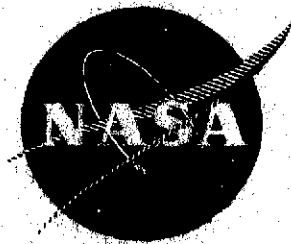


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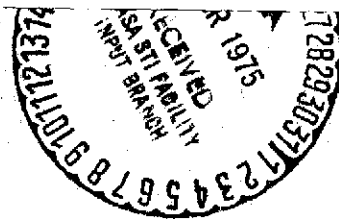


## FRACTURE TOUGHNESS TESTING DATA – A TECHNOLOGY SURVEY

By William F. Stuhrke, and James L. Carpenter, Jr.

**MARTIN MARIETTA AEROSPACE**  
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16. Abstract <p>This Technology Survey Report is comprised of reviewed and evaluated technical abstracts for about 90 significant documents relating to fracture toughness testing for various structural materials including information on plane strain and the developing areas of mixed mode and plane stress test conditions. The Introduction to the report includes an overview of the state-of-the-art represented in the documents that have been abstracted.</p> <p>The abstracts in the report are mostly for publications in the period April 1962 through April 1974. The purpose of this report is to provide, in quick reference form, a dependable source for current information in the subject field. It is a companion volume to NASA CR-134753, Fracture Toughness Testing Data - A Technology Survey.</p>		
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## FOREWORD

This Technology Survey was prepared by Martin Marietta Aerospace under Contract NAS 3-17640. It is one product of a research program initiated by the NASA Lewis Research Center to compile, evaluate, and organize for convenient access information on the mechanics of structural failure and structural materials limitations. The NASA Aerospace Safety Research and Data Institute (ASRDI) has technical responsibility for the research program. Preparation of this report was under the direction of George Mandel, ASRDI Program Manager.

Many people contributed to the preparation of the report. Their assistance and cooperation is appreciated and gratefully acknowledged. The authors wish to especially acknowledge the interest and assistance of the following individuals: H. Dana Moran, Battelle Memorial Institute; William F. Brown, Jr., and Stanley J. Klima, NASA Lewis Research Center; Walter P. Conrardy, Air Force Materials Laboratory; George R. Irwin, University of Maryland; and George C. Sih, Lehigh University.

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## KEYWORDS

Analysis methods; fracture mechanics; fracture strength; fracture tests; metallic materials; plane strain fracture toughness, stress intensity factor; testing methods.

## PREFACE

Since June 1972 the Orlando Division of Martin Marietta Aerospace has supported the NASA Lewis Research Center's Aerospace Safety Research and Data Institute (ASRDI) in an investigation of the mechanics of structural failure and structural materials limitations. A series of technical reports have been produced.

Under Contract NAS 3-16681 a Register of Experts for Information on the Mechanics of Structural Failure was published as NASA CR-121200. Its purpose was to give visibility to a listing of recognized experts who might be available for consultation related to the mechanics of structural failure. This contract also produced other products: NASA CR-121201, Register of Sources for Information on the Mechanics of Structural Failure; NASA CR-121202, Bibliography of Information on the Mechanics of Structural Failure; and NASA CR-12199, Thesaurus of Terms of Information on the Mechanics of Structural Failure. The last of these reports is comprised of key words which facilitate access to an ASRDI mechanized data base that was augmented under Contract NAS 3-16681.

This Technology Survey Report is the result of one of several tasks included in Contract NAS 3-17640. The contract provides for the expansion, revision and/or updating of NASA CR-121200 (Register of Experts), NASA CR-121200 (Bibliography), and the pertinent mechanized data base. It also provides for the preparation of two technology surveys, i.e., reports which include abstracts and assessments of key related documents published in the period April 1962 - April 1974, or "classics" published prior to 1962. One technology survey reports on information related to the problems of life prediction for aerospace structural materials subjected to specified environmental effects. This survey describes the availability and application of fracture toughness testing data, particularly for metallic materials.

The report is comprised of interpreted abstracts of about 100 key documents related to the subject. These documents have been surfaced and selected in a literature search performed between June 1972 and September 1974. Since a significant number of the documents relate to more than one aspect of fracture toughness testing there are often multiple citations of the same document. All of the documents selected and abstracted for this technology survey report are included in ASRDI's mechanized data base. In addition a majority of the references cited with the abstracted documents are also included in the ASRDI data bank. This affords a significant information resource for the interested researcher.

This report is a companion volume to NASA CR-134753, Fracture Toughness Testing Data - A Bibliography.

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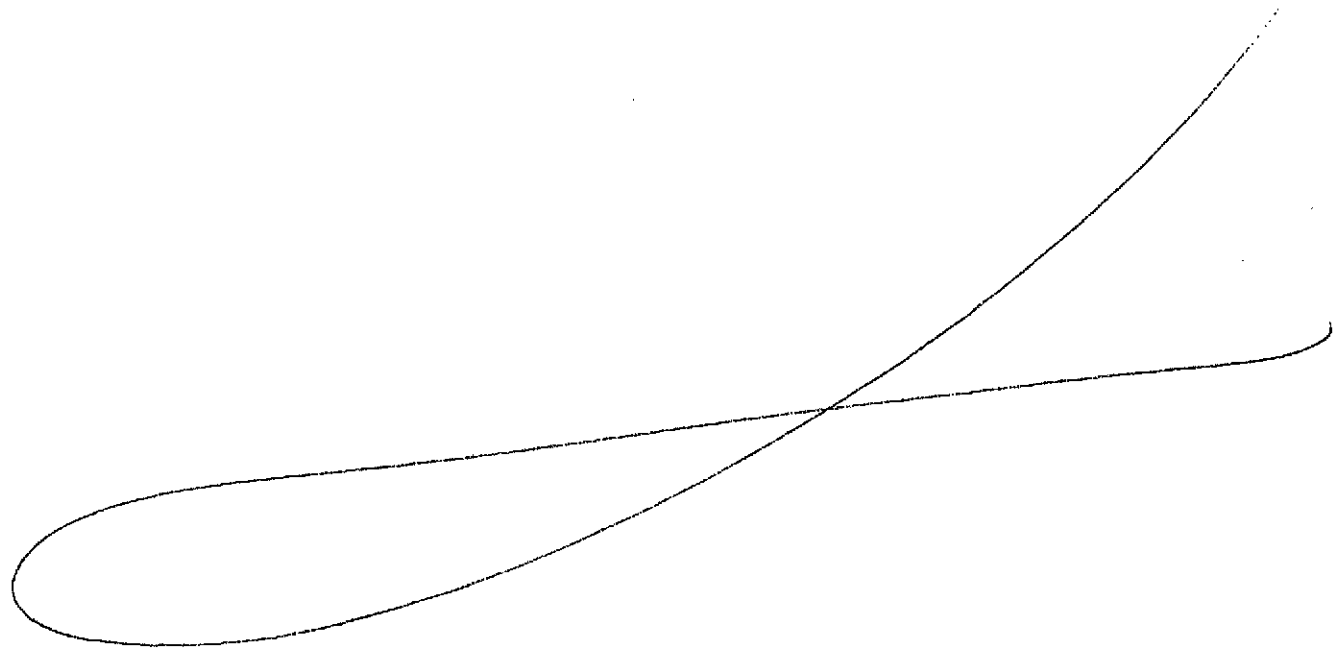
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## SUMMARY

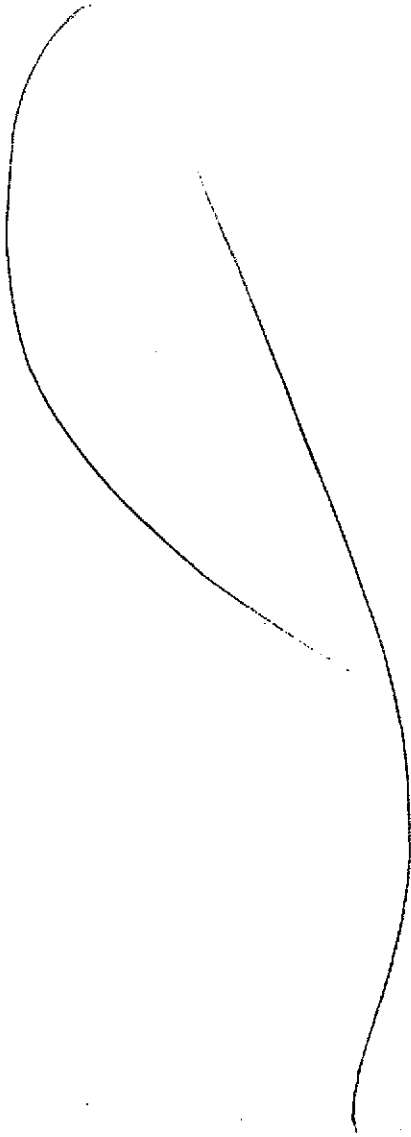
This Technology Survey Report is comprised of technical abstracts for 90 significant documents relating to fracture toughness testing data for various structural materials. The Introduction of the report includes an overview of the state-of-the-art represented in the documents that have been abstracted.

The abstracts in the report are mostly for publications in the period April 1962 through April 1974. There are exceptions. In some instances a pre-1962 "classic" has been included because it is still the most authoritative treatment available.

The purpose of the report is to provide, in quick reference form, a dependable source for current information on the subject field. The selection has been arbitrary but made with the guidance of outstanding researchers and authors in the field. The references supplied with the abstracts afford quick identification of additional documents.



INTRODUCTION-OVERVIEW OF THE REPORT



## INTRODUCTION - OVERVIEW OF THE REPORT

This report can only be a contribution toward the establishment of a larger and much needed information base. Nevertheless it is felt that the contribution is substantive and will cause the publication of other related, valuable knowledge. To introduce the abstracts included, the authors of the report have written an overview of the key contributions of the researchers represented by the abstracts. A significant reference list is offered to substantiate the authors conclusions.

The history of materials application to engineering structures is replete with unexpected failures. Fracture analysis has progressed from analyzing the failure of an early Roman broad sword to the complete reconstruction of a crashed modern aircraft. During most of this period many structural materials failures remained unexplained. With the development of the crystallographic theory and understanding of interatomic binding energies it became possible to determine a theoretical strength for metals. This strength was over 1000 times that observed in actual testing (ref. 1). Griffith while examining this paradox postulated that materials contained flaws which acted like infinitely sharp cracks. He showed that these cracks could propagate in a brittle manner with very little energy, thus reversing the question again from why are metals so weak, to why are they so strong (ref. 2). Griffith's analysis was largely ignored until a number of tragically catastrophic failures occurred at loads only a small fraction of the demonstrated strength of the materials. These failures which included the welded ships of World War II and the Comet jet liner fuselage have a common thread of exhibiting extremely brittle fracture surfaces.

The group of investigators at the Naval Research Laboratory under George Irwin examined the ship failures and building on the work of Griffith and others developed the technology of fracture mechanics. They introduced the concept of a stress intensity factor (K). This is a number typically presented in the awkward notation of thousands of pounds per square inch times inches to the one half power ( $\text{ksi} \sqrt{\text{in.}}$ ). It is related to the stress, crack tip sharpness and crack length and is a measure of the force working on propagating the crack. The crack growth resistance (G) is the force necessary to maintain a crack in neutral equilibrium and is expressed in thousands of pounds per square inch (ksi). Irwin and his coworkers have discussed this development from both a theoretical and experimental standpoint in some detail (ref. 3).

Irwin introduced the concept of crack tip plasticity or a finite plastic zone which represented an energy input to the Griffith equations sufficient to provide practical results. Also the concepts of plane strain and plane stress were introduced. In the plane strain condition the material behaves in a macroscopically brittle manner and exhibits a lower bound condition for critical crack propagation. In the plane stress case the stress intensity at which unstable crack growth initiates is designated as  $K_{IC}$ . The similar condition under conditions of plane stress (where the material is macroscopically ductile) is called  $K_C$ . The plane strain  $K_{IC}$  value is considered a materials property (ref. 4).

The American Society for Testing and Materials organized a committee (E-24) to develop and standardize test techniques and the understanding of fracture. They initially focused on the development of a test for the material property  $K_{IC}$ . This plane strain lower bound condition was recognized as a conservative value for design. Further it was shown that the plane strain condition is realistically approached in a number of applications including heavy section power generation rotors and pressure vessels such as rocket motor cases (ref. 5). This committee has now approved and standardized the production and presentation of  $K_{IC}$  data with the promulgation of ASTM Standard E399-72.

The plane stress condition in which the metal is fully plastic and unrestrained in the macroscopic condition is the subject of much discussion and continuing effort. The stress intensity factor representing the critical plane stress condition may be an upper bound but is probably not representative of a realistic structural condition. The present approaches to other than plane strain conditions which are termed mixed mode or thin section testing, are of two types. The first is based on the crack growth resistance curve or G value. This is an empirical approach which attempts to simulate the actual structural condition in which the thickness is such that the restraint in that direction is minimized and the plane strain balanced triaxiality reduces to a balanced biaxial strain condition at the crack tip (ref. 6). The other approach is to analytically reduce the plastic flow to an energy which can be related to a critical materials property. This J-Integral analysis attempts to produce a number of significance like  $K_{IC}$  in the form of  $J_{IC}$  (ref. 7). A number of fundamental questions remain to be answered about the utility of this approach and experimental and theoretical work is continuing (ref. 8, 9).

The designer has at his disposal a wealth of plane strain fracture toughness information. Much of this is in the form of a critical plane strain stress intensity factor ( $K_{IC}$ ) which is determined in accordance with the ASTM E399-72 test method. These values are catalogued along with other materials property information in several handbooks (ref. 10, 11). The damage tolerant design handbook was created particularly to display fracture toughness data after it was found that aircraft structures were particularly susceptible to fracture conditions approaching plane strain (ref. 12).

The designer can use the  $K_{IC}$  value in computing a failure stress ( $\sigma_f$ ) for a part containing a flaw of length (2a) by the equation:

$$\alpha \sigma_f \sqrt{\pi a} = K_{IC} \quad (1)$$

where  $\alpha$  is a factor associated with the geometry of the flaw and the type of part. The factor  $\alpha$  may be calculated by techniques of classic elasticity or finite element analysis. A large number of cases have been analyzed and are tabulated (ref. 13, 14).

The designer has a difficult task when faced with the technology of fracture mechanics. He must make a choice about its position in the design cycle. Fracture mechanics technology can be relegated to a minor position and be used after all major decisions are made to satisfy contractual requirements. Conversely, linear elastic fracture mechanics can be used (or abused) to make all decisions, even when very conservative, expensive decisions result from an abuse of the technology. Both extremes represent poor engineering and management.

The latter extreme results from missing pieces of the developing technology. Three types of information are needed to characterize materials and to apply quantitative fracture-mechanics analyses in its present state:

- a. A lower bound value of the fracture toughness parameter,  $K_{IC}$  or  $K_C$ ;
- b. Reliable values for the crack-growth parameters  $da/dN$  or  $da/dt$ ;
- c. The lower limit of reliable detection by NDE of a flaw or a crack.

The validity of  $K_{IC}$  data in accordance with ASTM E399-72 is a function of several variables. One of these is specimen thickness. It often occurs that this thickness is sufficiently different from the proposed application to introduce considerable doubt about the value of the  $K_{IC}$  obtained. In addition the structural geometry of the intended application often introduces additional complexities further reducing the usefulness of the  $K_{IC}$ . The plane stress condition is elusive since no established standard test or validity criteria exists for obtaining the  $K_C$  value. These problems have given rise to the efforts to examine mixed mode thin section problems. The values for the crack growth parameters are subject to wide variability. It has been shown that for a given stress intensity factor range the crack growth rate may vary over two or three orders of magnitude (ref. 15). Further the effect of the environment can be equally important on the crack growth rate. A variation of over three orders of magnitude was demonstrated in high strength maraging steel in the different environments of air vs distilled water (ref. 16). These variabilities require the use of excessively conservative factors resulting in increased systems weight, cost and complexity.

The third factor in the design equation is the NDE lower limit of detectability. The reliability and sensitivity of flaw detection is the subject of considerable development (ref. 17, 18). Two areas of NDE effort are of interest. The first is during testing. The critical nature of the fatigue precrack in fracture toughness testing is well established (ref. 19). NDE is employed to monitor the development and extent of this precrack as well as the "pop-in" or onset of rapid unstable crack growth, which in plane strain testing establishes the  $K_{IC}$  value. The pop-in is typically monitored by acoustic or continuous stress strain recording techniques (ref. 20).

The second and more challenging NDE task is monitoring cracks and flaws in structures during production, structural testing and in service. This is complicated by the limited accessibility of some structures and the limited availability of standards. This is an absolutely critical area for the application of fracture mechanics, as fracture prediction rests on the size, nature, orientation and type of flaw in the structure (ref. 21). The application of fracture mechanics concepts in design assumes that flaws exist in the part or structure. NDE must be employed to assure that cracks above some critical size do not exist.

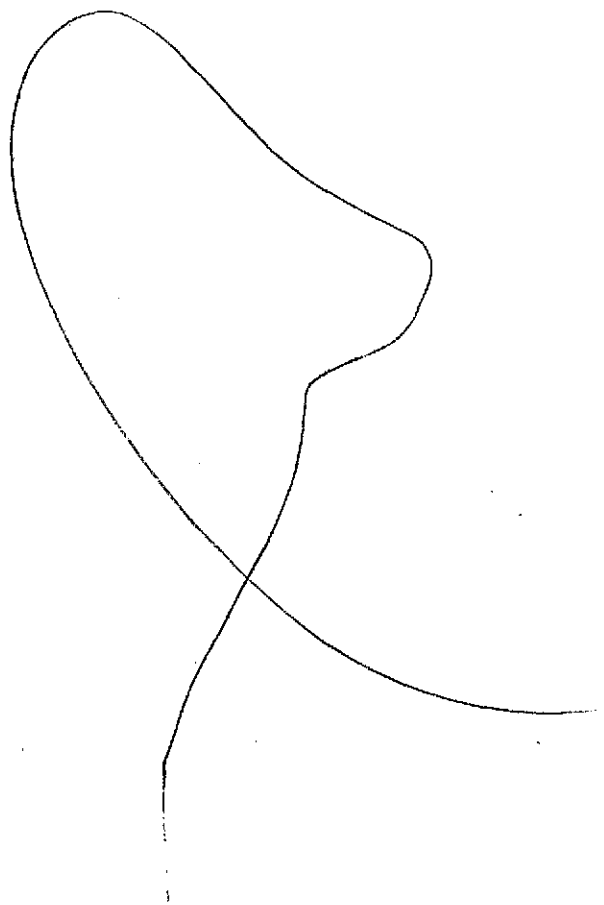


Future efforts must focus on the fracture toughness of materials insitu, in other words, the crack growth resistance or flaw tolerance of the material as it is employed in a structure. This involves the complete design task in the development of a fracture control plan. These technologies require extensive development, particularly fracture-toughness characterization of structural sections that are too thin for plane strain to apply. Also, fracture analysis under complex conditions of loading and environment present difficulties and excessive dependency on empirical testing. Although, NDE practices and techniques appear highly sophisticated and broadly based, they have serious deficiencies that must be overcome to permit using NDE in a quantitative engineering way as an integral part of the fracture-control plan (ref. 22).

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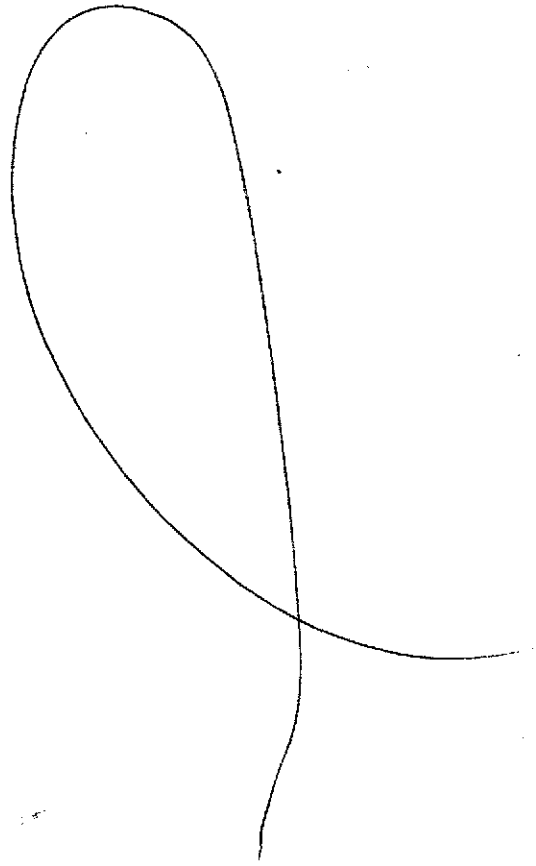
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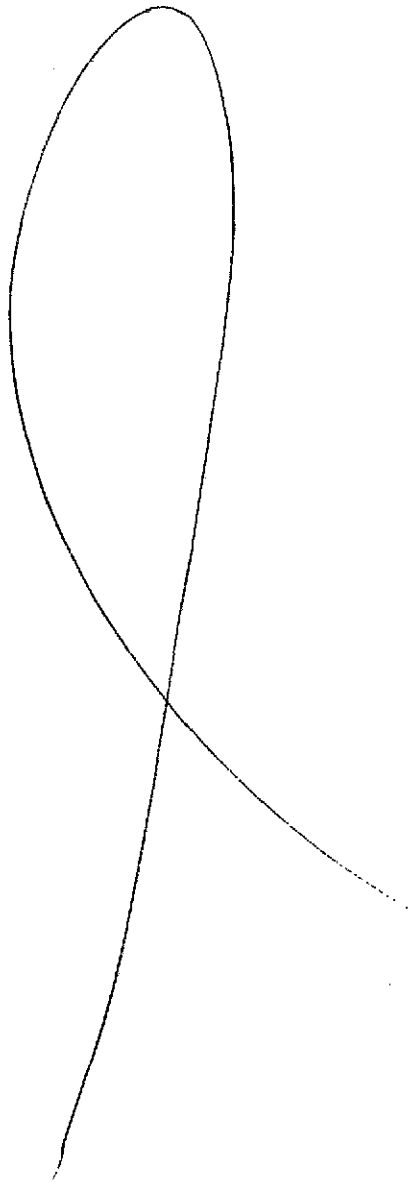
TECHNICAL ABSTRACTS

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I. STATE OF THE ART REVIEWS AND OVERVIEWS

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## IA. SURVEY REPORTS

### BASIC ASPECTS OF CRACK GROWTH AND FRACTURE

Irwin, G.R., Krafft, J.M., Paris, P.C. and Wells, A.A. (Naval Research Lab., Washington, DC; Lehigh Univ., Bethlehem, PA; Queens Univ., Belfast, Northern Ireland)

NRL Report 6598 (November 1967)

A near approach to absolute fracture safety in boiling water and pressurized water nuclear reactor pressure vessels requires a very conservative fracture control plan. Such a plan must assume that any plausible cracklike defect, which has not been proven absent by inspection, may exist in the vessel. Requirements for design, materials, and inspection may then be established in a conservative way relative to estimates of progressive crack extension behavior. These estimates are assisted by elastic and plastic methods of analysis of cracks in tension. Approximate methods of assigning  $K_{IC}$  values to measurements of crack toughness in terms of a brittle-ductile transition temperature are valuable in reviewing methods of fracture control which have received trial in the past, such as the NRL fracture analysis diagram and the leak-before-break toughness criterion.

#### Comments:

This report discusses in considerable detail the theoretical background and analytical development of fracture concepts leading to the development of fracture toughness testing standards. The concepts of plastic flow in fracture are treated in detail, examining the crack arrest phenomena leading the fail-safe criteria for design of thick walled nuclear containment vessels. The authors present an academic background for the technology.

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Key Words: Crack growth rate; critical flaw size; elastic-plastic analysis; fracture strength; fractures (materials); linear elastic fracture mechanics; pressure vessels; stress concentration; stress intensity factor.

#### PROGRESS IN FRACTURE TESTING OF METALLIC MATERIALS

Kaufman, J.G. (Aluminum Co. of America, New Kensington, PA)  
Review of Developments in Plane Strain Fracture Toughness Testing,  
ASTM STP 463, 3-21 (1970)

Progress in the development of fracture-toughness testing techniques by ASTM Committee E-24 is reviewed briefly. The evolution of the test method for plane strain stress-intensity factor,  $K_{IC}$ , is described, including treatment of some of the problems dealing with fatigue cracking, thickness limitations and crack growth detection and measurement. Attention is given also to the preparation of the screening test method for thin sections. Some cautions are presented concerning the necessity for meticulous standardization, despite the time required to do an acceptable job, and the timing problems in incorporating methods into specification requirements.

#### Comment:

The author has presented an excellent summary of the progress in fracture testing, principally by ASTM Committee E-24 in the area of plane strain fracture toughness. His cautionary notes should be heeded to prevent undisciplined application of data and invalid data from entering the critical design cycle. He indicates that the development of a test standard (such as ASTM E399-72) must be approached with caution and respect. Such standards must have wide applicability and not be sensitive to uncontrolled test variables. The inclusion of plane strain fracture toughness ( $K_{IC}$ ) values in materials specifications should be done only after due consideration of the scatter in the results, the influence of product variation (test direction, product dimension, product heat-treatment) and the specific design requirements for the application under consideration. He shows that the development of  $K_{IC}$  data for inclusion in design handbooks must be approached with caution.

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Key Words: Crack detection; crack growth rate; crack line loaded specimens; crack opening displacement; fracture mechanics; fracture strength; fractures (materials); laboratory tests; linear elastic fracture mechanics; metallic materials; plane strain; plane stress; stress intensity factor; testing methods; testing standards.

### COMMENTARY ON PRESENT PRACTICE

Brown, Jr., W.F. and Srawley, J.E. (National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH)  
Review of Developments in Plane Strain Fracture Toughness Testing, ASTM STP 463, 216-248 (1970)

Specimen size requirements and attempts to correlate  $K_{IC}$  with simpler mechanical test results are areas of considerable controversy among those engaged in plane strain fracture toughness testing. The tentative method of test for plane strain fracture toughness of metallic materials (E 399-70 T) may need revision before being advanced to a standard. Additional experimental data are needed in order to make a judgment concerning the need for revision.

