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Volume 1: Program Overview

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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 report constitutes volume 1 of 4 and serves as an overview and background for the program. The subsequent volumes provide a more focused look at the specific tests conducted and data generated. Though the sample size was limited, this program was not meant to develop any design allowables or present the Al-Li alloys as direct replacements for the traditional aluminums alloys. Rather, they 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.

Overall, the Al-Li tested as part of this program behaved in line with expectations. All static properties results, for both the Al-Li and baseline AAs, exceeded the applicable Metallic Materials Property Development and Standardization (MMPDS) handbook values. The Al-Li did show signs of anisotropy, in which strength at the 45-degree grain orientation was the lowest, but this is accounted for by the MMPDS values. Under fatigue loading, the Al-Li 2198-T8 performed similar to the baseline 2024-T3 for the threshold and stable crack-growth phase. The Al-Li showed higher fatigue crack-growth resistance nearing instability, with the best performance at the 45-degree grain orientation. Finally, for all of the supplemental testing, both the Al-Li and baseline AAs responded comparably to external conditions; namely, a corrosive 5% NaCl aqueous solution, 1800°F flame, and fastener hole cold working.

17. Key Words
Aluminum lithium, Aluminum, 2024-T3, 7075-T6, 2198-T8, 2196-T8511, Static properties, Fatigue crack growth, Supplemental properties

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LIST OF ACRONYMS

AA	Aluminum alloy
Al-Li	Aluminum lithium
FAA WJHTC	Federal Aviation Administration William J. Hughes Technical Center
FCG	Fatigue crack growth
FTI	Fatigue Technology Inc.
L	Longitudinal (rolling direction)
LT	Longitudinal transverse
MMPDS	Metallic Materials Property Development and Standardization
NASA-JSC	NASA Johnson Space Center
NAVAIR	US Navy Naval Air Systems Command
NIAR	National Institute for Aviation Research
OLMP	Operation Loads Monitoring Program
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 report constitutes volume 1 of 4 and serves as an overview and background for the program. The subsequent volumes provide a more focused look at the specific tests conducted and data generated. Though the sample size was limited, this program was not meant to develop any design allowables or present the Al-Li alloys as direct replacements for the traditional aluminums alloys. Rather, they 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.

Overall, the Al-Li tested as part of this program behaved in line with expectations. All static properties results for both the Al-Li and baseline AAs exceeded the applicable Metallic Materials Property Development and Standardization (MMPDS) handbook values. The Al-Li did show signs of anisotropy, in which strength at the 45-degree grain orientation was the lowest, but this is accounted for by the MMPDS values. Under fatigue loading, the Al-Li 2198-T8 performed similar to the baseline 2024-T3 for the threshold and stable crack-growth phase. The Al-Li showed higher FCG resistance nearing instability, with the best performance at the 45-degree grain orientation. Finally, for all of the supplemental testing, both the Al-Li and baseline AAs responded comparably to external conditions; namely, a corrosive 5% NaCl aqueous solution, 1800°F flame, and fastener hole cold working.

1. INTRODUCTION

Over the past decade, significant investments and advances have been made by industry in the development of new metallic alloys with optimized material properties for specific structural applications. The latest (third) generation of advanced aluminum-lithium (Al-Li) alloys offers weight savings compared to conventional aluminum alloys (AAs) and maintains mechanical performance. Al-Li alloys have a lower density, higher modulus, and improved resistance against corrosion over the widely used 2xxx and 7xxx series alloys [1]. Previous generations of Al-Li exhibited material behavior, such as low elongation and ductility, low transverse toughness, inadequate thermal stability and fatigue properties, and highly anisotropic behavior with respect to the rolling grain orientation, which restricted their use for many aerospace applications [2–4]. However, the latest generations of Al-Li alloys are reported to minimize these effects and also provide significant weight savings [5].

With these improvements, there has been increased use of Al-Li in recent aircraft and aerospace applications. Bombardier is constructing the entire fuselage of its new C-Series airplane (recently transitioned and designated as Airbus product A220), a certificated Title 14 Code of Federal Regulations Part 25 airplane, using Al-Li [6]. Extruded floor beams for the Airbus A380 are now being made of Al-Li. Additionally, Al-Li plate applications are being used for the internal structure of the fuselage in the Boeing 787. Although these manufacturers have generated substantial proprietary data to substantiate structural applications, there is a lack of data available in the public domain to thoroughly document the mechanical performance of these latest-generation Al-Li alloys.

The objective of this test program was to gain a better understanding of the material properties, mechanical behavior, and unique characteristics of the next-generation Al-Li being used in airframe structures through comparison with traditional AAs. It was not intended to develop any material design allowables or promote Al-Li as a direct replacement for the baseline materials. As a case study, two Al-Li alloys were considered—Al-Li 2198-T8 and 2196-T8511 alloys used for skin and extrusion applications, respectively. Several properties were assessed and compared with baseline AAs 2024-T3 and 7075-T6, including static properties, fatigue life and fatigue crack-growth (FCG) behavior, and supplemental properties. Resources and expertise were received from several organizations, including Constellium, Bombardier, NASA Johnson Space Center (NASA-JSC), US Navy Naval Air Systems Command (NAVAIR), University of Dayton Research Institute (UDRI), National Institute for Aviation Research (NIAR), Drexel University, and the FAA William J. Hughes Technical Center (FAA WJHTC).

This report is the first of four volumes detailing the effort sponsored by the FAA and provides a general overview of the program as a whole. The subsequent volumes are comprised of more detailed information for the specific tests completed and the results generated [7–9]. The four volumes of this report are organized as follows:

- Volume 1: Program Overview. This volume contains summary information that is relevant to the three remaining volumes. It serves as a program overview with information related to Al-Li background and use, program scope, brief test descriptions, representative results, and general conclusions.

