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Material Characterization of Aluminum Lithium Alloys Used in Aerospace Applications, Volume 2: Static Properties

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16. Abstract

This study was performed by the FAA to assess the material properties and mechanical behavior of next-generation aluminum lithium (Al-Li) alloys being used in aerospace structures through comparisons made to conventional aerospace aluminum alloys (AAs). The latest generation of Al-Li alloys purports to offer a significant weight savings over conventional aerospace aluminums resulting in significant use in recent aircraft and aerospace applications. The current public data provided for these alloys are limited and do not provide a comprehensive understanding of the strengths and weaknesses of these materials. Because previous generations of Al-Li alloys displayed material behaviors that limited their use for aerospace applications, it is necessary to understand the properties of these new alloys and identify if any unique behaviors exist.

Two Al-Li alloys were considered as a case study, namely Al-Li 2198-T8 and 2196-T8511 alloys used for skin and extrusion applications, respectively. Several properties were assessed and compared with the baseline AA 2024-T3/351 and 7075-T6 alloys, including static properties, fatigue and fatigue crack-growth behavior, and supplemental properties. This volume (volume 2 of 4) provides in-depth detail on the static properties tests performed as part of this program. In total, three types of static tests were conducted—tension, compression, and shear. Each test was performed on a uniaxial test frame to an applicable ASTM standard where possible. The results covered basic material properties, such as modulus and strength. Additionally, the test matrices included three material thicknesses and five grain orientations to evaluate the level of material thickness effect and anisotropy. Overall, the results were in line with expectations, as all material property values exceeded Metallic Materials Property Development and Standardization B basis values. There was some anisotropy seen in the Al-Li alloys with strength values at the 45-degree grain orientation differing from those at the longitudinal and longitudinal transverse directions.

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LIST OF ACRONYMS

AA	Aluminum alloy
Al-Li	Aluminum lithium
CV	Coefficient of variation
FAA WJHTC	Federal Aviation Administration William J. Hughes Technical Center
L	Longitudinal (rolling direction)
LT	Longitudinal transverse
LVDT	Linear variable differential transformer
MMPDS	Metallic Materials Property Development and Standardization
NIAR	National Institute for Aviation Research
UDRI	University of Dayton Research Institute

EXECUTIVE SUMMARY

This study was performed by the FAA to assess the material properties and mechanical behavior of next-generation aluminum lithium (Al-Li) alloys being used in aerospace structures through comparisons made to conventional aerospace aluminum alloys (AAs). The latest generation of Al-Li alloys purports to offer a significant weight savings over conventional aerospace aluminums resulting in significant use in recent aircraft and aerospace applications. The current public data provided for these alloys are limited and do not provide a comprehensive understanding of the strengths and weaknesses of these materials. Because previous generations of Al-Li alloys displayed material behaviors that limited their use for aerospace applications, it is necessary to understand the properties of these new alloys and identify if any unique behaviors exist.

Two Al-Li alloys were considered as a case study, namely Al-Li 2198-T8 and 2196-T8511 alloys used for skin and extrusion applications, respectively. Several properties were assessed and compared with the baseline AA 2024-T3/351 and 7075-T6 alloys, including static properties, fatigue, and fatigue crack growth behavior; and supplemental properties. This volume (volume 2 of 4) provides in-depth detail on the static properties tests performed as part of this program. In total, three types of static tests were conducted—tension, compression, and shear. Each test was performed on a uniaxial test frame to an applicable ASTM standard where possible. The results covered basic material properties, such as modulus and strength. Additionally, the test matrices included three material thicknesses and five grain orientations to evaluate the level of material thickness effect and anisotropy. Overall, the results were within expectations, as all material property values exceeded Metallic Materials Property Development and Standardization A and B basis allowable. There was some anisotropy seen in the Al-Li alloys with strength values at the 45-degree grain orientation differing from those at the longitudinal and longitudinal transverse directions.

1. INTRODUCTION

This report is the second of four volumes detailing an effort sponsored by the FAA to conduct a comparative evaluation of the latest generation of aluminum lithium (Al-Li) alloys [1–3]. The primary objective of this effort was to gain a better understanding of the overall mechanical behavior of the third-generation Al-Li alloys relative to traditional aerospace aluminums (AAs). As Al-Li alloys continue to gain more widespread use in primary aircraft structure [4] it is necessary to develop a better knowledge base on the material to ensure its safe implementation. In pursuit of this goal, the program test matrix consisted of eight tests grouped into three categories: static, fatigue and fatigue crack growth, and supplemental. This volume contains detailed information on the static properties tests conducted by the FAA William J. Hughes Technical Center (FAA WJHTC), University of Dayton Research Institute (UDRI), and National Institute for Aviation Research (NIAR). Tension, compression, and shear tests were performed to applicable ASTM standards where possible [5–9]. Table 1 shows an overview of the tests covered in this volume with the performing organization.

Table 1. Static properties test overview

Test Type	Test Name and Standard	Materials Tested	Variables*	Property Measured	Performing Organization
Tension Properties	Tension Properties, ASTM E8	2198-T8 2024-T3	t_s (in.): 0.071, 0.125, 0.25 θ: L, 22.5°, 45°, 67.5°, LT	F_{ty}, F_{tu}, E_t, *e%*	FAA WJHTC
	Elevated Temperature Tension Test, ASTM E8, E21	2198-T8 2024-T3	t_s (in.): 0.071, 0.125, 0.25 θ: L, 45°, LT T (°F) = RT, 200, 350	F_{ty}, F_{tu}, E_t, *e%*	UDRI
	Tension Properties, ASTM E8	2196-T8511 7075-T6	t_e (in.): 0.063, 0.125, 0.160 θ: L, 22.5°, 45°, 67.5°, LT	F_{ty}, F_{tu}, E_t	NIAR
Compression Properties	Compression Properties, ASTM E9	2198-T8 2024-T3	t_s (in.): 0.071, 0.125, 0.25 θ: L, 22.5°, 45°, 67.5°, LT	F_{cy}, E_c	FAA WJHTC
	Compression Properties, ASTM E9	2196-T8511 7075-T6	t_e (in.): 0.063, 0.125, 0.160 θ: L, 22.5°, 45°, 67.5°, LT	F_{cy}, E_c	NIAR
Shear Properties	Shear Properties, ASTM B831	2198-T8 2196-T8511 2024-T3 7075-T6	t_s (in.): 0.071, 0.125, 0.25 t_e (in.): 0.063, 0.125, 0.160 θ: L, 22.5°, 45°, 67.5°, LT	F_{su}, G	NIAR

* Variable definitions:

t_s = Typical sheet thickness for the 2198-T8 and 2024-T3, in inches
t_e = Typical extrusion thickness for the 2196-T8511 and 7075-T6, in inches
θ = Grain orientation, degree from longitudinal (rolling) direction
T = Temperature, °F

The static properties tests were conducted to provide a comparison of the basic material properties for the Al-Li alloys to the traditional aerospace aluminums. As shown in table 1, each material was tested at a variety of different thicknesses and grain orientations. This was performed to evaluate to what extent the subject alloys exhibited thickness effects or anisotropic behaviors. Each test generally involved three thicknesses and five grain orientations. The thicknesses for the Al-Li 2198-T8 and AA 2024-T3/351 were 0.071 inch, 0.125 inch, and 0.25 inch. The thicknesses for the Al-Li 2196-T8511 were driven by the extrusions available and were selected at 0.060 inch, 0.120 inch, and 0.145 inch. The AA 7075-T6 thicknesses were matched as closely as possible to the Al-Li 2196-T8511 using common sheet thicknesses available from commercial retailers. The AA 7075-T6 thicknesses tested were 0.063 inch, 0.125 inch, and 0.160 inch. The five grain orientations were evenly spaced at 22.5-degree intervals, ranging from the rolling or extrusion direction (0 degrees), referred to as longitudinal (L), through 90 degrees and ending transverse the rolling direction, referred to as longitudinal transverse (LT). Throughout this report the grain orientation indicates the direction of the applied load.

The subsequent sections detail each of the previously listed tests with additional data available in the respective appendices. The Al-Li alloys used in these tests were produced by Constellium (the 2196-T8511 extrusions were supplied through Bombardier Inc.), and the baseline aluminums were purchased through commercial retailers. All materials were tested at the thickness supplied with no additional surface machining. Additionally, all materials were tested in the bare condition with no cladding or other surface coat involved.

2. TENSION PROPERTIES

Static tension properties tests were conducted by the FAA WJHTC, UDRI, and the NIAR on the Al-Li 2198-T8 and 2196-T8511 alloys, and on the traditional aluminum baselines AA 2024-T3/351 and 7075-T6. The tension testing was divided into three segments with the overall test matrix shown in table 2. The data collected were used to derive values for properties such as Young's Modulus, yield strength (0.2% offset), ultimate strength, and percent elongation at failure. Three repeats were run for each combination of material, thickness, and grain orientation with reported values generally representing the average of the three tests.

Table 2. Tension properties test matrix

Performing Organization	Material	Thickness (inch)	Test Condition	Grain Orientation					Total
				L	22.5°	45°	67.5°	LT	
FAA WJHTC	2024-T3	0.071	RTA*	3	3	3	3	3	15
		0.125		3	3	3	3	3	15
	2024-T351	0.25		3	3	3	3	3	15
	2198-T8	0.071		3	3	3	3	3	15
		0.125		3	3	3	3	3	15
		0.25		3	3	3	3	3	15
UDRI	2024-T3	0.071	RTA*					3	3
			200°F					3	3
			350°F					3	3
	2198-T8		RTA*	3		3		3	9
			200°F	3		3		3	9
			350°F	3		3		3	9
NIAR	7075-T6	0.063	RTA*	6**	3	3	3	3	18
		0.125		6**	3	3	3	3	18
		0.160		6**	3	3	3	3	18
	2196-T8511	0.060		6**	3	3	3	3	18
		0.120		6**	3	3	3	3	18
		0.145		3	3	3	3	3	15

*RTA=room temperature, ambient
** Three micro-specimens (figure 3) and three full-size (figure 1) tested

2.1 TENSION SPECIMEN DESCRIPTIONS

Each lab used a variation of the standard ASTM E8 dog-bone geometry to accommodate specific requirements of the individual tests. The FAA WJHTC (see figure 1) used the standard dimensions; UDRI (see figure 2) used extended grips because of the dimension of the oven used for the elevated temperatures; and NIAR (see figure 3) used a micro-specimen geometry because of the size limitations of the Al-Li 2196-T8511 extrusions as detailed in volume 1 of this report. NIAR also tested full-size specimens in the longitudinal (L) grain direction, similar to those tested by the FAA WJHTC and UDRI, to evaluate the effect of specimen size on test results. Those full-size tension specimens were tested at each material and thickness except for the Al-Li 2196-T8511 at 0.145-inch thick because of insufficient material. Finally, a 0.005-inch taper was added to the gauge section of the FAA WJHTC and UDRI specimens to ensure failure of the specimen at the center of the gauge section. All specimens were tested at the thickness of the supplied material.

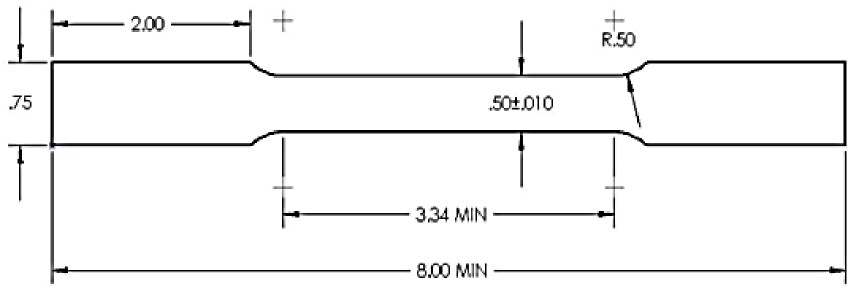

Figure 1. FAA WJHTC tension specimen geometry

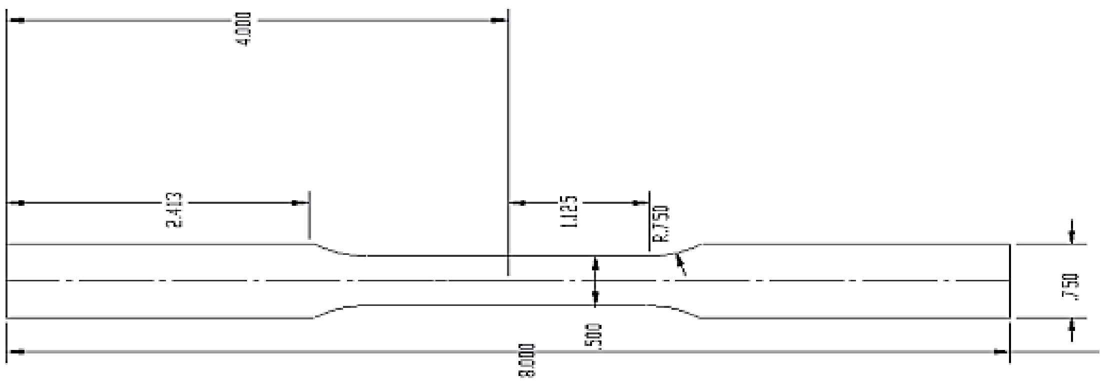

Figure 2. UDRI tension specimen geometry

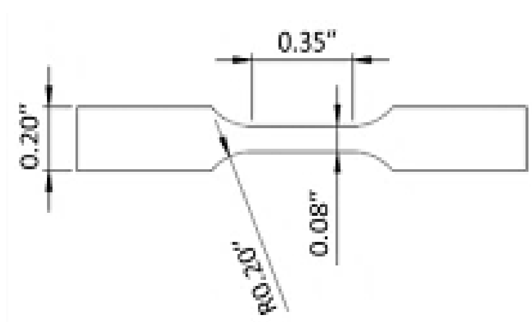

Figure 3. NIAR micro-tension specimen geometry

2.2 EXECUTION OF THE TESTING

2.2.1 Al-Li 2198-T8 and AA 2024-T3/351

The tension testing of the Al-Li 2198-T8 and AA 2024-T3/351 alloys at room temperature was conducted by the FAA WJHTC. There the tests were performed on a MTS 55 kip uniaxial, servo-hydraulic test frame with hydraulic wedge grips. A MTS model 632.11E-20 extensometer (1-inch gauge length, 0.16-inch travel) and Vishay model CEA-13-062UW-350 strain gauges were used on each specimen to record strain in the gauge section throughout the test (the Al-Li 2198-T8 specimens at the 0.071-inch thickness only equipped half of the specimens with strain gauges).

A 2-inch gauge section was also carefully marked in ink on each specimen per ASTM E8 to measure percent elongation.

The tests were run under a constant crosshead displacement rate of 0.25 inch/min with each specimen taken to final fracture. Data were collected using a MTS FlexTest SE controller at a rate of approximately 100 Hz and included the load, displacement, and strain (via extensometer and strain gauges). The reading from the extensometer was recorded directly as strain, whereas the signal from the strain gauge was conditioned by a Vishay 3210 signal-conditioning amplifier and recorded in volts. Each strain gauge was calibrated while installed on the specimen and a conversion factor was calculated to convert the volt readings to strain. The extensometer range was limited to 0.15 inch and the strain gauge range to 0.008 inch, which was sufficient to record data past the yield point of the test specimens. The strain gauge and extensometer results showed close agreement for all tests. Once each specimen was installed in the test frame, an image was taken at zero load next to a reference scale having 0.01-inch increments. After specimen failure, the actuator was raised until the two pieces were brought back together and a small load was seen on the load cell. A second image was taken with the same scale, and the two images were then used to calculate percent elongation.

2.2.2 Al-Li 2198-T8 and AA 2024-T3/351 Elevated Temperature

The tension testing of the Al-Li 2198-T8 and AA 2024-T3/351 alloys at elevated temperatures was conducted by UDRI. The test setup consisted of an MTS 22 kip uniaxial, servo-hydraulic test frame with a 10 kip Lebow load cell. Instron mechanical wedge grips were used to grip the sheet material. An Instron model 2630 2-inch extensometer was used to record the strain. The extensometer is a clip-on type linear variable differential transformer (LVDT). The test frame LVDT was a G.L. Collins +/-2.5-inch model LMT711-P34.

