AFWAL-TR-84-4018

(12)

FATIGUE CRACK GROWTH RATE DATA FOR ALUMINUM ALLOY 6061-T651 PLATE

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FEBRUARY 1984

Interim Technical Report for Period March 1983-August 1983

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFWAL-TR-84-4018	2. GOVT ACCESSION NO. AD-A140 325	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) FATIGUE CRACK GROWTH RATE DATA FOR ALUMINUM ALLOY 6061-T651 PLATE		5. TYPE OF REPORT & PERIOD COVERED Interim Technical Report March 1983-August 1983
		6. PERFORMING ORG. REPORT NUMBER UDR-TR-83-120
7. AUTHOR(s) John J. Ruschau		8. CONTRACT OR GRANT NUMBER(s) F33615-82-C-5039
9. PERFORMING ORGANIZATION NAME AND ADDRESS University of Dayton Research Institute 300 College Park Avenue Dayton, OH 45469		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 2421-03-18
11. CONTROLLING OFFICE NAME AND ADDRESS Materials Laboratory (AFWAL/MLSE) Air Force Wright Aeronatical Laboratories (AFSC) Wright-Patterson, AFB, Ohio 45433		12. REPORT DATE February 1984
		13. NUMBER OF PAGES 26
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release; Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Aluminum 6061
Fatigue Crack Growth Rate
Aluminum Plate
Tensile

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Constant amplitude fatigue crack growth rate data were obtained for aluminum alloy 6061-T651 plate. Such data were obtained at two stress ratios, R=0.1 and 0.5, at room temperature and 300°F. Both the T-L and L-T orientations of a single 1/2-inch (13mm) thick plate were examined. Final crack growth rate data are presented in both graphical and tabular formats, using the analyses and presentation schemes developed by the University of Dayton Research Institute for the Revised Damage Tolerant Design Handbook.

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PREFACE

This interim technical report was submitted by the University of Dayton Research Institute, Dayton, Ohio, under Air Force Contract Number F33615-82-C-5039, "Quick Reaction Evaluation of Materials". The work was initiated under Project Number 2421-03-18, "Evaluation of Materials and Processes", and administered under direction of the System Support Division of the Materials Laboratory, Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio.

This effort was conducted during the period of March 1983 to August 1983. The author, Mr. John J. Ruschau, would like to extend special recognition to Messrs. Richard Marton and John Eblin of the University of Dayton for performing all mechanical testing.

This report was submitted by the author in November 1983.

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SUMMARY

Constant amplitude fatigue crack growth rate data were obtained from a single plate of aluminum 6061-T651. Results obtained indicate no differences between the L-T and T-L plate orientations. Increasing the stress ratio from 0.1 to 0.5 increased the growth rates throughout the range of alternating stress intensity. The increase in test temperature from room temperature to 300°F (149°C) doubled the crack growth rates for both plate orientations and stress ratios.

The data generated in this report is in a format compatible with data on similar alloys currently in the Air Force Damage Tolerant Design Handbook.

SECTION I
INTRODUCTION

Aluminum 6061, perhaps the most versatile of all heat-treatable aluminum alloys, was developed for applications involving moderate strength, good formability, weldability, and corrosion resistance. Because of such a combination of desirable properties, it is not surprising this alloy is used in both civilian and military industries, where usages range from recreational items to component parts on the most advanced fighter aircraft.

Despite its wide usage, little or no published data exists with regards to fatigue crack growth rate properties even though there are usages that are the subject of durability or damage tolerance analysis. It is because of the lack of such data that this test program was conducted. In this effort constant amplitude fatigue crack growth rate data were developed for aluminum 6061-T651 plate under conditions of varying stress ratio, temperature, and plate orientation. Data obtained are presented in both the traditional form of a log-log plot of crack growth rate (da/dN) versus stress intensity range (ΔK), along with tabulated data of mean trend da/dN, ΔK values, obtained in the manner developed by the University of Dayton Research Institute for the Revised Damage Tolerant Design Handbook[1,2] (to be released in late 1983).

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[1] Stumpff, P. L., et al., Fourth Semiannual Report on "Damage Tolerant Design Handbook," Contract No. F33615-80-C-5149, December 1982.

[2] Personal communication with Dr. Peter Hovey of UDRI, September 1983.

SECTION II

MATERIALS, SPECIMENS, AND PROCEDURES

A single, 1/2-inch (13 mm) thick plate of aluminum 6061-T651 plate was provided for test. The chemical composition of the plate is furnished below, along with chemical composition limits, as provided by the Aluminum Association.[3]

CHEMICAL COMPOSITION OF TEST PLATE OF 6061-T651
(Wt. %)

Silicon	Iron	Copper	Manganese	Magnesium	Chromium	Titanium	Aluminum
0.6	0.42	0.23	0.097	0.92	0.17	0.067	Balance

CHEMICAL COMPOSITION LIMITS OF 6061*
(Wt. %)

Silicon	Iron	Copper	Manganese	Magnesium	Chromium	Zinc	Titanium	Aluminum
0.4-0.8	0.7	0.15-0.4	0.15	0.8-1.2	0.04-0.35	0.25	0.15	Balance

*Composition in % maximum unless shown as a range.