- Volume 2: Static Properties. This volume contains detailed information on the static properties tests conducted by the FAA WJHTC, UDRI, and NIAR. The tests conducted included tension, compression, and shear, and were performed to applicable ASTM standards when possible. Deliverable results were material properties for modulus, yield, and ultimate strengths.
- Volume 3: Fatigue Crack-Growth Properties. This volume contains detailed information on the FCG tests conducted by NASA-JSC and UDRI. The tests conducted by NASA-JSC were loaded under constant amplitude at either room or elevated temperatures. The UDRI tests were conducted at room temperature under either constant amplitude or spectrum loading. Deliverable results were fatigue crack-growth rate (FCGR) and crack-growth life.
- Volume 4: Supplemental Properties. This volume contains detailed information on the supplemental properties tests conducted by NAVAIR, FAA WJHTC, Fatigue Technology Inc. (FTI), and Drexel University. The test conducted by NAVAIR was a slow strain-rate test under environmental conditions. The FAA WJHTC conducted a flammability and burn resistance test. FTI, FAA WJHTC, and Drexel University partnered to look at the material response to fastener hole processing, namely cold expansion and interference fit fasteners. Deliverable results were material response to the various external factors.

2. BACKGROUND

The motivation to develop Al-Li as a structural alloy comes from the prospect of weight savings (because of lithium's low density) and increased stiffness (because of its higher elastic modulus) in airframe structures compared to those made of conventional aluminum [1]. However, earlier versions of these alloys exhibited reductions in other key mechanical properties, which limited their usefulness. The most recent generation of Al-Li alloys has reportedly addressed much of the drawbacks present in the older alloys while improving in other areas and, therefore, they are now seeing increased use in aerospace applications.

2.1 HISTORICAL DEVELOPMENT

The historical development of Al-Li alloys is summarized in table 1. The material and mechanical properties of Al-Li alloys have evolved because of significant metallurgical and processing changes in Al-Li alloys. The first Al-Li alloy (Scleron, Al-Zn-Cu-Li) was produced in Germany in the 1920s [10]. Further development of Al-Li alloys began in the 1950s with the first notable alloy Al-Li 2020. This alloy was used on the upper and lower skin of the RA-5C Vigilante aircraft, but it was withdrawn within 10 years of its production because of ductility and fracture toughness problems [2]. Al-Li 1420 was also developed in the 1950s and used in the cockpit and fuselage of the MIG-29. However, it was later discovered that this alloy was of relatively low strength [2] and its subsequent use was reduced.

Table 1. Timeline of Al-Li alloy development

Al-Li Alloy Generation	Timeline	Alloy Designation	Lithium Content	Aircraft Application
1st Generation	1920's	Scleron	0.1%	
	1950s – 1970s	1420	2.1%	MIG-29
		2020	1.2%	RA-5C Vigilante Aircraft
2nd Generation	1970s – 1980s	2090	2.1%	MIG-29, Augusta Westland EH101, Boeing C-17
		2091	2.0%	
		8090	2.4%	
3rd Generation	1990s - Present	2050	1.0%	Bombardier C Series, Airbus A350 & A380, Boeing 787
		2196	1.75%	
		2198	1.0%	
		2199	1.6%	

Increasing demand for fuel efficiency due to the oil crisis in the 1970s combined with larger aircraft payloads led to a revival of research in the field of high-performance AAs for airframe structures [11]. Among the second generation of alloys, Al-Li 2090, 2091, and 8090 were developed to compete with the long-serving commercial AAs, 7075-T6, 2024-T3, and 2014, respectively [12]. Whereas these alloys had an attractively high-elastic modulus, low density, and an improved FCG resistance, they still exhibited anisotropic mechanical properties [2]. Al-Li 2090 and 8090 were also seen to exhibit low stress-corrosion cracking thresholds as well as hole cracking and delaminations during drilling [3]. Several comprehensive studies aimed at characterizing the material properties of these second-generation Al-Li alloys, such as in reference [4], were performed during this time. In general, the drawbacks associated with early generation Al-Li alloys included less than desirable ductility and fracture toughness in the short-transverse direction, accelerated FCGR when the cracks were micro-structurally small, excessive anisotropy of in-plane mechanical properties, crack deviations, poor thermal stability, and a loss of fatigue advantage in compression-dominated fatigue spectra tests.

The development of the third generation of Al-Li alloys beginning in the 1990s started to overcome several drawbacks of the previous generations. The drawbacks of the previous Al-Li alloy generations, like low ST properties and poor thermal stability, were reduced by substantially lowering the lithium contents. This latest generation contains alloys, such as Al-Li 2050, 2096, 2097, 2197, 2196, 2198, and 2297, that are less than 2% lithium by weight. These alloys also contain a small amount of magnesium to improve the resistance to stress-corrosion cracking and manganese to prevent strain localization and increase ductility and strength [13]. In addition to the purported weight savings, the third generation of Al-Li alloys has claimed several property benefits, such as improvements to corrosion resistance, spectrum FCG performance, strength, and toughness [5].

Changes in the chemical composition of Al-Li alloys over the years as their development has progressed are shown in figure 1 [14]. Early generation Al-Li alloys contained approximately 2.5% lithium by weight, whereas newer generations have seen a reduced percentage of lithium and a higher copper content. There have also been changes in the thermo-mechanical and aging processes in the newer Al-Li alloys.