This extensometer was selected primarily because it was rated for use at all of the temperatures being tested. A decision was made to use a single extensometer and data-acquisition system for all tests rather than having to use different applicable extensometers for the elevated testing temperatures. A consequence of this decision was that the strain at failure could not be recorded because the elongation of the materials tested was beyond the measurable range of the extensometer, though strain was recorded through the proportionality limit. The elevated temperatures required for this test program were achieved and maintained using an Instron® oven with a UDRI construct controller.

Tests were run at a constant crosshead displacement rate of 0.25 inch/min. The data were collected using a National Instruments® PCI-6024E acquisition card and UDRI software at a rate of 20 Hz. Data included the load, displacement, strain (extensometer reading), and stress (calculated using pretest cross-sectional area measurements). The elevated temperature tests, governed by ASTM E21, were heated to the specified temperature and held there for 20 minutes prior to beginning the tension test. Type-K thermocouples on the surface of the dog-bone coupon allowed for the temperature to be monitored, although it was not recorded (temperatures did not vary by more than +/-5°F per visual verification).

2.2.3 Al-Li 2196-T8511 and AA 7075-T6

The tension testing of the Al-Li 2196-T8511 and AA 7075-T6 alloys at room temperatures was conducted by NIAR. The test setup consisted of an MTS 22 kip uniaxial, servo-hydraulic test frame with either an 11 kip load cell for the full-size specimens or a 5.5 kip load cell for the micro-specimens. Mechanical grips were used for the micro-specimens whereas hydraulic grips were used for the full-sized specimens. HBM model 1-XY93-1.5/350 strain gauges were bonded to the specimens to record strain during the test.

Tests were run at a constant displacement rate of 0.5 inch/min. The data were collected at a rate of 10 Hz and included the load, displacement, and strain. Measurements for elongation were not made because of the micro-specimen size.

2.3 DATA REDUCTION

The data recorded during each test were used to generate stress-strain curves and calculate Young's modulus, yield strength, ultimate strength, and percent elongation. Unless otherwise noted, data reductions were performed based on the ASTM E8 standard.

Young's modulus was calculated per ASTM E111 using the least-fit squares method. This method involves graphically plotting the stress-strain data for each specimen and fitting a straight line to the linear region of the stress-strain curve. The slope of the straight line is equal to the modulus. The boundaries of the linear region were identified using the strain deviation method.

Yield strength was calculated using a 0.2% offset method. In this method, a line is drawn parallel to the linear region of the stress-strain curve with an X intercept of 0.002 strain. The yield strength is then recorded as the stress where the offset line intersects the stress-strain curve.

The ultimate strength was calculated by dividing the maximum force carried by the specimen during the test by the original cross-sectional area of the specimen.

Percent elongation was only reported by the FAA WJHTC and UDRI and used a 2-inch gauge section. A pre- and posttest measurement of the gauge section was used to calculate percent elongation. The posttest measurement involved fitting the fractured ends back together and applying a small force to close the fractured ends together.

2.4 TEST RESULTS

2.4.1 Al-Li 2198-T8 and AA 2024-T3/351

Tensile properties at room temperature were measured by the FAA WJHTC for the Al-Li 2198-T8 and baseline AA 2024-T3/351 sheet materials. Overall, the Al-Li 2198-T8 material exhibited higher modulus, higher strength, and lower elongation compared to the baseline AA 2024-T3/351 materials, with the exception of a few specific points. The results presented are the average of three tests. The average modulus measured for the Al-Li 2198-T8 and AA 2024-T3/351 was 10.8 Msi and 10.4 Msi, respectively. The elongation for both alloys is shown in figure 4 as a function of grain orientation and thickness. The Al-Li 2198-T8 (solid columns) exhibited lower elongation for all thicknesses and grain orientations compared to the baseline AA 2024-T3 (hashed columns).

A comparison of the yield and ultimate strengths is shown in figures 5 and 6, respectively. In these figures, the variation of yield and ultimate strength as a function of grain orientation and thickness are shown for both alloys. Whereas the yield strength was always higher for the Al-Li 2198-T8 material compared to the baseline AA 2024-T3, the ultimate strength was lower for the 0.125-inch-thick material at the intermediate grain directions (22.5 degrees, 45 degrees, and 67.5 degrees) and the 45-degree direction for the 0.25-inch gauge thickness. For the 45-degree direction, the ultimate strength of the Al-Li 2198-T8 was lower by 10.1% and 7.1% at the 0.125-inch and 0.25-inch thicknesses, respectively.

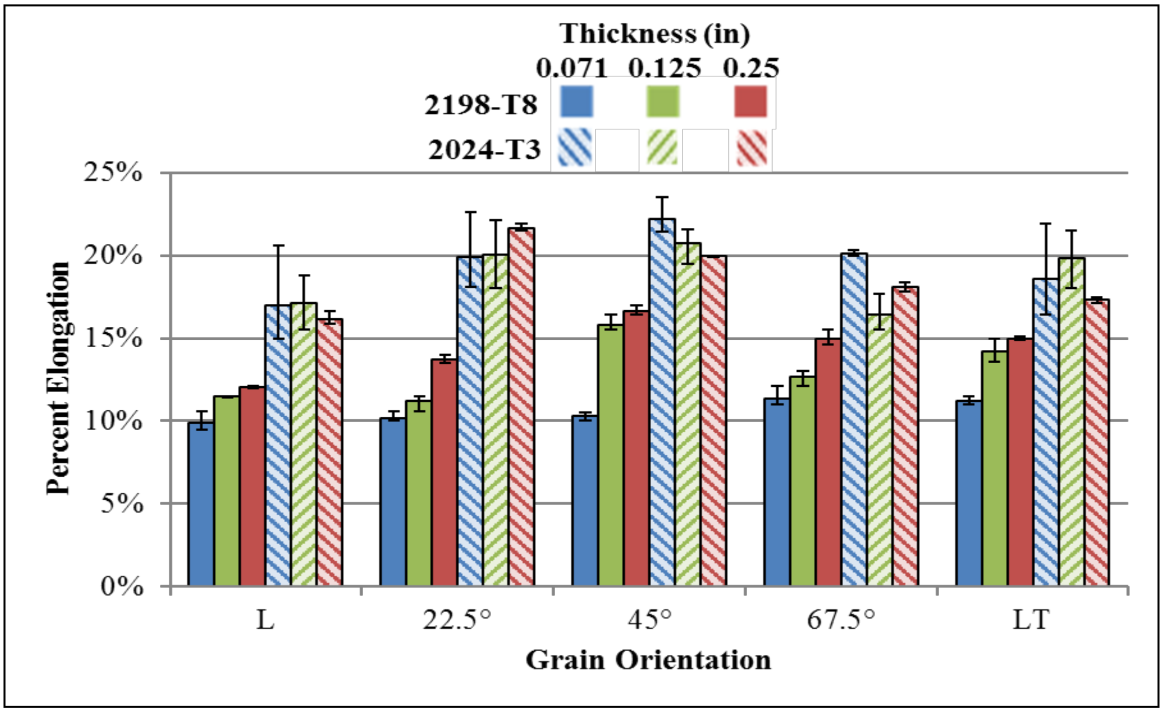

Figure 4. Tension properties results: Al-Li 2198-T8 vs. AA 2024-T3/351, average percent elongation comparison

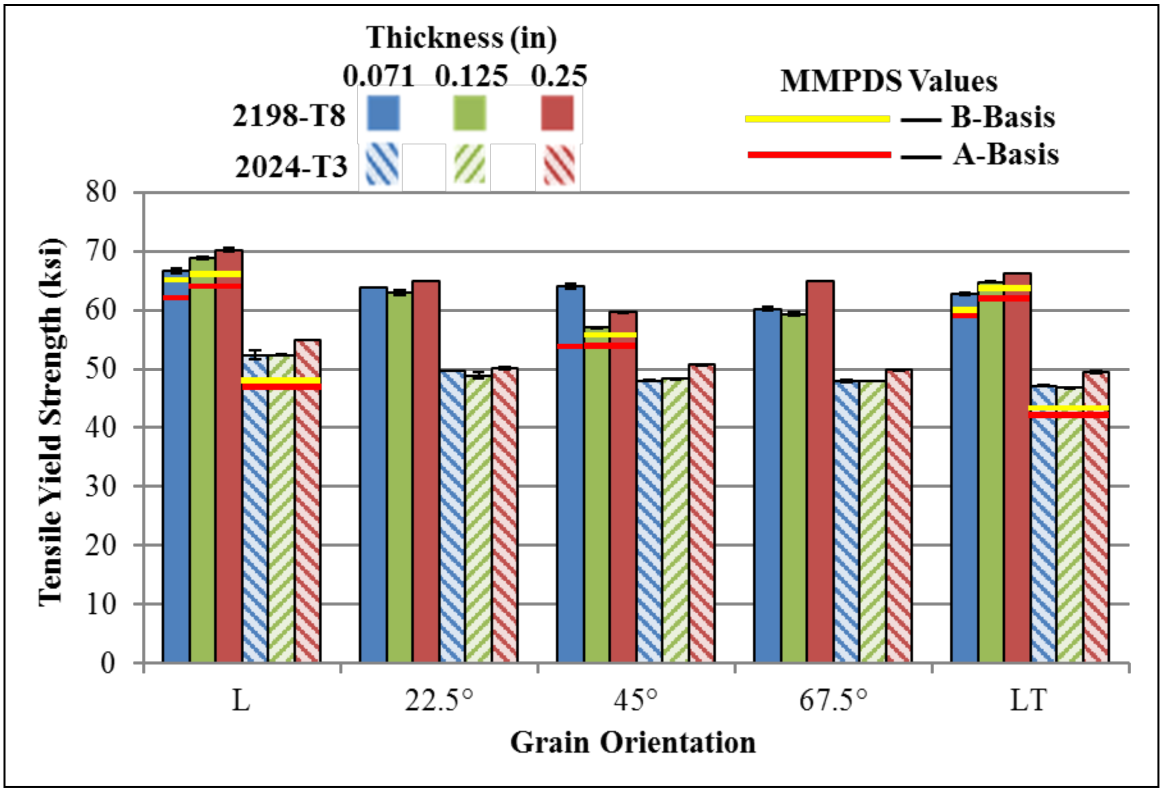

Figure 5. Tension properties results: Al-Li 2198-T8 vs. AA 2024-T3/351, average yield strength comparison

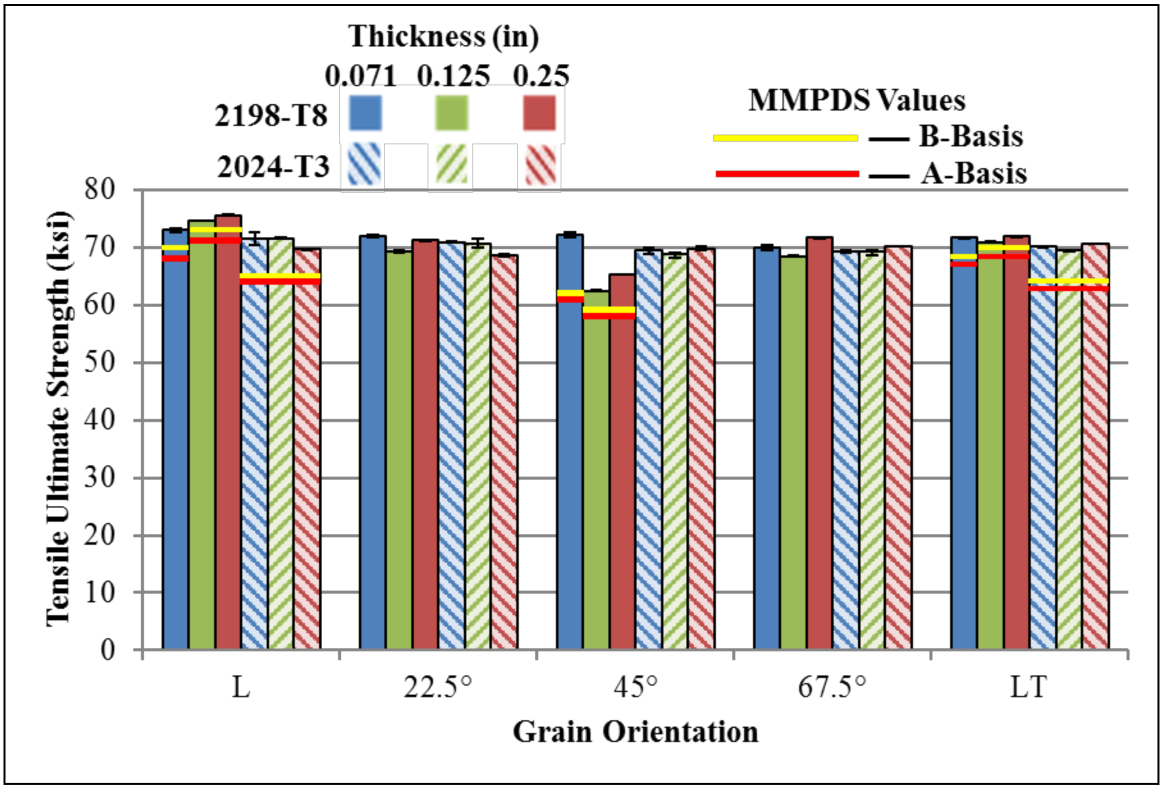

Figure 6. Tension properties results: Al-Li 2198-T8 vs. AA 2024-T3/351, average ultimate strength comparison

In general, the Al-Li 2198-T8 exhibited both grain orientation and thickness effects. At the 0.125-inch thickness, the Al-Li 2198-T8 material showed the greatest amount of strength variation across grain orientation, having approximately a 17% reduction in both yield strength (see figure 5) and ultimate strength (see figure 6) from the L direction to the 45-degree direction. The 0.125-inch-thick material also generally recorded the lowest yield and ultimate strengths within the Al-Li 2198-T8 results. The only exceptions to this were the L and LT directions for yield strength and the L direction for ultimate strength, each time only surpassing the 0.071-inch-thick results. However, for a thickness of 0.071 inch, the Al-Li 2198-T8 results were consistent across all grain directions. Expectedly, all of the measured values exceeded the applicable Metallic Materials Properties Development and Standardization (MMPDS) A and B basis allowables including the 45-degree direction [9]. Test results were also highly repeatable for both materials. The coefficients of variation (CVs), as shown in table 3, for both materials are considerably lower for the strength values when compared to the values listed in ASTM E8 for 2024-T351. The CV values reported throughout this report represent an average of the individual CV calculated for each specific combination of material, thickness, and grain orientation for the given test type (e.g., tension). Whereas the variation in elongation was higher for the AA 2024-T3 results generated in this program, the results for Al-Li 2198-T8 were comparable with the published value. Additional results are provided in appendix A.

Table 3. Tension properties results: Al-Li 2198-T8 vs. AA 2024-T3/351, coefficients of variation comparison

	Coefficient of Variation		
Material	Yield Strength	Ult Strength	Elongation
2024-T351 (ASTM E8 Value)	1.41%	1.24%	2.94%
2024-T3	0.29% *	0.46% *	6.22% *
2198-T8	0.29% *	0.24% *	3.02% *

*Average of 15 coefficients of variation

2.4.2 Al-Li 2198-T8 and AA 2024-T3/351 Elevated Temperature

Tensile properties at elevated temperatures of 200°F and 350°F were measured by UDRI for the Al-Li 2198-T8 and the baseline AA 2024-T3 (LT direction only) sheet materials at the 0.071-inch material thickness only. UDRI also ran tests at room temperature to determine the relative effect of elevated temperatures on the basic material properties. The results for modulus and elongation were varied though there were general trends of relatively lower modulus and higher elongation at 350°F. The results for the yield and ultimate strengths, which are shown in figures 7 and 8 respectively, were more consistent and showed a reduction in strength as temperature increased. Both materials showed approximately the same relative change from the room-temperature results. Additional results are provided in appendix B.

