NASA/TM-2000-210098

Fatigue Crack Growth Rate Test Results for Al-Li 2195 Parent Metal, Variable Polarity Plasma Arc Welds and Friction Stir Welds

Robert A. Hafley, John A. Wagner, and Marcia S. Domack
Langley Research Center, Hampton, Virginia

May 2000

The NASA STI Program Office ... in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the lead center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers, but having less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results ... even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at ***http://www.sti.nasa.gov***

- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA STI Help Desk at (301) 621-0134

- Phone the NASA STI Help Desk at (301) 621-0390

- Write to:
  NASA STI Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076-1320

NASA/TM-2000-210098

Fatigue Crack Growth Rate Test Results for Al-Li 2195 Parent Metal, Variable Polarity Plasma Arc Welds and Friction Stir Welds

Robert A. Hafley, John A. Wagner, and Marcia S. Domack
Langley Research Center, Hampton, Virginia

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

May 2000

Acknowledgments

This work was conducted under Space Act Agreement 298, funded by Lockheed-Martin Michoud Space Systems. The authors would like to acknowledge the contributions of Paula Hartley and William Arbegast of Lockheed-Martin Michoud Space Systems.

The use of trademarks or names of manufacturers in this report is for accurate reporting and does not constitute an official endorsement, either expressed or implied, of such products or manufacturers by the National Aeronautics and Space Administration.

Available from:

NASA Center for AeroSpace Information (CASI)
7121 Standard Drive
Hanover, MD 21076-1320
(301) 621-0390

National Technical Information Service (NTIS)
5285 Port Royal Road
Springfield, VA 22161-2171
(703) 605-6000

CONTENTS

LIST OF FIGURES

LIST OF TABLES

Abstract

The fatigue crack growth rate of aluminum-lithium (Al-Li) alloy 2195 plate and weldments was determined at 200°F, ambient temperature and –320°F. The effects of stress ratio (R), welding process, orientation and thickness were studied. Results are compared with plate data from the Space Shuttle Super Lightweight Tank (SLWT) allowables program. Data from the current series of tests, both plate and weldment, falls within the range of data generated during the SLWT allowables program.

1. Introduction

The application of advanced aluminum alloys to Reusable Launch Vehicle (RLV) structures required the characterization of the time dependent properties of candidate alloys. The candidate alloy studied in this investigation was aluminum-lithium (Al-Li) alloy 2195. Prior to this investigation, the database which existed for 2195 included strength and fracture data primarily developed for expendable launch vehicle applications. The application of 2195 in RLV systems required the full characterization of the fatigue crack growth rate behavior of both parent and welded 2195 at service temperatures. The thermal profile for RLV structures included ambient temperature, as well as elevated temperatures during ascent and descent, and cryogenic temperatures for oxidizer storage.

2. Symbols and Abbreviations

a	crack length
Al-Li	aluminum-lithium
ASTM	American Society for Testing and Materials
C	normalized K-gradient
C(T)	compact specimen
da/dN	fatigue crack growth rate
ΔK	stress-intensity factor range
FCGR	fatigue crack growth rate
FSW	friction stir welding
F_{tu}	ultimate tensile strength
F_{ty}	0.2% offset yield strength
HT	heat treatment
K	stress-intensity factor
K_{max}	maximum stress-intensity factor
K_{min}	minimum stress-intensity factor
L	direction parallel to rolling direction
L-T	denotes fracture plane normal to L with propagation in T direction
LN_2	liquid nitrogen
R	stress ratio
RLV	Reusable Launch Vehicle
SLWT	Super Lightweight Tank
t	thickness
T	direction perpendicular to rolling direction
T-L	denotes fracture plane normal to T with propagation in L direction
VPPAW	variable polarity plasma arc welding
W	specimen width

3. Materials, Specimen and Test Hardware

Fatigue crack growth rate (FCGR) tests were conducted on aluminum-lithium (Al-Li) alloy 2195-T8 plate and weldments. Two gages of plate, 0.25 in. and 0.50 in., were tested in two orientations, L-T and T-L, at 200°F and ambient temperature (~75°F). Weldments of the same gages, prepared by variable polarity plasma arc welding (VPPAW) using Al 4043 filler metal or friction stir welding (FSW), were also tested at 200°F, ambient temperature (~75°F) and/or -320°F.

Compact (C(T)) specimens, Fig.1, were tested per ASTM E647-95a (ref. 1). Plate specimen thickness was the nominal material thickness. Weldment specimen thicknesses were reduced the minimum amount required to ensure that specimen faces were flat and parallel. The machined notch on the weldments was located along the weld centerline. Clevises with flat bottom holes were fabricated per Fig A2.3 in ref. 1. Elevated temperature tests were conducted in an environmental chamber, while specimens were immersed in liquid nitrogen (LN_2) during cryogenic tests.

4. Test Procedure

Tests were conducted in servohydraulic test frames controlled by an automated fatigue crack growth test system. A constant stress ratio, R, of 0.1 or 0.5 was used in all tests. Specimens were fatigue precracked at ΔK=10 ksi√in from a/W=0.2 to a/W=0.3. A K-decreasing test was conducted over the range of ΔK=10 ksi√in to 5 ksi√in in order to obtain near-threshold crack growth rates. Tests were conducted using a constant K-gradient, C, of -2 in order to eliminate effects of prior loading on the K-decreasing portion of the test. A K-increasing test was then conducted from a ΔK=5 ksi√in until instrumentation ranges were exceeded. At the conclusion of the tests, the specimens were fractured to permit examination of the fracture surface and measurement of the final crack length. Data analysis was conducted in compliance with ref.1.

5. Results

Typical mechanical properties for Al2195-T8 plate and weldments are presented in Table 1(ref. 2, plate and private communication, weldments). FCGR results are presented in Tables 2-15 and Figures 2-15, are summarized in Table 16 at selected levels of stress intensity and compared with data from the Space Shuttle Super Lightweight Tank (SLWT) design allowables program (ref. 2) in Table 17.

5.1 Plate

Two thicknesses of 2195 plate, 0.25 in. and 0.50 in., were tested in two orientations, L-T and T-L, at two temperatures, 200°F and 75°F, and two stress ratios, R=0.1 and 0.5. Results of the FCGR tests illustrating the effects of temperature are presented in Table 2 and Figure 2 for 0.25 in. plate and Tables 6-7 and Figures 6-7 for 0.50 in. plate. The effect of stress ratio on the FCGR is shown in Table 3 and Figure 3 for 0.25in. plate and in Tables 4-5 and Figures 4-5 for 0.5 in. plate. The effect of thickness on the FCGR in 2195 plate is illustrated in Tables 8-9 and Figures 8-9. There appears to be little effect of orientation, thickness or test temperature on the FCGR, however increasing the stress ratio from 0.1 to 0.5 does increase the FCGR.

5.2 Variable Polarity Plasma Arc Welds

Variable polarity plasma arc welds of 0.25 in. plate were tested at 75°F with R=0.1 and 0.5. Results of the FCGR tests are presented in Table 10 and Figure 10. There was a significant effect of R on FCGR. At R=0.1, crack growth data could not be generated at or below ΔK=10 ksi√in, presumably due to residual stresses. Data was obtained at ΔK=10 ksi√in and an R of 0.5. At ΔK=20 ksi√in, the FCGR at R=0.5 is two orders of magnitude higher than at R=0.1.

Table 1. Typical Mechanical Properties for Al 2195-T8 Plate and Weldments

Temp., °F	Prop.	Orient.	Plate[1]		VPPAW[2]	FSW[2]	
			0.25 in.	0.5 in.	0.25 in.	0.25 in.	0.5 in.
200	Fty, ksi	L	66	66	—	—	—
		T	62	62	—	—	—
	Ftu, ksi	L	68	68	—	53	—
		T	65	65	—	—	—
75	Fty, ksi	L	84	85	—	39	35
		T	80	80	—	—	—
	Ftu, ksi	L	89	89	52	60	57
		T	86	86	—	—	—
-320	Fty, ksi	L	96	94	—	—	—
		T	92	91	—	—	—
	Ftu, ksi	L	108	107	—	75	—
		T	102	104	—	—	—

1. Ref. 2
2. Private communication

5.3 Friction Stir Welds

Friction stir welds of 0.25 in and 0.50 in plate were tested at 200°F, 75°F and/or -320°F at R=0.5. Results of the FCGR tests at ambient temperature are presented in Table 11 and Figure 11 for 0.25 in. welds and Table 14 and Figure 14 for 0.5 in. welds; cryogenic temperature results are presented in Table 12 and Figure 12 for 0.25 in. welds and Table 15 and Figure 15 for 0.5 in. welds; elevated temperature results are presented in Table 13 and Figure 13 for 0.5 in. welds. There does not appear to be any effect of thickness on the FCGR of Friction Stir Welds. However, the FCGR increases for tests conducted at 200°F and -320°F, compared to tests conducted at 75°F.

6. Discussion

The FCGR of Al-Li 2195-T8 plate and weldments at three selected levels of ΔK, 6, 10 and 20 ksi√in, for each specimen tested is shown in Table 16. Results from replicate specimens of 2195-T8 plate show excellent agreement. Tests conducted on weldments exhibit more scatter, possibly due to residual stress effects from the welding process.

The FCGR of the VPPAW material at a stress ratio of 0.1 is significantly lower than that of the Al-Li 2195-T8 plate at a comparable stress intensity. At a stress ratio of 0.5 and a stress intensity of 10 ksi√in, the FCGR of the VPPAW material is lower than that of the Al-Li 2195-T8 plate. However, at a stress ratio of 0.5 and a stress intensity of 20 ksi√in the FCGR of the VPPAW material is significantly higher than that of the Al-Li 2195-T8 plate. The FCGR of the FSW material is slightly higher than that of Al-Li 2195-T8 plate at similar stress ratios and stress intensities. This may be attributable to the low residual stress due to welding. These differences in rates for VPPAW material and FSW material as compared to plate may reflect differences in the level of residual stresses resulting from the two welding processes.

The results of this study are summarized in Table 17, along with data from the SLWT design allowables program. All data generated in this program falls to the low end of the broad range of room temperature FCGR data from the SLWT design allowables program. The broad range of data from the

SLWT design allowables can be accounted for by the different material thicknesses tested, 0.25 in. and 1.5 in., the inclusion of short transverse test specimen orientations, S-T and T-S, and testing several different production lots of material.

7. Conclusions

The FCGR of FSW Al-Li 2195-T8 plate is similar to that of unwelded Al-Li 2195-T8 plate at similar stress intensities and stress ratios.

The FCGR of VPPAW Al-Li 2195-T8 plate is lower than that of unwelded Al-Li 2195-T8 plate at similar stress ratios and stress intensities below 10 ksi√in. At stress intensities above 10 ksi√in, the FCGR of VPPAW Al-Li 2195-T8 plate is higher than that of unwelded Al-Li 2195-T8 plate.

8. References

1. Standard Test Method for Measurement of Fatigue Crack Growth Rates. ASTM Designation: E 647-95a, Volume 03.01 of the *1997 Annual Book of ASTM Standards,* 1997, pp. 557-593.
2. Reinmuller, R. E., SO 89818 Al-Li Materials Database, Lockheed Martin Manned Space Systems, New Orleans, LA 70189.