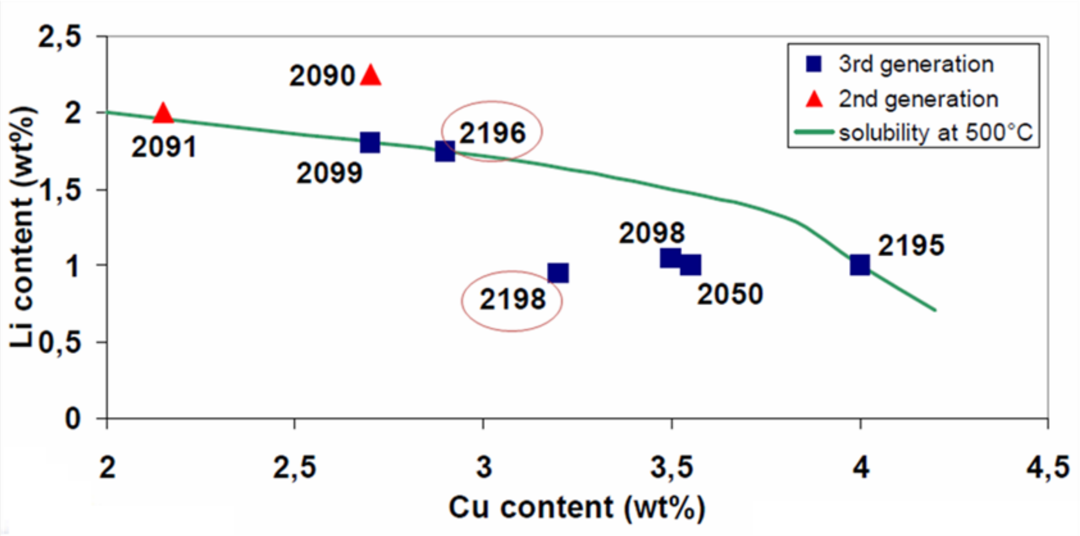

Figure 1. Chemical composition of second- and third-generation Al-Li alloys

Whereas the major advantages of adding lithium (e.g., density reduction and increase in modulus) are reduced in the latest alloys, the higher copper/lithium ratio in third-generation alloys helps increase their thermal stability and strengthens these alloys predominantly by the T1 (Al_2CuLi) phase rather than by δ' when processed conventionally [14]. It is seen that a reduction in the lithium content of the alloy leads to decreasing strength potential but increasing fracture toughness of the alloy. The solubility limit of the alloy at 500°C (a typical solutionizing temperature for such alloys) also drops by lowering the lithium content and increasing the copper content in the alloy [14].

2.2 CURRENT USE

In 2010, it was announced that more than 20% of all materials in the new Bombardier C-Series aircraft, which has since been transitioned to Airbus and designated the A220,would be comprised of Al-Li alloys, specifically targeting fuselage structural applications [15]. A map of the proposed materials is shown in figure 2. Al-Li alloys 2196 from Constellium and 2099 from Arconic (formerly Alcoa) have been successfully qualified for use in floor beam applications in the Airbus A380 in the form of extrusions [16]. There were also reports of trade studies for the use of Al-Li 2198 as a fuselage material for the Airbus A350 [17–18]. Additionally, Al-Li plate applications are being used for the internal structure of the fuselage in the Boeing 787.

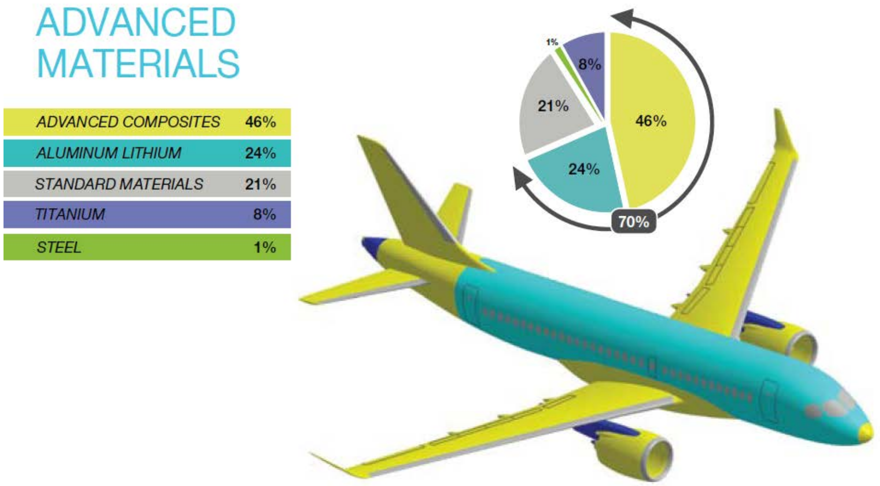

Figure 2. Former Bombardier C-series aircraft use of advanced materials

3. PROGRAM SUMMARY

3.1 PURPOSE

The objective of this test program was to generate data to better understand the overall behavior of third-generation Al-Li alloys through a comparative case study of the Al-Li 2198 and 2196 alloys. Whereas substantial proprietary data have been generated on these materials, regulators desire more information available in the public domain to properly assess Al-Li alloys as their use in aircraft certification proposals increases. Data from this program will be used by the regulators to better assess the adequacy of current regulations on this new material type being proposed by applicants in their aircraft designs. In addition, this new material needs to be explored for potential safety concerns and the boundaries checked for any cliff-type failure modes. Data provided by this program are not intended to establish design values, which would satisfy the regulatory requirements for designing and certifying civil aircraft. Additionally, the inclusion of traditional aerospace AAs (AA 2024 and 7075) in the test plan was for baselining purposes only to add perspective to data generated. All comparisons made are for reference only and are not meant to promote one alloy over another or suggest Al-Li as a direct replacement.

3.2 SCOPE

This program was conducted as a joint effort lead by the FAA in partnership with Bombardier and Constellium as a case study of the Al-Li 2198 and 2196 alloys. These alloys, produced and supplied by Constellium, were chosen because of their significant use in Bombardier's C-Series airplane, which was certified by the FAA in 2016 and transitioned to Airbus in 2017. Overall, eight different tests were completed and involved a number of other partner organizations, including UDRI, NIAR, NASA-JSC, NAVAIR, FTI, and Drexel University. Additional information on the program test matrix and subject Al-Li alloys is provided in the following subsections.

3.2.1 Program Test Matrix

To understand the overall behavior of the third-generation Al-Li alloys, the materials needed to be tested in different ways. Eight individual tests were carried out under three general test types, as shown in table 2. For baseline comparison purposes, two industry standard AAs—one for each Al-Li alloy—were also tested: AA 2024-T3 bare (except where noted as clad) for Al-Li 2198-T8, and AA 7075-T6 for Al-Li 2196-T8511. In addition to the multiple types of tests, specimens were machined in three major grain directions (longitudinal [L], longitudinal transverse [LT], and 45 degrees), plus two midpoints (22.5 degrees and 67.5 degrees), and at multiple thicknesses to assess the extent of anisotropy and thickness effects, respectively. All testing generally included at least three repeat tests, except where noted otherwise. As mentioned above, the different test types are covered in more detail in their own separate volumes of this report.