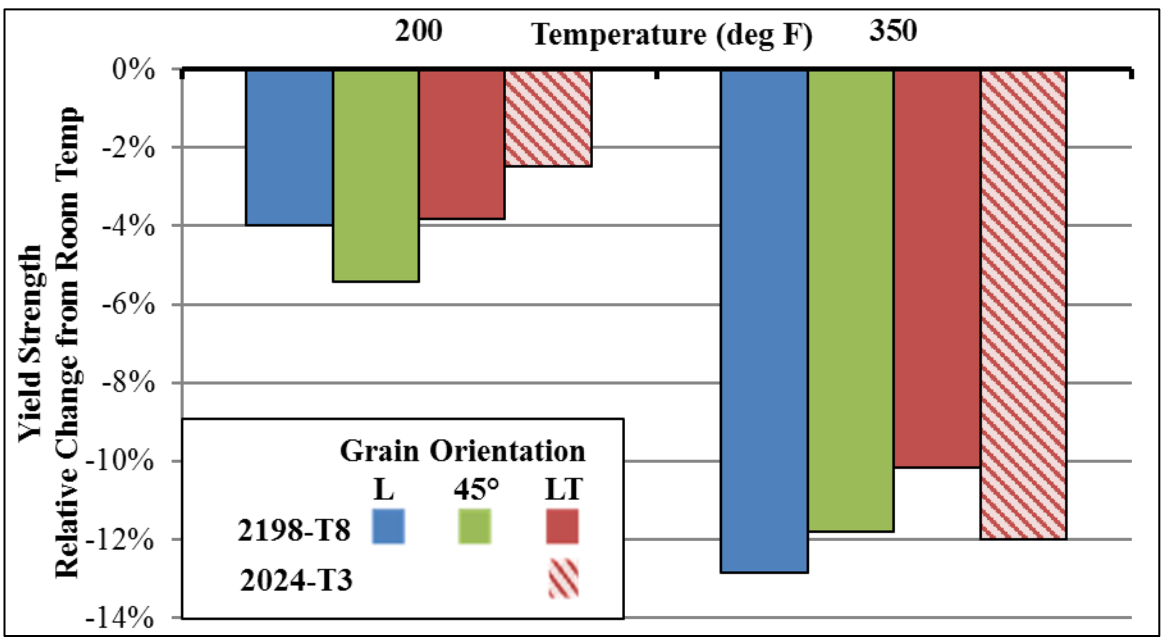

Figure 7. Elevated temperature tension properties results: Al-Li 2198-T8 vs. AA 2024-T3/351, average yield strength relative change from room temperature comparison

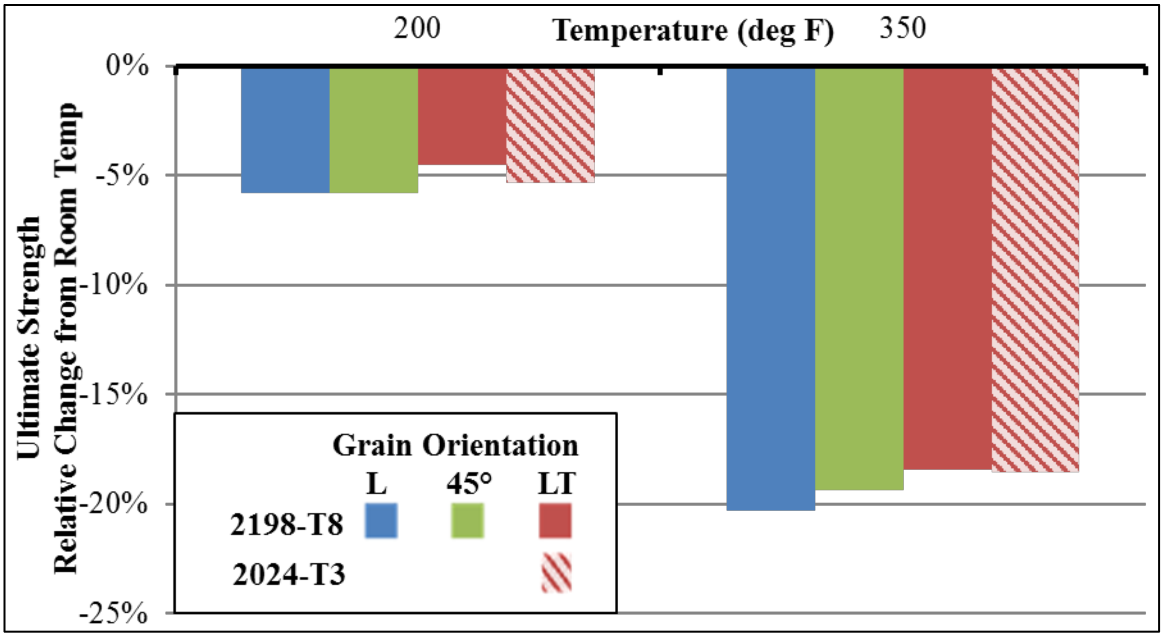

Figure 8. Elevated temperature tension properties results: Al-Li 2198-T8 vs. AA 2024-T3/351, average ultimate strength relative change from room-temperature comparison

2.4.3 Al-Li 2196-T8511 and AA 7075-T6

Tensile properties at room temperature were measured by NIAR for the Al-Li 2196-T8511 and baseline AA 7075-T6 materials. The results showed the Al-Li to have a higher modulus compared to the baseline aluminum with average values of 11.8 Msi and 10.2 Msi, respectively. Because of the micro-size specimens used, there were issues with the strain gauges failing right around the yield point. As a result, not enough data were generated for the yield strengths to present average values so that plot was not included. The ultimate strength values of the Al-Li 2196-T8511 were generally lower compared to the AA 7075-T6 across all grain directions and thicknesses, as shown in figure 9, with the exception of the L direction. The most noticeable reductions occur at the 45-degree direction in which the Al-Li 2196-T8511 results are more than 10% lower compared to the baseline material. This behavior is similar to the Al-Li 2198-T8 tensile strength results (see figures 7–8) in which both Al-Li alloys exhibited anisotropic behavior with lower strengths recorded at the 45-degree grain direction. The relative reduction in ultimate strength for the Al-Li 2196-T8511 at the 45-degree grain direction compared to the L direction results are approximately 14% for all thicknesses. The ultimate strength values measured were repeatable (average CV values of 0.42% for AA 7075-T6 and 0.72% for Al-Li 2196-T8511 were comparable with the values in table 3) and exceeded the published MMPDS values [10]. Further, the micro-specimen results in the L direction were generally within 1% of the full-size tests (Al-Li 2196-T8511 at 0.120 inch was off by 4.7% for yield strength as the lone exception) showing specimen size did not affect the results. Additional results are provided in appendix C.

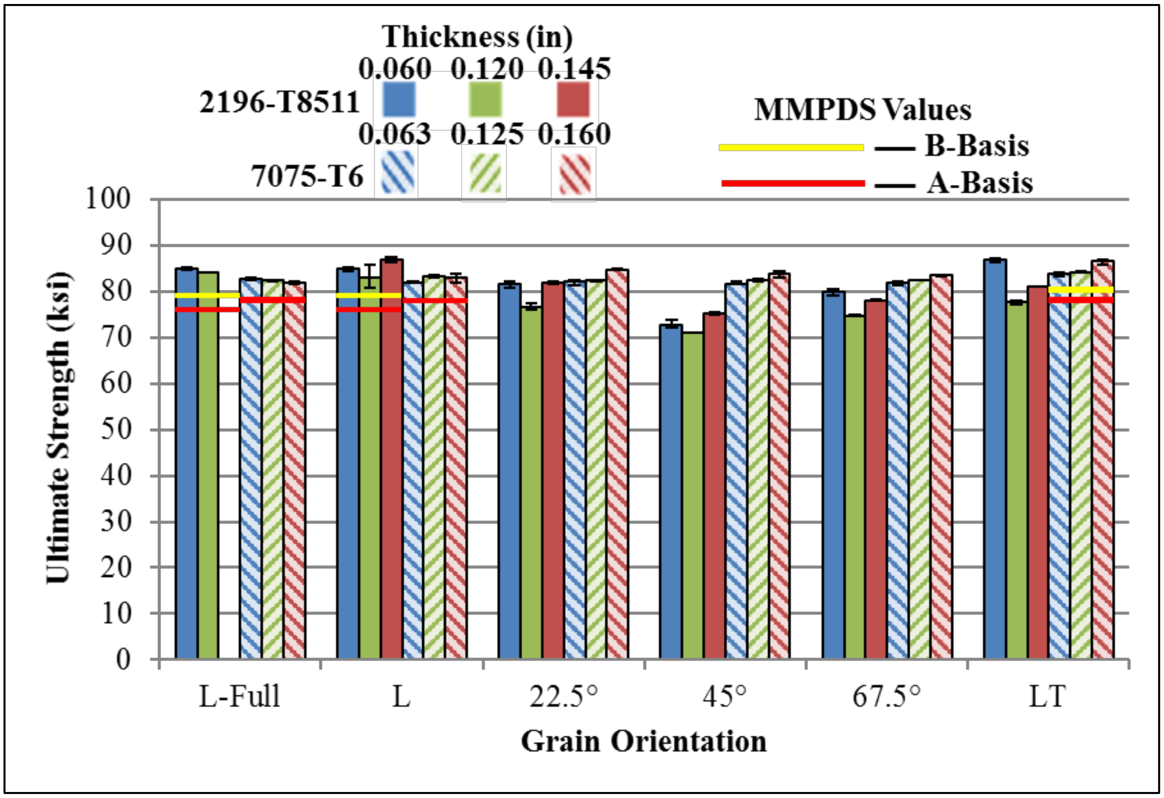

Figure 9. Tension properties results: Al-Li 2196-T8511 vs. AA 7075-T6, average ultimate strength comparison

3. COMPRESSION PROPERTIES

Static compression properties tests were conducted by the FAA WJHTC and NIAR on the Al-Li 2198-T8 and 2196-T8511 alloys and the traditional aluminum baselines AA 2024-T3/351 and 7075-T6. The compression testing was broken into two segments with the overall test matrix shown in table 4. The data collected were used to derive values for compressive modulus and yield strength (0.2% offset). Three tests were run for each combination of material, thickness, and grain orientation with reported values generally representing the average of the three tests. NIAR also conducted three additional L-direction tests for each material and thickness combination to evaluate the impact of specimen size on the results.

Table 4. Compression properties test matrix

Performing Organization	Material	Thickness (inch)	Grain Orientation					Total
			L	22.5°	45°	67.5°	LT	
FAA WJHTC	2024-T3	0.071	3	3	3	3	3	15
		0.125	3	3	3	3	3	15
	2024-T351	0.25	3	3	3	3	3	15
	2198-T8	0.071	3	3	3	3	3	15
		0.125	3	3	3	3	3	15
		0.25	3	3	3	3	3	15
NIAR	7075-T6	0.063	6	3	3	3	3	18
		0.125	6	3	3	3	3	18
		0.160	6	3	3	3	3	18
	2196-T8511	0.060	6	3	3	3	3	18
		0.120	6	3	3	3	3	18
		0.145	6	3	3	3	3	18

3.1 COMPRESSION SPECIMEN DESCRIPTIONS

Compression testing of thin sheet material must incorporate a support jig to prevent buckling during loading. Per ASTM E9, acceptable results can be obtained with a rather wide range of jig designs and as such the ASTM standard does not designate a specific jig or specimen geometry. The FAA WJHTC used a simple rectangular specimen (3.125 inches long by 0.625 inch wide) with a Material Testing Technology #BOEI.07260.33 anti-buckling jig (see figure 10). NIAR used the same micro-specimen dog-bone geometry from the tension program (see figure 3) with a Wyoming Test Fixtures model #WTF-BO-212 anti-buckling jig (see figure 11). Because NIAR was forced to use a micro-specimen configuration, they additionally tested full-size rectangular specimens (3.13 inches long by 0.5 inch wide) in the L direction to evaluate if specimen size affected the results.

Figure 10. FAA WJHTC anti-buckling jig

Figure 11. NIAR anti-buckling jig

3.2 EXECUTION OF THE TESTING

3.2.1 Al-Li 2198-T8 and AA 2024-T3/351

The compression testing of the Al-Li 2198-T8 and AA 2024-T3/351 alloys was conducted by the FAA WJHTC. The tests were performed on a MTS 55 kip uniaxial, servo-hydraulic test frame with Material Testing Technology model PLAT.SA041.10 self-aligning loading platforms installed in the hydraulic grips. A MTS model 632.17E-20 averaging extensometer (1-inch gauge length, 0.02-inch compressive travel) was used to record strain throughout the test.

The tests were run under a constant crosshead displacement rate of 0.05 inch/min. Data were collected using a MTS FlexTestSE controller at a rate of approximately 20 Hz and included the load, displacement, and strain. The reading from the extensometer was recorded directly as strain. The extensometer range was limited to 0.02 inch, but that was sufficient to record strain past the yield point. The specimen was placed in the support jig, which was lubricated and hand tightened.

The jig with specimen was then placed on the loading platforms with the specimen aligned at the center and the test started.

3.2.2 Al-Li 2196-T8511 and AA 7075-T6

The compression testing of the Al-Li 2196-T8511 and AA 7075-T6 alloys at room temperature was conducted by NIAR. The test setup consisted of an MTS 22 kip uniaxial, servo-hydraulic test frame with an 11 kip MTS load cell. HBM model 1-LY21-0.6/120 strain gauges were bonded to the specimens to record strain during the test.

Tests were run at a constant displacement rate of 0.007 inch/min. The data were collected at a sampling rate of 10 Hz and included the load, displacement, and strain.

3.3 DATA REDUCTION

The data recorded during each test were used to generate stress-strain curves and calculate compressive modulus and yield strength.

Compressive modulus was calculated per ASTM E111 using the least fit squares method. This method involves graphically plotting the stress-strain data for each specimen and fitting a straight line to the linear region of the stress-strain curve. The slope of the straight line is equal to the modulus. The boundaries of the linear region were identified using the strain deviation method.

Yield strength was calculated using a 0.2% offset method. In this method, a line is drawn parallel to the linear region of the stress-strain curve with an X intercept of 0.002. The yield strength is then recorded as the stress where the offset line intersects the stress-strain curve.

3.4 TEST RESULTS

3.4.1 Al-Li 2198-T8 and AA 2024-T3/351

Compression properties at room temperature were measured by the FAA WJHTC for the Al-Li 2198-T8 and baseline AA 2024-T3/351 sheet materials. Overall, the Al-Li 2198-T8 material recorded higher compressive modulus and yield strength compared to the baseline AA 2024-T3/351. The average modulus was 11.1 Msi and 10.6 Msi for the Al-Li 2198-T8 and AA 2024-T3 materials, respectively. The comparison of yield strengths is shown in figure 12. The Al-Li 2198-T8 had significantly higher results (30%–50%) compared to the baseline aluminum. In comparing the different grain orientations within the Al-Li 2198-T8 results, there again was some anisotropy similar to the tension results in which the two thicker gauges (0.125 inch and 0.25 inch) showed lower strengths at the 45-degree direction. These reductions were both approximately 7.5% compared to the L direction, whereas the thinnest gage (0.071 inch) was generally constant across orientation. Yield strength results for both materials were repeatable with the average CVs being 0.39% and 0.64% for the Al-Li 2198-T8 and AA 2024-T3, respectively. All recorded results were above the respective MMPDS values [10]. Additional results are provided in appendix D.