The composition of the test plate is well within the limits specified for 6061.

Tensile specimens were removed from both the longitudinal (L) and transverse (T) plate orientations and machined to the configuration shown in Figure 1. Compact-type crack growth samples, likewise removed from both the L-T and T-L plate directions, were machined to the dimensions shown in Figure 2.

Tensile testing was performed in a 10-KIP (45 kN) capacity Instron test machine, equipped with a Conrad-Missimer environmental chamber for the elevated temperature testing. An Instron 1-inch (25 mm) gage length extensometer was used on all tests to obtain specimen strain. Procedures outlined in ASTM Standard E-8, "Tension Testing of Metallic Materials" were closely followed.

[3] "Aluminum Standard and Data 1979," The Aluminum Association, Sixth Edition, March 1979.

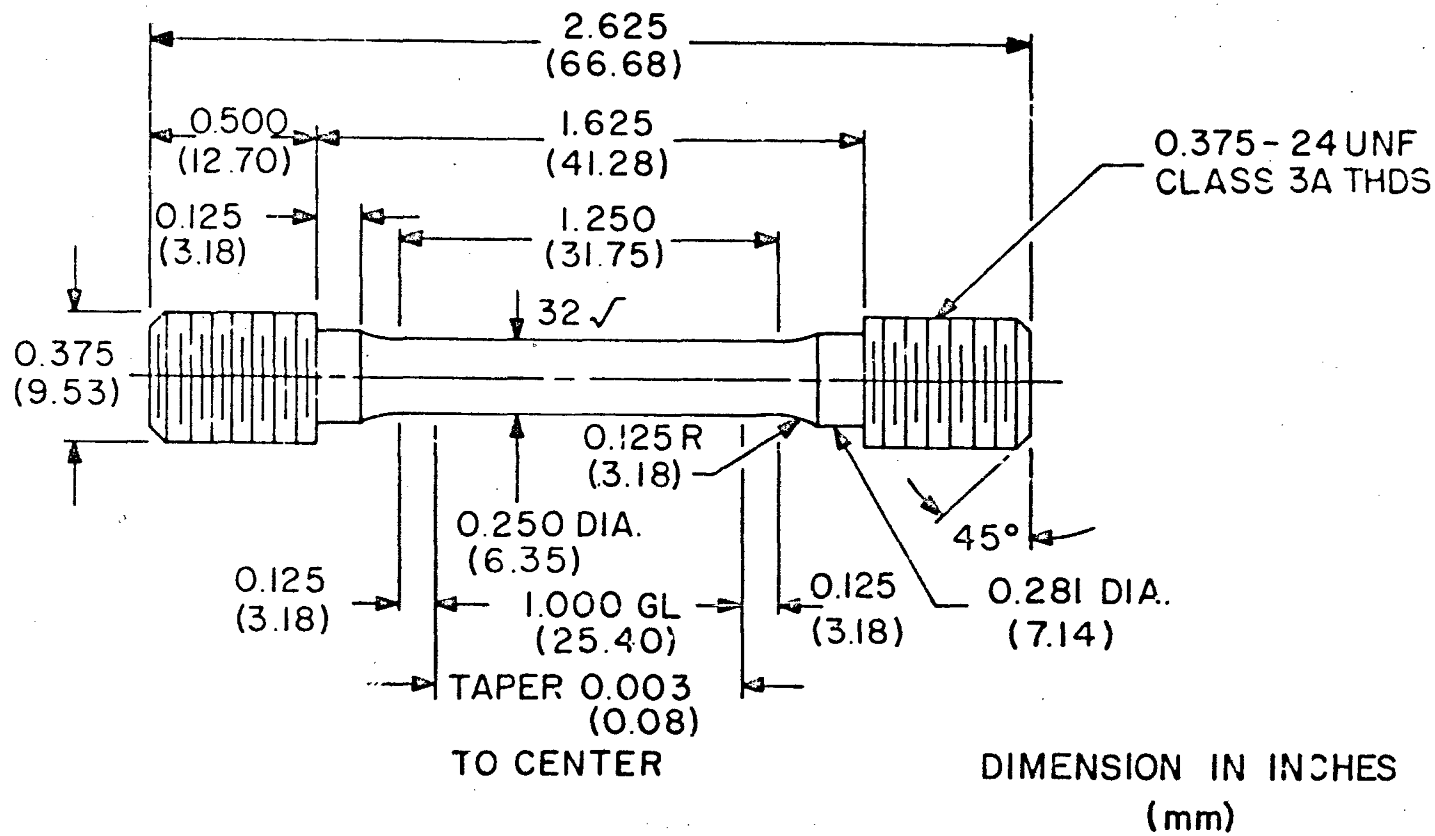
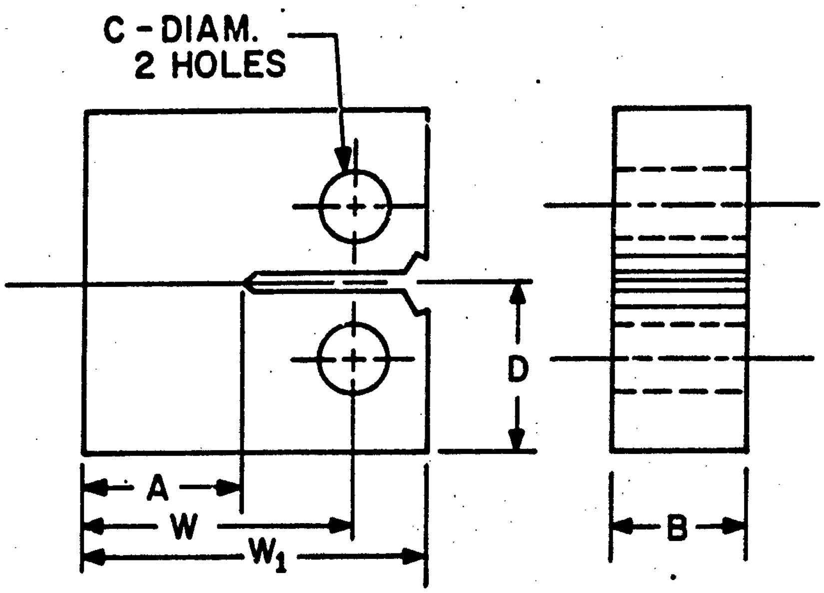


