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 $\Delta K_{th}$ and $K_f acc$. 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 $\Delta K_{th}$ 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 $\Delta K$ 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:

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

where $\Delta K$ is assumed to be the full range of $\Delta K$, 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 $q$: 598
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:

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

In Eqn. 2, \( \Delta K_1 \) is a baseline or known \( \Delta K \) value corresponding to a \( da/dN \) for \( R = R_1 \) (\( R_1 = 0 \) in NASA/FLAGRO). The \( \Delta K_2 \) variable is the \( \Delta K \) 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 \( \alpha \) 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 (\( \alpha \)) 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 \( \Delta K \) from \( \Delta K_1 \) to \( \Delta K_2 \) 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:

\[
\frac{K_c}{K_{Ic}} = 1 + C_k e^{-\pi(t/t_0)^2},
\]

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

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, $\Delta K_{th}$, and the stress ratio, $R$, for aluminum alloys. Fig. 4 shows a useful relationship developed from the $\Delta K_{th}$ data base for the variation in $\Delta K_0$ (the value of $\Delta K_{th}$ for $R = 0$) with the material yield strength. The general validity of the proposed relationships for other types of materials using the $\Delta K_{th}$ 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**


[3] Damage Tolerant Design Handbook, MCIC-HB-01R, Metals and Ceramics Information Center, Battelle Columbus Laboratories, Columbus, Ohio, December
1983.


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
- \( K_{I_{csc}} \): Environmental cracking threshold under sustained stress conditions
- \( \Delta K \): Stress-intensity factor range
- \( \Delta K_0 \): Fatigue threshold stress-intensity factor range at \( R = 0 \)
- \( \Delta K_{th} \): 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
- \( YS, \sigma_{YS} \): Tensile yield strength
- \( \alpha \): Three dimensional constraint factor on tensile yielding
- \( \sigma_0 \): Flow stress
TABLE I. Code system for material identification

(a) Material categories:

<table>
<thead>
<tr>
<th>FERROUS ALLOYS</th>
<th>NON-FERROUS ALLOYS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron, Alloy or Cast</td>
<td>2000-7000 Series Aluminum</td>
</tr>
<tr>
<td>Low Alloy or Carbon Steel</td>
<td>Foreign Aluminum Alloys</td>
</tr>
<tr>
<td>Ultra High Strength Steel</td>
<td>Misc. and Cast Aluminum</td>
</tr>
<tr>
<td>Stainless Steel</td>
<td>Titanium Alloys</td>
</tr>
<tr>
<td>Age Hardening Steel</td>
<td>Nickel Base Alloys</td>
</tr>
<tr>
<td>Ni Cr Steel</td>
<td>Ni Co Alloys</td>
</tr>
<tr>
<td>Tool Steel</td>
<td>Cobalt Base Alloys</td>
</tr>
<tr>
<td>Miscellaneous Ferrous Alloys</td>
<td>Miscellaneous Non-ferrous</td>
</tr>
</tbody>
</table>

(b) Example identification of material type:

<table>
<thead>
<tr>
<th>2000-7000 SERIES ALUMINUM</th>
<th>(CODE M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3000 Series</td>
<td>[14]</td>
</tr>
<tr>
<td>4000 Series</td>
<td>[15]</td>
</tr>
<tr>
<td>5000 Series</td>
<td>[16]</td>
</tr>
</tbody>
</table>

(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

<table>
<thead>
<tr>
<th>MAT. ID</th>
<th>REF</th>
<th>MATERIAL DESCRIPTION</th>
<th>ENVIR.</th>
<th>SPEC. NO.</th>
<th>TYPE</th>
<th>THK</th>
<th>W</th>
<th>2c</th>
<th>YS</th>
<th>UTS</th>
<th>ORIEN</th>
<th>S</th>
<th>$K_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>M4E1 J2</td>
<td>37</td>
<td>2219-T87 AL, 1.25 PLATE</td>
<td>LN2</td>
<td>520F</td>
<td>SA12-2</td>
<td>1.25</td>
<td>6.0</td>
<td>0.34</td>
<td>4.34</td>
<td>68</td>
<td>86</td>
<td>L-T</td>
<td>40.3</td>
</tr>
<tr>
<td>M4E1 J1</td>
<td>39</td>
<td>2219-T87 AL, 1.0 PLATE</td>
<td>LN2</td>
<td>520F</td>
<td>SBL-17</td>
<td>1.00</td>
<td>6.0</td>
<td>0.32</td>
<td>1.31</td>
<td>68</td>
<td>85</td>
<td>L-T</td>
<td>57.8</td>
</tr>
<tr>
<td>M4E1 J2</td>
<td>39</td>
<td>2219-T87 AL, 1.0 PLATE</td>
<td>LN2</td>
<td>520F</td>
<td>SBL-12</td>
<td>1.00</td>
<td>6.0</td>
<td>0.29</td>
<td>1.26</td>
<td>68</td>
<td>85</td>
<td>L-T</td>
<td>58.1</td>
</tr>
<tr>
<td>M4E2 A1</td>
<td>6</td>
<td>2219-T87 AL, 1.5 PLT</td>
<td>LN2</td>
<td>520F</td>
<td>2TL</td>
<td>1.50</td>
<td>5.0</td>
<td>3.10</td>
<td>68</td>
<td>84</td>
<td>T-L</td>
<td>34.0</td>
<td></td>
</tr>
<tr>
<td>M4E2 C1</td>
<td>55</td>
<td>2219-T87 AL, 1.5 PLT</td>
<td>LN2</td>
<td>520F</td>
<td>9B</td>
<td>1.47</td>
<td>5.0</td>
<td>2.60</td>
<td>68</td>
<td>84</td>
<td>T-L</td>
<td>35.1</td>
<td></td>
</tr>
</tbody>
</table>

