DOT/FAA/TC-18/21, V3

Federal Aviation Administration
William J. Hughes Technical Center
Aviation Research Division
Atlantic City International Airport
New Jersey 08405

Material Characterization of Aluminum Lithium Alloys Used in Aerospace Applications, Volume 3: Fatigue Crack-Growth Properties

March 2020

Final Report

This document is available to the U.S. public through the National Technical Information Services (NTIS), Springfield, Virginia 22161.

This document is also available from the Federal Aviation Administration William J. Hughes Technical Center at actlibrary.tc.faa.gov.

U.S. Department of Transportation
Federal Aviation Administration

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT/FAA/TC-18/21, V3		

4. Title and Subtitle	5. Report Date
MATERIAL CHARACTERIZATION OF ALUMINUM LITHIUM ALLOYS USED IN AEROSPACE APPLICATIONS, VOLUME 3: FATIGUE CRACK-GROWTH PROPERTIES	March 2020
	6. Performing Organization Code
7. Author(s) Kevin Stonaker[1], John Bakuckas[1], Ian Won[2], Mark Freisthler[2], Bruce Thomas[3], Michael Niedzinski[4]	8. Performing Organization Report No.
9. Performing Organization Name and Address [1] FAA William J Hughes Technical Center Atlantic City, NJ [2] FAA NW Mountain Regional Office Renton, WA [3] Bombardier Inc. Montreal, Quebec, Canada [4] Constellium Hoffman Estates, IL	10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address U.S. Department of Transportation FAA Seattle Headquarters 2200 S 216th St Des Moines, WA 98198	13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code ANM-100

15. Supplementary Notes

The FAA William J. Hughes Technical Center Aviation Research Division COR was Dr. John G. Bakuckas, Jr.

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 3 of 4) provides in-depth detail on the fatigue and fatigue crack-growth tests. The tests were conducted by National Aeronautics and Space Administration-Johnson Space Center (NASA-JSC) and University of Dayton Research Institute (UDRI) with both focusing on just the Al-Li 2198-T8 and its baseline AA 2024-T3/351 materials. All testing was performed on uniaxial test frames to an applicable ASTM standard where possible. The work by NASA-JSC focused on crack-growth rate at room and elevated temperatures using a constant-amplitude loading profile. The work by UDRI focused on crack-growth life and crack-growth rate using both constant-amplitude and complex stress spectrum loading. The spectrum was derived from in-flight aircraft data to simulate flight-by-flight loading of the fuselage crown just forward of the front wing spar of a typical narrow body aircraft. Additionally, specimens were tested at three major grain orientations (L-T, 45 degrees–45 degrees and T-L) at both labs and at two material thicknesses at NASA-JSC to evaluate the propensity for anisotropy and impact of material thickness. The results showed that grain orientation and thickness had little to no impact on the crack-growth rate of Al-Li 2198-T8 in the threshold and stable crack-growth regions of the crack-growth curve. These regions of the curve also tracked the baseline material closely; however, the Al-Li 2198-T8 showed higher crack-growth resistance in the upper region, defined for the subject materials as ΔK above 20 ksi$\sqrt{\text{in}}$. Additionally, the Al-Li 2198-T8 showed some anisotropy in the upper region with the highest crack-growth resistance at the 45–degree–45-degree grain orientation.

17. Key Words	18. Distribution Statement
Aluminum lithium, Aluminum, 2198-T8, 2196-T8511, Fatigue crack growth,	This document is available to the U.S. public through the National Technical Information Service (NTIS), Springfield, Virginia 22161. This document is also available from the Federal Aviation Administration William J. Hughes Technical Center at actlibrary.tc.faa.gov.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	45	

ACKNOWLEDGEMENTS

The work presented in this series of reports is the culmination of a multi-year program that owes its success to the contributions of numerous partner organizations. It is only because of the expertise and resources provided by these organizations that such a wide array of testing could be completed in such a condensed amount of time. Many thanks and much appreciation to those who have contributed.

Partner organizations and key contributors include: Frank Eberl, and Peter Bittner of Constellium; Prof. Jonathan Awerbuch, Prof. Tein Min Tan, David Stanley, Matthew Prokop, and Eric Prasalowicz of Drexel University; Patrick Safarian, Michael Gorelik, and Doug Ostgaard of the FAA; John Bakuckas, Tim Marker, Jeff Panco, Pat Sheehan, and Matt Lembo of the FAA William J. Hughes Technical Center; Joy Ransom of Fatigue Technology Inc.; Royce Foreman of NASA Johnson Space Center; Eun Lee of U.S. Navy Naval Air System Command; Paul Jonas, Royal Lovingfoss, and Elizabeth Clarkson of the National Institute for Aviation Research; and Todd Jones of the University of Dayton Research Institute.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

AA	Aluminum alloy
Al-Li	Aluminum lithium
da/dN	Crack-growth rate
FCG	Fatigue crack growth
FCGR	Fatigue crack-growth rate
L	Longitudinal direction
MATE	Material Analysis and Testing Environment
NASA-JSC	National Aeronautics and Space Administration Johnson Space Center
OLMP	Operation Loads Monitoring Program
R	Stress ratio
T	Transverse direction
UDRI	University of Dayton Research Institute
ΔK	Stress Intensity Factor Range

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 3 of 4) provides in-depth detail on the fatigue and fatigue crack-growth tests. The tests were conducted by National Aeronautics and Space Administration-Johnson Space Center (NASA-JSC) and University of Dayton Research Institute (UDRI) with both focusing on just the Al-Li 2198-T8 and its baseline AA 2024-T3/351 materials. All testing was performed on uniaxial test frames to an applicable ASTM standard where possible. The work by NASA-JSC focused on crack-growth rate at room and elevated temperatures using a constant-amplitude loading profile. The work by UDRI focused on crack-growth life and crack-growth rate using both constant-amplitude and complex stress spectrum loading. The spectrum was derived from in-flight aircraft data to simulate flight-by-flight loading of the fuselage crown just forward of the front wing spar of a typical narrow body aircraft. Additionally, specimens were tested at three major grain orientations (L-T, 45 degrees–45 degrees and T-L) at both labs and at two material thicknesses at NASA-JSC to evaluate the propensity for anisotropy and impact of material thickness. The results showed that grain orientation and thickness had little to no impact on the crack-growth rate of Al-Li 2198-T8 in the stable crack-growth regions of the crack-growth curve. This region of the curve also tracked the baseline material closely; however, the Al-Li 2198-T8 showed higher crack-growth resistance in the upper region, defined for the subject materials as ΔK above 20 ksi$\sqrt{\text{in}}$. Additionally, the Al-Li 2198-T8 showed some anisotropy in the upper region with the highest crack-growth resistance at the 45–degree–45–degree grain orientation.

1. INTRODUCTION

This report is the third 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 was to gain a better understanding of the overall mechanical behavior of the third-generation Al-Li alloys relative to traditional aerospace aluminum alloys (AA). As Al-Li continues to gain more widespread use in primary aircraft structures [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 (FCG), and supplemental. This volume contains detailed information on the fatigue and FCG tests conducted by National Aeronautics and Space Administration-Johnson Space Center (NASA-JSC) and University of Dayton Research Institute (UDRI). The fatigue tests were conducted on the Al-Li 2198-T8 and the baseline AA 2024-T3/351 alloys. Constant-amplitude tests were carried out at room and elevated temperatures to evaluate the FCG behavior of the Al-Li 2198-T8 alloy, whereas a complex flight-by-flight spectrum, developed by UDRI using inflight load data from transport category aircraft [5], was used to look at crack-growth life and the impact of stress history. Table 1 shows an overview of the tests covered in this volume with the performing organization. The constant-amplitude tests conducted by both labs were performed to ASTM standards, specifically ASTM E647 [6], where applicable.

Table 1. Fatigue and FCG properties test overview

Test Type	Test Name and Standard	Materials Tested	Variables*	Property Measured	Performing Organization
Constant Amplitude	Fatigue Crack Growth; ASTM E647	2198-T8 2024-T3 2024-T351	t_s (in.): 0.071, 0.25 θ: L-T, 45°–45°, T-L T (°F) = 74, 200, 350 R = 0.1, 0.4, 0.7, 0.8	da/dN vs. ΔK	NASA-JSC
Comprehensive Stress Sequence	Spectrum Fatigue Crack Growth; ASTM E647	2198-T8 2024-T3	t_s (in.): 0.071 θ: L-T, 45°–45°, T-L R = 0.1	da/dN vs. ΔK; crack length; cycles to failure	UDRI

* Variable definitions:

t_s = Typical sheet thickness for the 2198-T8 and 2024-T3, inches
θ = Specimen grain orientation (applied load-crack growth direction)
T = Temperature, °F
R = Stress ratio
da/dN = Crack growth rate

The subsequent sections detail each test shown in table 1 with additional data available in the respective appendices. The Al-Li alloy used in these tests was produced by Constellium, and the baseline aluminums were purchased through commercial retailers. All materials were tested at the thickness supplied with no additional surface machining.

2. TEST DESCRIPTION

The fatigue and FCG testing were carried out by NASA-JSC and UDRI, as shown in table 2. The Al-Li 2198-T8 and bare AA 2024-T3/351 alloys were tested at variable thicknesses, grain orientations, and temperatures. The tests performed by NASA-JSC were conducted as constant stress ratio (R), and the UDRI tests were performed as either constant-load amplitude or comprehensive stress spectrum. The grain orientation designations used throughout this volume refer to two directions separated by a hyphen. The first gives the loading direction, and the second gives the crack-growth direction. The designations refer to the rolling direction of the source sheet material as follows: "L" designates the rolling or longitudinal direction, "T" designates transverse or perpendicular to the rolling direction, and "45 degrees" designates the midpoint between the latter two. For example, a T-L specimen was loaded in the transverse (T) direction with crack growth in the longitudinal (L) direction. The test procedures are detailed further in the following subsections.

Table 2. Fatigue and FCG properties test matrix

Performing Organization	Material	Thickness (in.)	Temperature (°F)	Loading Profile	Orientation			Total
					L-T	45°	T-L	
NASA-JSC	2024-T3	0.071	74	R=0.1	3		3	6
				R=0.4	3		3	6
				R=0.7	3		3	6
			200	R=0.1	3	3	3	9
			350		3	3	3	9
	2024-T351	0.25	74	R=0.1	3		3	6
				R=0.4	3		3	6
				R=0.7	3		3	6
				R=0.8	3		3	6
	2198-T8	0.071	74	R=0.1	3	3	3	9
				R=0.4	3	3	3	9
				R=0.7	3	3	3	9
			200	R=0.1	3	3	3	9
			350		3	3	3	9
		0.25	74	R=0.1	3	3	3	9
				R=0.4	3	3	3	9
				R=0.7	3	3	3	9
				R=0.8	3	3	3	9
UDRI	2024-T3	0.071	74	R=0.1	3			3
				Spectrum	3			3
	2198-T8			R=0.1	3	3	3	9
				Spectrum	3	3	3	9

2.1 FATIGUE CRACK-GROWTH RATE

Fatigue crack-growth rate (FCGR) properties were generated by NASA-JSC using ASTM E647 as the standard. The tests covered the uniaxial fatigue testing of Al-Li 2198-T8 and AA 2024-T3/351 sheet and plate material to determine the crack-growth rate (da/dN) as a function of stress-intensity factor range (ΔK) for a given R. The specimens were tested at room or elevated temperatures (200°F and 350°F), two thicknesses (0.071 inch and 0.25 inch), and three grain orientations (L-T, 45 degrees–45 degrees, and T-L) using eccentrically loaded single-edge crack tension specimens (ESE[T]) with dimension shown in figure 1. Refer to ASTM E647 for further details on testing requirements.

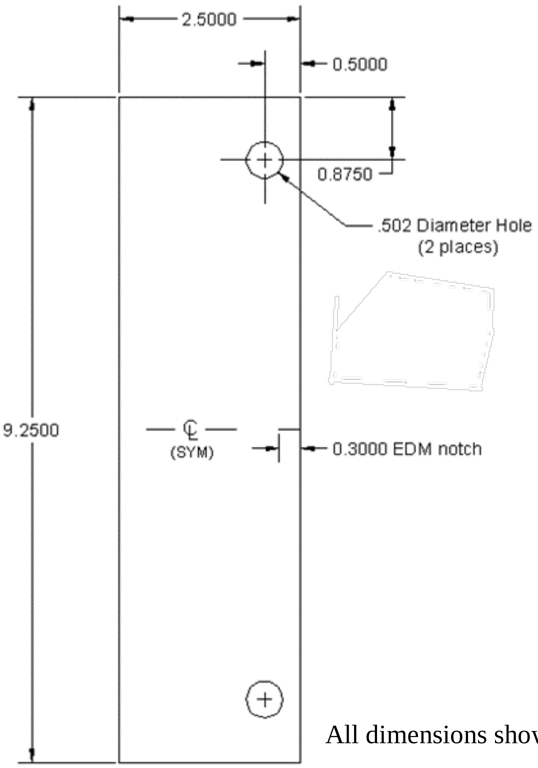


Figure 1. NASA-JSC FCGR specimen geometry

NASA-JSC used MTS test frames controlled by Fatigue Technology Associates software to perform the constant R, K control tests. This method maintains a constant R while varying the loads throughout the test based on the current crack length, allowing FCG data to be generated for the full da/dN versus ΔK range for each specimen. The tests were conducted in two phases to generate a full da/dN versus ΔK plot for each specimen. The first phase consisted of load shedding in which the applied load was systematically lowered until crack growth halted (FCGR of approximately 10^{-10} m/cycle) signaling the lower threshold. The second phase then used an increasing ΔK to characterize the stable and unstable crack-growth regions of the da/dN versus ΔK plot. The stress 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 elevated temperatures were created using an oven and maintained throughout the test. The tests were run at frequencies in the range of 60–80 Hz for threshold testing and 40–50 Hz for the FCGR portion.

2.2 COMPREHENSIVE STRESS SPECTRUM

Testing to evaluate the effect of stress history on FCG and crack growth life was carried out by UDRI for the Al-Li 2198-T8 and AA 2024-T3 materials at a thickness of 0.071 inch. Testing was carried out under either constant amplitude (R=0.1) or spectrum (R ~ 0) loading as detailed in the following subsections.

2.2.1 Comprehensive Spectrum

The comprehensive spectrum was developed by UDRI as part of a previous FAA program using incremental vertical load factor exceedance data from the FAA Operation Loads Monitoring Program (OLMP) as reported in FAA Report DOT/FAA/TC-12/17 [5]. That program developed stress spectrums for a circumferential cracking scenario in the fuselage skin at the crown directly above the wing front spar for various aircraft sizes. The spectrum developed from Boeing 737 aircraft data were used for the work presented in this report. The resulting spectrum is a block of 6000 flights of various lengths and conditions that cumulatively represent a typical aircraft's service history. Each flight represents a ground-air-ground cycle with a stress ratio of approximately zero. The maximum stress is the sum of the stress due to maximum cabin differential pressure (σ_{1P}) plus the inertial stress due to 1-g steady state flight (σ_{1g}). Incremental stresses, derived from the OLMP data and used to simulate stresses from maneuvers and gusts, are then superimposed onto the base maximum stress level to create a representative flight-by-flight sequence, as shown in figure 2. The figure is a rough representation of a spectrum flight as compared to an equivalent cycle from the constant-amplitude tests and is not drawn to scale.

One of the purposes of the original program was to identify a conservative load factor (n_{ZE}) that can be applied to the constant-amplitude sequence resulting in equal or conservative-bounding crack growth. The constant-amplitude test uses the base maximum stress level from the comprehensive spectrum and multiplies the 1-g inertia stress with an equivalent load factor to create a conservative, simplified constant-amplitude test. A factor of 1.3 was identified by UDRI and was used for this Al-Li program. However, the constant-amplitude tests in this study were run at R of 0.1 to allow for comparison with the data generated by NASA-JSC. Therefore, the constant-amplitude results are not conservative when compared to the comprehensive spectrum, which were run at R of approximately 0 so direct comparisons are not made in this report. Additional testing is the subject of future work.