Comment:

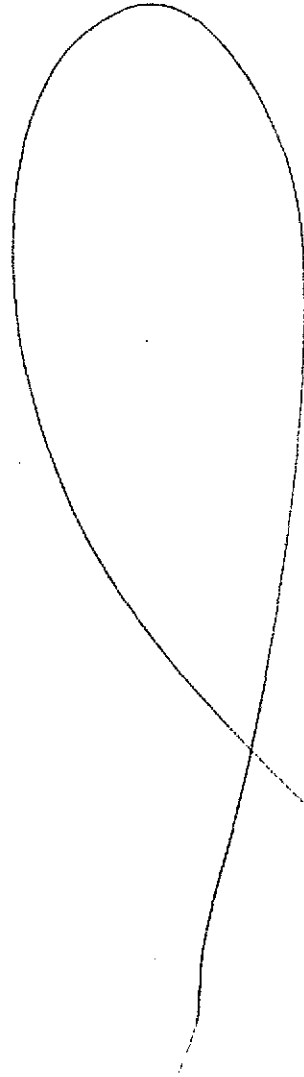
The authors present a balanced overview of the state of plane strain fracture toughness testing in the 1968 to 1970 time frame. Their continuing concern for validity in the measurement of  $K_{IC}$  is accurately expressed. They present convincing arguments, supported by experimental data for the misleading nature of the estimates of fracture strength resulting from Charpy type impact properties and subsized specimens. Their efforts as indicated in this paper continue to provide a necessary balance to short cuts almost daily proposed by many workers in the field.

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Key Words: Fracture strength; fractures (materials); plane strain; plane strain fracture toughness; plane stress; stress intensity factor; test specimen design; testing methods; testing standards.

## II. HANDBOOKS AND DATA



IIA. HANDBOOKS

DAMAGE TOLERANT DESIGN HANDBOOK

Campbell, J.E., Berry, W.E. and Feddersen, C.E. (Battelle Columbus Labs., OH)  
MCIC Handbook HB-01 (December 1972)

This is a compilation of fracture mechanics data on high-strength aluminum alloys, alloy steels, stainless steels, and titanium alloys. The data represent state-of-the-art information on critical plane strain stress intensity factors, plane stress and transitional stress intensity factors, threshold stress intensity factors in corrosive media, sustained-load crack-growth rates in corrosive media, and fatigue crack growth rates. This handbook is intended to be the primary source of fracture mechanics data for Air Force contractors for design of damage-tolerant structures according to requirements of MIL-STD-1530 Aircraft Structural Integrity Program and the supporting MIL-A-8866 services specifications. It is intended that the handbook will eventually be incorporated into the damage tolerance section of AFSC DH 2-0. New fracture mechanics data are being generated on many programs and compilation of data for the handbook will be continued. Up-to-date printouts for any of the parameters for any of the alloys are available from MCIC. This handbook is in looseleaf form to permit insertion of revised data sheets which become available at regular intervals.

Comments:

This massive and continually updated document provides a single source for much of the fracture toughness data available today. It is being used as the source document for procurement of Air Force systems in terms of the fracture criteria of materials such as in the B-1 program. Hopefully subsequent revisions will provide more information on the validity in terms of ASTM E399-72 of the reported values of  $K_{IC}$ . The over 150 references are specifically related to the tabular and graphical presentation of the data and are important in terms of providing the source information necessary in establishing the validity of a particular  $K_{IC}$  value.

Key words: Crack propagation; data; fatigue properties; fracture strength; metallic materials; plane strain fracture toughness; stress intensity factor.

MILITARY STANDARDIZATION HANDBOOK, METALLIC MATERIALS AND ELEMENTS FOR AEROSPACE VEHICLE STRUCTURES

Air Force/Army/Navy/FAA (Air Force Material Lab., Wright-Patterson AFB, OH)  
MIL-HDBK-5B

This document is intended primarily as a source of design allowables which are those strength properties of structural materials and alloys that have received general acceptance for use in design. The document contains strength properties, e.g., fracture toughness and fatigue data, and is issued to provide uniform data to minimize the necessity for referring to numerous materials handbooks and bulletins.

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Key words: Aircraft structures; data; design criteria; fatigue properties; fracture mechanics; fracture strength; heat resistant alloys; metallic materials; temperature effects; tensile properties; testing methods.

AEROSPACE STRUCTURAL METALS HANDBOOK

Weiss, V. and Sessler, J.G. (Editors) (Syracuse Univ., Utica, NY)  
ASD-TDR 63-741 and Subsequent Volumes and Supplements (Air Force Materials Laboratory, Wright-Patterson AFB, OH)

The "Aerospace Structural Metals Handbook", with the insertion of revision supplements contains physical, chemical and mechanical property information on over 170 metals and alloys of interest for aerospace structural applications. The Handbook consists of three volumes as follows:

- Volume I - Ferrous Alloys
- Volume II - Non-Ferrous, Light Metal Alloys
- Volume IIA - Non-Ferrous, Heat Resistant Alloys

Each volume is self-contained in a loose-leaf, standard 3 post binder. Volume I contains over 60 ferrous alloys chapters, Volume II contains over 50 light metal alloys chapters and Volume IIA contains over 50 heat resistant alloys chapters. Further revision and updating of alloy chapters are planned for the future. The Handbook also contains data source references, a general discussion of properties, a glossary of terms, a discussion of fracture toughness and cross-index of alloys contained therein.

Key words: Aluminum alloys; data; fatigue properties; fracture strength; mechanical properties; metallic materials; titanium alloys.

PLANE STRAIN FRACTURE TOUGHNESS ( $K_{IC}$ ) DATA HANDBOOK FOR METALS

Matthews, W.T. (Army Materials and Mechanics Research Center, Watertown, MA)  
AMMRS-MS-73-6

A compilation of plane strain  $K_{IC}$  data is presented for metals manufactured in the U.S.A. and Europe, including 50 steels, 21 titanium alloys, 38 aluminum alloys, and one beryllium material. The data corresponds to static loading in neutral laboratory environment. The effect of temperature is included in the tables along with the direction of testing, the form and size of the material, its composition and heat treatment, and the specimen type and size.

Comments:

The presentation of data is very useful in that it includes the ASTM E399-72 criteria for validity for all reported values where available. In addition, there is an extensive list of references (124) and a biography (62). It is a reference useful for designers involved in materials selected for fracture critical applications.

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Key words: Aluminum alloys; data; fracture mechanics; fracture strength; plane strain fracture toughness; steels; titanium alloys.



## IIB. DATA INTERPRETATION

ANALYSIS OF FATIGUE, FATIGUE - CRACK PROPAGATION, AND FRACTURE DATA  
Jaske, C.E., Feddersen, C.E., Davies, K.B. and Rice, R.C. (Battelle Memorial  
Inst., Columbus, OH)  
NASA-CR-132332 (November 1973)

Analytical methods have been developed for consolidation of fatigue, fatigue-crack propagation, and fracture data for use in design of metallic aerospace structural components. To evaluate these methods, a comprehensive file of data on 2024 and 7075 aluminums, Ti-6Al-4V, and 300M and D6AC steels was established. Data were obtained from both published literature and unpublished reports furnished by aerospace companies. Fatigue and fatigue-crack-propagation analyses were restricted to information obtained from constant-amplitude load or strain cycling of specimens in air at room temperature. Fracture toughness data were from tests of center-cracked tension panels, part-through crack specimens, and compact-tension specimens.

Both fatigue and fatigue-crack-propagation data were analyzed on a statistical basis using a least-squares regression approach. For fatigue, an equivalent strain parameter was used to account for stress ratio effects and was treated as the independent variable, and cyclic fatigue life was considered the dependent variable. An effective stress-intensity factor was used to account for the effect of load ratio on fatigue-crack propagation and was treated as the independent variable. In this latter case, crack-growth rate was considered to be the dependent variable.

Smooth-specimen and notched-specimen fatigue data were treated separately. Notched-specimen results were analyzed using a local stress-strain approach to account for fatigue damage at the notch root. Data for various types of notches and theoretical stress-concentration factors were consolidated by using a computer fatigue-strength reduction factor. Both the cyclic and monotonic stress-strain curves were employed in calculating the local stress-strain response from nominal loading information.

After computing mean fatigue and crack growth curves by least-squares regression, tolerance level curves were determined. Lower level tolerance curves for 90 and 99 percent probability of survival with 95 percent level of confidence were determined for each fatigue curve. Two-sided tolerance bands for 90 and 99 percent probability with 95 percent confidence were determined for each mean crack growth curve.

Fracture toughness data were tabulated for a particular material and specimen thickness in terms of average values at various temperatures and panel widths. Apparent, critical, and onset fracture toughness indexes were used in this tabulation.

Important references:

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Key words: Analysis methods; crack detection; crack propagation; data; fatigue (materials); fatigue properties; fracture analysis; fracture strength; fractures (materials); laboratory tests; life prediction; metallic materials; plane strain fracture toughness; residual strength; statistical analysis; stress intensity factor.

STATISTICAL VARIATION IN FRACTURE TOUGHNESS DATA OF AIRFRAME MATERIALS  
Liu, A.F. (The Boeing Co., Renton, WA)  
AFFDL-TR-70-144 (September 1970)

Fracture toughness data has been subjected to a graphical statistical treatment. The results show that the test values for the critical stress intensity factor (plane strain) could be approximated using either a log-normal or a Weibull distribution. By making use of the log-normal (2 parameter) distribution. The sample mean and the guaranteed minimum values, for some of the available data, were estimated and are tabulated for reference.

The nature of fracture toughness testing and factors that affect test results were reviewed. Emphasis has been placed on the fact that without paying close attention to the physical phenomenon involved, conclusions drawn from any statistical analysis would have little meaning. A graphical method was adopted for evaluating the closeness of fit between given probability density functions and fracture toughness data. It is concluded that these probability functions, commonly used to fit material mechanical properties data, are also applicable for fitting the fracture toughness data.

Comments:

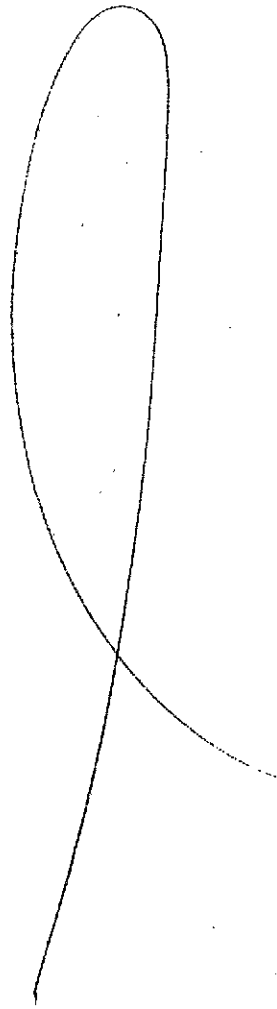
Statistical analysis of the variation of the stress intensity factor at failure with various specimen test parameters such as thickness was employed in the development of the ASTM Standard. This paper is instructive in predicting trends for tests which do not meet the ASTM plane strain fracture toughness test criteria.

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2. Scop, P.M. and Argon, A.S., Statistical Theory of Strength of Laminated Composites, J.Compos. Mater. I, 92 (1967).
3. Smith, S.H. and Liu, A.F., Fracture Mechanics Application to Materials Evaluation and Selection for Aircraft Structure and Fracture Analysis, Boeing Company, Report No. D6-17756 (1966).
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7. Weibull, W., A Criterion for the Acceptability of Assumed Distribution, AFML-TR-69-124 (1969).

Key words: Aircraft structures; fracture analysis; fracture mechanics; fracture strength; plane strain; statistical analysis; stress intensity factor; structural safety; tensile properties.

### III. MATERIALS



### IIIA. Steel

#### APPLICATION OF FRACTURE MECHANICS TECHNOLOGY TO MEDIUM-STRENGTH STEELS

Clark, Jr., W. G. and Wessel, E. T. (Westinghouse Research Labs., Pittsburgh, PA)

Review of Developments in Plane Strain Fracture Toughness Testing, ASTM STP 463, 160-190 (1970)

A review of fracture toughness versus temperature and room temperature fatigue crack growth rate data currently available for medium strength steels was presented. These data clearly illustrate that under conditions of sufficient restraint to ensure plane strain loading, existing linear elastic fracture mechanics technology is applicable to medium strength steels. It was noted that these steels tend to exhibit a very rapid increase in  $K_{IC}$  with temperature in the temperature range of practical interest. Hence, for most of the materials studied, the critical defect sizes necessary to cause failure under normal service conditions are extremely large.

It was shown also that the room-temperature fatigue crack growth rate properties of medium strength steels could be expressed in terms of the crack tip stress intensity factor range,  $\Delta K$ . Specifically, the fatigue crack growth rate properties of these steels conform to the general behavior observed for higher strength steels.

The practical usefulness and overall potential of fracture mechanics technology as a quantitative tool for the prevention of structural failure was demonstrated with a simple example problem. The details involved in computing the critical defect size for failure as well as the maximum initial allowable flaw size for a specified cyclic life were included in the example.

#### Comments:

This work helped to expand the usefulness of plane strain fracture toughness to include the medium strength steels such as employed for power generation rotors and housings. In addition, their presentation of the linear relationship between the log of the fatigue crack growth rate and the log of the stress intensity factor range helped to establish the dependency of the growth rate on crack tip stress intensity. The inclusion of the example problem in the paper is most illustrative of the application of plane strain fracture toughness technology to an actual design problem.

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7. Brown, Jr., W. F. and Srawley, J. E., Plane Strain Crack Toughness Testing of High Strength Metallic Materials, ASTM STP 410 (January 1967).

Key words: Cracks; data; fatigue (materials); fracture mechanics; fracture strength; fractures (materials); linear elastic fracture mechanics; plane strain; pressure vessels; steels; stress intensity factor; structural safety.

#### THE EFFECT OF LOADING RATE AND TEMPERATURE ON THE FRACTURE TOUGHNESS OF HIGH STRENGTH STEELS

Kendall, D. P. (Watervliet Arsenal, NY)  
AD-713357, WVT-7044 (1970)

This paper discusses the effects of loading rates, ranging from 10 to 100,000 psi, and temperatures, ranging from room temperature to minus 100 degrees F, on the plane strain fracture toughness of several high strength alloy steels. Materials investigated were a commercial 4340 steel, a modified 4330 steel from a gun tube forging having three different heat treatments and two different heats of 250 grade maraging steel. Test specimens utilized are essentially ASTM compact tension type specimens of one inch thickness. Tests were conducted on an open loop, hydraulic, high loading rate tensile testing machine. Results are presented in the form of graphs of fracture toughness versus temperature for the maximum and minimum loading rates (dynamic and static). Fracture toughness versus loading rate at minus 60 degrees F and yield strength versus elastic strain at room temperature, minus sixty degrees F and minus 100 degrees F for one heat of maraging steel are also reported.

#### Important references:

1. Krafft, J. M., Correlation of Plane Strain Crack Toughness with Strain Hardening Characteristics of a Low, Medium, and High Strength Steels, Appl. Mater. Res. 1, No. 1, 88-101 (April 1964).
2. Shoemaker, A. K. and Rolfe, S. T., Static and Dynamic Low Temperature K<sub>sub</sub> IC Behavior of Steels, presented at a meeting of ASTM Committee E-24 (March 1969).
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Key words: Elastic properties; fracture strength; fracture tests; high strength alloys; mechanical properties; plane strain; steels; strain rate; structural safety; tensile properties; yield strength.

PLANE STRAIN FRACTURE TOUGHNESS TESTS ON 2.4 AND 3.9-INCH-THICK MARAGING STEEL SPECIMENS AT VARIOUS YIELD STRENGTH LEVELS

Fisher, D. M. and Repko, A. J. (National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH)

J. Mater. 7, 167-174 (June 1972)

The specimen size requirements of the ASTM plane strain fracture toughness test method (E399-70T) were not sufficient to disqualify all the  $K_{IC}$  results of this investigation that were low relative to results from larger specimens. This could be remedied in these results by an increase in the specimen size requirement based on the square of the ratio of the conditional fracture toughness value to yield strength. Regardless of its severity, a specimen size requirement based on a  $K_Q$  value cannot be a sufficient single validity requirement for all  $K_{IC}$  test results. This requirement has an inherent deficiency which permits specimen dimensions to be undersize by an amount proportional to the difference between the square of the ratio of the plane strain fracture toughness to yield strength and the square of the ratio of the conditional fracture toughness to yield strength.

The test curve linearity requirement gave inconsistent results when applied to the test values obtained in this investigation. In some cases this requirement failed to invalidate 2.4 in-thick specimen  $K_Q$  values that were low in comparison with those of the 3.9 in-thick specimens. In other cases the curve linearity requirement was not met when the  $K_Q$  values were comparable to valid results for similar material conditions.

For any specific yield strength level of the 200 grade maraging steel of this investigation, greater plane strain fracture toughness was observed in an overaged condition than in an underaged. Specimen shear lip size was observed to remain reasonably constant as specimen size increased and no relation of shear fraction to test validity was indicated.

It is apparent from this investigation and other current work that refinements of E399-70T are advisable. The results of this investigation provide a basis for future work involving the test validity requirements.

Comments:

This paper highlights some of the shortcomings of the interim test standard E399-70T in terms of the plane strain fracture toughness ( $K_{IC}$ ) validity criteria. Some of the difficulties encountered are eliminated by applying the load ratio requirement of the standard E399-72 instead of the offset displacement ratio requirement of E399-70T.

Important references:

1. Srawley, J. E., Plane Strain Fracture Toughness Tests on Two-Inch-Thick Maraging Steel Plate at Various Strength Levels. Int. Conf. on Fracture, 2nd, England (1969).
2. Brown, W. F., Jr., and Srawley, J. E., Plane Strain Crack Toughness Testing of High Strength Metallic Materials ASTM STP 410 (1967).



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See also:

1. Heyer, R. H., Discussion to Fisher, D. M., and Repko, A. J., Plane Strain Fracture Toughness Tests on 2.4 and 3.9-Inch-Thick Maraging Steel Specimens at Various Yield Strength Levels, J. of Mater. 7, No. 2, 174-177 (June 1972).

Key words: Bend tests; deformation; elastic properties; fatigue properties; fracture strength; fracture tests; maraging steel; plane strain fracture toughness; tensile properties; testing methods; yield strength.

CORRELATION OF PLANE STRAIN CRACK TOUGHNESS WITH STRAIN HARDENING CHARACTERISTICS OF A LOW, A MEDIUM, AND A HIGH STRENGTH STEEL  
 Krafft, J. M. (Naval Research Lab., Washington, DC)  
 Appl. Mater. Res. 1, No. 1, 88-101 (April 1964)

The increase in true stress resulting from strain hardening can often be closely represented by raising the true strain to a power  $N$ , a positive number usually less than unity. Observations indicate the controlling influence of the strain hardening characteristics on the fracture process. A consistent interpretation of results is provided by assuming that the plane strain crack will become unstable when the crack tip stress field causes tensile strain equal to that for plastic flow instability in the material, a small, fixed distance in advance of the crack tip. The strain hardening characteristics determinative of the instability strain are those specific to conditions of strain rate and temperature calculated to exist at this fixed distance from the crack. This distance appears to be a constant for a given material over a large range of loading rate and temperature. It is the purpose of this paper to describe the evidence leading to this result, considering in turn: the tests for plane strain fracture toughness with the description of the strain field; tests for plastic flow properties, particularly of strain hardening characteristics with the effect of adiabaticity; apparatus for testing both fracture and flow specimens over a wide range of straining speeds and temperature; the correlation between these tests; and implications of the result.

(FOR LISTING OF IMPORTANT REFERENCES, KEY WORDS AND A DUPLICATE ABSTRACT, SEE PAGE 115).

## FRACTURE TOUGHNESS OF 180 TO 210 KSI YIELD STRENGTH STEELS

Puzak, P.P. and Lange, E. A. (Naval Research Lab., Washington, DC)  
Metals Eng. Quart. 10, 6-16 (February 1970)

The effects of chemical composition, yield strength, melting practice, heat treatment, and rolling practice on resistance to fracture was established for materials melted and processed under a variety of production conditions. The ratio analysis diagram was used for analyzing the effects of these factors on the structural performance in terms of critical flaw sizes and stress levels. Four alloys were included in the investigation: 18 Ni-8 Co-3 Mo and 12 Ni-5 Cr - 3 Mo maraging steels; 9 Ni-4 Co-1 Cr-1 Mo - 0.20 C and 10 Ni - 8 Co-2 Cr - 1 Mo - 0.11 C quenched and tempered steels. For these generic steels, chemical composition had a direct effect on yield strength, but other factors controlled fracture resistance. The intrinsic fracture resistance of all steels decreased sharply in the yield strength range of 124100 to 144900 N/cm<sup>2</sup> which is termed the strength transition, but the intrinsic level of fracture toughness at a specific yield strength is primarily dependent upon the cleanliness of the material in a particular product. Air melted materials in the 124100 to 144900 N/cm<sup>2</sup> yield strength range are brittle in sections over 2.54 cm thick. Vacuum melting significantly improves fracture resistance.

### Important references:

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Key words: Analysis methods; fracture strength; fractures (materials); high strength alloys; maraging steel; mechanical properties; stress intensity factor; yield strength.

PLANE STRAIN FRACTURE TOUGHNESS OF HIGH STRENGTH MATERIALS  
Steigerwald, E. A., (TRW Equipment Labs., Cleveland, OH)  
Eng. Fract. Mech. 1, No. 3, 473-494 (1969)

An experimental program was conducted to determine the plane strain fracture toughness ( $K_{IC}$ ) of the following classes of high strength materials: (1) AISI alloy steels (4340, 4140); (2) 5Cr-Mo-V steels; (3) Precipitation-hardening stainless steels (17-7PH, PH15-7Mo, 17-4PH, AM355); (4) Titanium alloy, Ti-6Al-4V. The precracked notched bend test was used as the test method and several heats of each material were evaluated over a range of temperatures from -100 to +200°F. The  $K_{IC}$  values, obtained under conditions which were believed to provide valid plane strain fracture toughness numbers, were plotted both as a function of material strength and test temperature. The resulting curves provide representative  $K_{IC}$  figures which can aid in the selecting of materials for reliable performance.

The low temperature data indicate that the decrease in  $K_{IC}$  that occurs with decreasing temperature cannot be accounted for solely on the basis of the increase in yield or tensile strength.

The data for the materials evaluated were combined with the limited  $K_{IC}$  data available in the literature to produce representative curves of  $K_{IC}$  as a function of both tensile strength level and test temperature. Although typical fracture toughness values are given which can aid in designing and selecting material conditions to preclude brittle fracture, the inherent variability in the  $K_{IC}$  value as a function of heat of material must receive adequate consideration. The scatter between heats can be as great as 30 percent and the material used for a specific design should be evaluated prior to use to insure that abnormally low fracture toughness does not exist.

Comment:

The author has examined a range of high strength steels and noted the inherent variability in the  $K_{IC}$  as a function of conventional heat to heat variation. His caution that the design value must be the value of the actual material employed should be emphasized, particularly for those applications where there is a critical safety and reliability factor involved.

Important references:

1. Brown, Jr., W. F. and Srawley, J. E., Plane Strain Crack Toughness Testing of High Strength Metallic Materials, American Society for Testing Materials, Special Technical Publication No. 410 (1966).
2. Srawley, J. E., Jones, M. H. and Brown, Jr., W. F., Determination of Plane Strain Fracture Toughness, Mater. Res. Stand. 7, No. 6 (1967).
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4. Fisher, D. M., Bubsey, R. T. and Srawley, J. E., Design and Use of Displacement Gage for Crack Extension Measurements, NASA Technical Note No. D-3724 (1966).
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Key words: Data; fracture strength; high strength alloys; plane strain; plane strain fracture toughness; structural reliability.

#### FRACTURE MECHANICS CONSIDERATION OF HYDROGEN SULFIDE CRACKING IN HIGH STRENGTH STEELS

Bucci, R. J., Paris, P. C., Loushin, L. L., and Johnson, H. H., (Del Research Corp., Bethlehem, PA., Esso Research and Engineering Co., Linden, NJ, Cornell Univ., Ithaca, NY.)

Stress Analysis and Growth of Cracks, Proc. 1971 Nat. Symp. on Fracture Mechanics, Part 1, ASTM STP 513, 292-307 (September 1972)

Hydrogen sulfide (H<sub>2</sub>S) stress corrosion cracking studies were conducted within the framework of fracture mechanics for several high strength steels (AISI 4340, 4140, HY-80 and HY-130). For all the steels and strength levels investigated ( $\sigma_{ys} = 80$  to 150 ksi), H<sub>2</sub>S stress corrosion cracking was found to exist. For each of the alloys investigated, a valid plane strain  $K_{ISCC}$  (which indicates the demarcation between detectable rates of crack extension,  $da/dt \geq 10^{-5}$  in./min. and those below these rates) was measured and found to depend significantly on yield stress with decreasing  $K_{ISCC}$  values reported for increasing yield stress.

A limited investigation of crack growth kinetics found crack growth rates to accelerate most rapidly from presharpended fatigue cracks when loaded to K levels just beyond the  $K_{ISCC}$  threshold. In several instances, especially with the highest strength alloys, stress corrosion crack velocities attained peak values before being "damped" to some steady state velocity at increased K levels. The crack velocity damping might in part be attributed to crack division or plasticity effects associated with increasing plastic zone size to thickness ratio at higher K levels.

(FOR LISTING OF IMPORTANT REFERENCES, KEY WORDS AND A DUPLICATE ABSTRACT, SEE PAGE 112).

THE STRESS INTENSITIES FOR SLOW CRACK GROWTH IN STEELS CONTAINING HYDROGEN  
Dautovich, D. P. and Floreen, S. (International Nickel Co., Inc., (NY)  
Met. Trans. 4, 2627-2630 (November 1973.)

A test technique has been developed to determine the stress intensity for slow crack growth in hydrogen precharged steels. Measurements on several grades of maraging steel and a 300M steel show that hydrogen contents on the order of  $2 \text{ ppm}$  reduce the stress intensity for slow crack growth by 50 percent or more of the  $K_{IC}$  values. At equivalent hydrogen contents the 300M steel was more severely embrittled than the maraging steels. Comparison of the present results with aqueous  $K_{ISCC}$  data indicates that the amount of hydrogen picked up by the steels in stress corrosion increases with increasing yield strength.

(FOR LISTING OF IMPORTANT REFERENCES, KEY WORDS AND A DUPLICATE ABSTRACT, SEE PAGE 110).

STRESS CORROSION CRACKING OF A HIGH STRENGTH STEEL  
Sheinker, A. A. and Wood, J. D. (Lehigh Univ., Bethlehem, PA)  
ASTM STP 518, 16-38 (September 1972)

Stress corrosion crack growth rates as a function of stress intensity factor were determined over a wide range of electrode potentials for AISI 4340 steel in deaerated 3.5% NaCl solution buffered to Ph 3.8. Particular emphasis was placed on conducting the stress corrosion tests under well defined electrochemical and mechanical conditions. At intermediate K levels, crack growth rate was essentially independent of K, suggesting that crack growth is limited by mass transport. Crack growth is apparently dominated by localized mechanical rupturing at high K levels, where crack growth rate increased rapidly with increasing K. Except at very cathodic potential, crack growth rate at intermediate K levels was also independent of potential, implying that electrochemical conditions at the tip of the stress corrosion crack are not the same as those outside the crack. The tendency for the stress corrosion cracks to branch was found to be electrochemically, as well as mechanically controlled.

