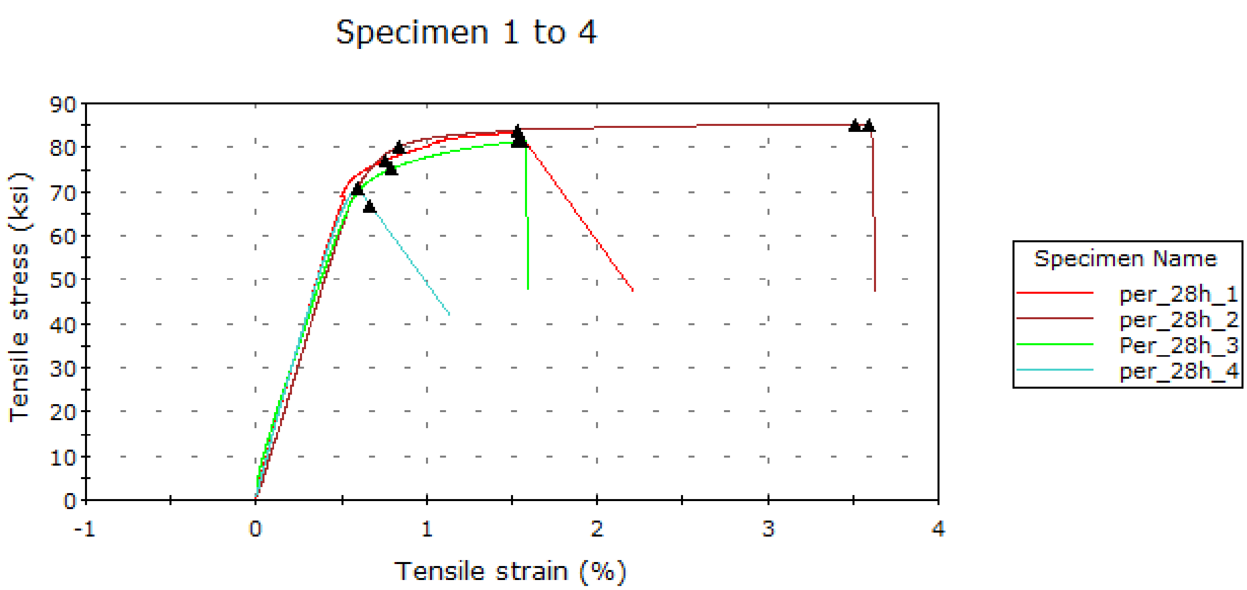
90° – 6 hour



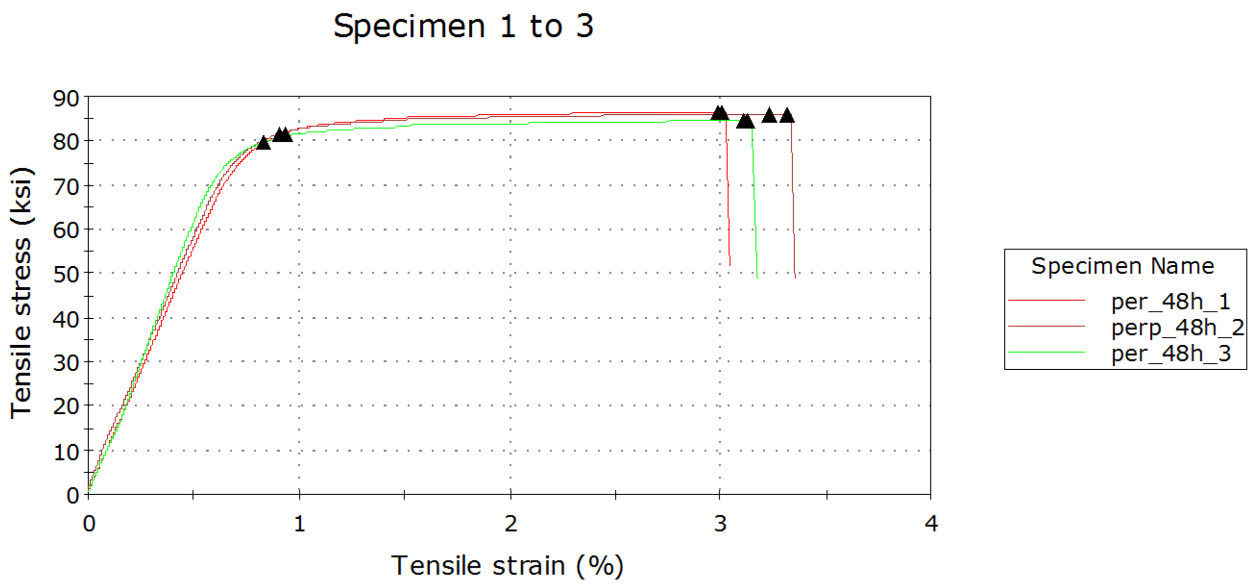
90° – 18 hour