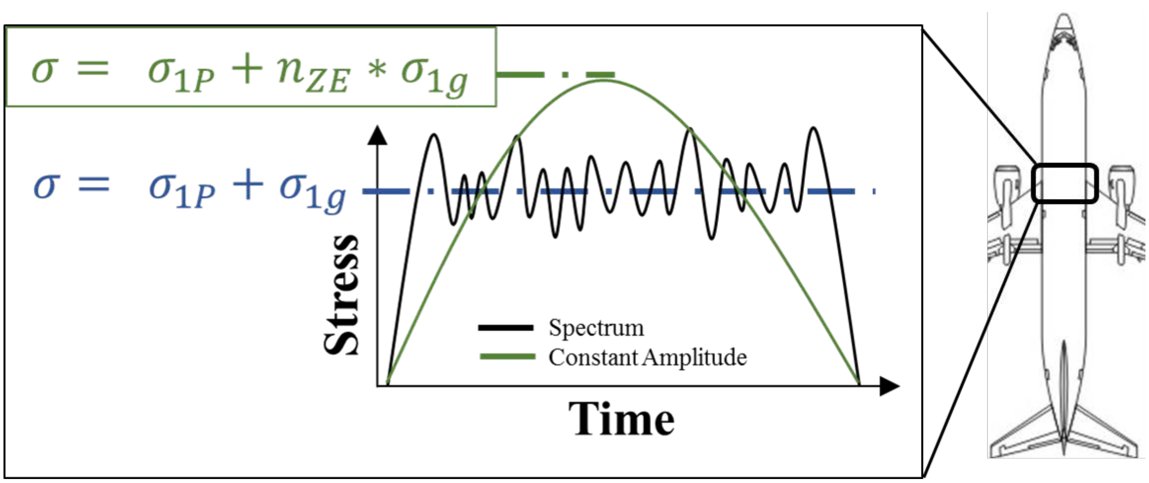
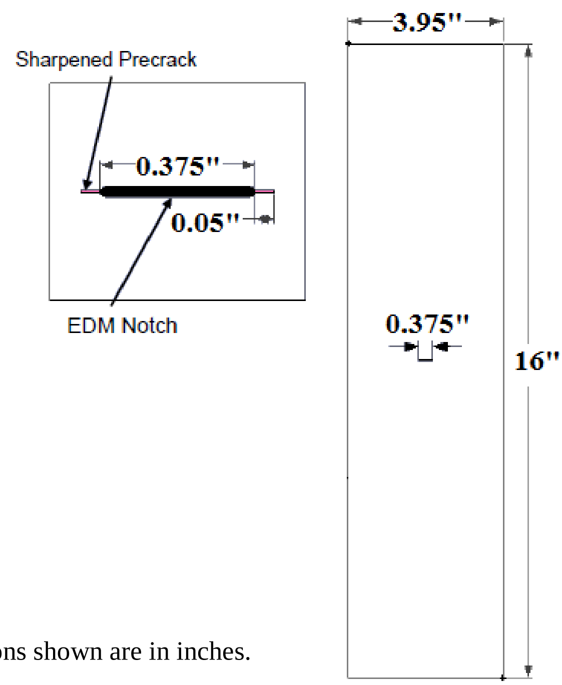


Figure 2. Spectrum FCG test by UDRI: simplified representation of a single flight cycle for the comprehensive spectrum compared to the constant amplitude for B737

2.2.2 Test Description and Procedure

The effect of spectrum loading on FCG properties was studied and FCGR data generated by UDRI using the comprehensive loading spectrum and complimentary constant-load amplitude series of tests detailed in section 2.2.1. The tests were performed on an MTS uniaxial test frame using the Material Analysis and Testing Environment (MATE) software developed by UDRI for system control. Specimens were tested in the Middle Tension Specimen M(T) configuration per ASTM E647 with dimensions as shown in figure 3. They were machined at three grain orientations and one thickness as shown in table 2. An electrical discharge machine was used to create the center notch. The notch was sharpened by means of pre-cracking using a load-shedding technique to an initial average crack extension of 0.05 inch from both sides of the notch.

A 20-kip servo-hydraulic MTS test frame was selected to run the tests for this program. The specimen pre-cracking and constant-amplitude tests were run using a high-frequency cycle capability within the MATE software that runs based on user-defined values for load and frequency while using feedback loop control. The spectrum tests were run using open-loop control with no feedback as a point-to-point sequence based on a user-created input file. The same input file was used for all spectrum tests; a constant load rate of 15 kips/sec was applied, which produced accurate reproduction of the command loads. For all tests, crack-growth measurements were taken manually using a traveling microscope with a resolution of $1x10^{-5}$ m. Measurements for the spectrum test were taken at the end of each 6000 flight block and at approximately 500-cycle intervals for the constant-amplitude specimens.



All dimensions shown are in inches.

Figure 3. UDRI spectrum specimen geometry

3. TEST RESULTS

A comparison of the constant-amplitude datasets from NASA-JSC and UDRI, shown in figure 4, reveals two important observations. First, there was good repeatability and limited lab-to-lab variation where the FCG data sets overlap closely. Second, the data generated by UDRI, reported in a subsequent section, represent the upper region (ΔK greater than 20 ksi√in) of the da/dN versus ΔK curve.

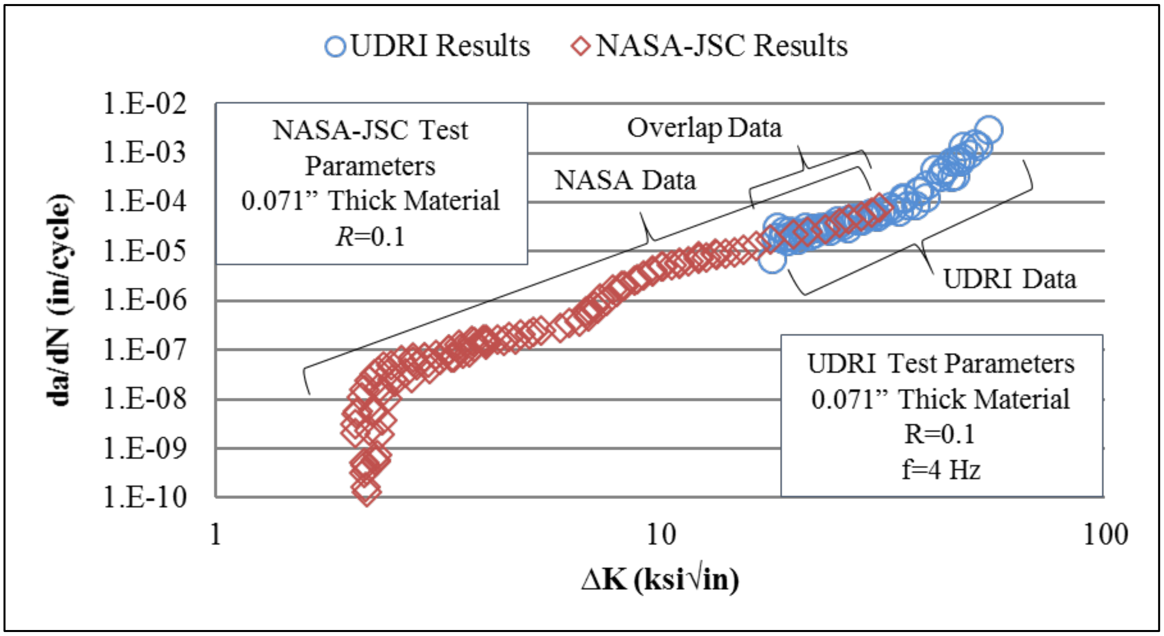


Figure 4. Comparison of FCG data generated by NASA-JSC and UDRI: Al-Li 2198-T8 material, 0.071-inch thick, 45–degree–45–degree grain orientation

3.1 FATIGUE CRACK-GROWTH RATE

The results for FCGR generated by NASA-JSC for the Al-Li 2198-T8 material show no significant anisotropic or thickness effects in the stable crack-growth region of the da/dN versus ΔK curves. As shown in figure 5, there was limited variation in the FCGR data for the 0.071-inch-thick Al-Li material tested at room temperature and R=0.1 for the three grain orientations tested. Figure 6 shows the 0.25-inch-thick results of Al-Li 2198-T8 where the three specimen orientations tested appear to have similar FCGRs in the upper portion of the stable crack growth region. However, the 0.25-inch-thick results did show more scatter, especially in the threshold region. These results were noteworthy considering the anisotropic behavior observed in the static properties for the Al-Li material, especially at the thicker gauges [2]. When comparing the Al-Li 2198-T8 results between the two thicknesses, there may be a slight increase in FCGR for the thicker 0.25-inch gauge material, as shown in figure 7, however, scatter in the data makes drawing conclusions difficult. The elevated temperature tests were conducted only for the 0.071-inch-thick material. The results for the Al-Li (see figure 8) showed similar FCGR for room temperature and 200°F. There appears to be a slight increase in FCGR at 350°F; however, results at that temperature exhibited a considerable amount of scatter relative to the other temperatures tested. The effect of stress ratio on FCGR, shown in figure 9, expectedly produced higher FCGR at higher stress ratios.

Issues with crack bifurcation and fanning in the threshold region for all materials and thicknesses tested make drawing any conclusions from that region difficult. This is a known challenge for AAs and was not addressed in this test program.

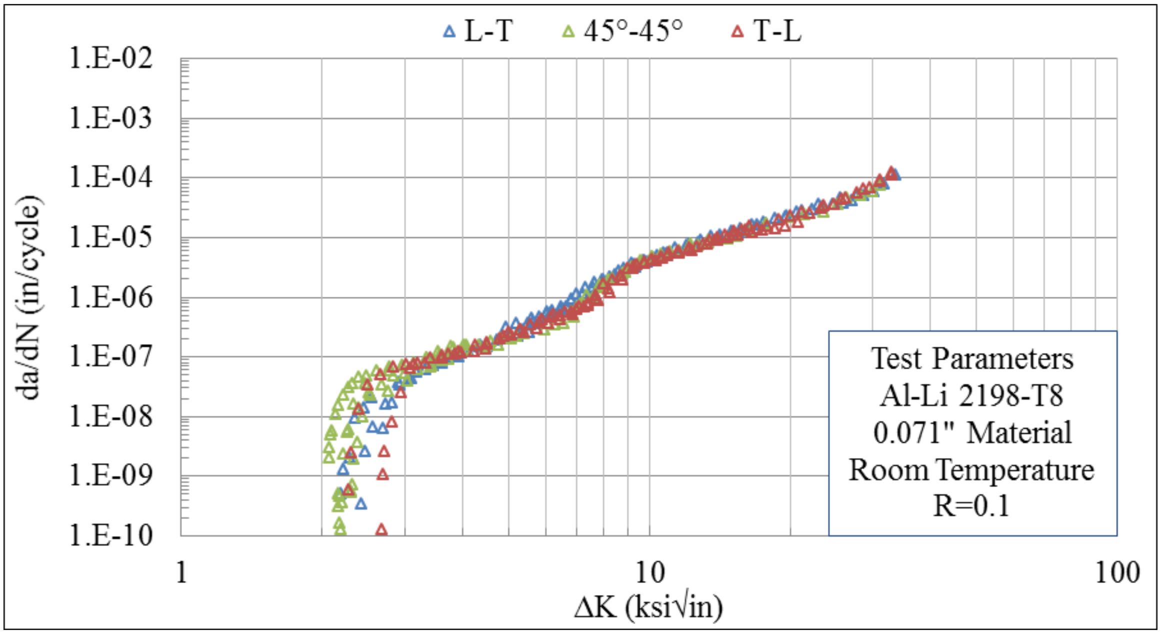


Figure 5. FCGR result: 0.071-inch Al-Li 2198-T8 sheet, R=0.1, grain orientation comparison at room temperature

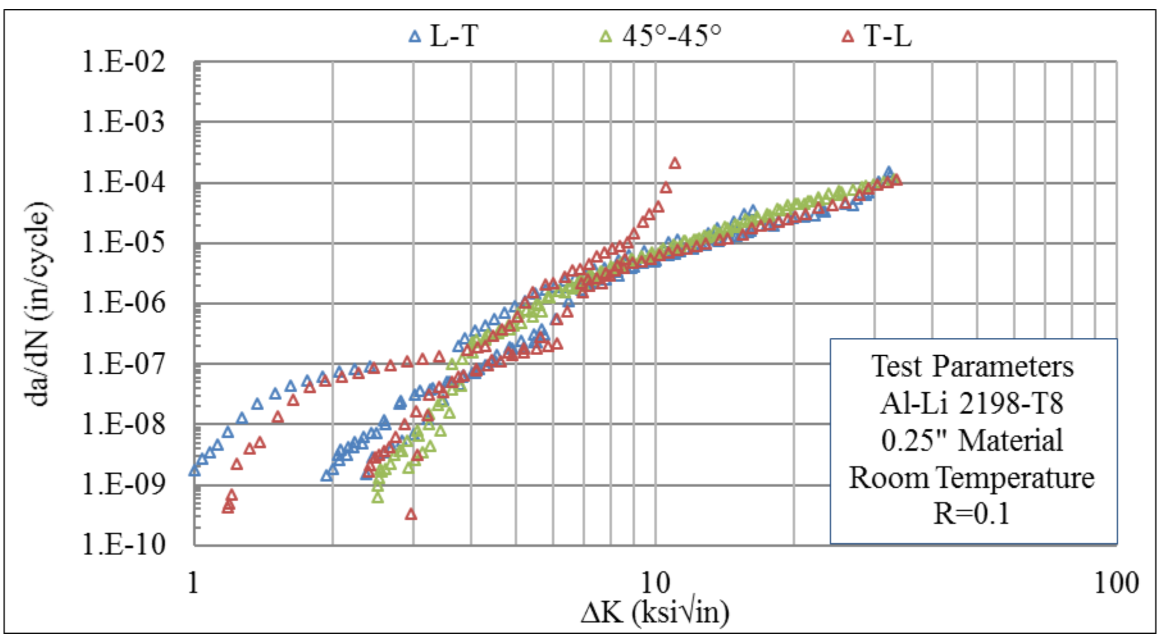


Figure 6. FCGR result: 0.25-inch Al-Li 2198-T8 plate, R=0.1, grain orientation comparison at room temperature

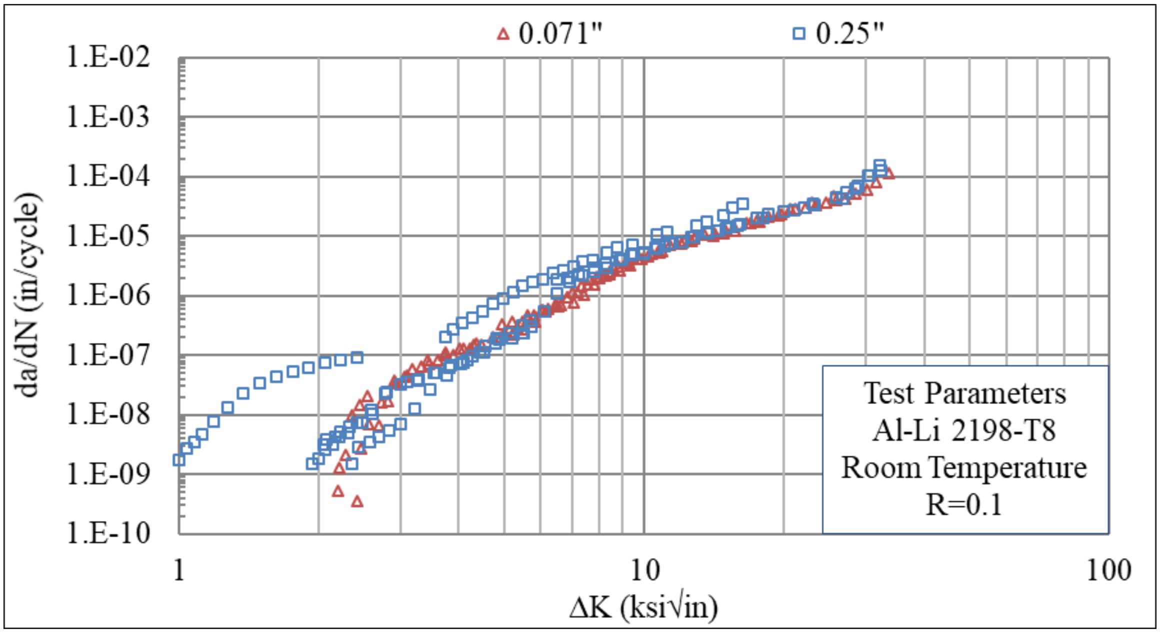


Figure 7. FCGR result: Al-Li 2198-T8, R=0.1, L-T grain orientation, thickness comparison at room temperature