(FOR LISTING OF IMPORTANT REFERENCES, KEY WORDS AND A DUPLICATE ABSTRACT, SEE PAGE 108).

STEELS FOR SEAMLESS HYDROGEN PRESSURE VESSELS  
Loginow, A. W. and Phelps, E. H. (United States Steel Corp., Monroeville, PA)  
Presented at Materials Symp. 1974 Petroleum Mechanical Eng. Conf., Dallas, TX  
(14-18 September 1974)

To provide engineering data useful in the design, manufacture, and operation of seamless pressure vessels, extensive tests have been conducted in hydrogen at pressures ranging from 21 to 97  $\text{MN/m}^2$  with precracked specimens of steels having a wide range of mechanical properties. The critical stress intensity level at which crack propagation spontaneously arrests,  $K_{IH}$ , was determined. The values of  $K_{IH}$  were used in an illustrative calculation to estimate the critical flaw size at which hydrogen crack propagation would be expected in thick members loaded in bending. In general, the susceptibility of steels tested increased with yield strength. For the steels with intermediate yield strengths (586 to 779  $\text{MN/m}^2$ ),  $K_{IH}$  tended to decrease as pressure was increased from 21 to 97  $\text{MN/m}^2$ . The crack path was

analyzed, and a sequence of events is described involving the initiation, growth, and arrest of cracking induced by gaseous hydrogen.

(FOR LISTING OF IMPORTANT REFERENCES, KEY WORDS AND A DUPLICATE ABSTRACT, SEE PAGE 111).

ENHANCEMENT OF FRACTURE TOUGHNESS IN HIGH STRENGTH STEEL BY MICROSTRUCTURAL CONTROL  
Parker, E. R. and Zackay, V. F. (California Univ., Berkeley)  
Eng. Fract. Mech. 5, No. 1, 147-165 (1973)

The development of new alloys with improved mechanical properties has been seriously hampered in the past by the inability of a metallurgist to relate quantitatively the variables of microstructure and fracture toughness. The emergence of a unified theory of fracture toughness in the past decade has done much to alleviate this difficulty. As a consequence of a recent interdisciplinary research effort involving both the disciplines of physical metallurgy and experimental fracture mechanics, we have been able to develop alloys with engineering properties superior to those of commercially available materials. This research has required the creation of new and unusual microstructures, utilizing a variety of thermo-mechanical processes.

The quantitative relationships of mechanical properties (strength, ductility, work hardening, and fracture toughness) with composition and microstructure are discussed in detail for the newly developed TRIP (transformation induced plasticity) steels. In the report of another development, it is shown how the fracture toughness of low alloy quenched and tempered steels with yield strengths over 200,000 psi can be improved by as much as 70 percent by microstructural control. Lastly, the initial results of research on alloys intended for cryogenic service are described. The composition, heat treatment, microstructure and properties of an alloy having more than three times the toughness of the presently used alloys are discussed.

Comments:

These steel alloys as described in the paper offer a unique combination of properties in particular improved fracture toughness at high yield strengths. The technology of TRIP steels should be exploited such that substantial progress can be made toward developing new and useful alloys.

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Key words: Fracture strength; high strength alloys; mechanical properties; microstructures; steels.

CORRELATION OF TWO FRACTURE TOUGHNESS TESTS FOR TITANIUM AND FERROUS ALLOYS  
 Freed, C. N. and Goode, R. G. (Naval Research Lab, Washington, DC)  
 NRL Report 6740 (January 1969)

This report presents preliminary correlations that have been developed between dynamic tear (DT) energy values and  $K_{IC}$  for the determination of the fracture toughness of steel and titanium alloys. The value of the low DT test energy numbers, which are associated with crack propagation under elastic loading conditions, is enhanced in that these provide a means of using results obtained with the simpler and less expensive DT test to predict approximate values of  $K_{IC}$ ,  $\beta_{IC}$  and  $G_{IC}$ . With additional refinement of these correlations, more accurate quantitative estimations of these parameters from DT test results should be possible. Further, using the relationships provided by fracture mechanics between  $K_{IC}$  and the critical flaw size and stress level for crack extension, the conditions for crack instability can be determined from the DT test energy.

(FOR LISTING OF IMPORTANT REFERENCES, KEY WORDS AND A DUPLICATE ABSTRACT, SEE PAGE 43).

### IIIB. Aluminum

#### COMPARISON OF FRACTURE TOUGHNESS TEST PROCEDURES FOR ALUMINUM ALLOYS

Freed, C. N., Goode, R. J. and Judy, Jr., R. W. (Naval Research Lab., Washington, DC)

NRL Report 6853 (February 1969)

The dynamic tear (DT) test provides a sensitive and quantitative measure of the fracture toughness of aluminum alloys. The test permits the measurement of fracture propagation energy across the toughness spectrum for metals which are definable by linear elastic analysis to those requiring gross plastic strains for fracture. The linear elastic fracture mechanics parameter  $K_{IC}$  provides a relationship between critical flaw size and stress level at which crack instability will occur. Unlike the DT test, the  $K_{IC}$  toughness test cannot be used for fracture under conditions of elastic-plastic or gross plastic strain. A correlation has been developed between the DT test and the  $K_{IC}$  parameter for aluminum alloys. The relationship may also be expressed in terms of  $\beta_{IC}$  - DT and  $G_{IC}$  - DT. The  $K_{IC}$  values were determined with several specimen types and a comparison of the values for different specimens was obtained. The correspondence between  $K_{IC}$  and DT serves several purposes. It provides a frame of reference for DT values obtained from frangible metals that fracture under linear elastic conditions. Accordingly, it permits use of the inexpensive DT test to approximate the flaw size-stress instability conditions which otherwise must be determined by the more expensive  $K_{IC}$  test. Another important aspect of the relationship between DT and  $K_{IC}$  is that through extrapolation, the correlation which exists in the linear elastic region can be extended into the elastic-plastic region. The loss of a plane-strain stress state requires calculation of approximate  $K_C$  values from the extrapolated  $K_{IC}$  values. Thus, it is possible to use the DT test to estimate the critical flaw size at crack instability for metals in which fracture occurs under an elastic-plastic strain field. Because of the relatively large flaws involved for this condition, the approximation is adequate for most engineering purposes.

#### Important References:

1. Pellini, W. S., Goode, R. J., Puzak, P. P., Lange, E. A. and Huber, R. W., Review of Concepts and Status of Procedures for Fracture-Safe Design of Complex Welded Structures Involving Metals of Low to Ultra-High Strength Levels, NRL Report 6300 (June 1965).
2. Sullivan, A. M., New Specimen Design for Plane-Strain Fracture Toughness Tests, Mater. Res. Stand. 4, No. 1, 20-24 (1964).
3. Gross, B., Srawley, J. E. and Brown, Jr., W. F., Stress Intensity Factors for a Single-Edge-Notch Tension Specimen by Boundary Collocation of a Stress Function, NASA-TN-D-2395 (August 1964).
4. Freed, C. N. and Krafft, J. M., Effect of Side Grooving on Measurements of Plane-Strain Fracture Toughness, J. Mater. 1, No. 4, 770-790 (1966)
5. Boyle, R. W., Sullivan, A. M. and Krafft, J. M., Determination of Plane Strain Fracture Toughness with Sharply Notched Sheets, Welding J. Res. Suppl. 41, No. 9, 428S-432S (1962).



Key words: Aluminum alloys; Charpy impact tests; crack propagation; critical flaw size; dynamic tear tests; fracture mechanics; fracture strength; plane strain fracture toughness; stress intensity factor; structural safety; toughness; yield strength.

PLANE STRAIN FRACTURE TOUGHNESS PROPERTIES OF THREE ALUMINUM ALLOYS AS A FUNCTION OF SPECIMEN GEOMETRY

Davis, S. O., Tupper, N. G., Niemi, R. M. (Air Force Materials Lab., Wright-Patterson AFB, OH, Monsanto Research Corp., Dayton, OH)  
AFML-TR-65-150 (1965)

The fracture toughness of three aluminum alloys, 7079-T6, 7075-T6, and 7001-T75, was determined at room temperature, utilizing the center notch and single edge notch test specimens. Alloy 7001-T75 has comparatively lower fracture toughness than the other two alloys, which were approximately equal. Various grain size and processing effects and characteristics and test results for the two specimen types are discussed.

(FOR LISTING OF IMPORTANT REFERENCES, KEY WORDS AND A DUPLICATE ABSTRACT, SEE PAGE 80).

FRACTURE TOUGHNESS OF ALUMINUM ALLOY PLATE DETERMINED WITH CENTER-NOTCH TENSION, SINGLE-EDGE-NOTCH TENSION AND NOTCH-BEND TESTS

Kaufman, J. G., Nelson, Jr., F. G. and Holt, M. (Aluminum Co. of America, New Kensington, PA)  
Eng. Fract. Mech. 1, 259-274 (1968)

The fracture toughness of 2.54 cm and 3.463 cm plates of ten combinations of alloy and temper has been determined with center-notch tension (CN), single-edge-notch-tension (SEN), and notch-bend (NB) tests. The latter were made in accordance with the E-24 draft recommended practice. Valid values of  $K_{IC}$  were obtained in the NB test of the high-strength alloys and tempers, and for these materials, there was fair agreement in the results obtained from the NB and SEN tests, which were made of large machine-notched panels, generally indicated high values of  $K_{IC}$ . For the medium-strength alloys and tempers, no valid measurement of  $K_{IC}$  could be made, and there were wide variations in the values from the various tests. Under these conditions, the test results cannot be considered reliable relative measures of resistance to unstable crack growth. The results of this series of tests provide some information on the effect of specimen dimensions and of face-grooving on the results of SEN tests. Only the CN tests provided information on the mixed-mode fracture characteristics of the alloys. Generally, the thick plate demonstrated considerably more crack toughness than that indicated by the plane strain intensity factor.

(FOR LISTING OF IMPORTANT REFERENCES, KEY WORDS AND A DUPLICATE ABSTRACT, SEE PAGE 79).

## INFLUENCE OF SHEET THICKNESS UPON THE FRACTURE RESISTANCE OF STRUCTURAL ALUMINUM ALLOYS

Sullivan, A. M., Stoop, J. and Freed, C. N. (Naval Research Lab., Washington, DC)  
Progress in Flaw Growth and Fracture Toughness Testing, ASTM STP 536, 323-333  
(July 1973)

Definition of fracture resistance for thin sheet material in terms of the linear-elastic fracture mechanics (LEFM) plane-stress parameter,  $K_{IC}$ , continues to reveal aspects of its geometrical dependency. The effect of sheet thickness upon the  $K_{IC}$  value of five structural aluminum alloys in current use has been determined over available thickness ranges of 1/32 to 1/4 inch within this range, less thickness dependence than anticipated has been observed. The fact that both economy and convenience would be served if fracture resistance for all sheet thicknesses could be estimated from a limited number of specimens have given impetus to several models purporting to explain this dependency in terms of the relative contributions of a surface phenomenon, flat fracture, and a volume sensitive mechanism, shear lip development. Attempts to fit present data to the model disclose inadequacies for which there is no apparent immediate solution.

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1. Brown, Jr., W. F., and Srawley, J. E., ASTM STP 410 (1966).
2. Sullivan, A. M. and Freed, C. M., The Influence of Geometric Variables on  $K_{IC}$  Values for Two Thin Sheet Aluminum Alloys, NRL Report 7270 (June 17, 1971).
3. Carman, C. M., Armiento, D. F. and Markus, H., Proc. Int. Conf. on Fracture, 1st, Sendai, Japan, 2, 995-1038 (1966).
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Key words: Aluminum alloys; crack propagation; critical flaw size; fatigue tests; fractures (materials); linear elastic fracture mechanics; plane stress; stress concentration; stress intensity factor.

THE EFFECT OF SPECIMEN SIZE ON THE RESULTS OF PLANE-STRAIN FRACTURE-TOUGHNESS TESTS  
Nelson, Jr., F. G., Schilling, P. E. and Kaufman, J. G. (Aluminum Co. of America,  
New Kensington, PA)  
Eng. Fract. Mech. 4, No. 1, 33-50 (1972)

The effect of specimen geometry, notably thickness and crack length, on the values of plane strain fracture toughness,  $K_{IC}$ , of five aluminum alloys have been determined. Notch-bend specimens of 2024-T851, 6061-T651, 7075-T7351 and 7079-T651 and compact tension specimens of 2219-T851 were tested; for some alloys, face-grooved specimens were also included. Constant values of  $K_Q$  (candidate value of  $K_{IC}$ ) are generally obtained for specimen thicknesses and crack lengths greater than  $2.5 (K_{IC}/\sigma_{ys})^2$ , while for thinner specimens values above or below the true  $K_{IC}$  value may be obtained, dependent upon other dimensions of the specimen. For the face-grooved specimens, problems were encountered with achieving satisfactory fatigue cracks and the influence of side-grooving on  $K_Q$  values appeared to vary from alloy to alloy; overall, no advantage in measuring  $K_{IC}$  was indicated for face grooving.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS, AND A DUPLICATE ABSTRACT, SEE PAGE 86).

COMPARISON OF FRACTURE TOUGHNESS VALUES OBTAINED USING SEMI-INFINITE ALUMINUM PLATES WITH VALUES OBTAINED USING LABORATORY SIZE SPECIMENS  
Jones, R. E. (Dayton Univ. Research Inst., Dayton, OH)  
AFML-TR-69-58 (April 1969)

Fracture toughness values obtained from small laboratory size specimens in four point slow-bend loading were compared with values obtained by ALCOA in testing large semi-infinite center notched plate specimens. The plane-strain stress intensity factor,  $K_{IC}$  determined in this investigation varied from those values obtained by ALCOA by 7 percent on the positive side and 18 percent on the negative side. Specimen ranking in descending order of toughness is as follows: (1) 2219-T851, (2) 7075-T7351, (3) 7075-T651, (4) 7079-T651, (5) 7001-T75, (6) 2024-T851, and (7) 2020-T651. The results tend to substantiate the specimen requirements suggested by Brown and Srawley.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 87).

FRACTURE-CRACK-PROPAGATION AND FRACTURE-TOUGHNESS CHARACTERISTICS OF 7079  
ALUMINUM-ALLOY SHEETS AND PLATES IN THREE AGED CONDITIONS  
Smith, S. H., Porter, T. R. and Sump, W. D. (Boeing Co., Renton, WA)  
NASA CR-996 (February 1968)

This experimental research and development program was conducted to characterize the fatigue-crack-propagation behavior, residual strength, and fracture toughness of 7079 aluminum alloy in the underaged, peak-age (T6), and overaged conditions for thickness of 0.16, 0.25, 0.50, and 0.63 inch. Tensile-property, fatigue-crack-propagation, and fracture-toughness tests were conducted to determine the effects of aging temperature and time, material thickness, specimen width, and configuration and physical environments of dry air, liquid nitrogen (-65°F), and distilled water on these properties. The materials were available in 36-by 96-inch sheets or plates. Using centrally notched specimens, the crack-growth and fracture toughness tests were performed on 36-, 12-, and 8-inch wide panels with the latter two sizes of specimens being cut from the fractured halves of the large panels. Residual strength characteristics were also determined with surface-flawed specimens in the 0.63-inch thickness tests. Precracked charpy impact-toughness tests also were conducted for the three aged conditions and for the four panel thicknesses. Aging conditions were determined from tensile tests and were verified by tensile specimens cut from the fracture tested material.

The results of the test program showed that 7079 peak-age (T6) material has a faster rate of fatigue crack growth and a lower fracture toughness and residual strength than underaged and overaged materials. Underaged material exhibited the greatest fracture toughness and essentially the same rate of fatigue crack growth as that of overaged material. A slower fatigue-crack-growth rate was found for a decrease in plate thickness, an increase in panel width, a dry-air environment compared to distilled water, and a -65°F temperature compared to room temperature. Higher fracture toughness and residual-strength values were found for a decrease in plate thickness, an increase in panel width, a longitudinal grain direction compared to transverse grain, and an increase in test temperature from -65°F to room temperature.

Comment:

This contractor report discusses the effect of aging on the fracture properties of 7079 aluminum-alloy. It is a contribution to the understanding of the relationships between microstructural phenomena and these fracture properties.

Important References:

1. Irwin, G. R., Analysis of Stresses and Strains Near the End of a Crack Traversing a Plate, J. Appl. Mech., Trans. ASME 24, No. 3 (September 1957).
2. Paris, P. C. and Erdogan, F., A Critical Analysis of Crack Propagation Laws, J. Basic Eng., Trans. ASME, Ser. D, 85, No. 4 (December 1963).

3. Irwin, G. R., Crack Extension Force for a Part Through Crack in a Plate, J. Appl. Mech., Trans. ASME, 62-WA-13.
4. Brown, B. F., A New Stress-Corrosion Cracking Test Procedure for High-Strength Alloys, Mater. Res. Stand. 6, No. 3 (March 1966).
5. Tiffany, C. F. and Masters, J. N., Fracture Toughness Testing and Its Applications, ASTM STP 381 (1965).

Key words: Aluminum alloys; charpy impact tests; crack propagation; fatigue (materials); fracture strength; fractures (materials); plane strain; plane strain fracture toughness; residual stress; stress analysis; structural safety; tensile properties.

#### USING FRACTURE MECHANICS WITH ALUMINUM ALLOY STRUCTURES

Kaufman, J. G., Clark, J. W. and Holt, M. (Aluminum Co. of America, New Kensington, PA) Metals Eng. Quart., 4-11 (February 1973)

Four examples demonstrate the applicability of fracture mechanics to the estimation of fracture conditions in high-strength aluminum alloys, ranging from the direct calculation of fracture instability conditions from  $K_{IC}$  values to the indirect estimates of fracture strengths of structure members. Specifically, these examples include: (1) calculation of fracture instability conditions in pressure vessels under cyclic internal pressure, and the relationship to  $K_{IC}$ ; (2) prediction of total service life from initial discontinuity size, fatigue crack growth data, stress-corrosion resistance, and fracture toughness; (3) analysis of ballistic damage through the use of fracture toughness parameters; and (4) estimation of the strengths of single and double-angle structural members from correlations of  $K_{IC}$  with data from small-scale structural tests.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 155).

### IIIC. TITANIUM

CORRELATION OF TWO FRACTURE TOUGHNESS TESTS FOR TITANIUM AND FERROUS ALLOYS  
Freed, C. N. and Goode, R. G. (Naval Research Lab., Washington, DC)  
NRL Report 6740 (January 1969)

Preliminary correlations that have been developed between dynamic tear (DT) energy values and  $K_{IC}$  for the determination of the fracture toughness of steel and titanium alloys are presented. The value of the low DT test energy numbers, which are associated with crack propagation under elastic loading conditions is enhanced in that they provide a means of using results obtained with the simpler and less expensive DT test to predict approximate values of  $K_{IC}$ ,  $\beta_{IC}$ , and  $G_{IC}$ . With additional refinement of these correlations, more accurate quantitative estimations of these parameters from DT test results should be possible. Further, using the relationships provided by fracture mechanics between  $K_{IC}$  and the critical flaw size and stress level for crack extension, the conditions for crack instability can be determined from the DT test energy.

#### Important References:

1. Pellini, W. S., Goode, R. J., Puzak, P. P., Lange, E. A. and Huber, R. W., Review of Concepts and a Status of Procedures for Fracture-Safe Design of Complex Welded Structures Involving Metals of Low to Ultra-High Strength Levels, NRL Report 6300 (June 1965).
2. Gross, B., Srawley, J. E. and Brown, Jr., W. F., Stress Intensity Factors for a Single-Edge Notch Tension Specimen by Boundary Collocation of a Stress Function, NASA TN-D-2396 (August 1964).
3. Srawley, J. E. and Brown, Jr., W. F., Fracture Toughness Testing, NASA TN-D-2599 (January 1965).
4. Freed, C. N. and Krafft, J. M., Effect of Side Grooving on Measurements of Plane-Strain Fracture Toughness, J. Mater. 1, No. 4, 770-790 (1966).

Key words: Cracks; data; dynamic tear tests; fracture mechanics; fracture strength; fracture tests; high strength alloys; linear elastic fracture mechanics; notched specimens; plane strain fracture toughness; steels; stress intensity factor; structural safety; testing methods; titanium alloys.

## A REVIEW OF FACTORS INFLUENCING THE CRACK TOLERANCE OF TITANIUM ALLOYS

Shannon, Jr., J. L. and Brown, Jr., W. F. (National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH)

Applications Related Phenomena in Titanium Alloys, ASTM STP 432, 33-63 (1968)

A number of factors are reviewed which influence the crack tolerance of titanium alloys, particularly those which are generally encountered in the application of titanium alloys to aerospace hardware. Among those factors are cryogenic temperatures, heat treatment, interstitial element content, elevated temperature exposure, cold working, and aggressive environments.

In the presence of cracks, aggressive liquid environments cause delayed failure under sustained load conditions in a great number of titanium alloys. Among these are aqueous solutions of certain halides, many organic solvents and several halogenated hydrocarbons. Environmental testing has thus become an essential prerequisite in the selection of titanium alloys for critical applications. In this respect, testing standards, preferably ones which will produce results interpretable in terms of linear elastic fracture mechanics, are greatly needed.

There is a dearth of valid plane strain fracture toughness data for titanium alloys. In those few instances where results are available, departure from recommended practice in testing and data analysis methods or disagreement of values obtained or both indicate that the application of fracture mechanics to titanium alloy systems is indeed in an early state of development and further work in this area is sorely needed.

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1. Brown, Jr., W. F., Fracture Testing and the ASTM, Mater. Res. Stand. 7, No. 3, 117-120 (March 1967)
2. Tiffany, C. F. and Masters, J. N., Applied Fracture Mechanics, ASTM STP 381, 249-277 (1965)
3. Shannon, Jr., J. L. and Brown, Jr., W. F., Effects of Several Production and Fabrication Variables on Sharp Notch Properties of 5Al-2.5 Sn Titanium Alloy Sheet at Liquid Hydrogen Temperature, Proc. ASTM 63, 809-829 (1963)
4. Repko, A. J. and Brown, Jr., W. F., Influence of Cold Rolling and Aging on Sharp Notch Properties of Titanium Sheet, Proc. ASTM 62, 869-877, (1962)
5. Brown, B. F., A New Stress-Corrosion Cracking Test for High Strength Alloys, Mater. Res. Stand. 6, No. 3, 129-133 (March 1966)

6. Hatch, A. J., Rosenberg, H. W., and Erbin, E. F., Effects of Environment on Cracking in Titanium Alloys, ASTM STP 397, pg. 122 (1966).
7. Tiffany, C. F. and Masters, J. N., Investigation of the Flow Growth Characteristics of 6Al-4V Titanium Used in Apollo Spacecraft Pressure Vessels, NASA-CR-65586 (1967)
8. Carman, C. M., Forney, J. W. and Katlin, J. M., Plane Strain Fracture Toughness and Mechanical Properties of 5Al - 2.5 Sn ELI Titanium at Room and Cryogenic Temperatures, NASA-CR-54296 (1966)

Key words: Corrosion; crack initiation; crack propagation; environmental effects; fracture mechanics; fracture strength; fracture tests; fractures (materials); low temperature; plane strain fracture toughness; testing methods; titanium alloys.



### IIID. COMPOSITES

#### THE EFFECT OF PLASTICITY AND CRACK BLUNTING ON THE STRESS DISTRIBUTION IN ORTHOTROPIC COMPOSITE MATERIALS

Tirosh, J. (Technion - Israel Inst. of Tech., Haifa, Israel)  
J. Appl. Mech., Trans. ASME, 785-790 (September 1973)

A detailed study of the plasticity and crack-tip blunting effects on toughening materials with rectilinear anisotropy is presented. The most important results are the prediction of the extent of plastic zone and the nature of stress distribution produced by the blunting effect in the tensile mode. The analysis was confirmed experimentally and numerically (finite-element method) on a unidirectional fiber-reinforced composite. It was shown that:

1. The length of the plastic zone in rectilinear anisotropic material was formulated in terms of its pertinent parameters, with the aid of a path-independent integral. The expression has fundamentally the same structure as the familiar solution derived from the antiplane shear mode, and agrees well with experimental and numerical results (finite-element methods).
2. The stress distribution was derived from a mathematical model which simulated the experimentally observed situation, i.e., the yield zone is a narrow rectilinear strip perpendicular to the crack which transfers a uniform shear traction to the bulk (uncracked) material ahead of the notch. As a result, the elastic tensile stress ahead of a blunted crack obeys a log (1/r) distribution preceded by local stress reduction of known magnitude. The toughening effect of the blunting manifests itself in these circumstances.
3. The transverse stress, markedly different from the isotropic biaxial stress situation ahead of the crack, is much smaller than its longitudinal counterpart (in the present case by two orders of magnitude) and reaches maximum some distance ahead of the crack. This information casts light on the conditions promoting delamination (fiber/matrix debonding) and/or transverse interlaminar crack propagation.

#### Comment:

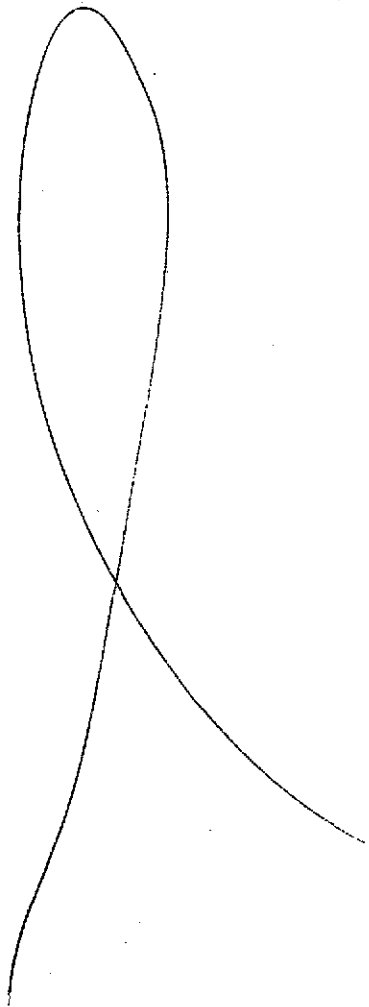
The author has made a significant contribution to the analytical understanding of the fracture behavior of fiber reinforced composite materials. The results are limited however to the uniformly orthotropic laminate situation and not the structurally more interesting multiplied multidirectioned composite.