Table 2. Al-Li material characterization test matrix

Test Type	Test Name and Standard	Materials Tested	Variables*	Property Measured	Performing Organization
Static Properties	Tension Properties, ASTM E8	2198-T8, 2196-T8511, 2024-T3, 7075-T6	t_s (in.): 0.071, 0.125, 0.25 t_e (in.): 0.06, 0.120, 0.145 θ: L, 67.5, 45, 22.5, LT T (°F) = RT, 200, 350	F_{ty}, F_{tu}, E_t, *e%*	FAA WJHTC, UDRI, NIAR
	Compression Properties, ASTM E9	2198-T8, 2196-T8511, 2024-T3, 7075-T6	t_s (in.): 0.071, 0.125, 0.25 t_e (in.): 0.06, 0.120, 0.145 θ: L, 67.5, 45, 22.5, LT	F_{cy}, E_c	FAA WJHTC, NIAR
	Shear Properties, ASTM B831	2198-T8, 2196-T8511, 2024-T3, 7075-T6	t_s (in.): 0.071, 0.125, 0.25 t_e (in.): 0.06, 0.120, 0.145 θ: L, 67.5, 45, 22.5, LT	F_{st}, G	NIAR
Fatigue and Fatigue Crack Growth Properties	Fatigue Crack Growth, ASTM E647	2198-T8, 2024-T3	t_s (in.): 0.071, 0.25 θ: L-T, 45-45, T-L T (°F) = RT, 200, 350 R = 0.1, 0.4, 0.7, 0.8	da/dN vs. ΔK	NASA-JSC, UDRI
	Spectrum Fatigue Crack Growth, ASTM E647	2198-T8, 2024-T3	t_s (in.): 0.071 θ: L-T, 45-45, T-L	Crack length during spectrum fatigue loading	UDRI
Supplemental Properties	Environmentally Assisted Cracking, ASTM G129	2198-T8, 2024-T3 Clad	t_s (in.): 0.125 θ: 45° V (ε/s): 10^{-5}, 10^{-6}, 10^{-7}	Time to fracture and strength	NAVAIR
	Flammability and Burn Resistance, AC 25.856-2A	2198-T8, 2024-T3	t_s (in.): 0.071, 0.125, 0.25	Burn-through time	FAA WJHTC
	Fastener Hole Process: Cold Work and Interference Fit	2198-T8, 2196-T8511, 2024-T3, 7075-T6	t_s (in.): 0.071, 0.125, 0.25 t_e (in.): 0.06, 0.120, 0.145 θ: L, 45, LT	Cracks and damage	FAA WJHTC, NIAR, FTI

* Variable definitions:

t_s = Typical sheet thickness for 2198-T8 and 2024-T3 in inches
t_e = Typical extrusion thickness for 2196-T8511; and plate thickness for 7075-T6 in inches
θ = Grain orientation, degree from L (rolling) direction

R = Load ratio (applied minimum to maximum)
T = Temperature, °F
V = Applied strain rate per second

3.2.2 Al-Li 2198-T8 Sheet and Al-Li 2196-T8511 Extruded Materials

All of the materials in this program were produced by Constellium and supplied by Bombardier to the FAA WJHTC for testing. Al-Li 2198-T8 is manufactured in sheet form with applications typically including aircraft fuselage/pressure cabin skins. For this program, sheet thicknesses of 0.071 inch, 0.125 inch, and 0.25 inch were tested. The sheets were supplied unclad and no additional finishing or coating was performed. The Al-Li 2196-T8511 is produced in extruded form with applications typically including internal structures such as frames, stringers, and floor beams. The chemical compositions of the two alloys are shown in table 3. Both alloys were added to the Metallic Materials Property Development and Standardization (MMPDS) handbook in April 2010 [19].

Table 3. Chemical composition of Al-Li 2198 and 2196 by weight percent

Alloy	Si	Fe	Cu	Mn	Mg	Ag	Li	Zr		Al
2198-T8	0.08 max	0.1 max	2.90 – 3.50	0.50 max	0.25 – 0.80	0.10 – 0.50	0.80 – 1.10	0.04 – 0.18		93
2196-T8511	0.12 max	0.15 max	2.5 – 3.3	0.35 max	0.25 – 0.8	0.25 – 0.6	1.4 – 2.1	0.25 max		93

The Al-Li 2196-T8511 extrusions were supplied in three shapes, with dimensions as shown in figure 3. The thicknesses tested were 0.06 inch, 0.120 inch, and 0.145 inch. Because of the limited dimensions of the extrusions, testing at multiple grain orientations under ASTM standards was not possible. Consequently, micro-specimens were used for all Al-Li 2196-T8511 static properties tests. This raised a concern over the validity of those results given the small width (0.080 inch) that was being tested. To alleviate those concerns, sections of the Al-Li 2196-T8511 extrusions were sent to Drexel University where they underwent a microstructural evaluation to determine the average grain size. The results of that work confirmed the grain size of approximately 5–10 µm reported by Constellium. This correlates to approximately 200 grains at minimum across the width of the micro-specimen, which is sufficient to produce valid results.

