

OCA PAD AMENDMENT - PROJECT HEADER INFORMATION

12/13/94

Active

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Project #: E-16-M57          Cost share #: E-16-358          Rev #: 6
Center # : 10/24-6-R7622-0A0  Center shr #: 10/22-1-F7622-0A0      OCA file #: 205
                                                                    Work type : RES
Contract#: F09603-91-G-0096-0013      Mod #: ADMIN.        Document : DO
Prime #:                            Contract entity: GTRC

Subprojects ? : N                CFDA: N/A
Main project #:                  PE #: 503300

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Project unit:	AERO ENGR	Unit code: 02.010.110
Project director(s):		
KARDOMATEAS G	AERO ENGR	(404)894-3003

Sponsor/division names: AIR FORCE / WARNER ROBINS AFB, GA
Sponsor/division codes: 104 / 005

Award period: 920901 to 941231 (performance) 941231 (reports)

Sponsor amount	New this change	Total to date
Contract value	0.00	120,000.00
Funded	0.00	120,000.00
Cost sharing amount		49,789.00

Does subcontracting plan apply?: N

Title: SHORT CRACKS TEST PROGRAM FOR MH-53J DYNAMIC SYSTEM & AIRFRAME COMPONENTS

PROJECT ADMINISTRATION DATA

DCA contact: Ina R. Lashley	894-4820
Sponsor technical contact	Sponsor issuing office
GARY CHAMBERLAIN (912)926-2209	CHARLES BROOKS (912)926-7272
WR-ALC/TIEDD ROBINS AFB, GA 31098	WR-ALC/LUKB 240 COCHRAN STREET ROBINS AFB, GA 31098-1622

Security class (U,C,S,TS) : U ONR resident rep. is ACO (Y/N): Y
Defense priority rating : N/A GOV'T supplemental sheet
Equipment title vests with: Sponsor X GIT
 *SEE BOA SECT H-196, P.11 FOR PROCEDURES. SPONSOR APPROVAL REQUIRED =>\$500.**
Administrative comments -
 BASED ON "VERBAL AUTHORIZATION" FROM MONICA KNIGHT, WR-ALC/LUKB, THIS PROJECT
 IS EXTENDED TO 12/31/94. (EXTENSION TO 2/28/95 HAS BEEN REQUESTED BY OCA.)

4

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 07/19/96

Project No. E-16-M57 _____ Center No. 10/24-6-R7622-0A0_

Project Director KARDOMATEAS G _____ Pool/Lab AERO ENGR _____

Sponsor AIR FORCE/WARNER ROBINS AFB, GA _____

Contract/Grant No. F09603-91-G-0096-0013 _____ Contract Entity GTRC

Prime Contract No. _____

Title SHORT CRACKS TEST PROGRAM FOR MH-53J DYNAMIC SYSTEM & AIRFRAME COMPONENTS

Effective Completion Date 941231 (Performance) 941231 (Reports)

Closeout Actions Required:	Y/N	Date Submitted
Final Invoice or Copy of Final Invoice	Y	_____
Final Report of Inventions and/or Subcontracts	Y	_____
Government Property Inventory & Related Certificate	Y	_____
Classified Material Certificate	N	_____
Release and Assignment	Y	_____
Other _____	N	_____
Comments _____		

Subproject Under Main Project No. _____

Continues Project No. _____

Distribution Required:

Project Director	Y
Administrative Network Representative	Y
GTRI Accounting/Grants and Contracts	Y
Procurement/Supply Services	Y
Research Property Management	Y
Research Security Services	N
Reports Coordinator (OCA)	Y
GTRC	Y
Project File	Y
Other _____	N
_____	N

NOTE: Final Patent Questionnaire sent to PDPI.

5-16-89
#1

Status Report - October 22, 1992

Short Cracks Test Program for MH-53J

Dynamic System & Airframe Components

Contract no: F09603-91-G-0096-0013

Project no: E-16-M57

Principal Investigator: Dr. George A. Kardomateas

Associate Professor, School of Aerospace Engineering

Georgia Institute of Technology, Atlanta GA 30332-0150

Tel: (404) 894-8198

Sponsor Technical Contact: Gary Chamberlain, WR-ALC/TIEDD

Robins AFB, GA 31098, Tel: (912) 926-2209

The primary objective of the proposed program is to obtain crack growth data in the form of da/dN versus ΔK curves for cracks between 0.005 to 0.020 inches long in MH-53J dynamic system and airframe materials.

Another secondary objective is to obtain data and perform studies which can serve as a basis for determining the parameters that govern "short" crack growth

This is the first status report being written. The paperwork was just received and the program is just starting.

At this point, our major focus is on the specimen and fixture design. Since specimen design is so crucial to the success of the testing program, we anticipate working on the

details of these designs and the machining of the specimens and fixtures over the next few months.

Furthermore, we are preparing the order for purchasing the motorized optical-video measurement system and the MTS testing machine digital controller which are needed for the implementation of the tests. It should be noted that these equipment will be purchased with Georgia Tech funds. The purchase order paperwork and the delivery of the equipment may require two to three months. In the meantime, some preliminary experiments may be performed after the specimen design is completed, by using our Instron test system (the latter can be used only for a limited time because it is also assigned for teaching purposes).

In this project, we are currently employing Preston Bates who is pursuing his Ph.D. degree at Georgia Tech in conjunction with his employment at GTRI, and Andy Soediono who is a Ph.D. student currently conducting a thesis on the short cracks problem.

Finally, we have already requested that we submit quarterly instead of monthly reports because, due to the nature of the project, the results would be reported in a better and more illustrative manner with quarterly letters.



E 16-M57
1182
School of Aerospace Engineering

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404-894-3000
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January 28, 1993

Gary Chamberlain
Damage Tolerance Analysis Lab
WR-ALC/TIEDD
Robins AFB, GA 31098-5149

Ref: Contract no: F09603-91-G-0096-0013.

Project no: E-16-M57.

Project Title: "Short Cracks Test Program for MH-53J Dynamic System
& Airframe Components".

Progress Report No. 2 (through December 31, 1992).

Dear Gary:

Following our first letter, which acknowledged initiation of the project, this second letter serves as our quarterly progress report through December 31, 1992 (the project initiation day was September 1 1992).

During this period we have finished the design of the specimen and test fixtures and these are now being made at the machine shop. We have also taken delivery of our motorized optical-video remote measurement system. This system is now being tested. We are still waiting for the delivery of the digital controller for the MTS testing machine (it should be noted that these equipment have been purchased with Georgia Tech funds). Until this comes, we shall conduct some preliminary tests on our Instron test system (the latter can be used only for a limited time because it is also assigned for teaching purposes).



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404-894-3000
Fax: 404-894-2760

A copy of the specimen design is attached.

Finally, expenditures for the period from initiation of the Project (September 1) through December 31, 1992 are attached.

Should you need to contact me, I can be reached at (404) 894-8198.

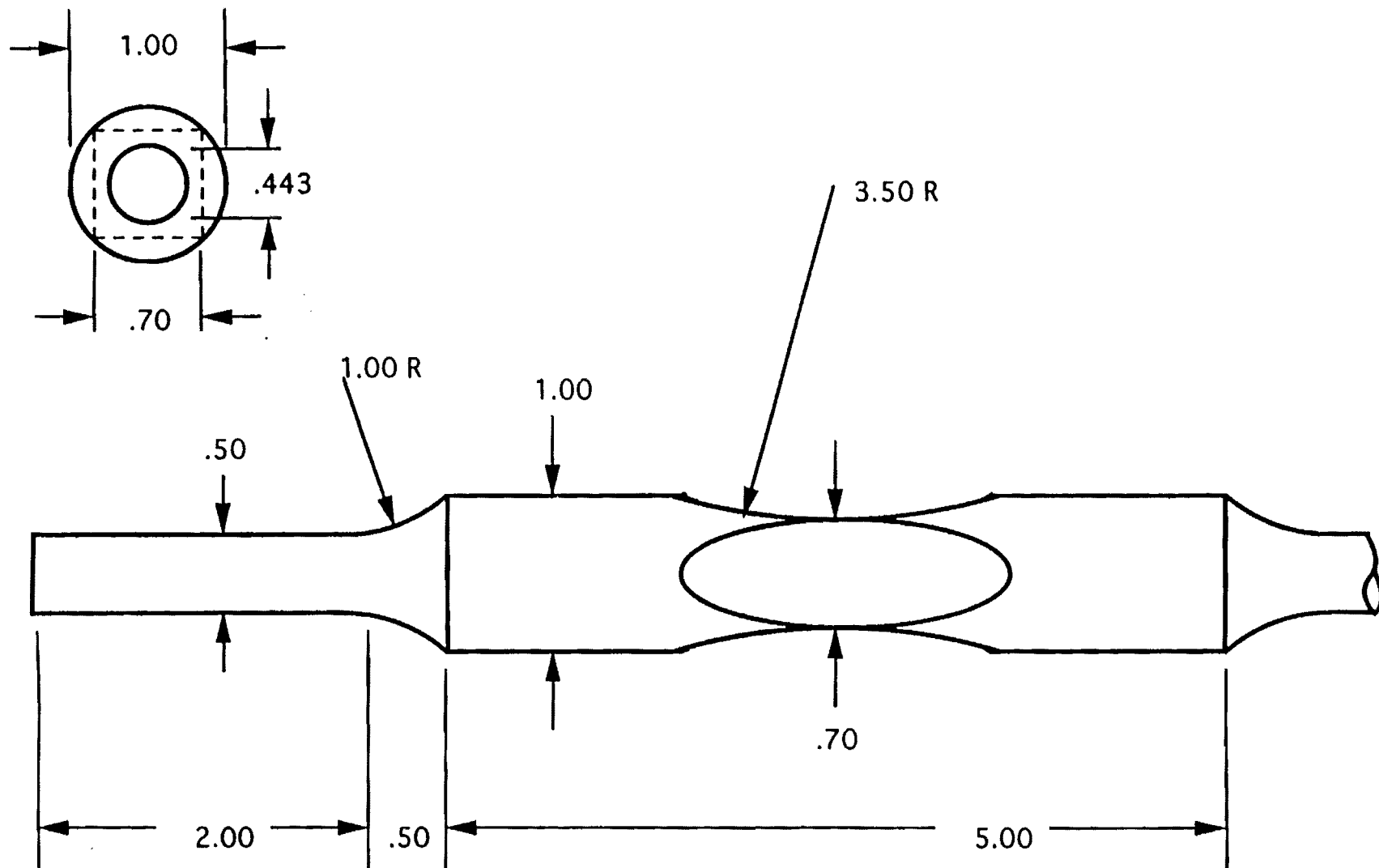
With all best regards, I remain,

Very truly yours,

Dr. George A. Kardomateas

Associate Professor of Aerospace Engineering

Project Director



Test Coupon

FINANCIAL STATUS SUMMARY

E-16-M57

09/01/92 -- 12/31/92

For:	Dr. Kardomateas
From:	Madelyne Watson
Date:	01/26/93

Budget Category	Total Allocation	Previous Expenditures	Current Expenditures	Total Expenditures	01/01/93 Balances
Personal Services	\$50,407	\$0	\$4,950	\$4,950	\$45,457
Fringe Benefits	\$6,367	\$0	\$408	\$408	\$5,959
Materials & Supplies	\$0	\$0	\$1,204	\$1,204	(\$1,204)
Travel	\$2,000	\$0	\$0	\$0	\$2,000
Capital Outlay	\$29,000	\$0	\$0	\$0	\$29,000
Subcontracts	\$0	\$0	\$0	\$0	\$0
Computer	\$0	\$0	\$0	\$0	\$0
Overhead	\$32,226	\$0	\$2,947	\$2,947	\$29,279
TOTALS	\$120,000	\$0	\$9,509	\$9,509	\$110,491

Please Note: No Encumbrances are included in above analysis.

6-16-93
3, 4, 5

April 19, 1993

Gary Chamberlain
Damage Tolerance Analysis Lab
WR-ALC/TIEDD
Robins AFB, GA 31098-5149

Ref: Contract no: F09603-91-G-0096-0013.

Project no: E-16-M57.

Project Title: "Short Cracks Test Program for MH-53J Dynamic System
& Airframe Components".

Progress Report No. 3 (through March 31, 1993).

Dear Gary:

This letter serves as our quarterly progress report from January 1, 1993 through March 31, 1993.

During this period, while we were testing and configuring the motorized optical-video remote measurement system (for measuring crack growth), progress was made on the analysis that is needed for a comprehensive representation of short crack growth data. Specifically, the study focused on identifying the crack length circumstances under which the requirements for a single parameter (K_I or ΔK_I if cyclic loading is considered) characterization are violated. It was postulated that a two-parameter characterization by K (the stress-intensity factor), and the T stress, as introduced by Rice, (or the related biaxiality ratio, B) is needed for the adequate description of the stress and strain field around a short crack. This can have significant implications regarding the prediction of cyclic (fatigue) growth of short cracks and the correlation with short crack growth data.

A related paper was authored and we request your approval for its publication in the International Journal of Fracture. Two copies of the paper are enclosed. I would appreciate if you could call me when approval has been granted.

We are still waiting for the delivery of the digital controller for the MTS testing machine (it should be again noted that both the optical and the MTS equipment have been purchased with Georgia Tech funds). We have been notified that the system will be delivered within the next month.

Once we properly configure and obtain familiarity with our optical system we plan to start (most probably next week) preliminary tests on our Instron test system (the latter can be used only for a limited time because it is also assigned for teaching purposes). The bulk of the experiments is planned to be performed on the MTS machine.

On the financial side, a statement of expenditures for the period from January 1 through March 31, 1993 is attached.

Should you need to contact me, I can be reached at (404) 894-8198.

With all best regards, I remain,

Very truly yours,

Dr. George A. Kardomateas

Associate Professor of Aerospace Engineering

Project Director



1050
[02.546

School of Aerospace Engineering

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July 21, 1993

Gary Chamberlain
Damage Tolerance Analysis Lab
WR-ALC/TIEDD
Robins AFB, GA 31098-5149

Ref: Contract no: F09603-91-G-0096-0013.

Project no: E-16-M57.

Project Title: "Short Cracks Test Program for MH-53J Dynamic System
& Airframe Components".

Progress Report No. 4 (through June 30, 1993).

Dear Gary:

This letter serves as our quarterly progress report from April 1, 1993 through June 30, 1993.

During this period, our cyclic bending tests on our aluminum alloy 7075-T651 specimen have demonstrated that we can successfully initiate short corner cracks of the order of 0.001 inch.

Work during this period has also been directed toward improving our surface finishing techniques for the "gage" section. We are currently hand finishing the milled surfaces by using successively finer abrasive papers and then polishing with an aluminum oxide paste. We are also evaluating a modified version of the specimen with a longer "gage" section that would allow better polishing of the surface.

Our original plan was to use our Instron testing machine for the bending fatigue tests (for the initiation of the short crack) and to conduct the fatigue crack growth tests under tension in our newly renovated MTS machine. Since the MTS machine will not be available for testing until late August, we have designed a smaller version of the specimen so that both bend and tensile fatigue testing can be conducted on the Instron. The tensile crack growth testing should, therefore, be initiated during the next report period.



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On the financial side, a statement of expenditures for the period from April 1 through June 30, 1993 is attached.

Should you need to contact me, I can be reached at (404) 894-8198.

With all best regards, I remain,

Very truly yours,

ℓ

Dr. George A. Kardomateas

Associate Professor of Aerospace Engineering

Project Director

KARDOMA.XLS

Financial Status Summary				For:	Dr. Kardomateas
E-16-M57				From:	J. Vanderboom
4/1/93 - 6/30/93				Date:	7/21/93
	Total	Previous	Current	Total	7/1/93
Budget Category	Allocation	Expended	Expended	Expended	Balances
Personal Services	50,407	12,054	4,659	16,713	33,694
Fringe Benefits	6,367	1,606	664	2,270	4,097
Materials & Supplies	0	1,539	354	1,893	-1,893
Travel	2,000	0	861	861	1,139
Capital Outlay	29,000	1,033	5,304	6,337	22,663
Subcontracts	0	0	0	0	0
Computer	0	0	0	0	0
Overhead	32,226	6,824	2,936	9,760	22,466
				0	
TOTALS	120,000	23,056	14,778	37,834	82,166
Please Note: No Encumbrances are included in above analysis					

E-16-M57
#6 + 27

October 5, 1993

Gary Chamberlain
Damage Tolerance Analysis Lab
WR-ALC/TIEDD
Robins AFB, GA 31098-5149

Ref: Contract no: F09603-91-G-0096-0013.

Project no: E-16-M57.

Project Title: "Short Cracks Test Program for MH-53J Dynamic System
& Airframe Components".

Progress Report No. 5 (through September 30, 1993).

Dear Gary:

This letter serves as our quarterly progress report from July 1, 1993 through September 30, 1993.

During this period, the details of the bend test procedure for initiating short cracks were finalized. Surface preparation of the gage section was improved by using four paper grades and 3 micron and 1 micron diamond paste for finish polishing. We are also having some specimens made by electro-spark machining as an alternative to traditional machining.

The new MTS testing system which will be used for tensile fatigue tests is ready for use, and these tests are expected to be started during the next report period.

The optical system used for tracking crack growth is functioning very well with good magnification. Furthermore, the use of replicas to supplement the results from the optical system is being explored.

To help formulated a predictive capability for the fatigue growth of short cracks, a finite element analysis for the plastic zone topography around a short crack under tension is being performed. This work is in continuation of our earlier studies that have been reported in our recent paper (in press, International Journal of Fracture).

On the financial side, a statement of expenditures for the period from July 1 through September 30, 1993 is attached.

Should you need to contact me, I can be reached at (404) 894-8198.

With all best regards, I remain,

Very truly yours,

Dr. George A. Kardomateas

Associate Professor of Aerospace Engineering

Project Director

E-16-M57
7 + n/a

January 18, 1994

Gary Chamberlain
Damage Tolerance Analysis Lab
WR-ALC/TIEDD
Robins AFB, GA 31098-5149

Ref: Contract no: F09603-91-G-0096-0013.

Project no: E-16-M57.

Project Title: "Short Cracks Test Program for MH-53J Dynamic System
& Airframe Components".

Progress Report No. 6 (through December 31, 1993).

Dear Gary:

This letter serves as our quarterly progress report from October 1, 1993 through December 31, 1993.

During this period, we continued exploring various methods for introducing short cracks in a repeatable fashion. It seems that we have succeeded in designing a new specimen/procedure for introducing short cracks. The method consists of machining a notch of depth of the order of thousands of an inch at a corner by using a numerically controlled milling machine with a slitting saw (fully automated and controlled) and then in growing from this notch a fatigue pre-crack. Therefore, short cracks have been initiated on a fully controlled/automated, repeatable fashion.

It should be noted that during our investigations to-date, significant experience has been accumulated by trying a variety of approaches, designs and surface preparation techniques. We plan to continue exploring other alternative ways of introducing short cracks, including razor blade cuts and glass filament with abrasive powder cuts.

The new MTS testing system which would be used for tensile fatigue tests turned out to have hydraulic control problems. Until these problems are remedied, a modified version of the specimen, suitable for our Instron machine will be used to conduct the cyclic tension tests in the Instron. We are working together with MTS in order to fix the hydraulic control problems of the MTS as soon as possible.

The finite element analysis for the plastic zone topography around a short crack under tension is being continued. This work is a follow-up of our earlier studies, which have already been published (*International Journal of Fracture* paper, vol. 62, pp. 219-232, 1993) and will help create a capability for predicting analytically the fatigue growth of short cracks.

On the financial side, a statement of expenditures for the period from October 1 through December 31, 1993 is attached.

Should you need to contact me, I can be reached at (404) 894-8198.

With all best wishes and regards, I remain,

Very truly yours,

Dr. George A. Kardomateas

Associate Professor of Aerospace Engineering

Project Director



E-16-M57

WIP

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April 27, 1994

Gary Chamberlain
Damage Tolerance Analysis Lab
WR-ALC/TIEDD
Robins AFB, GA 31098-5149

Ref: Contract no: F09603-91-G-0096-0013.

Project no: E-16-M57.

Project Title: "Short Cracks Test Program for MH-53J Dynamic System
& Airframe Components".

Progress Report No. 7 (through March 31, 1994).

Dear Gary:

This letter serves as our quarterly progress report from January 1, 1994 through March 31, 1994.

The following is a summary of our activities during this period:

- . The fatigue crack growth rate versus the range of stress intensity factor curve for the aluminum alloy 6061-T651 was determined from tests on our corner crack specimen. This included the determination of the threshold value for this specimen and material.
- . We designed and initiated a short crack test procedure for determining three types of loading responses for cases in which a short crack is present. These include:
 - (a) A no growth response
 - (b) A transient, stable growth and arrest response, and
 - (c) A continuing, stable growth response

These responses are load dependent and our tests will help to define the regimes into which they can be encountered.



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We formulated an analysis designed to determine the effect of specimen and crack geometry and loading on closure obstruction during crack growth (e.g., an edge crack in bending compared to a center crack in tension). This is of interest because an absence of closure obstruction has been suggested as a cause of short crack growth. Differences in geometry may, however, result in differences in closure obstruction for short cracks (e.g., thumbnail cracks versus corner cracks).

The tests are conducted on our Instron testing machine. As has already been mentioned, the new MTS testing system which would have been used for tensile fatigue tests turned out to have some hydraulic control problems. MTS has agreed to install several new hydraulic components that would presumably fix these problems, and they will do it during the month of May. Once MTS is fixed, our increased testing capacity will allow faster acquisition of test data.

Finally, we have drafted and sent to you an article for the *Leading Edge* US Air Force magazine. Please feel free to edit it as you wish. We look forward to your comments and suggestions.

On the financial side, a statement of expenditures for the period from January 1 through March 31, 1994 is attached.

Should you need to contact me, I can be reached at (404) 894-8198.

With all best wishes and regards, I remain,

Very truly yours,

Dr. George A. Kardomateas
Associate Professor of Aerospace Engineering
Project Director

Financial Status Summary			For:	Dr. Kardomateas	
E-16-M57			From:	J. Vanderboom	
7/1/92-3/31/94			Date:	4/28/94	
	Total	Previous	Current	Total	3/31/94
Budget Category	Allocation	Expended	Expended	Expended	Balances
Personal Services	50,407	28,871	6,013	34,884	15,523
Fringe Benefits	6,367	5,066	605	5,671	696
Materials & Supplies	0	3,436	428	3,864	-3,864
Travel	2,000	861	718	1,579	421
Capital Outlay	29,000	6,337	0	6,337	22,663
Subcontracts	0	3,500	3,000	6,500	-6,500
Computer	0	0	0	0	0
Overhead	32,226	17,159	3,983	21,142	11,084
TOTALS	120,000	65,230	14,747	79,977	40,023
Please Note: No Encumbrances are included in above analysis					

JOINT
Progress
Report

for the two quarters

4 - 7 / 94

7 - 10 / 94

(second and third quarter of 94)

November 9, 1994

Gary Chamberlain
Damage Tolerance Analysis Lab
WR-ALC/TIEDD
Robins AFB, GA 31098-5149

Ref: Contract no: F09603-91-G-0096-0013.

Project no: E-16-M57.

Project Title: "Short Cracks Test Program for MH-53J Dynamic System
& Airframe Components".

Progress Report No. 8 (through September 30, 1994).

Dear Gary:

This letter serves as our quarterly progress report from April 1, 1994 through September 30, 1994.

During the last report period, a modified method of specimen preparation was developed. Previously, the specimens were polished and then notched. For the new method, the specimen is notched first and then polished. By this procedure, we can, knowing how much material is removed during polishing, introduce very small notches. Thus, if a notch introduced has a depth of h and we consistently remove a layer of thickness, t , the final depth is $(h - t)$ times a constant geometric factor for the corner geometry. Since t is approximately fixed, we can simply change h to obtain different depths.

Testing with this new procedure is underway, and preliminary results indicate that we can both initiate and monitor small crack growth. These repeated tests on short cracks in aluminum alloy 6061-T651 have shown that the features of fatigue growth of short cracks, namely initially discontinuous growth, possible bifurcation, and continuous growth beyond a certain length, are consistently present.

We are also currently working on reporting our experimental procedure and our short fatigue crack growth test results in a refereed journal publication.

On the financial side, a statement of expenditures for the period from April 1 through September 30, 1994 is attached.

Should you need to contact me, I can be reached at (404) 894-8198.

With all best wishes and regards, I remain,

Very truly yours,

Dr. George A. Kardomateas

Associate Professor of Aerospace Engineering

Project Director

Georgia Tech

School of Aerospace Engineering

Georgia Institute of Technology

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February 22, 1995

Gary Chamberlain
Damage Tolerance Analysis Lab
WR-ALC/TIEDD
Robins AFB, GA 31098-5149

Progress Report for
quarter (last quarter
of 94)
10-12/94

Ref: Contract no: F09603-91-G-0096-0013.

Project no: E-16-M57.

Project Title: "Short Cracks Test Program for MH-53J Dynamic System
& Airframe Components".

Progress Report No. 9 (through December 31, 1994).

Dear Gary:

This letter serves as our quarterly progress report from October 1, 1994 through December 31, 1994.

During this report period, the main activities performed were: (1) the completion of testing for the third specimen; (2) manufacturing and surface preparation for the fourth specimen, which involves first notching and then polishing; (3) data processing for the third specimen; (4) interpretation of the results from the third specimen, in conjunction with previous results from specimens no. 1 and 2; (5) planning of testing program for the fourth specimen, scheduled to be performed in the upcoming period.

Our testing procedure is now refined and results to-date indicate that we can both initiate and monitor small crack growth in a controllable and repeatable fashion.

Georgia Tech

School of Aerospace Engineering

Georgia Institute of Technology

Atlanta, Georgia 30332-0150

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Fax: 404•894•2760

On the financial side, a statement of expenditures for the period from October 1 through December 31, 1994 is attached.

Should you need to contact me, I can be reached at (404) 894-8198.

With all best wishes and regards, I remain,

Very truly yours,

✓

Dr. George A. Kardomateas

Associate Professor of Aerospace Engineering

Project Director

Financial Status Report - Air Force Project #F09603-91-G-0096-0013

GT Project # E-16-M57
 Period: 10/1/94-12/31/94
 P.I.: George Kardomateas

Budget Category	Budget	Previous Expenditures	Current Period Expenditures	Total Expenditures	Balance
Personal Services	50,407.00	51,433.49	1,800.00	53,233.49	(2,826.49)
Fringe Benefits	7,840.35	8,212.95	0.00	8,212.95	(372.60)
Materials & Supplies	16,000.00	4,925.25	909.76	5,835.01	10,164.99
Travel	2,000.00	1,579.13	0.00	1,579.13	420.87
Capital Outlay	11,526.65	6,336.50	0.00	6,336.50	5,190.15
Subcontracts	0.00	11,000.00	0.00	11,000.00	(11,000.00)
Overhead	32,226.00	30,392.92	1,083.90	31,476.82	749.18
Total	120,000.00	113,880.24	3,793.66	117,673.90	2,326.10

**SHORT CRACKS TEST PROGRAM FOR MH-53J DYNAMIC
SYSTEM & AIRFRAME COMPONENTS**

Participants:

Dr. George A. Kardomateas (PI)
Associate Professor of Aerospace Engineering
Georgia Institute of Technology

Dr. Robert L. Carlson
Professor Emeritus of Aerospace Engineering
Georgia Institute of Technology

Other Participants as Graduate Research Assistants:
D. L. Steadman, D.S. Dancila, A.A. Pelegri, C.S. Valle

Air Force Contract
F09603-91-G-0096-0013

Final Report Prepared for the
Warner Robins Air Logistic Center
Damage Tolerance Analysis Lab (WR-ALC/TIEDD)
Program Monitor: Mr. Gary Chamberlain
Robins Air Force Base
Georgia 31098-5149

May 1996



School of Aerospace Engineering
Atlanta, Georgia 30332-0150 U.S.A.
PHONE 404-894-3000
FAX 404-894-2760

July 15, 1996

Ms. Wanda Simon
OCA - 0420

Ref: Project no: E-16-M57

Sponsor: Warner Robins Air Force Base (WR-ALC)

Contract no: F09603-91-G-0096-0013

Project Monitor: Gary Chamberlain

Project Title: "Short Cracks Test Program for MH-53J Dynamic System
& Airframe Components".

Final Report

Dear Ms. Simon:

I am enclosing two copies of the the Final Report for the above referenced project. Three copies have been directly mailed to the Sponsor (WR-ALC). Therefore, no further distribution is needed. Please update your database record on this project accordingly.

Should you need to contact me, I can be reached at (404) 894-8198 and my FAX no. is (404) 894-2760.

I remain,

Very truly yours,

, / , /

Dr. George A. Kardomateas

Associate Professor of Aerospace Engineering

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SUMMARY

Results of an experimental investigation of the fatigue growth of small corner cracks emanating from small flaws are presented. Tests were conducted in three point bending on specimens with square cross-sections, and the orientation of the specimens resulted in a maximum tensile stress on a corner at the midpoint of the gage section. Two types of tests were conducted. The results of the first test were used to quantify the threshold stress intensity for this specimen. The later tests measured fatigue crack growth through the small crack region. Growth-arrest behavior was observed and increases in crack length during growth periods were of the order of the transverse grain size, so it is inferred that grain boundaries acted as barriers to continuing growth. Growth exhibited the so-called anomalous behavior, i.e., growth occurred below the near fatigue threshold. The crack front samples, on the average, only three to six grains in the small crack regime monitored, so only a small number of constrained, interior grains are encountered. It is suggested that the presence of these partially constrained surface grains may contribute to the 'anomalous' behavior.

ACKNOWLEDGMENTS

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NOMENCLATURE

- a, c -- corner crack lengths
 ΔK -- stress intensity factor range
 ΔK_{eff} -- effective stress intensity factor range
 ΔK_{th} -- threshold stress intensity factor range
 K_{IC} -- mode one critical stress intensity factor
 P -- load amplitude
 R -- ratio of maximum to minimum load
 S_{max} -- applied maximum stress
 S_0 -- closure opening stress

INTRODUCTION

Background

The discovery by Pearson [1] that the growth behavior of 'small' fatigue cracks differed from that of 'long' cracks has served as an impetus for the initiation of many subsequent research investigations. Some of these have been designed to discover basic, operative mechanisms and others have focused on the development of analytical procedures for predicting growth histories. The latter approach has been motivated by the desire to provide methods that can be used by designers of structural systems. The results of these investigations have been reported in numerous papers. In a recent paper Halliday, Poole and Bowen [2] have referenced results which have been reported on both aspects of the small fatigue crack problem.

Many of the studies which have been reported have concentrated on the growth of 'natural' cracks which started on the surface of highly polished specimens. Often, the surface 'thumbnail' cracks which have been produced emanated from cracks in brittle intermetallic inclusions. Investigations based on crack initiation from small notches have also been conducted [3,4]. Results for edge and corner notched specimens tested in tension have been obtained, and recommendations for notch preparation are given in an Appendix to the American Society for Testing and Materials Test Method E647 [5].

Program Objectives

The objectives of this program were to develop procedures for initiating very small cracks by cyclic loading and then monitoring the growth under continued cyclic loading. The objective also included the development of analyses which describe, quantitatively, the crack growth history as a function of the loading and the geometry of the cracked specimen in terms of the range of stress intensity factor.

Summary of Testing and Results

Three-point bending fatigue experiments were conducted on a series of Al 6061-T651 specimen with square cross-sections at the gauge sections. A small corner notch was machined in each specimen to provide a corner crack initiation site. The growth of the corner crack during each experiment was monitored using a traversing tele-microscope with a video camera. One

experiment was conducted to quantify the near threshold behavior for small and comparatively long cracks for this specimen design. Subsequent experiments monitored the growth of small corner cracks and continued only while the crack was in the small crack regime. The Crack Length versus Cycles (S-N) experimental data were translated into Stress Intensity versus Growth Rate data, and then fitted to a growth rate law.

The experimental data exhibited the growth-arrest behavior commonly associated with small cracks. Also, it was observed that the advance during growth periods was on the order of the grain size.

EXPERIMENTAL PROGRAM

Test Specimen

The tests were conducted on specimens of the type shown schematically in Figure 1. Corner cracks initiate at a notch machined at the corner of two adjacent faces in the middle of the gauge section. This is in contrast to the Larsen[6] specimen, which allows for surface crack propagation at the bottom of a mild stress concentration. The specimens are designed such that three-point bending tests are used to initiate a small corner crack. The growth of small corner cracks can then be investigated by fatigue testing under continued three-point bending loading or tensile loading. For this work, all tests were conducted in three point bending.

Material

The test material for the investigation was the aluminum alloy 6061-T651 and specimens were machined from 16 mm diameter bar stock. The 0.2 per cent offset yield strength is 283 MPa and the ultimate strength is 293 MPa. The average transverse grain size is 200 microns. The longitudinal grains were elongated and varied widely about an average of 350 microns.

Machining

Each specimen had circular cross sections at the ends and a gage section with a square cross-section as shown in Figure 1. A small corner notch was introduced at the center of each specimen to serve as the site of crack initiation. This procedure was chosen to represent the presence of small mechanical flaws, such as nicks or gouges, which are often introduced during manufacturing or maintenance operations. Notches with a 60 degree included angle were cut by use of a digitally controlled slitting saw. The initial notch depth for each specimen is between 100-200 μm , but this depth was reduced by subsequent polishing.

Polishing

Polishing was used not only to provide a smooth surface for the optical observation, but also to eliminate potential crack initiation sites other than the notch. In addition, the surface disrupted by the machining process is removed. Two adjacent cracked faces were polished with six grades of abrasive papers and polishes, ranging from 600 to 2000 grit. For a consistent surface, the abrasive papers were attached to a square block and the specimen was passed over

them. Finally, the specimen were polished with three- and one- micron pastes using a hand-held buffing tool. During each stage, the polishing direction was perpendicular to the last. A low-magnification microscope was used to ensure removal of the previous polish lines. With the final paste the surface was polished perpendicular to the crack growth direction. After each stage, the notch depth was measured on both surfaces to ensure a consistent material removal process. By polishing after notching, it was possible to obtain very small notches.

Testing

Loading Condition

All experiments were conducted in three point bending, with the notch at the middle and at a bottom corner of the gauge section. The three point bending state of loading used is depicted in Figure 2. By virtue of the orientation of the specimen, the maximum tensile stress is developed at the notch location. The neutral axis is, therefore, horizontal and on a diagonal of the square cross-section. Since the region of high tensile stress is localized, the specimen should be suitable for developing 'natural' corner cracks in a reasonably predictable location. It should also be noted that this specimen could, after crack initiation, be tested in tension.

Note that the loading state used differs from that of Pickard, Brown and Hicks [3] who used tensile loading. It may also be observed that for a given crack geometry, the crack growth rate is less for the stress state developed by bending than that for tensile loading. This facilitates the monitoring of crack growth after initiation.

Equipment

Experiments were conducted on an Instron servo hydraulic testing machine under sinusoidal loading. The Instron is digitally controlled, with all tests conducted under load control. To conduct the tests, the three point loading assembly shown in Figure 3 was constructed. The center stationary mount has a square edged notch to fit the specimen, while the two outer mounts of the carriage are rounded to ensure that no torsion is applied. An optical measurement system was used to monitor crack growth. The Questar tele-microscope used has an optical resolution of 2.5 microns and a working range of 0.55 to 1.7m. A video camera outputs the image to a video enhancer. This enhancer allows manual or automatic control of contrast, brightness, and sharpness features, as well as superimposes a cross-hair onto the video image. The image is displayed on a high resolution (1000 TV lines) monitor. The tele-microscope is mounted to a three-axis translation stage with position transducers. An interface provides digital position

information as a cross-hair in the microscope video image is aligned with the crack. Position measurements are accurate to 10 microns.

Procedures and Results

Two types of experiments were conducted. For specimen #1, growth of a moderately long crack was monitored to establish the near threshold region. For specimens #2 and #3, the growth of a small crack was monitored from initiation throughout the small crack regime.

A thin paint film was applied prior to each measurement. The paint has an alcohol based solvent. The membrane film was locally distorted along the crack, and it enhanced the visual image of the crack tip. Crack lengths were measured at regular intervals to obtain data for records of crack length versus loading cycle

Specimen #1

This experiment was conducted to quantify the threshold behavior of corner cracks in the test configuration. The maximum load was incrementally increased every 100,000 cycles until crack initiation was observed, with a constant load ratio of 0.625. The crack was first observed to have grown after 1,300,000 cycles. After that point, the maximum load was incrementally reduced until the growth rate reached 10^{-8} m/cycle. The stress intensity range corresponding to this load and growth rate is the threshold stress intensity range, ΔK_{th} . The results of this experiment are shown in Figure 4.

Specimen #2

A load corresponding to 90 percent of yield at the notch base was applied until crack initiation. Crack initiation from the notch tip was first detected after 150,000 cycles. The maximum load was then reduced to produce a maximum stress of approximately 50 percent of the yield strength, but there was no additional growth after the initiation. After an additional 100,000 cycles, the load was increased to approximately 55 percent of the yield and crack growth restarted. Throughout the experiment, the load ratio was kept at 0.625. The results of this experiment are shown in Figure 5

Specimen #3

A load corresponding to 90 percent of yield at the notch base was applied until crack initiation. Crack initiation from the notch tip was first detected after 180,000 cycles. At this point, the maximum load was reduced to 50 percent of yield, and remained at this value for the duration of the experiment. Throughout the experiment, the load ratio was kept at 0.625. The results of this experiment are shown in Figure 6.

Comparison with Other Methods

The corner crack specimen have several advantages over types of fatigue specimen in use. For example, the commonly used Larsen[6] test involves a specimen with a surface crack on one face with a mild stress concentration. The specimen is loaded in tension. A disadvantage of a surface crack is that only the length can be easily measured; the depth is usually estimated through an assumption of a circular crack front or through analysis of the opening displacement at the surface. In contrast, the two surface dimensions of a corner crack correspond to the depth of a surface crack. The front is only assumed to be quarter-elliptical instead of perfectly semi-circular. This weaker assumption allows a more rigorous estimation of the stress intensity factor, which is critical for small crack calculations. In addition, the use of three-point bending provides a more localized stress field, so that the location of naturally initiated cracks can be anticipated. Also, crack growth is slower under three-point bending than tension for the same maximum stress. Finally, the presence of small imperfections away from the notch site are not as detrimental as with tension loading.

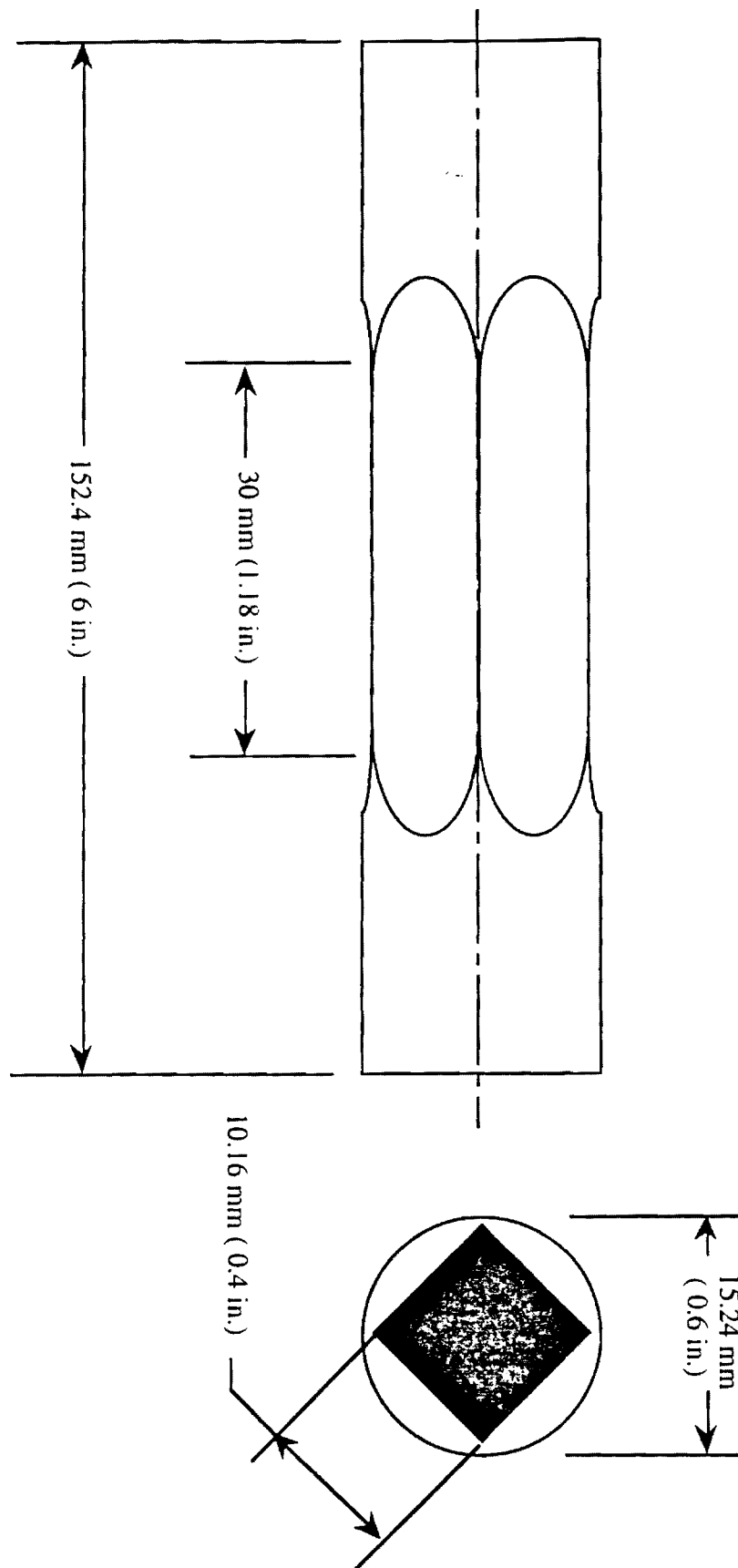


Figure 1: Test Specimen

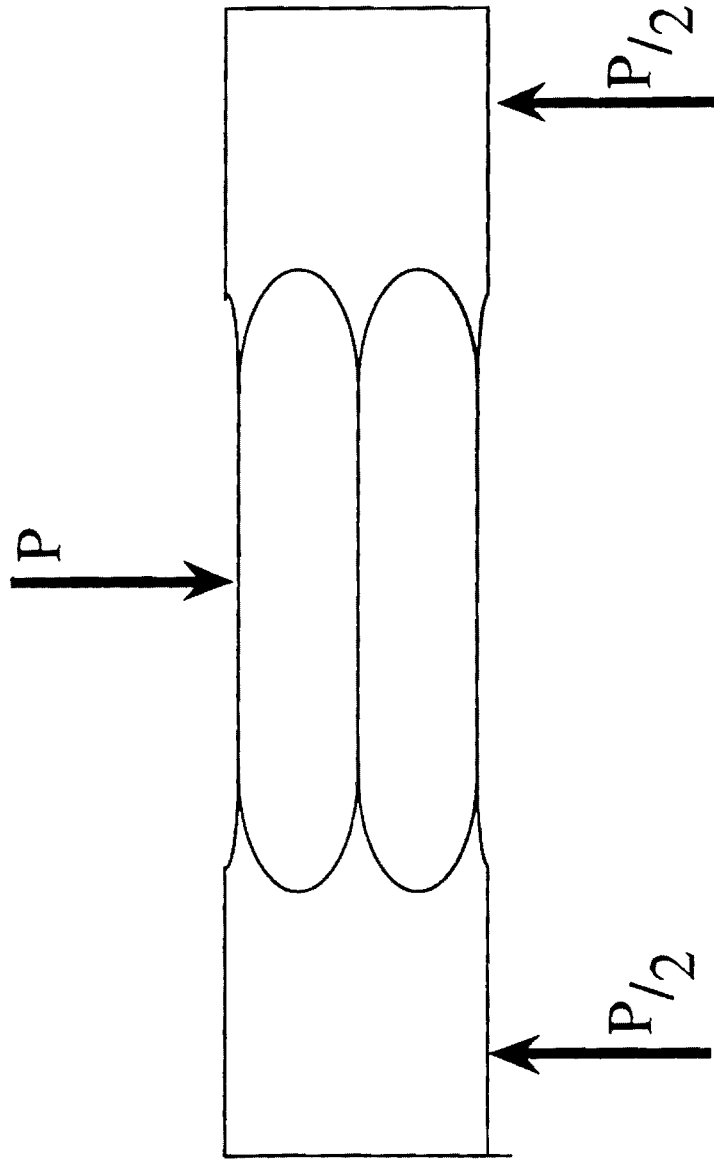


Figure 2: Loading State

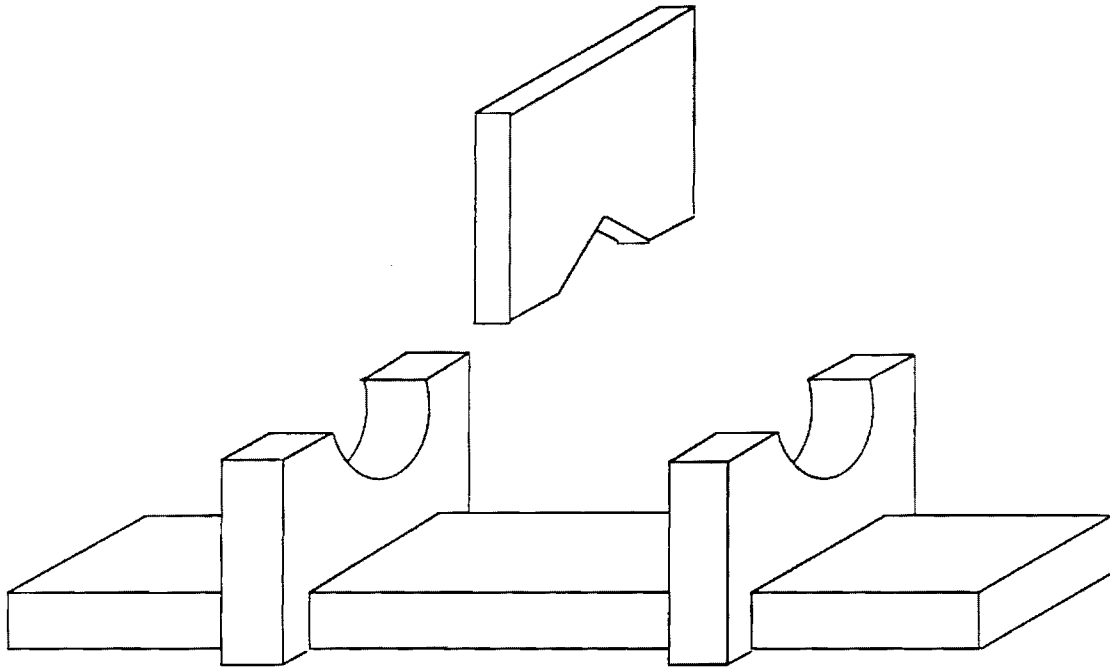


Figure 3: Schematic of Three-Point Bending Assembly

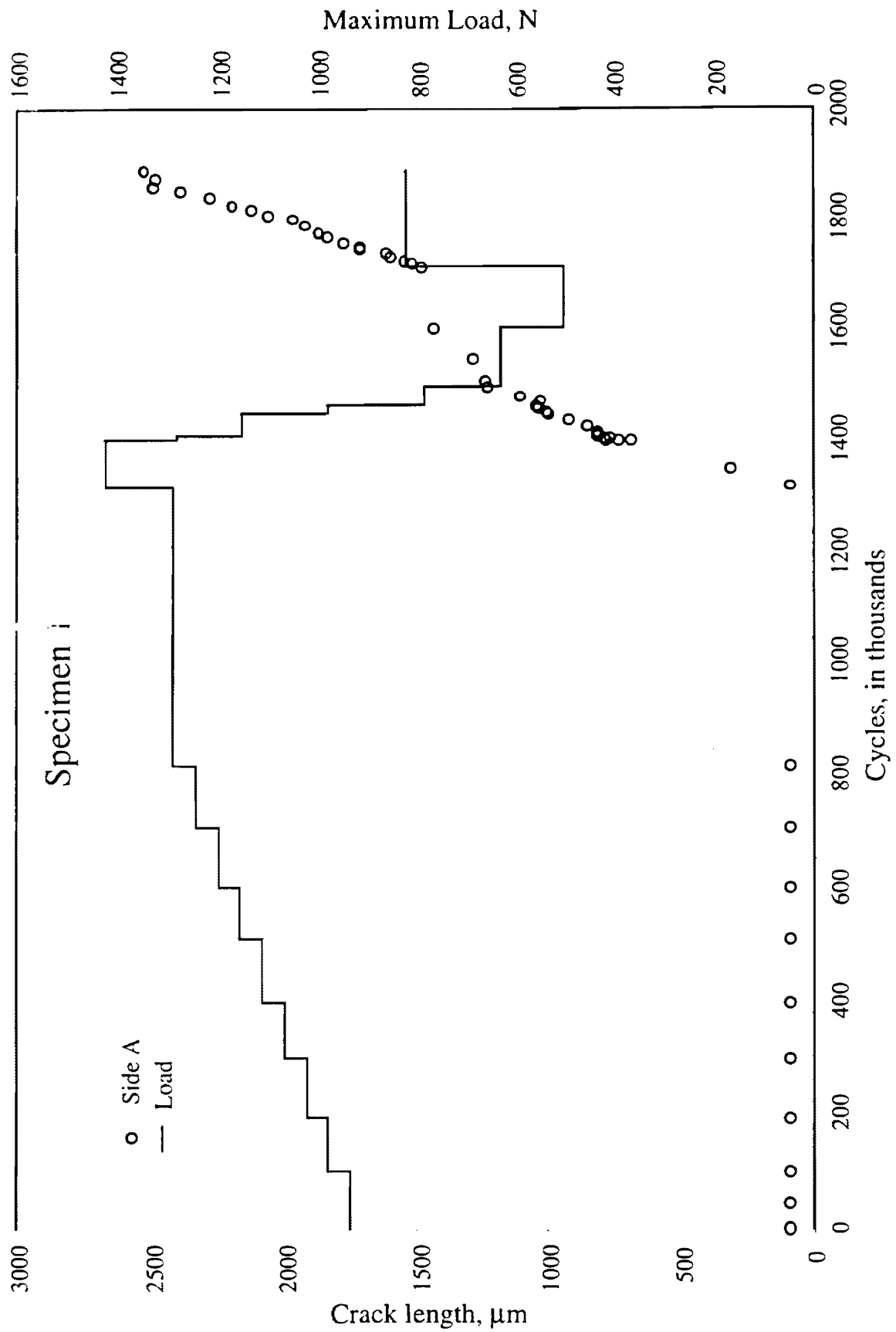


Figure 4: Crack Length and Loading versus Number of Cycles, Specimen 1

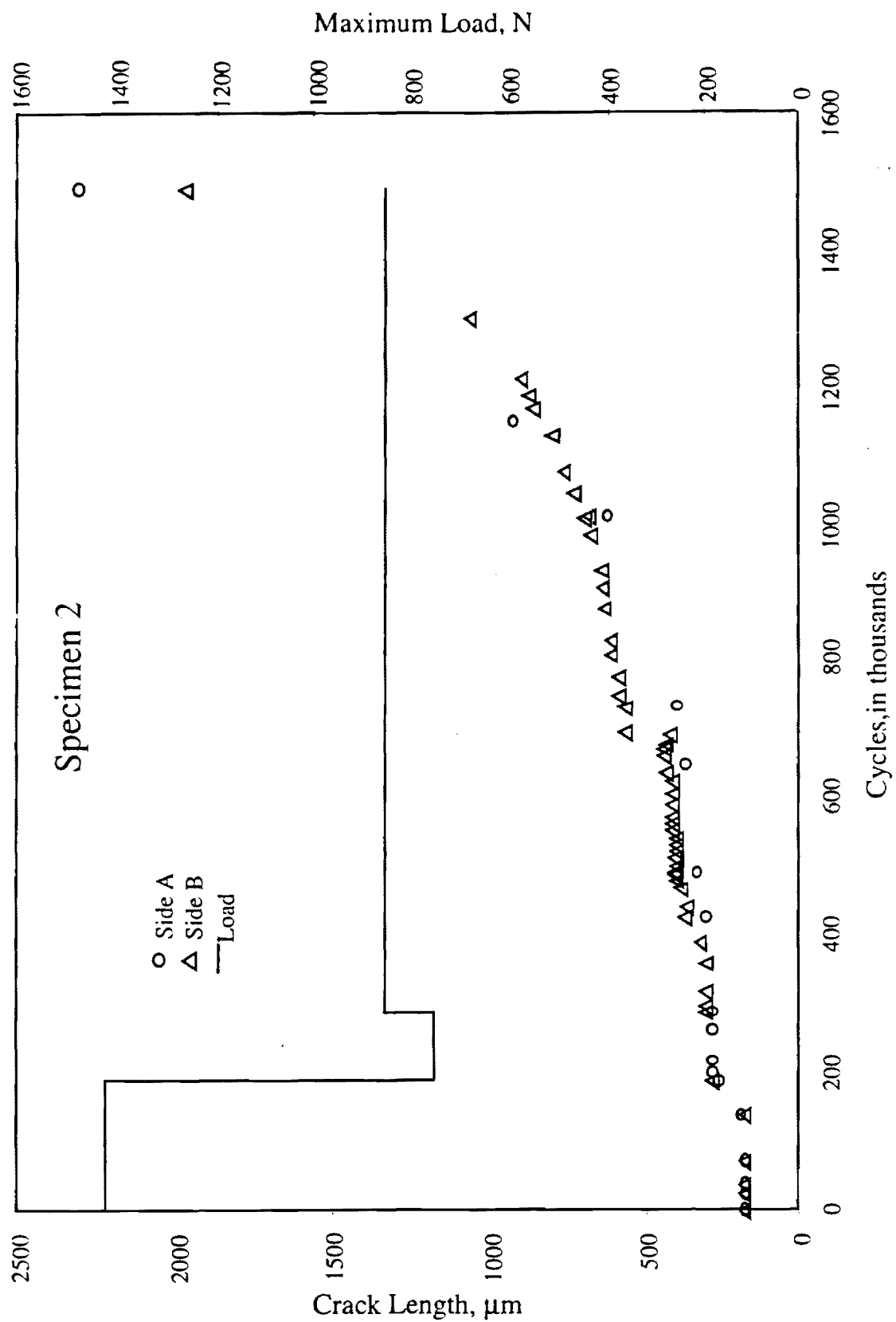


Figure 5: Crack Length and Loading versus Number of Cycles, Specimen 2

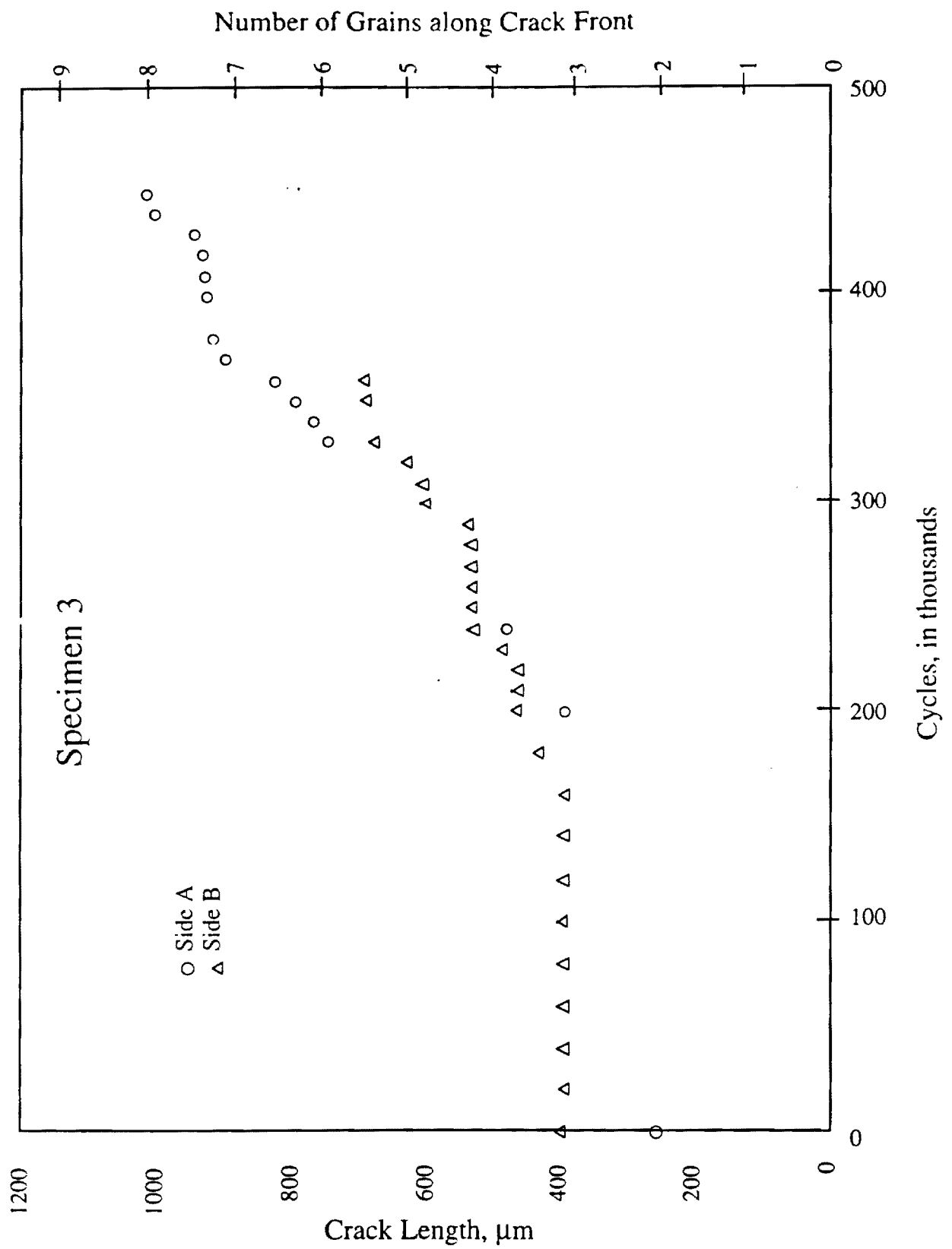


Figure 6: Crack Length and Number of Grains on Crack Front versus Cycles

EXPERIMENTAL ANALYSIS

The analysis discussed in this section is based on the results of experiments on specimen 3. The growth-arrest pattern observed by other investigators is clearly present. Readings were most frequently taken on side B. Initially growth on side A lagged behind that for side B. The observed crack paths were not always normal to the specimen axis, and branching was observed. However, one branch eventually became dominant.

Fractographic Analysis

A photograph of the fatigue fracture surface is shown in Figure 8. The corner notch is at the bottom. After the fatigue crack had extended about 2000 microns from the corner, the cyclic bending was discontinued and the specimen was fractured under a tensile load. The small region at the top edge is part of the surface resulting from the tensile fracture. Note that the crack front at the end of the cyclic loading is very nearly on a circular arc centered at the corner.

A fractograph of a representative site on the fatigue fracture surface is shown in Figure 9. The crack advance was upward and angled toward the left. An examination of the surfaces revealed that they were non-flat or torturous and typical of Stage I crack propagation. Separation was dominantly by shearing with petal-like or tunneling advances. Some evidence of ridge-like offsets were observed.

Stress Intensity Calculation

Although the use of the stress intensity factor as a correlation parameter for small crack growth has been questioned [7,8,9,10], its use does provide a means of comparing long and small crack growth. It is, therefore, used for that purpose here. Its incorporation as a parameter for design for small crack growth is another issue which is discussed in a subsequent section.

The stress intensity factor used is based on results for a corner crack in a bar with a rectangular cross-section in the NASA/FLAGRO computer program [11]. The analyses in this program were for bending moments whose vector axes were parallel to the faces of the bar. For the current tests the test specimens had square cross-sections and two equal bending moments whose vector sum provides a bending moment about a cross-section diagonal: i.e., the neutral axis of the bending coincided with a cross section diagonal. Based on the fractographic results, we have taken the crack fronts to be circular arcs with a center at the corner. For cases where the a and c lengths (see Figure 7) were measured to be different, an average value was used. The stress

intensity for any experimental point is calculated as outlined in [11]. One difference is that because of the small range of a/t and c/W during the experiment, linear interpolation is used instead of Hermite polynomials. For a general crack under combined loading, the stress intensity factor can be expressed as

$$K = [S_0 F_0 + S_1 F_1 + S_2 F_2 + S_3 F_3] \sqrt{\pi a} \quad (1)$$

where S_0 , S_1 , S_2 , and S_3 represent applied stresses in tension, compression, bending, or pin bearing pressure.

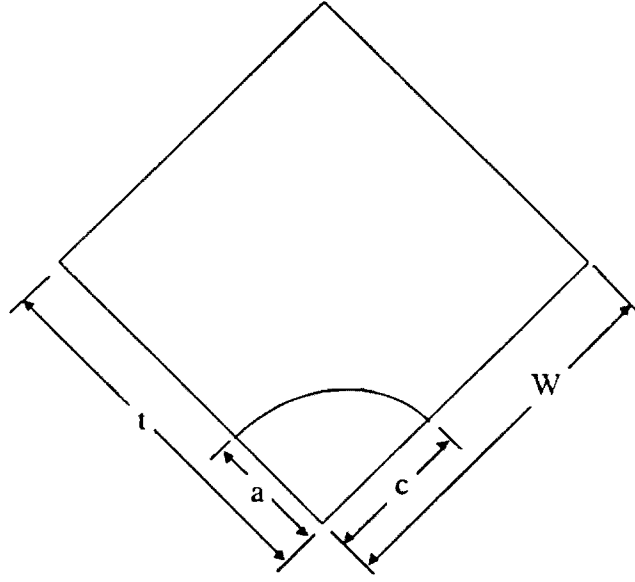


Figure 7: Corner Crack Schematic

F_i factors account for the geometry of the problem. For a corner crack, each geometric factor F_i is defined by:

$$F_i = f_x f_\theta f_d f_i \quad (2)$$

where

$$f_x = \left[1 + 1.464 \left(\frac{a}{c} \right)^{1.65} \right]^{-1/2} \text{ for } a/c \leq 1 \quad (3)$$

$$f_s = \left[1 + 1.464 \left(\frac{a}{c} \right)^{-1.65} \right]^{-1/2} \text{ for } a/c > 1 \quad (4)$$

and

$$f_\phi = \left[\left(\frac{a}{c} \cos \phi \right)^2 + \sin^2 \phi \right]^{1/4} \text{ for } a/c \leq 1 \quad (5)$$

$$f_\phi = \left[\cos^2 \phi + \left(\frac{c}{a} \sin \phi \right)^2 \right]^{1/4} \text{ for } a/c > 1 \quad (6)$$

with ϕ defined as 0° at the a-tip and 90° at the c-tip. Note that $f_\phi = 1$ for $a = c$. Thus, K is constant everywhere on the crack front. Finally,

$$f_u = 1 \text{ for } a/c \leq 1 \quad (7)$$

$$f_u = \sqrt{c/a} \text{ for } a/c > 1 \quad (8)$$

Values for $f_i(a/c, a/t, c/W)$ are obtained from an interpolation of tabular data. Reference [11] contains the complete table, but only a small portion of the table is required for our experimental results. The tables for f_0 , f_1 , and f_2 are reproduced in Table 1, Table 2, and Table 3, respectively.

All of the specimen tested have a square cross-section, so $t = W$. In addition, the treatment of the crack front as a circular arc as discussed before requires that $a = c$. The geometry of the three-point load condition leads to

$$\sigma = \frac{3 P L}{\sqrt{2} t^3}, \quad (9)$$

where P is the load and L is the distance between the bending supports. This stress σ is the result of the combined loading of S_1 and S_2 in the FLAGRO notation, such that

$$S_1 = S_2 = \frac{\sigma}{2}. \quad (10)$$

Therefore, for this specimen configuration, the stress intensity for a given load and crack length is

$$K = 0.676 \frac{P L}{t^3} \sqrt{\pi a}. \quad (11)$$

Growth Rate Analysis

Data for the long crack test are presented on the log-log plot of Figure 10. Data for both a decreasing and constant load were obtained and the straight line through the data points can be represented by the equation

$$\frac{da}{dN} = 10^{-8} \left[\frac{\Delta K}{6.7} \right]^{28}. \quad (12)$$

The exponent here is not to be confused with the exponent in the Paris equation for region II growth rate behavior. The large value of this exponent is the result of the fact that the da/dN versus ΔK curve in region I (the threshold region) is much steeper than the curve in region II. It is clear from the steepness of the slope that small errors in the determination of a stress intensity factor could result in large errors in a computed growth rate in the near threshold region.

The log-log plot of Figure 10 distorts the relationship between growth rate and range of stress intensity factor. Since the range of the variables in the near threshold region is not too large, it is possible to examine the near threshold behavior by use of the Cartesian coordinate plot of Figure 11. The curve shown is a plot of Equation (12). As to be expected, the growth rate goes to zero as ΔK goes to zero. The additional data points shown are discussed in a subsequent section.

Miller [7] has given a qualitative description of crack growth history by using crack length on a left-hand ordinate and sizes of microstructural features on a right-hand ordinate. This provides a perspective for comparing the length of a growing crack with such features as inclusions and grain size. If for the corner crack, it is assumed that the circular arc of the crack front is centered at the crack corner, the number of grains, on the average, along a crack front for a given crack length can be determined from the equation

$$n = \frac{\pi a}{2D}, \quad (13)$$

where a is the crack length (or radius to the crack front from the corner), n is the number of grains along the crack front and D is the transverse grain size. The photograph of the fracture surface in Figure 8 confirms that this is an acceptable assumption. Equation (13) has been used to determine the scale of the right-hand ordinate of Figure 6. Comparisons of the two ordinates, then, indicates the number of grains encountered, on the average, for a given crack length.

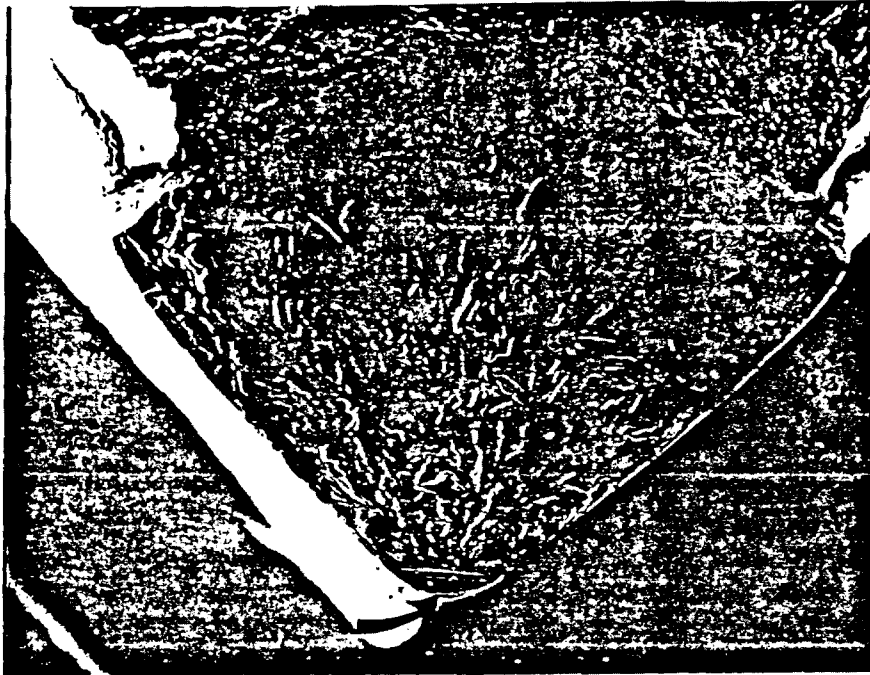


Figure 8: Fatigue Fracture Surface



Figure 9: Fractograph of Fracture Surface

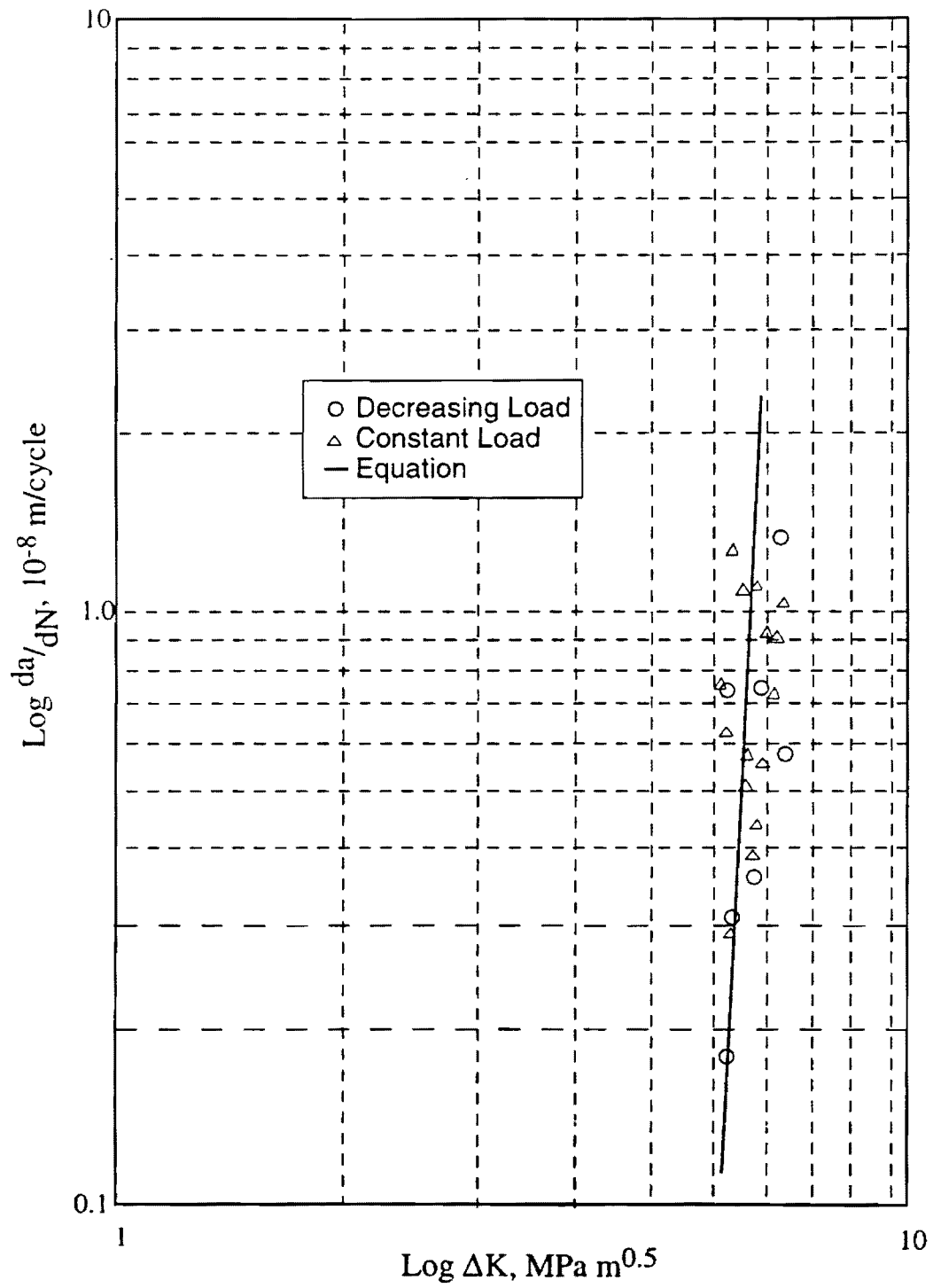


Figure 10: Data in the Near Threshold Region

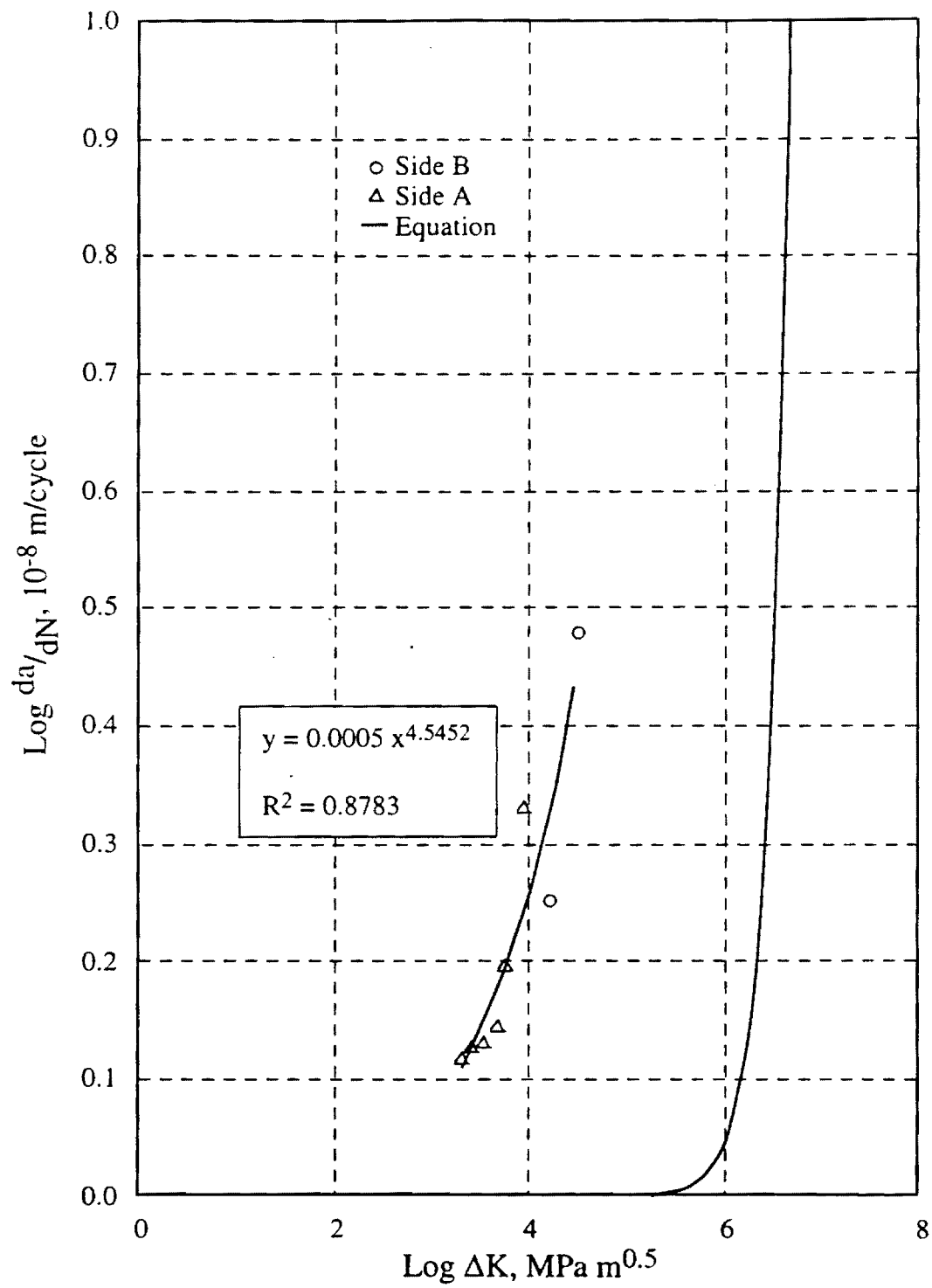


Figure 11: Cartesian Plot of Near Threshold Curve and Small Crack Data

Tables from FLAGRO Users Manual [10]

a/c	a/t	c/W = 0.0		c/W = .1		c/W = .2	
		a-tip	c-tip	a-tip	c-tip	a-tip	c-tip
0.5	0.0	1.086	1.158	1.090	1.160	1.097	1.165
	0.1	1.102	1.179	1.106	1.180	1.113	1.185
	0.2	1.130	1.211	1.134	1.217	1.147	1.228
1.0	0.0	1.138	1.138	1.142	1.141	1.145	1.144
	0.1	1.141	1.142	1.144	1.144	1.154	1.152
	0.2	1.144	1.145	1.152	1.154	1.172	1.172

Table 1: Values of f_0

a/c	a/t	c/W = 0.0		c/W = .1		c/W = .2	
		a-tip	c-tip	a-tip	c-tip	a-tip	c-tip
0.5	0.0	1.086	1.158	1.090	1.160	1.097	1.165
	0.1	0.946	1.130	0.952	1.039	0.965	1.148
	0.2	0.808	1.114	0.820	1.126	0.840	1.140
1.0	0.0	1.138	1.138	1.142	1.141	1.145	1.144
	0.1	0.965	1.807	0.977	1.097	0.993	1.111
	0.2	0.785	1.047	0.810	1.060	0.838	1.080

Table 2: Values of f_1

a/c	a/t	c/W = 0.0		c/W = .1		c/W = .2	
		a-tip	c-tip	a-tip	c-tip	a-tip	c-tip
0.5	0.0	1.086	1.158	1.055	0.989	1.020	0.789
	0.1	1.102	1.179	1.074	1.000	1.040	0.809
	0.2	1.130	1.211	1.100	1.025	1.070	0.846
1.0	0.0	1.138	1.138	1.087	0.965	1.047	0.785
	0.1	1.141	1.142	1.097	0.977	1.060	0.810
	0.2	1.144	1.145	1.111	0.993	1.080	0.838

Table 3: Values of f_2

DISCUSSION OF RESULTS

When a crack front encounters a small number of grains, the effects of grain boundaries and grain orientations can be expected to influence the manner in which the crack extends [12,13,14]. A comparison of values on the ordinate scales of Figure 6 provides insight into the microstructural features encountered by the crack front. For the initial portion of the growth history the abrupt growth steps are about one third of the grain size.

The role of grain boundaries in the growth behavior observed may be illustrated by reference to Figure 12. Grains on the crack plane at the corner are represented by an hexagonal array. The scale on this figure has been chosen so that the sizes of the hexagons correspond to the transverse grain size. Since grain boundaries have been observed to arrest crack growth, it may be anticipated that a uniform growth-arrest behavior could be developed for the pattern exhibited in Figure 12(a) as a crack propagated from the corner. The pattern of Figure 12(a) is symmetric with respect to a line bisecting the corner, however, and this arrangement of the grains is not likely to occur. Figure 12(b) represents a case in which the above symmetry is not present. For this pattern it again may be anticipated that a growth-arrest behavior could develop. In addition, however, it can be seen that the arrangement of the grains may be expected to lead to slightly different growth histories on the monitored faces adjacent to the corner. Measurable differences in growth on the two faces may be expected to continue until the ratio of the grain size to the crack length becomes so small that they are a small fraction of the crack lengths.

An examination of the initial growth features in Figure 6 would indicate that an elaborate scheme for computing growth rates is not warranted. Often, in fact, growth rate data are simply represented by clusters of unconnected data points on log-log plots of growth rate versus range of stress intensity factor [13,15]. Nevertheless, continuing growth is occurring and a growth trend is indicated. A simple method for representing the growth rates has been adopted. A trend curve has been developed by connecting successive inner corners of the steps. The rates so determined, are indicated in Figure 11 for both faces of the corner. An equation for growth rate is given in Figure 11 along with its correlation coefficient. The small crack growth curve is to the left of the near threshold curve. Thus, for a given ΔK , the small crack growth rates are greater than those for long cracks.

The number of grains encountered by the crack front of a long crack can generally be expected to be relatively large. For corner and 'thumbnail' cracks this number increases with increasing crack depth; i.e. as the small crack grows and becomes a long crack. An examination of Figure 6 indicates that over the range for which growth-arrest behavior has occurred, the number of grains encountered by the crack front is small. Thus, when four grains are encountered, two, or one half of the grains, have free surfaces. Thus, only the two internal grains are completely

surrounded and constrained. Even when the number of grains is five, two grains are not constrained on their free surfaces. It has been suggested [16] that when the number of grains is small, the effect of the surface grain contributions to crack extension may be expected to be greater than when the surface grains are a small fraction of the total number of grains along the crack front. This is somewhat analogous to the behavior in which the gross yield strength increases with decreasing grain size because of increasing grain boundary constraint [17].

Thus, although reduced closure obstruction for small cracks has often been cited as the reason that growth rates for small cracks are larger than those for long cracks, the small number of grains encountered and its consequences may also be a contributing factor. If this conjecture is correct, there could be, for the same alloy and crack depth, differences in crack growth rates for small corner cracks, small thumbnail cracks and short cracks. Note that for the alloy tested a short, through edge crack in a 5 mm thick sheet would encounter about 25 grains. Also, the number of grains along the front of a small thumbnail crack would be about twice that for a small corner crack of the same depth. The stress intensity factor is insensitive to these details, so it cannot be expected to account for behaviors which may result from these differences.

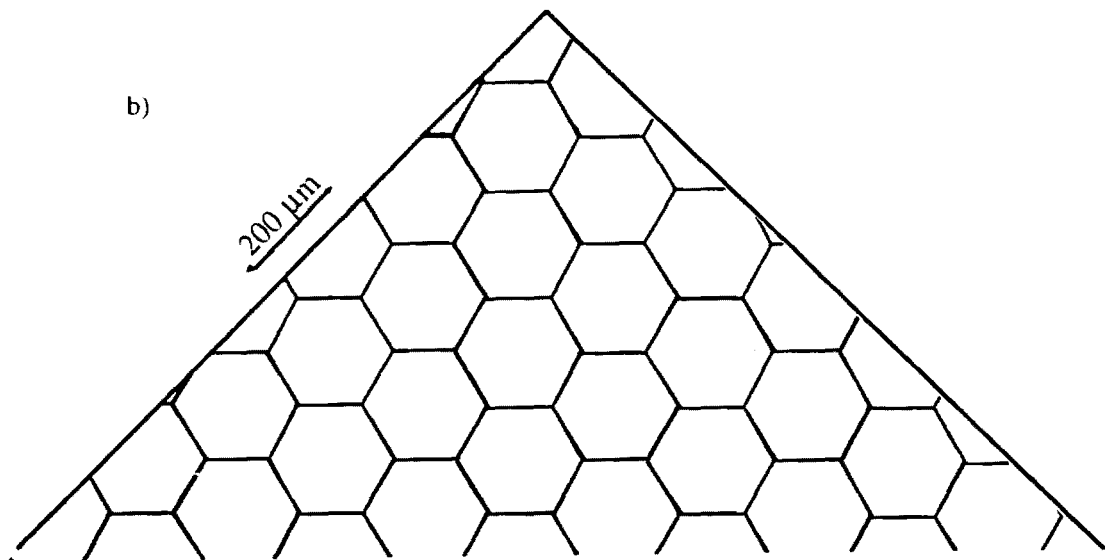
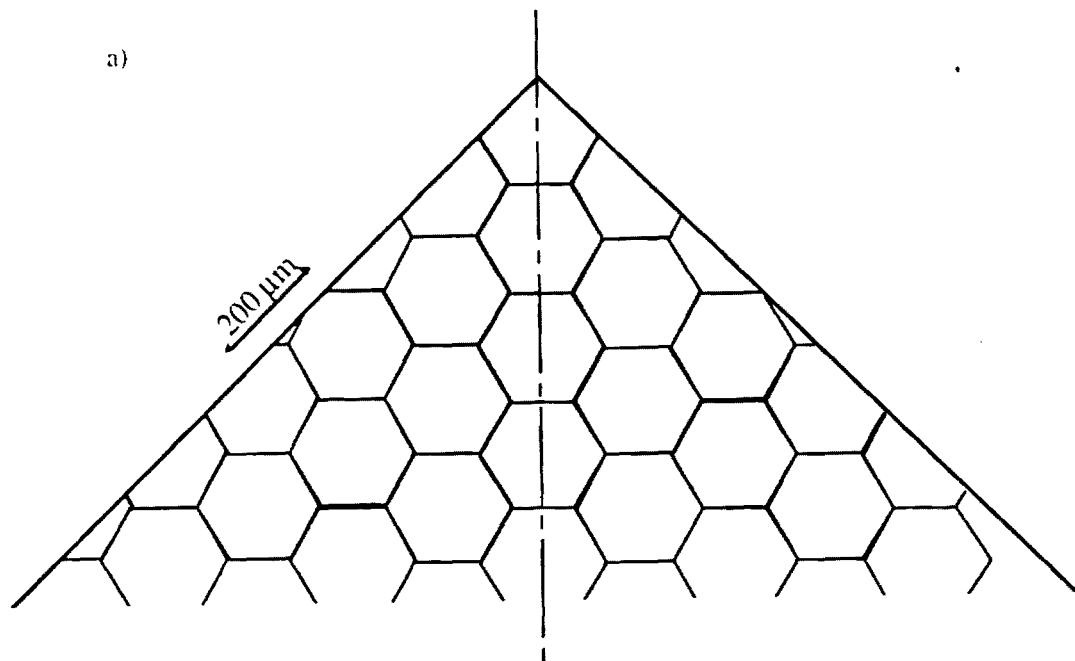


Figure 12: Models of Grain Patterns on Crack Surface Plane

ANALYSIS

Predictive codes that use fatigue crack growth rate equations which include near threshold effects, stress ratio effects, closure obstruction effects and the transition from stable to unstable crack growth are available for long cracks (see Ref. 10, for example). It is of interest to note, however, that Heuler and Schütz [18] have suggested that a safety factor of two should be used predicting crack growth for service components. This reservation about confidence in the use of predictive codes has also been cited by Blom [19] who has suggested that in applications in which there is limited experience, a factor of two may even be 'too optimistic'.

Effective Stress Intensities for Small Cracks

The growth of small fatigue cracks is less well understood than that for long cracks. It may, therefore, be anticipated that methods for predicting the growth of small cracks should incorporate greater margins of safety than those recommended for long cracks. Of the methods that have been proposed for analyzing the growth of small cracks, three are considered here. Of these, the simplest has been described by Owen, Bucci and Kegarise [20]. This method proposes that the $\log da/dN$ versus $\log \Delta K$ curve be extended by a straight line to the left from the Paris region. This does not directly address the small crack growth issue, but it introduces a simple procedure for compensating for the uncertainties associated with small crack behavior. This proposal is illustrated in Figure 13 for the aluminum alloy 2024-T3. One reaction to this procedure has been that it is drastically conservative. This reaction, however, may partially be a consequence of the type of plot (log-log) used. A Cartesian plot of the same curves in the near threshold region is presented in Figure 14. Clearly, the apparent conservatism indicated by a casual examination of Figure 13 is shown to be a property of the scaling used; i.e., Figure 14 provides a better basis for viewing the degree of conservatism.

A proposal by Blom et al [21] is most easily described by reference to the stress versus crack length Kitagawa diagram [22] shown in Figure 15. The solid curve of the diagram provides a lower bound below which fatigue failure should not occur for a stress ratio of $R=0$. The lower bound for very small cracks in region I is the endurance limit stress. In region III linear elastic fracture mechanics applies and the lower bound is a straight line given by the equation

$$\Delta\sigma = \sigma = \frac{K_{th}}{Y\sqrt{\pi a}}, \quad (14)$$

where the subscript th denotes the threshold value of the range of stress intensity factor and Y is a coefficient for specimen geometry and loading.

In an extension of the Kitagawa diagram an upper, dashed curve represents an upper bound for fatigue failure. On the ordinate the curve passes through the stress value for the ultimate strength. The portion of the upper bound curve emerging from the ultimate strength value represents failures which are governed by nonlinear, inelastic fracture mechanics. The inclined straight line on the right is given by the equation

$$\sigma = \frac{K_{IC}}{Y\sqrt{\pi a}}, \quad (15)$$

where the subscript IC denotes the critical value of the stress intensity factor. The addition of an upper bound provides a perspective on how ultimate fracture behavior can vary from stress levels which can be described by linear elastic fracture mechanics analyses to levels which require inelastic fracture mechanics analyses.

The behavior in region II is not described by extensions of either of the solid straight lines of regions I and III. Rather, experimental data fall below these extensions as indicated by the connecting curve. The transition crack length values, a_1 and a_2 , are dependent on microstructure, and can vary widely. Taylor and Knott [23] suggest that a_2 is approximately ten times a microstructural unit, such as the grain size. A dependency on grain size may be inferred from the experimental data presented in Figure 6.

Experiments conducted by Blom et al [21] were designed to determine the values of stress in region II. After crack nucleation, the load was successively decreased and increased to determine the levels of loading for which crack growth was arrested and resumed. By this procedure they established the transition curve between regions I and III. They then constructed a line (shown dashed in Figure 15) which was parallel to that for ΔK_{th} and passed through the transition point from region I to region II. They then used this new line to define an effective threshold value for the range of stress intensity factor, $eff\Delta K_{th}$. Since the effect of the threshold value diminishes with increasing ΔK , only the lower part of the da/dN diagram is affected. The result is a shift of this lower portion to the left. This effect is not unlike that illustrated in Figure 13 and Figure 14. For the Blom et al [21] proposal the value of a_1 must be determined for each material. It may, of course, be possible to deduce this value.

Results obtained in a number of investigations have indicated that low load ratio tests on small cracks appear to correlate with long crack data for high load ratio tests. It can be inferred from this that either an absence or a reduction in obstruction to closure common for these test conditions provides an explanation for the anomalous small crack behavior. Edwards and Newman [24] have proposed the use of an effective stress intensity factor which has been formulated to account for this reduction in closure obstruction. In the proposed equation the effective range of the stress intensity factor is

$$\Delta K_{eff} = \frac{(S_{max} - S_0)\Delta K}{(1 - R)S_{max}}, \quad (16)$$

where S_{max} is the applied maximum stress and S_0 represents the opening stress. The result has been used in a predictive code based on a modified Dugdale model [25].

Newman [26] has also proposed a method for accounting for the elastic-plastic behavior of small cracks at notches and holes. In addition to a closure obstruction correction he has introduced a fictitious crack length which adds the cyclic plastic zone size to the actual crack length. These adjustments provide an effective range of stress intensity factor which is larger than the unmodified range of stress intensity factor.

Accounting for the Effects of Grain Boundaries

The results presented here and those of other researchers [2,7,8,9,10,13,14,23] suggest that microstructural features can have an important affect on small crack behavior. Only the method proposed by Blom et al [21] appears to possess the potential for accounting for this variable. It may also be noted, however, that if differences between small corner cracks, short cracks and small thumbnail cracks are found to be significant, a standard test for determining the value of a_1 in Fig. 10 may not be generally applicable. Also, as noted earlier, the stress intensity factor is insensitive to microstructural differences on the scale involved.

Halliday, Poole and Bowen [2] have presented experimental evidence that indicates that for cracks which are of the order of the grain size, significant levels of obstruction to closure can be present. They suggest that effects of grain boundaries and local microstructure on surface roughness may be particularly important during early stages of crack growth. This is supported by the observation in this investigation that the initial crack paths on the corner surfaces did not lie in the same plane.

The possibility of incorporating details of crack surface features which are dependent on microstructure in a crack growth rate equation has been demonstrated previously. Knott [27], using experimental results obtained for steel by Beevers, Knott and Ritchie [28], has shown how a change in the area percentage of cleavage facets on a fatigue crack surface can be used to derive a crack growth rate equation which exhibits the final stage of fatigue life in which K_{max} approaches K_{IC} . A high rate of growth occurs when the area percent of cleavage cracking exceeds about 25%. The law derived, which resembles Forman's equation [29], thus correlates this growth behavior with fractographic features of a test material.

It has been suggested here that the anomalous small crack growth behavior may be due at least in part to the fact that the ratio of the total number of grains on the crack front to the number of partially constrained, surface grains is small. This ratio increases, of course, with increasing crack

size. A modification of the methods discussed earlier may be introduced by multiplying a growth rate equation by a function of this ratio. Thus, let

$$\frac{da}{dN} = f\left(\frac{n_t}{n_s}\right)F(\Delta K, \Delta K_{th}, R, K_{IC}), \quad (17)$$

where n_t is the total number of grains intersected by the crack front, and n_s is the number of surface grains crossed by the crack front. The value of n_s will here be taken as 2.

A form of f which could be used is

$$f = \left[1 + g\left(\frac{n_t}{n_s}\right) \right] \quad (18)$$

where the function g should be constructed so that f is large for small cracks and approaches unity for long cracks. A function of g which satisfies these requirements is

$$g = C_1 e^{-C_2 \left(\frac{n_t}{n_s}\right)}. \quad (19)$$

An example of a form of the function f is illustrated in Figure 16 for values of $C_1 = 10^8$ and $C_2 = 4$.

Note that since the number of grains on a crack front depends upon the size of the grains, grain size is explicitly included in Equation (16). Also, it distinguishes, through the ratio n_t/n_s , differences between small corner cracks and small thumbnail cracks of the same depth; i.e., n_t for a thumbnail crack is twice that for a corner crack.

The suggested modification does not account for the apparent reduction or absence of closure obstruction which has been cited [2] for small cracks. This effect could be accounted for by the use of an effective ΔK_{th} as has been suggested in other investigations.

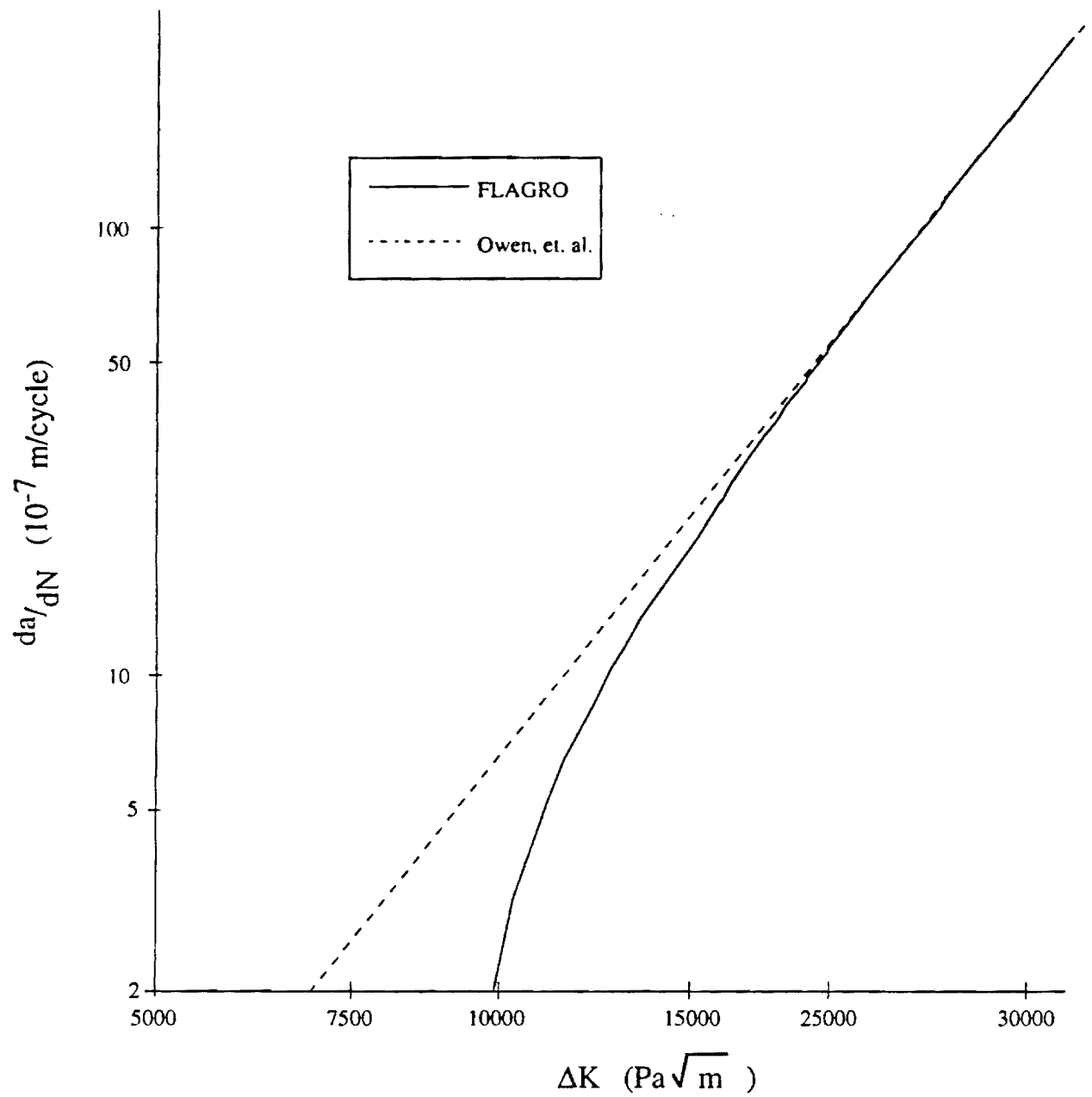


Figure 13: Log-log Plot of da/dN versus K with Proposed Modification for Small Behavior for 2024 -T3 Aluminum

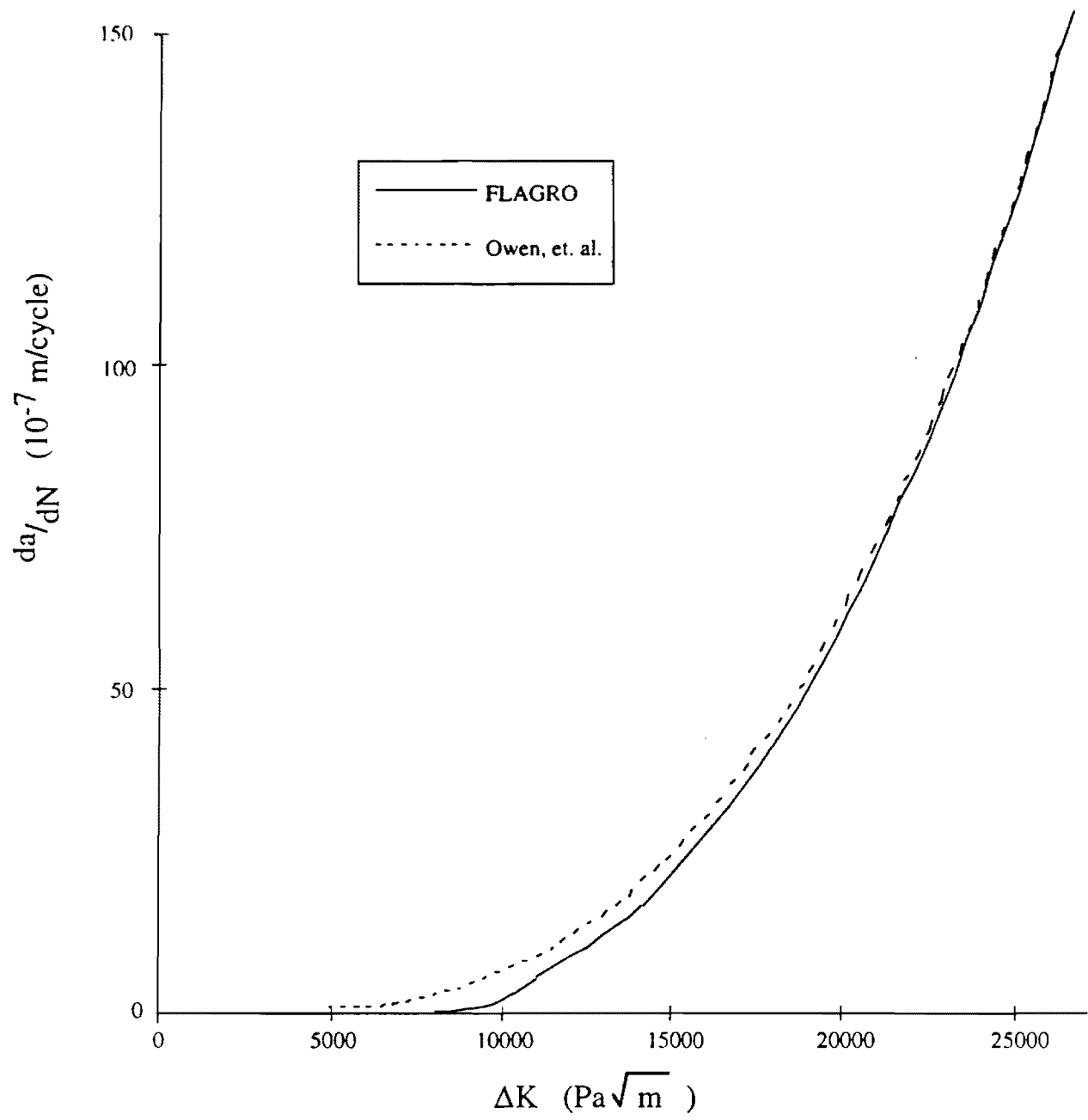


Figure 14: Cartesian Plot of Data from Figure 13

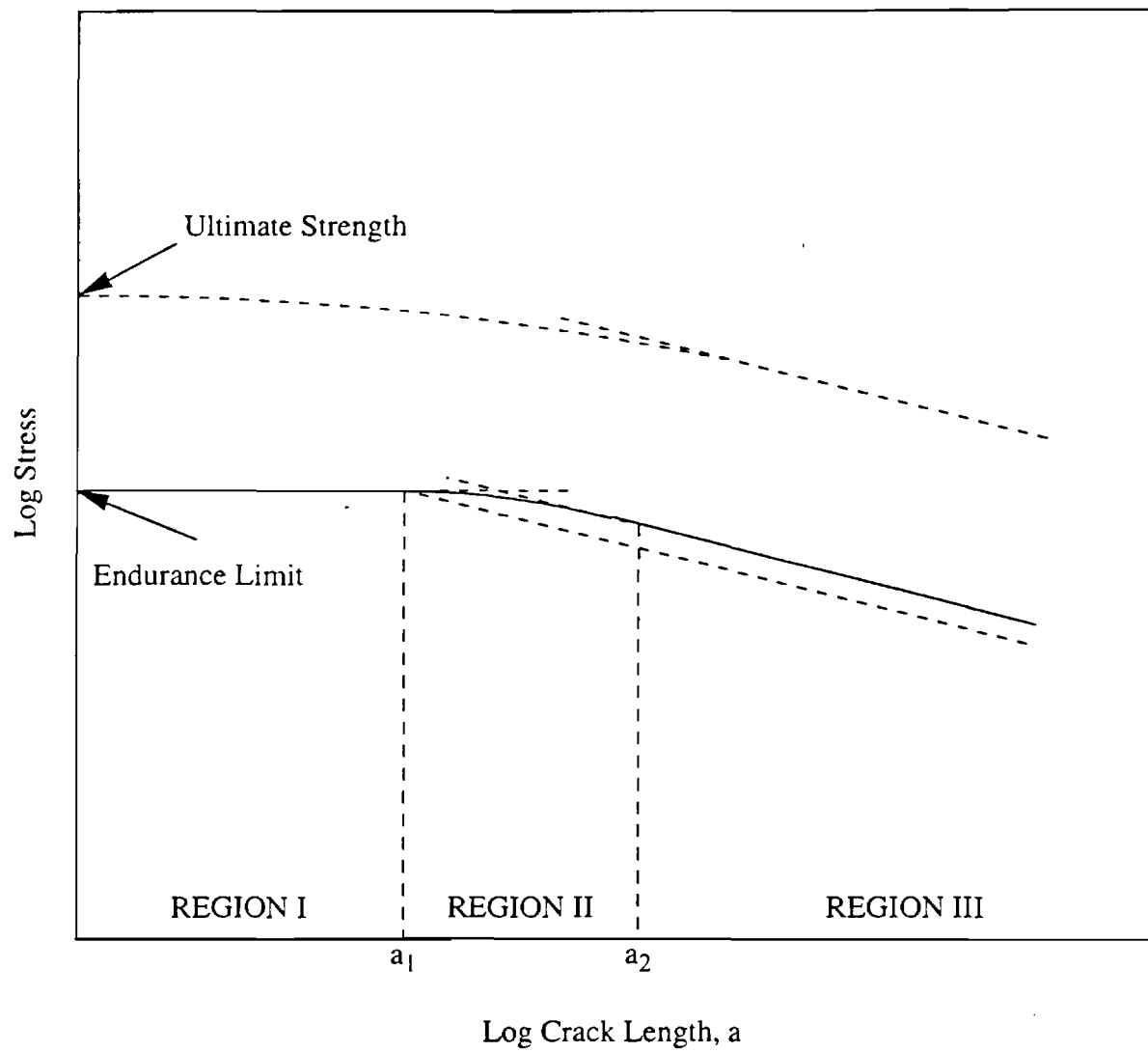


Figure 15: A Modified Kitagawa Plot

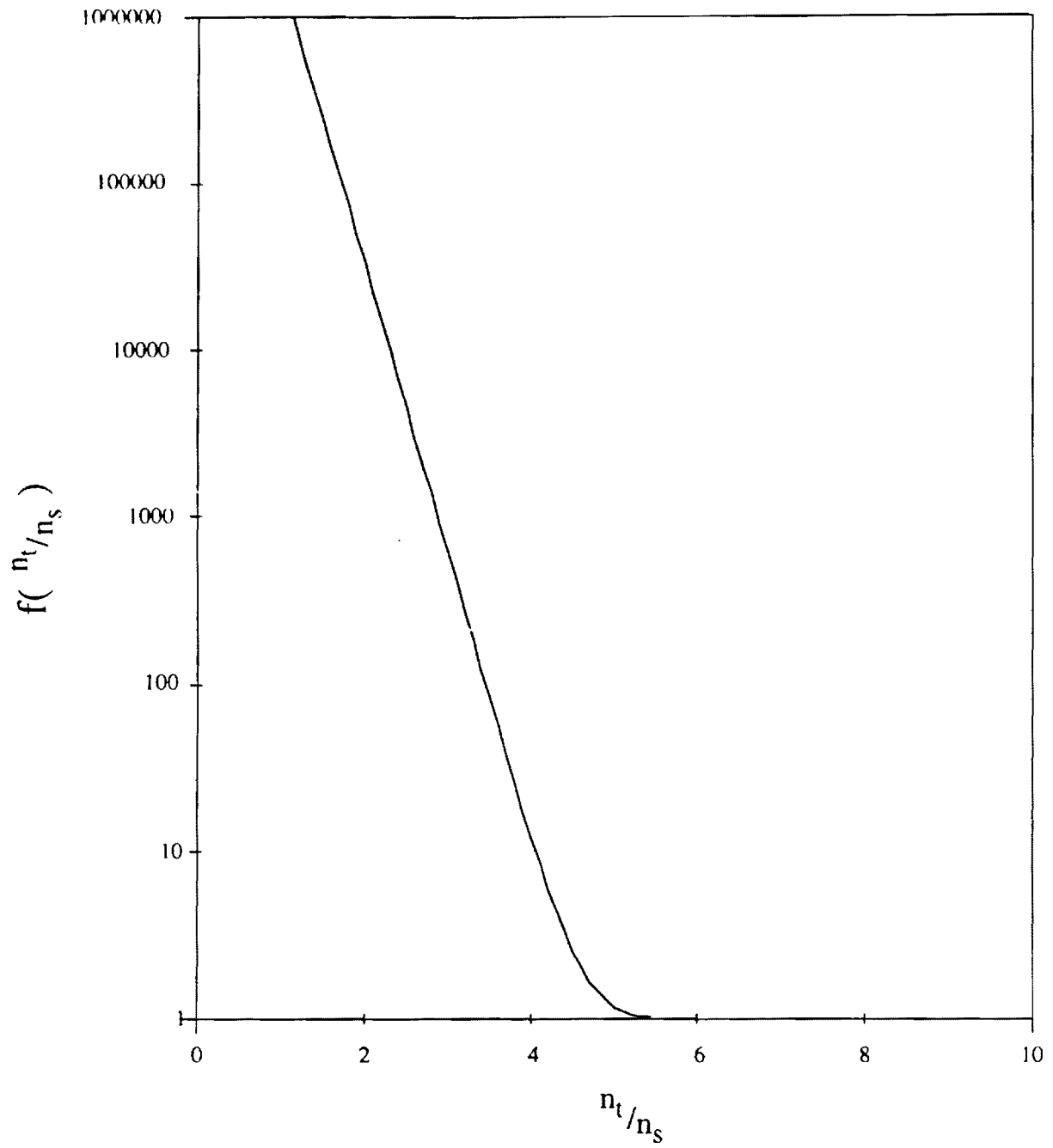


Figure 16: A Semi-log Plot of the Function $f(n/n_s)$

CONCLUSIONS

1. Fatigue failure of MH-53 components often starts with the appearance of corner cracks. For example, corner cracks are documented as failure modes for the upper pylon hinge fitting, the swashplate components, and the pitch horn and pitch control rods (see reference [30]).
2. A new specimen for small fatigue crack growth was designed based on corner cracks. The tests are performed in three point bending, which produces a localized stress for tighter control on crack location and growth. Furthermore, corner cracks allow direct measurement of crack depth, unlike surface cracks for which depth must be inferred.
3. Aluminum alloy 6061-T651 has been tested. Crack Length versus Cycles (S-N) data were recorded and are included in detail in this report.
4. Growth was of a discontinuous nature with alternating periods of growth and arrest.
5. The crack extensions during the growth periods were of the order of the grain size for the 6061-T651 aluminum alloy tested, i.e. 200 μ m.
6. Small cracks were observed to grow below the threshold for the small load ratio used.
7. The initial crack growth behaviors of short cracks (small in one length dimension) and small cracks (small in all length dimensions) may differ because of the large difference in grains along their crack fronts. Also, since small thumbnail cracks can, for the same crack depth, be expected to have about twice as many grains along their fronts as small corner cracks, their growth behaviors may differ. The stress intensity factor is insensitive to these differences. A growth rate law based only on the stress intensity range, fitted to the experimental data is

$$\frac{da}{dN} = 10^{-8} \left[\frac{\Delta K}{6.7} \right]^{28}.$$

8. A modified crack growth rate equation which incorporates an effect of a difference in internal and surface grain constraints on small crack growth has been developed. This equation,

$$\frac{da}{dN} = \left[1 + C_1 e^{-C_2 \left(\frac{n_i}{n_s} \right)} \right] F(\Delta K, \Delta K_{th}, R, K_{IC}),$$

adjusts the growth rate as the crack propagates away from the surface. The parameter n_t is the total number of grains intersected by the crack front, n_s is the number of surface grains crossed by the crack front, and C_1 and C_2 are empirical constants. Evaluation of the function F is explained within this report.

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