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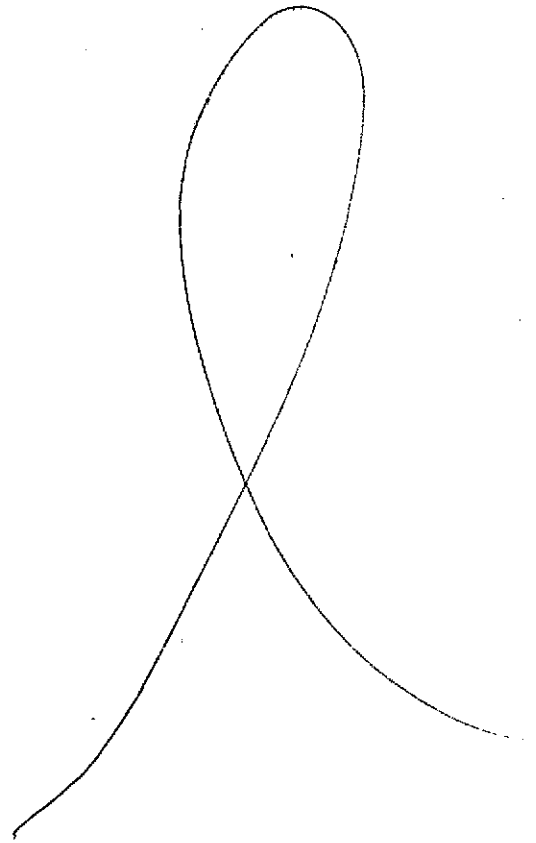
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6. McClintock, F. A., A Criterion for Ductile Fracture by the Growth of Holes, J. Appl. Mech. 35, Trans. ASME 90, Series E, 363-371 (1968).
7. Rice, J. R., A Path Independent Integral and the Approximate Analysis of Strain Concentration by Notches and Cracks, J. Appl. Mech., Trans. ASME 35, Series E, 379-386 (1968).

Key words: Composite materials; crack analysis; crack propagation; fracture strength; plastic properties; plastic zone; stress concentration.



#### IV. ANALYSIS METHODS

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#### IVA. RESISTANCE CURVES

##### CRACK GROWTH RESISTANCE CURVES (R-CURVES) - LITERATURE REVIEW

Heyer, R.H. (Armco Steel Corp., Middletown, OH)

Fracture Toughness Evaluation by R-Curve Methods ASTM STP 527, 3-16 (April 1973).

The development of the concept of crack-growth resistance as a means of characterizing fracture toughness is reviewed. While the first model was proposed in 1954, major developments, experimental determinations, and applications of R-curves data from 1960.

Crack growth resistance curves have been found to be useful for characterizing fracture toughness over a wide range of material properties and specimen thickness. They are likely to become most useful for tougher materials exhibiting mixed mode or full slant fracture surfaces.

##### Comment:

This review examines the development of crack growth resistance curves which provide a measure of fracture strength in the mixed mode condition in which the specimen is neither fully plane strain or plane stress. A number of examples illustrate both the theoretical basis and experimental application of this technique.

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1. Srawley, J.E. and Brown, Jr., W.F., In Fracture Toughness Testing Methods, ASTM STP 381, 133-198 (1965).
2. Pellini, W.S. and Judy, Jr., R.W., Fracture Extension Resistance (R-Curve) Features of Nonfrangible Aluminum Alloys, NRL Report 7262 (11 June 1971).
3. Jones, M.H., and Brown, Jr., W.F., The Influence of Crack Length and Thickness in Plane Strain Fracture Toughness Tests, ASTM STP 463, 63-101 (1970).
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Key words: Aluminum alloys; crack propagation; fracture strength; fracture tests; resistance curves; transition temperature.

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CRACK GROWTH RESISTANCE IN PLANE STRESS FRACTURE TESTING  
Heyer, R.H. and McCabe, D.E. (Armco Steel Corp., Middletown, OH)  
Eng. Fract. Mech. 4, 413-430 (1972)

New developments in crack growth resistance measurement using crack line-wedge loaded specimens include improved fixtures, and a double compliance technique for obtaining both load and effective crack length. The latter results in marked improvement in the accuracy of R-curves for materials having large plastic zones. The CLWL specimen, developed for high strength sheet materials, is now being used for light plates, at intermediate strength levels. Several investigations are reported in which center-cracked-tension (CCT) and CLWL specimens have been used in attempts to determine whether R-curves are specimen independent, and whether  $K_{IC}$  instability stress intensity of CCT specimens can be predicted from CLWL determined R-curves. Systems proposed by Feddersen and Allen for predicting the specimen width and crack length dependency of  $K_{IC}$  in CCT specimens are examined, and R-curves are compared over the wide range of specimen sizes and crack lengths tested by T.W. Orange. Principal stresses along the crack path are determined by strain gauges for CCT and CLWL specimens. The stress patterns are widely different, but the effective combined stresses near the elastic-plastic border are similar, which may account for similarity of R-curve development for the two specimen types, it is concluded from available evidence that R-curves appear to be characteristic of a material, in a given thickness, but the data are not conclusive and more verification is needed.

(FOR LISTING OF IMPORTANT REFERENCES, KEY WORDS AND A DUPLICATE ABSTRACT, SEE PAGE 123).

ARTIFICIAL SLOW CRACK GROWTH UNDER CONSTANT STRESS. THE R-CURVE CONCEPT IN PLANE STRESS

Broek, D. (National Aerospace Lab., Amsterdam, Netherlands)  
Eng. Fract. Mech. 5, 45-53 (1973).

Tests were carried out on large center-notched tensile panels in which the crack was extended at both ends by means of sawing under constant load. The critical crack lengths were much longer than in normal residual strength tests. This leads to the conclusions that: (1) the execution of a fail-safe test by means of extending a crack by sawing under constant load leads to an overestimation of the critical crack length, and (2) fracture instability both under monotonic loading and in case of crack growth under constant load can be considered to be determined by an energy concept. The energy concept (R-curve) is compatible with the fact that crack growth under constant load leads to a larger critical crack length than monotonic loading, but the physical background of the observations is not yet clearly understood.

Comment:

The author has demonstrated that one of short cuts employed in fracture testing, i.e., the use of a saw cutting to provide critical crack length, is not valid. In addition the contribution that the energy concept is compatible

with a plane stress condition is significant. This paper should provide a basis for further research and concept development.

Important references:

1. Broek, D., The Effect of Finite Specimen Width on the Residual Strength of Light Alloy Sheet. NLR-TR-M-2152 (1965).
2. Broek, D., The Residual Strength of Aluminum Alloy Sheet Specimens Containing Fatigue Cracks or Saw Cuts. NLR-TR-2143 (1965)
3. Broek, D., The Energy Criterion for Fracture of Sheets Containing Cracks. Appl. Mater. Res. 4, 188-189 (1965).
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Key words: Aluminum alloys; center crack specimens; crack propagation; fractures (materials); plane stress; residual strength; resistance curves; stress intensity factor.

CRACK GROWTH RESISTANCE CHARACTERISTICS OF HIGH-STRENGTH SHEET ALLOYS

Freed, C.N., Sullivan, A.M., and Stoop, J. (Naval Research Lab., Washington, DC) NRL Report 7374 (January 31, 1972).

Crack propagation in a metal sheet is impeded by the inherent resistance to fracture of the alloy. The resistance is manifested by the requirement that crack growth will occur only under a rising load up to an instability load at which unstable fracture commences. If the fracture resistance curve which designates the load-crack extension relationship to instability has a unique shape for each material and is independent of most specimen dimensions, it can be a valuable tool in failure-safe design.

The fracture resistance curves (R-curves) have been obtained for six high-strength sheet alloys which fractured under elastic loads. The influence of three specimen geometric variables and yield strength on the shape of the R-curve and the critical stress intensity factor  $K_C$  was investigated. On several alloys a comparison was made between the R-curve and  $K_C$  value generated with a center-cracked tension (CCT) specimen and data derived from a crack-line loaded (CCL) used at Armco Steel Corporation.

The radius of the slit tips in the CCT specimen did not affect the  $K_C$  value for aluminum 7075-T6 in which stable crack growth preceded instability. The R-curves emanating from fatigue-cracked specimens did indicate longer crack growth at lower loads than was evident from the blunter slit tips. Both  $K_C$  and R curves were generally independent of initial slit length for aluminum alloys, although some scatter was observed for one steel and the titanium alloy.



The  $K_C$  value was independent of specimen width for high-strength aluminum alloys. The shape of the R-curve for the different CCT specimen widths of 2024-T3 was identical. The inverse relationship between  $K_C$  and yield strength was obvious for the aluminum alloys and for 4130 steel.

A comparison of  $K_C$  values for the CCT specimen and the CLL specimen indicated some differences for alloys which manifest crack growth under constant load. Since the commencement of constant load crack growth marks the end of structural integrity, its recognition is crucial to a rational interpretation of fracture resistance. This behavior is observable on the CCT specimen test record, and the  $K$  value at initiation of constant load crack growth is designated as  $K_C$ . Because the behavior was not directly observed on the CLL specimen test record, the  $K_C$  criterion applied to these specimens was different. Thus, the differences between the  $K_C$  values reported by CCT and CLL specimens are attributable to interpretation of data and not to the different methods of load application employed by the specimens.

Comment:

This effort represents a contribution to the continuing effort to characterize ductile fracture phenomena. The identification of the causes of the differences between the  $K_C$  values obtained from the CLL and CCT specimens is a significant contribution and will help to clarify some otherwise difficult results. The continuing effort in this problem area at NRL should lead to test techniques and validity criteria for ductile fracture of the quality of those established as ASTM E399-72 for plane strain fracture.

Important references:

1. Sullivan, A.M. and Freed, C.N., The Influence of Geometric Variables on  $K_C$  Values for Two Thin Sheet Aluminum Alloys, NRL Report 7270 (June 17, 1971).
2. Broek, D., The Residual Strength of Aluminum Sheet Alloy Specimens containing Fatigue Cracks or Saw Cuts, National Aerospace Laboratory, Amsterdam Report NLR-TR M. 2143 (March 1966).
3. Heyer, R.H. and McCabe, D.E., Test Method-Fracture Toughness Measured by Crack Growth Resistance, ARMC0 Research and Technology Report, Middletown, OH (January 27, 1971).
4. Brown, Jr. W.F. and Srawley, J.E., Plane Strain Crack Toughness Testing of High Strength Metallic Materials, ASTM STP 410 (1966).

Key words: Center crack specimens; crack line loaded specimens; elastic-plastic behavior; fracture mechanics; linear elastic fracture mechanics; resistance curves; stress intensity factor; structural safety.

## COMPARISON OF R-CURVES DETERMINED FROM DIFFERENT SPECIMEN TYPES

Sullivan, A.M., Freed, C.N. and Stoop, J. (Naval Research Lab., Washington, DC)  
ASTM STP 527, 85-104 (April 1973).

Crack growth resistance curves (R-curves) have been obtained by testing center-cracked tension specimens (CCT) for direct comparison with R-curves determined from crackline loaded specimens (CLL). Some differences between the two specimens are found in the reported values of  $K_C$ . These appear to be a direct consequence of the type of stress-crack length relationship noted during testing. In tough materials tested using the CCT specimen, the crack grows fast under a rising load but finally continues to extend at a constant load. Since this constant load crack growth marks the end of structural integrity, its recognition is crucial to a rational interpretation of fracture resistance. The CLL specimen type does not discriminate between the changes in crack growth behavior observed for these tough materials. Further, it is shown that fatigue precracking may influence the amount of crack growth prior to instability even though the final value of  $K_C$  remains unchanged. No evidence of variation in the  $K_C$  value with initial crack length has been observed over the range of slit lengths investigated.

### Important References:

1. Clausing, D.P., Crack Stability in Linear Elastic Fracture Mechanics, Int. J. Fract. Mech. 5, No. 3 (September 1969).
2. Heyer, R.H. and McCabe, D.E., Plane Stress Fracture Toughness Testing Using a Crack-Line-Loaded Specimen, Third National Symposium on Fracture Mechanics, Bethlehem, Pa. (August 1969).
3. Sullivan, A.M. and Freed, C.N., The Influence of Geometric Variables on  $K_C$  Values for Two Thin Sheet Aluminum Alloys, NRL Report 7270 (17 June 1971).
4. Heyer, R.H. and McCabe, D.E., Test Method-Fracture Toughness Measured by Crack Growth Resistance, Research and Technology Report, ARMCO (27 January 1971).

Key words: Crack propagation; fracture analysis; fracture strength; fractures (materials); resistance curves; testing methods.

## R-CURVE CHARACTERIZATION AND ANALYSIS OF FRACTURES IN HIGH-STRENGTH STRUCTURAL METALS

Judy, Jr., R.W. and Goode, R.J. (Naval Research Lab., Washington, DC)  
Metal Eng. Quart., 23-24 (November 1973).

Dynamic tear (DT) test R-curves define the inherent resistance of structural materials to fracture in terms of energy-per-unit extension required

to cause rapid crack extension. The R-curve characterizations are translated to useful form for design of structures to preclude fracture by the use of ratio analysis diagrams (RAD). R-curve concepts and RAD's have been established for steels, aluminum alloys, and titanium alloys. An equation involving DT test specimen cross-section dimensions and a constant related to R-curve slope has been shown to apply for steels and aluminum alloys. Use of this equation permits separation of metallurgical variables and specimen geometry variables for both fracture tests and structural applications, thereby enabling independent analysis of each aspect. This report summarizes available R-curve data and analysis methods to illustrate the use of R-curve concepts for fracture-safe structural design.

#### Important References:

1. Pellini, W.S. and Judy, Jr., R.W., Significance of Fracture Extension Resistance (R-curve) Factors in Fracture-Safe Design for Nonfrangible Metals, Weld, Res. Coun. Bull. 157 (December 1970).
2. Goode, R. J. and Judy, Jr., R.W., Fracture Extension Resistance (R-Curve) Features of Nonfrangible Aluminum Alloys, Metals Eng. Quart. 11, No. 4 39-49 (November 1971).
3. Judy, Jr., R.W. and Goode, R.J., Fracture Extension Resistance (R-Curve) Concepts for Fracture-Safe Design with Nonfrangible Titanium Alloys, NRL Report 7313 (August 1971).
4. Lange, E.A., Puzak, P.P. and Cooley, L.A., Standard Method for the 5/8 inch Dynamic Tear Test, NRL Report 7159 (August 1970).
5. Puzak, P.P. and Lange, E.A., Standard Method for the 1-inch Dynamic Tear Test, NRL Report 6851 (February 1969).
6. Judy, Jr., R.W. and Goode, R.J., Fracture Extension Resistance (R-Curve) Characteristics for three High-Strength Steels, NRL Report 7361 (30 December 1971).

Key words: Aluminum alloys; analysis methods; crack propagation; data; dynamic tear tests; fractures (materials); high strength; resistance curves; steels; structural design; structural safety; titanium alloys.

A NOTE ON THE USE OF A SIMPLE TECHNIQUE FOR FAILURE PREDICTION USING RESISTANCE CURVES

Creager, M.

Fracture Toughness Evaluation by R-Curve Methods ASTM STP 527, 105-112 (April 1973).

The use of resistance curves in the prediction of catastrophic failure in a structure normally requires the determination of the point of tangency between the resistance curve and the applied stress intensity versus crack length curve evaluated for the failure stress. Since the failure stress is unknown a priori a number of iterations or interpolations or both are necessary. This is often a cumbersome task. A simple procedure utilizing a transparency is presented which enables the critical stress intensity factor based on final crack length, and the failure stress to be found directly without iteration or interpolation.

Comment:

The authors schematic prediction technique is simple and an effective short cut, provided the data is available for the construction of the required curves. In addition the required curves are dependent on details of the structure and physical metallurgy of the material requiring a very large atlas of curves to be effective for any given situation.

Important references:

1. Liu, A.F. and Creager, M., On the Slow Stable Crack Growth Behavior of Thin Aluminum Sheet, 1971 Int. Conf. on the Mechanical Behavior of Materials, Kyoto, Japan (1971).
2. Creager, M. and Liu, A.F., The Effect of Reinforcements on the Slow Stable Tear and Catastrophic Failure of Thin Metal Sheet, Paper No. 71-113, AIAA, Aerospace Sciences Meeting, 9th, New York, NY (1971).

Key words: Fracture strength; fractures (materials); life prediction; resistance curves; stress intensity factor.

## IVB. J-INTEGRAL ANALYSIS

### A PATH INDEPENDENT INTEGRAL AND THE APPROXIMATE ANALYSIS OF STRAIN CONCENTRATION BY NOTCHES AND CRACKS

Rice, J.R. (Brown Univ., Providence, RI)  
J. Appl. Mech., Trans. ASME, 379-386 (June 1968)

A line integral is exhibited which has the same value for all paths surrounding the tip of a notch in the two-dimensional strain field of an elastic or deformation-type elastic-plastic material. Appropriate integration path choices serve both to relate the integral to the near tip deformations and, in many cases, to permit its direct evaluation. This averaged measure of the near tip field leads to approximate solutions for several strain concentration problems. Contained perfectly plastic deformation near a crack tip is analyzed for the plane-strain case with the aid of the slip line theory. Near tip stresses are shown to be significantly elevated by hydrostatic tension, and a strain singularity results varying inversely with distance from the tip in centered fan regions above and below the tip opening displacement, and the important role of large geometry changes in crack blunting is noted. Another application leads to a general solution for crack tip separations in the Barenblatt-Dugdale crack model. A proof follows on the equivalence of the Griffith energy balance and cohesive force theories of elastic-brittle fracture, and hardening behavior is included in a model for plane-stress yielding. A final application leads to approximate estimates of strain concentrations at smooth-ended notch tips in elastic and elastic-plastic materials.

#### Comment:

This is the original paper proposing the J-integral and describing mathematically its characteristics. It is particularly important because it includes the details of the assumptions and mathematical proofs, which often are obscured in subsequent efforts. This paper illustrates the two dimensional nature of this line integral and properly cautions against the unrestricted usage in a three dimensional stress crack tip situation.

#### Important references:

1. Rice, J.R., The Mechanics of Crack Tip Deformation and Extension by Fatigue, Fatigue Crack Growth, ASTM STP 415 (1967).
2. Williams, M.L., On the Stress Distribution at the Base of a Stationary Crack, J. of Appl. Mech. 24, No. 1, Trans. ASME 79, 109-114 (March 1957).
3. Sanders, J.L., On the Griffith-Irwin Fracture Theory, J. of Appl. Mech. 27, No.2, Trans. ASME, 82, Series E, 352-353 (June 1960).
4. Rice, J.R. and Drucker, D.C., Energy Changes in Stressed Bodies due to Void and Crack Growth, Int. J. of Fract. Mech. 3, No.1 (1967).
5. Barenblatt, G.I., Mathematical Theory of Equilibrium Cracks in Brittle Fracture, Advances in Applied Mechanics, 7, Academic Press (1962).

6. Dugdale, D., Yielding of Steel Sheets Containing Slits, *J. of Mech. and Phys. of Solids*, 8, (1960).
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8. Rice, J.R., Contained Plastic Deformation Near Cracks and Notches under Longitudinal Shear, *Int. J. of Fract. Mech.* 2, No. 2 (1966).
9. Hahn, G.T., and Rosenfield, A.R., Local Yielding and Extension of a Crack under Plane Stress, *Acta Meta.* 13, No. 3 (1965).

Key words: Analysis methods; crack tip plastic zone; cracks; elastic-plastic behavior; J-integral; plane strain; stress concentration; stress intensity factor.

#### J-INTEGRAL ESTIMATION PROCEDURES

Bucci, R.J., Paris, P.C., Landes, J.D. and Rice, J.R. (Del Research Corp., Bethlehem, PA., Westinghouse Research Lab., Pittsburgh, PA., Brown Univ., Providence, RI.)  
*Fracture Toughness Proc. 1971 Nat. on Fracture Mechanics, Part 2 ASTM STP 514, 40-69 (1972)*

By making use of plastically adjusted linear elastic fracture mechanics analysis and plastic limit load solutions, a method is developed for reasonable approximation of Rice's path independent J-integral which is applicable for test specimens or other configurations which exhibit considerable plasticity prior to fracture. Employing this, J is expressed as a function of load point displacement. Estimations of the J versus displacement relationships developed compared quite well to those previously established experimentally at Westinghouse Research Laboratories for Ni-Cr-Mo-V and A533B steels. For these comparisons, the test specimen configurations considered were three point bend, center notch, and compact tension test specimen configurations. all of which exhibit significantly different plastic limit load slip line flow fields. Thus, the method developed for approximating J is thought to be widely applicable.

#### Comment:

The J-integral has shown promise for theoretically and experimentally examining the fracture behavior between plane strain and plane stress. This paper offers considerable theoretical and experimental illumination of this concept. Of particular significance is the relatively simple technique, based on load point displacement, for determination of an experimental value of the J-integral.

Important references:

1. Begley, J.A. and Landes, J.D., The J-Integral as a Fracture Criterion, and the Effect of Specimen Geometry on  $K_{IC}$ , Fracture Toughness, Proc. 1971 Nat. Symp. on Fracture Mechanics, ASTM STP 514, 1-20 and 24-39 (1972).
2. Rice, J. R., A Path Independent Integral and the Approximate Analysis of Strain Concentration by Notches and Cracks, J. Appl. Mech., 379-386 (June 1968).
3. McClintock, F. A., Plastic Aspects of Fracture, Fracture: An Advanced Treatise - Engineering Fundamentals and Environmental Effects 3, Academic Press, NY (1971)
4. Paris, P. C. and Sih, G. C., Stress Analysis of Cracks, ASTM STP 381, 30-81 (1965).
5. Irwin, G. R. and Paris, P. C., Fundamental Aspects of Crack Growth and Fracture, Fracture: An Advanced Treatise-Engineering Fundamentals and Environmental Effects 3, 1-46, Academic Press, NY (1971).

Key words: Cracking (fracturing); elastic-plastic analysis; fracture mechanics; fracture strength; fracture tests; fractures (materials); J-integral; steels; tensile properties; toughness.

A NUMERICAL AND EXPERIMENTAL INVESTIGATION ON THE USE OF J-INTEGRAL  
Kobayashi, A.S., Chiu, S.T. and Beeuwkes, R. (Washington Univ., Seattle)  
Eng. Fract. Mech. 5, 293-308 (1973)

Finite element analysis was used to determine Rice's J-integral values in centrally notched plates of 4340 steel. These numerical values were compared with corresponding J-integral values using Dugdale model and antiplane strain model with a power law hardening of  $N = 0.3$ . J-integral (was also computed for a crack extending into its own plastic yield region under constant loading. For increasing level of loading,  $\sigma$ , the rate of increase in J-integral) decreases and J-integral remains almost constant at  $\sigma/\sigma_{ys}$  under such crack extension. A limited number of fracture tests were conducted with centrally notched 4340 steel specimens heat treated to yield strength levels of 150, 180, 210, and 240 ksi. Fracture data showed that the critical J-integral, is insensitive to crack tip sharpness for the lower strength 4340 material and thus the J-fracture criteria appears suited in correlating fracture data.

Comment:

This paper experimentally demonstrates the applicability of the J-integral to blunt crack or flaw situations. This is in contrast to the  $K_{IC}$  criteria which requires an infinitesimally small radius crack tip in the test specimen. In addition the paper demonstrates the growing base of theoretical and experimental effort supporting the validity of J-integral fracture criteria.

Important references:

1. Wells, A.A., Notched Bar Tests, Fracture Mechanics and the Brittle Strengths of Welded Structures, Brit. Weld. J. 2, (January 1965).
2. Beeuwkes, Jr., R., Characteristics of Crack Failure, Proc. Sagamore Army Materials Research Conf., 14th, Syracuse University Press, 277 (1968).
3. Rice, J.R., A Path Independent Integral and the Approximate Analysis of Strain Concentration by Notches and Cracks, J. Appl. Mech., Trans. ASME, 35, No.2, 379-386 (June 1968)
4. Rice, J.R., Mathematical Analysis in the Mechanics of Fracture, Fracture 2, 191-311 (1968).
5. Kobayashi, A.S., Chiu, S.T. and Beeuwkes, Jr., R., Elastic-Plastic State in a Plate with an Extending Crack, Proc. Army Symp. on Solid Mechanics, 1970-Light Weight Structure, AMMRC MS-70-5, 4 87-98 (December 1970).
6. Irwin, G.R., Relation of Crack Toughness Measurements to Practical Applications, Weld. J. Res. Suppl., 5195-5285 (1962).

Key words: Analysis methods; fracture analysis; fracture strength; fracture tests; J-integral; plastic deformation; steels.

CONSERVATION LAWS AND ENERGY-RELEASE RATES

Budiansky, B., and Rice, J.R. (Harvard Univ., Cambridge, MA., Brown Univ., Providence, RI)

J. Appl. Mech., Trans. ASME, 201-203 (March 1973).

New path independent integrals recently discovered by Knowles and Sternberg are related to energy-release rates associated with cavity of crack rotation and expansion. Complex-variable forms are presented for the conservation laws in the cases of linear, isotropic, plane elasticity. A special point concerning plastic stress distributions around cracks is discussed briefly.



Comment:

The authors critically examine the L integral and W integral in terms of the solution to the mixed mode cracking problems. It is shown that the new integrals do not provide unique solutions to the mixed mode problem.

Important references:

1. Rice, J.R., A Path Independent Integral and the Approximate Analysis of Strain Concentration by Notches and Cracks, *J. of Appl. Mech.* 35, Transactions ASME, 90, Series E, 379-386 (June 1968)
2. Rice, J.R., Mathematical Analysis in the Mechanics of Fracture, Fracture An Advanced Treatise, 2, Liebowitz, H., Ed., Academic Press, 191-311 (1968).
3. Hutchinson, J.W., Singular Behavior at the End of a Tensile Crack in a Hardening Material, *J. of Mech. and Phys. of Solids*, 16, 13-31 (1968).
4. Hutchinson, J.W., Plastic Stress and Strain Fields at a Crack Tip, *J. of Mech. and Phys. of Solids*, 16, 337-347 (1968).

Key words: Analysis methods; fracture mechanics; fractures (materials); J-integral.

SOME FURTHER RESULTS OF J-INTEGRAL ANALYSIS AND ESTIMATES

Rice, J.R., Paris, P.C., Merkle, J.G. (Brown Univ., Providence, RI., Del Research Corp., Bethlehem, PA., Oak Ridge National Lab., TN)  
Progress in Flaw Growth and Fracture Toughness Testing, ASTM STP 536, 231-245 (July 1973)

This discussion attempted to point out analysis advantages in certain configurations with a single dominating characteristic (crack plane) dimension, these analyses result in methods of evaluating J from single load versus load point displacement relationships or tests results. This makes single test evaluation of fracture toughness, as evaluated by  $J_{IC}$  feasible for several commonly used test configurations. Moreover, these special analytical results lead to better possibilities for understanding upper shelf charpy versus fracture toughness,  $K_{IC}$  correlations and the like. It is also implied that the equivalent-energy approach is applicable to bend and compact tension type tests. Finally, some estimating formulas were developed for approximate calculations of J from single load-displacement points for notched round, bending, and compact tension configurations. It was suggested that these estimating formulas for J, which should be noted to be just as simple to use as procedures or formulas for K (for example, ASTM E 399-72), are put forth as practical quick-estimate possibilities. And though J-integral methods may be as yet relatively unexplored compared to linear-elastic fracture mechanics, it is hoped that the simplicities and usefulness of these methods are illustrated herein.