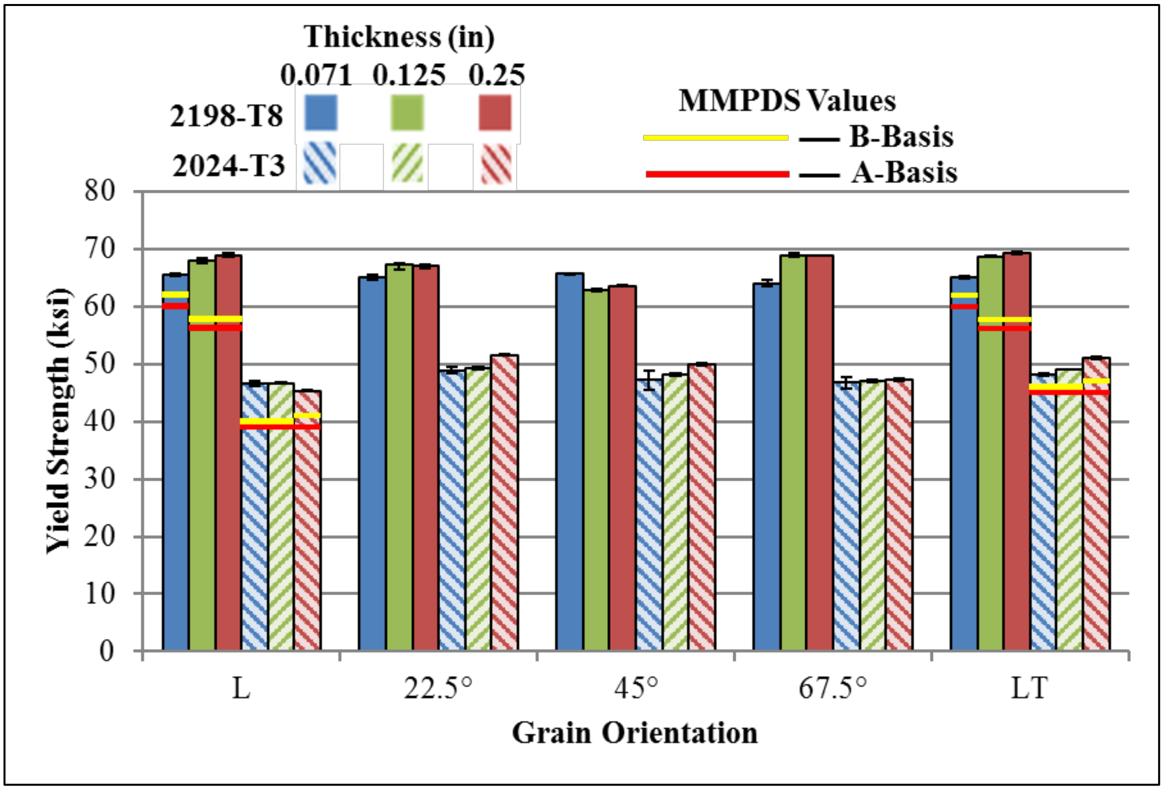

Figure 12. Compression properties results: Al-Li 2198-T8 vs. AA 2024-T3/351, average yield strength comparison

3.4.2 Al-Li 2196-T8511 and AA 7075-T6

Compression properties at room temperature were measured by the NIAR for the Al-Li 2196-T8511 and baseline AA 7075-T6 sheet materials. Overall, the Al-Li 2196-T8 material recorded higher compressive modulus and yield strength compared to the baseline AA 7075-T6. The average modulus was 13.7 Msi and 11.6 Msi for the Al-Li 2196-T8511 and AA 7075-T6 materials, respectively. Comparing yield strength results between the two materials showed some mixed results as shown in figure 13. The Al-Li 2196-T8511 results were higher for the L grain direction at all thicknesses but generally lower for the other orientations. Comparing the yield strength results for the micro- and full-size specimens (L direction only) did show an impact of specimen size. The full-size specimens recorded lower strengths ranging from 2.5% up to 18%, though no distinction was discernable between the two materials. The Al-Li did again exhibit anisotropic behavior with relative strength reductions of 7%, 18%, and 11% for the 0.06-inch, 0.120-inch, and 0.145-inch thicknesses, respectively. The average CVs for yield strength of these materials were higher compared to the other tests, but at 1.47% and 2.08% for the Al-Li 2196-T8511 and AA 7075-T6 alloys, respectively, it is still at an acceptable level. All recorded results exceeded the respective MMPDS values [10]. Additional results are provided in appendix E.

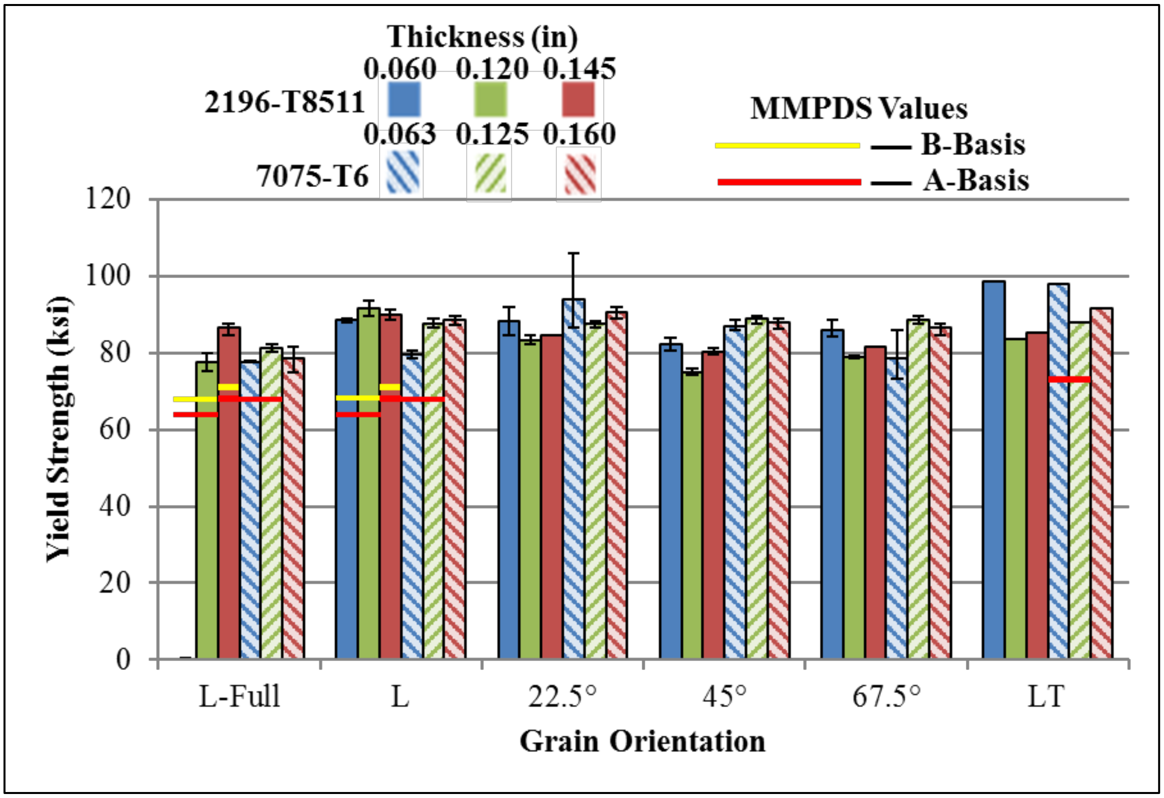

Figure 13. Compression properties results: Al-Li 2196-T8511 vs. AA 7075-T6, average yield strength comparison

4. SHEAR PROPERTIES

Static shear properties tests were conducted by NIAR on the Al-Li 2198-T8 and 2196-T8511 alloys and the traditional baseline AA 2024-T3/351 and 7075-T6. The full shear properties tests matrix is shown in table 5. The data collected were used to derive values for shear modulus and shear strength. Three tests were run for each combination of material, thickness, and grain orientation with reported values generally representing the average of the three tests.

Table 5. Shear properties test matrix

Performing Organization	Material	Thickness (inch)	Grain Orientation					Total
			L	22.5°	45°	67.5°	LT	
NIAR	2024-T3	0.071	3	3	3	3	3	15
		0.125	3	3	3	3	3	15
	2024-T351	0.25	3	3	3	3	3	15
	2198-T8	0.071	3	3	3	3	3	15
		0.125	3	3	3	3	3	15
		0.25	3	3	3	3	3	15
	7075-T6	0.063	3	3	3	3	3	15
		0.125	3	3	3	3	3	15
		0.160	3	3	3	3	3	15
	2196-T8511	0.060	3	3	3	3	3	15
		0.120	3	3	3	3	3	15
		0.145	3	3	3	3	3	15

4.1 SHEAR SPECIMEN DESCRIPTIONS

ASTM B831 is the standard for shear testing of thin sheet AAs. However, the prescribed specimen geometry exceeds the available material area afforded by the Al-Li 2196-T8511 extrusions used in this program. To accommodate the size of the extrusion, NIAR conducted a study of micro-specimen configurations to experimentally determine an appropriate micro-specimen geometry. The final specimen geometry used by NIAR is shown in figure 14. This specimen geometry was used for all materials tested. All specimens were tested at the thickness of the supplied material.

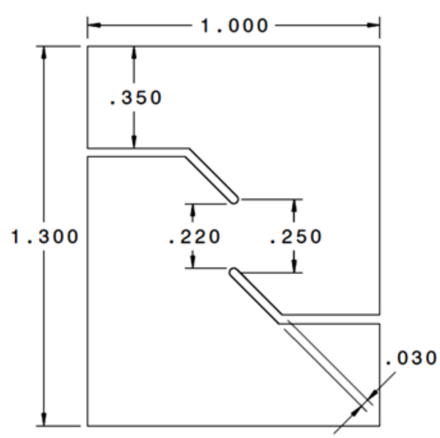

Figure 14. NIAR micro-shear specimen geometry

4.2 EXECUTION OF THE TESTING

The test setup consisted of an MTS 22 kip test frame with an 11 kip MTS load cell and mechanical grips. HBM model 1-XY93-1.5/350 strain gauges were bonded to the specimens to record strain during the test.

Tests were run at a constant displacement rate of 0.05 inch/min. The data were collected at a data sampling rate of 10 Hz and included the load, displacement, and strain.

4.3 DATA REDUCTION

The data recorded during each test were used to generate stress-strain curves and calculate shear modulus and shear strength.

Shear modulus was calculated per ASTM E111 using the least fit squares method. This method involves graphically plotting the stress-strain data for each specimen and fitting a straight line to the linear region of the stress-strain curve. The slope of the straight line is equal to the modulus. The boundaries of the linear region were identified using the strain deviation method.

The shear strength was calculated by dividing the maximum force carried by the specimen during the test by the original cross-sectional area of the specimen.

4.4 TEST RESULTS

The shear properties measured by NIAR revealed that the shear modulus for the Al-Li 2198-T8 material was higher than the AA 2024-T3/351 baseline with values of 4.3 Msi and 3.5 Msi, respectively. The shear strength values for the two materials were similar and relatively consistent for all thicknesses and grain orientations, as shown in figure 15. There was little scatter in the shear strength test results, with an average CV of 0.56% and 1.01% for AA 2024-T3 and

Al-Li 2198-T8, respectively, and all measured values for both materials exceeded the published MMPDS values [10]. Additional results are provided in appendix F.

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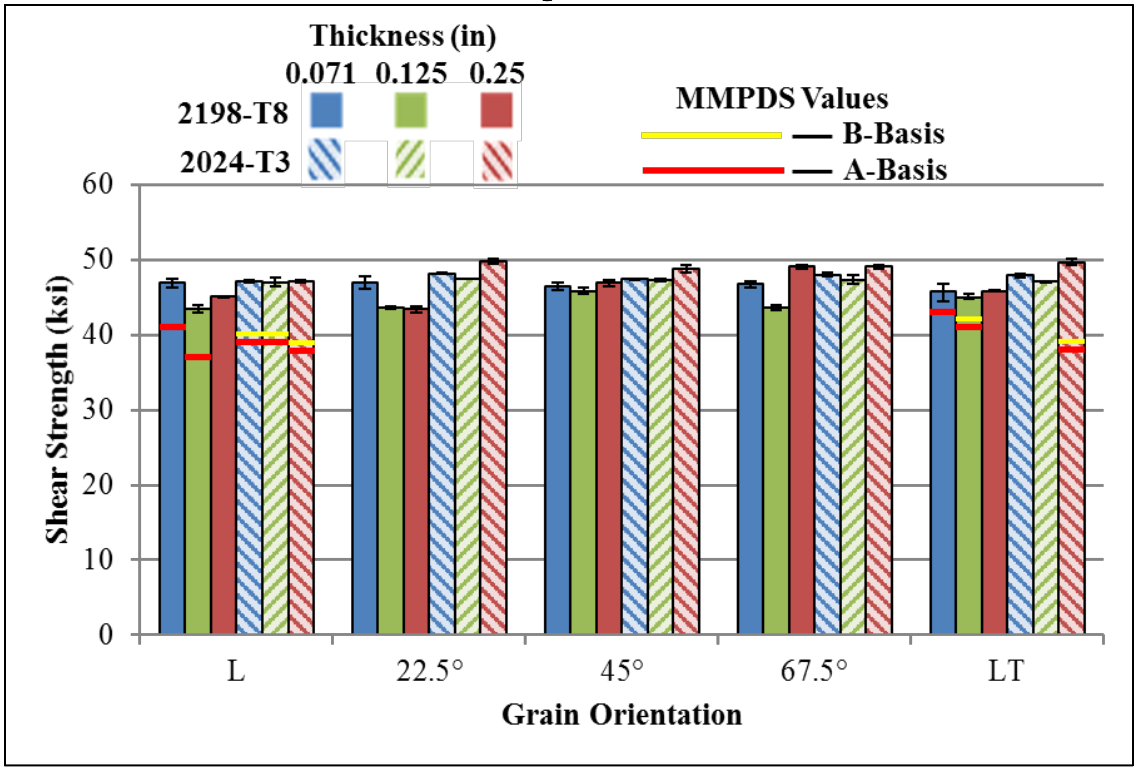

Figure 15. Shear properties results: Al-Li 2198-T8 vs. AA 2024-T3/351, average shear strength comparison

The results for the Al-Li 2196-T8511 shear tests were similar to those of the Al-Li 2198-T8, as shown in figure 16. Again, the shear modulus was higher for the Al-Li compared to the baseline AA 7075-T6 at 4.5 Msi and 4.3 Msi, respectively. The Al-Li material did show signs of anisotropy with the intermediate grain directions having the highest strength. On average, the shear strength tended to be highest in the 45-degree direction. In comparison to the baseline AA 7075-T6 material, shear strength values measured in Al-Li 2196-T8511 were lower for all thicknesses and grain orientations. Results were repeatable for both materials (average CV of 0.63% and 1.10% for AA 7075-T6 and Al-Li 2196-T8511, respectively) and exceeded the published MMPDS values [10]. Additional results are provided in appendix G.

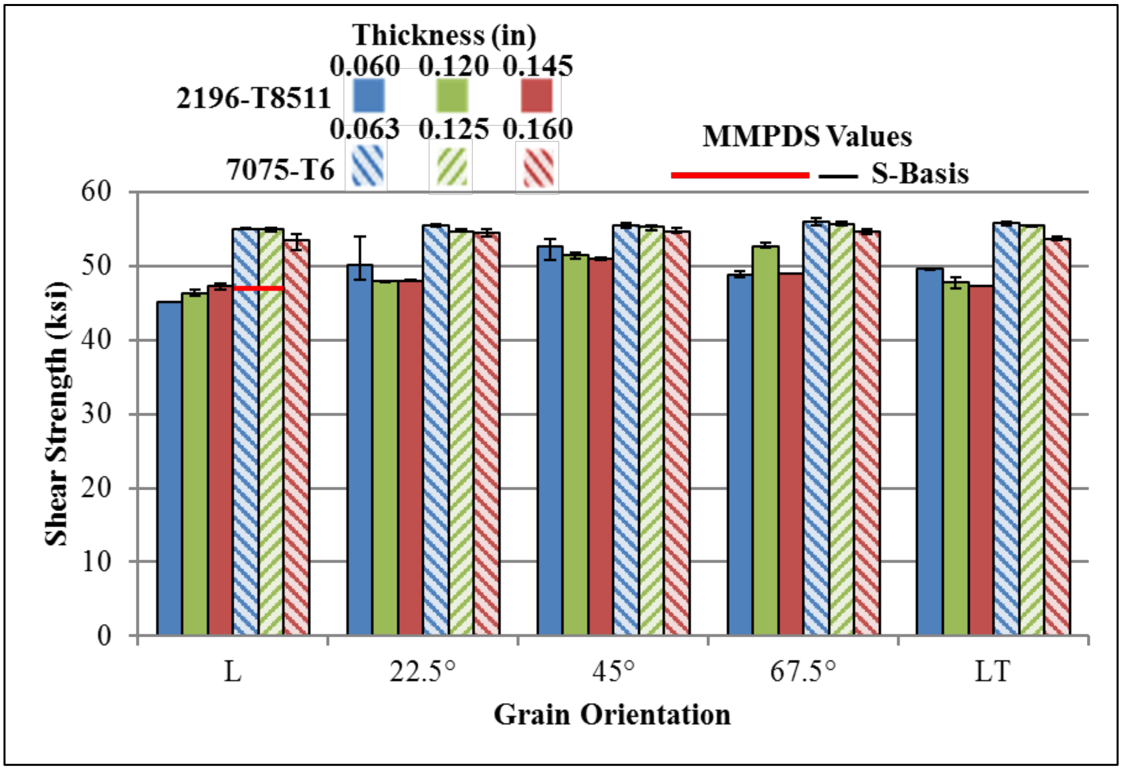

Figure 16. Shear properties results: Al-Li 2196-T8511 vs. AA 7075-T6, average shear strength comparison

5. CONCLUSION

The test programs in this report were conducted as a comparative study of two third-generation Al-Li alloys (2198-T8 and 2196-T8511) against traditional aerospace aluminums (2024-T3/351 and 7075-T6). The sample size was limited, and this program was not meant to develop any design allowables or present the Al-Li alloys as direct replacements for the traditional aluminums. Rather, the tests were conducted to provide a broad, high-level look at the materials to determine if there are any unique behaviors in the Al-Li alloys that may need further vetting as these materials (and other third-generation Al-Li alloys) see more widespread use in new aircraft design.