Figure 1. C(T) Specimen Design

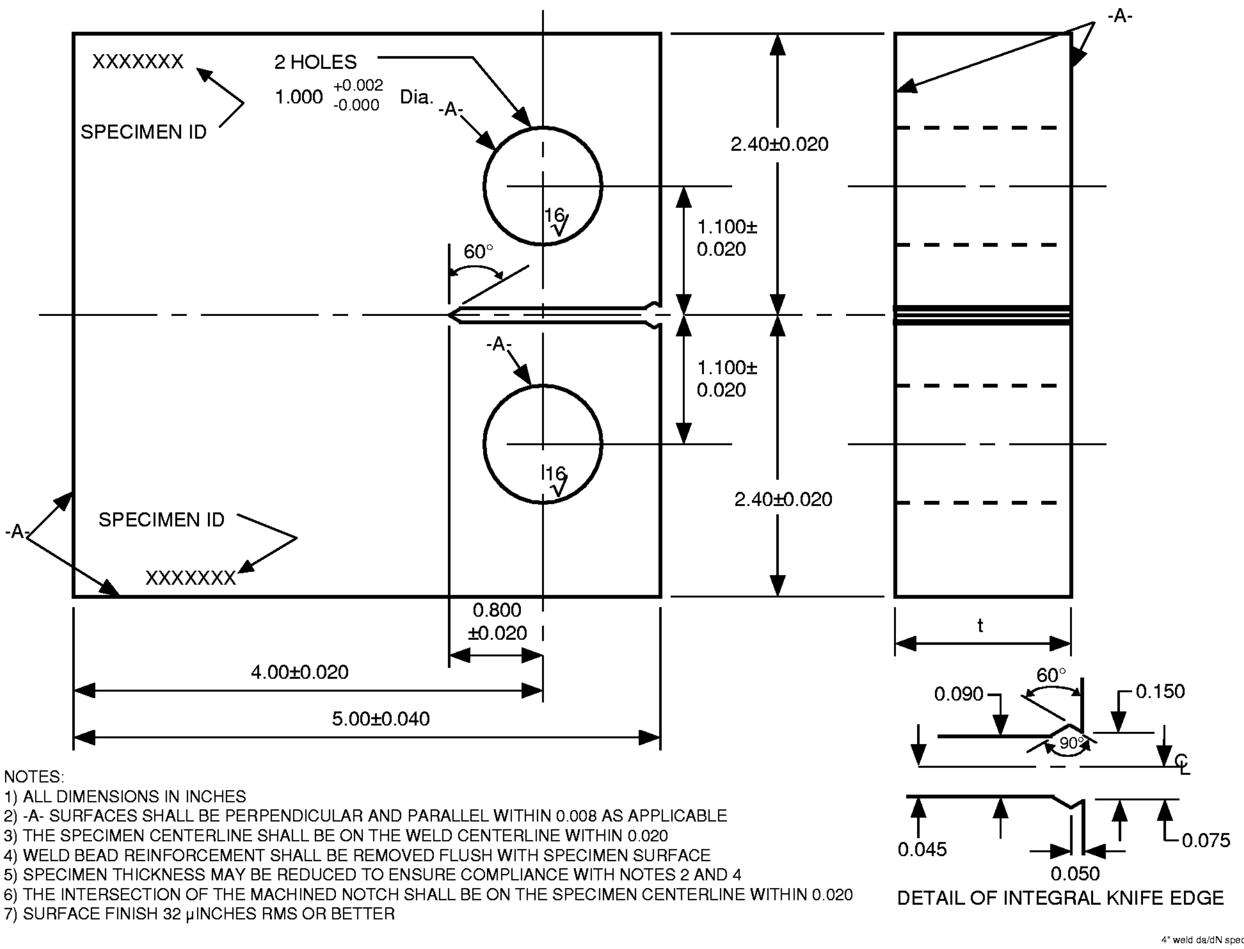


Table 2. Effect of Temperature on the Fatigue Crack Growth Rate in 0.25 in. AL-Li 2195-T8 Plate in the L-T Orientation

Fatigue Crack Growth Rates at Defined Levels of Stress Intensity Factor Taken From K-Increasing Curve

Data Associated with Figure 2 Indicating Effect of Temperature

Material: Aluminum 2195
Condition: T8
Environment: Lab Air
Stress Ratio (R): 0.1

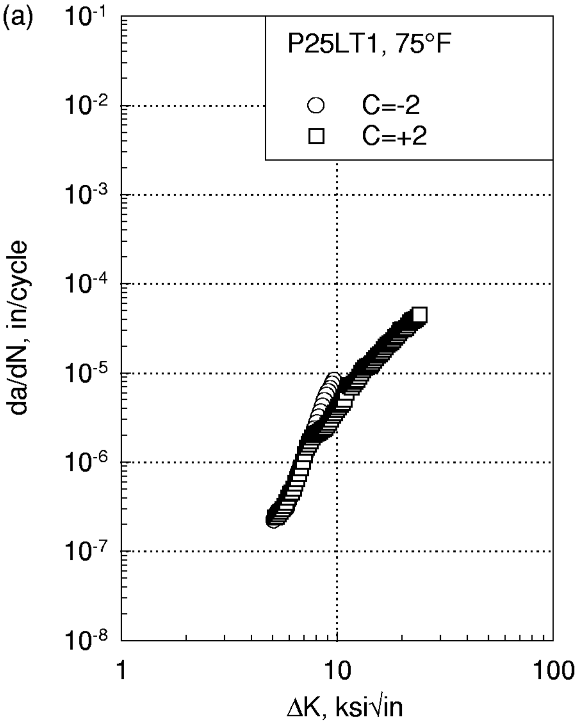
	ΔK (ksi√in)	da/dN (10^{-6} in/cycle) (a) P25LT1	(c) P25LT2	(d) P25LT3
		75°F	200°F	200°F
	5.15	0.24		
ΔK_{min}	5.16		0.24	
	5.15			0.23
	6.00	0.42	0.43	0.46
	7.00	1.09	1.20	1.45
	8.00	2.10	2.24	2.59
	9.00	2.57	3.59	4.31
	10.00	3.91	5.33	5.94
	11.00	5.86	7.00	8.04
	12.00	7.68	9.02	10.50
	13.00	10.19	11.33	13.19
	14.00	12.05	13.63	15.56
	15.00	14.22	15.47	18.53
	16.00	16.87	17.95	21.55
	17.00	20.38	19.82	19.82
	18.00	22.91	22.50	27.64
	19.00	26.54	24.89	31.77
	20.00	30.70	28.20	35.00
	24.07	45.13		
ΔK_{max}	24.09		40.34	
	24.08			52.01

Figure 2. Effect of Temperature on the Fatigue Crack Growth Rate in 0.25 in. AL-Li 2195-T8 Plate in the L-T Orientation

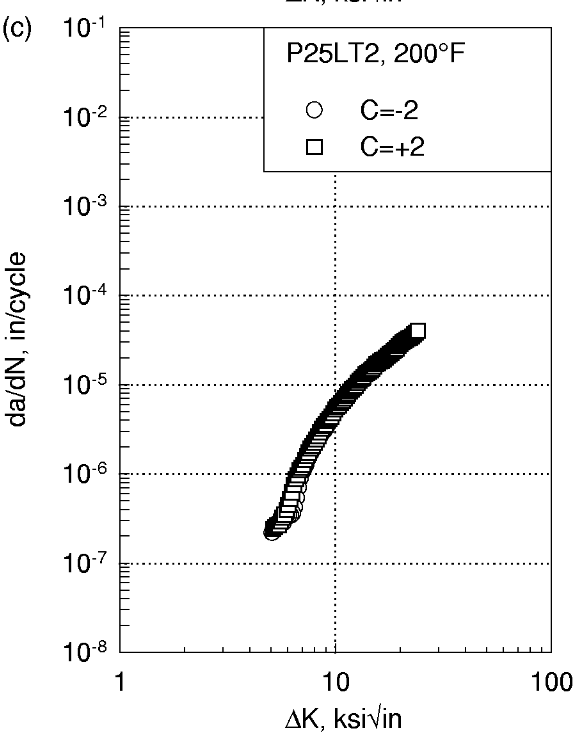
CONDITION/HT: T8
FORM: 0.25 in. thick plate
SPECIMEN TYPE: C(T)
ORIENTATION: L-T
FREQUENCY; 15 HZ
ENVIRONMENT: Lab Air

STRESS RATIO (R): 0.1
SPECIMEN THICKNESS: 0.285-0.286 in.
SPECIMEN WIDTH: 4.002-4.003 in.

(a)



(c)



(d)

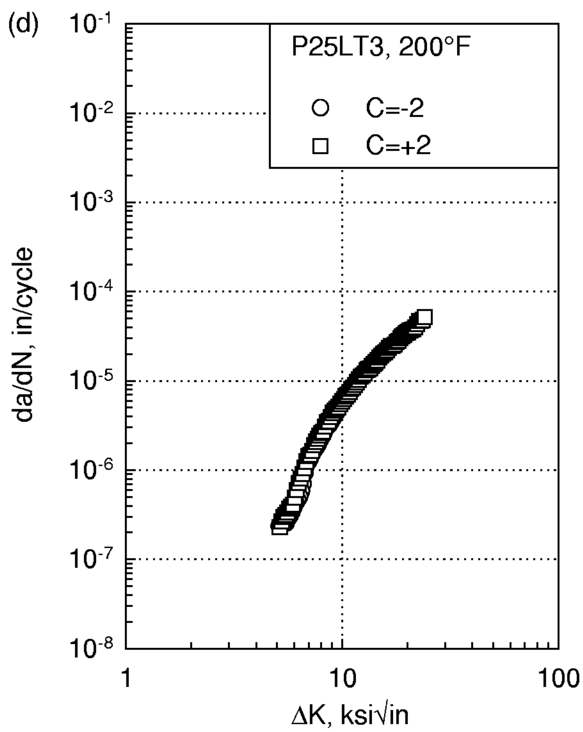


Table 3. Effect of Stress Ratio on the Fatigue Crack Growth Rate in 0.25 in. AL-Li 2195-T8 Plate in the T-L Orientation

Fatigue Crack Growth Rates at Defined Levels of Stress Intensity Factor Taken From K-Increasing Curve

Data Associated with Figure 3 Indicating Effect of Stress Ratio

Material: Aluminum 2195
Condition: T8
Environment: 200°F, Lab Air

	ΔK (ksi√in)	da/dN (10^{-6} in/cycle) (a) P25TL5 R=0.1	(b) P25TL6 R=0.1	(c) P25TL7 R=0.5	(d) P25TL8 R=0.5
	5.07	0.21			
ΔK_{min}	5.06		0.18		
	5.16			3.31	
	5.16				3.78
	6.00	0.26	0.31	1.09	1.36
	7.00	0.51	0.48	2.73	2.69
	8.00	1.75	1.02	4.47	4.40
	9.00	3.03	1.98	6.52	6.48
	10.00	4.51	2.80		
	11.00	5.65	3.97		
	12.00	7.63	5.21		
	13.00	9.94	6.67		
	14.00	12.04	8.18		
	15.00	15.11	10.32		
	16.00				
	17.00				
	18.00				
	19.00				
	20.00				
	15.98	17.37			
ΔK_{max}	15.14		10.66		
	9.99			8.95	
	9.41				7.36

Figure 3. Effect of Stress Ratio on the Fatigue Crack Growth Rate in 0.25 in. AL-Li 2195-T8 Plate in the T-L Orientation

CONDITION/HT: T8
FORM: 0.25 in. thick plate
SPECIMEN TYPE: C(T)
ORIENTATION: T-L
FREQUENCY; 15 HZ
ENVIRONMENT: 200°F, Lab Air
SPECIMEN THICKNESS: 0.270-0.271 in.
SPECIMEN WIDTH: 4.001 in.