Comment:

This paper continues the development of the J-integral techniques as a complimentary tool both analytically and experimentally to the  $K_{IC}$  procedures. A large amount of further work is required in order to increase the usefulness of the J-integral values, particularly in the areas of test techniques and validity criteria.

Important references:

1. Rice, J. R., A Path Independent Integral and the Approximate Analysis of Strain Concentration by Notches and Cracks, J. Appl. Mech. 35, 379-386 (June 1968)
2. Begley, J. A. and Landes, J. D., the J-Integral as a Fracture Criterion, ASTM STP 514, 1-23 (1972)
3. Broberg, K. B., Crack-Growth Criteria and Non-linear Fracture Mechanics, J. Mech. Phys. Solids 19, No. 6, 407-418 (1971)
4. Bucci, R. J., Paris, P. C., Landes, J. D. and Rice, J. R., J-Integral Estimation Procedures, ASTM STP 514, 40-69 (1972)
5. Witt, F. J., Fracture Behavior of Reactor Pressure Vessel Steel in the Frangible, Transitional, and Tough Regimes, Nucl. Eng. and Design, 20, (1972)
6. Wilson, W. K., Stress Intensity Factors for Deep Cracks in Bending and Compact Tension Specimens, J. Eng. Fract. Mech. 2, (November 1970)

Key words: Analysis methods; crack propagation; cracks; fracture strength; fractures (materials); J-intergral; mechanical properties; plastic deformation; plastic properties; toughness.

## IVC. FAILURE PREDICTION

FROM GRIFFITH TO COD AND BEYOND

Boyd, G.M.

Eng. Fract. Mech. 4, No.3, 459-482 (1972)

This broad review of current concepts in the field of fracture mechanics, from a mainly engineering point of view, raises many more questions than it answers. It may therefore be regarded not as destructive criticism but as a challenge to greater effort and research aimed at a radical improvement in the present unsatisfactory state of knowledge. Radical because it aims not to repair the multiple defects of present systems in detail, but to take a new look at the subject.

To take this new look and follow it to its conclusions is a daunting venture. The complications of metallurgy and the mathematical complexities, even in dealing with such an apparently simple problem as a 3-dimensional elasto-plastic solution, are enough to daunt the stoutest spirit.

Nevertheless, it seems clear that unless such radical re-evaluation is made we are in danger of becoming more and more immersed in a morass of detail, entangled in the meshes of inadequate theoretical networks. There is already a strong tendency for some such confused concepts to become entrenched in textbooks and standard specifications.

### Comment:

The author examines the basic assumptions of Griffith and subsequently of Irwin and shows that these assumptions do not permit the extension, which has been made to the complexities of modern fracture mechanics. He makes some valid points, particularly with regard to the problems introduced by the two dimensional nature of fracture mechanics as used to describe the three dimensional phenomena. The author has taken an unnecessarily rigid position with regard to modern fracture mechanics, particularly in light of the large body of empirically based development, which has the singular saving grace that it works.

### Important references:

1. Irwin, G.R., Relation of Stress Near a Crack to the Crack Extension Force, Int. Cong. of Appl. Mech. 8 (1957).
2. Boyd, G.M., The Conditions for Unstable Rupturing of a Wide Plate, Trans. Royal Instit. of Naval Architects 99, 349 (1957).
3. Wells, A.A., Unstable Crack Propagation in Metals, Proc. Conf. on Crack Propagation, Cranfield, England, September 1961, 210 (1962).

4. Dugdale, D.S., Yielding of Steel Sheets Containing Slits, J. of Mech. and Phys. of Solids, 8, (1960).
5. Dixon, J.R., Effects of Crack-Front Geometry and Plate Thickness on the Stress Distribution in Cracked Plates, Institute of Physics, Physical Society Conference Series No.1 (December 1966).
6. Griffith, A.A., Phil. Trans. Royal Soc., A-221, 163-198 (1920)

Key words: Analysis methods; crack initiation; crack propagation; elastic-plastic analysis; fractures mechanics; stress analysis.

A NOTE ON THE USE OF A SIMPLE TECHNIQUE FOR FAILURE PREDICTION USING RESISTANCE CURVES

Creager, M.

Fracture Toughness Evaluation by R-Curve Methods (ASTM STP 52-, pp. 105-112)

The use of resistance curves in the prediction of catastrophic failure in a structure normally requires the determination of the point of tangency between the resistance curve and the applied stress intensity versus crack length curve evaluated for the failure stress. Since the failure stress is unknown a priori a number of iterations or interpolations or both are necessary. This is often a cumbersome task. A simple procedure utilizing a transparency is presented which enables the critical stress intensity factor based on final crack length, and the failure stress to be found directly without iteration or interpolation.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 57).

COMPATIBILITY OF LINEAR ELASTIC  $K_{IC}$  AND GENERAL YIELDING (COD) FRACTURE MECHANICS

Egan, G.R. (Welding Inst., Cambridge, England.  
Eng. Fract. Mech. 5, 167-185 (1973)

An investigation of the applicability of the general yielding fracture mechanics concept of crack opening displacement is made in relation to the well established concepts of linear elastic fracture mechanics. The nature of the relationship between crack opening displacement and stress intensity factor is explored using the concepts of linear elasticity and model analysis proposed by Dugdale.

The test results described in this paper indicated the compatibility of linear elastic ( $K_{IC}$ ) and general yielding (COD) fracture mechanics. As a result of this it is possible for any particular fracture control program to specify a test procedure based on current Standards to determine either  $K_{IC}$  or COD irrespective of the stress conditions at failure. There is no need for a separate test procedure to determine crack opening displacement values although, in the past, a different type of test piece geometry has been used for this purpose.

For the materials and geometries considered, the J at fracture seems to reflect the same order of change with temperature as the COD at fracture, as would be expected from the theoretical relationships of these two parameters. J values at fracture calculated from J calibrations determined by finite element methods indicate that there is only a large increase in the value of J when extensive plasticity is present. With small scale yielding near the crack tip the J values calculated by such methods are the same as those determined from linear elastic fracture mechanics K type analyses, ignoring the fact that these analyses are outside the range of ASTM validity.

Comment:

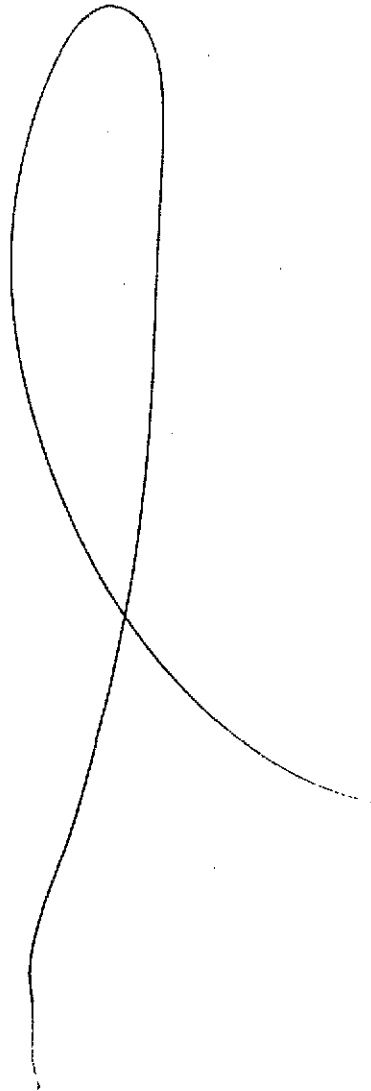
The author has made an attempt to relate the K, J, and COD values for fracture mechanics in a single test. His use of experimental data in an empirical approach is somewhat successful. However, the degree of scatter in the results that he accepts is quite extensive. The use of a single test to determine all three values appears to ask too much and result in a possibly unacceptable scatterband of values.

Important references:

1. Rice, J.R. and Rosengren, G.F., Plane Strain Deformation Near a Crack Tip in a Power Law Hardening Material, *J. of Mech. and Phys. of Solids*, 16 (1968).
2. Rice, J.R., A Path Independent Integral and the Approximate Analysis of Strain Concentration by Notches and Cracks, *J. of Appl. Mech.* 35, 379-386 (1968)
3. Wells, A.A., Application of Fracture Mechanics at and Beyond General Yielding, *Brit. Weld. J.* 10, 563 (1963).
4. Crosley, P.B., Mostovoy, S. and Ripling, E.J., An Optical Interference Method for Experimental Stress Analysis of Cracked Structures. *Eng. Fract. Mech.* 3, 421 (1971).
5. Barenblatt, G.I., The Mathematical Theory of Equilibrium Cracks in Brittle Fracture, *Advances in Applied Mechanics*, 7, 55 (1962.)
6. Dugdale, D.S., Yielding of Steel Sheets Containing Slits, *J. Mech. Phys. Solids* 8, 100 (1960).
7. Gross, B. and Srawley, J.E., Stress Intensity Factors for Three Point Bend Specimens by Boundary Collocation, NASA-TN-D-3092 (December 1965).

Key words: Compact tension specimen; crack initiation; crack opening displacement; crack propagation; elastic deformation; fracture mechanics; J-integral; plastic deformation; stress concentration; stress intensity factor; structural safety.

## V. PLANE STRAIN TESTING



VA - STANDARDS

STANDARD METHOD OF TEST FOR PLANE-STRAIN FRACTURE TOUGHNESS OF METALLIC MATERIALS  
ASTM Committee E-24 on Fracture Testing of Metals

ASTM Standard Designation E399-72, Annual Book of ASTM Standards, Part 31, 960-979 (1974)

Also: American National Standard Z260.2-1973, approved March 29, 1973 by  
American National Standards

This method covers the determination of the plane-strain fracture toughness ( $K_{IC}$ ) of metallic materials by a bend or a compact test of a notched and fatigue-cracked specimen having a thickness of 0.25 inch (6.4 mm) or greater. The method involves tension or three-point bend testing of notched specimens that have been precracked in fatigue. Load versus displacement across the notch at the specimen edge is recorded autographically. The load corresponding to a 2 percent increment of crack extension is established by a specified deviation from the linear portion of the record. The  $K_{IC}$  value is calculated from this load by equations which have been established on the basis of elastic stress analysis of specimens of the types described above. The validity of the determination of  $K_{IC}$  value by this method depends upon the establishment of a sharp-crack condition at the tip of the fatigue crack, in a specimen of adequate size. To establish a suitable crack-tip condition, the stress intensity level at which the fatigue precracking of the specimen is conducted is limited to a relatively low value.

Comment:

This is the accepted technique for determination of  $K_{IC}$  values for handbook and specification purposes. It represents the cumulative work of the members of ASTM Committee E-24 over a ten year period.

Important References:

1. Brown, Jr., W. F. and Srawley, J. E., Plane Strain Crack Toughness Testing of High Strength Metallic Materials, ASTM STP 410 (1966).
2. Fracture Toughness Testing and Its Applications, ASTM STP 381 (April 1965).
3. Jones, M. H., Bubsey, R. T. and Brown, Jr., W. F., Clevis Design for Compact Tension Specimens Used in  $K_{IC}$  Testing, Mater. Res. Stand. 9, No. 5 (May 1969).
4. Wessel, E. T., State of the Art of the WOL Specimen for  $K_{IC}$  Fracture Toughness Testing, Eng. Fract. Mech. 1, No. 1 (January 1968).
5. Srawley, J. E., Jones, M. H. and Brown, Jr., W. F., Determination of Plane Strain Fracture Toughness, Mater. Res. Stand. 7, No. 6, 262 (June 1967).
6. Fisher, D. M., Bubsey, R. T. and Srawley, J. E., Design and Use of a Displacement Gage for Crack Extension Measurements, NASA TN-D-3724 (1966).

Key words: Bend tests; compact tension specimens; compliance measurements; fracture strength; metallic materials; plane strain fracture toughness; stress intensity factor; testing standards.

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PLANE STRAIN CRACK TOUGHNESS TESTING OF HIGH STRENGTH METALLIC MATERIALS  
Brown, Jr., W. F. and Srawley, J. E. (National Aeronautics and Space Administration,  
Lewis Research Center, Cleveland, OH)  
ASTM STP 410

The design and testing of crack-notched specimens for determination of the resistance of high strength metallic materials to unstable opening-mode crack extension under plane strain conditions is discussed. Test methods concerned with subcritical crack extension due to repeated loading or aggressive environments are not discussed.

The plane strain crack toughness  $K_{IC}$  is a material property which is measured in terms of the opening-mode stress intensity factor  $K_I$  expressed in units of (stress) x (length)<sup>1/2</sup>. The distinction between  $K_{IC}$  and  $K_I$  is important, and is comparable to the distinction between strength and stress. To determine a  $K_{IC}$  value, a crack-notched specimen of suitable dimensions is increasingly loaded until the crack becomes unstable and extends abruptly. The  $K_I$  value corresponding to the load at which unstable crack extension is observed is the  $K_{IC}$  value determined in the test. This property is a function of temperature and strain rate.

It is necessary to develop specifications for valid  $K_{IC}$  testing because real materials do not deform in the elastic-brittle manner assumed in linear elastic fracture mechanics. Nevertheless, when a sufficiently large crack-notched specimen is tested, the behavior is sufficiently close to elastic brittle because the crack tip plastic region remains small relative to the significant specimen dimensions. The conditions for valid  $K_{IC}$  testing comprise both minimum limits for specimen dimensions and a maximum limit on deviation from linearity of the load-displacement record. These limits are established on the basis of test data obtained for the purpose, as discussed in subsequent sections. It should be clearly understood, however, that a certain degree of arbitrariness is unavoidable in specifying these limits. As the amount of useful data increases it should be possible to reduce the degree of arbitrariness in setting the conditions for valid  $K_{IC}$  testing.

Comment:

This book presents a state-of-the-art survey of the analytical and experimental basis for determining the plane strain crack toughness of metallic materials. It deals with the design and testing of crack-notched specimens for determination of the resistance of high strength metallic materials to crack extension under plane strain conditions. Mathematical models for various test specimen types provided insight into the pertinent aspects of the stress intensity factor and plane strain crack toughness determination. The distribution of the plane strain crack toughness values, determination through test, is often considerable and the lower confidence limits rather than mean values are recommended.

This book has become the classic statement of the basics of plane strain fracture toughness. It successfully addressed both the testing of metals and the engineering significance of the experimental values.

Important References:

1. Irwin, G. R., Plastic Zone Near a Crack and Fracture Toughness, Proc. Sagamore Ord. Mat. Res. Conf., 7th, Report No. METE 661-611/F, Syracuse Univ. Res. Inst. 4-63 (August 1960).
2. Boyle, R. W., Sullivan, A. M. and Krafft, J. M., Determination of Plane Strain Fracture Toughness with Sharply Notched Sheets, Welding J. Res. Suppl. 41, 428S (1962).
3. McClintock, F. A. and Irwin, G. R., Plasticity Aspects of Fracture Mechanics, ASTM STP 381, 84-113 (1965).
4. Irwin, G. R. and Kies, J. A., Critical Energy Rate Analysis of Fracture Strength, Weld. J. Res. Suppl. 33, 193S (1954).
5. Gross, B., Srawley, J. E. and Brown, Jr., W. F., Stress-Intensity Factors for a Single-Edge-Notch Tension Specimen by Boundary Collocation of a Stress Function, NASA TN-D-2395 (August 1964).

See Also:

1. Discussion to Plane Strain Crack Toughness Testing of High Strength Metallic Materials, ASTM STP 410

a.	Manjoine, M. J.	page 66-70
b.	Ripling, E. J.	page 70
c.	Wilson, W. K.	page 75-76
d.	Feddersen, C. E.	page 77-79
e.	Chu, H. P.	page 79-81
f.	Orner, G. M. and Lement, B. S.	page 82-83
g.	Kaufman, J. G.	page 86
h.	Heyer, R. H.	page 86-87
i.	Randall, P. N.	page 88-125
j.	Novak, S. R. and Rolfe, S. T.	page 126-128
k.	Brown, Jr., W. F. and Srawley, J. E., authors replies	pages 71-74, 76-77, 79, 81-82, 83-86, 87-88, 125-126, 128-129

Key words: Aluminum alloys; crack propagation; cyclic loads; elastic-plastic analysis; fracture mechanics; fracture strength; laboratory tests; maraging steels; metallic materials; plane strain fracture toughness; plastic zone; stress analysis; stress intensity factor; structural safety; yield strength.

## EXPERIMENTAL TECHNIQUES IN FRACTURE MECHANICS

Kobayashi, A. S., Editor (University of Washington, Seattle, WA)  
Society for Experimental Stress Analysis, Monograph No. 1

Experimental techniques related to fracture mechanics which are scattered throughout the many publications and committee reports are assembled in several chapters. The material contained in this first monograph is intended to provide information on the principles, procedures, applications and, finally, limitations on some basic experimental techniques currently used in experimental fracture mechanics. Standard experimental details such as fracture-specimen configurations and loading procedures are amply described in special publications of the American Society for Testing and Materials and are, thus, not elaborated in this monograph. Rather, it is hoped that by limiting the coverage of each topic, the reader can obtain an overview of representative experimental techniques in fracture mechanics, and then turn to the quoted references for specific details which fit his particular requirement. Thus, this monograph is primarily written for the initiates in fracture mechanics, but it also contains advanced and current information for the experts in this field.

Five major areas are covered in this monograph. These are (1) Theory of Fracture Mechanics (Kobayashi, A. S.); (2) Acoustic-Emission Techniques (Dunegan H. L. and Harris, D. O., Dunegan/Endevco, Livermore, Calif.); (3) Compliance Measurements (Bubsey, R. T., Fisher, D. M., Jones, M. H. and Srawley, J. E., NASA Lewis Research Center, Cleveland, Ohio); (4) Testing Systems and Associated Instrumentation, Swanson, S. R.; MTS Systems Corp., Minneapolis, Minn.); and (5) Photoelastic Techniques (Kobayashi, A. S.).

### Comment:

This monograph is an excellent source reference for experimental techniques in fracture mechanics. In particular the chapters on acoustic-emission techniques and on compliance measurements are contributions to the literature as well as being excellent reviews of the subject.

### Important References:

Consistent with the purpose of the monograph each chapter is extensively referenced and no attempt will be made here to extract the most significant of these except to note that the ASTM Special Technical Publications have provided the background and basis on which the monograph is constructed. These would include:

1. Fracture Toughness Testing and Its Application, ASTM STP 381 (1965).
2. Plane Strain Crack Toughness Testing of High Strength Metallic Materials, ASTM STP 410 (1966).
3. Fatigue Crack Propagation, ASTM STP 415 (1967).
4. Review of Developments in Plane Strain Fracture Toughness Testing, ASTM STP 463 (1970).

Key words: Analysis methods; compliance measurement; crack initiation; crack propagation; fracture mechanics; fracture strength; fracture tests; linear elastic fracture mechanics; NDE; photoelasticity; static crack growth; structural reliability; testing methods; ultrasonic tests.

#### STATISTICAL VARIATION IN FRACTURE TOUGHNESS DATA OF AIRFRAME MATERIALS

Liu, A. F. (The Boeing Co., Renton, WA)

AFFDL-TR-70-144, 323 (September 1970)

Fracture toughness data has been subjected to graphical and statistical treatments. The results show the test values for the critical stress intensity factor (plane strain) could be approximated using either a log-normal or a Weibull distribution. By making use of the log-normal (2 parameter) distribution, the sample mean and the guaranteed minimum values, for some of the available data, were estimated and are tabulated for reference.

The nature of fracture toughness testing and factors that affect the test results were reviewed. Emphasis has been placed on the fact that without paying close attention to the physical phenomenon involved, conclusions drawn from any statistical analysis would have little meaning. A graphical method was adopted for evaluating closeness of fit between given probability density functions and fracture toughness data. It is concluded that those probability functions commonly used to fit material mechanical properties data, are also applicable for fitting the fracture toughness data.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 23).

#### COMPARISON OF FRACTURE TOUGHNESS TEST PROCEDURES FOR ALUMINUM ALLOYS

Freed, C. N., Goode, R. J. and Judy, Jr., R. W. (Naval Research Lab, Washington, DC) NRL Report 6853 (February 1969)

The dynamic tear (DT) test provides a sensitive and quantitative measure of the fracture toughness of aluminum alloys. The test permits the measurement of fracture propagation energy across the toughness spectrum for metals which are definable by linear elastic analysis to those requiring gross plastic strains for fracture. The linear elastic fracture mechanics parameter  $K_{IC}$  provides a relationship between critical flaw size and stress level at which crack instability will occur. Unlike the DT test, the  $K_{IC}$  toughness test can not be used for fracture under conditions of elastic-plastic or gross plastic strain. A correlation has been developed between the DT test and the  $K_{IC}$  parameter for aluminum alloys. The relationship may also be expressed in terms of  $\beta_{IC} - DT$  and  $G_{IC} - DT$ . The  $K_{IC}$  values were determined with several specimen types, and a comparison of the values for different specimens was obtained. The correspondence between  $K_{IC}$  and DT serves several purposes. It provides a frame of reference for DT values obtained from frangible metals that fracture under linear elastic conditions. Accordingly, it permits use of the inexpensive DT test to approximate the flaw size-stress instability conditions which otherwise must be determined by the more expensive  $K_{IC}$  test. Another important aspect of the relationship between DT and  $K_{IC}$  is that through extrapolation, the correlation which exists in the linear elastic region can be extended into the elastic-plastic region. The loss of a plane-

strain stress state requires calculation of approximate  $K_C$  values from the extrapolated  $K_{IC}$  values. Thus, it is possible to use the DT test to estimate the critical flaw size at crack instability for metals in which fracture occurs under an elastic-plastic strain field. Because of the relatively large flaws involved for this condition, the approximation is adequate for most engineering purposes.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 37).

EVALUATION OF THE COMPACT TENSION SPECIMEN FOR DETERMINING PLANE STRAIN FRACTURE TOUGHNESS OF HIGH STRENGTH MATERIALS

McCabe, D. E. (ARMCO Steel Corp., Middletown, OH)

J. Mater. 7, No. 4, 449-454 (December 1972)

Results of cooperative tests on compact specimens for the determination of  $K_{IC}$  values are evaluated. Specimens were obtained from broken halves of three-point bend specimens used in a prior cooperative program, affording an opportunity to compare the results for two specimen types. For a given material; all laboratories reported average  $K_{IC}$  values within 10 percent of the grand mean  $K_{IC}$  value. The three point bend specimen and compact specimen were found to give the same average  $K_{IC}$  value. The replicated variation is significantly greater with the three-point bend specimen. Problems associated with certain of the requirements are discussed and suggestions for areas of future research are made.

Comment:

This report of the ASTM Committee E-24 round robin fracture toughness testing program was significant in the adoption of the plane strain fracture toughness testing standard E399-72.

Important References:

1. Heyer, R. H. and McCabe, D. E., Plane Strain Fracture Toughness Testing, ASTM STP 463 (1970).
2. Brown, Jr., W. F. and Srawley, J. E., Plane Strain Crack Toughness Testing of High Strength Metallic Materials, ASTM STP 410 (1967).

Key words: Aluminum alloys; bend tests; compact tension specimens; cracks; fracture mechanics; fracture tests; fractures (materials); high strength alloys; plane strain; plane strain fracture toughness; statistical analysis; steels; tensile properties; testing methods; toughness.

EVALUATION OF A METHOD OF TEST FOR PLANE STRAIN FRACTURE TOUGHNESS USING A BEND SPECIMEN

Heyer, R. H. and McCabe, D. E. (Armco Steel Corp., Middletown, OH)  
Review of Developments in Plane Strain Fracture Toughness Testing, ASTM STP 463, 22-41 (1970)

A task group of ASTM Committee E-24 conducted an interlaboratory test program on determination of  $K_{IC}$  using the proposed recommended practice for plane strain fracture toughness testing of high strength metallic materials using a fatigue-cracked bend specimen.

Analysis of  $K_{IC}$  data for an aluminum alloy and two high-strength alloy steels showed that laboratory mean values were within  $\pm 10$  percent of grand mean values. Replication was generally satisfactory, although not as good as for smooth specimen tension tests.

Information obtained on fatigue cracking and other details of the procedure will be useful in planned revisions, leading to a standard method of test.

Comment:

This is the summary report on the E-24 round robin bend test program and contains the basic summary information.

Important References:

1. Lashof, T. W., Ranking Laboratories and Evaluating Methods of Measurement in Round Robin Tests, Mater. Res. Stand. 4, No. 8, page 397 (August 1964)

Key words: Aluminum alloys; bend tests; crack initiation; crack propagation; data; fracture mechanics; fracture strength; laboratory tests; maraging steel; plane strain fracture toughness; stress intensity factor; testing methods; testing standards.

## COMMENTARY ON PRESENT PRACTICE

Brown, Jr., W. F. and Srawley, J. E. (National Aeronautics and Space Administration, Lewis Research Center, Cleveland, Ohio)  
Review of Developments in Plane Strain Fracture Toughness Testing, ASTM STP 463, 216-248 (1970)

Specimen size requirements and attempts to correlate  $K_{IC}$  with simpler mechanical test results are areas of considerable controversy among those engaged in plane strain fracture toughness testing. The tentative method of test for plane strain fracture toughness of metallic materials (E 399-70T) may need revision before being advanced to a standard. Additional experimental data are needed in order to make a judgment concerning the need for revision.

(FOR LISTING OF IMPORTANT REFERENCES, KEY WORDS AND A DUPLICATE ABSTRACT, SEE PAGE 15).

## THE INFLUENCE OF CRACK LENGTH AND THICKNESS IN PLANE STRAIN FRACTURE TOUGHNESS TESTS

Jones, M. H. and Brown, Jr., W. F. (National Aeronautics and Space Administration, Lewis Research Center, Cleveland, Ohio) Review of Developments in Plane Strain Fracture Toughness Testing, ASTM STP 463, 63-101 (1970)

Results are presented from a systematic investigation of the influence of crack length and specimen thickness on the fracture properties of 4340 steel bend specimens heat treated to yield strength levels between 180 and 213 ksi. It is shown that  $K_{IC}$  values determined in accordance with the present ASTM Tentative Method of Test for Plane Strain Fracture Toughness of Metallic Materials (E399-70T) can vary moderately within the specimen size and geometric limitations imposed by the Test Method. The magnitude of these variations will depend on material properties and would be increased by relaxation of the size requirements.

The possibility of employing subsized specimens for screening materials regarding their plane strain fracture toughness was explored as well as several methods for relating  $K_{IC}$  values to uniaxial tensile data. The results indicated that use of subsized specimens with the ASTM Committee E-24 Test Method does not constitute a useful screening procedure. For steels subject to single aging or tempering reactions, it appears that the relation  $K_{IC} \sim \sigma_{ys}^{-m}$  may be useful for estimating  $K_{IC}$  values. However, on the basis of present knowledge, it is not possible to calculate  $K_{IC}$  with useful accuracy from uniaxial tensile data alone.