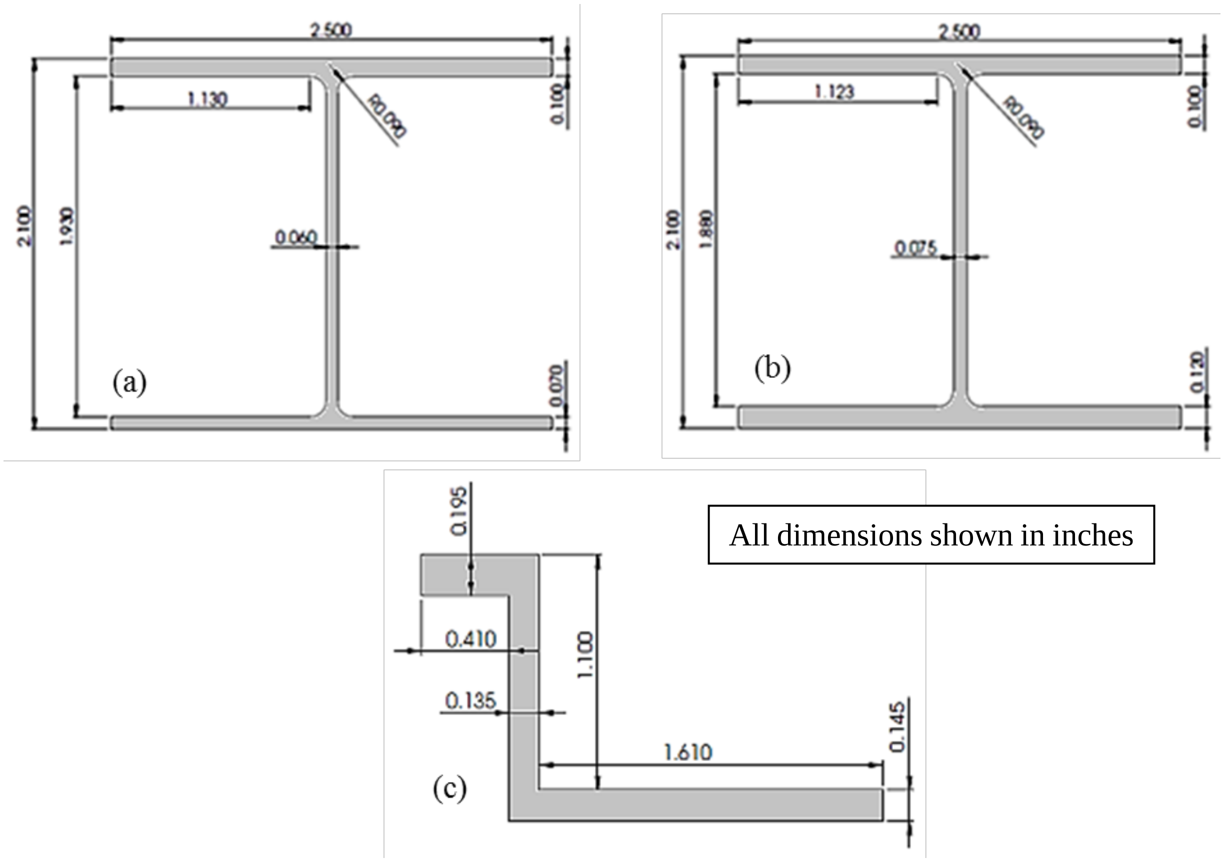

Figure 3. Al-Li 2196-T8511 extrusion shapes and dimensions: (a) 0.06-inch web I-beam, (b) 0.075-inch web I-beam, and (c) 0.145-inch flange Z-beam

4. TEST OVERVIEWS

The following subsections provide an overview of the individual tests conducted as part of this program and some representative results that were generated. More detailed information can be found in the respective volumes of this report.

4.1 STATIC PROPERTIES

The static properties considered in this study included tension, compression, and shear. Tests to generate these properties were governed by the associated ASTM standards, and the results are compared with published values in the MMDPS handbook [19]. Three repeat tests were conducted for each of the three material thicknesses and at five grain orientations to assess any anisotropic behavior of the materials.

4.1.1 Tension Properties

The tension properties were generated by three laboratories, namely the FAA WJHTC, UDRI, and NIAR, using the ASTM E8 standard for tension testing [20] and ASTM E21 standard for elevated temperatures [21], where applicable. Flat dog-bone specimen geometry was used for each test with modifications as needed. Specimens tested at an elevated temperature had an extended grip section to allow clearance for the oven. For the Al-Li 2196-T8511 alloys, micro-sized, dog-bone specimens were used because of the restrictive size of the extrusions. Additionally, for Al-Li 2196-T85111, a set of full-size specimens were tested at the L grain direction to evaluate if there were any effects of specimen geometry. Each test was conducted under displacement-controlled conditions with load and strain recorded throughout. The data collected were used to calculate tensile modulus, E_t; yield strength, F_{ty}; ultimate strength, F_{tu}; and percent elongation, $e\%$. The elevated temperature tests were run at 200°F and 350°F. The specimens were held at temperature for 20 minutes prior to testing.

4.1.2 Compression Properties

The compression property tests were performed by the FAA WJHTC and NIAR using the ASTM E9 standard [22] where applicable. Support jigs were used for all tests to prevent specimen buckling. Micro-sized, dog-bone specimens were used for the Al-Li 2196-T8511 extrusion because of the limited cross-section size; full-sized specimens at the L grain orientation were also tested to evaluate any size influence on results. Each test was conducted under displacement-controlled conditions with load and strain recorded throughout. The data collected were used to calculate compressive modulus, E_c, and yield strength, F_{cy}.

4.1.3 Shear Properties

The shear properties were determined by NIAR following the ASTM B831 standard [23], when applicable. Because of the limiting size of the extrusions, modified micro-shear specimen geometry was used for all materials. The geometry, shown in figure 4, was determined experimentally through a study plan of various configurations. Each test was conducted under displacement-controlled conditions with load and strain recorded throughout. The data collected were used to calculate shear modulus, G, and ultimate strength, F_{st}.

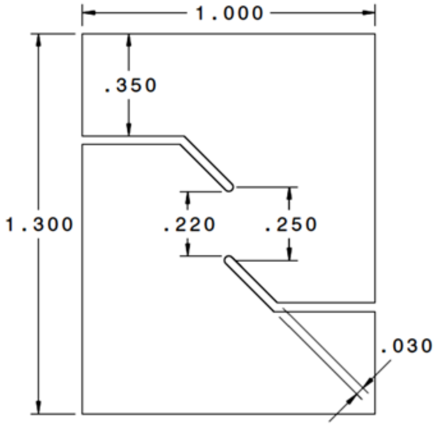

Figure 4. Micro-shear specimen geometry

4.2 FATIGUE AND FCG

Two separate test programs were used to assess the crack-growth life and FCG behavior of the Al-Li materials when subjected to various loading conditions. Typically, each test was run under load-controlled conditions, and different specimen configurations were used to achieve the desired results. Generally, three repeat tests were run for each test condition.

4.2.1 FCG

FCG properties at room and elevated temperatures were generated by NASA-JSC and UDRI using ASTM E647 [24] when applicable. The test covered the uniaxial fatigue testing of Al-Li 2198-T8 and AA 2024-T3 sheet material to determine the crack-growth rate, *da/dN*, as a function of stress-intensity factor range, *ΔK*, for a given load ratio, *R*. The tests conducted by NASA-JSC were at either room or elevated temperatures (200°F and 350°F) for two thicknesses (0.071 inch and 0.25 inch) and three grain directions (L-T, 45 degrees–45 degrees, and T-L) using eccentrically loaded single-edge crack tension specimens. To check for lab-to-lab variation, FCG data were also generated by UDRI using middle tension specimens in the same three grain orientations having a thickness of 0.071 inch and at room temperature only.