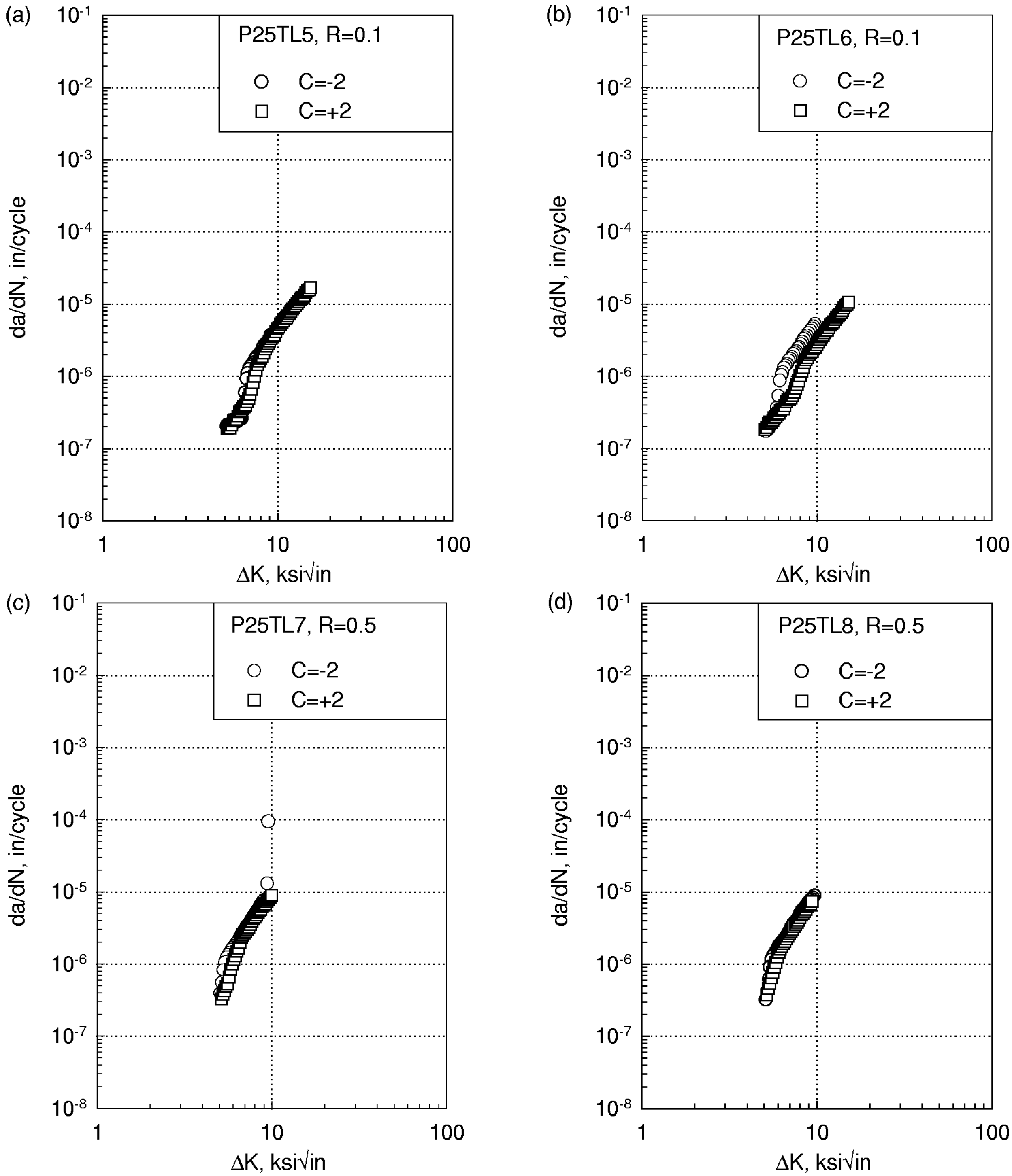


Table 4. Effect of Stress Ratio on the Fatigue Crack Growth Rate in 0.50 in. AL-Li 2195-T8 Plate in the L-T Orientation

Fatigue Crack Growth Rates at Defined Levels of Stress Intensity Factor Taken From K-Increasing Curve

Data Associated with Figure 4 Indicating Effect of Stress Ratio

Material: Aluminum 2195
Condition: T8
Environment: 200°F, Lab Air

	ΔK (ksi√in)	da/dN (10^{-6} in/cycle)		
		(a) P50LT1 R=0.1	(b) P50LT2 R=0.1	(c) P50LT3 R=0.5
	5.48	0.24		
ΔK_{min}	5.16		0.16	
	5.16			0.27
	6.00	0.33	0.25	0.78
	7.00	0.62	0.41	2.16
	8.00	1.82	1.10	3.62
	9.00	3.21	2.21	5.50
	10.00	4.67	3.42	7.30
	11.00	6.41	5.05	9.76
	12.00	8.59	7.30	12.08
	13.00	10.55	8.68	14.91
	14.00	13.38	10.96	18.36
	15.00	15.83	13.31	21.65
	16.00	19.92	17.50	26.65
	17.00	21.23	19.51	32.43
	18.00	24.53	22.21	37.10
	19.00	26.27	24.53	43.88
	20.00	31.95	26.75	51.68
	24.05	44.25		
ΔK_{max}	27.72		67.05	
	21.83			73.13

Figure 4. Effect of Stress Ratio on the Fatigue Crack Growth Rate in 0.50 in. AL-Li 2195-T8 Plate in the L-T Orientation

CONDITION/HT: T8
FORM: 0.50 in. thick plate
SPECIMEN TYPE: C(T)
ORIENTATION: L-T
FREQUENCY; 15 HZ
ENVIRONMENT: 200°F, Lab Air

SPECIMEN THICKNESS: 0.494-0.497 in.
SPECIMEN WIDTH: 3.999-4.003 in.

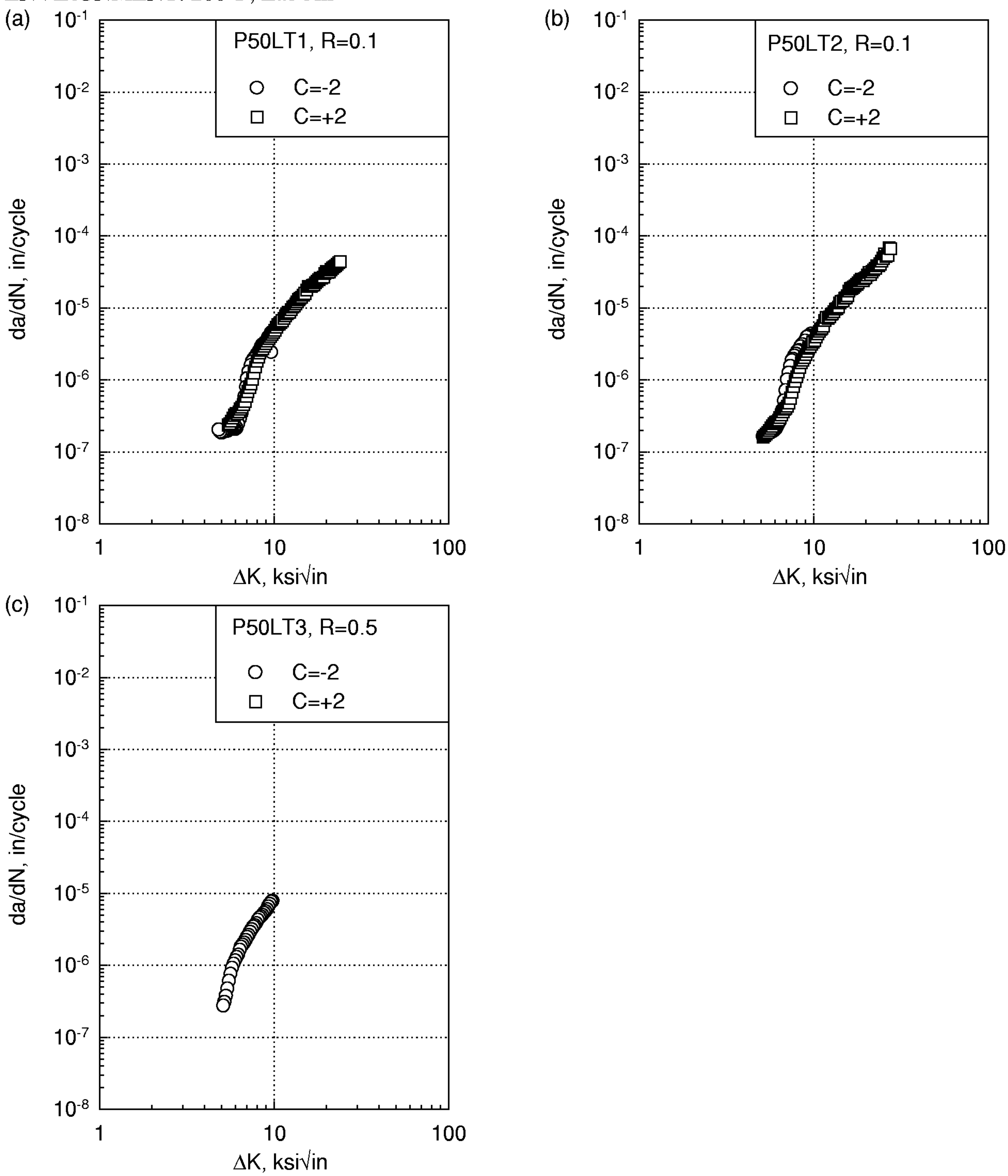


Table 5. Effect of Stress Ratio on the Fatigue Crack Growth Rate in 0.50 in. AL-Li 2195-T8 Plate in the T-L Orientation

Fatigue Crack Growth Rates at Defined Levels of Stress Intensity Factor Taken From K-Increasing Curve

Data Associated with Figure 5 Indicating Effect of Stress Ratio

Material: Aluminum 2195
Condition: T8
Environment: 200°F, Lab Air

	ΔK (ksi√in)	da/dN (10^{-6} in/cycle) (a) P50TL1 R=0.1	(b) P50TL2 R=0.1	(c) P50TL3 R=0.5
	5.16	0.16		
ΔK_{min}	5.16		0.16	
	5.16			0.18
	6.00	0.25	0.25	0.28
	7.00	0.44	0.36	1.04
	8.00	0.97	0.56	2.31
	9.00	2.31	1.32	4.32
	10.00	3.79	2.42	6.37
	11.00	5.48	3.69	8.82
	12.00	7.42	5.64	11.97
	13.00	9.63	7.73	14.92
	14.00	12.13	9.79	18.57
	15.00	15.55	12.38	24.33
	16.00	19.85	17.21	36.52
	17.00	20.88	18.10	35.98
	18.00	25.83	20.78	46.84
	19.00	30.25	23.20	58.68
	20.00	33.54	28.06	70.30
	26.58	74.44		
ΔK_{max}	27.25		65.94	
	24.16			216.99

Figure 5. Effect of Stress Ratio on the Fatigue Crack Growth Rate in 0.50 in. AL-Li 2195-T8 Plate in the T-L Orientation

CONDITION/HT: T8
FORM: 0.50 in. thick plate
SPECIMEN TYPE: C(T)
ORIENTATION: T-L
FREQUENCY; 15 HZ
ENVIRONMENT: 200°F, Lab Air

SPECIMEN THICKNESS: 0.493-0.494 in.
SPECIMEN WIDTH: 3.999-4.003 in.