Figure 1. Tensile Specimen Configuration.



B	A	W	W1	D	C
0.50 (12.7)	1.60 (40.6)	2.000 (50.8)	2.500 (63.5)	1.200 (30.5)	0.50 (12.7)

DIMENSIONS IN INCHES (mm)

Figure 2. Crack Growth Specimen Configuration.

All fatigue crack growth rate testing was conducted in a 2.5 KIP (11 kN) capacity MTS hydraulic fatigue testing machine, similarly equipped with a furnace for 300°F (149°C) testing. A 30X Gaertner traveling microscope with digital readout was employed for visual determination of crack length. Crack growth rate data were obtained using guidelines set forth in ASTM Standard E647, "Constant-Load-Amplitude Fatigue Crack Growth Rates Above 10^{-8} m/Cycle." A seven-point incremental polynomial technique was used to reduce the raw test record to final form.

Upon development of the final da/dN-ΔK record, the data were further analyzed to obtain a mean trend curve of crack growth rate versus stress intensity range, using statistical routines developed by UDRI for the revised Damage Tolerant Handbook. Details of the analysis routines are thoroughly described in the Appendix. From the individual mean trend curves for each specimen/condition, selected da/dN-ΔK points were tabulated. again using the same methods and formats which will be used in the Handbook.

SECTION III

RESULTS

The average tensile test results (average of three tests) are presented in Table 1. Room temperature properties are consistent with similar reference data.[4,5] At 300°F (149°C), yield strength diminished slightly (~10-15%), with the ultimate strength essentially equal to yield strength.

Fatigue crack growth rate curves developed for 6061-T651 plate are presented in Figures 3 and 4 for room temperature conditions, and Figures 5 and 6 for the 300°F (149°C) test temperature. Data for the L-T plate direction are shown in Figures 3 and 5; the T-L orientation data are furnished in Figures 4 and 6. Each plot reflects the results of two specimens per condition. Scatter between the two individual specimens per condition is minimal, with the exception of the room temperature, T-L oriented data at R=0.1 (Figure 4). Reasons for the wide variations in crack growth behavior at the lower stress intensity ranges are unclear.

Tabulated crack growth rate data, obtained from the mean trend line for each figure, is also presented in Tables 2 through 5 for each set of figures shown.

Results shown in both the figures and tables indicate no difference in crack growth rate with respect to plate orientation at either temperature within the midrange of the ΔK values. At room temperature, the higher stress ratio (R=0.5) produced growth rates typically 5 to 10 times greater than the R=0.1 data. Relative to test temperature, the 300°F (149°C) environment yielded crack growth rates roughly double those obtained at room temperature.

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[4] Military Standardization Handbook-5C, "Metallic Materials and Elements for Aerospace Vehicle Structures," Volume 1, September 1976.

[5] Metals Handbook, Volume 1, "Properties and Selection," American Society for Metals, Eighth Edition.

TABLE 1

AVERAGE* TENSILE PROPERTIES OF
ALUMINUM 6061-T651 PLATE

Plate Orientation	Temperature °F (°C)	Yield Str. KSI (MPa)	Ult. Str. KSI (MPa)	% Elong. in 2 in. (51 mm) G.L.
Longitudinal	70 (21)	42.0 (290)	44.6 (308)	19
Transverse	70 (21)	40.4 (278)	45.8 (316)	14
Longitudinal	300 (149)	36.2 (250)	36.2 (250)	24
Transverse	300 (149)	35.8 (247)	37.6 (260)	22

*Values represent the average of three tests.

CONDITION/HT: T651
FORM: 0.50"TH PLATE
SPECI 'EN TYPE: CT
ORIENTATION: L-T
FREQUENCY: 30.00 HZ
ENVIRONMENT: R.T., LAB AIR

YIELD STRENGTH: 42.0 KSI
ULT. STRENGTH: 44.5 KSI
SPECIMEN THK: 0.500"
SPECIMEN WIDTH: 2.000"
REFERENCES:

ALUM. ALLOY

6061

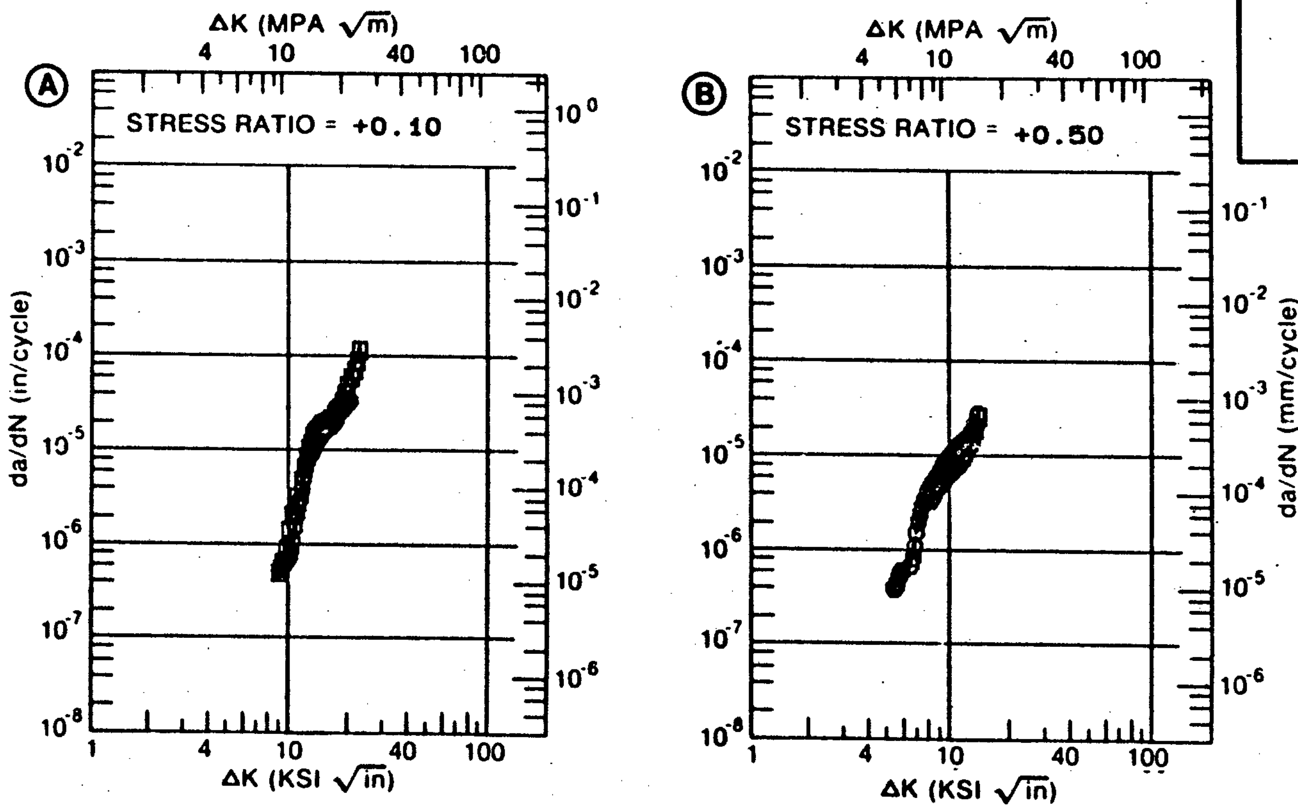

Figure 3. Fatigue Crack Growth Rate Data for Aluminum 6061-T651, L-T Orientation, at Room Temperature.

CONDITION/HT: T651
FORM: 0.50"TH PLATE
SPECIMEN TYPE: CT
ORIENTATION: T-L
FREQUENCY: 30.00 HZ
ENVIRONMENT: R.T., LAB AIR

YIELD STRENGTH: 40.0 KSI
ULT. STRENGTH: 46.0 KSI
SPECIMEN THK: 0.500"
SPECIMEN WIDTH: 2.000"
REFERENCES:

ALUM. ALLOY

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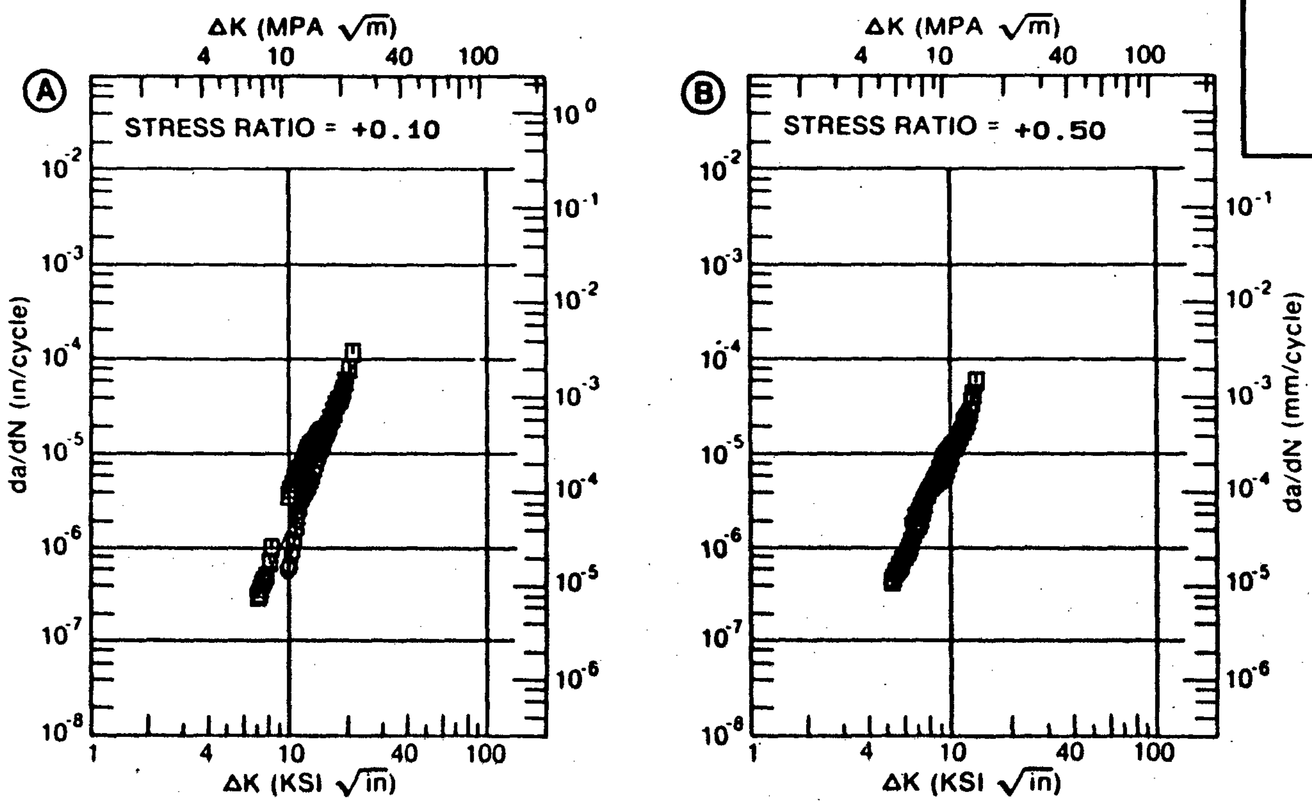

Figure 4. Fatigue Crack Growth Rate Data for Aluminum 6061-T651, T-L Orientation, at Room Temperature.

CONDITION/HT: T651
FORM: 0.50"TH PLATE
SPECIMEN TYPE: CT
ORIENTATION: L-T
FREQUENCY: 25.00 HZ
ENVIRONMENT: + 300° F, FURNACE

YIELD STRENGTH: 38.0 KSI
ULT. STRENGTH: 38.0 KSI
SPECIMEN THK: 0.500"
SPECIMEN WIDTH: 2.000"
REFERENCES:

ALUM. ALLOY

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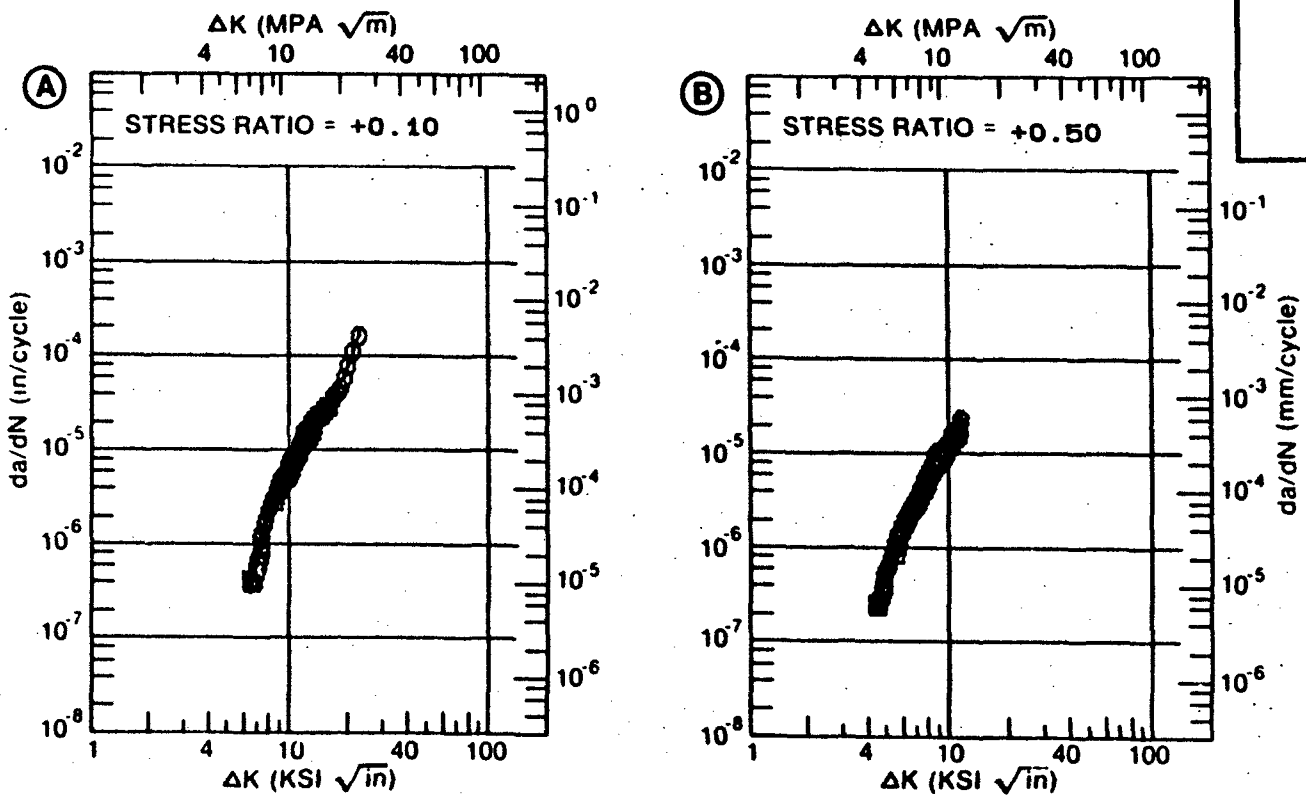

Figure 5. Fatigue Crack Growth Rate Data for Aluminum 6061-T651, L-T Orientation, at 300°F (149°C).

CONDITION/HT: T651
FORM: 0.50"TH PLATE
SPECIMEN TYPE: CT
ORIENTATION: T-L
FREQUENCY: 25.00 HZ
ENVIRONMENT: + 300° F, FURNACE

YIELD STRENGTH: 35.5 KSI
ULT. STRENGTH: 37.5 KSI
SPECIMEN THK: 0.500"
SPECIMEN WIDTH: 2.000"
REFERENCES:

ALUM. ALLOY

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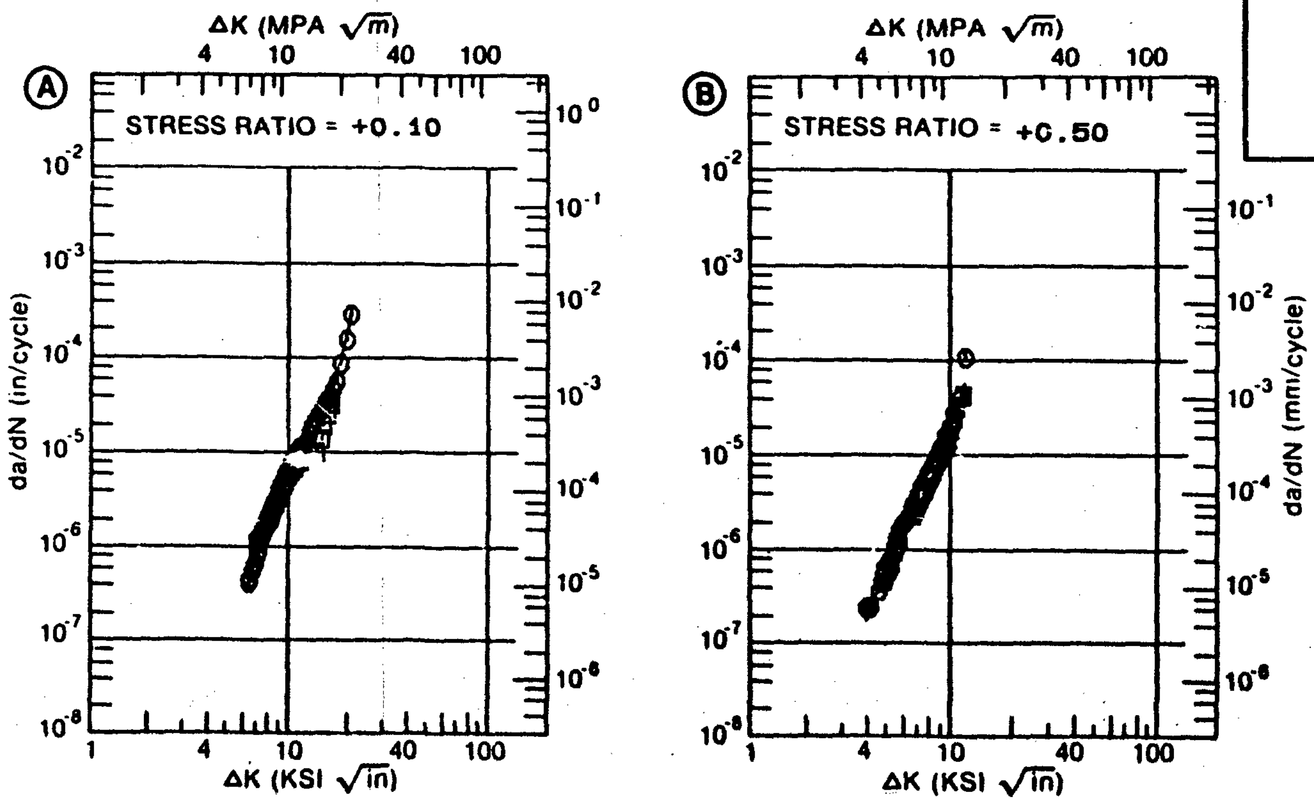

Figure 6. Fatigue Crack Growth Rate Data for Aluminum 6061-T651, T-L Orientation, at 300°F (149°C).

TABLE 2

TABULATED FATIGUE CRACK GROWTH RATE DATA FOR ALUMINUM 6061-T651, L-T ORIENTATION, 70°F

Reference: Figure 3

ΔK (KSI$\sqrt{in}$)			da/dN (10^{-6} inches/cycle) R=0.1	da/dN (10^{-6} inches/cycle) R=0.5
ΔK_{min}:	@R=0.1	8.73	0.416	
	@R=0.5	5.07		0.505
		4.0		
		5.0		
		6.0		0.743
		7.0		2.21
		8.0		4.56
		9.0	0.508	7.19
		10.0	1.17	9.34
		13.0	10.6	19.8
		16.0	22.2	
		20.0	42.7	
ΔK_{max}:	@R=0.1	22.54	140.0	
	@R=0.5	13.67		28.0

TABLE 3

TABULATED FATIGUE CRACK GROWTH RATE DATA
FOR ALUMINUM 6061-T651, T-L
ORIENTATION, 70°F

Reference: Figure 4

ΔK (KSI$\sqrt{in}$)			da/dN (10^{-6} inches/cycle)	
			R=0.1	R=0.5
ΔK_{min}:	@R=0.1	6.81	0.404	
	@R=0.5	5.06		0.361
		4.0		
		5.0		
		6.0		1.07
		7.0	0.429	2.39
		8.0	0.648	4.41
		9.0	1.06	7.34
		10.0	1.80	11.5
		13.0	7.91	40.4
		16.0	25.7	
		20.0	74.9	
ΔK_{max}:	@R=0.1	20.74	86.3	
	@R=0.5	13.21		44.1

TABLE 4

TABULATED FATIGUE CRACK GROWTH RATE DATA
FOR ALUMINUM 6061-T651, L-T
ORIENTATION, 300°F

Reference: Figure 5

ΔK (KSI$\sqrt{in}$)			da/dN (10^{-6} inches/cycle)	
			R=0.1	R=0.5
ΔK_{min}:	@R=0.1	6.26	0.303	
	@R=0.5	4.26		0.220
		4.0		
		5.0		0.693
		6.0		1.91
		7.0	0.865	3.75
		8.0	2.29	6.16
		9.0	4.40	9.16
		10.0	6.99	12.9
		13.0	16.5	
		16.0	31.5	
		20.0	82.6	
ΔK_{max}:	@R=0.1	22.47	169.0	
	@R=0.5	11.37		19.8

TABLE 5

TABULATED FATIGUE CRACK GROWTH RATE DATA
FOR ALUMINUM 6061-T651, T-L
ORIENTATION, 300°F

Reference: Figure 6

ΔK (KSI$\sqrt{in}$)			da/dN (10^{-6} inches/cycle) R=0.1	da/dN (10^{-6} inches/cycle) R=0.5
ΔK_{min}:	@R=0.1	6.19	0.390	
	@R=0.5	3.82		0.180
		4.0		0.239
		5.0		0.799
		6.0		1.87
		7.0	0.977	3.74
		8.0	2.22	6.96
		9.0	4.05	12.6
		10.0	6.39	22.5
		13.0	16.1	
		16.0	34.7	
		20.0	241.0	
ΔK_{max}:	@R=0.1	20.31	297.0	
	@R=0.5	11.60		57.5

APPENDIX

MEAN TREND CURVE ANALYSIS

APPENDIX

MEAN TREND CURVE ANALYSIS

The Damage Tolerant Design Data Handbook will present fatigue crack growth rate (FCGR) data, i.e., da/dN behavior in both graphical and tabular formats. A graphical format will be used to present da/dN versus ΔK data and the mean trend of these data will be tabulated. This attachment describes the method that will be used to generate the mean trend tables.

A least squares cubic spline approximation which is essentially an analytic method of fitting a "French" curve to a data set, is the method selected to generate tables of da/dN values at fixed ΔK values. The curve is constructed by fitting different cubic polynomials on non-overlapping, connecting subintervals over the range of the independent variable. In the handbook, the independent variable will be ΔK. The boundary points of the intervals are referred to as knots and the cubic polynomials meet at the knots. The polynomials are also constrained so that the first and second derivatives are continuous at the knots. The result of this process is a smooth curve which passes through the center of the data. Figure A1 shows an example of a spline curve fit to a FCGR data set. The knots are marked in the figure by the large dots.

In general, FCGR data are well enough behaved so that a maximum of five knots should be sufficient in generating the handbook tables. The actual number of knots used in fitting a curve to a set of data will be a function of the number of FCGR data points and their pattern in da/dN-ΔK space.

The mean trend table for a set of FCGR data will be generated by selecting points from the spline curve that have been fit to the data. The ΔK values will be chosen such that they are approximately equally spaced in a logarithmic scale and cover the complete range of ΔK values expected. The da/dN values are

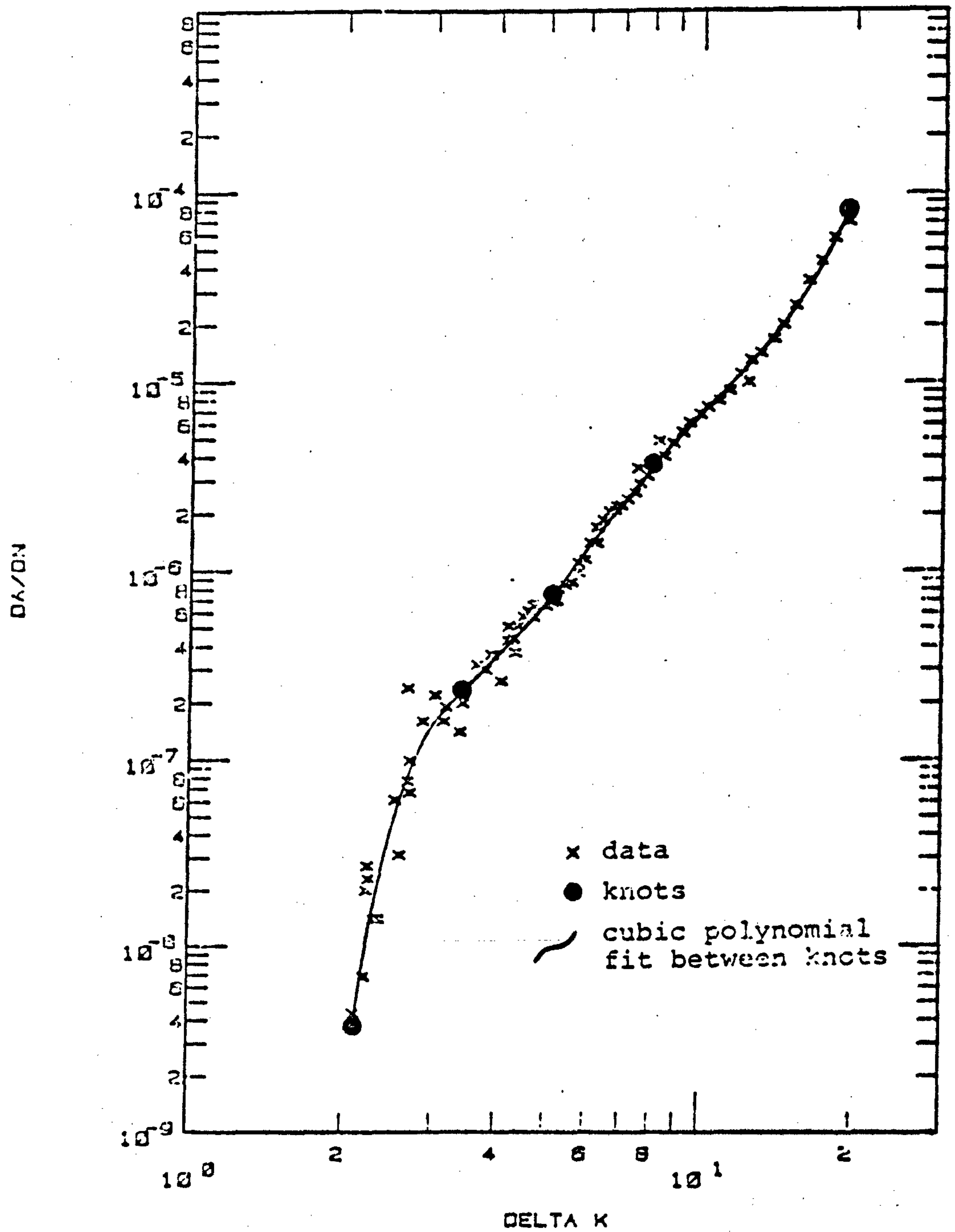

Figure A1. Typical Crack Growth Data Set Showing Cubic Polynomial Fit.

obtained through the interpolation of the spline curve at the preselected ΔK values. The complete set of ΔK values are: 1.0, 1.3, 1.6, 2.0, 2.5, 3.0, 3.5, 4.0, 5.0, 6.0, 7.0, 8.0, and 9.0 as well as 10 times these values and 100 times these values up to 200. Because it is expected that the da/dN data will not always span the complete ΔK range, the table will also report the minimum and maximum da/dN values corresponding to the recorded minimum and maximum ΔK values. The extreme pairs of points (ΔK, da/dN) correspond to the extremes of the spline curve.

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