Important References:

1. Brown, Jr., W. F. and Srawley, J. E., Plane Strain Crack Toughness Testing of High Strength Metallic Materials, ASTM STP 410 (1966)
2. Srawley, J. E., Jones, M. H. and Brown, Jr., W. F., Determination of Plane Strain Fracture Toughness, Mater. Res. Stand. 7, No. 6, 262-266 (June 1967)
3. Hahn, G. and Rosenfield, A., Source of Fracture Toughness: The Relation Between  $K_{IC}$  and the Ordinary Tensile Properties of Metals, ASTM STP 432, (1968)
4. Jones, M. H. and Brown, Jr., W. F., Acoustic Detection of Crack Initiation in Sharply Notched Sheet Specimens, Mater. Res. Stand. 4, No. 3, 120-129 (March 1964)
5. Krafft, J. and Sullivan, A. M., Effects of Speed and Temperature on Crack Toughness and Yield Strength in Mild Steel, Trans. Quart. 56, 160 (1963).
6. Krafft, J. Correlation of Plane Strain Crack Toughness with Strain Hardening Characteristics of a Low, a Medium, and a High Strength Steel, Appl. Mater. Res. 3, (1964)

Key words: Crack analysis; crack initiation; crack propagation; cracking (fracturing); data; fracture mechanics; fracture tests; fractures (materials); plane strain; plane strain fracture toughness; stress intensity factor; testing methods; testing standards.



## VB - SPECIMEN TYPES

### EFFECT OF SPECIMEN TYPE AND CRACK ORIENTATION ON FRACTURE TOUGHNESS

Davis, S. O., Tupper, N. G. and Niemi, R. M. (Air Force Materials Lab., Wright-Patterson AFB, OH; Monsanto Research Corp., Dayton, OH)  
AFML-TR-67-38 (1967)

The effect of specimen type on the room temperature plane strain fracture toughness of three aluminum alloys, 7079-T6, and 7001-T75, is presented. The difference in plane strain fracture toughness as evaluated with center notch, single edge notch, slow bend, surface flaw, and wedge opening loading specimens is discussed. The orientation of the crack plane and crack propagation direction with respect to the working direction, or grain orientation, of the alloys is considered.

The possible influence of crack plane and propagation direction on the resulting plane strain fracture toughness value is discussed. The surface flaw specimens seem to yield the highest  $K_{IC}$  value followed by slow bend, single edge notch and center notch specimens. The slow bend and surface flaw specimens were the most sensitive to material variability. Differences in orientation between crack propagation direction and material grain morphology are shown to affect  $K_{IC}$ . For 7001-T75 and 7079-T6 the order of decreasing fracture resistance with respect to crack propagation direction is short transverse, and longitudinal. For 7075-T6, the order is long transverse, short transverse, and longitudinal.

#### Comment:

The authors have demonstrated the effect of specimen orientation on plane strain fracture toughness. This is similar to the yield strength variation observed in forged or roll textured metals. These experimental results were influential in the inclusion of orientation criteria in the ASTM E399-72 standard test method.

#### Important References:

1. Srawley, J. E. and Brown, Jr., W. F., Fracture Toughness Testing, NASA TM-X-52030 (June 1965).
2. Brown, Jr., W. F. and Srawley, J. E., Current Status of Plane Crack Toughness Testing, NASA TM-X-52209 (June 1966).
3. Davis, S. O., Tupper, N. G. and Niemi, R. M., Plane Strain Fracture Toughness Properties of Three Aluminum Alloys as a Function of Specimen Geometry, AFML-TR-65-150 (1965).

Key words: Aluminum alloys; crack propagation; cracks; fracture strength; fracture tests; notched specimens; plane strain fracture toughness.

FRACTURE TOUGHNESS AND CRACK GROWTH MEASUREMENTS WITH "C" SHAPED SPECIMENS  
Kendall, D. P., Underwood, J. H. and Winters, D. C. (Watervliet Arsenal, New York, NY) R-WV-T-6-39-73 (October 1973)

A series of "C" shaped fracture toughness specimens from 4340 steel forged cylinders were tested using the general test procedure recommended by ASTM E399. A wide range of specimen sizes were tested and no significant size effect on the fracture toughness, as measured by this specimen, was found. Crack growth during fracture toughness tests was measured using an ultrasonic technique. From these measurements the relationship between crack extension and secant offset of the load-displacement curve can be obtained. It is demonstrated that "C" shaped specimens give the expected value of fracture toughness over a range of sizes for thick-walled cylinders.

Important references:

1. ASTM, Standard Method of Test for Plane-Strain Fracture Toughness of Metallic Materials, E399, 1973 Annual Book of ASTM Standards, part 31 (1973).
2. Underwood, J. H., Scanlon, R. D. and Kendall, D. P., K Calibration for "C" Shaped Fracture Toughness Specimens of Various Geometries, Benet Weapons Lab, Report R-WV-T-6-15-73 (April 1973).
3. Irwin, G. R., Structural Aspects of Brittle Fracture, Appl. Mater. Res. 3, 65-81 (April 1964).

Key words: Compliance measurements; crack propagation; fatigue (materials); forgings; fracture mechanics; fracture strength; fracture tests; fractures (materials); high strength alloys; plane strain; plane strain fracture toughness; pre-cracked specimens; steels; stress intensity factor; test specimen design; testing methods; ultrasonic tests.

FRACTURE TOUGHNESS OF ALUMINUM ALLOY PLATE DETERMINED WITH CENTER-NOTCH TENSION, SINGLE-EDGE-NOTCH TENSION AND NOTCH-BEND TESTS

Kaufman, J. G., Nelson, Jr., F. G. and Holt, M. (Aluminum Co., of America, New Eng. Fract. Mech. 1, 259-274 (1968))

The fracture toughness of 2.54 cm and 3.463 cm plates of ten combinations of alloy and temper has been determined with center-notch tension (CN), single-edge-notch-tension (SEN), and notch-bend (NB) tests. The latter were made in accordance with the E-24 draft recommended practice. Valid values of  $K_{IC}$  were obtained in the NB test of the high-strength alloys and tempers, and for these materials, there was fair agreement in the results obtained from the NB and SEN tests, which were made of large machine-notched panels, generally indicated high values of  $K_{IC}$ . For the medium-strength alloys and tempers, no valid measurement of  $K_{IC}$  could be made, and there were wide variations in the values from the various tests. Under these conditions, the test results can not be considered reliable relative measures of resistance to unstable crack growth. The results of this series of tests provide some information on the mixed-mode fracture characteristics of the alloys. Gen-

erally, the thick plate demonstrated considerably more crack toughness than that indicated by the plane strain intensity factor.

Important References:

1. Kaufman, J. G. and Hunsicker, H. Y., Fracture-Toughness Testing at ALCOA Research Laboratories, ASTM STP 381, 290-309 (1965).
2. Brown, Jr., W. F. and Srawley, J. E., Plane-Strain Crack Toughness Testing of High Strength Metallic Materials, ASTM STP 410 (December 1967).
3. Kaufman, J. G., Nordmark, G. E. and Lifka, B. W., Fracture Toughness, Fatigue and AFML-TR-65-170 (1965).
4. Freed, C. N. and Krafft, J. M., Effect of Side Grooving on Measurements of Plane Strain Fracture Toughness, J. Mater. 1, 770-790 (1966).

Key words: Aluminum alloys; bend tests; center crack specimens; crack propagation; cracks; fatigue (materials); fracture mechanics; fracture strength; fractures (materials); high strength; linear elastic fracture mechanics; plane strain; stress intensity factor; tensile stress.

PLANE STRAIN FRACTURE TOUGHNESS PROPERTIES OF THREE ALUMINUM ALLOYS AS A FUNCTION OF SPECIMEN GEOMETRY

Davis, S. O., Tupper, N. G. and Niemi, R. M. (Air Force Materials Lab., Wright-Patterson AFB, OH: Monsanto Research Corp., Dayton, OH)  
AFML TR-65-150

The fracture toughness of three aluminum alloys, 7079-T6, 7075-T6 and 7001-T75, was determined at room temperature, utilizing the center notch and single edge notch test specimens. Alloys 7001-T75 had comparatively lower fracture toughness than the other two alloys, which were approximately equal. Various grain size and processing effects and characteristics and test results for the two specimen types are discussed.

Comment:

This report identified aspects of the property of plane strain fracture toughness. It demonstrated that metallurgical variables such as grain size, texture and inclusions affect the  $K_{IC}$  value.

Important References:

1. Srawley, J. E. and Brown, Jr., W. F., Fracture Toughness Testing, NASA TM-X-52030.
2. Srawley, J. E., Jones, M. H. and Gross, B., Experimental Determination of Dependence of Crack Extension Force on Crack Length for a Single Edge Notch Tension Specimen, NASA TN-D-2396 (August 1964).
3. Jones, M. H. and Brown, Jr., W. F., Acoustic Detection of Crack Initiation in Sharply Notched Specimens, Mater. Res. Stand. 4, No. 3, 120-129 (March 1964).
4. Sullivan, A. M., New Specimen Design for Plane-Strain Fracture Toughness Tests, Mater. Res. Stand. 4, No. 1, 20-24 (January 1964).

Key words: Aluminum alloys; center crack specimens; fracture strength; geometric effects; high strength alloys; plane strain fracture toughness.

THE INFLUENCE OF SPECIMEN GEOMETRY ON CRACK TIP PLASTICITY

Pettit, D. E. and Hoepfner, D. W. (Lockheed-California Co., Burbank, CA)  
Lockheed-California Report No. LR-25318 (June 1972)

The effect of panel width and thickness on the crack tip plasticity of center-cracked fracture panels of 7075-T6 aluminum alloy was examined. The plastic zone formation was continually monitored photographically during the fracture test and the zone size and shape determined by an image distortion technique. The influence of specimen width and thickness was examined to determine its effect on the plastic zone behavior and the mode (stable tear or pop-in) of initial crack extension. Plastic zone models were then compared with the characteristic plastic zone size parameters measured experimentally and the models evaluated. From these results, the effect of panel thickness and geometry on the characteristics of crack tip plasticity and initial crack extension was assessed. The effects of these findings on methods of evaluating material toughness are examined. The applicability of these zone size models in linear elastic fracture mechanics applications are discussed.

Important References:

1. Hahn, G. T. and Rosenfield, A. R., Elastic-Plastic Fracture Mechanics, ARML TR-67-143 (January 1968).
2. Pettit, D. E. and Hoepfner, D. W., The interaction of Material and Geometric Aspects in the Fracture of Aluminum Alloys, Proc. Int. Conf. Mechanical Behavior of Materials, Kyoto, Japan (15-20 August 1971).
3. Broek, D. and Schijve, J., The Effect of Sheet Thickness on the Fatigue Crack Propagation in 2024-T3 Alclad Sheet Material, NRL Report M-2129 (April 1963).

4. Hoepfner, D. W., Danford, V. and Pettit, D. E., A New Technique for Viewing Deformation Zones at Crack Tips, *Exper. Mech.* (June 1971).
5. McClintock, F. A. and Irwin, G. R., *Plasticity Aspects of Fracture Mechanics*, ASTM STP 381, 84-113 (1965).
6. Kuhn, P., Residual Strength in the Presence of Fatigue Cracks, paper presented to the Structures and Materials Panel, AGARD, Turin, Italy (April 1967).

Key words: Aluminum alloys; analysis methods; center crack specimens; crack propagation; crack tip plastic zone; distortion; fracture mechanics; fracture strength; fracture tests; fractures (materials); geometric effects; linear elastic fracture mechanics; mechanical properties; metallic materials; plane strain; plane stress; plastic properties; plastic zone; stress intensity factor; toughness.

INFLUENCE OF STRESS INTENSITY LEVEL DURING FATIGUE PERCRACKING ON RESULTS OF PLANE-STRAIN FRACTURE TOUGHNESS TESTS

Kaufman, J. G. and Schilling, P. E. (Aluminum Co. of America, New Kensington, PA) *Progress in Flaw Growth and Fracture Toughness Testing*, ASTM STP 536, 312-319 (July 1973)

One of the more troublesome parts of conducting a plane strain fracture toughness test in accordance with ASTM test for plane strain fracture toughness of metallic materials (E399-72) is producing a satisfactory fatigue crack in the specimen prior to fracturing it. The 1968 version of ASTM E399 indicated that the stress intensity during the last stage of fatigue cracking should not exceed 0.0012 inch  $1/2$  E (Modulus of Elasticity) or 0.5  $K_{IC}$ , but that has been gradually eased so that the current limits are 0.002 inch  $1/2$  E or 0.6  $K_{IC}$ . Data for four aluminum alloys support the fact that it is satisfactory to use stress intensities up to 0.002 inch  $1/2$  E and suggest that the other limit could be increased to 0.8  $K_{IC}$ . This may be unique to aluminum alloys and additional data should be generated for other metals to determine whether or not this is generally true.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 99).

EXPERIMENTAL DETERMINATION OF THE DEPENDENCE OF CRACK EXTENSION FORCE ON CRACK LENGTH FOR A SINGLE-EDGE-NOTCH TENSION SPECIMEN

Srawley, J. E., Jones, M. H. and Gross, B. (National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH)

NASA TN-D-2396 (August 1964)

The single-edge-notch form of a plane-strain (or opening mode) crack toughness specimen is particularly economical in regard to available test material and testing machine capacity. The necessary calibration relation for a particular design of a single-edge-notch specimen, centrally loaded in tension, was determined from a series of compliance measurements at crack lengths ranging from zero to one-half the specimen width. The accuracy of the calibration is estimated to be  $\pm 1/2$  percent in the range of interest. Agreement with concurrent results obtained by boundary collocation of an appropriate stress function is excellent. Alternative types of specimens are discussed, and the relation between necessary specimen size and the ratio of toughness to yield strength is emphasized.

Important References:

1. Sullivan, A. M., New Specimen Design for Plane-Strain Fracture Toughness Tests, Mater. Res. Stand. 4, No. 1, 20-24 (January 1964).
2. Gross, B., Srawley, J. E. and Brown, Jr., W. F., Stress Intensity Factors for a Single-Edge-Notch Tension Specimen by Boundary Collocation of a Stress Function, NASA TN-D-2395 (1964).

Key words: Compliance measurements; fracture strength; notched specimens; plane strain; plane strain fracture toughness; pre-cracked specimens; tensile stress.

CLEVIS DESIGN FOR COMPACT TENSION SPECIMENS USED IN PLANE-STRAIN FRACTURE TOUGHNESS TESTING

Bubsey, R. T., Jones, M. H. and Brown, Jr., W. F. (National Aeronautics and Space Administration, Langley Research Center, Cleveland, OH)

NASA TM-X-1796 (May 1969)

An experimental investigation was made of friction effects in a conventional round-hole clevis used for testing compact tension fracture toughness specimens. The results showed measured plane-strain fracture toughness  $K_{IC}$  values could be too high by about 10 percent when the loading-pin-to-hole clearances are only a few thousandths of an inch. Lubrication was found to have only a small effect. Increasing the pin clearance reduces the friction effects, but uncertainties in the initial position of the load axis with respect to the slot tip (equivalent to variation in crack length to width ratio  $(a/W)$  result in a possible spread in  $K_{IC}$  values of nearly 5 percent. A new clevis design is described which greatly minimizes the errors caused by friction and variations in effective  $K_{IC}$ . This design is proportioned to permit testing of materials having a wide range of toughness and yield strengths.

Comment:

This excellent experimental effort demonstrates the degree of control over specimen test fixturing required to avoid the introduction of errors. The unique clevis pin hole shape recommended in this paper was made a part of the ASTM E399-72 standard.

Important References:

1. Manjoine, M. J., Biaxial Brittle Fracture Tests, J. Basic Eng. 87, No. 2, 293-298 (June 1965).
2. Srawley, J. E. and Gross, B., Stress Intensity Factors for Crackline-Loaded Edge-Crack Specimens, Mater. Res. Stand. 7, No. 4, 155-162 (April 1967).
3. Pook, L. P., The Effect of Friction on Pin Jointed Single Edge Notch Tension Specimen, Int. J. Fract. Mech. 4, No. 3, 295-297 (September 1968).
4. Fisher, D. M., Bubsey, R. T. and Srawley, J. E., Design and Use of Displacement Gage for Crack-Extension Measurements, NASA TN-D-3724 (1966).
5. Mostovoy, S., Crosley, P. B. and Ripling, E. J., Use of Crackline-Loaded Specimens for Measuring Plane-Strain Fracture Toughness, J. Mater. 2, No. 3, 661-681 (September 1967).

Key words: Compact tension specimen; fracture strength; fracture tests; plane strain fracture toughness; test specimen design; testing methods.

ACOUSTIC DETECTION OF CRACK INITIATION IN SHARPLY NOTCHED SPECIMENS

Jones, M. H. and Brown, Jr., W. F. (National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH)  
Mater. Res. Stand. 4, No. 3, 120-129 (March 1964).

Of the several techniques employed for pop-in load determination, acoustic detection appears to offer the greatest flexibility under a wide variety of testing conditions. This paper describes an acoustic system using an ordinary phonograph pickup and a tape recorder. Both sound and load are recorded on the tape. Results obtained with this technique are described for tests on several sheet alloys using different specimen types provided with both sharp machined notches and fatigue cracks. In addition, acoustic pop-in data for one alloy are compared with data obtained with a compliance gage.

Comment:

This technique of acoustically determining pop-in and correlating it with the load strain curve has been widely used and contributed significantly to the development of plane strain fracture toughness testing technology.

Important References:

1. Steigerwald, E. A. and Hanna, G. L., Initiation of Slow Crack Propagation in High Strength Materials, Proc. ASTM 62, 885 (1962)

Key words: Crack initiation; fracture strength; fracture tests; plane strain; stress intensity factor; test specimen design; testing methods.

#### MEASURING FRACTURE TOUGHNESS - A SIMPLIFIED APPROACH USING CONTROLLED CRACK PROPAGATION

Weitzmann, R. H. and Finnie, I. (Space Science, Inc., Monrovia, CA, California University, Berkeley, CA)

J. Mater. 7, No. 3, 294-298 (September 1972)

During the loading cycle of the conventional fracture toughness test, the point of load application remains fixed with respect to specimen geometry except for small displacements in-line with the applied load. By contrast, in the present method, the point of load application advances toward the crack-front during the loading cycle in a path parallel to the plane of the crack. Since displacement is the controlled variable, it is thus possible to obtain a continuous functional relationship between load and crack length. It is shown that this relationship is directly relatable to the strain energy release rate on crack advance. The concept reduces the complexity of fracture toughness testing to a level comparable to a conventional tension test. that is, recording of load and displacement. Characteristic features of the method are very stable crack propagation, efficient use of test material, and the ability to measure toughness gradients. Results of applying the concept to a 7075-T6 aluminum alloy are presented.

#### Comment:

The authors have significantly broken with tradition by proposing and experimentally examining a fracture toughness test technique in which the point of load application remains relatively fixed. This complicates the test fixturing but introduced significant testing flexibility and potential cost savings. The initial results as indicated in the paper are promising and significant addition effort appears indicated. This technique could supplement the ASTM Standard E399-72, particularly in terms of information on materials where gradients of toughness may exist such as in welded structures and textured metals.

#### Important References:

1. Rolfe, S. T. and Novak, S. R., Slow-Bend  $K_{IC}$  Testing of Medium-Strength, High-Toughness Steels, ASTM STP 463, 124-159 (1970).
2. Mostovoy, S., Crosley, P. G. and Ripling E. R., Use of Crack Line Loaded Specimens for Measuring Plane Strain Fracture Toughness, J. Mater. 2, 661-681 (1967).
3. Barenblatt, G. I., Mathematical Theory of Equilibrium Cracks in Brittle Fracture. Advances in Applied Mechanics 7, Academic Press, New York, NY (1962).

Key words: Aircraft structures; aluminum alloys; crack analysis; crack propagation; cracks; fracture strength; fracture tests; metallic materials; stress; structural safety; testing methods; toughness.



## VC - SPECIMEN SIZE

THE EFFECT OF SPECIMEN SIZE ON THE RESULTS OF PLANE-STRAIN FRACTURE-TOUGHNESS TESTS  
Nelson, F. G., Schilling, P. E. and Kaufman, J. G. (Aluminum Co. of America, New  
Kensington, PA)  
Eng. Fract. Mech 4, No. 1, 33-50 (1972)

The effect of specimen geometry, notably thickness and crack length, on the values of plane strain fracture toughness,  $K_{IC}$ , of five aluminum alloys have been determined. Notch-bend specimens of 2024-T851, 6061-T651, 7075-T7351 and 7079-T651 and compact tension specimens of 2219-T851 were tested; for some alloys, face-grooved specimens were also included. Constant values of  $K_Q$  (candidate value of  $K_{IC}$ ) are generally obtained for specimen thicknesses and crack lengths greater than  $2.5 (K_{IC}/\sigma_{ys})^2$ , while for thinner specimens values above or below the true  $K_{IC}$  value may be obtained, dependent upon other dimensions of the specimen. For the face-grooved specimens, problems were encountered with achieving satisfactory fatigue cracks and the influence of side-grooving on  $K_Q$  values appeared to vary from alloy to alloy; overall, no advantage in measuring  $K_{IC}$  was indicated for face grooving.

### Comment:

The authors have examined for several aluminum alloys the specimen dimension geometry and yield strength criteria for the measurement of  $K_{IC}$  as embodied in ASTM Standard E399-72. This experimental effort demonstrates that the ASTM criteria is conservatively applicable to this range of structural aluminum alloys.

### Important References:

1. Brown, Jr., W. F. and Srawley, J. E., Plane Strain Crack Toughness Testing of High Strength Metallic Materials, ASTM STP 410 (1966).
2. McClintock, F. A. and Irwin, G. R., Plasticity Aspects of Fracture Mechanics, ASTM STP 381 (1965).
3. Kaufman, J. G. and Holt, M., Fracture Characteristics of Aluminum Alloys ARL Tech. Paper No. 18, Alcoa, Pittsburgh, PA (1965).
4. Freed, C. N. and Krafft, J. M., Effect of Side Grooving on Measurements of Plane Strain Fracture Toughness, J. Mater 1, 770 (1966).
5. Kaufman, J. G., Nelson, Jr., F. G. and Holt, M., Fracture Toughness of Aluminum Alloy Plate Determined with Center-Notch Tension, Single-Edge-Notch Tension and Notch-Bend Tests, Eng. Fract. Mech. 1, 259 (1968).

Key words: Aluminum alloys; bend tests; cracks; deformation; fatigue (materials); fracture tests; notched specimens; notch tests; plane strain fracture toughness; pre-cracked specimens; tensile properties; yield strength.

COMPARISON OF FRACTURE TOUGHNESS VALUES OBTAINED USING SEMI-INFINITE ALUMINUM PLATES WITH VALUES OBTAINED USING LABORATORY SIZE SPECIMENS  
Jones, R. E. (Dayton Univ. Research Institute, Dayton, OH)  
AFML-TR-69-58 (April 1969)

Fracture toughness values obtained from small laboratory size specimens in four point slow-bend loading were compared with values obtained by ALCOA in testing large semi-infinite center notched plate specimens. The plane-strain stress intensity factor,  $K_{IC}$  determined in this investigation varied from those values obtained by ALCOA by 7 percent on the positive side and 18 percent on the negative side. Specimen ranking in descending order of toughness is as follows: (1) 2219-T851, (2) 7075-T7351, (3) 7075-T651, (4) 7079-T651, (5) 7001-T75, (6) 2024-T851, and (7) 2020-T651. The results tend to substantiate the specimen requirements suggested by Brown and Srawley.

Important References:

1. Brown, Jr., W. F. and Srawley, J. E., Plane Strain Crack Toughness Testing of High Strength Metallic Materials, ASTM STP 410 (December 1966).
2. Kaufman, J. G., Nordmark, G. E. and Lifka, B. W., Fracture Toughness Fatigue and Corrosion Characteristics of 2020-T651, 2024-T851, and 7001-T75 Aluminum Alloys, AFML-TR-66-291 (1966).
3. Kaufman, J. G., Nordmark, G. E. and Lifka, B. W., Fracture Toughness Fatigue and Corrosion Characteristics of 7075-T651, 7075-T351, and 7079-T651 Aluminum Alloys, AFML-TR-65-170 (May 1965).
4. Kaufman, J. G., Nelson, Jr., F. G. and Holt, M., Fracture Toughness of Aluminum Alloy Plate, Eng. Fract. Mech., 264 (August 1968).

Key words: Aluminum alloys; bend tests; center crack specimens; charpy impact tests; crack propagation; fatigue (materials); fracture mechanics; fracture strength; fractures (materials); laboratory tests; linear elastic fracture mechanics; notched specimens; plane strain; plane strain fracture toughness; plastic zone; stress intensity factor; tensile stress; yield strength.

EFFECT OF SHEET THICKNESS ON THE FRACTURE-RESISTANCE PARAMETER  $K_C$  FOR STEELS  
Sullivan, A. M. and Stoop, J. (Naval Research Lab, Washington, DC)  
NRL Report 7601 (August 1973)

Definition of fracture resistance for thin sheet material in terms of the linear-elastic fracture mechanics plane stress parameter  $K_C$  continues to reveal aspects of its geometrical dependency. The effect of sheet thickness on the  $K_C$  value of three structural steels representing four yield stress levels has been determined over available thickness ranges of 0.794 to 6.350 mm. Within this range, less thickness dependence has been observed than was anticipated. The fact that both economy and convenience would be served if fracture resistance for all sheet thicknesses could be estimated from a limited number of specimens have given impetus to several models purporting to explain this dependency in terms of the relative contributions of a surface phenomenon, flat fracture, and a volume-sensitive mechanism, shear lip development. Attempts to fit present data to one of the models disclose inadequacies for which there are no apparent immediate solutions.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT,  
SEE PAGE 127).

INFLUENCE OF SHEET THICKNESS UPON THE FRACTURE RESISTANCE OF STRUCTURAL ALUMINUM ALLOYS

Sullivan, A. M., Stoop, J. And Freed, C. N. (Naval Research Lab., Washington, DC)  
Progress in Flaw Growth and Fracture Toughness Testing, ASTM STP 536, 323-333  
(July 1973)

Definition of fracture resistance for thin sheet material in terms of the linear-elastic fracture mechanics (LEFM) plane-stress parameter,  $K_C$ , continues to reveal aspects of its geometrical dependency. The effect of sheet thickness upon the  $K_C$  value of five structural aluminum alloys in current use has been determined over available thickness ranges of 1/32 to 1/4 inch within this range, less thickness dependence than anticipated has been observed. The fact that both economy and convenience would be served if fracture resistance for all sheet thicknesses could be estimated from a limited number of specimens have given impetus to several models purporting to explain this dependency in terms of the relative contributions of a surface phenomenon, flat fracture, and a volume sensitive mechanism, shear lip development. Attempts to fit present data to the model disclose inadequacies for which there is no apparent immediate solution.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT,  
SEE PAGE 39).