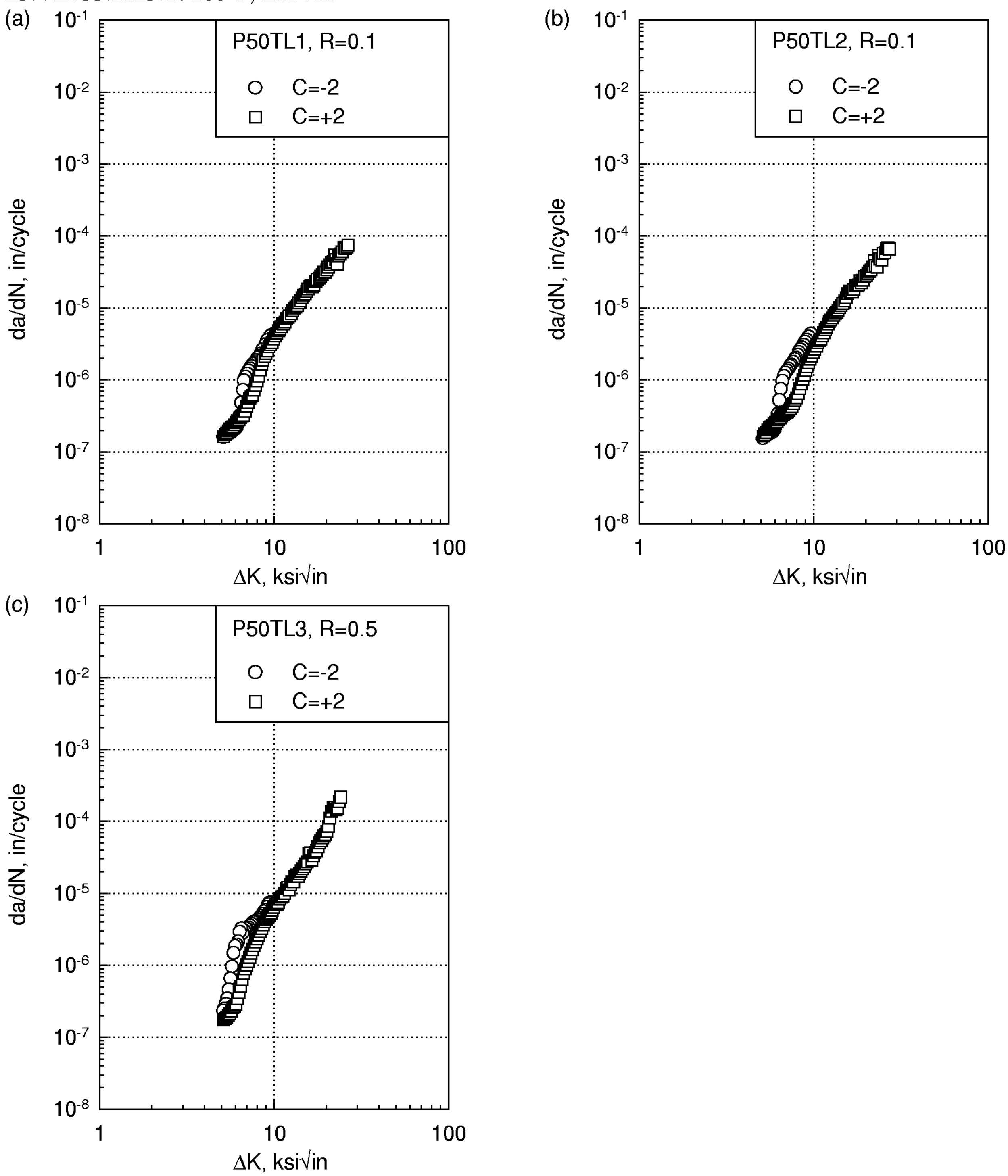


Table 6. Effect of Temperature on the Fatigue Crack Growth Rate in 0.50 in. AL-Li 2195-T8 Plate in the L-T Orientation

Fatigue Crack Growth Rates at Defined Levels of Stress Intensity Factor Taken From K-Increasing Curve

Data Associated with Figure 6 Indicating Effect of Temperature

Material: Aluminum 2195
Condition: T8
Environment: Lab Air
Stress Ratio (R): 0.5

	ΔK (ksi√in)	da/dN (10^{-6} in/cycle) (a) P50LT3 200°F	(b) P50LT4 75°F
ΔK_{min}	5.16	0.27	
	5.16		0.55
	6.00	0.78	1.26
	7.00	2.16	2.23
	8.00	3.62	3.47
	9.00	5.50	4.92
	10.00	7.30	6.79
	11.00	9.76	8.53
	12.00	12.08	10.73
	13.00	14.91	13.01
	14.00	18.36	16.37
	15.00	21.65	20.04
	16.00	26.65	24.54
	17.00	32.43	27.57
	18.00	37.10	33.52
	19.00	43.88	42.95
	20.00	51.68	55.74
ΔK_{max}	21.83	73.13	
	24.65		135.39

Figure 6. Effect of Temperature on the Fatigue Crack Growth Rate in 0.50 in. AL-Li 2195-T8 Plate in the L-T Orientation

CONDITION/HT: T8
FORM: 0.50 in. thick plate
SPECIMEN TYPE: C(T)
ORIENTATION: L-T
FREQUENCY; 15 HZ
ENVIRONMENT: Lab Air

STRESS RATIO (R): 0.5
SPECIMEN THICKNESS: 0.497 in.
SPECIMEN WIDTH: 4.002-4.003 in.

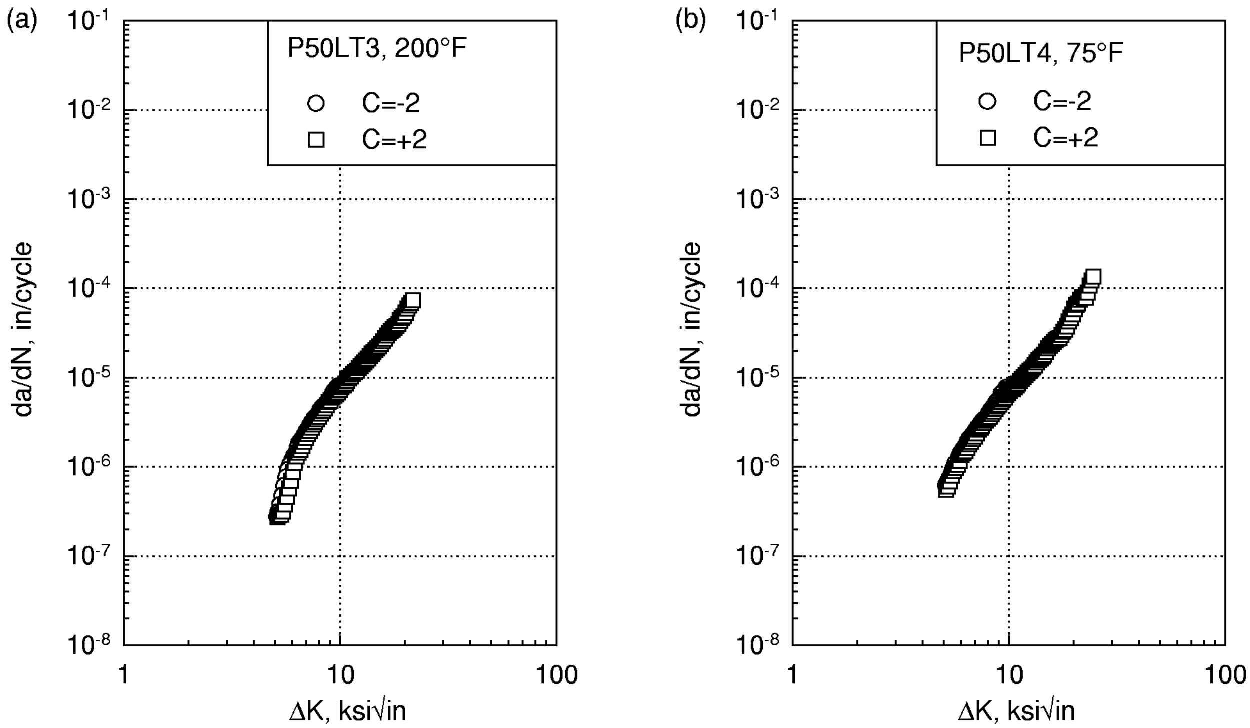


Table 7. Effect of Temperature on the Fatigue Crack Growth Rate in 0.50 in. AL-Li 2195-T8 Plate in the T-L Orientation

Fatigue Crack Growth Rates at Defined Levels of Stress Intensity Factor Taken From K-Increasing Curve

Data Associated with Figure 7 Indicating Effect of Temperature

Material: Aluminum 2195
Condition: T8
Environment: Lab Air
Stress Ratio (R): 0.5

	ΔK (ksi√in)	da/dN (10^{-6} in/cycle) (a) P50TL3 200°F	(b) P50TL4 75°F
ΔK_{min}	5.16	0.18	
	5.16		0.41
	6.00	0.28	0.84
	7.00	1.04	2.46
	8.00	2.31	3.87
	9.00	4.32	5.30
	10.00	6.37	7.09
	11.00	8.82	9.00
	12.00	11.97	11.74
	13.00	14.92	14.90
	14.00	18.57	19.09
	15.00	24.33	24.07
	16.00	36.52	30.50
	17.00	35.98	36.06
	18.00	46.84	42.99
	19.00	58.68	57.97
	20.00	70.30	71.04
ΔK_{max}	24.16	216.99	
	24.19		170.27

Figure 7. Effect of Temperature on the Fatigue Crack Growth Rate in 0.50 in. AL-Li 2195-T8 Plate in the T-L Orientation

CONDITION/HT: T8
FORM: 0.50 in. thick plate
SPECIMEN TYPE: C(T)
ORIENTATION: T-L
FREQUENCY; 15 HZ
ENVIRONMENT: Lab Air

STRESS RATIO (R): 0.5
SPECIMEN THICKNESS: 0.494-0.498 in.
SPECIMEN WIDTH: 3.999-4.003 in.