The static property tests completed for the Al-Li 2198-T8 and 2196-T8511 alloys all produced good repeatable results. The reported results for all materials, Al-Li alloys and baseline aluminums, exceeded all respective MMPDS [10] A and B basis allowables. Anisotropic behavior was evident in the Al-Li at the intermediate grain directions, especially 45 degrees, at which the tensile and compressive strengths were lowest compared to the other orientations. This behavior was expected and is addressed with values at the 45-degree grain orientation published in MMPDS.

6. REFERENCES

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APPENDIX A—TENSION RESULTS FOR AA 2024-T3 AND AL-LI 2198-T8

Table A-1. AA 2024-T3 average results

	Young's Modulus (Msi)	Yield Str (ksi)	Ultimate Str (ksi)	% Elongation
AA 2024-T3; 0.071-Inch Thick				
L	10.6	52.2	71.4	17.0%
22.5°	10.5	49.6	70.9	19.9%
45°	10.3	48.0	69.4	22.2%
67.5°	10.4	48.0	69.2	20.1%
LT	10.5	47.2	70.1	18.6%
AA 2024-T3; 0.125-Inch- Thick				
L	10.4	52.3	71.6	17.1%
22.5°	10.4	48.8	70.7	20.1%
45°	10.3	48.3	68.7	20.7%
67.5°	10.4	47.9	69.2	16.4%
LT	10.4	46.8	69.4	19.8%
AA 2024-T351; 0.25-Inch- Thick				
L	10.3	54.9	69.7	16.1%
22.5°	10.4	50.2	68.6	21.7%
45°	10.5	50.7	69.8	20.0%
67.5°	10.5	49.8	70.2	18.1%
LT	10.4	49.5	70.6	17.4%

Table A-2. Al-Li 2198-T8 average results

	Young's Modulus (Msi)	Yield Str (ksi)	Ultimate Str (ksi)	% Elongation
Al-Li 2198-T8; 0.071-Inch- Thick				
L	10.8	66.6	73.0	9.9%
22.5°	10.8	63.9	72.0	10.2%
45°	11.0	63.8	72.1	10.3%
67.5°	11.0	60.2	70.0	11.4%
LT	11.0	62.8	71.7	11.2%
Al-Li 2198-T8; 0.125-Inch- Thick				
L	10.9	68.8	74.6	11.5%
22.5°	10.8	63.0	69.4	11.2%
45°	10.5	57.0	62.4	15.8%
67.5°	10.8	59.3	68.5	12.7%
LT	11.0	64.8	70.9	14.2%
Al-Li 2198-T8; 0.25-Inch- Thick				
L	10.8	70.2	75.6	12.0%
22.5°	10.7	64.9	71.2	13.7%
45°	10.5	59.6	65.2	16.6%
67.5°	10.9	64.9	71.6	15.0%
LT	10.9	66.2	71.9	15.0%

Table A-3. AA 2024-T3; 0.071-inch-thick; individual specimen results

Specimen	Direction	Modulus (Msi)		Yield Str (ksi)		Ultimate Str (ksi)	% Elongation
		Ext*	SG*	Ext*	SG*		
2024-Tension-071-L-1B	L		10.4		52.2	71.5	15.0%
2024-Tension-071-L-2B	L	10.7	10.8	51.7	52.5	70.9	16.0%
2024-Tension-071-L-3B	L	10.6	10.2	51.7	51.6	70.9	15.5%
2024-Tension-071-L-4B	L	10.6		51.9		71.4	
2024-Tension-071-L-5B	L	10.6	10.3	51.7	51.6	70.4	15.0%
2024-Tension-071-L-6B	L	10.8		52.1		70.9	17.0%
2024-Tension-071-L-7B	L	10.8		52.1		70.6	16.0%
2024-Tension-071-L-1	L	10.7	10.5	52.9	52.7	72.7	18.0%
2024-Tension-071-L-2	L	10.8	10.4	53.1	52.9	72.6	20.6%
2024-Tension-071-L-3	L	10.7	10.3	52.8	52.8	72.2	19.6%
2024-Tension-071-225-1	22.5°	10.4	10.7	49.7	49.7	71.1	19.1%
2024-Tension-071-225-2	22.5°	10.7	10.3	49.6	49.6	70.8	18.1%
2024-Tension-071-225-3	22.5°	10.5		49.6		70.9	22.6%
2024-Tension-071-45-1	45°	10.6	10.3	48.1	48	69.9	21.6%
2024-Tension-071-45-2	45°	10.5	10.3	48	47.9	68.8	21.4%
2024-Tension-071-45-3	45°	10.3	10	48	48.2	69.6	23.5%
2024-Tension-071-675-1	67.5°	10.5	10.3	48	48.1	69	20.0%
2024-Tension-071-675-2	67.5°	10.4	10.3	48	47.9	69.1	20.3%
2024-Tension-071-675-3	67.5°	10.3	10.3	47.8	47.9	69.5	20.0%
2024-Tension-071-LT-1	LT	10.4		47.1		70.1	21.9%
2024-Tension-071-LT-2	LT	10.7	10.3	47.1	47.2	70.1	16.4%
2024-Tension-071-LT-3	LT	10.6		47.2		70	17.5%

*Properties measured by an extensometer (Ext) and strain gage (SG)

Table A-4. AA 2024-T3; 0.125-inch-thick; individual specimen results

Specimen	Direction	Modulus (Msi)		Yield Str (ksi)		Ultimate Str (ksi)	% Elongation
		Ext*	SG*	Ext*	SG*		
2024-Tension-125-L-1	L	10.4	10.4	52.4	52.4	71.6	17.0%
2024-Tension-125-L-2	L	10.3	10.2	52.2	52.2	71.5	18.8%
2024-Tension-125-L-3	L	10.5	10.4	52.4	52.4	71.7	15.5%
2024-Tension-125-225-1	22.5°	10.6	10.4	49.4	49.4	71.6	22.1%
2024-Tension-125-225-2	22.5°	10.4	10.2	48.5	48.5	70	18.0%
2024-Tension-125-225-3	22.5°	10.4	10.3	48.4	48.5	70.4	20.1%
2024-Tension-125-45-1	45°	10.2	10.3	48.3	48.3	69.1	19.5%
2024-Tension-125-45-2	45°	10.4	10.4	48.4	48.3	68.9	21.1%
2024-Tension-125-45-3	45°	10.4	10.2	48.3	48.2	68.2	21.6%
2024-Tension-125-675-1	67.5°	10.6	10.4	47.9	47.9	68.6	15.5%
2024-Tension-125-675-2	67.5°	10.4	10.2	48	48	69.5	16.0%
2024-Tension-125-675-3	67.5°	10.5	10.3	47.9	47.9	69.6	17.7%
2024-Tension-125-LT-1	LT	10.4	10.4	46.8	46.8	69.3	20.0%
2024-Tension-125-LT-2	LT	10.2	10.4	46.6	46.7	69.6	18.0%
2024-Tension-125-LT-3	LT	10.6		46.8		69.4	21.5%

*Properties measured by an extensometer (Ext) and strain gage (SG)

Table A-5. AA 2024-T3; 0.25-inch-thick; individual specimen results

Specimen	Direction	Modulus (Msi)		Yield Str (ksi)		Ultimate Str (ksi)	% Elongation
		Ext*	SG*	Ext*	SG*		
2024-Tension-25-L-1	L	10.4	10.2	54.9	54.9	69.8	15.9%
2024-Tension-25-L-2	L	10.3	10.4	55	54.9	69.6	16.6%
2024-Tension-25-L-3	L	10.3	10.2	54.9	54.8	69.7	15.9%
2024-Tension-25-225-1	22.5°	10.6	10.2	50.2	50.2	68.6	21.9%
2024-Tension-25-225-2	22.5°	10.5	10.2	50.1	49.9	68.3	21.5%
2024-Tension-25-225-3	22.5°	10.4	10.2	50.3	50.2	68.9	21.6%
2024-Tension-25-45-1	45°	11	10.3	50.5	50.6	69.8	19.9%
2024-Tension-25-45-2	45°	10.5	10.4	50.7	50.8	70.1	20.0%
2024-Tension-25-45-3	45°	10.5	10.4	50.8	50.6	69.4	20.0%
2024-Tension-25-675-1	67.5°	10.5	10.4	49.7	49.9	70.2	18.4%
2024-Tension-25-675-2	67.5°	10.5	10.4	49.8	49.7	70.1	18.0%
2024-Tension-25-675-3	67.5°	10.8	10.4	49.9	49.9	70.2	17.8%
2024-Tension-25-LT-1	LT	10.5	10.1	49.5	49.3	70.5	17.5%
2024-Tension-25-LT-2	LT	10.6	10.4	49.6	49.5	70.6	17.5%
2024-Tension-25-LT-3	LT	10.5	10.4	49.7	49.6	70.6	17.1%

*Properties measured by an extensometer (Ext) and strain gage (SG)

Table A-6. Al-Li 2198-T8; 0.071-inch-thick; individual specimen results

Specimen	Direction	Modulus (Msi)		Yield Str (ksi)		Ultimate Str (ksi)	% Elongation
		Ext*	SG*	Ext*	SG*		
2198-Tension-071-L-1	L	10.6		66.3		72.6	9.5%
2198-Tension-071-L-2	L	10.8	10.8	66.5	66.5	73.1	10.6%
2198-Tension-071-L-3	L	11		67		73.3	9.5%
2198-Tension-071-225-1	22.5°	10.6	10.7	63.8	63.9	72	10.1%
2198-Tension-071-225-2	22.5°	10.9		63.9		72.2	10.6%
2198-Tension-071-225-3	22.5°	10.8	10.8	63.8	63.8	71.8	10.0%
2198-Tension-071-45-1	45°	11.2		63.7		72	10.5%
2198-Tension-071-45-2	45°	10.9	10.9	64.1	64.4	72.6	10.0%
2198-Tension-071-45-3	45°	11		63.5		71.8	10.5%
2198-Tension-071-675-1	67.5°	10.8	11	60.5	60.6	70.3	12.1%
2198-Tension-071-675-2	67.5°	11.1		60.3		70.3	11.0%
2198-Tension-071-675-3	67.5°	10.9	10.9	59.8	59.8	69.5	11.0%
2198-Tension-071-LT-1	LT	11.2		62.9		71.8	11.1%
2198-Tension-071-LT-2	LT	10.8	10.8	62.6	62.9	71.5	11.0%
2198-Tension-071-LT-3	LT	11		62.8		71.7	11.5%

*Properties measured by an extensometer (Ext) and strain gage (SG)

Table A-7. Al-Li 2198-T8; 0.125-inch-thick; individual specimen results

Specimen	Direction	Modulus (Msi)		Yield Str (ksi)		Ultimate Str (ksi)	% Elongation
		Ext*	SG*	Ext*	SG*		
2198-Tension-125-L-1	L	10.8	10.9	68.7	68.8	74.6	11.5%
2198-Tension-125-L-2	L	10.9	10.9	68.8	69	74.6	11.5%
2198-Tension-125-L-3	L	11	10.9	68.6	68.7	74.6	11.4%
2198-Tension-125-225-1	22.5°	11	10.6	62.8	62.5	69	10.6%
2198-Tension-125-225-2	22.5°	10.8	10.8	63.3	63.3	69.6	11.5%
2198-Tension-125-225-3	22.5°	10.9	10.8	63.2	63.1	69.5	11.5%
2198-Tension-125-45-1	45°	10.6	10.5	56.8	57	62.3	15.5%
2198-Tension-125-45-2	45°	10.5	10.6	56.9	57.1	62.3	16.4%
2198-Tension-125-45-3	45°	10.5	10.5	57.1	57	62.5	15.6%
2198-Tension-125-675-1	67.5°	10.9	10.7	59.1	59	68.3	13.0%
2198-Tension-125-675-2	67.5°	10.7	10.8	59.3	59.2	68.5	12.1%
2198-Tension-125-675-3	67.5°	10.9	10.8	59.5	59.6	68.6	12.9%
2198-Tension-125-LT-1	LT	11.1	11	64.8	64.9	71	14.1%
2198-Tension-125-LT-2	LT	10.9	11.1	64.6	64.8	70.9	15.0%
2198-Tension-125-LT-3	LT	10.8	11	64.8	64.8	70.9	13.6%

*Properties measured by an extensometer (Ext) and strain gage (SG)

Table A-8. Al-Li 2198-T8; 0.25-inch-thick; individual specimen results

Specimen	Direction	Modulus (Msi)		Yield Str (ksi)		Ultimate Str (ksi)	% Elongation
		Ext*	SG*	Ext*	SG*		
2198-Tension-25-L-1	L	10.8	10.9	70.5	70.5	75.7	12.0%
2198-Tension-25-L-2	L	10.7	10.7	70	70	75.5	12.1%
2198-Tension-25-L-3	L	10.7	10.8	70	70	75.5	12.1%
2198-Tension-25-225-1	22.5°	10.8	10.5	64.9	64.9	71.1	14.0%
2198-Tension-25-225-2	22.5°	10.8	10.5	64.9	64.8	71.2	13.6%
2198-Tension-25-225-3	22.5°	10.8	10.6	65	64.9	71.2	13.5%
2198-Tension-25-45-1	45°	10.5	10.5	59.7	59.6	65.3	16.4%
2198-Tension-25-45-2	45°	10.5	10.4	59.6	59.6	65.2	16.5%
2198-Tension-25-45-3	45°	10.6	10.4	59.6	59.4	65.2	17.0%
2198-Tension-25-675-1	67.5°	11	10.7	64.8	64.8	71.6	14.9%
2198-Tension-25-675-2	67.5°	11.1	10.7	65	64.9	71.7	14.6%
2198-Tension-25-675-3	67.5°	11.1	10.8	64.9	64.9	71.6	15.5%
2198-Tension-25-LT-1	LT	11.1	10.8	66.2	66.2	71.9	15.1%
2198-Tension-25-LT-2	LT	10.9	10.7	66.3	66.2	71.9	14.9%
2198-Tension-25-LT-3	LT	10.9	10.8	66.2	66.2	71.8	15.0%

*Properties measured by an extensometer (Ext) and strain gage (SG)