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

### TABLE III. Format for $K_{facc}$ data

<table>
<thead>
<tr>
<th>MAT. ID</th>
<th>REF</th>
<th>MATERIAL DESCRIPTION</th>
<th>TYPE</th>
<th>ENVIRONMENT</th>
<th>TEMP</th>
<th>TYPE</th>
<th>YS</th>
<th>UTS</th>
<th>ORIEN</th>
<th>$K_e$</th>
<th>$K_Q$</th>
<th>$K_{facc}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1D-C-1F</td>
<td>B21</td>
<td>2014-T6 AL</td>
<td>SYNTH. SEAWATER</td>
<td>75</td>
<td>CANT</td>
<td>61</td>
<td>S-L</td>
<td>10</td>
<td>16</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M1P-D-1F</td>
<td>C128</td>
<td>2014-T651 AL</td>
<td>INDUSTRIAL ATM</td>
<td>75</td>
<td>CT</td>
<td>60</td>
<td>S-L</td>
<td>10</td>
<td>7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M1P-E-1F</td>
<td>C128</td>
<td>2014-T651 AL</td>
<td>SEACOAST ATM</td>
<td>75</td>
<td>CT</td>
<td>60</td>
<td>S-L</td>
<td>10</td>
<td>7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M5C-A-13F</td>
<td>C212</td>
<td>2020-T651 AL</td>
<td>3.5% NaCl</td>
<td>75</td>
<td>DCB</td>
<td>60</td>
<td>S-L</td>
<td>13</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### TABLE IV.
**Typical plane-strain fracture toughness values**

<table>
<thead>
<tr>
<th>Material Description</th>
<th>$K_{IC}$, ksi-$\sqrt{in}$ (ref#)*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L-T</td>
</tr>
<tr>
<td>2014-T651 Al</td>
<td>22 (B14)</td>
</tr>
<tr>
<td>2219-T851 Al</td>
<td>25 (DTDH)</td>
</tr>
<tr>
<td>2219-T852 Al</td>
<td>27 (DTDH)</td>
</tr>
<tr>
<td>2219-T87 Al</td>
<td>22 (DTDH)</td>
</tr>
<tr>
<td>2219-T87 Al at -400°F to -300°F</td>
<td>41 (DTDH)</td>
</tr>
<tr>
<td>2219-T87 Al at 300°F</td>
<td>30 (DTDH)</td>
</tr>
<tr>
<td>2419-T851 Al</td>
<td>43 (DTDH)</td>
</tr>
<tr>
<td>AISI 301 S.S.</td>
<td>200(ASMH)</td>
</tr>
<tr>
<td>AISI 301 S.S., at -320°F</td>
<td>170(ASMH)</td>
</tr>
</tbody>
</table>


### TABLE V.
**Typical threshold values for aluminum alloys**

<table>
<thead>
<tr>
<th>Material</th>
<th>Envir.</th>
<th>Ref.</th>
<th>YS</th>
<th>UTS</th>
<th>R</th>
<th>$\Delta K_{th}$</th>
<th>$\Delta K_{th}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2024-T3 Al, (T-L)</td>
<td>75°F</td>
<td>C98</td>
<td>76</td>
<td>unk.</td>
<td>0.3</td>
<td>2.3</td>
<td>0.86</td>
</tr>
<tr>
<td>2024-T3 Al</td>
<td>75°F</td>
<td>D243</td>
<td>55</td>
<td>65</td>
<td>-1.0</td>
<td>4.2</td>
<td>1.40</td>
</tr>
<tr>
<td>2024-T3 Al</td>
<td>128</td>
<td>55</td>
<td>65</td>
<td>-1.0</td>
<td>4.9</td>
<td>1.63</td>
<td></td>
</tr>
<tr>
<td>2024-T3 Al</td>
<td>T149</td>
<td>50</td>
<td>65</td>
<td>-1.0</td>
<td>4.0</td>
<td>1.33</td>
<td></td>
</tr>
<tr>
<td>2024-T3 Al, (L-T)</td>
<td>128</td>
<td>55</td>
<td>65</td>
<td>0.0</td>
<td>4.15</td>
<td>1.38</td>
<td></td>
</tr>
<tr>
<td>2024-T3 Al</td>
<td>D243</td>
<td>55</td>
<td>65</td>
<td>0.05</td>
<td>3.5</td>
<td>1.17</td>
<td></td>
</tr>
<tr>
<td>2024-T3 Al</td>
<td>T149</td>
<td>50</td>
<td>65</td>
<td>0.05</td>
<td>3.27</td>
<td>1.09</td>
<td></td>
</tr>
<tr>
<td>2024-T3 Al</td>
<td>D243</td>
<td>55</td>
<td>65</td>
<td>0.2</td>
<td>3.0</td>
<td>1.00</td>
<td></td>
</tr>
</tbody>
</table>
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
\[ \frac{\Delta K_{th}}{\Delta K_0} = \frac{4}{\pi} \arctan(1 - R) \]

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

**FIG. 4** $\Delta K_0$ vs $YS$ for aluminum alloys
\[ \frac{\Delta K_{th}}{\Delta K_0} = \frac{4}{\pi} \arctan(1 - R) \]

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

\[ \Delta K_{th} = \frac{4}{\pi} \arctan(1 - R) \]

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

\[ \Delta K_{th} = \frac{4}{\pi} \arctan(1 - R) \]
**FIG. 7** Base $da/dN$ data curve fit & NASA/FLAGRO parameters for 2124-T851 AL, L-T, 70F in high humidity air