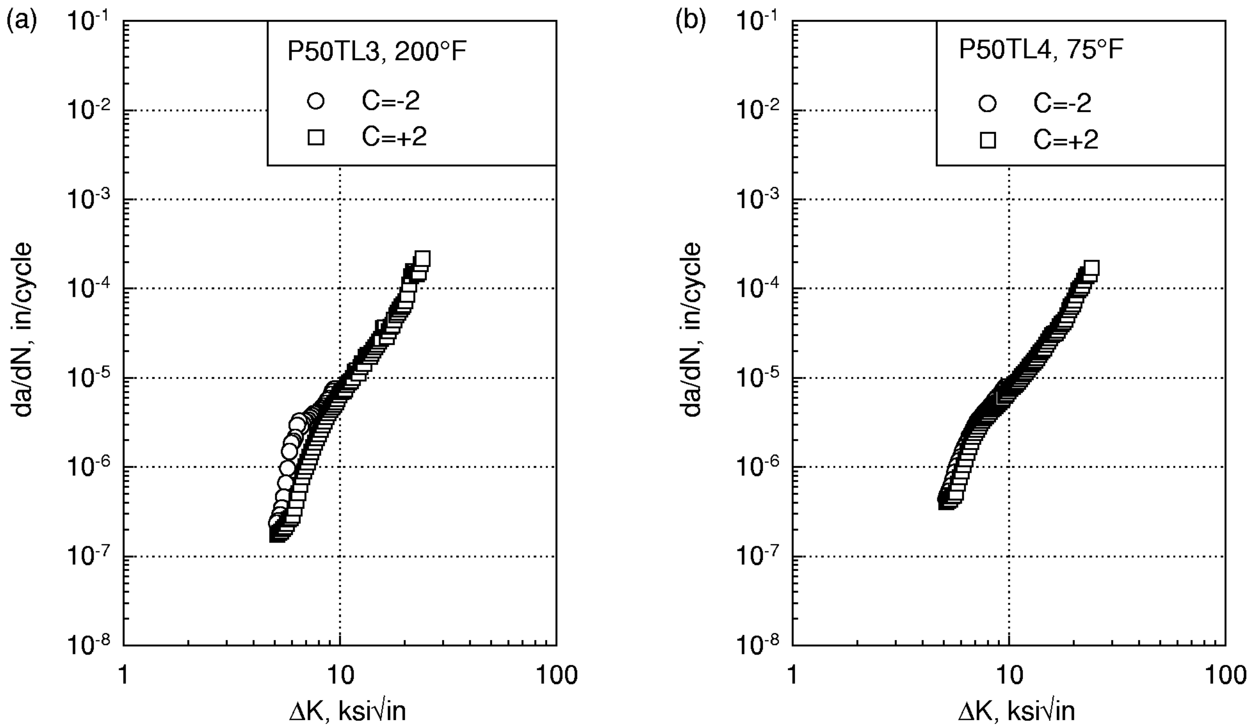


Table 8. Effect of Thickness on the Fatigue Crack Growth Rate in AL-Li 2195-T8 Plate in the L-T Orientation

Fatigue Crack Growth Rates at Defined Levels of Stress Intensity Factor Taken From K-Increasing Curve

Data Associated with Figure 8 Indicating Effect of Thickness

Material: Aluminum 2195
Condition: T8
Orientation: L-T
Environment: 200°F, Lab Air
Stress Ratio (R): 0.1

	ΔK (ksi√in)	da/dN (10^{-6} in/cycle) (a) P25LT2 0.25 in.	(b) P25LT3 0.25 in.	(c) P50LT1 0.50 in.	(d) P50LT2 0.50 in.
	5.16	0.24			
ΔK_{min}	5.15		0.23		
	5.48			0.24	
	5.16				0.16
	6.00	0.43	0.46	0.33	0.25
	7.00	1.20	1.45	0.62	0.41
	8.00	2.24	2.59	1.82	1.10
	9.00	3.59	4.31	3.21	2.21
	10.00	5.33	5.94	4.67	3.42
	11.00	7.00	8.04	6.41	5.05
	12.00	9.02	10.50	8.59	7.30
	13.00	11.33	13.19	10.55	8.68
	14.00	13.63	15.56	13.38	10.96
	15.00	15.47	18.53	15.83	13.31
	16.00	17.95	21.55	19.92	17.50
	17.00	19.82	19.82	21.23	19.51
	18.00	22.50	27.64	24.53	22.21
	19.00	24.89	31.77	26.27	24.53
	20.00	28.20	35.00	31.95	26.75
	24.09	40.34			
ΔK_{max}	24.08		52.01		
	24.05			44.25	
	27.72				67.05

Figure 8. Effect of Thickness on the Fatigue Crack Growth Rate in AL-Li 2195-T8 Plate in the L-T Orientation

CONDITION/HT: T8
FORM: 0.25 in. and 0.50 in. thick plate
SPECIMEN TYPE: C(T)
ORIENTATION: L-T
FREQUENCY; 15 HZ
ENVIRONMENT: 200°F, Lab Air

STRESS RATIO (R): 0.5
SPECIMEN THICKNESS: 0.286 in., 0.494-0.496 in.
SPECIMEN WIDTH: 4.002-4.003 in., 3.999-4.003 in.

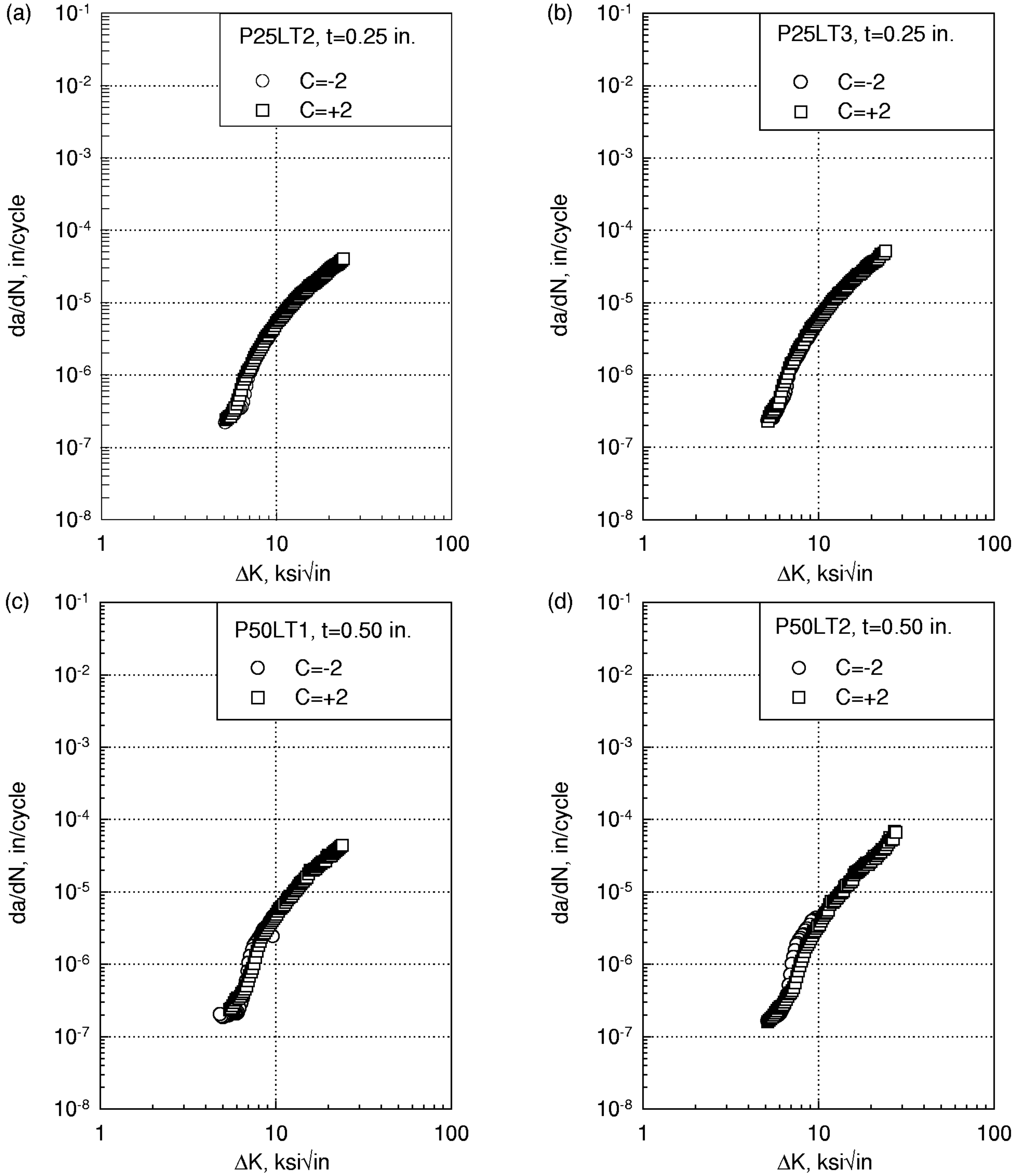


Table 9. Effect of Thickness on the Fatigue Crack Growth Rate in AL-Li 2195-T8 Plate in the T-L Orientation

Fatigue Crack Growth Rates at Defined Levels of Stress Intensity Factor Taken From K-Increasing Curve

Data Associated with Figure 9 Indicating Effect of Thickness

Material: Aluminum 2195
Condition: T8
Orientation: T-L
Environment: 200°F, Lab Air
Stress Ratio (R): 0.1

	ΔK (ksi√in)	da/dN (10^{-6} in/cycle) (a) P25TL5 0.25 in.	(b) P25TL6 0.25 in.	(c) P50TL1 0.50 in.	(d) P50TL2 0.50 in.
	5.07	0.21			
ΔK_{min}	5.06		0.18		
	5.16			0.16	
	5.16				0.16
	6.00	0.26	0.31	0.25	0.25
	7.00	0.51	0.48	0.44	0.36
	8.00	1.75	1.02	0.97	0.56
	9.00	3.03	1.98	2.31	1.32
	10.00	4.51	2.80	3.79	2.42
	11.00	5.65	3.97	5.48	3.69
	12.00	7.63	5.21	7.42	5.64
	13.00	9.94	6.67	9.63	7.73
	14.00	12.04	8.18	12.13	9.79
	15.00	15.11	10.32	15.55	12.38
	16.00			19.85	17.21
	17.00			20.88	18.10
	18.00			25.83	20.78
	19.00			30.25	23.20
	20.00			33.54	28.06
	15.98	17.37			
ΔK_{max}	15.14		10.66		
	26.58			74.44	
	27.25				65.94

Figure 9. Effect of Thickness on the Fatigue Crack Growth Rate in AL-Li 2195-T8 Plate in the T-L Orientation

CONDITION/HT: T8
FORM: 0.25 in. and 0.50 in. thick plate
SPECIMEN TYPE: C(T)
ORIENTATION: T-L
FREQUENCY; 15 HZ
ENVIRONMENT: 200°F, Lab Air

STRESS RATIO (R): 0.1
SPECIMEN THICKNESS: 0.270-0.271 in., 0.493-0.494 in.
SPECIMEN WIDTH: 4.001 in., 4.003 in.