APPENDIX B—ELEVATED TEMPERATURE TENSION RESULTS FOR AA 2024-T3/351 AND AL-LI 2198-T8

Table B-1. AA 2024-T3 and Al-Li 2198-T8 average results

	Temp (°F)	Young's Modulus (Msi)	Yield Str (ksi)	Ultimate Str (ksi)	% Elongation
AA 2024-T3; 0.071" Thick					
LT	74	11.2	44.2	67.5	17.1%
	200	11.1	43.1	63.9	15.4%
	350	9.2	38.9	55.0	17.4%
Al-Li 2198-T8; 0.071-Inch- Thick					
L	74	11.5	65.4	72.4	8.5%
	200	12.6	62.8	68.2	9.5%
	350	10.1	57	57.7	11.6%
45°	74	10.6	61	70.3	9.4%
	200	12.3	57.7	66.2	9.4%
	350	11.1	53.8	56.7	13.5%
LT	74	11.8	60	68.9	9.3%
	200	11.5	57.7	65.8	9.1%
	350	10.6	53.9	56.2	11.1%

Table B-2. AA 2024-T3; 0.071-inch-thick; individual specimen results

Specimen	Direction	Temp (°F)	Modulus (Msi)	Yield Str (ksi)	Ultimate Str (ksi)	% Elongation
2024-Tension-071-LT-RT-1	LT	74	12.0	43.9	67.8	17.1%
2024-Tension-071-LT-RT-2	LT	74	11.3	44.8	67.1	17.0%
2024-Tension-071-LT-RT-3	LT	74	10.2	43.9	67.6	17.2%
2024-Tension-071-LT-200-1	LT	200	11.5	42.5	63.3	15.3%
2024-Tension-071-LT-200-2	LT	200	12.1	43.2	64.2	15.3%
2024-Tension-071-LT-200-3	LT	200	9.8	43.6	64.2	15.4%
2024-Tension-071-LT-350-1	LT	350	9.6	39.0	55.0	17.0%
2024-Tension-071-LT-350-2	LT	350	8.8	39.1	55.1	18.0%
2024-Tension-071-LT-350-3	LT	350	9.3	38.6	54.8	17.3%

Table B-3. Al-Li 2198-T8; 0.071-inch thick; individual specimen results

Specimen	Direction	Temp (°F)	Modulus (Msi)	Yield Str (ksi)	Ultimate Str (ksi)	% Elongation
2198-Tension-071-L-RT-1	L	74	13.4	65.4	72.9	9.3%
2198-Tension-071-L-RT-2	L	74	11.2	65.9	72.7	8.0%
2198-Tension-071-L-RT-3	L	74	10.0	64.8	71.7	8.0%
2198-Tension-071-L-200-1	L	200	13.1	62.9	68.2	11.2%
2198-Tension-071-L-200-2	L	200	12.2	62.0	67.8	9.2%
2198-Tension-071-L-200-3	L	200	12.6	63.5	68.5	8.2%
2198-Tension-071-L-350-1	L	350	10.6	56.2	57.3	13.4%
2198-Tension-071-L-350-2	L	350	9.6	57.4	58.1	10.0%
2198-Tension-071-L-350-3	L	350	10.0	57.5	57.8	11.4%
2198-Tension-071-45-RT-1	45°	74	10.0	61.2	70.2	9.7%
2198-Tension-071-45-RT-2	45°	74	11.2	60.8	70.3	7.9%
2198-Tension-071-45-RT-3	45°	74	10.6	61.1	70.5	10.7%
2198-Tension-071-45-200-1	45°	200	10.8	58.1	66.1	7.9%
2198-Tension-071-45-200-2	45°	200	13.7	57.3	65.9	9.9%
2198-Tension-071-45-200-3	45°	200	12.5	57.7	66.6	10.5%
2198-Tension-071-45-350-1	45°	350	10.9	53.2	56.7	9.2%
2198-Tension-071-45-350-2	45°	350	10.5	54.5	56.7	14.7%
2198-Tension-071-45-350-3	45°	350	12.0	53.7	56.8	16.5%
2198-Tension-071-LT-RT-1	LT	74	11.9	60.2	68.9	9.4%
2198-Tension-071-LT-RT-2	LT	74	11.5	59.7	68.8	10.4%
2198-Tension-071-LT-RT-3	LT	74	11.8	60.0	68.8	8.0%
2198-Tension-071-LT-200-1	LT	200	11.3	57.7	65.9	8.9%
2198-Tension-071-LT-200-2	LT	200	11.7	57.7	65.8	9.7%
2198-Tension-071-LT-200-3	LT	200	11.5	57.9	65.7	8.6%
2198-Tension-071-LT-350-1	LT	350	11.3	54.3	56.4	11.4%
2198-Tension-071-LT-350-2	LT	350	10.0	53.7	56.3	9.5%
2198-Tension-071-LT-350-3	LT	350	10.4	53.6	56.0	12.3%

APPENDIX C—MICRO-TENSION RESULTS FOR AA 7075-T6 AND AL-LI 2196-T8511

Table C-1. AA 2024-T3/351 average results

	Young's Modulus (Msi)	Yield Strength (ksi)	Ultimate Strength (ksi)
AA 7075-T6; 0.063-Inch- Thick			
L-Full	10.3	75.6	82.8
L	10.3	75.3*	81.9
22.5°	10.1	73.6	82
45°	10.7	72.7	81.7
67.5°	10	72.8	81.8
LT	10.1	75.4	83.7
AA 7075-T6; 0.125-Inch- Thick			
L-Full	10.3	75.2	82.3
L	10.1	76	83.2
22.5°	10.2	74.3**	82.3
45°	10.2	74.3	82.4
67.5°	10.3	73.7	82.4
LT	10.2	76.1	84.2
AA 7075-T6; 0.16-Inch- Thick			
L-Full	10.3	77.3	81.9
L	10.3	76.5	83
22.5°	10.2	76.1	84.7
45°	10.2	76	83.7
67.5°	10.2	74.8	83.4
LT	10.6	77.6	86.5

* One test value; **Average of two; "-Full" represents full-scale specimen size

Table C-2. Al-Li 2196-T8511 average results

	Young's Modulus (Msi)	Yield Strength (ksi)	Ultimate Strength (ksi)
Al-Li 2196-T8511; 0.060-Inch- Thick			
L-Full	11.1	79.9	84.9
L	11.6	80.4*	84.9
22.5°	11.3	77.2**	81.7
45°	11.1	NA	72.8
67.5°	11.3	72.6*	79.9
LT	11.8	NA	86.8
Al-Li 2196-T8511; 0.120-Inch- Thick			
L-Full	11.1	77.9	84.2
L	12.6	74.2**	83.1
22.5°	11.2	69*	76.6
45°	11.2	64.1**	71.1
67.5°	11.3	64.1	74.7
LT	11.6	70.6**	77.6
Al-Li 2196-T8511; 0.145-Inch- Thick			
L-Full	NA	NA	NA
L	13.4	74.9*	86.9
22.5°	11.9	74.8**	81.9
45°	11.9	NA	75.2
67.5°	12.7	69.2*	78.1
LT	11.8	75*	81

* One test value; **Average of two; "-Full" represents full-scale specimen size

Table C-3. AA 7075-T6; 0.063-inch-thick; individual specimen results

Specimen	Direction	Young's Modulus (Msi)	Yield Str (ksi)	Ultimate Str (ksi)
7075-Tension-063-L-1-Full	L	10.2	75.0	82.3
7075-Tension-063-L-2-Full	L	10.3	75.8	83.0
7075-Tension-063-L-3-Full	L	10.2	76.0	83.0
7075-Tension-063-L-1	L	10.1		82.1
7075-Tension-063-L-2	L	10.6		81.8
7075-Tension-063-L-3	L	10.2	75.3	81.8
7075-Tension-063-225-1	22.5°	10.1	73.8	82.4
7075-Tension-063-225-2	22.5°	10.2	73.9	82.2
7075-Tension-063-225-3	22.5°	10.1	73.1	81.3
7075-Tension-063-45-1	45°	10.9	72.3	81.7
7075-Tension-063-45-2	45°	11.0	73.1	82.0
7075-Tension-063-45-3	45°	10.1	72.8	81.5
7075-Tension-063-675-1	67.5°	10.1	73.1	82.1
7075-Tension-063-675-2	67.5°	10.1	73.1	81.9
7075-Tension-063-675-3	67.5°	9.8	72.2	81.4
7075-Tension-063-LT-1	LT	10.1	74.7	83.3
7075-Tension-063-LT-2	LT	10.2	75.8	84.0
7075-Tension-063-LT-3	LT	10.1	75.6	83.8

Table C-4. AA 7075-T6; 0.125-inch-thick; individual specimen results

Specimen	Direction	Young's Modulus (Msi)	Yield Str (ksi)	Ultimate Str (ksi)
7075-Tension-125-L-1-Full	L	10.3	75.2	82.3
7075-Tension-125-L-2-Full	L	10.3	75.0	82.1
7075-Tension-125-L-3-Full	L	10.3	75.4	82.5
7075-Tension-125-L-1	L	10.0	76.2	83.4
7075-Tension-125-L-2	L	10.1	75.4	83.1
7075-Tension-125-L-3	L	10.1	76.3	83.1
7075-Tension-125-225-1	22.5°	10.1	74.2	82.5
7075-Tension-125-225-2	22.5°	10.1	74.3	82.2
7075-Tension-125-225-3	22.5°	10.3		82.0
7075-Tension-125-45-1	45°	10.1	74.0	82.2
7075-Tension-125-45-2	45°	10.2	74.6	82.7
7075-Tension-125-45-3	45°	10.2	74.3	82.4
7075-Tension-125-675-1	67.5°	10.0	73.5	82.4
7075-Tension-125-675-2	67.5°	10.2	73.7	82.4
7075-Tension-125-675-3	67.5°	10.6	73.8	82.4
7075-Tension-125-LT-1	LT	10.1	76.0	84.0
7075-Tension-125-LT-2	LT	10.2	76.2	84.3
7075-Tension-125-LT-3	LT	10.2	76.2	84.2

Table C-5. AA 7075-T6; 0.160-inch-thick; individual specimen results

Specimen	Direction	Young's Modulus (Msi)	Yield Str (ksi)	Ultimate Str (ksi)
7075-Tension-160-L-1-Full	L	10.2	77.0	81.7
7075-Tension-160-L-2-Full	L	10.3	77.2	81.9
7075-Tension-160-L-3-Full	L	10.3	77.6	82.1
7075-Tension-160-L-1	L	10.3	78.2	83.7
7075-Tension-160-L-2	L	10.4	77.9	83.4
7075-Tension-160-L-3	L	10.1	73.5	81.8
7075-Tension-160-225-1	22.5°	10.2	76.0	84.7
7075-Tension-160-225-2	22.5°	10.2	75.7	84.7
7075-Tension-160-225-3	22.5°	10.2	76.6	84.9
7075-Tension-160-45-1	45°	10.2	74.5	83.6
7075-Tension-160-45-2	45°	10.2	79.0	84.4
7075-Tension-160-45-3	45°	10.2	74.5	83.0
7075-Tension-160-675-1	67.5°	10.0	74.7	83.2
7075-Tension-160-675-2	67.5°	10.2	74.8	83.3
7075-Tension-160-675-3	67.5°	10.3	75.0	83.5
7075-Tension-160-LT-1	LT	10.4	77.7	86.9
7075-Tension-160-LT-2	LT	11.1	78.0	86.9
7075-Tension-160-LT-3	LT	10.3	77.1	85.8

Table C-6. Al-Li 2196-T8511; 0.060-inch-thick; individual specimen results

Specimen	Direction	Young's Modulus (Msi)	Yield Str (ksi)	Ultimate Str (ksi)
2196-Tension-060-L-1-Full	L	11.2	80.2	85.3
2196-Tension-060-L-2-Full	L	11.1	80.0	84.7
2196-Tension-060-L-3-Full	L	11.1	79.5	84.6
2196-Tension-060-L-1	L	11.5		84.3
2196-Tension-060-L-2	L	11.6	80.4	85.1
2196-Tension-060-L-3	L	11.7		85.2
2196-Tension-060-225-1	22.5°	11.3		82.1
2196-Tension-060-225-2	22.5°	11.3	76.3	80.8
2196-Tension-060-225-3	22.5°	11.2	78.2	82.1
2196-Tension-060-45-1	45°	11.2		73.8
2196-Tension-060-45-2	45°	10.9		72.5
2196-Tension-060-45-3	45°	11.1		72.1
2196-Tension-060-675-1	67.5°	11.0		79.0
2196-Tension-060-675-2	67.5°	11.6		80.6
2196-Tension-060-675-3	67.5°	11.2	72.6	80.0
2196-Tension-060-LT-1	LT	11.9		87.2
2196-Tension-060-LT-2	LT	11.6		86.3
2196-Tension-060-LT-3	LT	11.9		87.1

Table C-7. Al-Li 2196-T8511; 0.120-inch-thick; individual specimen results

Specimen	Direction	Young's Modulus (Msi)	Yield Str (ksi)	Ultimate Str (ksi)
2196-Tension-120-L-1-Full	L	11.1	78.0	84.1
2196-Tension-120-L-2-Full	L	11.1	78.3	84.2
2196-Tension-120-L-3-Full	L	11.2	77.6	84.2
2196-Tension-120-L-1	L	11.6		85.8
2196-Tension-120-L-2	L	12.7	74.7	82.7
2196-Tension-120-L-3	L	13.6	73.8	80.7
2196-Tension-120-225-1	22.5°	11.4		76.4
2196-Tension-120-225-2	22.5°	11.6	69.0	76.0
2196-Tension-120-225-3	22.5°	10.7		77.5
2196-Tension-120-45-1	45°	11.0	64.3	71.1
2196-Tension-120-45-2	45°	10.9		71.1
2196-Tension-120-45-3	45°	11.6	63.8	71.0
2196-Tension-120-675-1	67.5°	11.5	63.8	74.6
2196-Tension-120-675-2	67.5°	11.3	64.0	74.6
2196-Tension-120-675-3	67.5°	11.1	64.6	74.9
2196-Tension-120-LT-1	LT	11.3		77.6
2196-Tension-120-LT-2	LT	11.6	71.4	78.1
2196-Tension-120-LT-3	LT	11.8	69.9	77.1

Table C-8. Al-Li 2196-T8511; 0.145-inch-thick; individual specimen results

Specimen	Direction	Young's Modulus (Msi)	Yield Str (ksi)	Ultimate Str (ksi)
2196-Tension-145-L-1	L	13.2		86.3
2196-Tension-145-L-2	L	13.0		87.4
2196-Tension-145-L-3	L	14.0	74.9	87.1
2196-Tension-145-225-1	22.5°	12.2	74.2	81.7
2196-Tension-145-225-2	22.5°	11.9		81.8
2196-Tension-145-225-3	22.5°	11.6	75.4	82.2
2196-Tension-145-45-1	45°	11.8		74.8
2196-Tension-145-45-2	45°	12.5		75.6
2196-Tension-145-45-3	45°	11.5		75.2
2196-Tension-145-675-1	67.5°	12.1		78.1
2196-Tension-145-675-2	67.5°	12.8	69.2	78.2
2196-Tension-145-675-3	67.5°	13.3		78.1
2196-Tension-145-LT-1	LT	11.7		81.0
2196-Tension-145-LT-2	LT	11.3	75.0	81.0
2196-Tension-145-LT-3	LT	12.5		80.9

APPENDIX D—COMPRESSION RESULTS FOR AA 2024-T3/351 AND AL-LI 2198-T8

Table D-1. AA 2024-T3/351 Average Results

	Compression Modulus (Msi)	Yield Strength (ksi)
AA 2024-T3; 0.071-Inch Thick		
L	10.6	46.5
22.5°	10.8	48.8
45°	10.7	47.3
67.5°	10.7	46.8
LT	10.7	48.1
AA 2024-T3; 0.125-Inch Thick		
L	10.4	46.6
22.5°	10.4	49.2
45°	10.4	48.2
67.5°	10.3	47
LT	10.6	49.1
AA 2024-T351; 0.25-Inch Thick		
L	10.7	45.3
22.5°	10.9	51.5
45°	10.8	50
67.5°	10.7	47.3
LT	10.8	51