PLANE STRAIN FRACTURE TOUGHNESS TESTS ON 2.4 AND 3.9-INCH-THICK MARAGING STEEL SPECIMENS AT VARIOUS YIELD STRENGTH LEVELS

Fisher, D. M. and Repko, A. J. (National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH)  
J. Mater. 7, 167-174 (June 1972)

The specimen size requirements of the ASTM plane strain fracture toughness test method (E399-70T) were not sufficient to disqualify all the  $K_{Ic}$  results of this investigation that were low relative to results from larger specimens. This could be remedied in these results by an increase in the specimen size requirement based on the square of the ratio of the conditional fracture toughness value to yield strength. Regardless of its severity, a specimen size requirement based on a  $K_Q$  value cannot be a sufficient single validity requirement for all  $K_{Ic}$  test results. This requirement has an inherent deficiency which permits specimen dimensions to be undersize by an amount proportional to the difference between the square of the ratio of the plane strain fracture toughness to yield strength and the square of the ratio of the conditional fracture toughness to yield strength.

The test curve linearity requirement gave inconsistent results when applied to the test values obtained in this investigation. In some cases this requirement failed to invalidate 2.4 inch-thick specimen  $K_Q$  values that were low in comparison with those of the 3.9 inch-thick specimens. In other cases the curve linearity requirement was not met when the  $K_Q$  values were comparable to valid results for similar material conditions.

For any specific yield strength level of the 200 grade maraging steel of this investigation, greater plane strain fracture toughness was observed in an overaged condition than in an underaged. Specimen shear lip size was observed to remain reasonably constant as specimen size increased and no relation of shear fraction to test validity was indicated.

It is apparent from this investigation and other current work that refinements of E399-70T are advisable. The results of this investigation provide a basis for future work involving the test validity requirements.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 29).

HANDBOOK OF STRESS-INTENSITY FACTORS FOR RESEARCHERS AND ENGINEERS  
Sih, G. C. (Institute of Fracture and Solid Mechanics, Lehigh University,  
Bethlehem, PA)  
Institute of Fracture and Solid Mechanics (1973)

The objective of this handbook is to compile a catalog of stress-intensity factor solutions. Each problem is clearly stated and illustrated schematically so that the users can extract the necessary information with minimum effort. The numerical solutions are given in tabulated form instead of graphically whenever possible. A complete set of references are also listed for those who wish to know the details of the analysis. The various methods of solution leading to  $K_I$ ,  $K_{II}$  and  $K_{III}$  are also introduced briefly in each section. The first of two volumes includes solutions of straight and circularly shaped cracks in isotropic elasticity. The problem of cracks in plates and shells and anisotropic, composite materials as well as results for other special problems such as dynamic loading of cracked bodies will be reported in the second volume.

Comment:

This handbook provides a ready encyclopedia of solutions for the various crack problems. It is a useful tool for the designer or researcher.

Important References:

1. Sih, G. C., Editor, Methods of Analysis and Solutions to Crack Problems, Noordoff International Publishing, Holland (1973)
2. Brown, Jr., W. F., Review of Developments in Plane Strain Fracture Toughness Testing, ASTM-STP-463 (1970)
3. Sih, G. C., Some Basic Problems in Fracture Mechanics and New Concepts, J. Eng. Fract. Mech. 5, No. 2, 365 (1973)
4. Sih, G. C., A Review of the Three-Dimensional Stress Problem for a Cracked Plate, Int. J. Fract. Mech. 7, No. 1, 39 (1971)
5. Rice, J. R. and Sih, G. C., Plane Problems of Cracks in Dissimilar Materials, J. Appl. Mech. 32, No. 2, 418 (1965)

Key words: Analysis methods; crack analysis; cracks; design criteria; fracture mechanics; linear elastic fracture mechanics; plane strain; plane strain fracture toughness; plane stress; stress analysis; stress intensity factor.

## THE STRESS ANALYSIS OF CRACKS HANDBOOK

Tada, H., Paris, P. C. and Irwin, G. R. (Del Research Corp., Bethlehem, PA)  
(1973)

This handbook is intended to provide a comprehensive source of formulas and stress analysis information on crack problems. The emphasis is on information for treatment of actual problems on crack propagation through fracture mechanics correlation parameters and current fracture criteria, such as  $K_I$  approaching  $K_{IC}$  as a plane strain fracture criterion. The information includes not only current practice, but also embodies other fundamental stress analysis results. For example, where stress functions are known for the complete solution to a crack problem they are either listed or referenced; again, where they are known, functions are listed which may be readily converted to displacements, such as integrals of stress functions. Each numerical solution and approximation method is accompanied by an estimate of the accuracy of the results or the method; moreover, source references are listed in all cases. In addition, sections are devoted to: (a) the theory and useful method of compliance calibration analysis; (b) Green Function analysis for handling certain cases of arbitrary loading; (c) orthotropic, anisotropic and dynamic effects; and (d) plasticity analysis of crack problems, including a discussion of the J-integral methods. Other implications of crack stress analysis (such as to stress concentrations and notch field equations) and related results (such as electric fields in plates with cracks for electrical potential calibration) are given where available.

### Comment:

This handbook of crack stress analysis is a particularly useful tool for those interested in this area as it is an exhaustively complete compilation of solutions. Of particular help is the detailed reference and accuracy statement.

### Important References:

1. Isida, M., On the Determination of Stress Intensity Factors for Some Common Structural Problems, Eng. Fract. Mech. 2, 61 (1970).
2. Isida, M., Effect of Width and Length on Stress Intensity Factors of Internally Cracked Plates Under Various Boundary Conditions, Int. J. Fract. Mech. 7, 301 (1971).
3. Rice, J. R., A Path Independent Integral and the Approximate Analysis of Strain Concentration by Notches and Cracks, J. Appl. Mech. 35, Series E, 379-386 (June 1968).
4. Tada, H., Studies of the Crack Opening Stretch Concept in Application to Several Fracture Problems, PHD Dissertation, Lehigh University (June 1968).
5. Wilson, W. K., Stress Intensity Factors for Deep Cracks in Bending and Compact Tension Specimens, Eng. Fract. Mech. 2, 169 (1970).

Key words: Analysis methods; compliance measurements; crack analysis; cracks; elastic-plastic analysis; J-integral; plane strain; plane stress; statistical analysis; strain; stress; stress analysis; stress concentration; stress intensity factor.

#### STRESS INTENSITY FACTORS FOR CRACKLINE-LOADED EDGE-CRACK SPECIMENS

Srawley, J. E. and Gross, B. (National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH)  
NASA-TN-D-3820 (February 1967)

Crackline-loaded edge-crack specimens are flat plate specimens which have a single crack notch extending normally from one edge and which are loaded in tension at positions close to the intersection of the crack with that edge. These specimens are of interest in fracture mechanics testing because they require comparatively little material and because there are some varieties for which the stress intensity factor  $K$  is almost independent of crack length over a considerable range. Stress intensity factors were determined for a variety of these specimens, all with straight boundaries, by boundary collocation of the Williams form of stress function. The boundary conditions were determined with the aid of another stress function due to filon. The results presented are considered to be comprehensive enough for a wide variety of applications of these specimens. Two complementary types of semi-finite crackline-loaded specimen are treated in detail. The results for these specimens can be used graphically to obtain a useful preliminary estimate of the results for any finite specimen with straight boundaries. Boundary collocation analysis need then be conducted only on those cases which appear to be of most practical interest. The boundary collocation results were used to calculate values of the stress intensity coefficient for a crackline-loaded specimen of nonlinear contour. These values are in excellent agreement with the published experimental compliance data for this specimen configuration.

#### Comment:

The elastic solutions obtained by the authors, employing boundary collocation results are significant in the development of specimen configurations. The appendix on an approximate treatment of crackline-loaded edge-crack specimens as pairs of cantilever beams is important for the analysis of real cases which include boundaried specimens.

#### Important References:

1. Gross, B. and Srawley, J. E., Stress-Intensity Factors by Boundary Collocation for Single-Edge-Notch Specimens Subject to Splitting Forces, NASA-TN-D-3295 (1966).
2. Wilson, W. K., Analytical Determination of Stress Intensity Factors for the Manjoine Brittle Fracture Test Specimen, Report No. WERL-0029-3, Westinghouse Research Laboratories (August 1965).

3. Gross, B. and Srawley, J. E., Stress-Intensity Factors for Single-Edge-Notch Specimens in Bending or Combined Bending and Tension by Boundary Collocation of a Stress Function, NASA-TN-D-2603 (1965).
4. Gross, B., Srawley, J. E. and Brown, Jr., W. F., Stress-Intensity Factors for a Single-Edge-Notch Tension Specimen by Boundary Collocation of a Stress Function, NASA-TN-D-2395 (1964).
5. Gross, B. and Srawley, J. E., Stress-Intensity Factors for Three-Point Bend Specimens by Boundary Collocation, NASA-TN-D-3092 (1965).
6. Paris, P. C., Sih, G. C., Stress Analysis of Cracks, Symposium on Fracture ASTM STP 381, 30-83 (1965).
7. Brown, Jr., W. F. and Srawley, J. E., Current Status of Plane Crack Toughness Testing, ASTM STP 410 (January 1967).
8. Mostovoy, S., Crosley, P. B. and Ripling, E. J., Use of Crackline Loaded Specimens for Measuring Plane Strain Fracture Toughness, J. Mater. 2, 661-681 (1967).

Key words: Compliance measurements; fracture mechanics; fracture tests; stress intensity factor; test specimen design; testing methods.

#### CRACK SHAPES AND STRESS INTENSITY FACTORS FOR EDGE-CRACKED SPECIMENS

Orange, T. W. (National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH)

Stress Analysis and Growth of Cracks, ASTM 513, 71-78 (1972)

A simple stress intensity factor expression is given for a deep edge crack in plate in tension. The shapes of cracks opened by tension or bending are approximated by very simple empirical equations. The magnitude of the crack displacement is a function of applied load, plate geometry, and the elastic constants of the plate material. The shape of a loaded crack in a semi-infinite plate is, approximately, a portion of an ellipse where semimajor axis is about three times the crack length. As the crack length (relative to the plate width) increases, the crack shape becomes parabolic, then hyperbolic, the acuity for the hyperbola increasing with the relative crack length.

#### Comment:

The author has developed a useful simple stress intensity factor that provides a useful approximation for a very common type of service crack. The deep edge crack in tension is very common in aircraft skin stiffened structures.



Important References:

1. Wilson, W. K., Stress Intensity Factors for Deep Cracks in Bending and Compact Tension Specimens, Eng. Fract. Mech. 2, 169-171 (1970).
2. Gross, B., Srawley, J. E. and Brown, Jr., W. F., Stress-Intensity Factors for a Single-Edge-Notch Tension Specimen by Boundary Collocation of a Stress Function, NASA-TN-D-2395 (1964).
3. Gross, B., Some Plane Problem Elastostatic Solutions for Plates Having a V-Notch, PhD Thesis, Case Western Reserve University, Cleveland, OH (1970).
4. Gross, B., Roberts, Jr., E. and Srawley, J. E., Elastic Displacements for Various Edge-Cracked Plate Specimens, Int. J. Fract. Mech. 4, 267-276 (1968).
5. Brown, Jr., W. F. and Srawley, J. E., Plane Strain Crack Toughness Testing of High Strength Metallic Materials, ASTM STP 410 (1966).

Key words: Bending loads; crack analysis; crack opening displacement; cracks; elastic properties; geometric effects; stress intensity factor; tensile stress

THE EFFECT OF PLASTICITY AND CRACK BLUNTING ON THE STRESS DISTRIBUTION IN ORTHOTROPIC COMPOSITE MATERIALS

Tirosh, J. (Technion - Israel Inst. of Tech., Haifa, Israel)  
J. Appl. Mech., Trans. ASME, 785-790 (September 1973)

A detailed study of the plasticity and crack-tip blunting effects on tough materials with rectilinear anisotropy is presented. The most important results are the prediction of the extent of plastic zone and the nature of stress distribution produced by the blunting effect in the tensile mode. The analysis was confirmed experimentally and numerically (finite-element method) on a unidirectional fiber-reinforced composite.

1. The length of the plastic zone in rectilinear anisotropic material is formulated in terms of its pertinent parameters, with the aid of a path-independent integral. The expression has fundamentally the same structure as the familiar solution derived from the antiplane shear mode, and agrees well with experimental and numerical results (finite-element methods).

2. The stress distribution is derived from a mathematical model which simulates the experimentally observed situation, i.e., the yield zone is a narrow rectilinear strip perpendicular to the crack which transfers a uniform shear traction to the bulk (uncracked) material ahead of the notch. As a result, the elastic tensile stress ahead of a blunted crack obeys a log (1/r) distribution preceded by local stress reduction of known magnitude. The toughening effect of the blunting manifests itself in these circumstances.

3. The transverse stress, markedly different from the isotropic biaxial stress situation ahead of the crack, is much smaller than its longitudinal counterpart (in the present case by two orders of magnitude) and reaches maximum some distance ahead of the crack. This information casts light on the conditions promoting delamination (fiber/matrix debonding) and/or transverse interlaminar crack propagation.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 46).

#### COMPLIANCE MEASUREMENTS

Bubsey, R. T., Fisher, D. M., Jones, M. H. and Srawley, J. E. (National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH) Society for Experimental Stress Analysis, Monograph Series, No. 1, Exp. Tech. in Fract. Mech., 76-95 (1973)

The experimental method of compliance calibration can be applied to certain quasi-two-dimensional configurations, such as plate or bar specimens, to obtain a relation for the crack-extension force (or fixed-grip strain-energy release rate with crack extension) in terms of load, specimen dimensions, and elastic constants. The method is generally less precise than refined methods of numerical analysis, but it has the advantage that the boundary conditions of load application can be (and should be) practically the same as those which will be used in applications of the specimen to the testing of materials. Numerical methods of analysis suffer from the necessity of simplification of boundary conditions in order that the problem shall be traceable. It is always desirable to obtain and compare results by both the compliance method and a numerical method because their advantages are complementary. The measurement precision needed to obtain good results by the compliance method is no less than that needed for Young's modulus because it is obtained from the direct measurements by differentiation with respect to crack length, which produces a relative error of an order greater than that in the primary data.

#### Comment:

This chapter in the monograph on experimental techniques is an excellent introduction to compliance techniques. It adequately explains the purpose and practice of compliance measurement. In addition, several common specimen configurations are treated in detail.

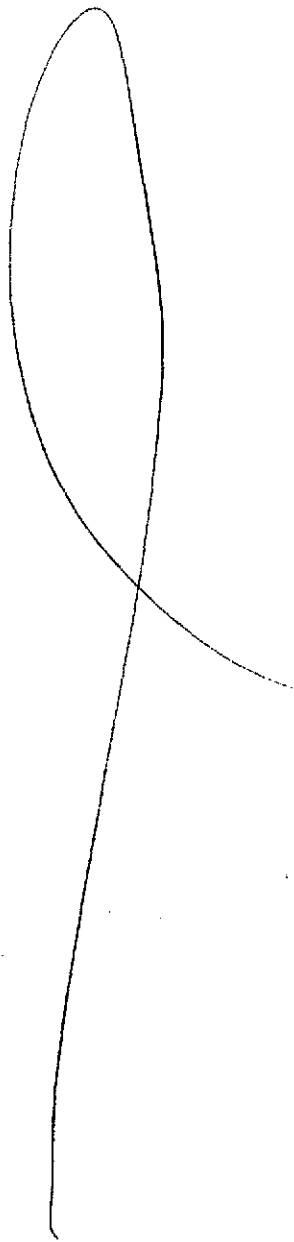
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2. Gross, B. and Srawley, J. E., Stress-Intensity Factors for Single-Edge-Notch Specimens in Bending or Combined Bending and Tension by Boundary Collocation of a Stress Function, NASA-TN-D-3820 (1967).
3. Roberts, Jr., E., Elastic Crack-Edge Displacements for the Compact Tension Specimen, Mater. Res. Stand. 9, No. 2, 27 (1969).
4. Gross, B. and Srawley, J. E., Stress-Intensity Factors by Boundary Collocation for Single-Edge-Notch Specimens Subject to Splitting Forces, NASA-TN-D-3295 (1966).
5. Srawley, J. E. and Gross, B., Stress-Intensity Factors for Crackline-Loaded Edge-Crack Specimens, NASA TN-D-3820 (1967).
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7. Paris, P. C. and Sih, G. C., Stress Analysis of Cracks, Fracture Toughness Testing and Its Applications, ASTM STP 381 (1965).
8. Gross, B. and Srawley, J. E., Stress-Intensity Factors for Three-Point Bend Specimens by Boundary Collocations, NASA TN-D-3092 (1965).

Key words: Compact tension specimens; compliance measurements; fracture mechanics; fracture strength; stress intensity factor.

## VI. CRACK TIP PLASTIC ZONE



## VIA. Fatigue Precracking

### INFLUENCE OF STRESS INTENSITY LEVEL DURING FATIGUE PRECRACKING ON RESULTS OF PLANE-STRAIN FRACTURE TOUGHNESS TESTS

Kaufman, J. G. and Schilling, P. E., (Aluminum Co. of America, New Kensington, PA)  
Progress in Flaw Growth and Fracture Toughness Testing, ASTM STP 536, 312-319  
(July 1973)

One of the more troublesome parts of conducting a plane strain fracture toughness test in accordance with ASTM test for plane strain fracture toughness of metallic materials (E 399-72) is producing a satisfactory fatigue crack in the specimen prior to fracturing it. The 1968 version of ASTM E 399 indicated that the stress intensity during the last stage of fatigue cracking should not exceed 0.0012 in.  $1/2 E$  (Modulus of Elasticity) or  $0.5 K_{IC}$ , but that has been gradually eased so that the current limits are 0.002 in.  $1/2 E$  or  $0.6 K_{IC}$ . Data for four aluminum alloys support the fact that it is satisfactory to use stress intensities up to 0.002 in.  $1/2 E$  and suggest that the other limit could be increased to 80 percent of  $K_{IC}$ . This may be unique to aluminum alloys and additional data should be generated for other metals to determine whether or not this is generally true.

#### Comment:

The author's careful experimental effort indicates that the ASTM standard E 399-72 may in some areas be unnecessarily conservative for certain aluminum alloys. These results should not be considered as indicating that the final fatigue crack stress intensity requirements should be relaxed, for as the author indicates much more detailed and broader based experimental effort would be required.

#### Important References:

1. Brown, Jr., W. F. and Srawley, J. E., Plane Strain Crack Toughness Testing of High Strength Metallic Materials, ASTM STP 410 (December 1967).
2. May, M. J., British Experience with Plane Strain Fracture Toughness ( $K_{IC}$ ) Testing, ASTM STP 463, 42-61 (September 1970).
3. Brown, Jr., W. F. and Srawley, J. E., Commentary on Present Practice, ASTM STP 463, 216-248 (September 1970).

Key words: Aluminum alloys; compact tension specimens; crack initiation; crack propagation; cyclic loads; fatigue tests; fracture mechanics; fracture strength; fracture tests; fractures (materials); plane strain fracture toughness; stress intensity factor.

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THE INFLUENCE OF SPECIMEN GEOMETRY ON CRACK TIP PLASTICITY  
Pettit, D. E. and Hoeppe, D. W. (Lockheed-California Co., Burbank)  
Lockheed-California Report No. LR-25318 (June 1972)

The effect of panel width and thickness on the crack tip plasticity of center-cracked fracture panels of 7075-T6 aluminum alloy was examined. The plastic zone formation was continually monitored photographically during the fracture test and the zone size and shape determined by an image distortion technique. The influence of specimen width and thickness was examined to determine its effect on the plastic zone behavior and the mode (stable tear or pop-in) of initial crack extension. Plastic zone models were then compared with the characteristic plastic zone size parameters measured experimentally and the models evaluated. From these results, the effect of panel thickness and geometry on the characteristics of crack tip plasticity and initial crack extension was assessed. The effects of these findings on methods of evaluating material toughness are examined. The applicability of these zone size models in linear elastic fracture mechanics applications are discussed.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS, AND A DUPLICATE ABSTRACT, SEE PAGE 81).

## VIB. Steady Load Slow Crack Growth

THE STRESS INTENSITIES FOR SLOW CRACK GROWTH IN STEELS CONTAINING HYDROGEN  
Dautovich, D. P. and Floreen, S. (International Nickel Co., Inc., NY)  
Met. Trans. 4, 2627-2630 (Nov. 1973)

A test technique has been developed to determine the stress intensity for slow crack growth in hydrogen precharged steels. Measurements on several grades of maraging steel and a 300M steel show that hydrogen contents on the order of 2 ppm reduce the stress intensity for slow crack growth by 50 percent or more of the  $K_{IC}$  values. At equivalent hydrogen contents the 300M steel was more severely embrittled than the maraging steels. Comparison of the present results with aqueous  $K_{ISCC}$  data indicates that the amount of hydrogen picked up by the steels in stress corrosion increases with increasing yield strength.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS, AND A DUPLICATE ABSTRACT, SEE PAGE 110).

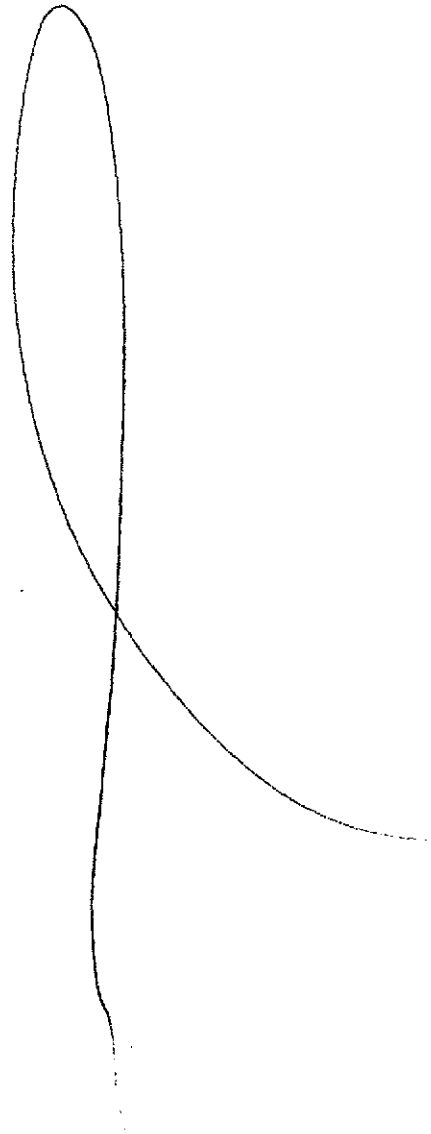
## MEASURING FRACTURE TOUGHNESS - A SIMPLIFIED APPROACH USING CONTROLLED CRACK PROPAGATION

Weitzmann, R. H. and Finnie, I. (Space Science, Inc., Monrovia, CA; California University, Berkely).  
J. Mater. 7, No. 3, 294-298 (September 1972)

During the loading cycle of the conventional fracture toughness test, the point of load application remains fixed with respect to specimen geometry except for small displacements in-line with the applied load. By contrast, in the present method, the point of load application advances toward the crack-front during the loading cycle in a path parallel to the plane of the crack. Since displacement is the controlled variable, it is thus possible to obtain a continuous functional relationship between load and crack length. It is shown that this relationship is directly relatable to the strain energy release rate on crack advance. The concept reduces the complexity of fracture toughness testing to a level comparable to a conventional tension test, that is, recording of load and displacement. Characteristic features of the method are very stable crack propagation, efficient use of test material, and the ability to measure toughness gradients. Results of applying the concept to a 7075-T6 aluminum alloy are presented.

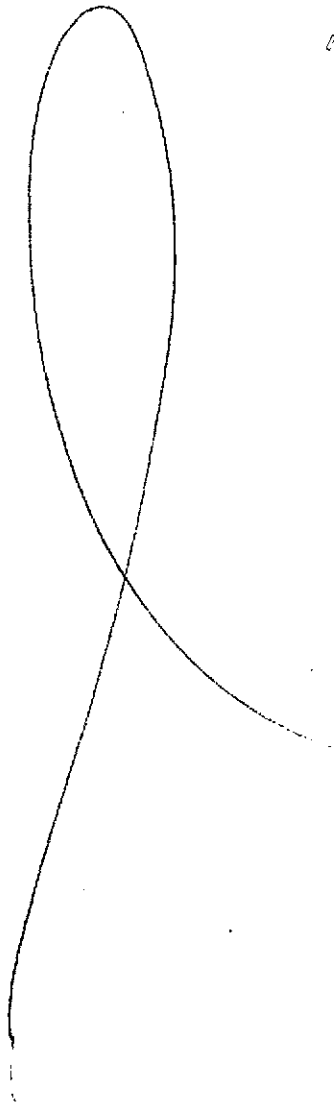
(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS, AND A DUPLICATE ABSTRACT, SEE PAGE 85).





VII. ENVIRONMENTAL EFFECTS ON CRACK GROWTH

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## VIIA. PRECRACKED STRESS CORROSION CRACKING

### SOME IMPORTANT CONSIDERATIONS IN THE DEVELOPMENT OF STRESS CORROSION CRACKING TEST METHODS

Wei, R. P., Novak, S. R. and Williams, D. P. (Lehigh Univ., Bethlehem, PA, United States Steel Corp., Monroeville, PA, National Aeronautics and Space Administration, Ames Research Center, Moffett Field, CA) NASA-TM-X-68303 (January 1972)

The need for recognizing certain potentially serious problems in the development of standard test methods for stress corrosion cracking studies is discussed. To obtain valid data from fracture mechanics based test methods, the basic assumptions of the linear-elastic fracture mechanics analyses must be clearly recognized and satisfied in experimentation. The effects of incubation and non-steady-state crack growth must be taken into account in determining the crack growth kinetics. These effects and the influences of steady-state crack growth kinetics as well as a host of geometrical, material and environmental variables, must be considered in arriving at suitable criteria for  $K_{ISCC}$  determination.

#### Comment:

The authors have performed a valuable service in experimentally demonstrating the difficulties associated with specifying the standardization criteria for  $K_{ISCC}$  testing. They show for example that the apparent  $K_{ISCC}$  can vary depending only on the elapsed time of the test from 170 ksi  $\sqrt{\text{in}}$  at 10 hours to 25 ksi  $\sqrt{\text{in}}$  for a 10,000 hour test. In addition it is demonstrated that effective standardization of a  $K_{ISCC}$  test employing present specimens and techniques would provide only relative values at best.