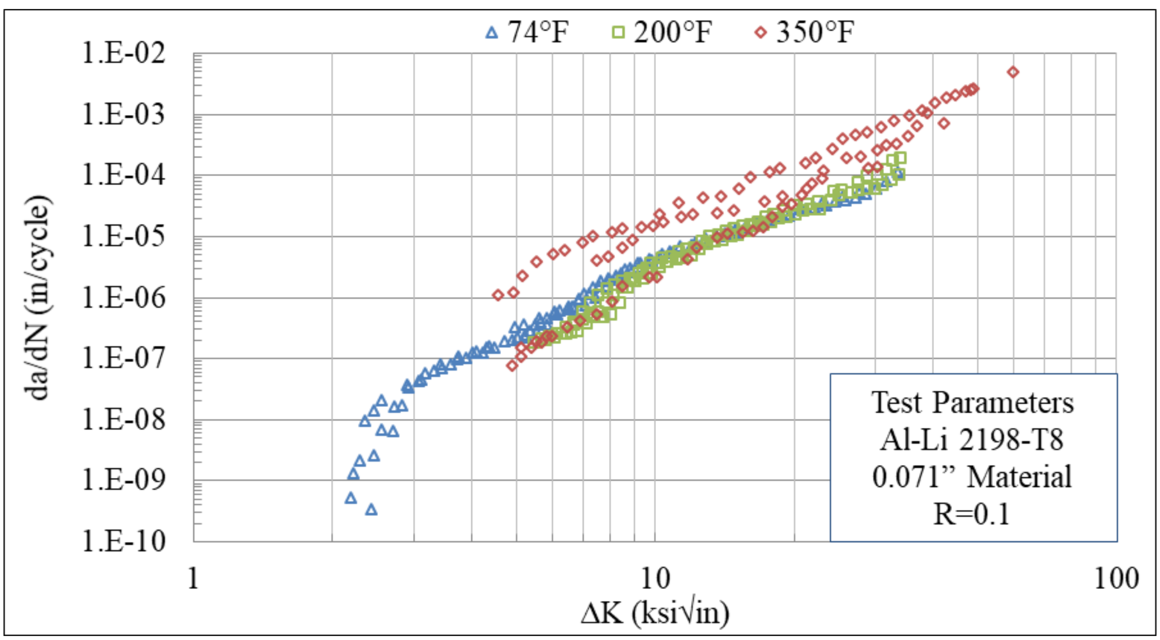


Figure 8. FCGR results: 0.071-inch Al-Li 2198-T8 sheet, R=0.1, L-T grain orientation, temperature comparison

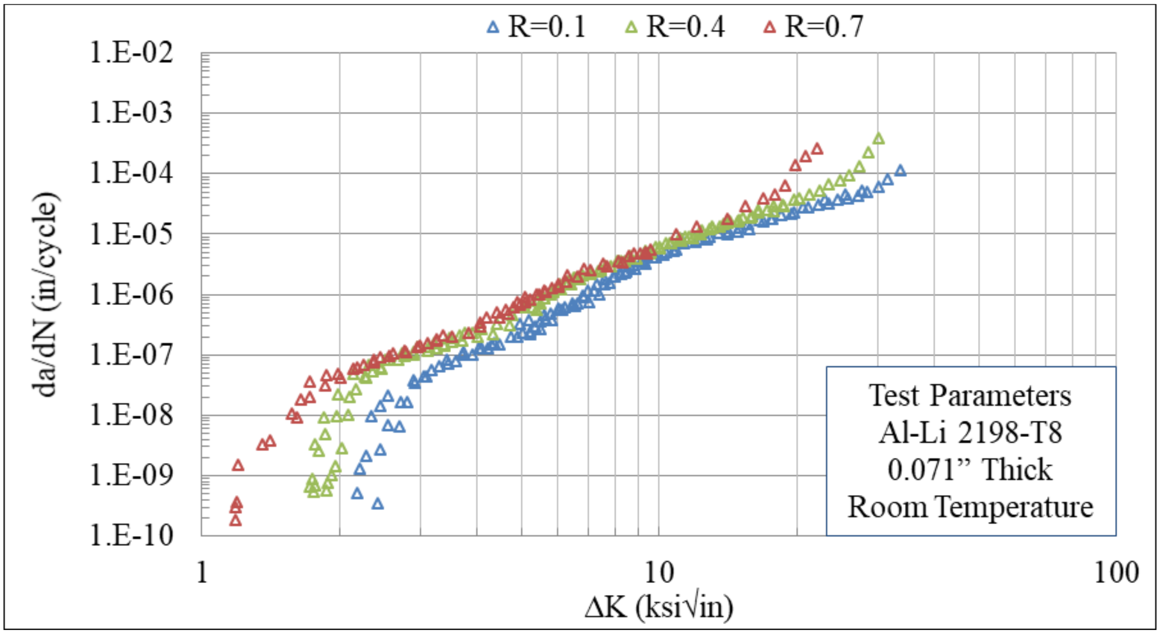


Figure 9. FCGR result: 0.071-inch Al-Li 2198-T8 sheet, L-T grain orientation, room temperature, stress ratio comparison

Figures 10 and 11 show a comparison of the Al-Li 2198-T8 results to the baseline AA 2024-T3 for the two thicknesses. The 0.071-inch-thick results, Figure 10, suggest that the Al-Li 2198-T8 material has a lower FCGR, however the scatter in the baseline data and limited number of specimens tested make drawing definitive conclusions difficult. At 0.25-inch-thick the two materials exhibited similar FCGR but again the scatter in both datasets make drawing further conclusions difficult. Further, crack bifurcation made threshold testing challenging and so no conclusions are made for that region. The upper region of the FCGR curve was generally not evaluated by NASA as shown in Figure 4 but is addressed for the 0.071-inch-thick material in the following section.

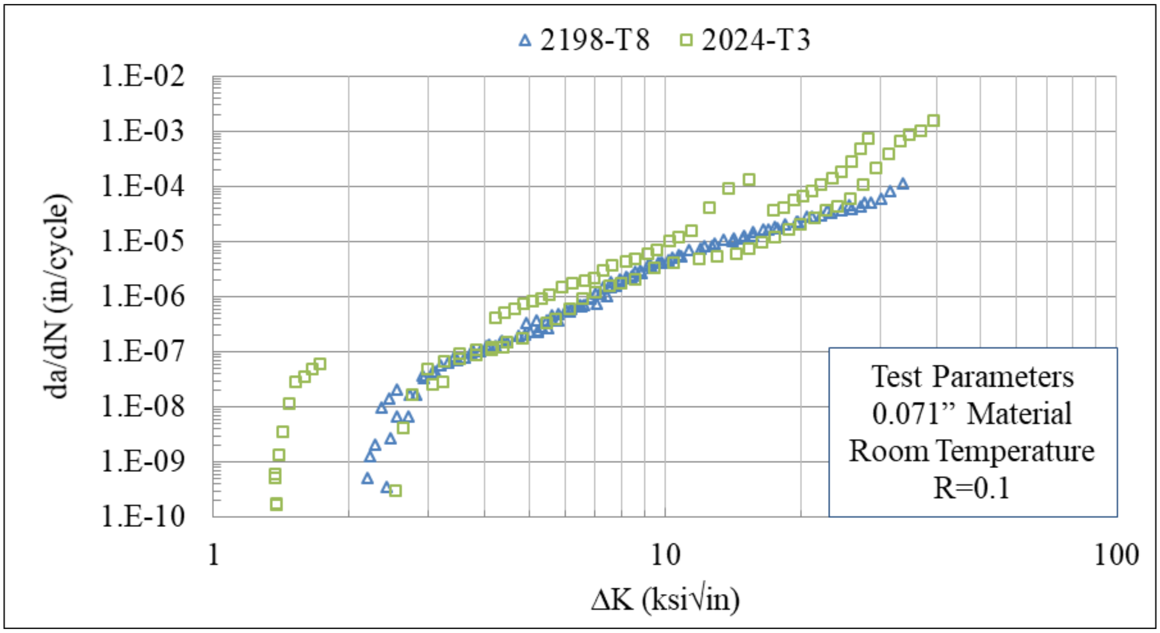


Figure 10. FCRG result: comparison of Al-Li 2198-T8 and AA 2024-T3, 0.071-inch thick, R=0.1, L-T grain orientation, room temperature

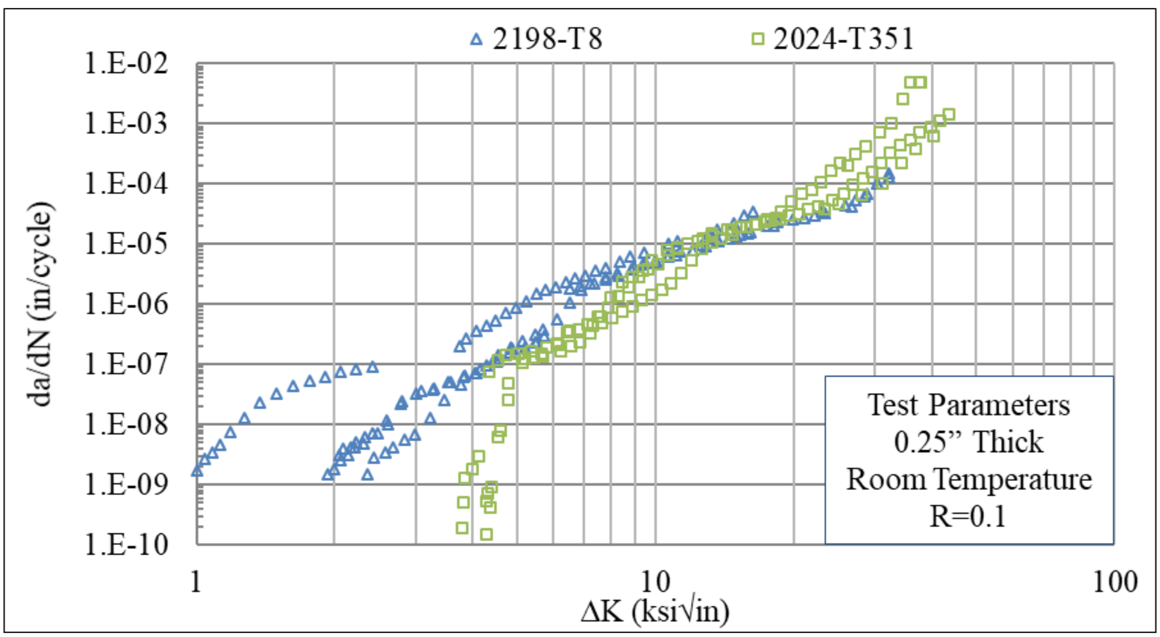


Figure 11. FCGR result: comparison of Al-Li 2198-T8 and AA 2024-T351, 0.25-inch thick, R=0.1, L-T grain orientation, room temperature

3.2 COMPREHENSIVE STRESS SPECTRUM

The effects of spectrum loading on FCG behavior were investigated by UDRI. As stated previously, the spectrum sequence that was applied represented the general life cycle at the crown of a Boeing 737 just forward of the wing. Additionally, the FCG data generated coincide with the upper region of the da/dN versus ΔK curve, as shown in figure 4. The comprehensive spectrum results in figure 12, similar to the NASA-JSC data, show that the Al-Li 2198-T8 material at all three grain orientations had higher crack-growth resistance as crack size approached instability compared to the baseline AA 2024-T3 L-T direction. Comparing just the Al-Li 2198-T8 results reveals that the 45–degree–45-degree grain orientation had the longest crack growth life despite this orientation having the lowest strength in the static tensile tests. These results were also consistent with the constant-amplitude tests, which showed higher crack-growth resistance for the Al-Li 2198-T8 material, especially at the 45–degree–45–degree orientation. Also shown in figure 12 is that the FCG data exhibited good repeatability and limited scatter where the individual specimen results (dashed lines) are grouped closely with the average (solid line). FCGR data from the constant-amplitude tests in figure 13 show the Al-Li had a higher FCG resistance when approaching instability compared to the baseline aluminum.

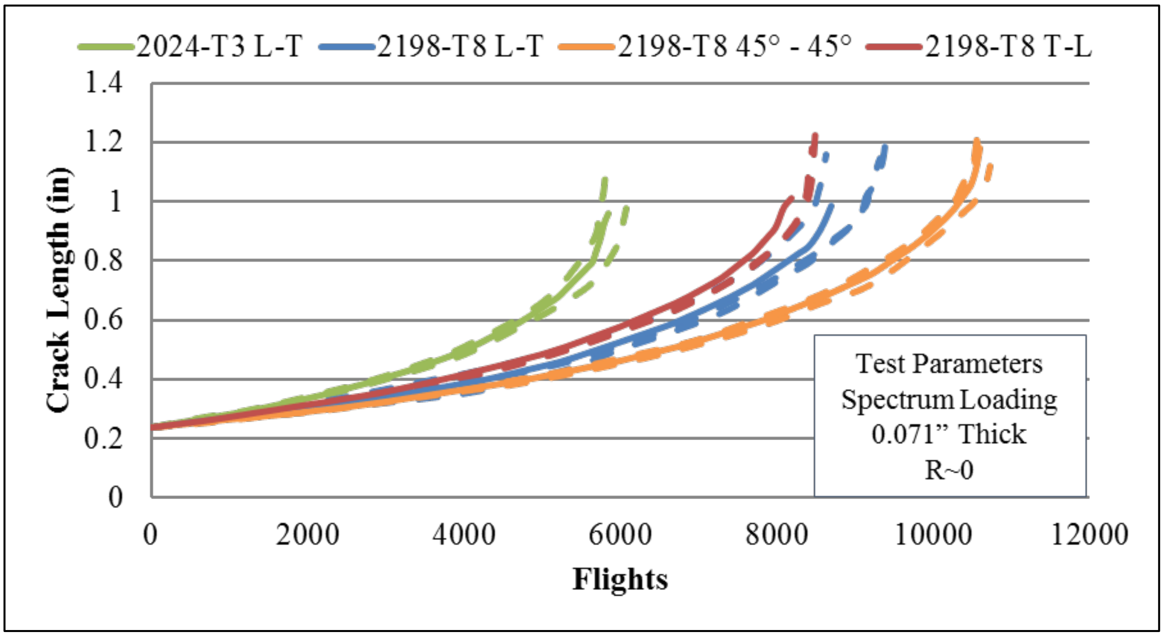


Figure 12. Spectrum result: comparison of FCGR for comprehensive spectrum tests for Al-Li 2198-T8 and AA2024-T3 sheet material

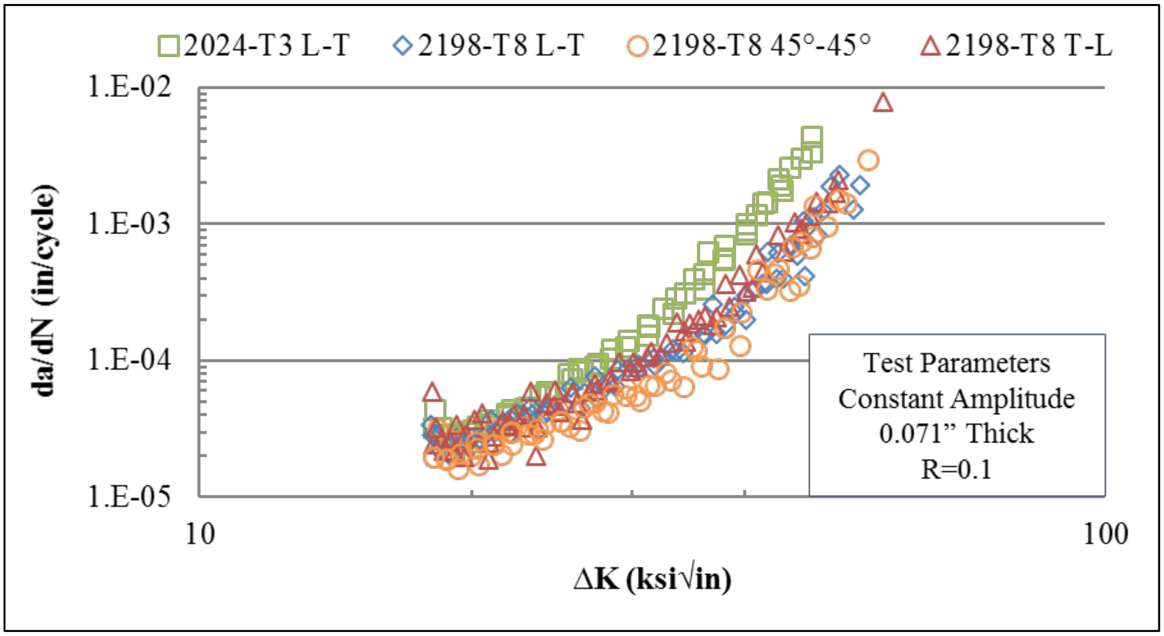


Figure 13. Spectrum result: comparison of FCGR for constant-amplitude tests for Al-Li 2198-T8 and AA2024-T3 sheet material

4. CONCLUSION

The test programs were conducted as a comparative study for a third-generation aluminum lithium (Al-Li) alloy (2198-T8) against a traditional aerospace aluminum (2024-T3/351). Though the sample size is limited, this program was not meant to develop any design allowables or present the Al-Li alloy as a direct replacement for the traditional aluminum alloy tested. 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 that may warrant further vetting as this material (and other Al-Li alloys) see more widespread use in new aircraft design.

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 stable crack-growth regions of the da/dN versus ΔK curve. For both thicknesses, the stable crack-growth region of the curve tracked the baseline material closely, whereas, the Al-Li 2198-T8 showed higher crack-growth resistance in the upper region (ΔK greater than 20 ksi√in) near instability. 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, which was contrary to that orientation showing lower strength during the static tensile tests reported in volume 2.