Table D-2. Al-Li 2198-T8 Average Results

	Compression Modulus (Msi)	Yield Strength (ksi)
Al-Li 2198-T8; 0.071-Inch Thick		
L	10.7	65.4
22.5°	10.9	65.1
45°	10.9	65.6
67.5°	10.8	64
LT	10.9	65
Al-Li 2198-T8; 0.125-Inch Thick		
L	11.6	67.9
22.5°	11.5	67.2
45°	11.2	62.9
67.5°	11.4	68.9
LT	11.7	68.7
Al-Li 2198-T8; 0.25-Inch Thick		
L	11.2	68.8
22.5°	11.2	67
45°	10.9	63.5
67.5°	11	68.9
LT	11.4	69.3

Table D-3. AA 2024-T3; 0.071-inch thick; individual specimen results

Specimen	Direction	Compression Modulus (Msi)	Yield Str (ksi)
2024-Compression-071-L-1	L	10.6	46.2
2024-Compression-071-L-2	L	10.7	46.1
2024-Compression-071-L-3	L	10.6	47.1
2024-Compression-071-225-1	22.5°	10.8	48.4
2024-Compression-071-225-2	22.5°	10.7	48.4
2024-Compression-071-225-3	22.5°	10.8	49.5
2024-Compression-071-45-1	45°	10.6	45.5
2024-Compression-071-45-2	45°	10.7	47.8
2024-Compression-071-45-3	45°	10.7	48.7
2024-Compression-071-675-1	67.5°	10.8	45.6
2024-Compression-071-675-2	67.5°	10.6	47.3
2024-Compression-071-675-3	67.5°	10.7	47.6
2024-Compression-071-LT-1	LT	10.7	48.0
2024-Compression-071-LT-2	LT	10.7	48.1
2024-Compression-071-LT-3	LT	10.8	48.3

Table D-4. AA 2024-T3; 0.125-inch thick; individual specimen results

Specimen	Direction	Compression Modulus (Msi)	Yield Str (ksi)
2024-Compression-125-L-1	L	10.3	46.7
2024-Compression-125-L-2	L	10.3	46.5
2024-Compression-125-L-3	L	10.6	46.6
2024-Compression-125-225-1	22.5°	10.4	49.4
2024-Compression-125-225-2	22.5°	10.4	49.0
2024-Compression-125-225-3	22.5°	10.5	49.3
2024-Compression-125-45-1	45°	10.4	48.0
2024-Compression-125-45-2	45°	10.4	48.3
2024-Compression-125-45-3	45°	10.4	48.3
2024-Compression-125-675-1	67.5°	10.3	46.8
2024-Compression-125-675-2	67.5°	10.3	46.8
2024-Compression-125-675-3	67.5°	10.4	47.3
2024-Compression-125-LT-1	LT	10.6	49.1
2024-Compression-125-LT-2	LT	10.5	49.1
2024-Compression-125-LT-3	LT	10.7	49.1

Table D-5. AA 2024-T351; 0.25-inch thick; individual specimen results

Specimen	Direction	Compression Modulus (Msi)	Yield Str (ksi)
2024-Compression-25-L-1	L	10.8	45.4
2024-Compression-25-L-2	L	10.7	45.3
2024-Compression-25-L-3	L	10.7	45.3
2024-Compression-25-225-1	22.5°	10.8	51.5
2024-Compression-25-225-2	22.5°	11.0	51.4
2024-Compression-25-225-3	22.5°	10.8	51.6
2024-Compression-25-45-1	45°	10.8	50.1
2024-Compression-25-45-2	45°	10.9	49.7
2024-Compression-25-45-3	45°	10.8	50.1
2024-Compression-25-675-1	67.5°	10.7	47.2
2024-Compression-25-675-2	67.5°	10.8	47.1
2024-Compression-25-675-3	67.5°	10.7	47.5
2024-Compression-25-LT-1	LT	10.8	50.9
2024-Compression-25-LT-2	LT	10.9	51.2
2024-Compression-25-LT-3	LT	10.7	51.0

Table D-6. Al-Li 2198-T8; 0.071-inch thick; individual specimen results

Specimen	Direction	Compression Modulus (Msi)	Yield Str (ksi)
2198-Compression-071-L-1	L	10.8	65.8
2198-Compression-071-L-2	L	10.7	65.2
2198-Compression-071-L-3	L	10.7	65.3
2198-Compression-071-225-1	22.5°	10.9	65.4
2198-Compression-071-225-2	22.5°	10.9	64.5
2198-Compression-071-225-3	22.5°	10.9	65.4
2198-Compression-071-45-1	45°	10.9	65.7
2198-Compression-071-45-2	45°	10.9	65.7
2198-Compression-071-45-3	45°	10.8	65.5
2198-Compression-071-675-1	67.5°	10.9	63.9
2198-Compression-071-675-2	67.5°	10.8	63.5
2198-Compression-071-675-3	67.5°	10.8	64.5
2198-Compression-071-LT-1	LT	10.9	64.8
2198-Compression-071-LT-2	LT	10.9	64.9
2198-Compression-071-LT-3	LT	10.9	65.2

Table D-7. Al-Li 2198-T8; 0.125-inch thick; individual specimen results

Specimen	Direction	Compression Modulus (Msi)	Yield Str (ksi)
2198-Compression-125-L-1	L	11.5	67.7
2198-Compression-125-L-2	L	11.6	67.6
2198-Compression-125-L-3	L	11.6	68.4
2198-Compression-125-225-1	22.5°	11.3	66.4
2198-Compression-125-225-2	22.5°	11.5	67.6
2198-Compression-125-225-3	22.5°	11.6	67.6
2198-Compression-125-45-1	45°	11.2	62.8
2198-Compression-125-45-2	45°	11.2	62.7
2198-Compression-125-45-3	45°	11.1	63.1
2198-Compression-125-675-1	67.5°	11.4	68.5
2198-Compression-125-675-2	67.5°	11.4	68.8
2198-Compression-125-675-3	67.5°	11.4	69.3
2198-Compression-125-LT-1	LT	11.7	68.5
2198-Compression-125-LT-2	LT	11.8	68.8
2198-Compression-125-LT-3	LT	11.7	68.7

Table D-8. Al-Li 2198-T8; 0.25-inch thick; individual specimen results

Specimen	Direction	Compression Modulus (Msi)	Yield Str (ksi)
2198-Compression-25-L-1	L	11.2	68.8
2198-Compression-25-L-2	L	11.2	68.5
2198-Compression-25-L-3	L	11.3	69.2
2198-Compression-25-225-1	22.5°	11.2	66.7
2198-Compression-25-225-2	22.5°	11.2	66.9
2198-Compression-25-225-3	22.5°	11.3	67.3
2198-Compression-25-45-1	45°	11.0	63.4
2198-Compression-25-45-2	45°	10.9	63.8
2198-Compression-25-45-3	45°	10.9	63.4
2198-Compression-25-675-1	67.5°	11.0	68.8
2198-Compression-25-675-2	67.5°	11.0	68.9
2198-Compression-25-675-3	67.5°	11.0	68.9
2198-Compression-25-LT-1	LT	11.4	69.5
2198-Compression-25-LT-2	LT	11.4	69.4
2198-Compression-25-LT-3	LT	11.4	69.0

APPENDIX E—COMPRESSION RESULTS FOR AA 7075-T6 AND AL-LI 2196-T8511

Table E-1. AA 7075-T6 average results

	Compression Modulus (Msi)	Yield Strength (ksi)
AA 7075-T6; 0.063-Inch Thick		
L-Full	10.6	77.7*
L	10.5	79.6
22.5°	11.2	93.9
45°	10.9	86.9
67.5°	11.1	78.5
LT	11.7	97.8
AA 7075-T6; 0.125-Inch Thick		
L-Full	10.6	81.2
L	12.4	87.7
22.5°	11.8	87.5
45°	12.1	88.8
67.5°	11.9	88.7
LT	11.7	87.8
AA 7075-T6; 0.160-Inch Thick		
L-Full	10.8	78.6
L	11.6	88.6
22.5°	12.4	90.5
45°	11.6	87.8
67.5°	11.7	86.6
LT	12	91.6

* One test value; **Average of two; "-Full" represents full-scale specimen size

Table E-2. Al-Li 2196-T8511 average results

	Compression Modulus (Msi)	Yield Strength (ksi)
Al-Li 2196-T8511; 0.060-Inch Thick		
L-Full	11.6	NA
L	13.2	88.5
22.5°	13.2	88.1**
45°	12	82.3
67.5°	13.7	85.9**
LT	13.1	98.5
Al-Li 2196-T8511; 0.020-Inch Thick		
L-Full	11.6	77.7
L	14.2	91.6**
22.5°	14.1**	83.2**
45°	12.8	75
67.5°	13.3	78.8
LT	13.5	83.7
Al-Li 2196-T8511; 0.145-Inch Thick		
L-Full	11.6**	86.5**
L	13.3	89.9
22.5°	13.6	84.5**
45°	13.4	80.3**
67.5°	14.8	81.6**
LT	16.8	85.1*

* One test value; **Average of two; “-Full” represents full-scale specimen size

Table E-3. AA 7075-T6; 0.063-inch thick; individual specimen results

Specimen	Direction	Modulus (Msi)	Yield Str (ksi)
7075-Compression-063-L-1-Full	L	10.6	
7075-Compression-063-L-2-Full	L	10.5	77.7
7075-Compression-063-L-3-Full	L	10.6	
7075-Compression-063-L-1	L	10.7	79.4
7075-Compression-063-L-2	L	10.2	79.6
7075-Compression-063-L-3	L	10.5	79.9
7075-Compression-063-225-1	22.5°	11.2	94.2
7075-Compression-063-225-2	22.5°	10.9	94.8
7075-Compression-063-225-3	22.5°	11.4	92.8
7075-Compression-063-45-1	45°	10.4	79.4
7075-Compression-063-45-2	45°	10.7	82.4
7075-Compression-063-45-3	45°	11.6	98.9
7075-Compression-063-675-1	67.5°	11.3	80.1
7075-Compression-063-675-2	67.5°	11.1	77.4
7075-Compression-063-675-3	67.5°	10.9	78.1
7075-Compression-063-LT-1	LT	12.5	105.2
7075-Compression-063-LT-2	LT	11.2	92.6
7075-Compression-063-LT-3	LT	11.4	95.7

Table E-4. AA 7075-T6; 0.125-inch thick; individual specimen results

Specimen	Direction	Modulus (Msi)	Yield Str (ksi)
7075-Compression-125-L-1-Full	L	10.6	80.9
7075-Compression-125-L-2-Full	L	10.6	81.5
7075-Compression-125-L-3-Full	L	10.6	81.4
7075-Compression-125-L-1	L	13.0	86.6
7075-Compression-125-L-2	L	12.9	88.0
7075-Compression-125-L-3	L	11.4	88.6
7075-Compression-125-225-1	22.5°	11.3	87.6
7075-Compression-125-225-2	22.5°	12.6	86.3
7075-Compression-125-225-3	22.5°	11.6	88.7
7075-Compression-125-45-1	45°	11.8	89.4
7075-Compression-125-45-2	45°	11.6	89.1
7075-Compression-125-45-3	45°	12.9	88.0
7075-Compression-125-675-1	67.5°	12.2	89.5
7075-Compression-125-675-2	67.5°	11.7	89.1
7075-Compression-125-675-3	67.5°	11.8	87.3
7075-Compression-125-LT-1	LT	12.8	88.8
7075-Compression-125-LT-2	LT	11.0	86.5
7075-Compression-125-LT-3	LT	11.4	88.1

Table E-5. AA 7075-T6; 0.160-inch thick; individual specimen results

Specimen	Direction	Modulus (Msi)	Yield Str (ksi)
7075-Compression-160-L-1-Full	L	11.0	79.0
7075-Compression-160-L-2-Full	L	10.7	78.4
7075-Compression-160-L-3-Full	L	10.7	78.6
7075-Compression-160-L-1	L	11.3	91.6
7075-Compression-160-L-2	L	11.6	89.3
7075-Compression-160-L-3	L	12.0	85.0
7075-Compression-160-225-1	22.5°	12.3	90.9
7075-Compression-160-225-2	22.5°	12.5	91.4
7075-Compression-160-225-3	22.5°	12.3	89.1
7075-Compression-160-45-1	45°	11.4	88.0
7075-Compression-160-45-2	45°	11.3	89.1
7075-Compression-160-45-3	45°	12.2	86.2
7075-Compression-160-675-1	67.5°	11.4	85.1
7075-Compression-160-675-2	67.5°	11.7	87.7
7075-Compression-160-675-3	67.5°	12.0	87.2
7075-Compression-160-LT-1	LT	12.1	89.7
7075-Compression-160-LT-2	LT	12.1	92.7
7075-Compression-160-LT-3	LT	11.8	92.6

Table E-6. Al-Li 2196-T8511; 0.060-inch thick; individual specimen results

Specimen	Direction	Young's Modulus (Msi)	Yield Str (ksi)
2196-Compression-060-L-1-Full	L	11.6	
2196-Compression-060-L-2-Full	L	11.6	
2196-Compression-060-L-3-Full	L	11.6	
2196-Compression-060-L-1	L	14.8	88.6
2196-Compression-060-L-2	L	12.5	89.0
2196-Compression-060-L-3	L	12.3	87.8
2196-Compression-060-225-1	22.5°	12.1	88.6
2196-Compression-060-225-2	22.5°	11.8	87.6
2196-Compression-060-225-3	22.5°	15.6	
2196-Compression-060-45-1	45°	11.6	82.0
2196-Compression-060-45-2	45°	12.5	86.1
2196-Compression-060-45-3	45°	11.8	78.9
2196-Compression-060-675-1	67.5°	12.4	87.4
2196-Compression-060-675-2	67.5°	16.6	
2196-Compression-060-675-3	67.5°	12.0	84.3
2196-Compression-060-LT-1	LT	13.4	101.1
2196-Compression-060-LT-2	LT	13.0	96.9
2196-Compression-060-LT-3	LT	12.9	97.5

Table E-7. Al-Li 2196-T8511; 0.120-inch thick; individual specimen results

Specimen	Direction	Young's Modulus (Msi)	Yield Str (ksi)
2196-Compression-120-L-1-Full	L	11.6	77.1
2196-Compression-120-L-2-Full	L	11.6	78.3
2196-Compression-120-L-3-Full	L	11.6	77.7
2196-Compression-120-L-1	L	12.5	89.2
2196-Compression-120-L-2	L	16.9	
2196-Compression-120-L-3	L	13.2	93.9
2196-Compression-120-225-1	22.5°	13.0	81.0
2196-Compression-120-225-2	22.5°	15.2	85.3
2196-Compression-120-225-3	22.5°		
2196-Compression-120-45-1	45°	13.1	76.4
2196-Compression-120-45-2	45°	12.9	74.0
2196-Compression-120-45-3	45°	12.5	74.6
2196-Compression-120-675-1	67.5°	13.6	79.7
2196-Compression-120-675-2	67.5°	13.5	78.1
2196-Compression-120-675-3	67.5°	12.9	78.6
2196-Compression-120-LT-1	LT	13.4	84.1
2196-Compression-120-LT-2	LT	14.3	83.7
2196-Compression-120-LT-3	LT	12.7	83.4

Table E-8. Al-Li 2196-T8511; 0.145-inch thick; individual specimen results

Specimen	Direction	Young's Modulus (Msi)	Yield Str (ksi)
2196-Compression-145-L-1-Full	L	11.6	86.7
2196-Compression-145-L-2-Full	L	11.7	86.3
2196-Compression-145-L-3-Full	L		
2196-Compression-145-L-1	L	13.6	88.0
2196-Compression-145-L-2	L	12.8	90.6
2196-Compression-145-L-3	L	13.6	91.0
2196-Compression-145-225-1	22.5°	13.4	
2196-Compression-145-225-2	22.5°	13.3	83.1
2196-Compression-145-225-3	22.5°	14.0	85.9
2196-Compression-145-45-1	45°	14.0	
2196-Compression-145-45-2	45°	13.3	80.5
2196-Compression-145-45-3	45°	13.0	80.2
2196-Compression-145-675-1	67.5°	12.9	80.8
2196-Compression-145-675-2	67.5°	17.3	
2196-Compression-145-675-3	67.5°	14.3	82.5
2196-Compression-145-LT-1	LT	18.1	85.1
2196-Compression-145-LT-2	LT	13.1	
2196-Compression-145-LT-3	LT	19.4	