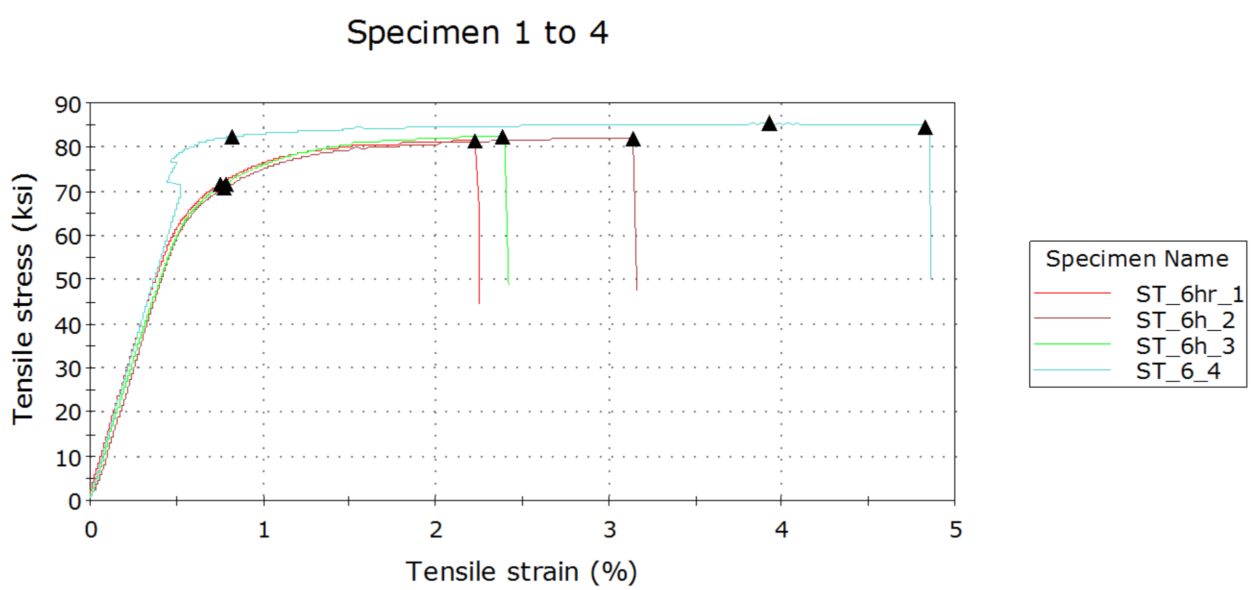
90° – 28 hour



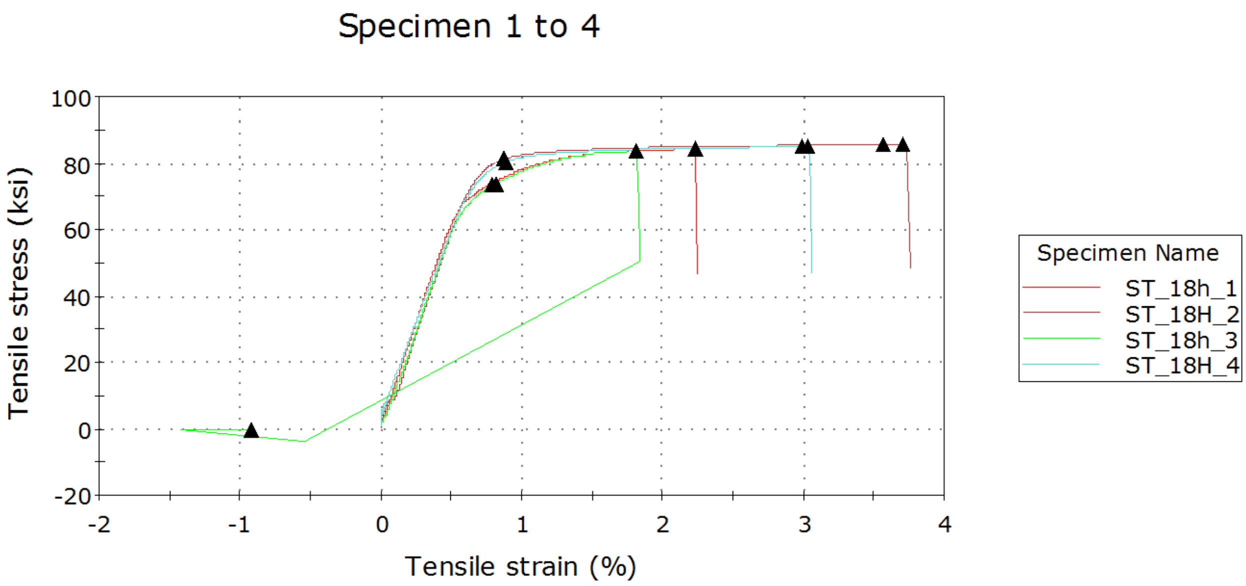
90º – 48 hour



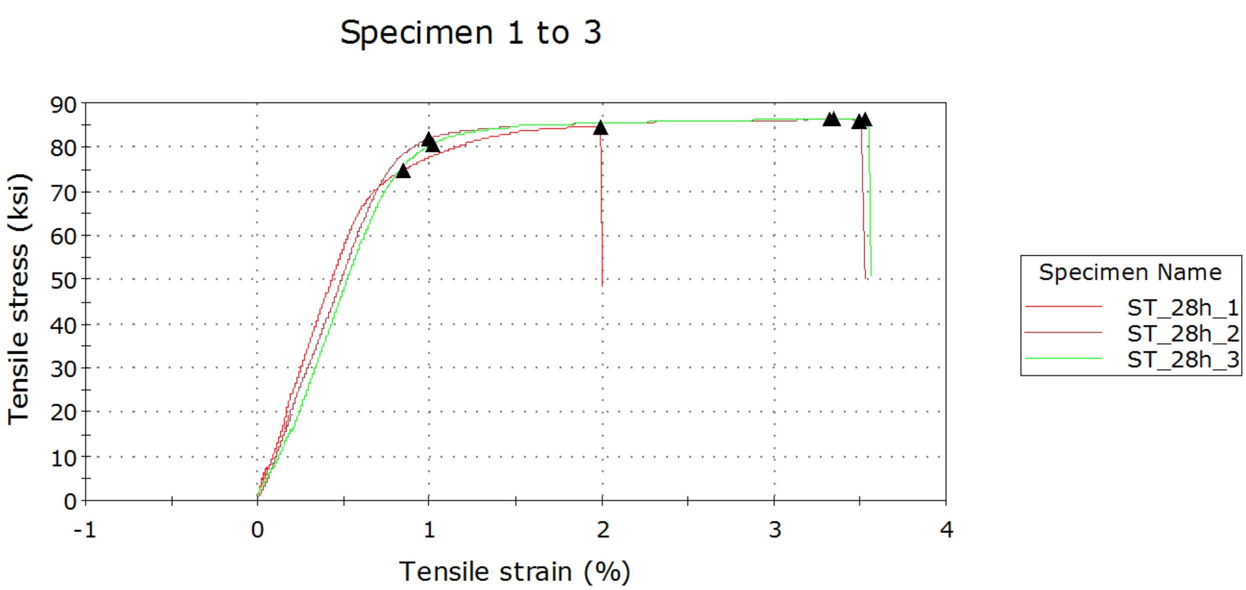
Short Transverse – 6 hour



Short Transverse – 18 hour



Short Transverse – 28 hour



Short Transverse – 48 hour