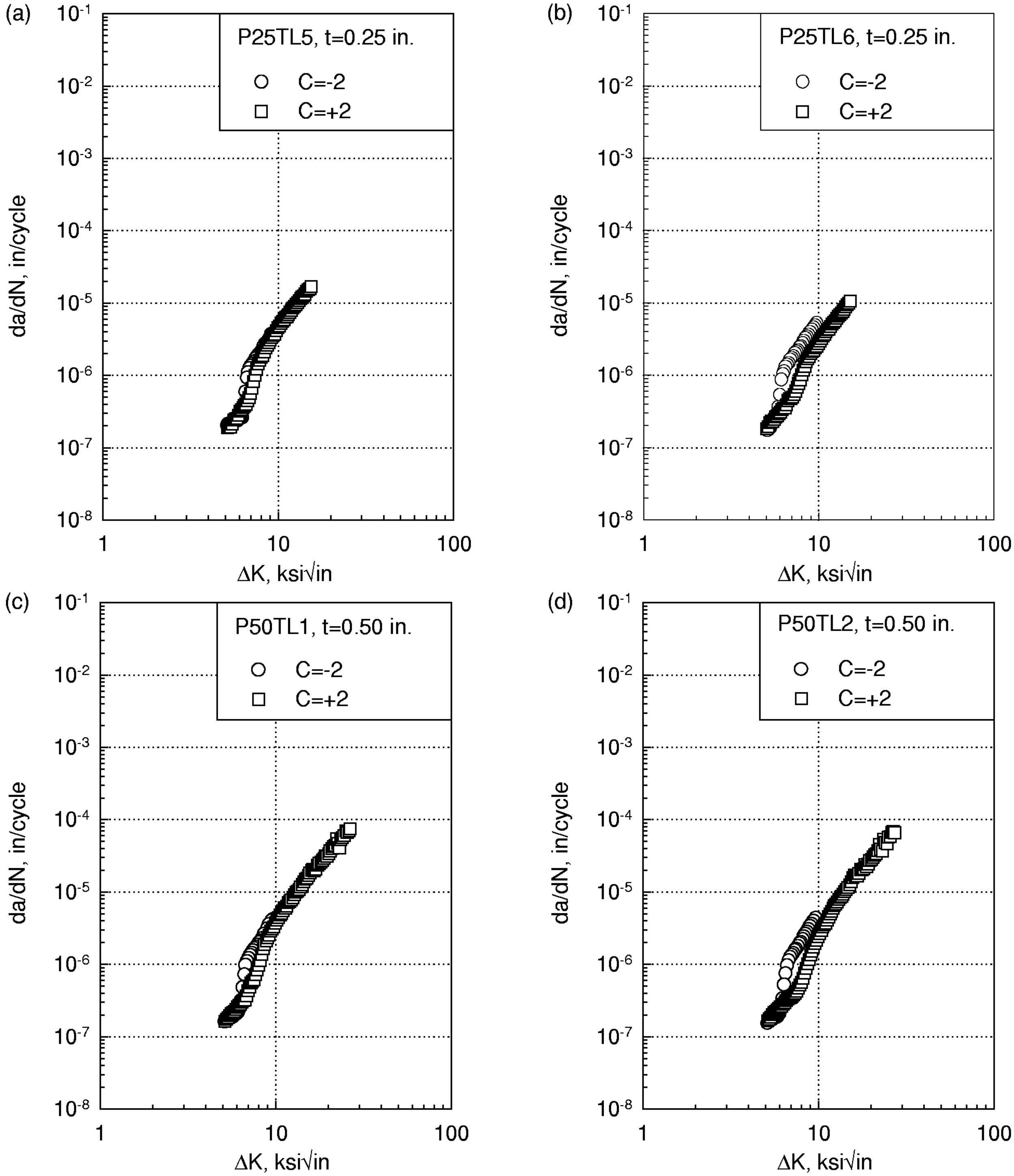


Table 10. Effect of Stress Ratio on the Fatigue Crack Growth Rate in 0.25 in AL-Li 2195-T8 Variable Polarity Plasma Arc Welds in the L-T Orientation

Fatigue Crack Growth Rates at Defined Levels of Stress Intensity Factor Taken From K-Increasing Curve

Data Associated with Figure 10 Indicating Effect of Stress Ratio and Variable Polarity Plasma Arc Welding

Material: Aluminum 2195
Condition: T8, Variable Polarity Plasma Arc Welded
Environment: 75°F, Lab Air

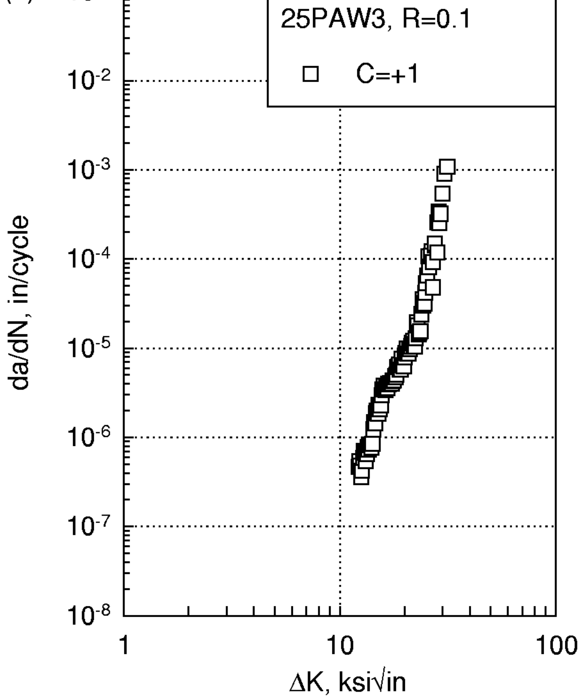
	ΔK (ksi√in)	da/dN (10^{-6} in/cycle) (a) 25PAW3 R=0.1	(c) 25PAW6 R=0.5	(d) 25PAW7 R=0.5
	12.20	0.47		
ΔK_{min}	9.89		1.12	
	8.63			0.13
	6.00			
	7.00			
	8.00			
	9.00			0.58
	10.00		1.62	0.90
	11.00		3.23	3.58
	12.00		6.28	7.98
	13.00	0.70	11.99	13.04
	14.00	0.78	56.38	37.95
	15.00	1.90	147.1	64.92
	16.00	3.69	326.4	129.0
	17.00	4.02	138.1	220.7
	18.00	4.84	333.4	430.2
	19.00	5.78	491.3	580.4
	20.00	8.18	971.9	1029.7
	31.47	1075.3		
ΔK_{max}	20.28		1149.2	
	20.06			1055.7

Figure 10. Effect of Stress Ratio on the Fatigue Crack Growth Rate in 0.25 in AL-Li 2195-T8 Variable Polarity Plasma Arc Welds in the L-T Orientation

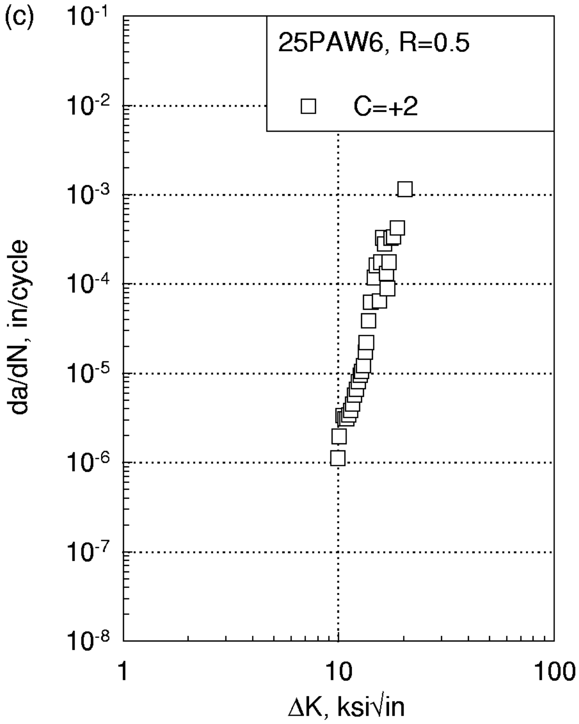
CONDITION/HT: T8, WELDED
FORM: PAW 0.25 in. thick plate
SPECIMEN TYPE: C(T)
ORIENTATION: L-T
FREQUENCY; 15 HZ
ENVIRONMENT: 75°F, Lab Air

SPECIMEN THICKNESS: 0.217-0.219 in.
SPECIMEN WIDTH: 4.000-4.002 in.

(a)



(c)



(d)

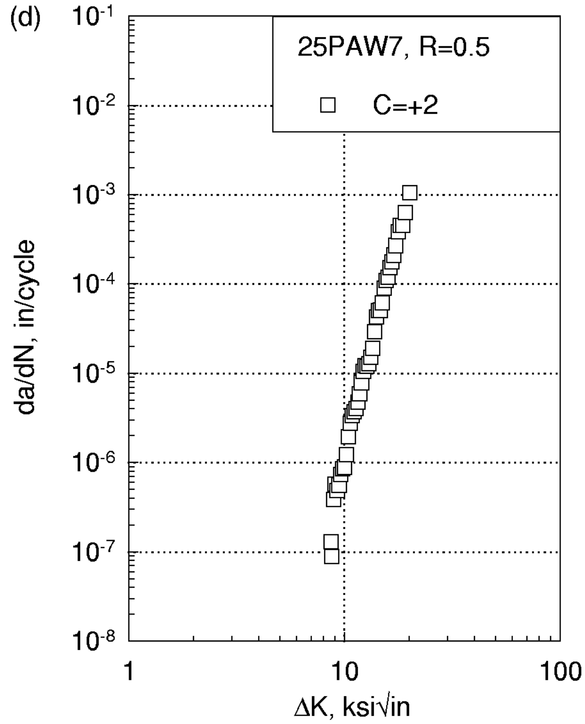


Table 11. Fatigue Crack Growth Rate in 0.25 in. Al-Li 2195-T8 Friction Stir Welds in the L-T Orientation at Ambient Temperature

Fatigue Crack Growth Rates at Defined Levels of Stress Intensity Factor Taken From K-Increasing Curve

Data Associated with Figure 11 Indicating Effect of Friction Stir Welding

Material: Aluminum 2195
Condition: T8, Friction Stir Welded
Environment: 75°F, Lab Air

	ΔK (ksi√in)	da/dN (10^{-6} in/cycle) (a) 25FSW2 R=0.5	(b) 25FSW5 R=0.5
ΔK_{min}	6.89	3.55	
	7.89		1.13
	6.00		
	7.00	1.38	
	8.00	1.31	
	9.00	3.11	7.16
	10.00	5.08	7.18
	11.00	7.15	8.24
	12.00	11.49	13.50
	13.00	11.82	11.00
	14.00	13.21	12.69
	15.00	14.87	14.57
	16.00	17.54	17.25
	17.00	20.52	19.83
	18.00	23.56	23.65
	19.00	27.26	27.34
	20.00	31.19	28.02
ΔK_{max}	20.02	31.38	
	21.93		29.78

Figure 11. Fatigue Crack Growth Rate in 0.25 in. Al-Li 2195-T8 Friction Stir Welds in the L-T Orientation at Ambient Temperature

CONDITION/HT: T8, WELDED
FORM: FSW 0.25 in. thick plate
SPECIMEN TYPE: C(T)
ORIENTATION: L-T
FREQUENCY; 15 HZ
ENVIRONMENT: 75°F, Lab Air

STRESS RATIO (R): 0.5
SPECIMEN THICKNESS: 0.209 - 0.213 in.
SPECIMEN WIDTH: 3.999 - 4.001 in.