5. REFERENCES

1. FAA Report. (2018). Material Characterization of Aluminum Lithium Alloys used in Aerospace Applications – Volume 1 Overview. (DOT/FAA/CT-#)

2. FAA Report. (2018). Material Characterization of Aluminum Lithium Alloys used in Aerospace Applications – Volume 2 Static Properties. (DOT/FAA/CT-#).

3. FAA Report. (2018). Material Characterization of Aluminum Lithium Alloys used in Aerospace Applications – Volume 4 Supplemental Properties. (DOT/FAA/CT-#).

4. Prasad, N. E., Gokhale, A. A., and Wanhill, R. J. H. (2014). *Aluminum-Lithium Alloys: Processing, Properties, and Applications.* Waltham, MA: Elsevier.

5. FAA Report. (2012). Development and Assessment of Simplified Stress Sequences for Fuselage Structures. (DOT/FAA/TC-12/17).

6. ASTM Standard E647-15e1, "Standard Test Method for Measurement of Fatigue Crack Growth Rates," ASTM International, West Conshohocken, PA, 2015

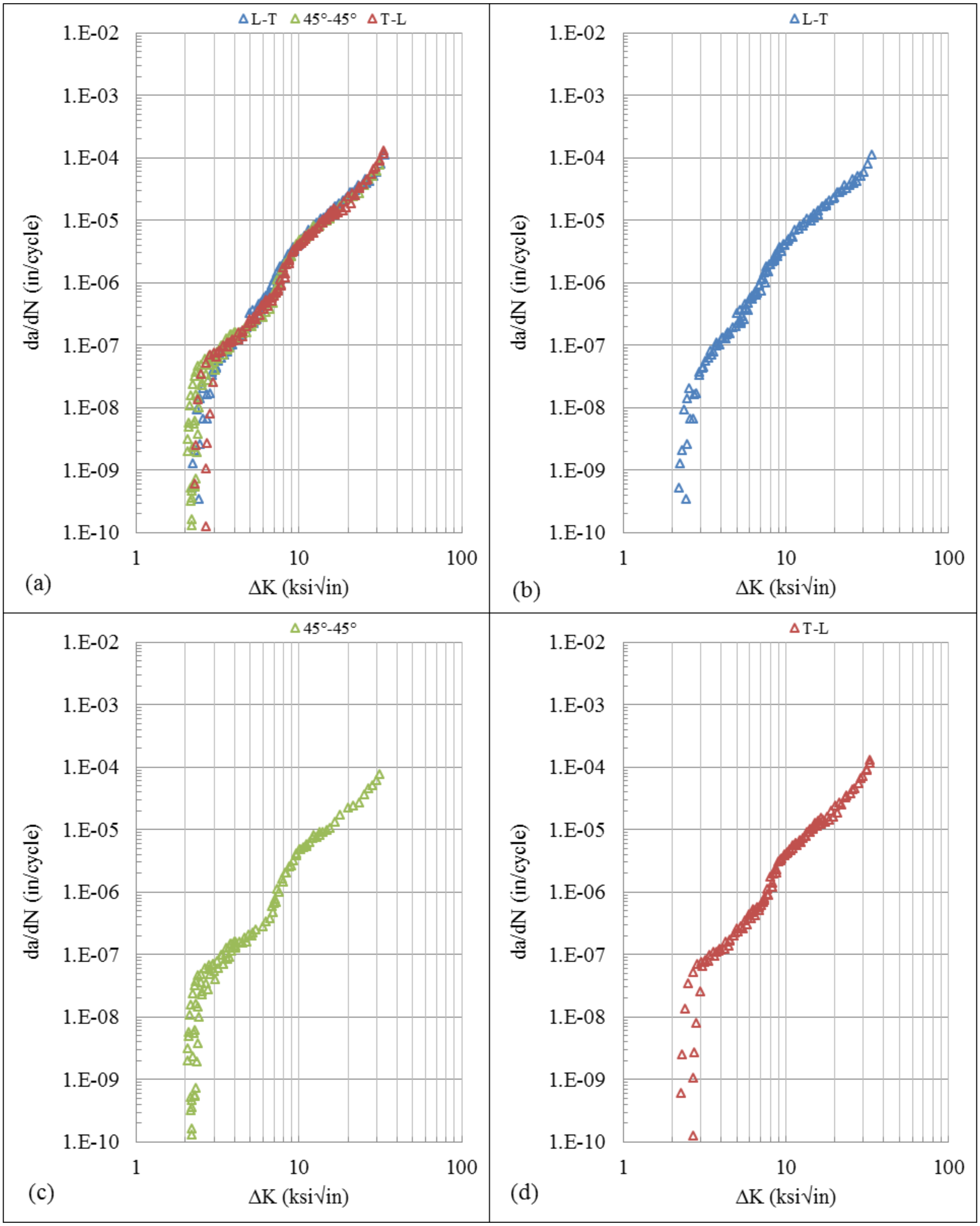


Figure A-1. Al-Li 2198-T8; 0.071-inch thick; 74°F; R=0.1; (a) all grain orientations; (b) L-T; (c) 45 degrees–45 degrees; (d) T-L

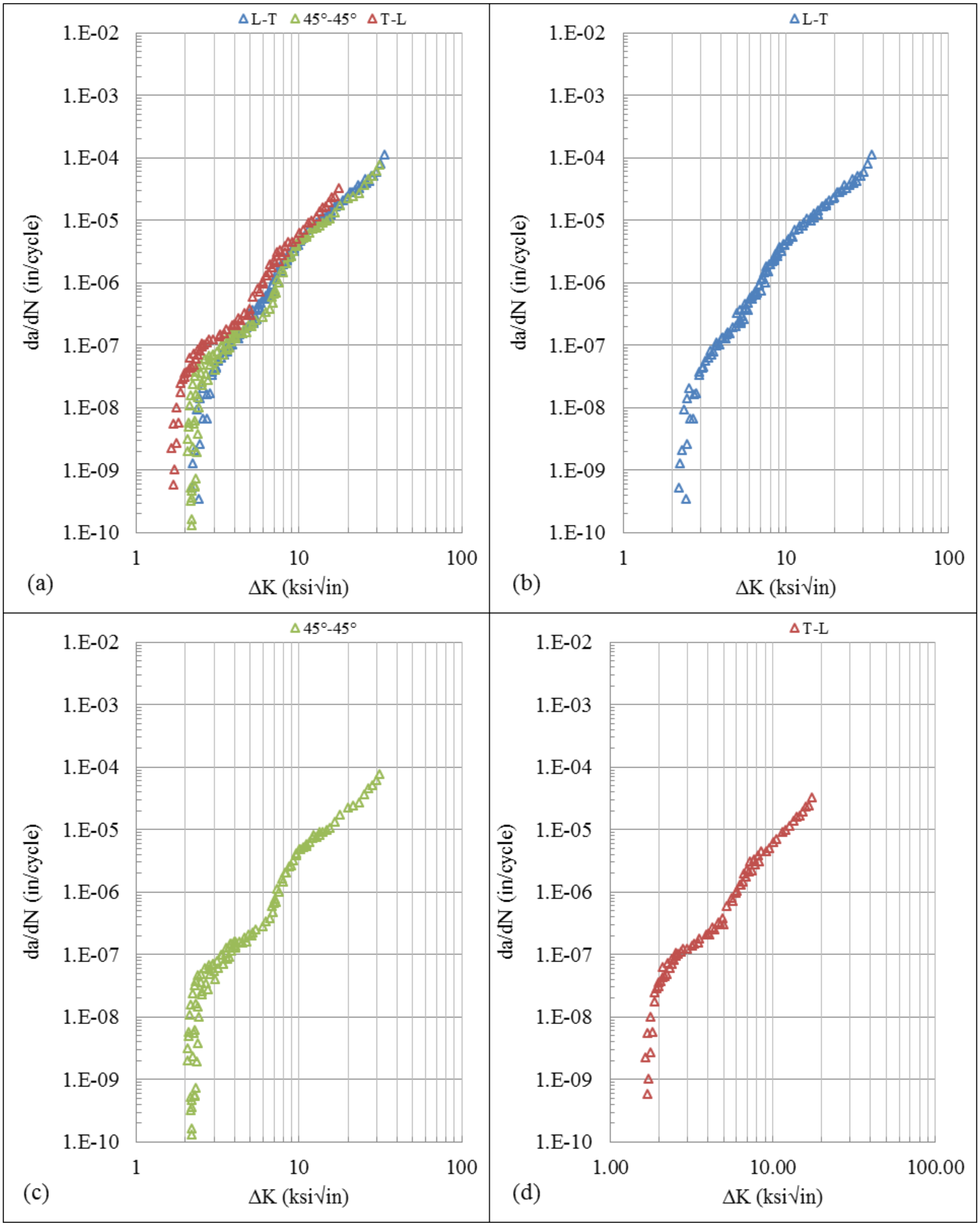


Figure A-2. Al-Li 2198-T8; 0.071-inch thick; 74°F; R=0.4; (a) all grain orientations; (b) L-T; (c) 45 degrees–45 degrees; (d) T-L

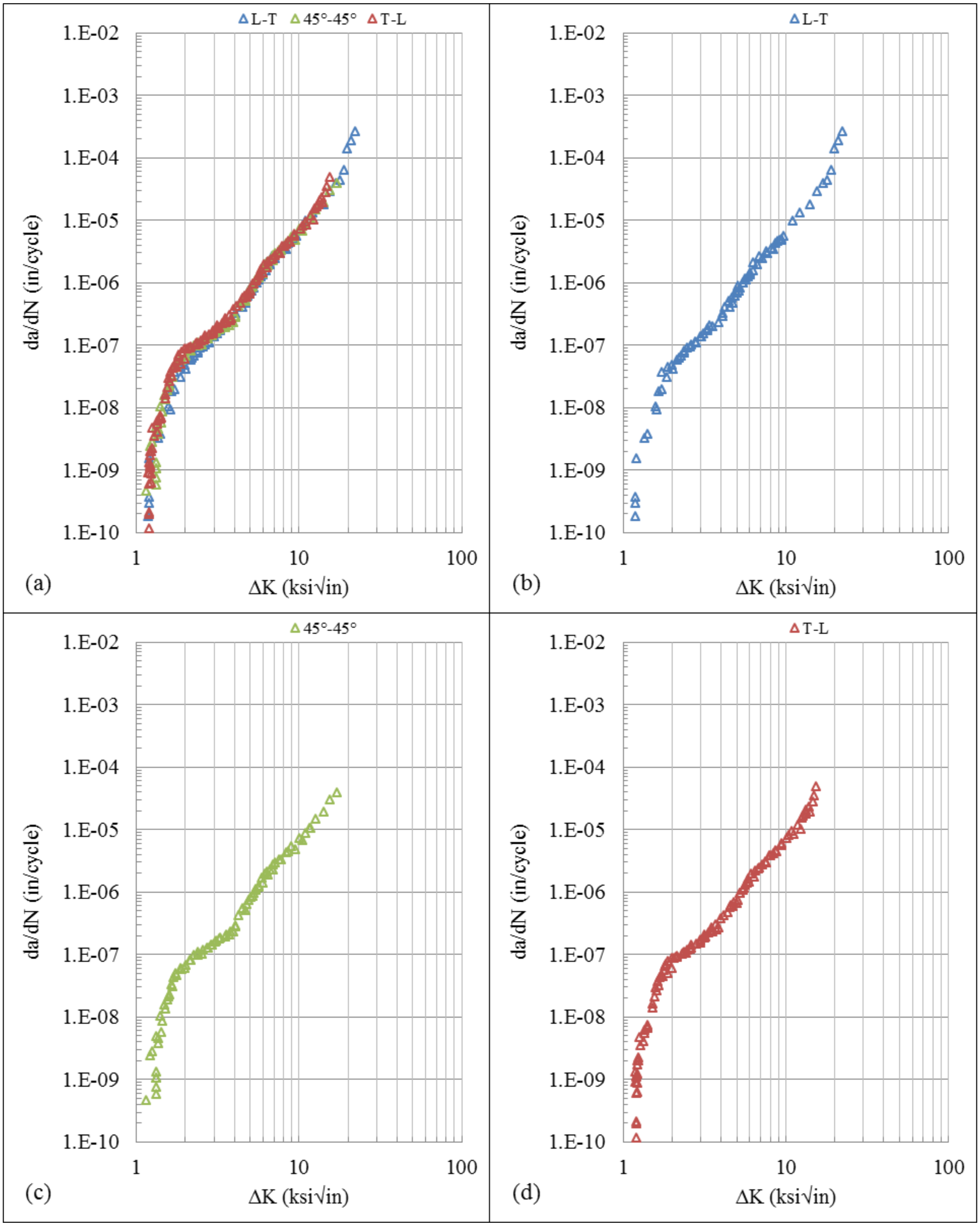


Figure A-3. Al-Li 2198-T8; 0.071-inch thick; 74°F; R=0.7; (a) all grain orientations; (b) L-T; (c) 45 degrees–45 degrees; (d) T-L

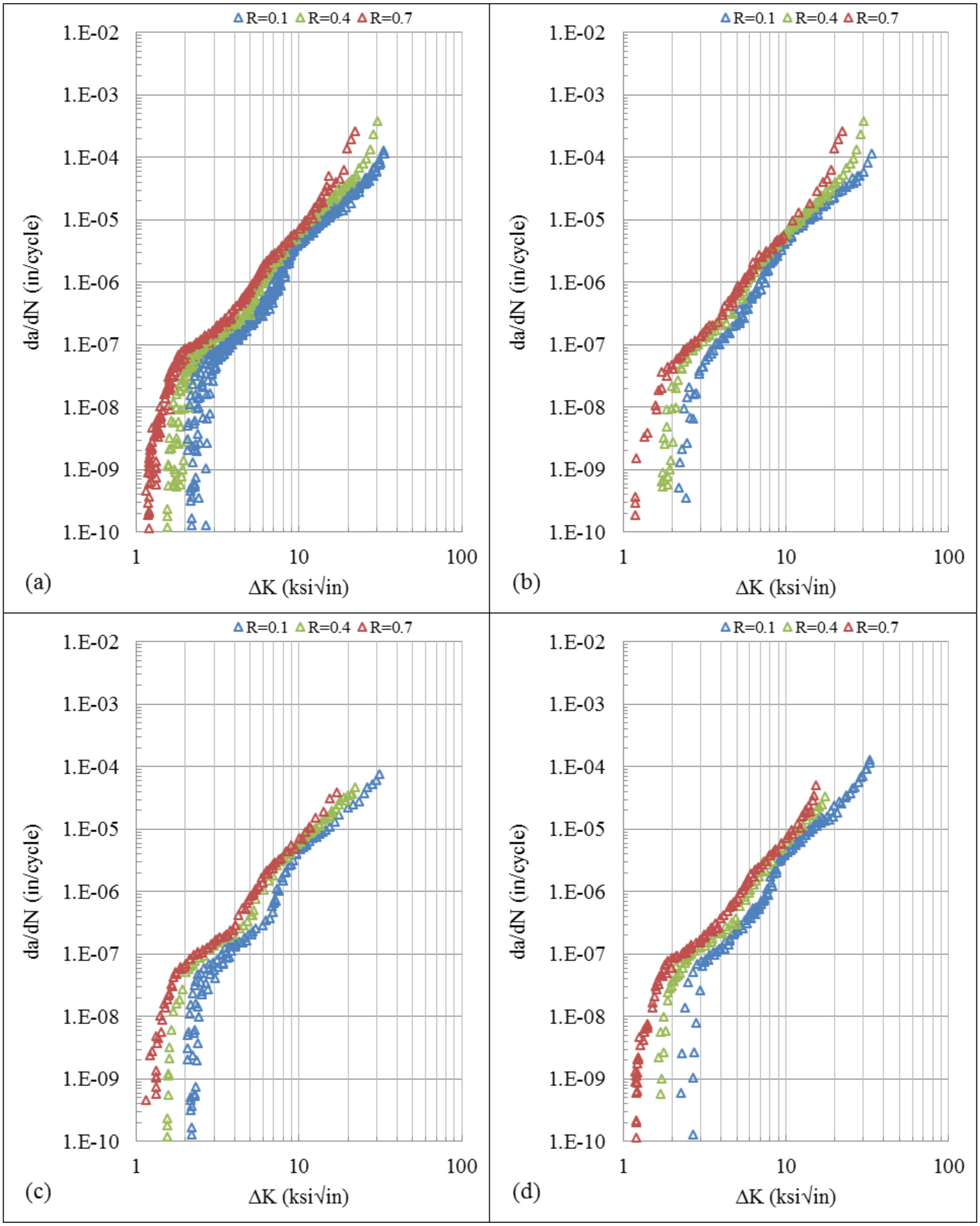


Figure A-4. Al-Li 2198-T8; 0.071-inch thick; 74°F; all stress ratios; (a) all grain orientations; (b) L-T; (c) 45 degrees–45 degrees; (d) T-L

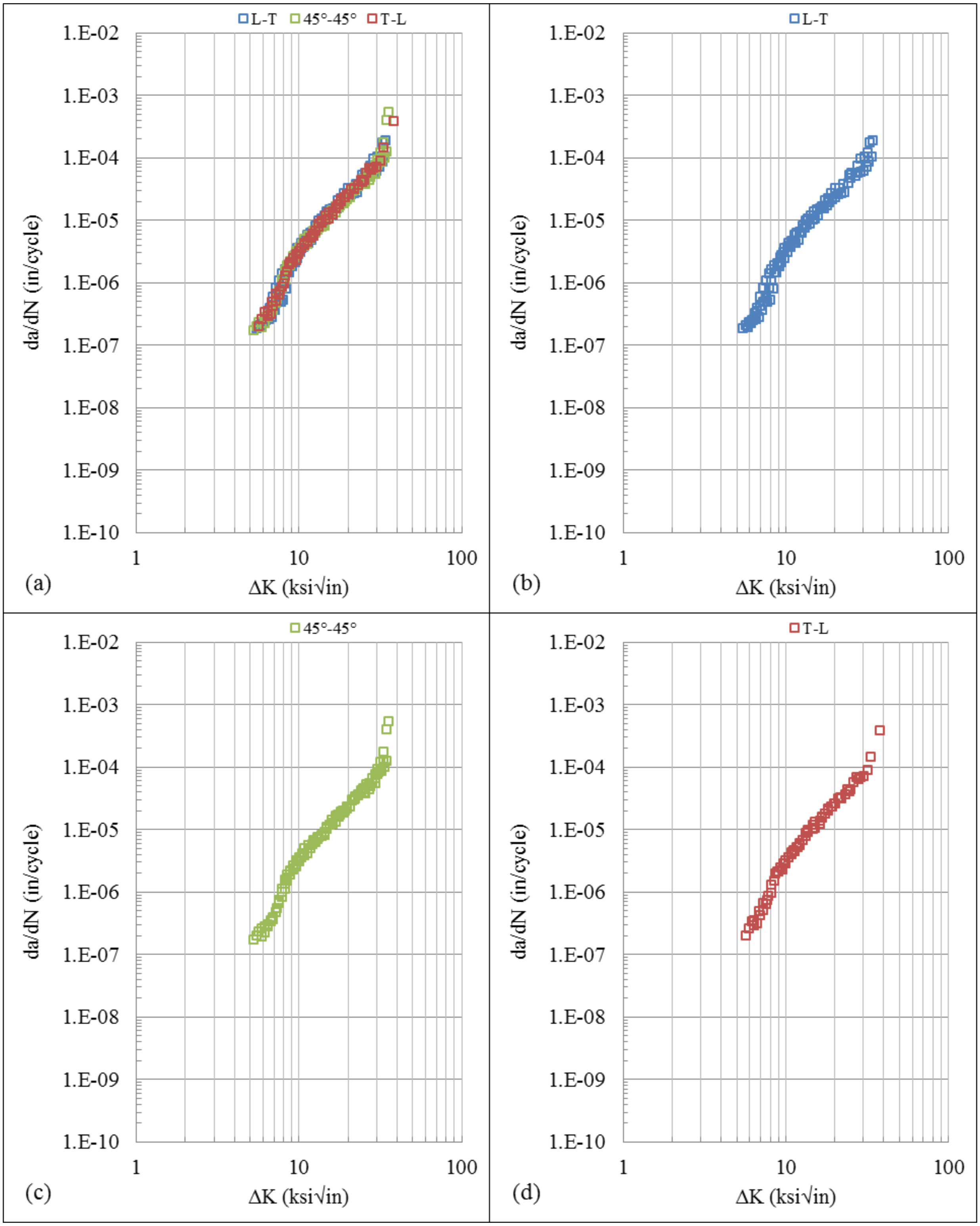


Figure A-5. Al-Li 2198-T8; 0.071-inch thick; 200°F; R=0.1; (a) all grain orientations; (b) L-T; (c) 45 degrees–45 degrees; (d) T-L

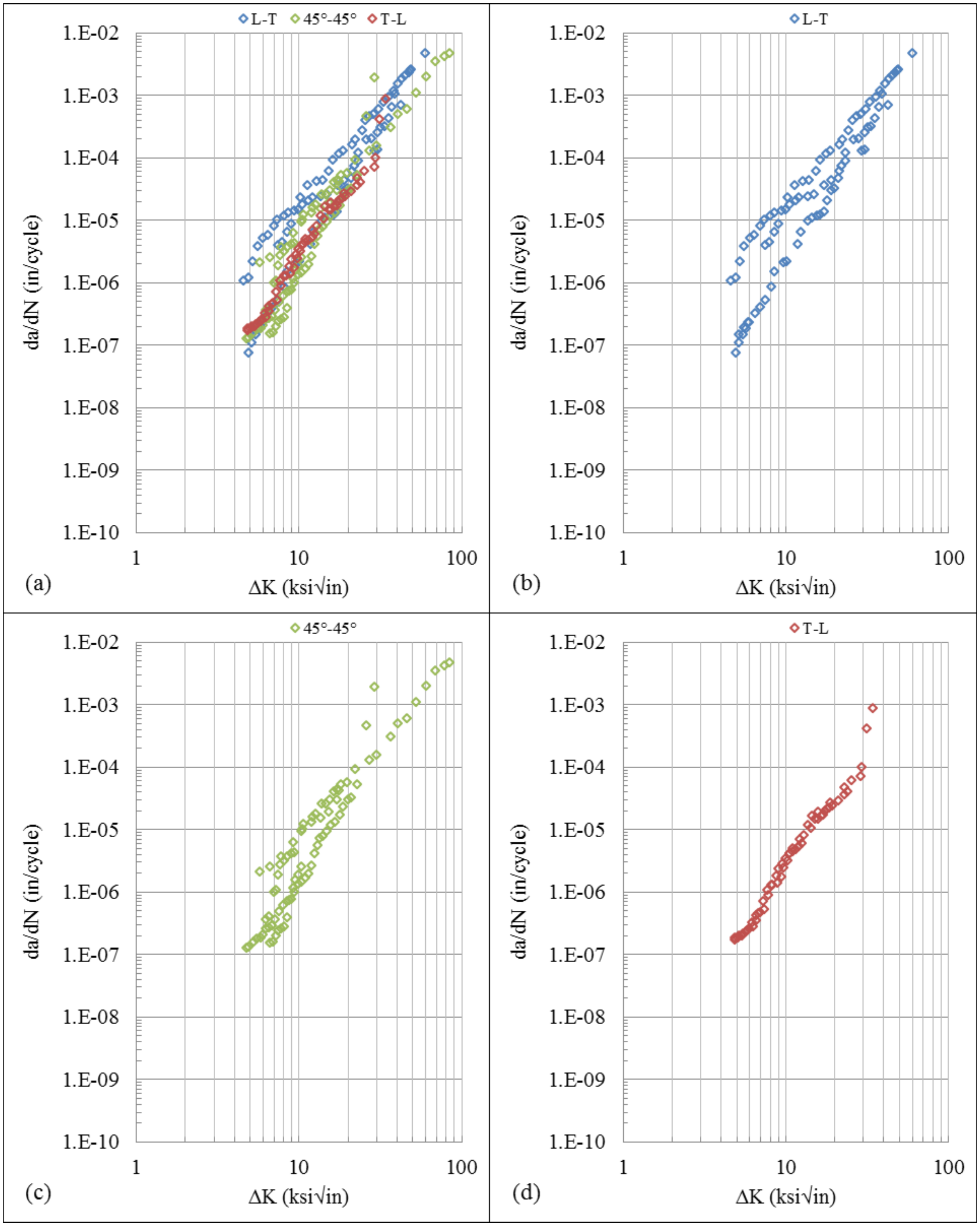


Figure A-6. Al-Li 2198-T8; 0.071-inch thick; 350°F; R=0.1; (a) all grain orientations; (b) L-T; (c) 45 degrees–45 degrees; (d) T-L

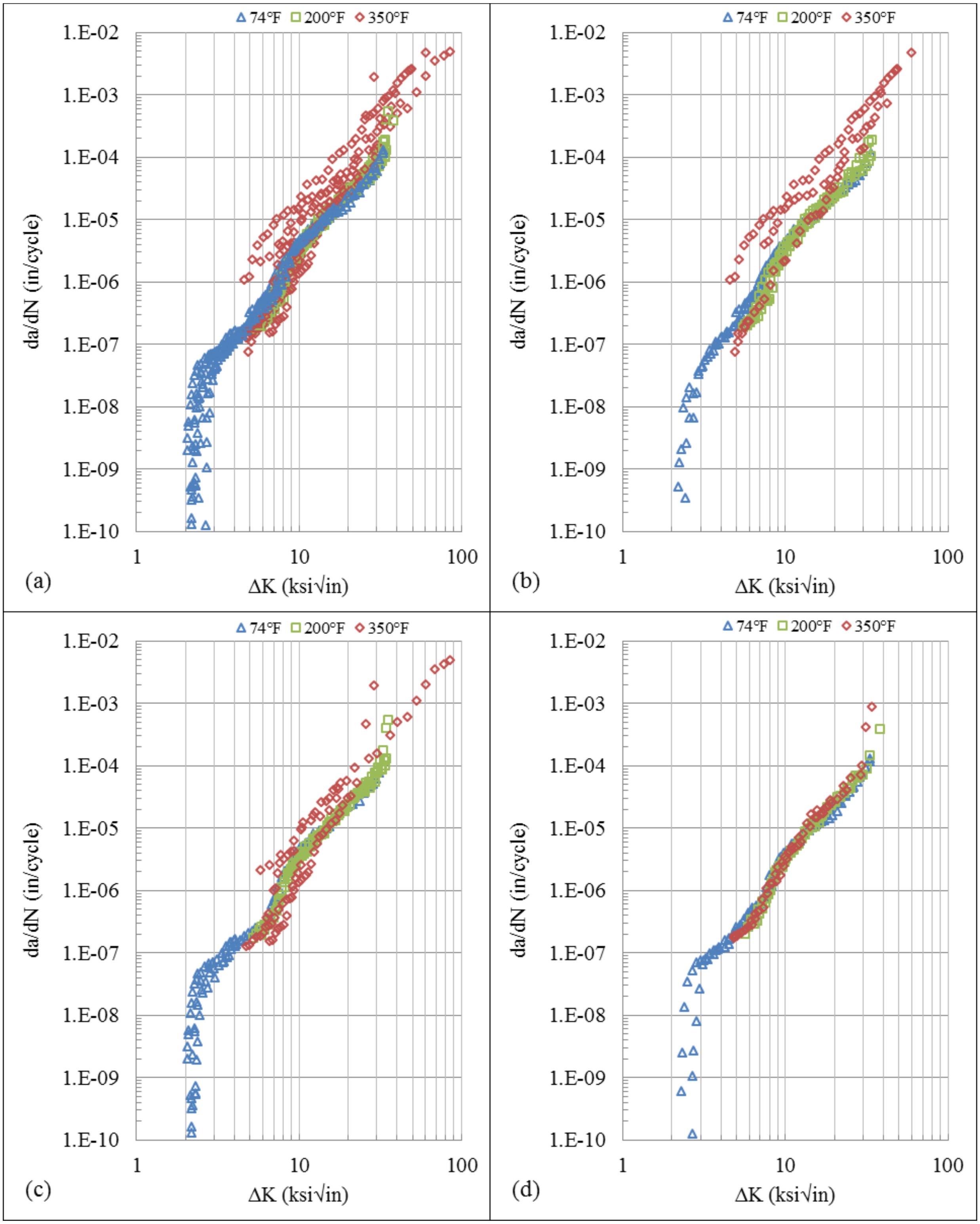


Figure A-7. Al-Li 2198-T8; 0.071-inch thick; all temperatures; R=0.1; (a) all grain orientations; (b) L-T; (c) 45 degrees–45 degrees; (d) T-L

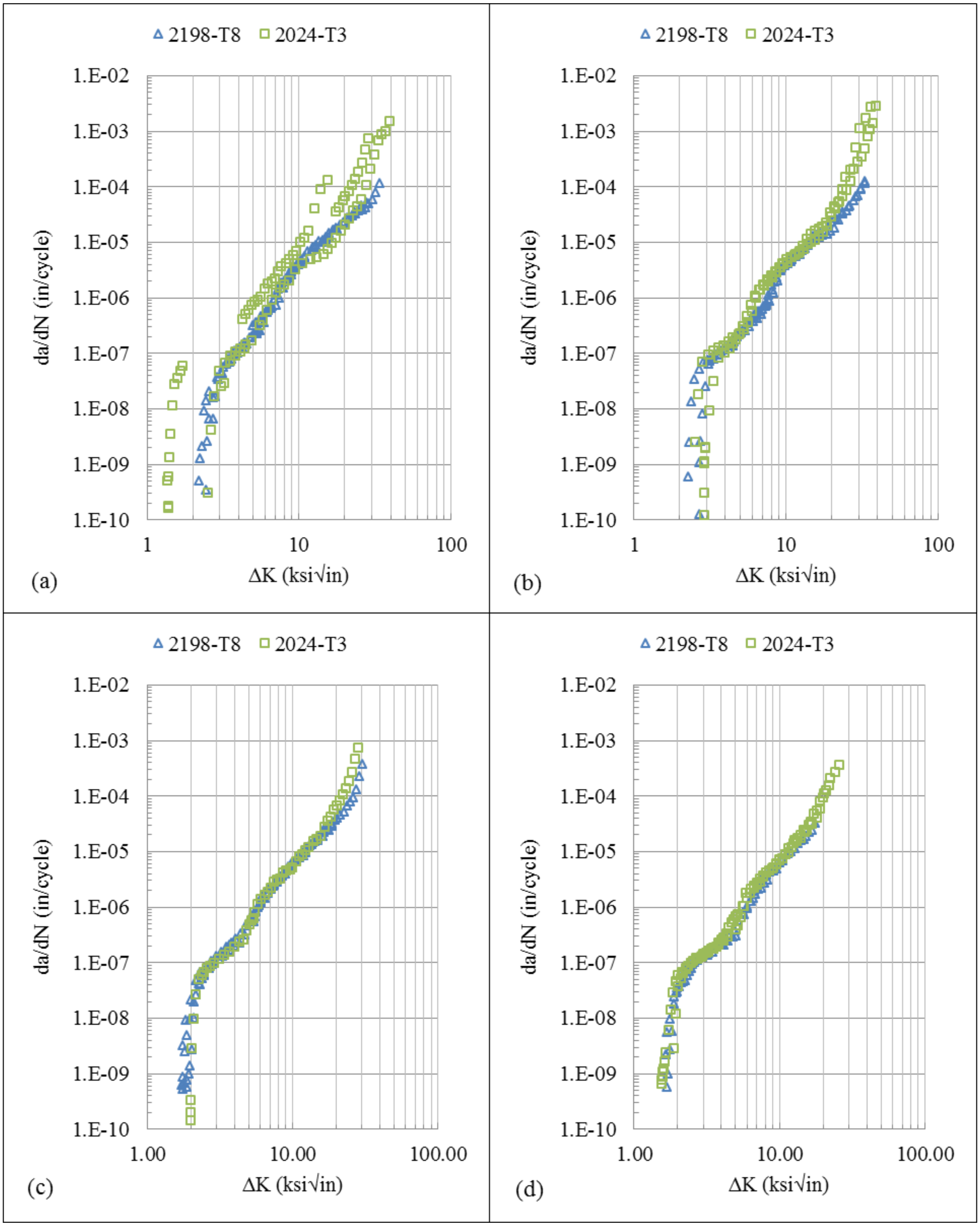


Figure A-8. Al-Li 2198-T8 vs. AA 2024-T3; 0.071-inch thick; 74°F; R=0.1 and R=0.4; (a) L-T, R=0.1; (b) T-L, R=0.1; (c) L-T, R=0.4; (d) T-L, R=0.4

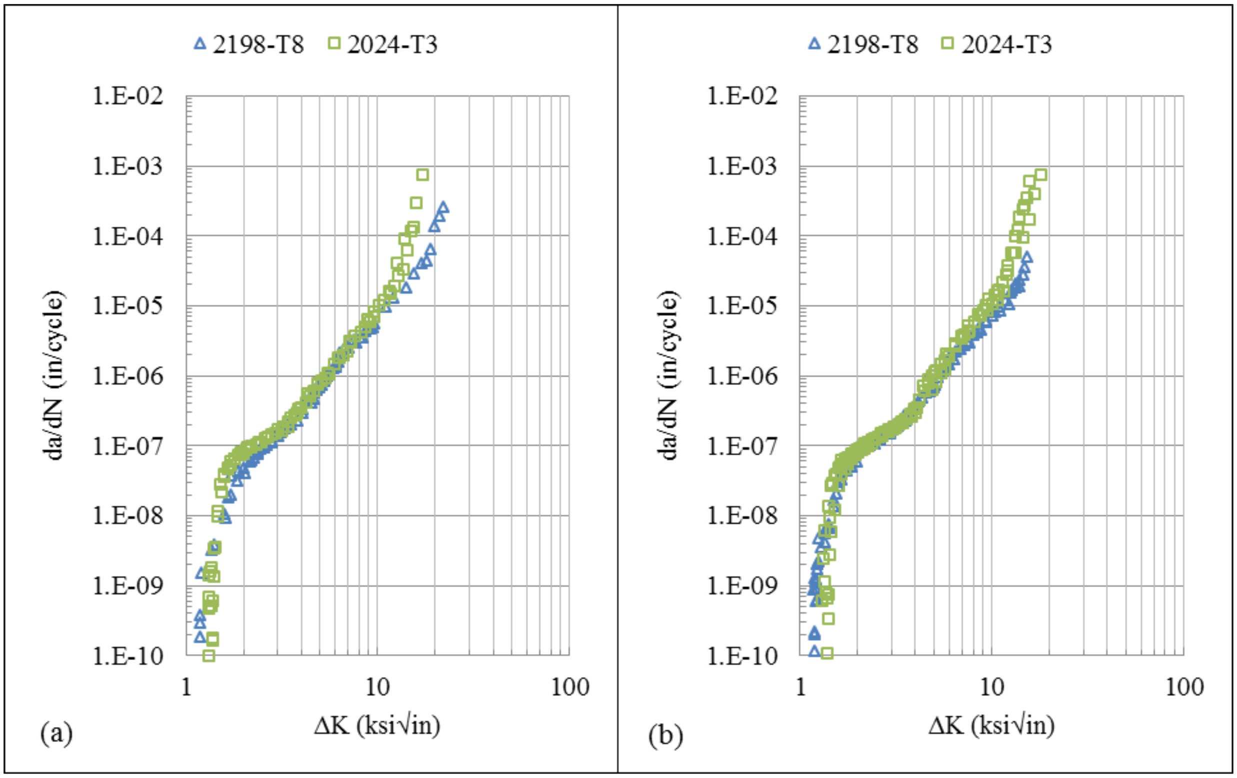


Figure A-9. Al-Li 2198-T8 vs. AA 2024-T3; 0.071-inch thick; 74°F; R=0.7; (a) L-T; (b) T-L

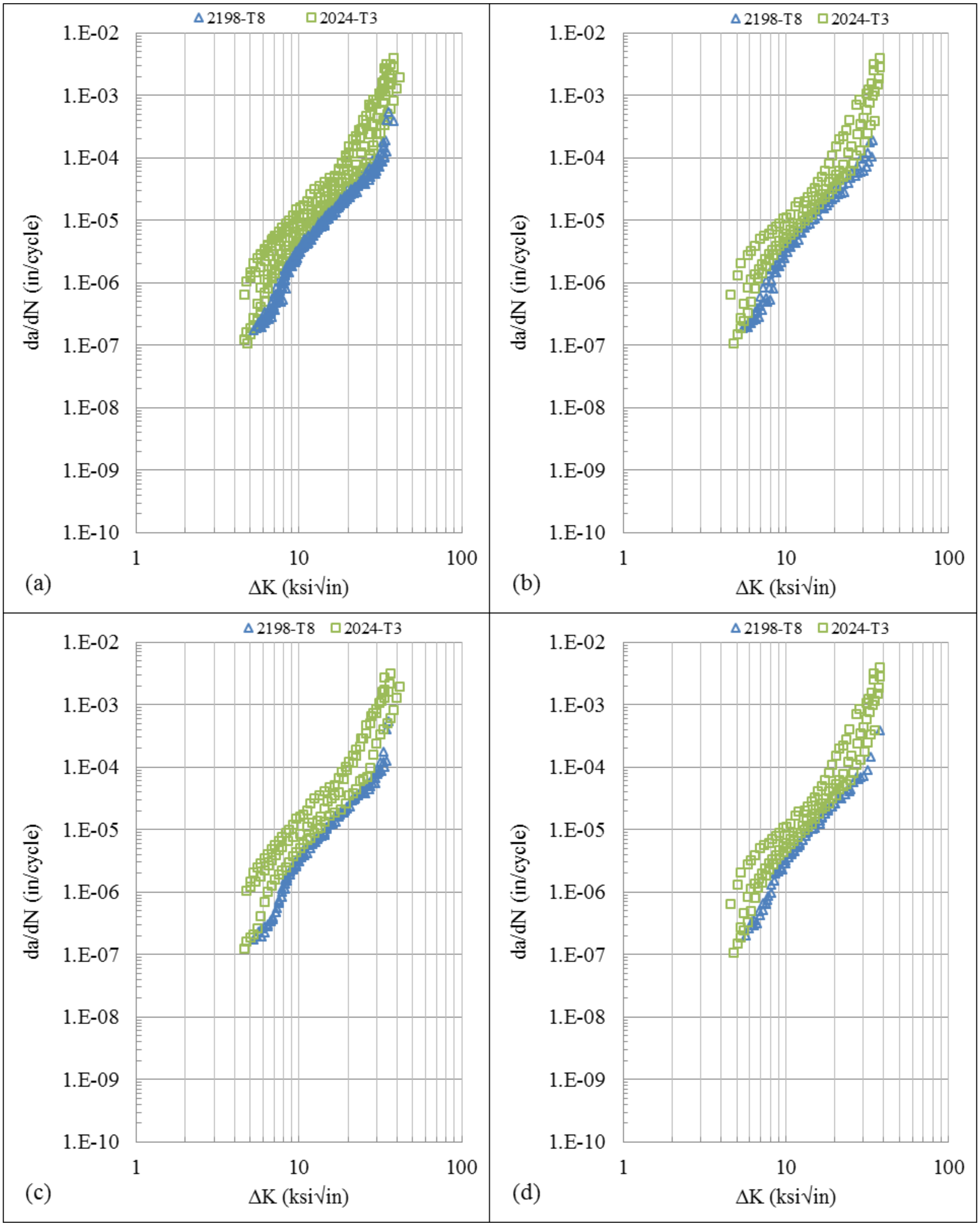


Figure A-10. Al-Li 2198-T8 vs. AA 2024-T3; 0.071-inch thick; 200°F; R=0.1; (a) all grain orientations; (b) L-T; (c) 45 degrees–45 degrees; (d) T-L

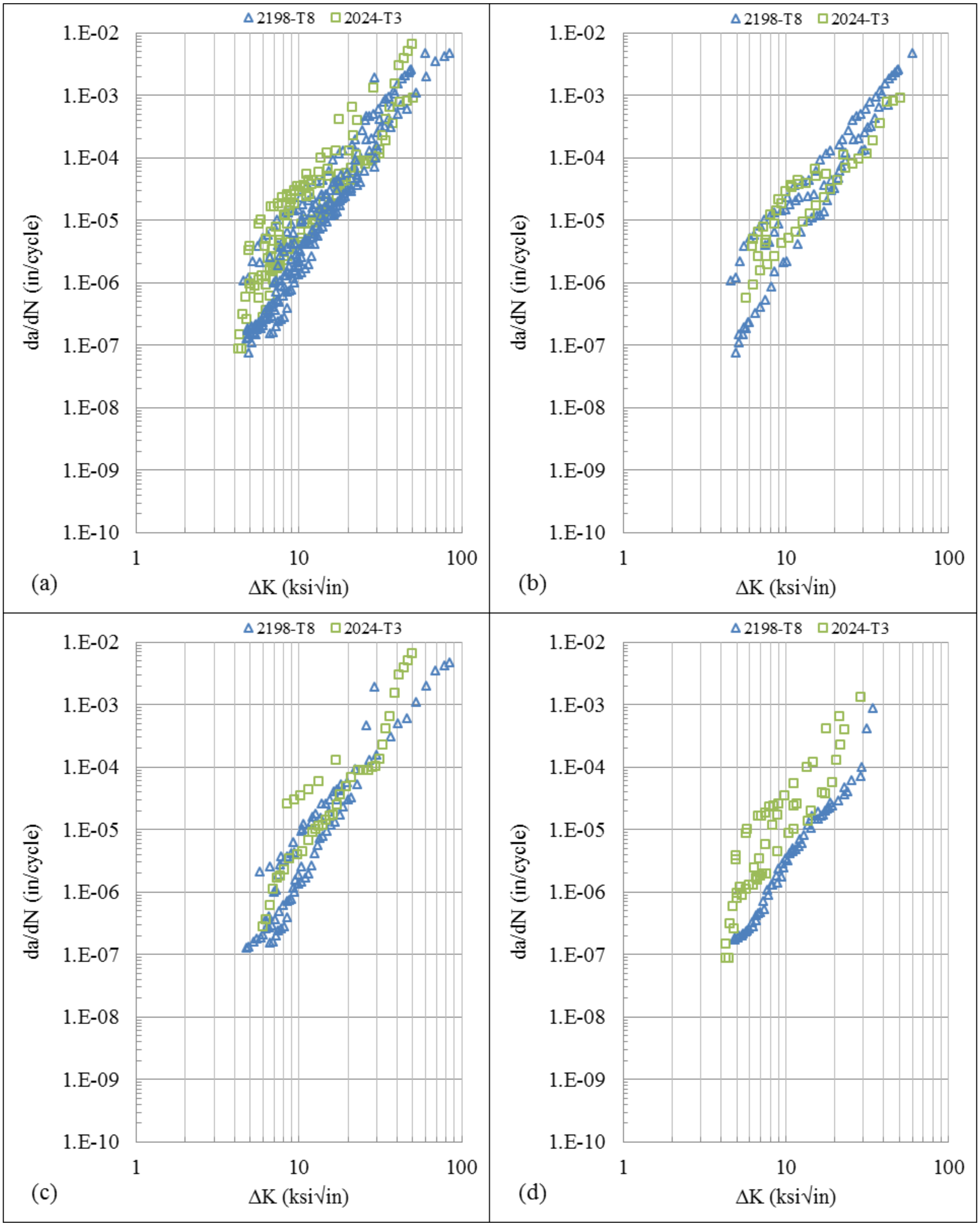


Figure A-11. Al-Li 2198-T8 versus AA 2024-T3; 0.071-inch thick; 350°F; R=0.1; (a) all grain orientations; (b) L-T; (c) 45 degrees–45 degrees; (d) T-L

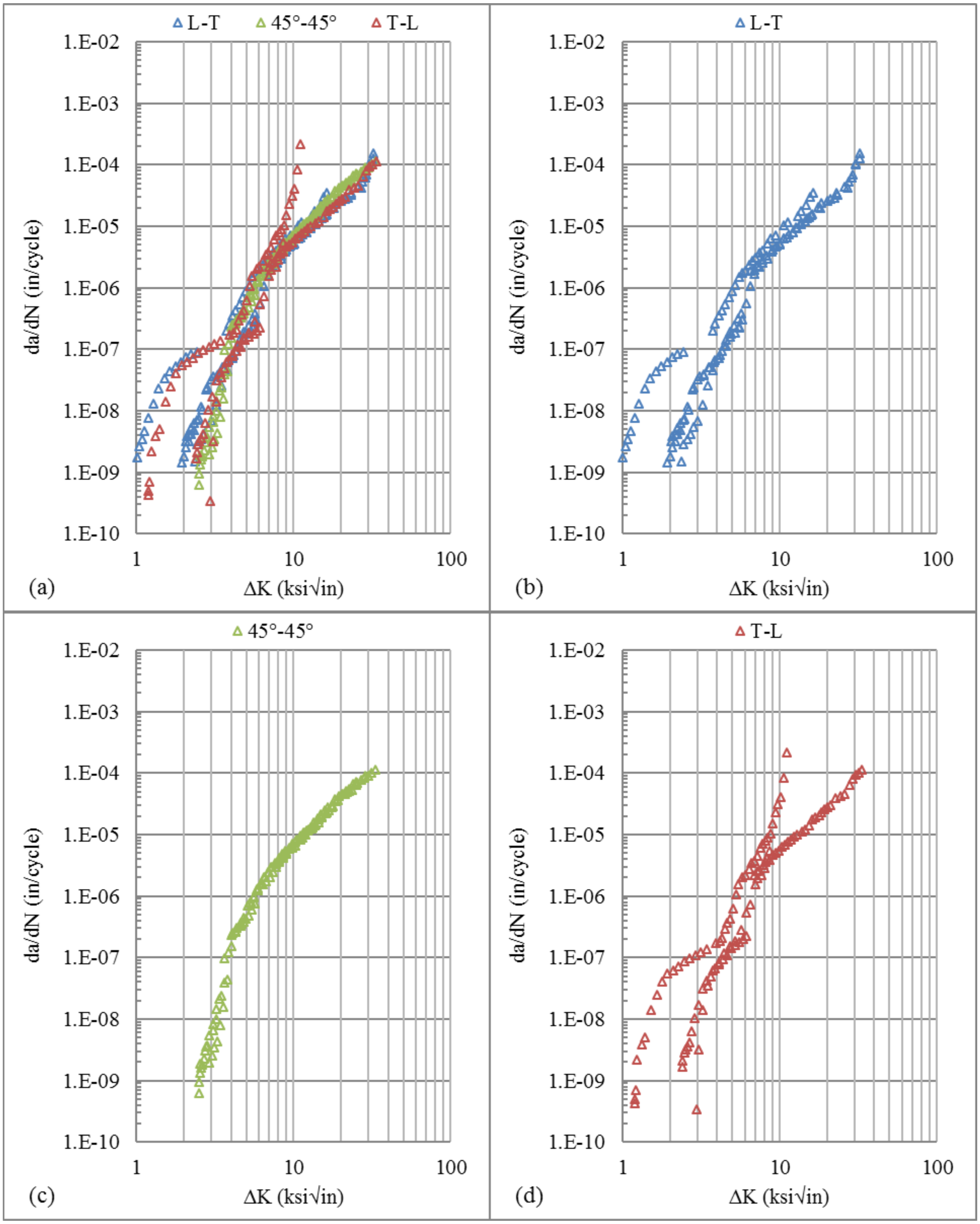


Figure A-12. Al-Li 2198-T8; 0.25-inch thick; 74°F; R=0.1; (a) all grain orientations; (b) L-T; (c) 45 degrees–45 degrees; (d) T-L

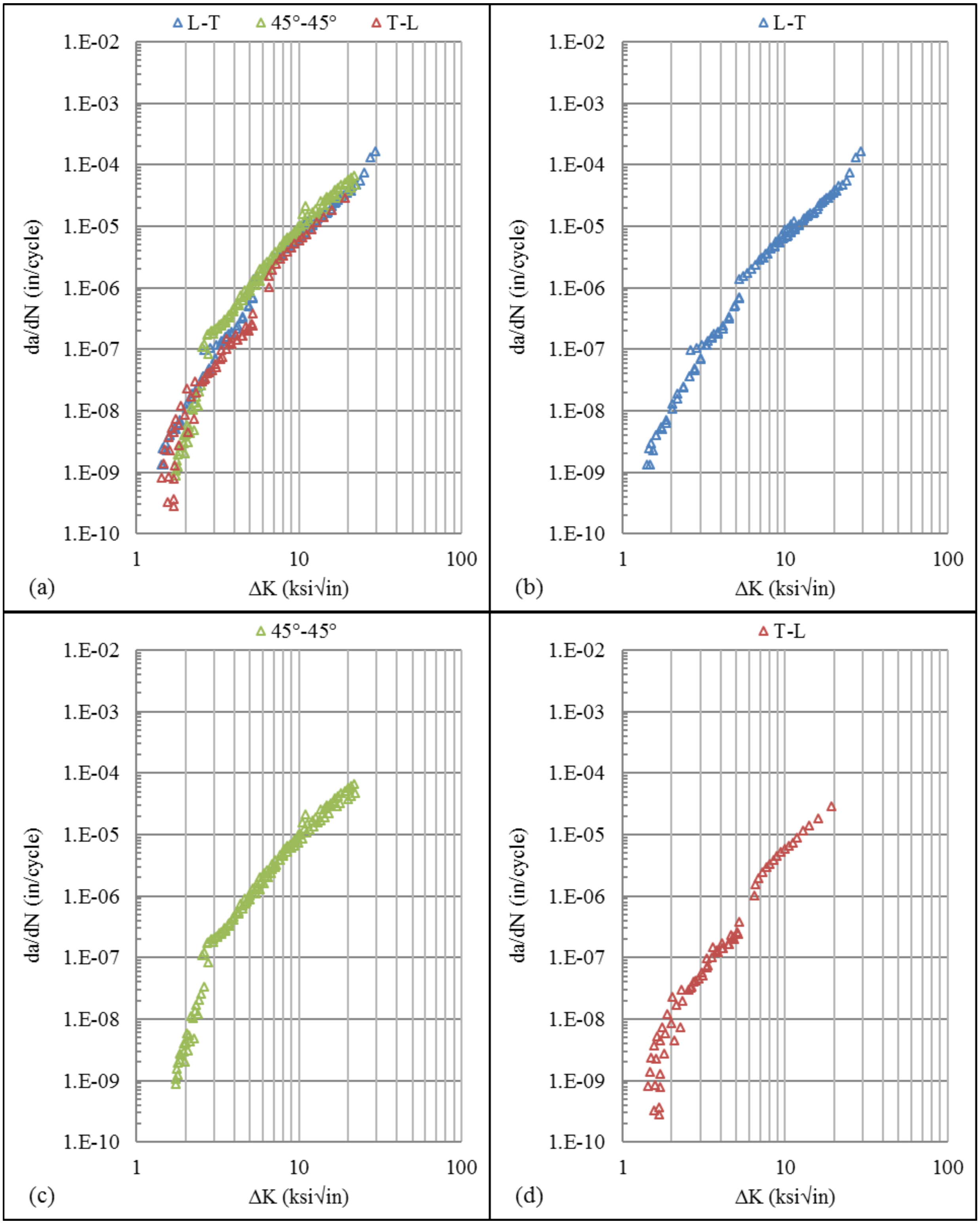


Figure A-13. Al-Li 2198-T8; 0.25-inch thick; 74°F; R=0.4; (a) all grain orientations; (b) L-T; (c) 45 degrees–45 degrees; (d) T-L