The tests conducted by NASA-JSC used MTS machines controlled by Fatigue Technology Associates software for the constant *R-K* control test method. This method maintains a constant load ratio and varies the loads throughout the test, allowing FCG data to be generated for the full *da/dN* versus *ΔK* range for each specimen. The load ratios used were 0.1, 0.4, 0.7, and 0.8. Crack-growth data were recorded using DC potential drop KRAK gauges bonded to each specimen. The crack-growth data were reduced using the adjusted compliance ratio method to derive *da/dN* and *ΔK* data for each test. The tests by UDRI were conducted under constant-amplitude loading with crack progression tracked using a traveling microscope having a 20X magnification.

4.2.2 Spectrum FCG

The effects of spectrum loading on FCG properties of Al-Li 2198-T8 and AA 2024-T3 sheet materials were studied by UDRI [9]. Specimens were machined at one thickness (0.071 inch) and three grain directions (L-T, 45 degrees–45 degrees, and T-L) in a middle tension specimen configuration. Each test was monitored using a traveling optical microscope, and crack length data were recorded throughout the test.

Fatigue tests were performed using a uniaxial tension test machine under load-controlled mode using two loading profiles: constant amplitude loading ($R = 0.1$) and comprehensive flight spectrum typical of the crown section of a fuselage forward of the wing ($R \sim 0$). The comprehensive spectrum was developed as part of a previous FAA program by UDRI using incremental vertical load factor exceedances from the FAA Operation Loads Monitoring Program (OLMP) for the upper crown of the fuselage above the wing front spar for a B737 aircraft [25]. Data from the OLMP were used to create a representative flight-by-flight sequence, which included stresses from maneuvers and gusts from typical flights. Results from spectrum specimens were then compared to constant amplitude tests for the purpose of identifying a conservative constant amplitude equivalent to the spectrum sequence. A simplified representation of this is shown in figure 5. It should be noted that all tests were run at $R \sim 0$ in the previous UDRI program [25], whereas constant amplitude tests were run at $R = 0.1$ in this study to allow for comparison with the data generated by NASA-JSC.

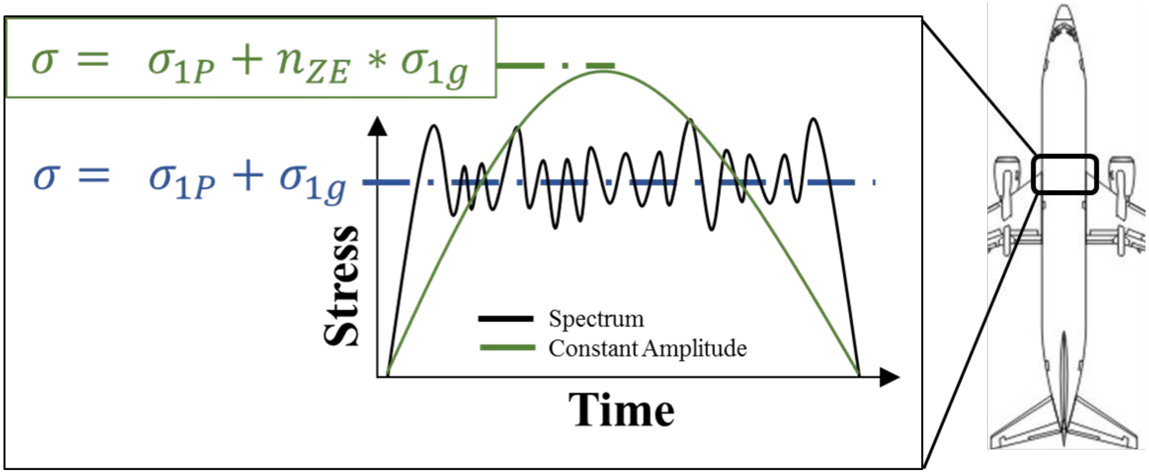

Figure 5. Spectrum FCG test by UDRI: simplified representation of a single flight cycle for the comprehensive spectrum compared to the constant amplitude for B737

4.3 SUPPLEMENTAL PROPERTY TESTS

The supplemental property tests were designed to evaluate the material response of the Al-Li alloys in comparison to the baseline aluminums when subjected to external conditions and machining processes, as described in sections 4.3.1–4.3.3.

4.3.1 Environmentally Assisted Cracking

Environmentally assisted cracking using slow strain-rate testing was studied by NAVAIR per ASTM G129 standard [26] to determine the corrosion resistance of the material under a gradually increasing tensile strain. The specimens were machined at one thickness (0.125 inch) and one grain direction (45 degrees) for both the Al-Li 2198-T8 and clad AA 2024-T3 alloys. The specimen geometry used was the sub-sized tension dog bone per ASTM E8 standard [20].

The test was run at three strain rates (10^{-5}/s, 10^{-6}/s, and 10^{-7}/s) to determine if rate has an effect on the material properties. An aqueous 5% NaCl solution was used to create the corrosive environment during the test; duplicates were also conducted at lab air conditions as a baseline. The tests were run until specimen failure with information on load, extension, and duration recorded.

4.3.2 Flammability and Burn Resistance

Testing was conducted by the FAA Fire Safety Branch at the FAA WJHTC to determine flame penetration, flammability, and burn resistance of the Al-Li 2198-T8 material. The specimens were machined at three thicknesses (0.071 inch, 0.125 inch, and 0.25 inch); grain directions were inconsequential to this test.

The test was performed using a NexGen burner specified by AC 25.856-2A [27], which created a flame temperature of 1800°F. Each specimen was mounted on a test frame and moved into direct contact with the open flame. The tests were run until the flame was visually seen to penetrate the specimen with test duration and general observations being recorded.

4.3.3 Fastener Hole Process

The effects of the cold expansion process on open holes and the installation of interference fit fasteners was studied by the FAA WJHTC. Both the Al-Li 2198-T8 and 2196-T8511 materials were tested at three thicknesses (0.071 inch, 0.125 inch, and 0.25 inch for 2198-T8; 0.06 inch, 0.120 inch, and 0.145 inch for 2196-T8511). Comparisons were made with baseline AA 2024-T3 and 7075-T6 alloys. The specimen processing was completed by FTI. A split-sleeve method was used to create the cold work holes with the sleeve opening oriented at three different angles (L, 45 degrees, and LT). Through this method, a maximum of 5% cold working was accomplished. The interference fit fasteners were selected for a 0.003-inch interference. Post-processing inspections were then made using surface eddy current nondestructive inspections at the FAA WJHTC and high-magnification images from a scanning electron microscope by Drexel University.

5. REPRESENTATIVE RESULTS

5.1 STATIC PROPERTIES

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 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. The tensile yield strength comparison for Al-Li 2198-T8 and AA 2024-T3/351 is shown in figure 6 as an example. This behavior was expected and is addressed with values at the 45-degree grain orientation published in MMPDS.

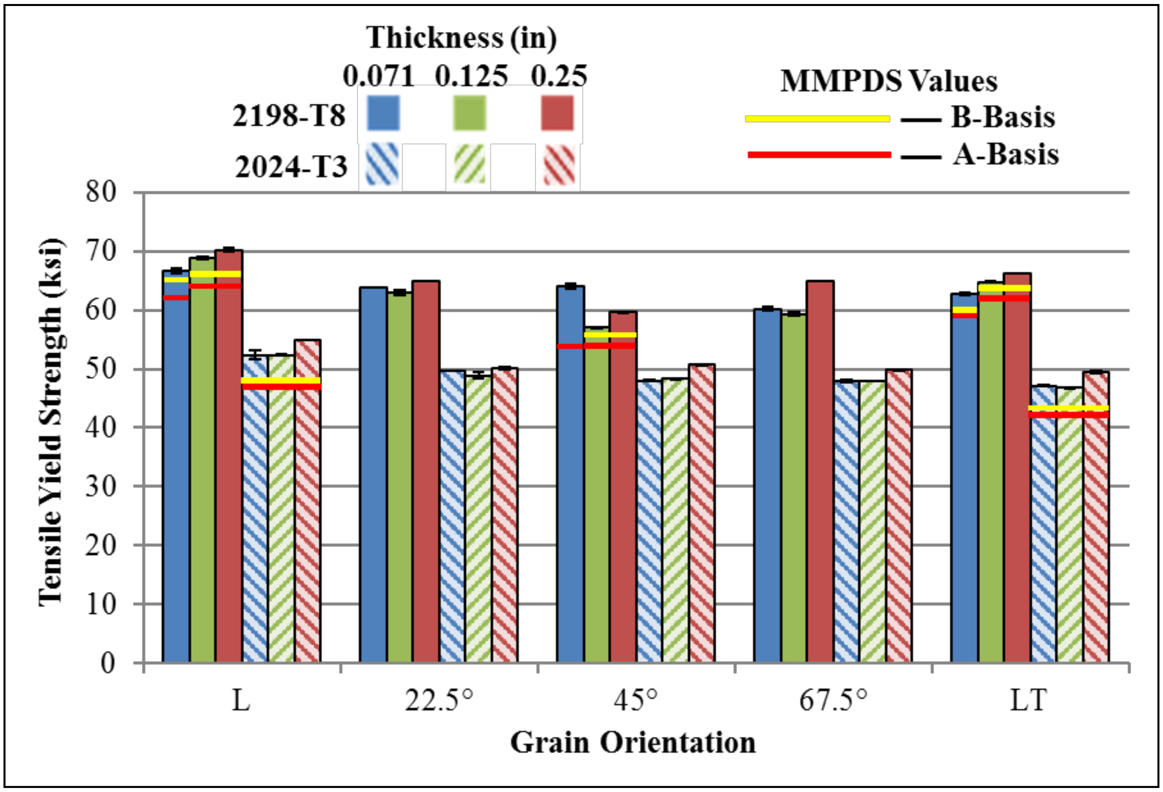

Figure 6. Tension properties results: Al-Li 2198-T8 versus AA 2024-T3/351, average yield strength comparison

5.2 FATIGUE CRACK-GROWTH PROPERTIES

The results of the FCG work showed that grain orientation and thickness had little-to-no impact on the FCGR of Al-Li 2198-T8 in the threshold and stable crack-growth regions of the da/dN versus ΔK curve, as shown in figure 7. The Al-Li appeared to track the baseline AA closely for the threshold and stable crack-growth regions for both thicknesses; however, scatter in the data made drawing definitive conclusions difficult. The Al-Li 2198-T8 did show higher crack-growth resistance in the upper region (ΔK greater than 20 ksi√in) near instability compared to the baseline. Additionally, the Al-Li2198-T8 showed some anisotropy in the upper region with the highest crack-growth resistance at the 45 degree–45 degree grain orientation, as seen in figure 8, which was contrary to that orientation showing lower strength during the static tensile tests.

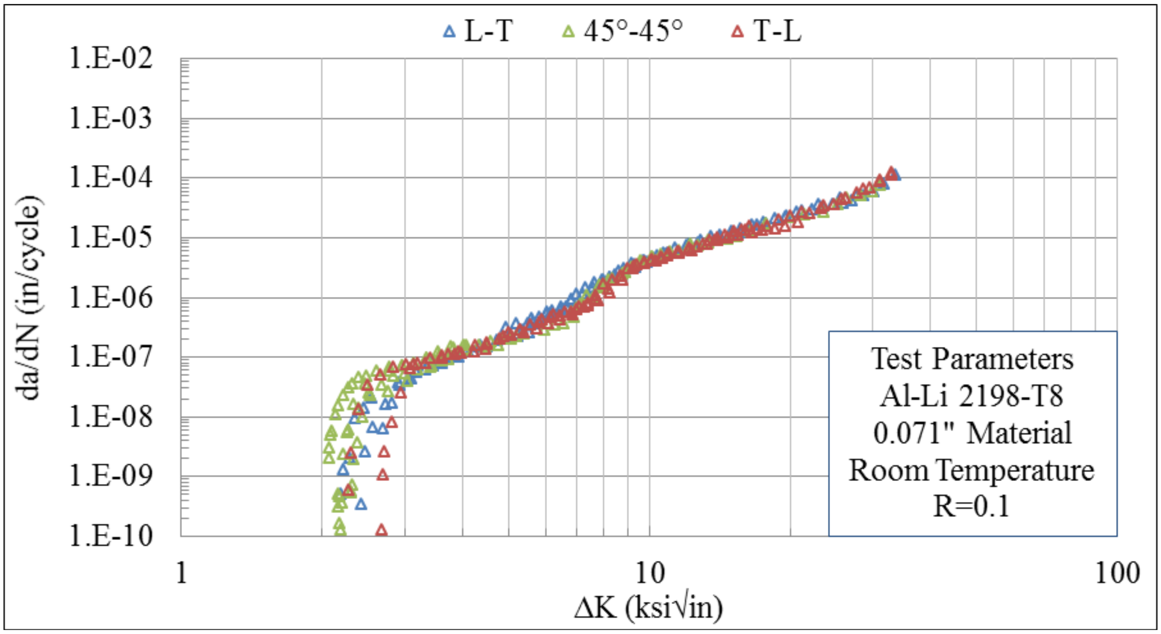

Figure 7. FCGR result: 0.071-inch Al-Li 2198-T8 sheet, R=0.1, grain orientation comparison at room temperature

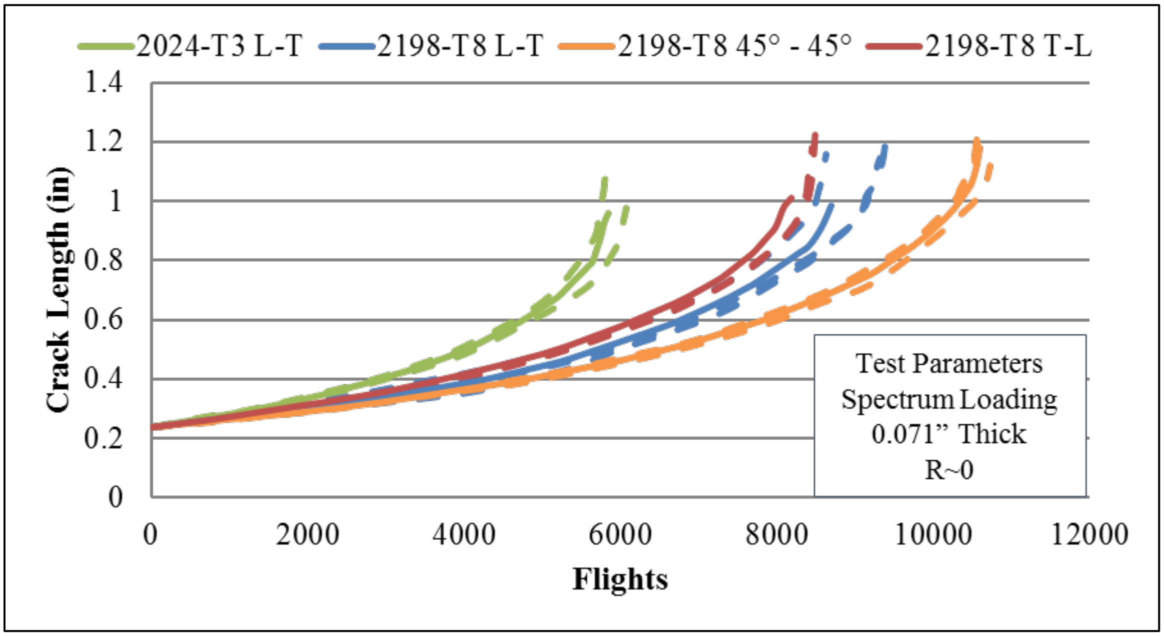

Figure 8. Spectrum result: comparison of FCGR for comprehensive spectrum tests for Al-Li 2198-T8 and AA2024-T3 sheet material

5.3 SUPPLEMENTAL PROPERTIES

The results of the supplemental testing showed that the Al-Li alloys responded comparably to baseline AAs. The environmentally assisted cracking using slow strain-rate testing showed no effect on ultimate tensile strength for Al-Li 2198-T8 or AA 2024-T3 for the testing completed at the 10^{-5}/s and 10^{-6}/s strain rates. The flammability tests did not produce any unusual smoking, burning, ignition, or reignition for the Al-Li 2198-T8 and AA 2024-T3. The Al-Li also recorded approximately a 50% longer burn-through time against the baseline aluminum when comparing identical thicknesses. Finally, the fastener hole processing test showed no cracking or other damage for any material after high-frequency eddy current and high-magnification visual inspections.

6. CONCLUSION

The test programs previously detailed were conducted as a comparative study for two third-generation Al-Li alloys (2198-T8 and 2196-T8511) against traditional aerospace aluminums (2024-T3/351 and 7075-T6). Though the sample size is limited, this program was not meant to develop any design allowables or present the Al-Li alloys as direct replacements for the traditional aluminums. Rather, 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.

In general, the mechanical properties and behaviors of the Al-Li materials were in accordance with expectations for the tests completed and comparisons made to the baseline AAs. The static properties for both the Al-Li and baseline materials tested were comparable, and the values exceed all MMPDS A and B basis values. 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, which may need to be further investigated.

There was general improvement in the FCG properties in the Al-Li 2198-T8 compared to the baseline AA 2024-T3 bare material. Under constant amplitude loading, FCG behavior was similar for both materials in the near-threshold and linear stable crack-growth regions. In the upper instability region of the FCG curves, the Al-Li 2198-T8 showed a higher crack-growth resistance compared to the baseline. Likewise, under spectrum loading, the Al-Li 2198-T8 exhibited better FCG compared to AA 2024-T3. Interestingly, the 2198-T8 tested in the 45 degree–45 degree grain orientation had the longest crack-growth life despite this orientation having the lowest tensile and compressive strengths.

The supplemental properties tests also showed the Al-Li compared favorably to the baseline material. For the environmentally assisted cracking using slow strain-rate testing, both the 2198-T8 and 2024-T3 clad reported no reduction in strength at 10^{-5}/s and 10^{-6}/s strain rates when tested in aqueous 5% NaCl solution. Additionally, the 2198-T8 had a longer burn-through time compared to the baseline and showed no signs of reigniting when removed from direct contact with the flame. Finally, none of the alloys tested showed any sign of damage or cracking due to the fastener hole processing.

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