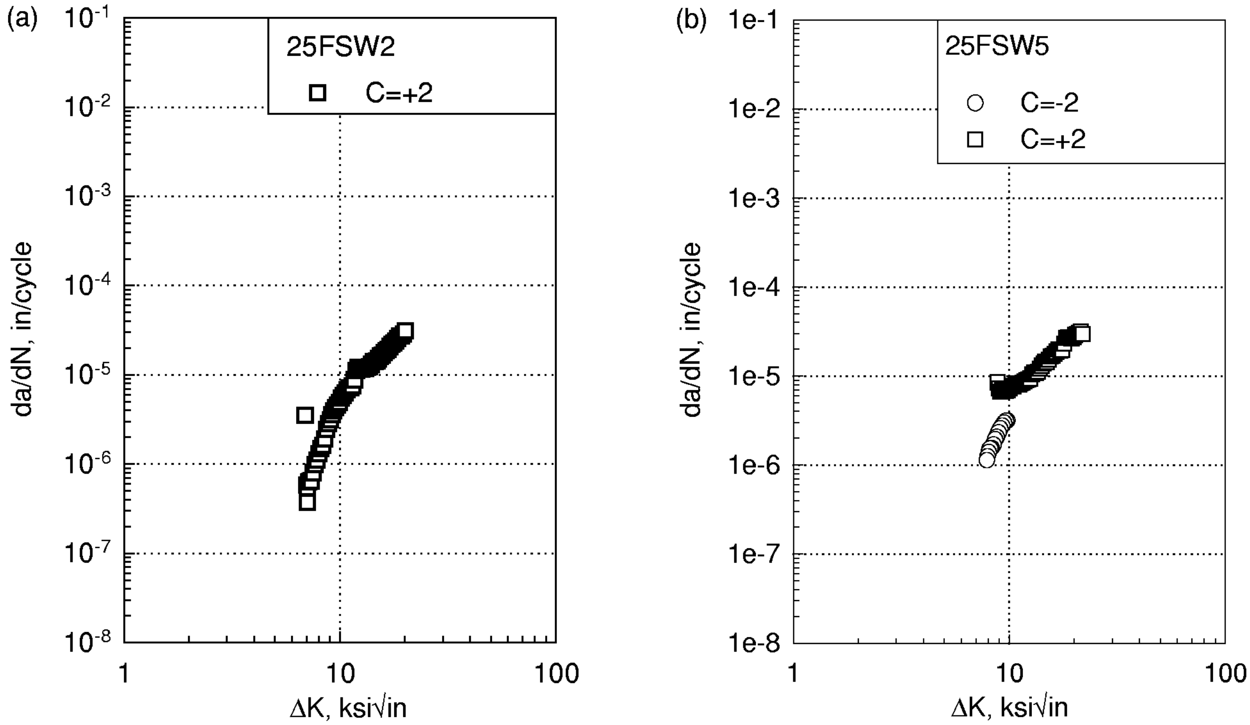


Table 12. Fatigue Crack Growth Rate in 0.25 in. Al-Li 2195-T8 Friction Stir Welds in the L-T Orientation at Cryogenic Temperature

Fatigue Crack Growth Rates at Defined Levels of Stress Intensity Factor Taken From K-Increasing Curve

Data Associated with Figure 12 Indicating Effect of Friction Stir Welding

Material: Aluminum 2195
Condition: T8, Friction Stir Welded
Environment: -320°F, LN_2

	ΔK (ksi√in)	da/dN (10^{-6} in/cycle) (a) 25FSW6 R=0.5
ΔK_{min}	11.00	11.19
	6.00	
	7.00	
	8.00	
	9.00	
	10.00	
	11.00	11.19
	12.00	15.59
	13.00	19.41
	14.00	25.53
	15.00	31.93
	16.00	40.14
	17.00	46.96
	18.00	58.96
	19.00	69.93
	20.00	89.73
ΔK_{max}	28.22	279.48

Figure 12. Fatigue Crack Growth Rate in 0.25 in. Al-Li 2195-T8 Friction Stir Welds in the L-T Orientation at Cryogenic Temperature

CONDITION/HT: T8, WELDED
FORM: FSW 0.25 in. thick plate
SPECIMEN TYPE: C(T)
ORIENTATION: L-T
FREQUENCY; 15 HZ
ENVIRONMENT: -320°F, LN_2

STRESS RATIO (R): 0.5
SPECIMEN THICKNESS: 0.209 in.
SPECIMEN WIDTH: 3.999 in.

(a)

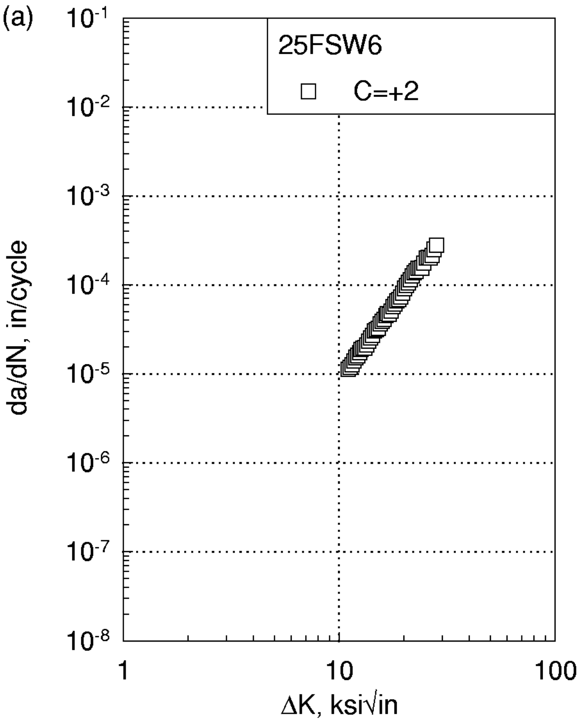


Table 13. Fatigue Crack Growth Rate in 0.50 in. Al-Li 2195-T8 Friction Stir Welds in the L-T Orientation at Elevated Temperature

Fatigue Crack Growth Rates at Defined Levels of Stress Intensity Factor Taken From K-Increasing Curve

Data Associated with Figure 13 Indicating Effect of Friction Stir Welding

Material: Aluminum 2195
Condition: T8, Friction Stir Welded
Environment: 200°F, Lab Air

	ΔK (ksi√in)	da/dN (10^{-6} in/cycle) (a) 50FSW1 R=0.5	(b) 50FSW4 R=0.5
ΔK_{min}	5.17	1.69	
	5.17		1.44
	6.00	2.48	2.37
	7.00	4.21	4.30
	8.00	6.55	6.50
	9.00	9.06	9.22
	10.00	12.13	12.29
	11.00	15.28	15.75
	12.00	18.91	18.93
	13.00	22.78	23.19
	14.00	26.64	26.98
	15.00	30.90	31.58
	16.00	34.62	
	17.00		
	18.00		
	19.00		
	20.00		
ΔK_{max}	16.14	35.23	
	15.86		35.84

Figure 13. Fatigue Crack Growth Rate in 0.50 in. Al-Li 2195-T8 Friction Stir Welds in the L-T Orientation at Elevated Temperature

CONDITION/HT: T8, WELDED
FORM: FSW 0.50 in. thick plate
SPECIMEN TYPE: C(T)
ORIENTATION: L-T
FREQUENCY; 15 HZ
ENVIRONMENT: 200°F, Lab Air
STRESS RATIO (R): 0.5
SPECIMEN THICKNESS: 0.471-0.476 in.
SPECIMEN WIDTH: 4.000 in.

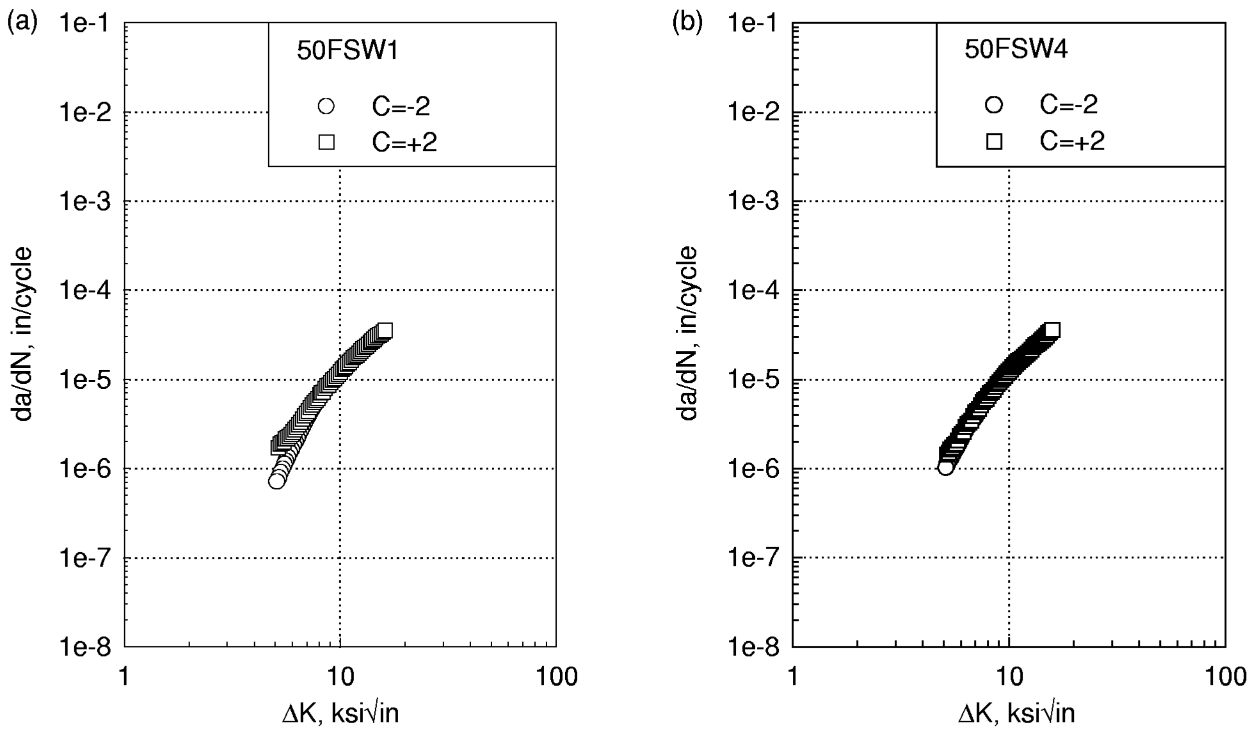


Table 14. Fatigue Crack Growth Rate in 0.50 in. Al-Li 2195-T8 Friction Stir Welds in the L-T Orientation at Ambient Temperature

Fatigue Crack Growth Rates at Defined Levels of Stress Intensity Factor Taken From K-Increasing Curve

Data Associated with Figure 14 Indicating Effect of Friction Stir Welding

Material: Aluminum 2195
Condition: T8, Friction Stir Welded
Environment: 75°F, Lab Air

	ΔK (ksi√in)	da/dN (10^{-6} in/cycle) (a) 50FSW2 R=0.5	(b) 50FSW5 R=0.5
ΔK_{min}	7.78	1.06	
	6.72		3.06
	6.00		
	7.00		1.24
	8.00	1.43	6.35
	9.00	12.46	7.62
	10.00	6.07	10.53
	11.00	6.46	14.72
	12.00	9.44	16.70
	13.00	14.97	20.67
	14.00	12.81	23.14
	15.00	16.90	23.79
	16.00	24.56	22.72
	17.00	31.60	23.43
	18.00	36.27	31.52
	19.00	40.91	48.85
	20.00		
ΔK_{max}	19.67	42.12	
	19.69		49.15

Figure 14. Fatigue Crack Growth Rate in 0.50 in. Al-Li 2195-T8 Friction Stir Welds in the L-T Orientation at Ambient Temperature

CONDITION/HT: T8, WELDED
FORM: FSW 0.50 in. thick plate
SPECIMEN TYPE: C(T)
ORIENTATION: L-T
FREQUENCY; 15 HZ
ENVIRONMENT: 75°F, Lab Air

STRESS RATIO (R): 0.5
SPECIMEN THICKNESS: 0.477-0.478 in.
SPECIMEN WIDTH: 4.000-4.001 in.