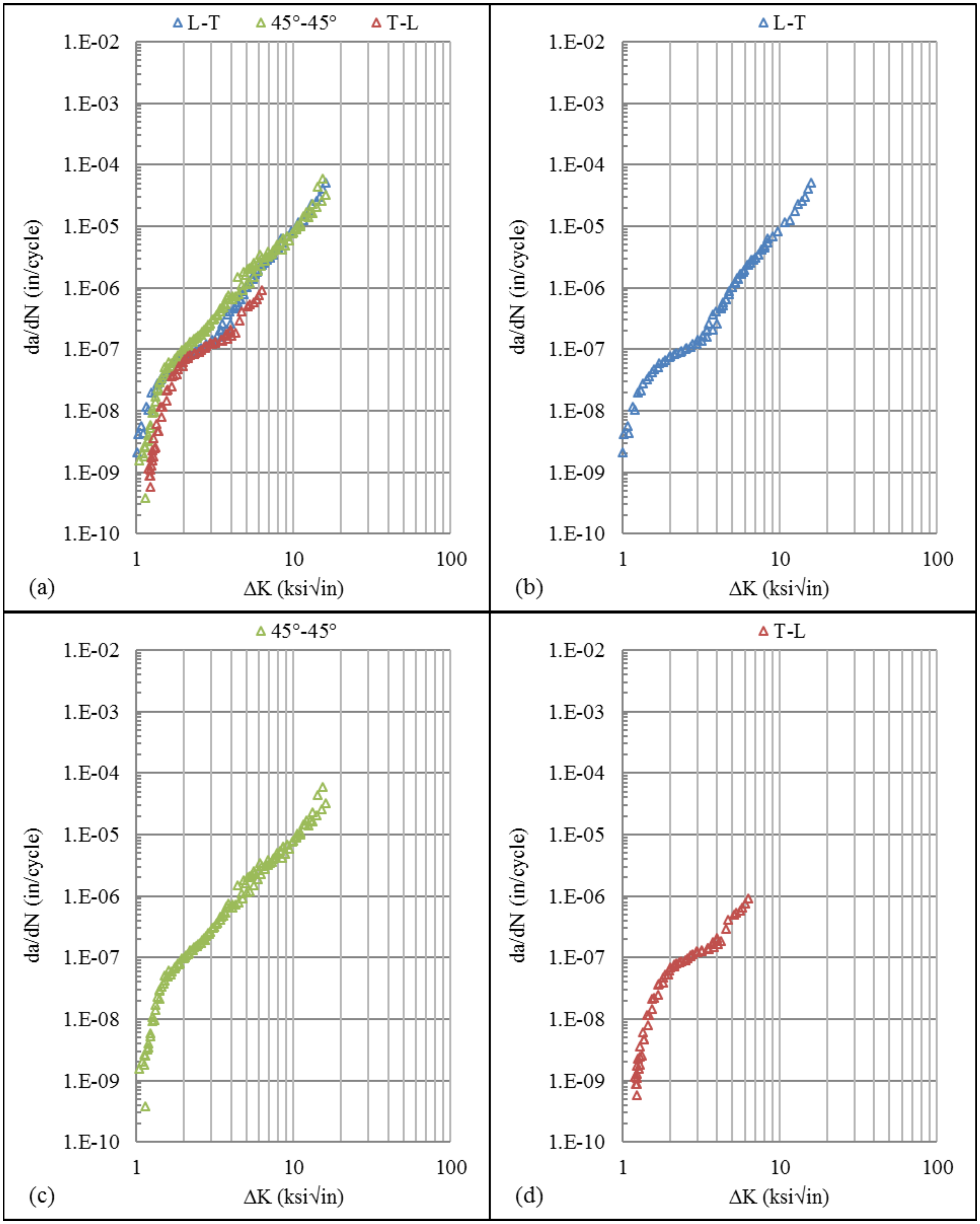


Figure A-14. Al-Li 2198-T8; 0.25-inch thick; 74°F; R=0.7; (a) all grain orientations; (b) L-T; (c) 45 degrees–45 degrees; (d) T-L

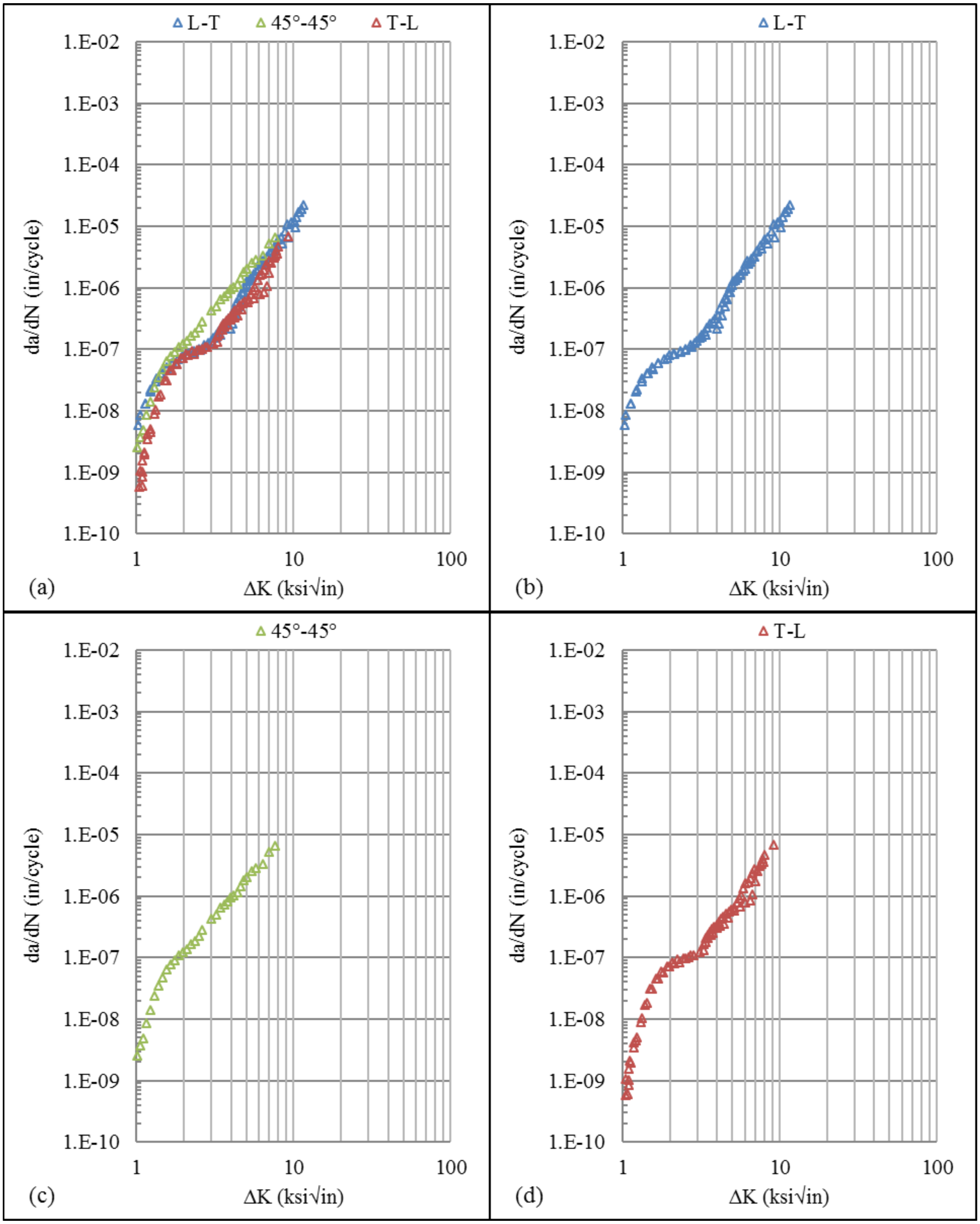


Figure A-15. Al-Li 2198-T8; 0.25-inch thick; 74°F; R=0.8; (a) all grain orientations; (b) L-T; (c) 45 degrees–45 degrees; (d) T-L

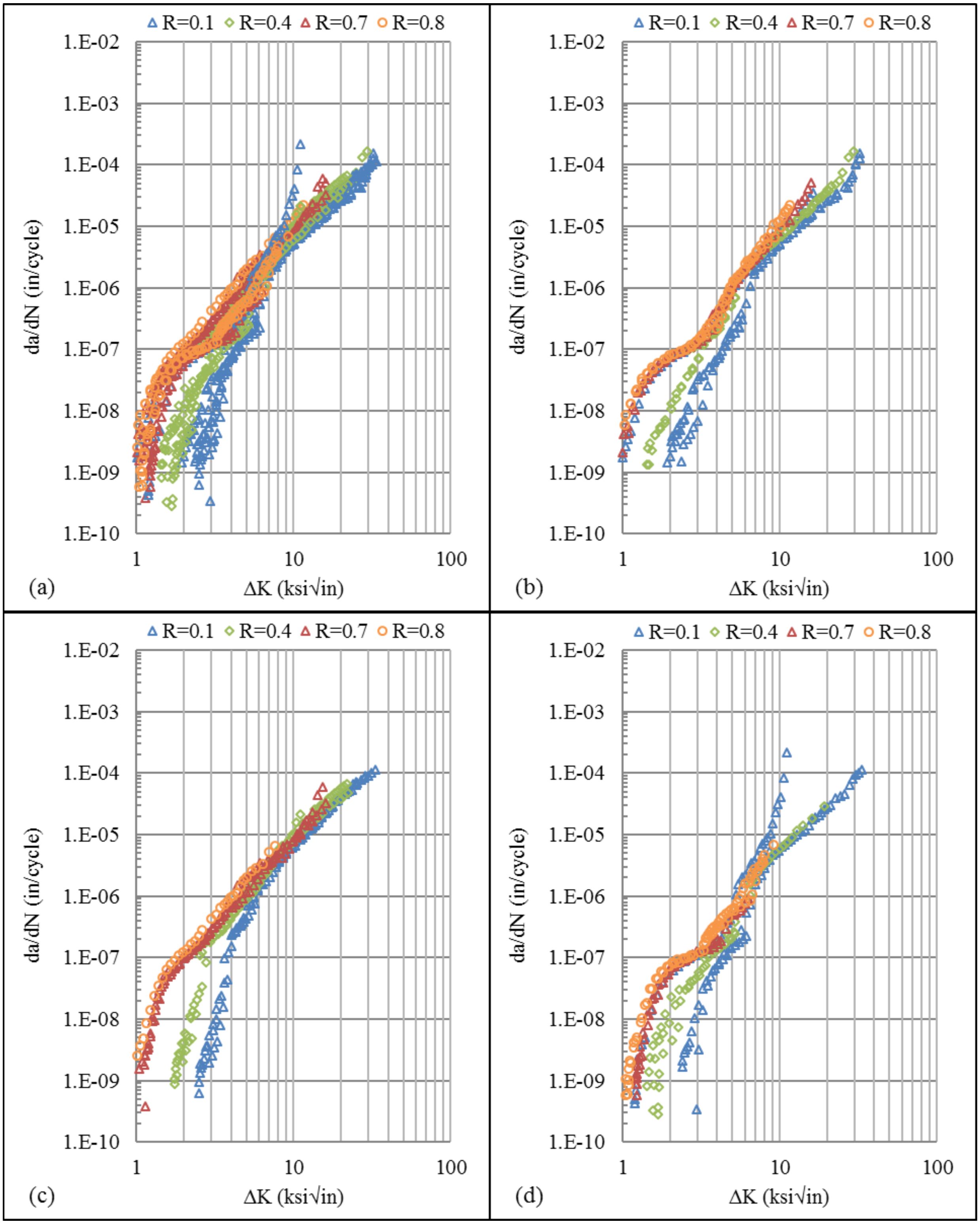


Figure A-16. Al-Li 2198-T8; 0.25-inch thick; 74°F; all stress ratios; (a) all grain orientations; (b) L-T; (c) 45 degrees–45 degrees; (d) T-L

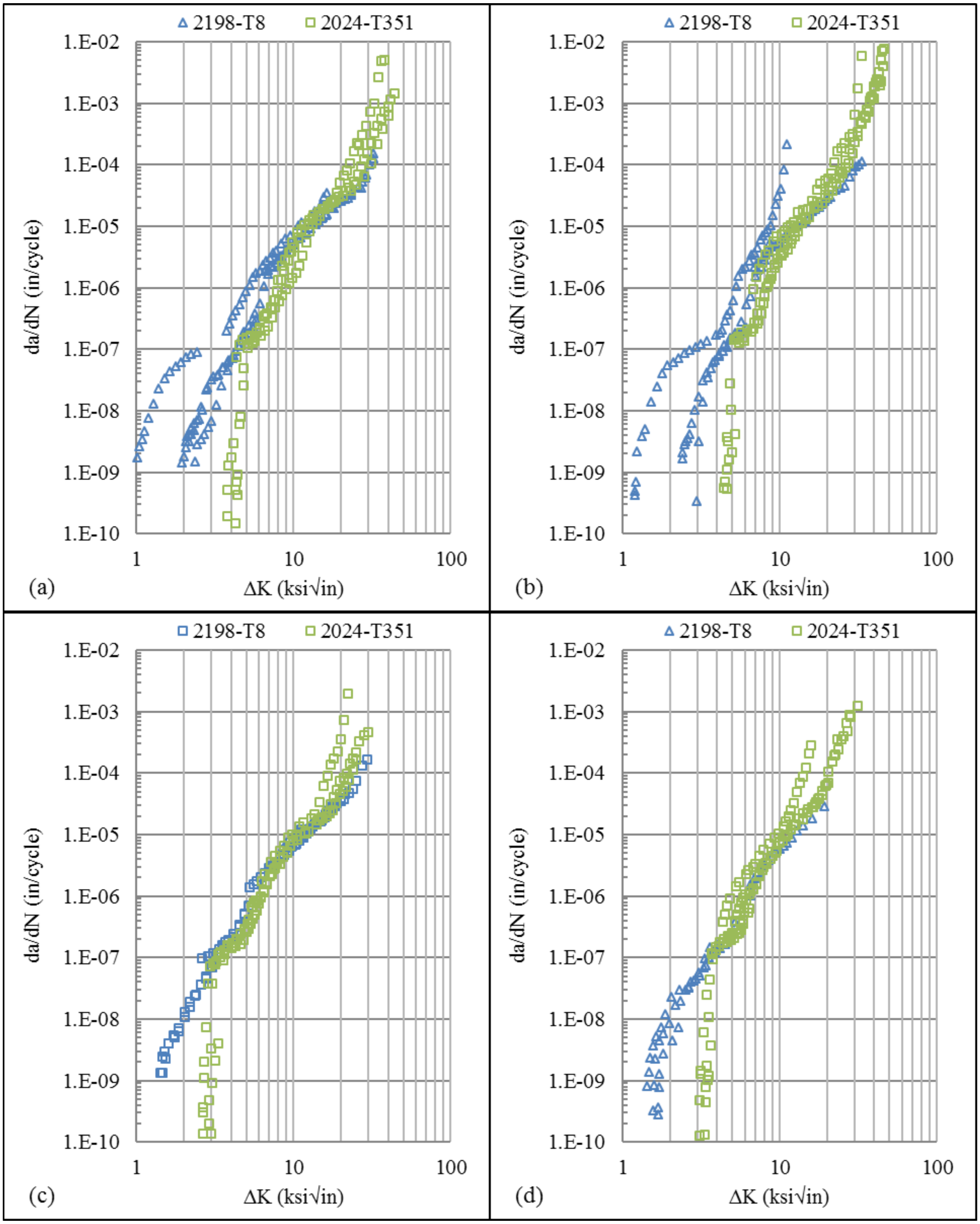


Figure A-17. Al-Li 2198-T8 vs. AA 2024-T351; 0.25-inch thick; 74°F; R=0.1 and R=0.4; (a) L-T, R=0.1; (b) T-L, R=0.1; (c) L-T, R=0.4; (d) T-L, R=0.4

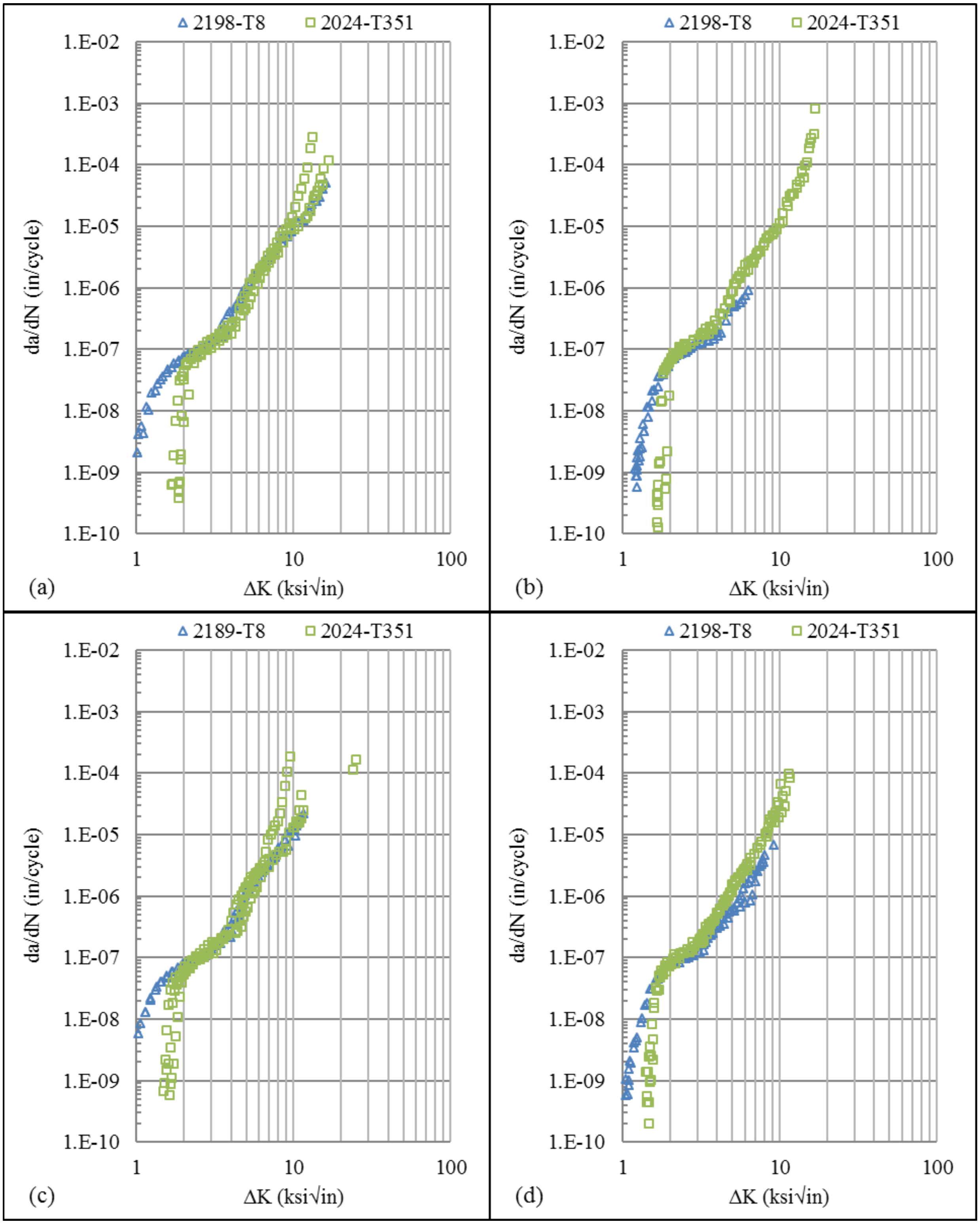


Figure A-18. Al-Li 2198-T8 vs. AA 2024-T351; 0.25-inch thick; 74°F; R=0.7 and R=0.8; (a) L-T, R=0.7; (b) T-L, R=0.7; (c) L-T, R=0.8; (d) T-L, R=0.8

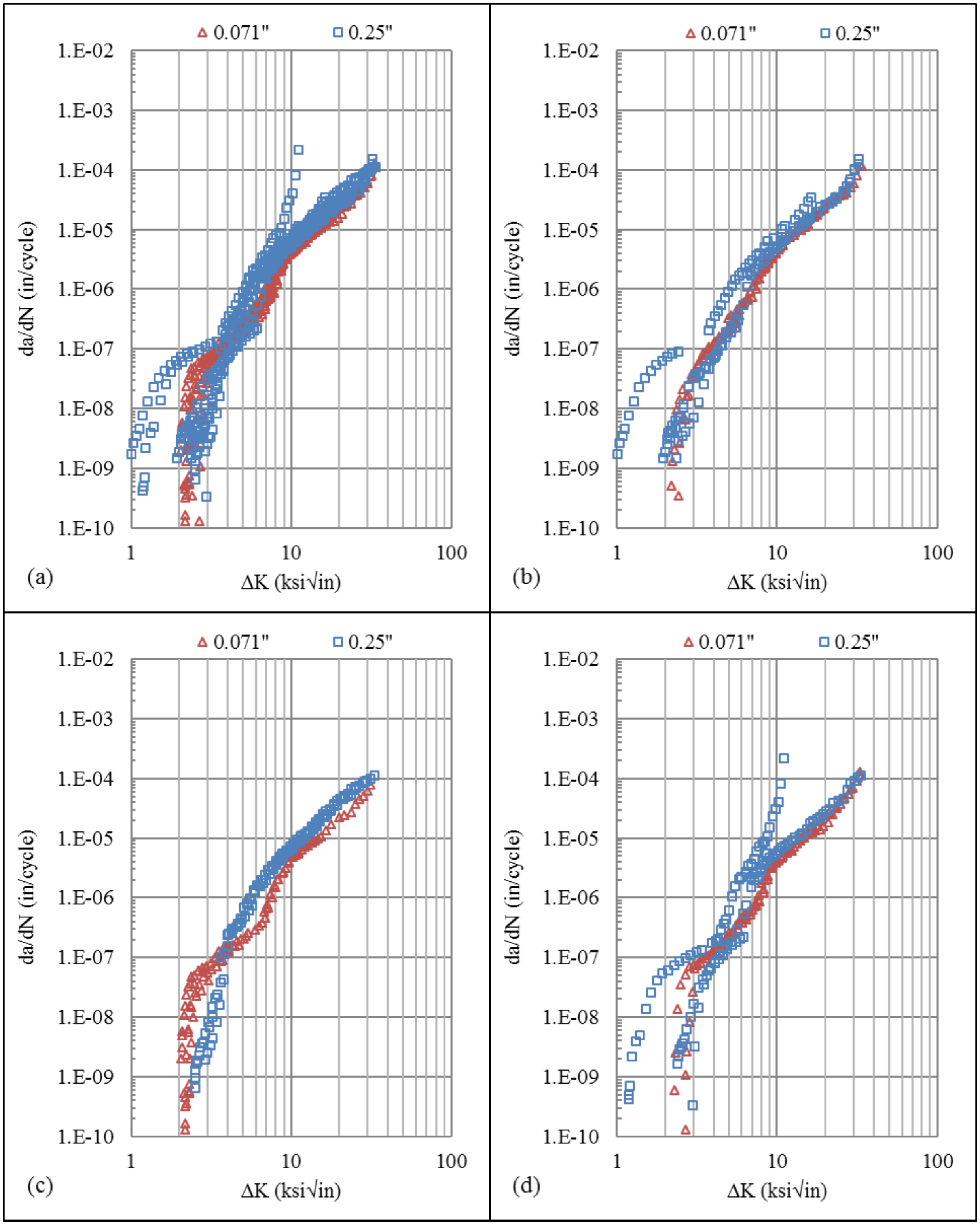


Figure A-19. Al-Li 2198-T8; 0.071-inch vs. 0.25-inch thick; 74°F; R=0.1; (a) all grain orientations; (b) L-T; (c) 45 degrees– 45 degrees; (d) T-L

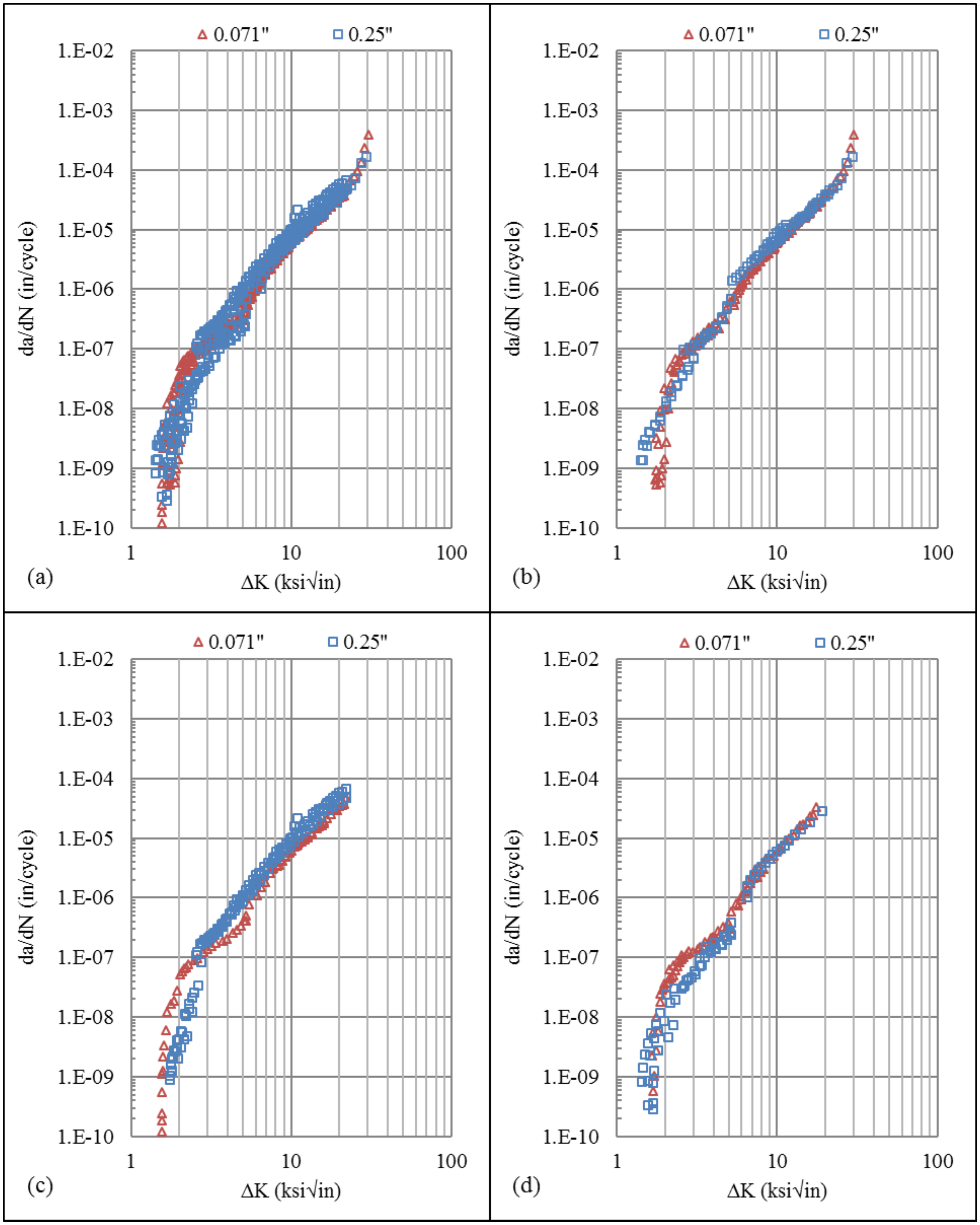


Figure A-20. Al-Li 2198-T8; 0.071-inch vs. 0.25-inch thick; 74°F; R=0.4; (a) all grain orientations; (b) L-T; (c) 45 degrees–45 degrees; (d) T-L

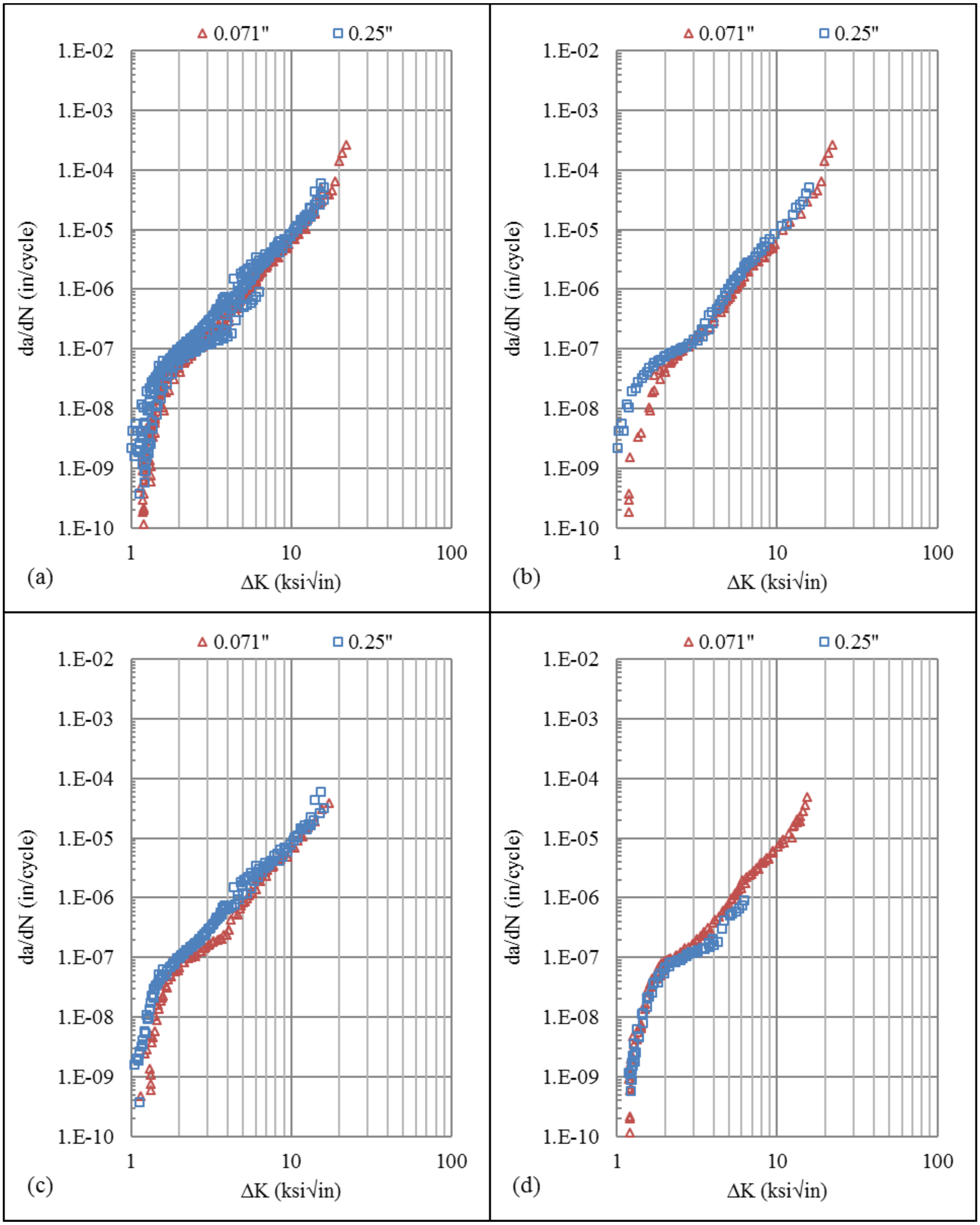


Figure A-21. Al-Li 2198-T8; 0.071-inch vs. 0.25-inch thick; 74°F; R=0.7; (a) all grain orientations; (b) L-T; (c) 45 degrees–45 degrees; (d) T-L

APPENDIX B—UDRI FCGR DATA

Table B-1. UDRI crack-growth life data

Material	Direction	Load Profile	Crack Growth Life	Profile Average
2024-T3	L-T	R=0.1	8002	7790
			7643	
			7724	
		Spectrum	5813	5945
			6076	
2198-T8	L-T	R=0.1	11344	11308
			10180	
			12400	
		Spectrum	9392	9121
			8642	
			9330	
	45°–45°	R=0.1	15693	14754
			14422	
			14146	
		Spectrum	10592	10631
			10727	
			10575	
	T-L	R=0.1	10518	10732
			10960	
			10718	
		Spectrum	8509	8356
			8448	
			8112	