APPENDIX F—SHEAR RESULTS FOR AA 2024-T3/351 AND AL-LI 2198-T8

Table F-1. AA 2024-T3/351 average results

	Shear Modulus (Msi)	Shear Strength (ksi)
AA 2024-T3; 0.071-Inch Thick		
L	3.3	47.1
22.5°	3.3	48.1
45°	3.5	47.4
67.5°	3.4	48.0
LT	3.3	47.9
AA 2024-T3; 0.125-Inch Thick		
L	3.6	46.9
22.5°	3.7	47.5
45°	3.9	47.3
67.5°	3.8	47.3
LT	3.5	47.1
AA 2024-T351; 0.25-Inch Thick		
L	3.6	47.1
22.5°	3.7	49.8
45°	3.7	48.7
67.5°	3.6	49.1
LT	3.5	49.6

Table F-2. Al-Li 2198-T8 average results

	Shear Modulus (Msi)	Shear Strength (ksi)
Al-Li 2198-T8; 0.071-Inch Thick		
L	4.3	47
22.5°	4.4	46.9
45°	4.3	46.4
67.5°	4.3	46.7
LT	4.1	45.8
Al-Li 2198-T8; 0.125-Inch Thick		
L	4.1	43.5
22.5°	4.4	43.6
45°	4.5	45.8
67.5°	4.5	43.6
LT	4.1	44.9
Al-Li 2198-T8; 0.25-Inch Thick		
L	4.2	45.1
22.5°	4.2	43.4
45°	4.5	46.9
67.5°	4	49.1
LT	4.1	45.8

Table F-3. AA 2024-T3; 0.071-inch thick; individual specimen results

Specimen	Direction	Modulus (Msi)	Shear Strength (ksi)
2024-Shear-071-L-1	L	3.3	47.22
2024-Shear-071-L-2	L	3.3	46.96
2024-Shear-071-L-3	L	3.3	47.16
2024-Shear-071-225-1	22.5°	3.4	48.07
2024-Shear-071-225-2	22.5°	3.3	48.18
2024-Shear-071-225-3	22.5°	3.1	48.13
2024-Shear-071-45-1	45°	3.5	47.53
2024-Shear-071-45-2	45°	3.4	47.38
2024-Shear-071-45-3	45°	3.5	47.26
2024-Shear-071-675-1	67.5°	3.3	48.08
2024-Shear-071-675-2	67.5°	3.3	47.74
2024-Shear-071-675-3	67.5°	3.5	48.23
2024-Shear-071-LT-1	LT	3.3	47.56
2024-Shear-071-LT-2	LT	3.2	47.99
2024-Shear-071-LT-3	LT	3.3	48.14

Table F-4. AA 2024-T3; 0.125-inch thick; individual specimen results

Specimen	Direction	Modulus (Msi)	Shear Strength (ksi)
2024-Shear-125-L-1	L	3.6	46.39
2024-Shear-125-L-2	L	3.6	46.63
2024-Shear-125-L-3	L	3.6	47.55
2024-Shear-125-225-1	22.5°	3.7	47.52
2024-Shear-125-225-2	22.5°	3.7	47.51
2024-Shear-125-225-3	22.5°	3.7	47.41
2024-Shear-125-45-1	45°	3.9	47.30
2024-Shear-125-45-2	45°	3.8	47.36
2024-Shear-125-45-3	45°	3.9	47.10
2024-Shear-125-675-1	67.5°	3.8	48.00
2024-Shear-125-675-2	67.5°	3.8	46.95
2024-Shear-125-675-3	67.5°	3.8	46.84
2024-Shear-125-LT-1	LT	3.4	47.04
2024-Shear-125-LT-2	LT	3.5	47.10
2024-Shear-125-LT-3	LT	3.5	47.13

Table F-5. AA 2024-T3; 0.25-inch thick; individual specimen results

Specimen	Direction	Modulus (Msi)	Shear Strength (ksi)
2024-Shear-25-L-1	L	3.7	47.11
2024-Shear-25-L-2	L	3.5	47.17
2024-Shear-25-L-3	L	3.5	46.93
2024-Shear-25-225-1	22.5°	3.6	50.16
2024-Shear-25-225-2	22.5°	3.7	49.92
2024-Shear-25-225-3	22.5°	3.6	49.43
2024-Shear-25-45-1	45°	3.7	49.18
2024-Shear-25-45-2	45°	3.5	48.31
2024-Shear-25-45-3	45°	3.8	48.65
2024-Shear-25-675-1	67.5°	3.7	48.75
2024-Shear-25-675-2	67.5°	3.6	49.21
2024-Shear-25-675-3	67.5°	3.5	49.34
2024-Shear-25-LT-1	LT	3.4	49.51
2024-Shear-25-LT-2	LT	3.4	49.22
2024-Shear-25-LT-3	LT	3.6	50.06

Table F-6. Al-Li 2198-T8; 0.071-inch thick; individual specimen results

Specimen	Direction	Modulus (Msi)	Shear Strength (ksi)
2198-Shear-071-L-1	L	4.4	47.55
2198-Shear-071-L-2	L	4.2	46.31
2198-Shear-071-L-3	L	4.3	47.07
2198-Shear-071-225-1	22.5°	4.4	47.77
2198-Shear-071-225-2	22.5°	4.5	46.96
2198-Shear-071-225-3	22.5°	4.3	46.09
2198-Shear-071-45-1	45°	4.4	46.18
2198-Shear-071-45-2	45°	4.2	46.92
2198-Shear-071-45-3	45°	4.3	45.95
2198-Shear-071-675-1	67.5°	4.3	46.21
2198-Shear-071-675-2	67.5°	4.3	46.75
2198-Shear-071-675-3	67.5°	4.3	47.09
2198-Shear-071-LT-1	LT	4.0	44.45
2198-Shear-071-LT-2	LT	4.2	46.23
2198-Shear-071-LT-3	LT	4.2	46.70

Table F-7. Al-Li 2198-T8; 0.125-inch thick; individual specimen results

Specimen	Direction	Modulus (Msi)	Shear Strength (ksi)
2198-Shear-125-L-1	L	4.1	44.00
2198-Shear-125-L-2	L	4.1	43.56
2198-Shear-125-L-3	L	4.1	42.86
2198-Shear-125-225-1	22.5°	4.3	43.65
2198-Shear-125-225-2	22.5°	4.3	43.66
2198-Shear-125-225-3	22.5°	4.5	43.46
2198-Shear-125-45-1	45°	4.6	46.23
2198-Shear-125-45-2	45°	4.6	45.79
2198-Shear-125-45-3	45°	4.4	45.46
2198-Shear-125-675-1	67.5°	4.4	43.26
2198-Shear-125-675-2	67.5°	4.5	44.01
2198-Shear-125-675-3	67.5°	4.4	43.45
2198-Shear-125-LT-1	LT	4.1	45.44
2198-Shear-125-LT-2	LT	4.1	44.68
2198-Shear-125-LT-3	LT	4.0	44.66

Table F-8. Al-Li 2198-T8; 0.25-inch thick; individual specimen results

Specimen	Direction	Modulus (Msi)	Shear Strength (ksi)
2198-Shear-25-L-1	L	4.2	45.10
2198-Shear-25-L-2	L	4.1	44.95
2198-Shear-25-L-3	L	4.3	45.13
2198-Shear-25-225-1	22.5°	4.2	43.63
2198-Shear-25-225-2	22.5°	4.3	43.70
2198-Shear-25-225-3	22.5°	4.2	42.91
2198-Shear-25-45-1	45°	4.5	47.08
2198-Shear-25-45-2	45°	4.4	46.48
2198-Shear-25-45-3	45°	4.5	47.19
2198-Shear-25-675-1	67.5°	4.0	49.27
2198-Shear-25-675-2	67.5°	4.1	49.24
2198-Shear-25-675-3	67.5°	4.0	48.73
2198-Shear-25-LT-1	LT	4.1	46.04
2198-Shear-25-LT-2	LT	4.2	45.85
2198-Shear-25-LT-3	LT	4.1	45.66

APPENDIX G—SHEAR RESULTS FOR AA 7075-T6 AND AL-LI 2196-T8511

Table G-1. AA 7075-T6 average results

	Shear Modulus (Msi)	Shear Strength (ksi)
AA 7075-T6; 0.063-Inch Thick		
L	4.4	55.0
22.5°	4.4	55.4
45°	4.4	55.4
67.5°	4.4	56.0
LT	4.4	55.8
AA 7075-T6; 0.125-Inch Thick		
L	4.2	54.9
22.5°	4.3	54.7
45°	4.2	55.3
67.5°	4.3	55.7
LT	4.3	55.4
AA 7075-T6; 0.160-Inch Thick		
L	4.1	53.4
22.5°	4.3	54.4
45°	4.3	54.7
67.5°	4.3	54.6
LT	4.2	53.7

Table G-2. Al-Li 2196-T8511 average results

	Shear Modulus (Msi)	Shear Strength (ksi)
Al-Li 2196-T8511; 0.060-Inch Thick		
L	4.6	45.1
22.5°	4.6	50.1
45°	4.8	52.6
67.5°	4.6	48.8
LT	4.4	49.6
Al-Li 2196-T8511; 0.020-Inch Thick		
L	4.4	46.3
22.5°	4.9	47.9
45°	4.7	51.4
67.5°	4.6	52.7
LT	4.2	47.7
Al-Li 2196-T8511; 0.145-Inch Thick		
L	4.4	47.2
22.5°	4.6	48
45°	4.8	51
67.5°	4.3	48.9
LT	4.3	47.3

Table G-3. AA 7075-T6; 0.063-inch thick; individual specimen results

Specimen	Direction	Modulus (Msi)	Shear Strength (ksi)
7075-Shear-063-L-1	L	4.4	54.9
7075-Shear-063-L-2	L	4.3	55.1
7075-Shear-063-L-3	L	4.4	55.0
7075-Shear-063-225-1	22.5°	4.4	55.3
7075-Shear-063-225-2	22.5°	4.4	55.3
7075-Shear-063-225-3	22.5°	4.3	55.6
7075-Shear-063-45-1	45°	4.4	55.8
7075-Shear-063-45-2	45°	4.4	55.2
7075-Shear-063-45-3	45°	4.4	55.2
7075-Shear-063-675-1	67.5°	4.4	56.5
7075-Shear-063-675-2	67.5°	4.4	55.5
7075-Shear-063-675-3	67.5°	4.3	56.0
7075-Shear-063-LT-1	LT	4.4	55.9
7075-Shear-063-LT-2	LT	4.4	55.4
7075-Shear-063-LT-3	LT	4.4	55.9

Table G-4. AA 7075-T6; 0.125-inch thick; individual specimen results

Specimen	Direction	Modulus (Msi)	Shear Strength (ksi)
7075-Shear-125-L-1	L	4.2	54.7
7075-Shear-125-L-2	L	4.2	55.2
7075-Shear-125-L-3	L	4.2	54.9
7075-Shear-125-225-1	22.5°	4.3	54.6
7075-Shear-125-225-2	22.5°	4.2	55.0
7075-Shear-125-225-3	22.5°	4.3	54.6
7075-Shear-125-45-1	45°	4.3	54.8
7075-Shear-125-45-2	45°	4.3	55.5
7075-Shear-125-45-3	45°	4.1	55.5
7075-Shear-125-675-1	67.5°	4.3	55.7
7075-Shear-125-675-2	67.5°	4.2	55.9
7075-Shear-125-675-3	67.5°	4.3	55.5
7075-Shear-125-LT-1	LT	4.3	55.5
7075-Shear-125-LT-2	LT	4.3	55.4
7075-Shear-125-LT-3	LT	4.3	55.3

Table G-5. AA 7075-T6; 0.160-inch thick; individual specimen results

Specimen	Direction	Modulus (Msi)	Shear Strength (ksi)
7075-Shear-160-L-1	L	4.1	52.1
7075-Shear-160-L-2	L	4.0	54.3
7075-Shear-160-L-3	L	4.2	53.8
7075-Shear-160-225-1	22.5°	4.2	53.9
7075-Shear-160-225-2	22.5°	4.2	54.9
7075-Shear-160-225-3	22.5°	4.4	54.6
7075-Shear-160-45-1	45°	4.3	54.4
7075-Shear-160-45-2	45°	4.2	54.6
7075-Shear-160-45-3	45°	4.3	55.1
7075-Shear-160-675-1	67.5°	4.3	54.3
7075-Shear-160-675-2	67.5°	4.3	54.6
7075-Shear-160-675-3	67.5°	4.2	54.9
7075-Shear-160-LT-1	LT	4.2	53.4
7075-Shear-160-LT-2	LT	4.2	53.8
7075-Shear-160-LT-3	LT	4.0	53.9

Table G-6. Al-Li 2196-T8511; 0.060-inch thick; individual specimen results

Specimen	Direction	Modulus (Msi)	Shear Strength (ksi)
2196-Shear-060-L-1	L	4.5	45.1
2196-Shear-060-L-2	L	4.5	45.1
2196-Shear-060-L-3	L	4.7	45.1
2196-Shear-060-225-1	22.5°	4.5	53.9
2196-Shear-060-225-2	22.5°	4.7	48.2
2196-Shear-060-225-3	22.5°	4.7	48.1
2196-Shear-060-45-1	45°	5.0	53.6
2196-Shear-060-45-2	45°	4.9	53.4
2196-Shear-060-45-3	45°	4.5	50.8
2196-Shear-060-675-1	67.5°	4.5	48.4
2196-Shear-060-675-2	67.5°	4.6	49.2
2196-Shear-060-675-3	67.5°	4.6	48.9
2196-Shear-060-LT-1	LT	4.4	49.6
2196-Shear-060-LT-2	LT	4.4	49.6
2196-Shear-060-LT-3	LT	4.4	49.5

Table G-7. Al-Li 2196-T8511; 0.120-inch thick; individual specimen results

Specimen	Direction	Modulus (Msi)	Shear Strength (ksi)
2196-Shear-120-L-1	L	4.5	46.7
2196-Shear-120-L-2	L	4.4	46.2
2196-Shear-120-L-3	L	4.3	45.9
2196-Shear-120-225-1	22.5°	4.8	47.9
2196-Shear-120-225-2	22.5°	4.9	48.0
2196-Shear-120-225-3	22.5°	5.0	47.7
2196-Shear-120-45-1	45°	4.6	51.4
2196-Shear-120-45-2	45°	4.7	51.8
2196-Shear-120-45-3	45°	4.8	50.9
2196-Shear-120-675-1	67.5°	4.5	52.7
2196-Shear-120-675-2	67.5°	4.5	53.1
2196-Shear-120-675-3	67.5°	4.6	52.4
2196-Shear-120-LT-1	LT	4.1	46.9
2196-Shear-120-LT-2	LT	4.1	47.6
2196-Shear-120-LT-3	LT	4.4	48.5

Table G-8. Al-Li 2196-T8511; 0.145-inch thick; individual specimen results

Specimen	Direction	Modulus (Msi)	Shear Strength (ksi)
2196-Shear-145-L-1	L	4.4	47.3
2196-Shear-145-L-2	L	4.4	46.8
2196-Shear-145-L-3	L	4.5	47.6
2196-Shear-145-225-1	22.5°	4.5	48.0
2196-Shear-145-225-2	22.5°	4.7	47.9
2196-Shear-145-225-3	22.5°	4.6	48.1
2196-Shear-145-45-1	45°	4.8	50.8
2196-Shear-145-45-2	45°	4.9	50.9
2196-Shear-145-45-3	45°	4.8	51.2
2196-Shear-145-675-1	67.5°	4.4	49.0
2196-Shear-145-675-2	67.5°	4.3	48.9
2196-Shear-145-675-3	67.5°	4.3	48.9
2196-Shear-145-LT-1	LT	4.3	47.2
2196-Shear-145-LT-2	LT	4.3	47.3
2196-Shear-145-LT-3	LT	4.2	47.3