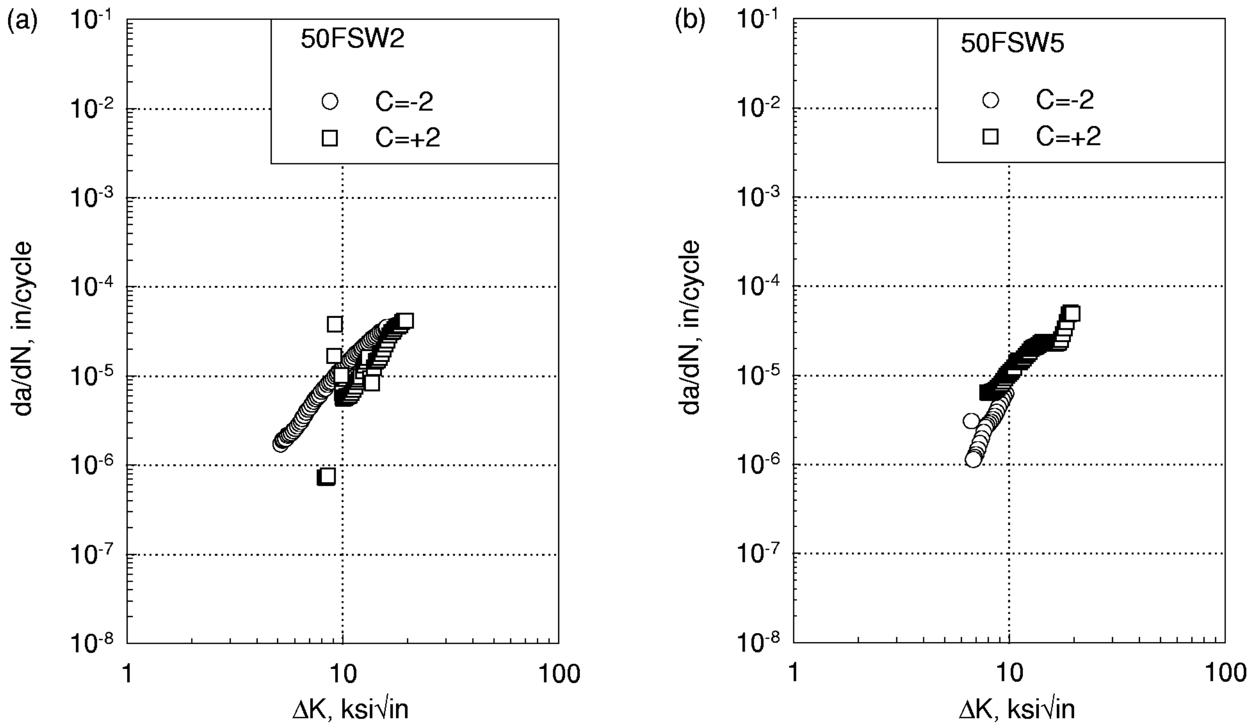


Table 15. Fatigue Crack Growth Rate in 0.50 in. Al-Li 2195-T8 Friction Stir Welds in the L-T Orientation at Cryogenic Temperature

Fatigue Crack Growth Rates at Defined Levels of Stress Intensity Factor Taken From K-Increasing Curve

Data Associated with Figure 15 Indicating Effect of Friction Stir Welding

Material: Aluminum 2195
Condition: T8, Friction Stir Welded
Environment: -320°F, LN_2

	ΔK (ksi√in)	da/dN (10^{-6} in/cycle) (a) 50FSW3 R=0.5	(b) 50FSW6 R=0.5
ΔK_{min}	10.33	6.85	1.71
	9.46		
	6.00		
	7.00		
	8.00		
	9.00		
	10.00		13.46
	11.00	9.34	11.19
	12.00	13.50	15.30
	13.00	19.51	21.41
	14.00	26.91	29.33
	15.00	36.17	40.24
	16.00	47.54	50.50
	17.00	59.28	63.07
	18.00	70.93	78.45
	19.00	80.17	89.66
	20.00	92.07	103.90
ΔK_{max}	21.22	113.03	
	21.53		141.77

Figure 15. Fatigue Crack Growth Rate in 0.50 in. Al-Li 2195-T8 Friction Stir Welds in the L-T Orientation at Cryogenic Temperature

CONDITION/HT: T8, WELDED
FORM: FSW 0.50 in. thick plate
SPECIMEN TYPE: C(T)
ORIENTATION: L-T
FREQUENCY; 15 HZ
ENVIRONMENT: -320°F, LN_2
STRESS RATIO (R): 0.5
SPECIMEN THICKNESS: 0.477-0.478 in.
SPECIMEN WIDTH: 4.000 in.

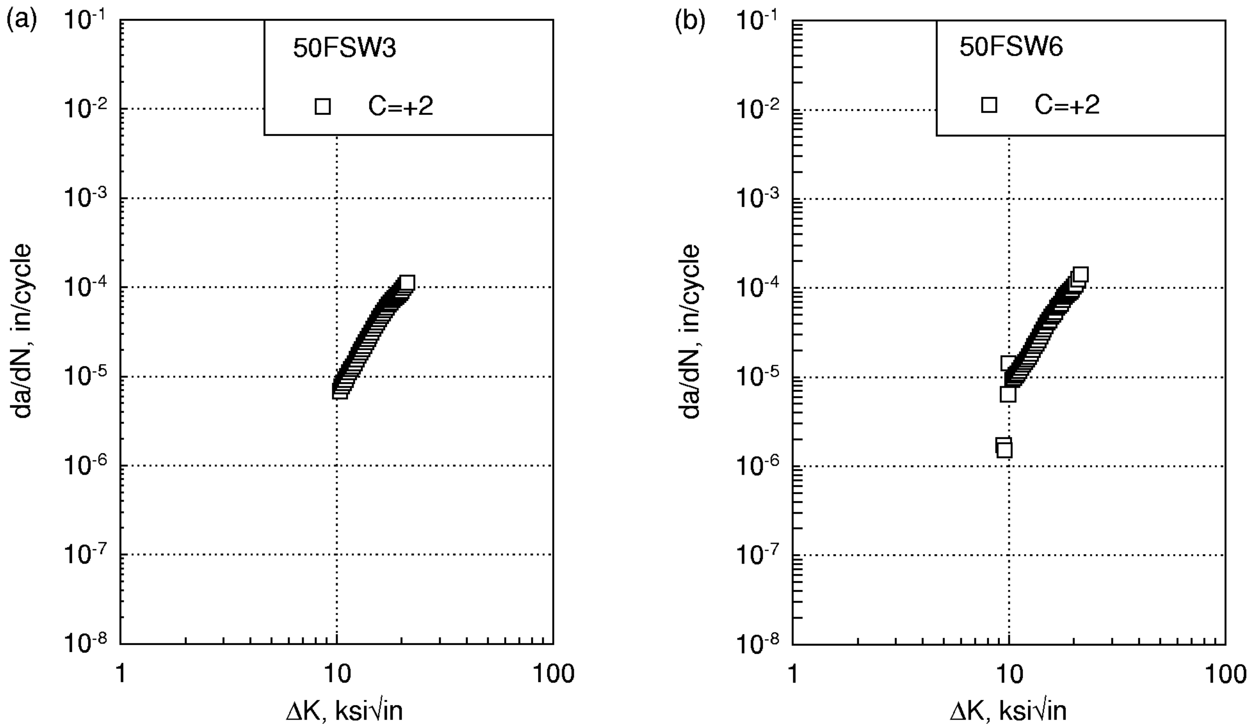


Table 16. Fatigue Crack Growth Rate, da/dN (10^{-6} in/cycle), for Al-Li 2195-T8 Plate and Weldments

Condition	t, in.	Orientation	R	Test Temp., °F	ΔK, ksi√in			Specimen ID
					6	10	20	
2195-T8 Plate	0.25	L-T	0.1	75	0.42	3.91	30.70	P25LT1
				200	0.43	5.33	28.20	P25LT2
					0.46	5.94	35.00	P25LT3
		T-L	0.1	200	0.26	4.51	N/A	P25TL5
					0.31	2.80	N/A	P25TL6
			0.5	200	1.09	N/A	N/A	P25TL7
					1.36	N/A	N/A	P25TL8
	0.50	L-T	0.1	200	0.33	4.67	31.95	P50LT1
					0.25	3.42	26.75	P50LT2
			0.5	75	1.26	6.79	55.74	P50LT4
				200	0.78	7.30	51.98	P50LT3
		T-L	0.1	200	0.25	3.79	33.54	P50TL1
					0.25	2.42	28.06	P50TL2
			0.5	75	0.84	7.09	71.04	P50TL4
				200	0.28	6.37	70.30	P50TL3
VPPAW	0.25	L-T	0.1	75	N/A	N/A	8.18	25PAW3
			0.5	75	N/A	1.62	971.9	25PAW6
					N/A	0.90	1029.7	25PAW7
FSW	0.25	L-T	0.5	-320	N/A	N/A	89.73	25FSW6
				75	N/A	5.08	31.19	25FSW2
					N/A	7.18	28.02	25FSW5
	0.50	L-T	0.5	-320	N/A	N/A	92.07	50FSW3
					N/A	13.46	103.9	50FSW6
				75	N/A	6.04	N/A	50FSW2
					N/A	10.53	N/A	50FSW5
				200	2.48	12.13	N/A	50FSW1
					2.37	12.29	N/A	50FSW4

Table 17. Summary of Fatigue Crack Growth Rate, da/dN (10^{-6} in/cycle), for Al-Li 2195-T8 Plate and Weldments

Condition	t, in.	Orientation	R	Test Temp., °F	ΔK, ksi√in			Specimen ID
					6	10	20	
2195-T8 Plate[1]	0.25, 0.50	L-T, T-L	0.1, 0.5	75	0.42 – 1.26	3.91 – 7.09	30.70 – 71.04	All
				200	0.25 – 1.36	2.42 – 7.30	26.75 – 70.30	All
VPPAW[1]	0.25, 0.50	L-T	0.1, 0.5	75	N/A	0.90 – 1.62	8.18 – 1029.7	All
FSW[1]	0.25, 0.50	L-T	0.5	-320	N/A	13.46	89.73 – 103.9	All
				75	N/A	5.08 – 10.53	31.19	All
				200	2.37 – 2.48	12.13 – 12.29	N/A	All
2195 (ref. 2)[2]	0.25, 1.25	All	0.1, 0.5	-320	N/A	0.4 - 4	10 - 100	All
				75	0.06 – 15.0	0.2 - 50	N/A	All

1 – summary of results from this study
2 – summary of results from SLWT design allowables program

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	May 2000	Technical Memorandum

4. TITLE AND SUBTITLE
Fatigue Crack Growth Rate Test Results for Al-Li 2195 Parent Metal, Variable Polarity Plasma Arc Welds and Friction Stir Welds

5. FUNDING NUMBERS
WU 242-20-05

6. AUTHOR(S)
Robert A. Hafley, John A. Wagner, and Marcia S. Domack

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, VA 23681-2199

8. PERFORMING ORGANIZATION REPORT NUMBER
L-17984

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA/TM-2000-210098

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category 26 Distribution: Standard
Availability: NASA CASI (301) 621-0390

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)
The fatigue crack growth rate of aluminum-lithium (Al-Li) alloy 2195 plate and weldments was determined at 200°F, ambient temperature and -320°F. The effects of stress ratio (R), welding process, orientation and thickness were studied. Results are compared with plate data from the Space Shuttle Super Lightweight Tank (SLWT) allowables program. Data from the current series of tests, both plate and weldment, falls within the range of data generated during the SLWT allowables program.

14. SUBJECT TERMS
Al-Li alloy; 2195; da/dN; fatigue; cryogenic properties; friction stir welding; FSW; Variable polarity plasma arc welding; VPPAW

15. NUMBER OF PAGES
43

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL