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DATA BASE FOR CRACK GROWTH PROPERTIES OF MATERIALS

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ABSTRACT

A computerized data base of crack growth properties of materials has been developed for use in fracture control analysis of rocket engine components and other NASA space hardware. The software system has files of basic crack growth rate data, other fracture mechanics material properties such as fracture toughness and environmental crack growth threshold values, and plotting and fitting routines for deriving material properties for use in fracture control analysis. An extensive amount of data has been collected and entered, and work is continuing on compiling additional data. The data base and software codes are useful both for fracture control analysis and for evaluation or development of improved crack growth theories.

INTRODUCTION

One of the most important tasks in fracture control analysis is acquiring valid crack growth properties of the materials. These properties usually include values for fracture toughness, fatigue and sustained load crack growth rate, and crack growth threshold values ΔK_{th} and K_{Iscc}. Establishing a data base has importance, not only for obtaining accurate analysis results, but also for reducing the cost and time to obtain the properties. For space applications, such as propulsion systems and payloads on the Space Shuttle, acquiring needed crack growth properties has been a major effort. The number of different materials and environments encountered has been an order of magnitude greater than that for other systems, such as aircraft.

To help alleviate the problem of acquiring valid crack growth data, a computerized data base is being developed for use in fracture control of NASA space programs. The purpose of this paper is to describe the development and characteristics of this data base, and to illustrate some examples of its use, both for typical analysis applications and for improvements in analysis methodology.

APPROACH

The NASA data base for fracture mechanics data on materials is an extension of the work in deriving these properties for the NASA/FLAGRO computer code. The data base stores basic data including crack growth rate, fracture toughness, and crack growth thresholds. Also stored are relevant test and specimen information, and the identification of data sources.

The code system for the materials identification in NASA/FLAGRO and the data base is designed to be simple and highly expandable:

1. Letter to identify material category, followed by
2. number to identify material type, followed by
3. letter and number to identify material condition/heat treatment and environmental condition.

An example of the code system for a particular case is shown in Table I. The code system of the data base differs from that of NASA/FLAGRO only by a letter which is added to the data base code to identify the data set, and a final number for da/dN data to identify the subsets having constant R values. The primary sources of the collected crack growth data are listed as follows:

1. References in Hudson's compendium of references (1184 listed) of published da/dN and fracture toughness data [1] and [2].
2. Data tape of fracture mechanics data used for generating the Air Force Damage Tolerant Design Handbook [3].
3. Contractor fracture mechanics test reports (25 total) written for the space shuttle program.
4. NASA contractor reports related to the Apollo program.
5. Lyndon B. Johnson Space Center internal test reports and data sheets of unreported data.
6. European contractor test reports forwarded by the European Space Agency.
7. Open literature references not in Hudson's compendiums (e.g. references later than 1980).

Even though an extensive amount of data from the above references has been collected, only data of primary interest for space application have been entered into the data base system at this writing. These include more than one thousand data sets for da/dN data. All data entered have been screened when possible for acceptability in meeting ASTM standards, such as those for compact tension specimens. The acceptance criterion for all data, however, consists of having sufficient information specifying:

1. Specimen type
2. Grain direction
3. Specimen thickness
4. Material strength or condition/heat treatment

Examples of the formats for printed files of fracture toughness data and K_{Iscc} data are shown in Tables II and III. Similar examples for typical plane-strain fracture toughness properties and ΔK_{th} values are shown in Tables IV and V. For the da/dN files, a header page describing the test and specimen information is filled out, and the information is stored along with the data. The input of the da/dN data is either by data tape from other data sources, such as the tape for the Damage Tolerant Design Handbook, from digitizing plotted data, such as from technical papers or reports, or from numerical data entered using a computer terminal.

In addition to the data files which can be printed or viewed on a computer terminal, the software system also contains plotting and curve fitting options. All software in the data base system is written in standard Fortran 77 language, including the graphics code which allows plotting by numerous types of graphics terminals and printers. These plotting and curve fitting capabilities are currently limited to da/dN versus ΔK data and K_c versus specimen thickness data. Other capabilities will be added in the future.

THEORETICAL BACKGROUND AND APPLICATIONS

The fatigue crack growth rate equation incorporated in the data base system and in NASA/FLAGRO is a modified Forman equation expressed as:

$$\frac{da}{dN} = \frac{C(1-R)^m \Delta K^n [\Delta K - \Delta K_{th}]^p}{[(1-R)K_c - \Delta K]^q} \tag{1}$$

where ΔK is assumed to be the full range of ΔK, even for R values less than zero. The form of Eqn. 1 gives improved accuracy, versatility, and can be fit to data using standard least squares methods. In addition, Eqn. 1 can be converted to the following commonly used equations by assigning the following values for the exponents m, p, and q:

EXPONENT VALUES	EQUATION FORM
$m = p = q = 0$	Paris
$m = p = 0, q = 1$	Forman
$p = q = 0, m = (m_w - 1)n$	Walker

The least squares routine also incorporates the option to use crack closure analysis for predicting the effect of R on crack growth rate under constant amplitude loading. The analysis is based on Newman's [4] equation expressed in the form:

$$\Delta K_2 = \left[\frac{1 - (S_0/S_{max})_1}{1 - (S_0/S_{max})_2}\left(\frac{1 - R_2}{1 - R_1}\right)\right]\Delta K_1 \tag{2}$$

In Eqn. 2, ΔK_1 is a baseline or known ΔK value corresponding to a da/dN for $R = R_1$ ($R_1 = 0$ in NASA/FLAGRO). The ΔK_2 variable is the ΔK value that gives the same da/dN at a different R value (i.e., R_2). S_0 is the crack opening stress, and S_{max} is the maximum cyclic stress.

The solution to Eqn. 2 was derived numerically by Newman for a center crack tension specimen and is a function of a "constraint" factor α on tensile yielding, the stress ratio R, and the stress level ratio S_0/S_{max}. Equations for S_0/S_{max} for various R ratios, stress levels (S_{max}), and constraint (α) values are also given in [4].

The method used to incorporate crack closure into Eqn. 1 is to calculate the value of m which gives the needed shift in ΔK from ΔK_1 to ΔK_2 for a given R_2 and specified constant da/dN. The value of da/dN for this calculation is set at approximately the midrange of the linear part of the da/dN curve (for most materials) as shown in Fig. 1. The exponent values of $p = q \leq 0.50$ were found to give satisfactory linear behavior in the central part of the curve and also give a good fit to experimental results in the upper and lower parts which are representative of instability and threshold behavior.

The second plotting and curve fitting capability is for the variation in fracture toughness with specimen thickness. The following equation is used for representing this variation:

$$\frac{K_c}{K_{Ic}} = 1 + C_k\, e^{-\pi(t/t_0)^2} \quad , \tag{3}$$

where $\quad t_0 = 2.5(K_{Ic}/YS)^2$

is the minimum thickness required to meet plane-strain fracture toughness criteria. An example of this fit to fracture toughness data for specimens where $t < t_0$ is shown in Fig. 2. The figure also shows the typical scatter in the K_c data. The scatter is a result of the commonly recognized variation in K_c with stress level or crack length. Future development work using the data base will incorporate Newman's [5] two parameter failure criteria (TPFC) in Eqn. 3 and determine the fitting constants for different materials. The resistance, R, curve is an alternative method for predicting the variation in K_c, but this method would be more difficult than the TPFC method for general use in a computer code like NASA/FLAGRO.

Another example of using the data base to develop improved analysis methodology is shown in Fig. 3. The figure shows a simple equation for the relationship between the fatigue crack growth rate threshold, ΔK_{th}, and the stress ratio, R, for aluminum alloys. Fig. 4 shows a useful relationship developed from the ΔK_{th} data base for the variation in ΔK_0 (the value of ΔK_{th} for $R = 0$) with the material yield strength. The general validity of the proposed relationships for other types of materials using the ΔK_{th} data files is shown in Fig. 5 and Fig. 6.

Finally, Fig. 7 shows a typical least squares curve fit to different da/dN data sets and the calculated growth rate constants of Eqn. 1. In addition to the curve fit, another important option, not shown, is the ability to check the accuracy of a fit with different data sets of various material thicknesses and R ratio values using previously calculated constants.

CONCLUDING REMARKS

The development and use of a NASA data base for crack growth properties of materials has numerous benefits for fracture control applications. The data base will result in more accurate analysis, be cost effective, result in shorter schedule time for analysis, and provide data for evaluating different crack growth models or analysis methodology. Further development of the data base will continue, both for space and non-space related applications.

REFERENCES

[1] Hudson, M.C. and Seward, S.K., "Compendium of Sources of Fracture Toughness and Fatigue Crack Growth Data for Metallic Alloys", *International Journal of Fracture*, Vol. 14, 1978, pp R151–R184.

[2] Hudson, C.M. and Seward, S.K., "A Compendium of Sources of Fracture Toughness and Fatigue Crack Growth Data for Metallic Alloys–Part II", *International Journal of Fracture*, Vol. 20, 1982, pp R59–R117.

[3] Damage Tolerant Design Handbook, MCIC-HB-01R, Metals and Ceramics Information Center, Battelle Columbus Laboratories, Columbus, Ohio, December

1983.

[4] Newman, J.C. Jr., "A Crack Opening Stress Equation for Fatigue Crack Growth", *International Journal of Fracture*, Vol 24, No. 3, March 1984, pp R131 - R135.

[5] Newman, J.C. Jr., "Fracture Analysis of Surface- and Through-cracked Sheets and Plates", *Engineering Fracture Mechanics*, 5, 1973, pp 667-689.

LIST OF SYMBOLS

a	Depth, length, or half-length of crack
c	Half-length of surface crack
m, n, p, q	Exponents in Eqn. 1
m_w	Exponent in Walker's growth rate equation
t	Thickness of plate or shell
t_0	Thickness to meet plane-strain condition
C	Growth rate coefficient in Eqn. 1
C_k	Fit parameter in Eqn. 3
K_c	Critical stress-intensity factor for fracture
K_{Ic}	Plane-strain fracture toughness
K_{Ie}	Effective fracture toughness for surface or elliptically shaped cracks
K_{Iscc}	Environmental cracking threshold under sustained stress conditions
ΔK	Stress-intensity factor range
ΔK_0	Fatigue threshold stress-intensity factor range at $R = 0$
ΔK_{th}	Fatigue threshold stress-intensity factor range
N	Number of fatigue cycles
R	Cyclic ratio, K_{min}/K_{max}
S_{max}	Maximum applied stress
S_0	Crack opening stress
UTS	Ultimate tensile strength
YS, σ_{YS}	Tensile yield strength
α	Three dimensional constraint factor on tensile yielding
σ_0	Flow stress

TABLE I. Code system for material identification

(a) Material categories:

FERROUS ALLOYS		NON-FERROUS ALLOYS	
Iron, Alloy or Cast	[A]	2000-7000 Series Aluminum	[M]
Low Alloy or Carbon Steel	[B]	Foreign Aluminum Alloys	[N]
Ultra High Strength Steel	[C]	Misc. and Cast Aluminum	[O]
Stainless Steel	[D]	Titanium Alloys	[P]
Age Hardening Steel	[E]	Nickel Base Alloys	[Q]
Ni Cr Steel	[F]	Ni Co Alloys	[R]
Tool Steel	[G]	Cobalt Base Alloys	[S]
Miscellaneous Ferrous Alloys	[H]	Miscellaneous Non-ferrous	[T]

(b) Example identification of material type:

2000-7000 SERIES ALUMINUM (CODE M)

2014	[1]	6000 Series	[9]
2024	[2]	7050	[10]
2124	[3]	7075	[11]
2219	[4]	7079	[12]
Misc. 2000 Series	[5]	7175	[13]
3000 Series	[6]	7178	[14]
4000 Series	[7]	7475	[15]
5000 Series	[8]	Misc. 7000 Series	[16]

(c) Example identification of material condition/heat treatment and environmental condition:

7075-T6 Al, L-T	[A1]
7075-T6 Al, L-T, HHA (0-9Hz)	[A5]
7075-T6 Al, T-L, HHA (0-9Hz)	[A6]
7075-T651 Al, L-T	[B1]
7075-T651 Al, S-T	[B3]
7075-T651 Al, L-T HHA (0-9Hz)	[B5]
7075-T651 Al, T-L HHA (0-9Hz)	[B6]
7075-T73 Al, L-T, LHA & HHA	[F1]
7075-T73 Al, T-L, LHA & HHA	[F2]
7075-T7351 Al, L-T, LHA & HHA	[G1]
7075-T7351 Al, T-L, LHA & HHA	[G2]
7075-T7651 Al, T-L	[L2]

(d) Example da/dN data set for 7075-T7651 Al, T-L, having four R values:

M11L2A4

TABLE II. Format for fracture toughness data

MAT. ID	REF	MATERIAL DESCRIPTION	ENVIR.	SPEC. NO.	TYPE	THK	W	a	2c	YS	UTS	ORIEN	S	K_c
M4E1 I2	37	2219-T87 AL, 1.25 PLATE	-320F LN2	SA12-2	PTSC	1.23	6.0	0.34	1.34	68	86	L-T	40.3	39.3
M4E1 J1	39	2219-T87 AL, 1.0 PLATE	-320F LN2	SBL-17	PTSC	1.00	6.0	0.32	1.31	68	85	L-T	57.8	56.3
M4E1 J2	39	2219-T87 AL, 1.0 PLATE	-320F LN2	SBL-12	PTSC	1.00	6.0	0.29	1.26	68	85	L-T	58.1	54.4
M4E2 A1	6	2219-T87 AL, 1.5 PLT	-320F LN2	2TL	CT(da)	1.50	5.0	3.10		68	84	T-L		34.0
M4E2 C1	55	2219-T87 AL, 1.5 PLT	-320F LN2	9B	CT	1.47	5.0	2.60		68	84	T-L		35.1

Note: a - initial crack size or depth
2c - initial crack length for part-through surface crack
S - failure stress

TABLE III. Format for K_{Iscc} data

MAT. ID	REF	MATERIAL DESCRIPTION	TYPE ENVIRONMENT	TEMP	TYPE	YS	UTS	ORIEN	K_c, K_Q	K_{Iscc}
M1D-C-6F	B21	2014-T6 AL	SYNTH. SEAWATER	75	CANT	61		S-L	19	16
M1F-D-1F	C128	2014-T651 AL	INDUSTRIAL ATM	75	CT	60		S-L	19	7
M1F-E-1F	C128	2014-T651 AL	SEACOAST ATM	75	CT	60		S-L	19	7
M5C-A-13F	C212	2020-T651 AL	3.5% NaCl	75	DCB	60		S-L	13	9

TABLE IV.

Typical plane-strain fracture toughness values

Material Description	K_{Ic}, $ksi\sqrt{in}$ (ref#) *					
	L-T	T-L	S-L	T-S	L-S	S-T
2014-T651 Al	22 (B34)	20 (B34)	17 (B34)	22(DTDH)	24(DTDH)	—
2219-T851 Al	33 (DTDH)	29 (DTDH)	23(DTDH)	25(DTDH)	30(DTDH)	—
2219-T852 Al	39 (DTDH)	27 (DTDH)	25(DTDH)	29(DTDH)	—	24(DTDH)
2219-T87 Al	28 (DTDH)	22 (DTDH)	—	31(DTDH)	—	—
2219-T87 Al at -400°F to -300°F	41 (DTDH)	32 (DTDH)	—	31 (MH)	—	—
2219-T87 Al at 300°F	30 (DTDH)	—	—	—	—	—
2419-T851 Al	43 (DTDH)	37 (DTDH)	25(DTDH)	—	—	24(DTDH)
AISI 301 S.S.	200(ASMH)	150(ASMH)	—	—	—	—
AISI 301 S.S., at -320°F	170(ASMH)	90 (ASMH)	—	—	—	—

* DTDH — Damage Tolerant Design Handbook, ASMH — Aerospace Structural Metals Handbook, MH — ASM Metals Handbook

TABLE V.

Typical threshold values for aluminum alloys

Material	Envir.	Ref.	YS	UTS	R	ΔK_{th}	$\frac{\Delta K_{th}}{\Delta K_0}$
2020-T651 Al, (T-L)	75°F	C98	76	unk.	0.3	2.3	0.85
2024-T3 Al	75°F	D243	53	65	-1.0	4.2	1.40
2024-T3 Al, (L-T)		123	53	65	-1.0	4.9	1.63
2024-T3 Al		T149	50	65	-1.0	4.0	1.33
2024-T3 Al, (L-T)		123	53	65	0.0	4.15	1.38
2024-T3 Al		D243	53	65	0.05	3.5	1.17
		T149	50	65	0.05	3.27	1.09
		D243	53	65	0.2	3.0	1.00

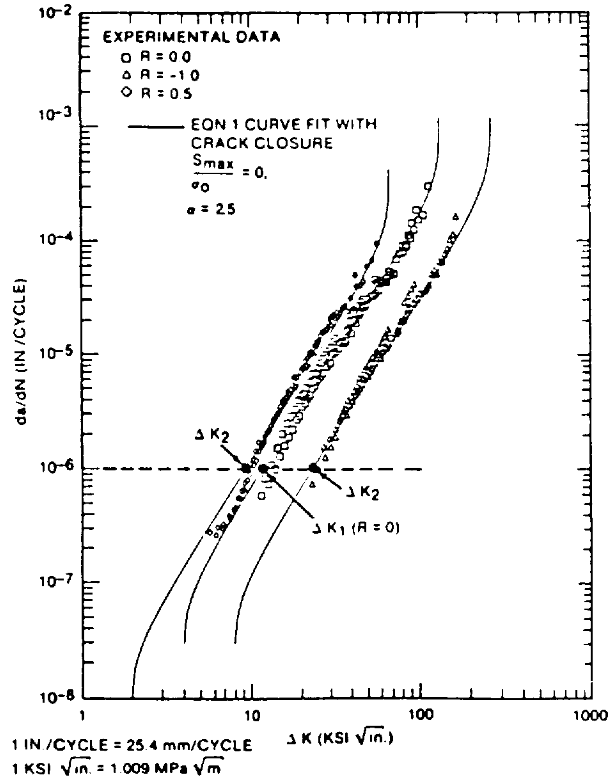

FIG. 1 Curve fit of Eqn. 1 with crack closure to crack growth rate

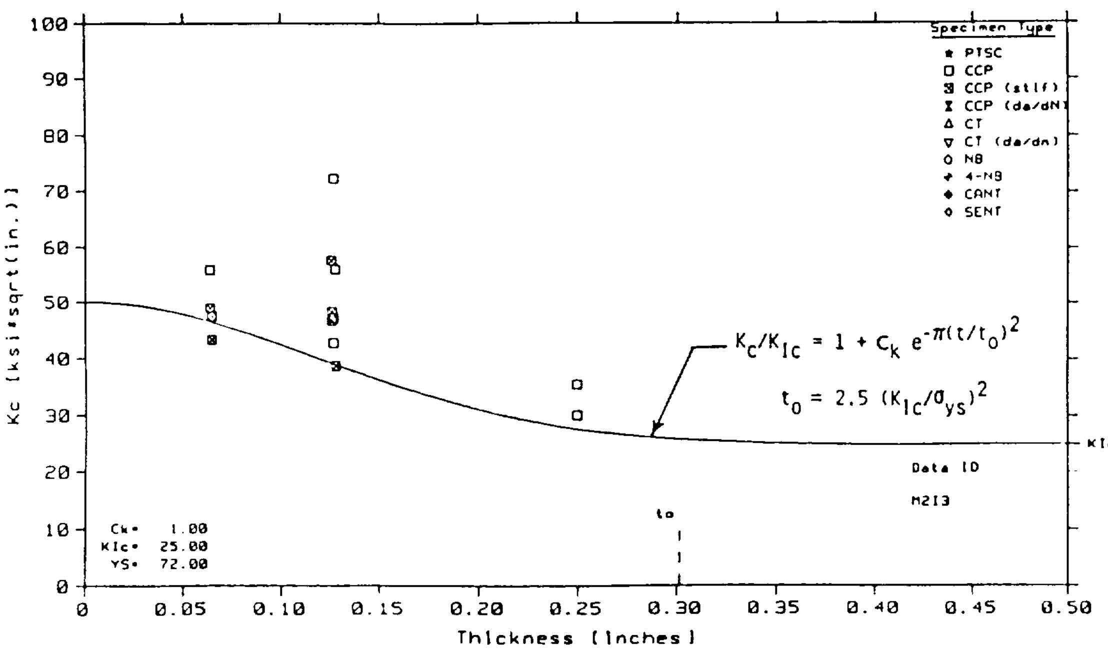

FIG. 2 K_c vs thickness for 2024-T861 Al, L-T, 75F

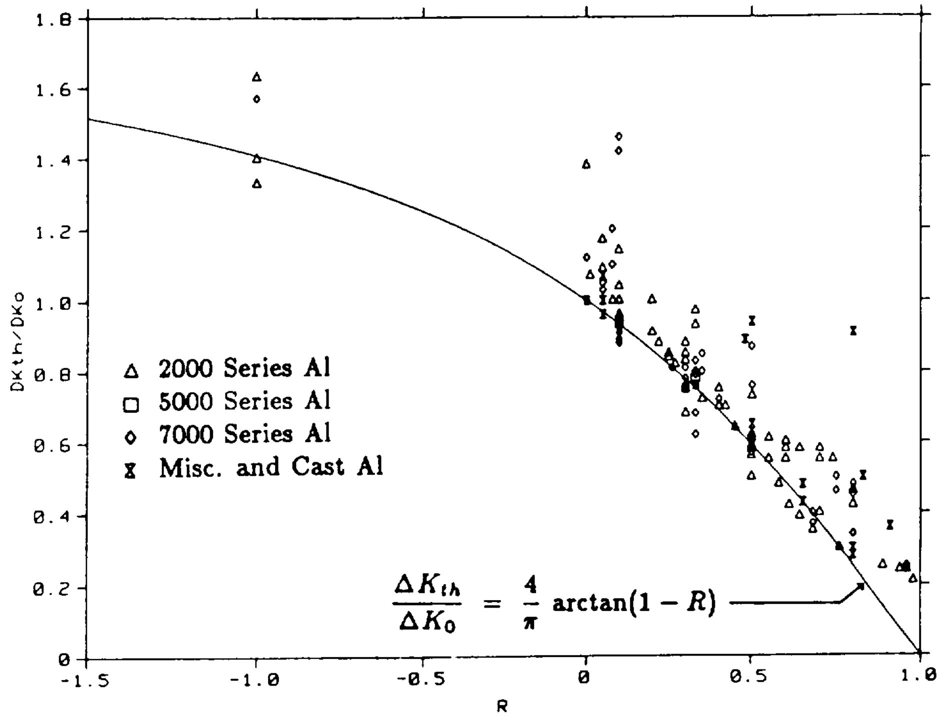

FIG. 3 $\Delta K_{th}/\Delta K_0$ vs R for aluminum alloys

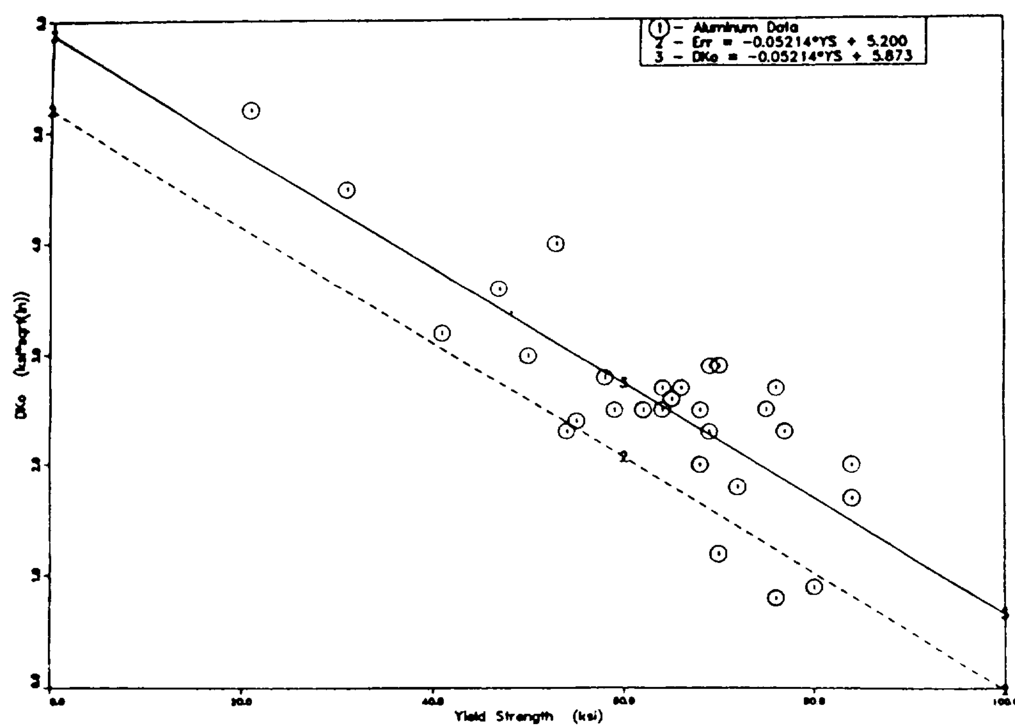

FIG. 4 ΔK_0 vs YS for aluminum alloys

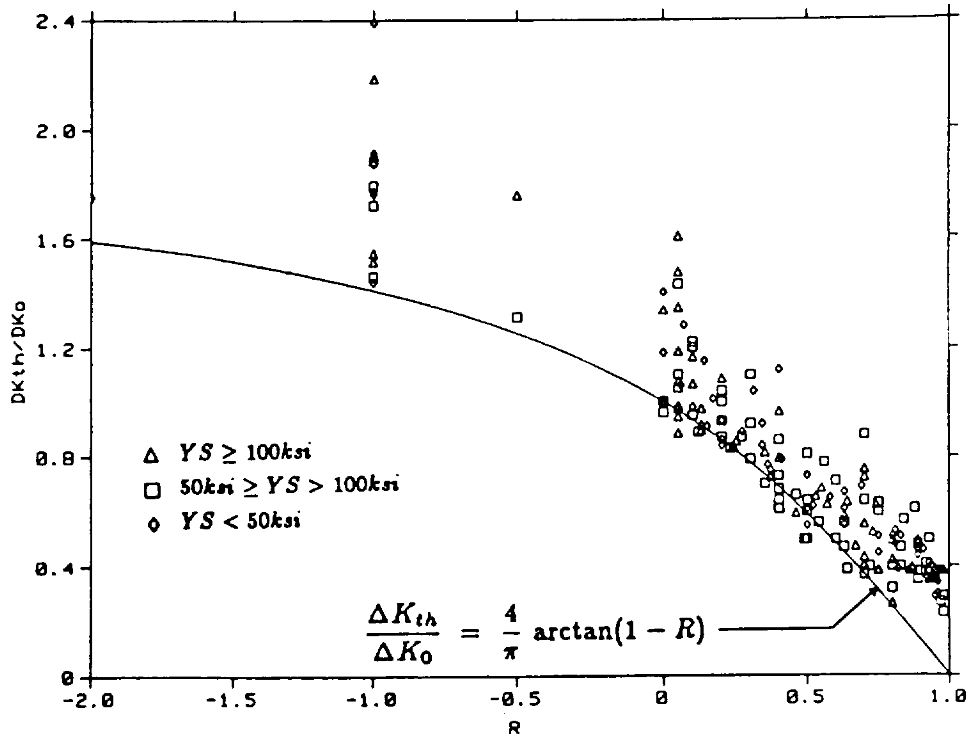

FIG. 5 $\Delta K_{th}/\Delta K_0$ vs R for alloy steels

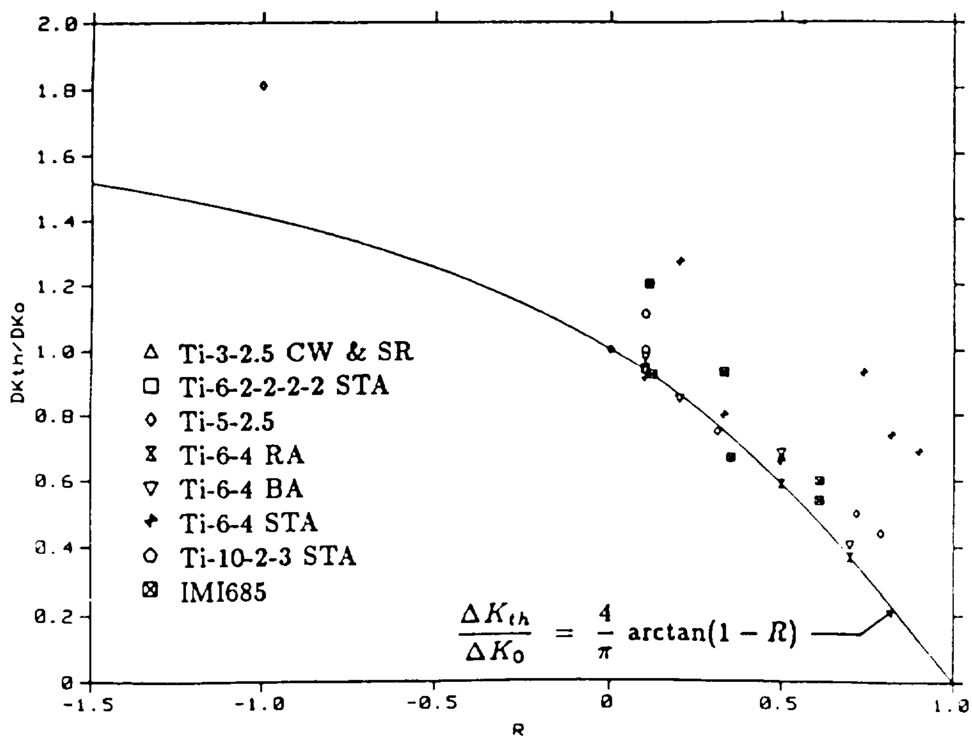

FIG. 6 $\Delta K_{th}/\Delta K_0$ vs R for titanium alloys

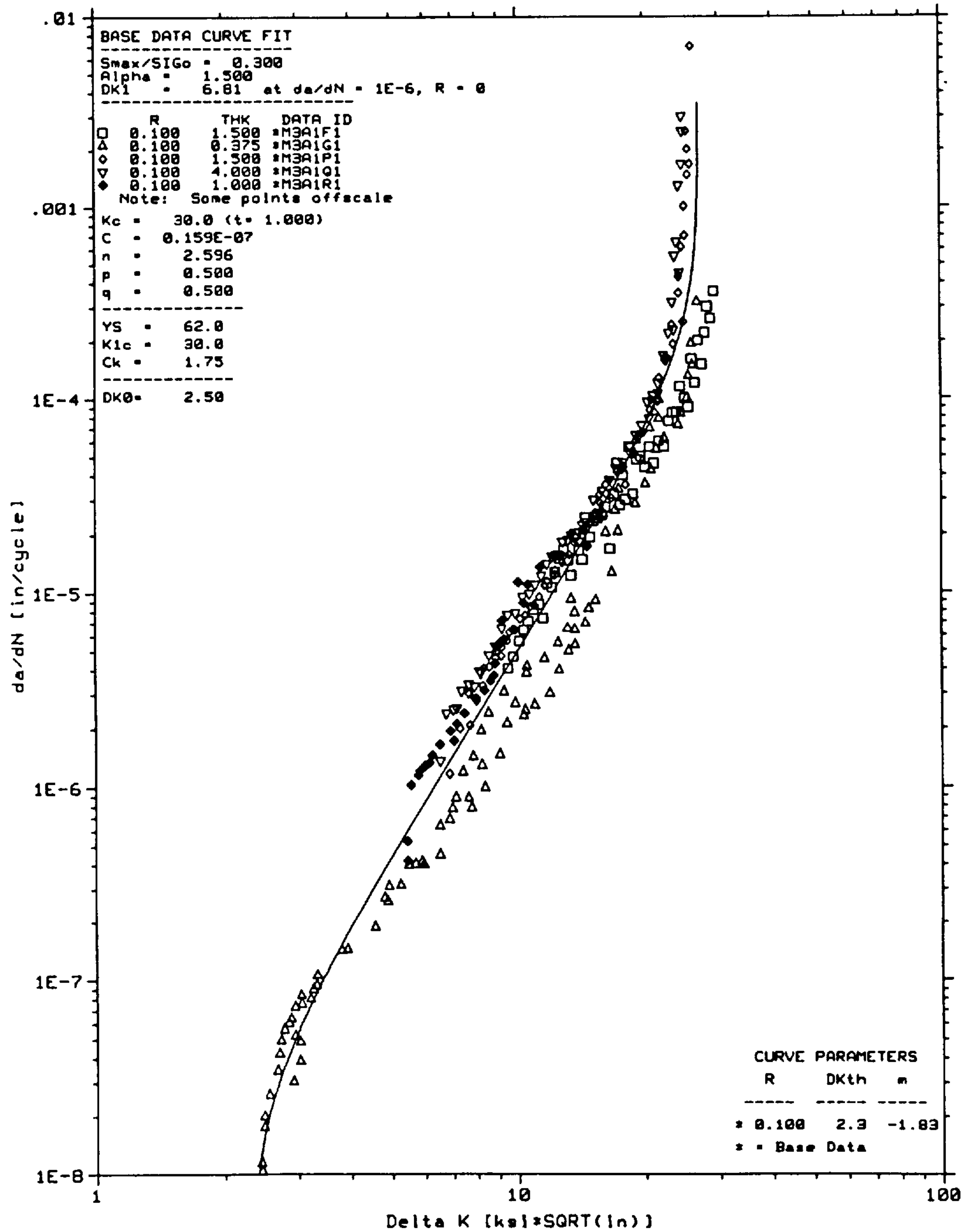

FIG. 7 Base da/dN data curve fit & NASA/FLAGRO parameters for 2124-T851 AL, L-T, 70F in high humidity air