#### Important References:

1. Smith, H. R., Piper, D. E. and Downey, F. K., A Study of Stress-Corrosion Cracking by Wedge-Force Loading, Eng. Fract. Mech. 1, No. 1, 123-128, (June 1968)
2. Novak, S. R. and Rolfe, S. T., Comparison of Fracture Mechanics and Nominal Stress Analyses in Stress Corrosion Cracking, Corrosion, 26, No. 4, 121-130 (April 1970)
3. Smith, H. R. and Piper, D. E., Stress Corrosion Testing with Precracked Specimens, Boeing Document D6-24872 (June 1970)
4. Carter, C. S., Effect of Prestressing on the Stress-Corrosion Resistance of Two High-Strength Steels, Boeing Document D6-25275, (May 1970)

Key words: Crack propagation; cracking (fracturing); fracture mechanics; stress corrosion; testing methods.

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## MODIFIED WOL SPECIMEN FOR $K_{ISCC}$ ENVIRONMENTAL TESTING

Novak, S. R. and Rolfe, S. T. (United States Steel Corp., Monroeville, PA)  
Mater. 4, No. 3, 701-728 (September 1969)

Because structures that are loaded in hostile environments may contain small flaws, the most significant method for quantitatively analyzing materials for use in critical structural applications is the fracture mechanics approach. The most widely used fracture mechanics specimen is the precracked cantilever beam specimen. By dead-weight loading such specimens in the environment of interest and recording the time-to-failure, the plane strain stress intensity threshold,  $K_{ISCC}$ , can be determined. The  $K_{ISCC}$  value of a material describes the stress, crack-size threshold below which subcritical cracks (SCC) do not extend to a critical size in a particular environment. To eliminate the need for the larger testing fixtures required with dead-weight-loaded cantilever-beam specimens, as to reduce the number of specimens required to determine a  $K_{ISCC}$  value, the wedge-opening-loading (WOL) fracture specimen was investigated to develop a precracked, self-stressed, portable specimen for determining  $K_{ISCC}$  values. The results show that a modified WOL specimen can be used successfully for  $K_{ISCC}$  environmental testing. In addition, techniques for testing and a compliance calibration for accurately measuring crack growth rates without the necessity of specimen unloading are established. Because the specimen is self-stressed with a bolt, the loading is constant displacement, so that the  $K_I$  value decreases from the initial value to  $K_{ISCC}$  as the crack propagates. Thus, the  $K_{ISCC}$  for a given material and environment can be established with a single specimen at considerably less expense than with a constant load technique. Furthermore, because the modified WOL specimen is self-stressed and portable, it can be easily used in many environments that are normally difficult to test in. To compare the  $K_{ISCC}$  values obtained with cantilever-beam and modified WOL specimens, two 12Ni-5Cr - 3Mo steels were tested. The  $K_{ISCC}$  values obtained with the two types of specimens were essentially identical and showed the invariant nature of  $K_{ISCC}$  for a particular material and environment.

The modified WOL specimen should serve as a useful tool for the research metallurgist concerned with developing alloys that are resistant to environmental subcritical cracking, as well as for the design engineer concerned with material selection.

### Important References:

1. Brown, B.F. and Beacham, C.D., A Study of the Stress Factor in Corrosion Cracking by Use of the Precracked Cantilever-Beam Specimen, Corros. Sci. 5, 745-750 (1965)
2. Brown, B.F., A New Stress-Corrosion Cracking Test for High-Strength Alloys, Mater. Res. Stand. 6, No. 3, 129-133 (March 1966)
3. Wessel, E. T., State of the Art of the WOL Specimen for  $K_{IC}$  Fracture Toughness Testing, Eng. Fract. Mech. 1, No. 1, 77-103 (June 1968)
4. Clark, Jr., W. G., Ultrasonic Detection of Crack Extension in the WOL Type Fracture Toughness Specimen, Mater. Eval. 25, No. 8 (August 1967)

6. Gross, B. and Srawley, J. E., Stress Intensity Factors by Boundary Collocation for Single-Edge-Notch Specimens Subject to Splitting Forces, NASA-TD-3295 (February 1966)

Keywords: Compact tension specimens; compliance measurements; environmental tests; fracture mechanics; fracture strength; NDE; plane strain fracture toughness; steels; stress corrosion; stress intensity factor; subcritical crack growth; test specimen design; testing methods; wedge loaded specimens

#### THE APPLICATION OF FRACTURE MECHANICS TO STRESS-CORROSION CRACKING

Brown, B. F., (Naval Research Lab., Washington, DC)  
Metals Mater. 2, No. 12, 171-183 (1968)

The interacting roles of stress corrosion cracking and fracture mechanics are discussed. The interrelationships between the stress intensity factor, specimen geometry and the plastic zone are examined in detail. The response to stress corrosion is characterized in terms of the apparent threshold stress, kinetics of crack growth, methods of measurement and morphology of stress corrosion cracks. A brief discussion of the translation of laboratory data to service, highlights the difficulty of predicting this type of behavior. It is shown that the most useful design parameter is  $a_{CR}$  which is the depth of the shallowest crack expected to propagate a stress corrosion crack.

#### Comment:

This comprehensive review serves not only to discuss the development of the technology but to indicate the areas for future effort. Among these have been the development of more reliable and reproducible test techniques and particularly important the improvement required in the translation of laboratory data to service.

#### Important references:

1. Brown, Jr., W. F. and Srawley, J. E., Plane Strain Crack Toughness Testing of High Strength Metallic Materials, ASTM 410 (December 1967)
2. Smith, H. R., Piper, D. E. and Downey, F. K., A Study of Stress Corrosion Cracking by Wedge Force Loading, Document D6-19768, The Boeing Co. (1967).
3. Fisher, D. M., Busbey, R. T. and Srawley, J. E., Design and Use of Displacement Gage for Crack Extension Measurement NASA-TN-D-3724 (November 1966)
4. Brown, B. F. and Beachem, C. D., Study of Stress Factor in Corrosion Cracking by Use of Precracked Contilever Beam Specimen Corros. Sci., 5, 745 (1965)

6. Goode, R. J., Huber, R. W., Howe, D. G., Judy, Jr., R. W., Crooker, T. W., Lange, E. A., Freed, C. N. and Puzak, P. P., High Strength Structural Materials, NRL Rep. 6607 (1967)
7. Irwin, G. R. and Wells, A. A., Continuum-Mechanics View of Crack Propagation, Met. Rev. 10, No. 38, 223-270 (1965)

Key words: Analysis methods; crack detection; crack tip plastic zone; critical flaw size; environmental tests; fracture strength; fractures (materials); NDE; stress corrosion; stress intensity factor; testing methods.

#### STRESS CORROSION CRACKING OF A HIGH STRENGTH STEEL

Sheinker, A. A. and Wood, J. D. (Lehigh Univ., Bethlehem, Pa.)  
ASTM STP 518, 16-38 (September 1972)

Stress corrosion crack growth rates as a function of stress intensity factor were determined over a wide range of electrode potentials for AISI 4340 steel in deaired 3.5% NaCl solution buffered to Ph 3.8. Particular emphasis was placed on conducting the stress corrosion tests under well defined electrochemical and mechanical conditions. At intermediate K levels, crack growth rate was essentially independent of K, suggesting that crack growth is limited by mass transport. Crack growth is apparently dominated by localized mechanical rupturing at high K levels, where crack growth rate increased rapidly with increasing K. Except at very cathodic potential, crack growth rate at intermediate K levels was also independent of potential, implying that the electrochemical conditions at the tip of the stress corrosion crack are not the same as those outside the crack. The tendency for the stress corrosion cracks to branch was found to be electrochemically, as well as mechanically controlled.

#### Important References:

1. Brown, Jr., W. F. and Srawley, J. E., Plane Strain Crack Toughness Testing of High Strength Metallic Materials, ASTM STP 410 (1967)

Key words: Bend tests; crack growth rate; crack initiation; crack propagation; high strength; hydrogen embrittlement; plastic deformation; pre-cracked specimens; steels; stress corrosion; stress intensity factor.

## VIIB. HYDROGEN

### INFLUENCE OF GASEOUS HYDROGEN ON METALS-FINAL REPORT

Walter, R. J. and Chandler, W. T. (Rocketdyne, Canoga Park, CA)  
NASA-CR-124410 (1973)

Tensile, fracture toughness ( $K_{IC}$ ), threshold stress intensity for sustained-load crack growth ( $K_{TH}$ ), and cyclic and sustained-load crack growth rate measurements were performed on a number of alloys in high pressure hydrogen and helium environments to provide design data and safe operating parameters for rocket engine components and test facilities, and data relative to high-pressure hydrogen storage bottles. Tensile tests under a stress of  $34.5 \text{ MN/m}^2$  and at ambient and  $144^\circ\text{K}$  indicated that some alloys were more affected by hydrogen at room temperature while others were more affected at low temperature.

#### Important References:

1. Walter, R. J. and Chandler, W. T., Effect of High-Pressure Hydrogen on Metals, presented at 1968 Materials Engineering Congress, Detroit, Mich., ASM Report D8-14 (October 1968)
2. Walter, R. J. and Chandler, W. T., Effect of High-Pressure Hydrogen on Storage Vessel Materials, Presented at WESTEC Conf., Los Angeles, ASM Report W8-2.4 (March 1968)
3. Steinman, J. B., Van Ness, H. C. and Ansell, G. S., The Effect of High-Pressure Hydrogen Upon the Notch Tensile Strength and Fracture Mode of 4140 Steel, Welding J., 2215-2245 (May 1965)
4. Benson, Jr., R. B., Dann, R. K. and Roberts, Jr., L. W., Hydrogen Embrittlement of Stainless Steel, Trans AIME 242, page 2199 (1968)
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6. Lorenz, P. M., Effect of Pressurized Hydrogen Upon Inconel 718 and 2219 Aluminum, Presented at WESTEC Conf., Los Angeles, CA., ASM Report W9-13.2 (March 1969)

Key words: Aluminum alloys; compact tension specimens; crack growth rate; crack propagation; cyclic loads; data; environmental effects; fracture mechanics; fracture strength; high strength; hydrogen embrittlement; mechanical properties; metallic materials; notched specimens; steels; stress intensity factor; structural safety; tensile properties; titanium alloys; wedge loaded specimens.



THE STRESS INTENSITIES FOR SLOW CRACK GROWTH IN STEELS CONTAINING HYDROGEN  
Dautovich, D. P. and Floreen, S. (International Nickel Co., Inc., NY)  
Met. Trans. 4, 2627-2630 (November 1973)

A test technique has been developed to determine the stress intensity for slow crack growth in hydrogen precharged steels. Measurements on several grades of maraging steel and a 300M steel show that hydrogen contents on the order of 2 ppm reduce the stress intensity for slow crack growth by 50 percent or more of the  $K_{IC}$  values. At equivalent hydrogen contents the 300M steel was more severely embrittled than the maraging steels. Comparison of the present results with aqueous  $K_{ISCC}$  data indicates that the amount of hydrogen picked up by the steels in stress corrosion increases with increasing yield strength.

Comment:

The authors have identified that relationships exist between stress intensity, slow crack growth, yield strength and hydrogen. These appear to be significant, however, more experimental effort will be required before the full role of hydrogen in this area can be illuminated.

Important references:

1. Smith, J. A., Peterson, M. H. and Brown, B. F., Electrochemical Conditions at the Tip of an Advancing Stress Corrosion Crack in AISI 4340 Steel, *Corrosion* 20 539 (1970)
2. Sandoz, G., Unified Theory for Some Effects of Hydrogen Source, Alloying Elements, and Potential on Crack Growth in Martensitic AISI 4340 Steel, *Met. Trans.* 3, 1169-1176 (May 1972)
3. Beachem, C. D., New Models for Hydrogen Assisted Cracking (Hydrogen "Embrittlement"), *Met. Trans.* 3, No. 2, 1055 (1970)
4. Sandoz, G., *Met. Trans.* 2, 1055 (1970)
5. Brown, B. F., The Application of Fracture Mechanics to Stress Corrosion Cracking, *Metals Mater.* 2, No. 12, 171-183 (1968)

Key words: High strength alloys; hydrogen embrittlement; stress corrosion; stress intensity factor; subcritical crack growth.

## STEELS FOR SEAMLESS HYDROGEN PRESSURE VESSELS

Loginow, A. W. and Phelps, E. H. (United States Steel Corp., Monroeville, PA)  
Presented at Materials Symp. 1974 Petroleum Mechanical Eng. Conf., Dallas,  
TX (14-18 September 1974)

To provide engineering data useful in the design, manufacture, and operation of seamless pressure vessels, extensive tests have been conducted in hydrogen at pressures ranging from 21 to 97 MN/m<sup>2</sup> with precracked specimens of steels having a wide range of mechanical properties. The critical stress intensity level at which crack propagation spontaneously arrests,  $K_{IH}$ , was determined. The values of  $K_{IH}$  were used in an illustrative calculation to estimate the critical flaw size at which hydrogen crack propagation would be expected in thick members loaded in bending. In general, the susceptibility of steels tested increased with yield strength. For the steels with intermediate yield strengths (586 to 779 MN/m<sup>2</sup>),  $K_{IH}$  tended to decrease as pressure was increased from 21 to 97 MN/m<sup>2</sup>. The crack path was analyzed, and a sequence of events is described involving the initiation, growth, and arrest of cracking induced by gaseous hydrogen.

### Important References:

1. Walter, R. J. and Chandler, W. T., Influence of Gaseous Hydrogen on Metals, NASA-CR-124410 (October 1973)
2. Johnson, H. H., On Hydrogen Brittleness in High Strength Steels, Fundamental Aspects of Stress Corrosion Cracking, Nat'l. Assoc. Corrosion Engineers, Houston, TX (1969)
3. Williams, D. P. and Nelson, H. G., Kinetics of Slow Crack Growth and Gas Permeation of 4130 Steel in Gaseous Hydrogen, Presented at Symp. Effect of Gaseous Hydrogen on Metals, 1968 Mater. Eng. Cong., Detroit, MI (1968)
4. Oriani, R. A. and Josephic, P. H., Testing of the Decohesion Theory of Hydrogen-Induced Crack Propagation, Scr. Met. 6, 681 (1972)
5. Novak, S. R. and Rolfe, S. T., Modified WOL Specimen for  $K_{ISCC}$  Environment Testing, J. Mater. 4, No. 3, 701-728 (1969)
6. Wilson, W. K., Stress-Intensity Factors for Deep Cracks in Bending and Compact Tension Specimens, Eng. Fract. Mech. 2, No. 2, 169-172 (November 1970)

Key words: Crack propagation; cracks; critical flaw size; data; fracture mechanics; fracture strength; high strength; hydrogen embrittlement; mechanical properties; pre-cracked specimens; pressure vessels; steels; stress intensity factor; wedge loaded specimens.

## FRACTURE MECHANICS CONSIDERATION OF HYDROGEN SULFIDE CRACKING IN HIGH STRENGTH STEELS

Bucci, R. J., Paris, P. C., Loushin, L. L. and Johnson, H. H., (Del Research Corp., Bethlehem, PA, Esso Research and Engineering Co., Linden, NJ, Cornell Univ., Ithaca, NY.)

Stress Analysis and Growth of Crack, ASTM STP 513, 292-307 (September 1972)

Hydrogen sulfide (H<sub>2</sub>S) stress corrosion cracking studies were conducted within the framework of fracture mechanics for several high strength steels (AISI 4340, 4140, HY-80 and HY-130). For all the steels and strength levels investigated ( $\sigma_{ys}$  = 80 to 150 ksi), H<sub>2</sub>S stress corrosion cracking was found to exist. For each of the alloys investigated, a valid plane strain  $K_{ISCC}$  (which indicates the demarcation between detectable rates of crack extension,  $\Delta a/\Delta t \geq 10^{-5}$  in./min. and those below these rates) was measured and found to depend significantly on yield stress with decreasing  $K_{ISCC}$  values reported for increasing yield stress.

A limited investigation of crack growth kinetics found crack growth rates to accelerate most rapidly from presharpended fatigue cracks when loaded to  $K$  levels just beyond the  $K_{ISCC}$  threshold. In several instances, especially with the highest strength alloys, stress corrosion crack velocities attained peak values before being "damped" to some steady state velocity at increased  $K$  levels. The crack velocity damping might in part be attributed to crack division or plasticity effects associated with increasing plastic zone size to thickness ratio at higher  $K$  levels.

### Comment:

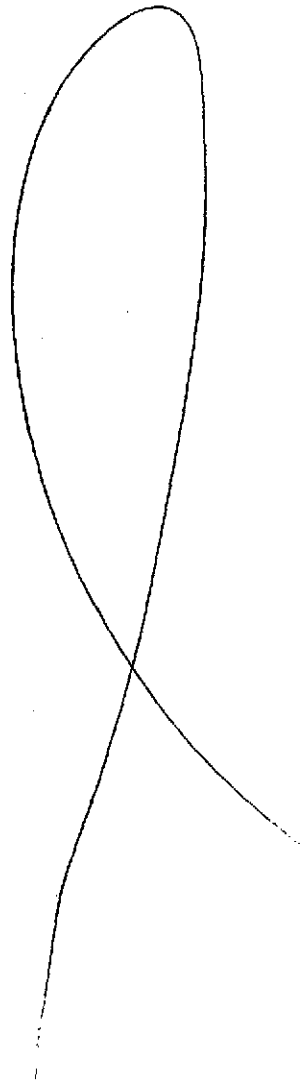
These fracture toughness measurements in the aggressive hydrogen sulfide environment illustrate the usefulness of the fracture mechanics approach. As with most determinations of  $K_{ISCC}$  the accuracy of the value is related to the time of exposure; thus presenting problems in relating one alloy to another, nevertheless, the trends and relationships observed are valid.

### Important references:

1. Dvoracek, L. M., Sulfide Stress Corrosion Cracking of Steels, *Corrosion* 26, No. 5, 177-188 (May 1970)
2. Novak, S. R. and Rolfe, S.T., Comparison of Fracture Mechanics and Nominal Stress Analysis in Stress Corrosion Cracking, *Corrosion* 26, No. 4, 121-130 (April 1970)
3. Wessel, E. T., State of the Art of the WOL Specimen for  $K_{IC}$  Fracture Toughness Testing, *Eng. Fract. Mech.* 1, No. 1, 77-103 (June 1968)
4. Gallagher, J. P. Corrosion Fatigue Crack Growth Behavior Above and Below  $K_{ISCC}$ , NRL Report 7064 (May 28, 1970)

Key words: Crack initiation; fracture mechanics; fractures (materials); high strength alloys; hydrogen embrittlement; stress corrosion.

## VIII. PREDICTION TECHNIQUES



## VIIIA. PLANE STRAIN FRACTURE TOUGHNESS

PLANE STRAIN FRACTURE TOUGHNESS OF HIGH STRENGTH MATERIALS  
Steigerwald, E. A., (TRW Equipment Lab., Cleveland, OH)  
Eng. Fract. Mech. 1, No. 3, 473-494 (1969)

An experimental program was conducted to determine the plane strain fracture toughness ( $K_{IC}$ ) of the following classes of high strength materials: (1) AISI alloy steels (4340, 4140); (2) 5Cr-Mo-V steels; (3) Precipitation-hardened stainless steels (17-7PH, PH15-7Mo, 17-4PH, AM355); (4) Titanium alloy, Ti-6Al-4V. The precracked notched bend test was used as the test method and several heats of each material were evaluated over a range of temperatures from -100 to +200°F. The  $K_{IC}$  values, obtained under conditions which were believed to provide valid plane strain fracture toughness numbers, were plotted both as a function of material strength and test temperature. The resulting curves provide representative  $K_{IC}$  figures which can aid in the selecting of materials for reliable performance.

The low temperature data indicate that the decrease in  $K_{IC}$  that occurs with decreasing temperature cannot be accounted for solely on the basis of the increase in yield or tensile strength.

The data for the materials evaluated were combined with the limited  $K_{IC}$  data available in the literature to produce representative curves of  $K_{IC}$  as a function of both tensile strength level and test temperature. Although typical fracture toughness values are given which can aid in designing and selecting conditions to preclude brittle fracture, the inherent variability in the  $K_{IC}$  value as a function of heat of material must receive adequate consideration. The scatter between heats can be as great as 30 percent and the material used for a specific design should be evaluated prior to use to insure that abnormally low fracture toughness does not exist.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 32).

CORRELATION OF PLANE STRAIN CRACK TOUGHNESS WITH STRAIN HARDENING CHARACTERISTICS OF A LOW, A MEDIUM, AND A HIGH STRENGTH STEEL  
Krafft, J. M. (Naval Research Lab., Washington, DC)  
Appl. Mater. Res. 1, No. 1, 88-101 (April 1964)

The increase in true stress resulting from strain hardening can often be closely represented by raising the true strain to a power  $N$ , a positive number usually less than unity. Observations indicate the controlling influence of the strain hardening characteristics on the fracture process. A consistent interpretation of results is provided by assuming that the plane strain crack will

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become unstable when the crack tip stress field causes tensile strain equal to that for plastic flow instability in the material, a small, fixed distance in advance of the crack tip. The strain hardening characteristics determinative of the instability strain are those specific to conditions of strain rate and temperature calculated to exist at this fixed distance from the crack. This distance appears to be a constant for a given material over a large range of loading rate and temperature. It is the purpose of this paper to describe the evidence leading to this result, considering in turn: the tests for plane strain fracture toughness with the description of the strain field; tests for plastic flow properties, particularly of strain hardening characteristics with the effect of adiabaticity; apparatus for testing both fracture and flow specimens over a wide range of straining speeds and temperature; the correlation between these tests; and implications of the result.

Comment:

The author has experimentally investigated this relationship between plane strain crack toughness and strain hardening characteristics by employing controlled strain rate testing. His characterization of plastic zone sizes has been employed in the development of further understanding of this plasticity influence in other than ideal plane strain conditions.

Important References:

1. Irwin, G. R. Structural Mechanics, Pergamon, Oxford, 557 (1960).
2. Krafft, J. M., Bird, F. W. and Hahn, J.C., Report of NRL Progress, 24 (August 1962).
3. Krafft, J. M., and Sullivan, A. M., Effects of Speed and Temperature on Crack Toughness and Yield Strength in Mild Steel; Trans. ASM 56, 160-175 (1963).

Key words: Analysis methods; fractures (materials); plane strain; steels; strain hardening.

SOURCES OF FRACTURE TOUGHNESS: THE RELATION BETWEEN  $K_{IC}$  AND THE ORDINARY TENSILE PROPERTIES OF METALS  
Rosenfield, A. R. and Hahn, G. T. (Battelle Columbus Labs, OH)  
ASTM STP 432, 5-31 (1968)

Crack extension from a metallurgical standpoint is examined. Stress and strain intensification at the crack tip and the basic flow and fracture properties of the material are considered. Insights derived from etch-pitting experiments are reviewed. These reveal the two characteristic types of local yielding:

1. Plane strain or hinge-type relaxation
2. Plane stress or through-the-thickness relaxation.

Two simplified elastic-plastic treatments that model plane strain and plane stress are identified. A method of relating the crack-tip displacement to the peak strain is described and this is combined with a critical strain criterion for ductile fracture. In this way the plane strain fracture toughness parameter is formulated in terms of ordinary tensile properties.

Important References:

1. Brown, Jr., W. F. and Srawley, J. E. Current Status of Plane Crack Toughness Testing, NASA-TM-X-52209, (June 29, 1966).
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Keywords: Crack opening displacement; crack tip plastic zone; ductility; fracture strength; metallic materials; plane strain; plane strain fracture toughness; plane stress; plastic zone; strain hardening; stress intensity factor; tensile properties; yield strength.

RELATIONSHIP BETWEEN  $K_{IC}$  AND PLANE-STRAIN TENSILE DUCTILITY AND MICROSCOPIC MODE OF FRACTURE

Barsom, J. M. and Pellegrino, J. V., (United States Steel Corp., Monroeville, PA) Eng. Fract. Mech. 5, No. 2, 209-221 (1973)

In most structural steels, the critical plane-strain stress-intensity factor,  $K_{IC}$ , increases markedly with increasing test temperature. Because of this transition behavior with temperature and the inherently high fracture toughness of many steels, very thick specimens must be tested to determine valid  $K_{IC}$  values. The large size of these specimens and the cost of conducting the tests minimize the usefulness of this procedure as a research tool for analyzing the fracture behavior of steels under plane-strain conditions. Therefore, as part of a long-range program to obtain  $K_{IC}$  values from small specimens and to extend linear elastic fracture mechanics to the region of elastic-plastic fracture mechanics, the Research Laboratory investigated the relationship between  $K_{IC}$  and ordinary tensile material properties for four steels ranging in yield strength from 80 to 250 ksi (552-1720 MN/m<sup>2</sup>).



The results showed that, for these steels, the variation of  $K_{IC}$  with temperature was similar to the variation of the plane-strain tensile ductility with temperature. Scanning electron micrographs showed that the increase in the plane-strain stress-intensity factor for unstable crack extension,  $K_{IC}$ , with increasing temperature could be related to changes in the microscopic mode of fracture at the crack tip. That is, at temperatures below the fracture-toughness transition temperature, the mode of fracture was cleavage, whereas at temperatures well above the transition-temperature region, the fracture mode was ductile tear. In the transition-temperature region, a gradual change in fracture mode from cleavage to ductile tear occurred at the tip of the fatigue crack in the  $K_{IC}$  specimens.

Scanning electron micrographs of the fracture-initiation region in the plane-strain tensile ductility specimens showed that the increase in plane-strain tensile ductility with increasing temperature for steels ranging in yield strength from 80 to 250 ksi was accompanied by a change in the microscopic mode of fracture in the plane-strain tensile-ductility specimens was similar to the change observed in the crack-initiation region in the  $K_{IC}$  specimens. That is, the microscopic mode of fracture in the plane-strain tensile-ductility specimens gradually changed from cleavage at cryogenic temperatures to ductile tear at room temperature. Thus, it is suggested that the increase in  $K_{IC}$  with increasing temperature is caused by an increase in the plane-strain tensile ductility with increasing temperature and that this increase in ductility is related to a change in the microscopic mode of fracture from cleavage to ductile tear.

Comment:

The authors have made a contribution to the technology by illuminating the transition temperature behavior of structural steels. This transition temperature is the temperature at which the plane strain fracture toughness ( $K_{IC}$ ) takes a stepwise change from a high number at elevated temperatures to a relatively lower one at lower temperatures. A large amount of additional effort is needed in this area, particularly, as structural metals are employed more commonly in cryogenic applications.

Important References:

1. Barsom, J. M. and Rolfe, S.T., Correlations Between  $K_{IC}$  and Charpy V-Notch Test Results in the Transition Temperature Range, Impact Testing of Metals, ASTM STP 466, 281 (1970).
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Key words: Ductility; fracture strength; fractures (materials); steels; stress intensity factor; temperature effects.

RELATIONSHIP BETWEEN MATERIAL FRACTURE TOUGHNESS USING FRACTURE MECHANICS AND TRANSITION TEMPERATURE TESTS

Sailors, R. H. and Corten, H. T. (Illinois Univ., Urbana)  
Fracture Toughness, ASTM STP 514, 164-191, (September 1972)

Although the effect of flaws in stressed bodies can be quantitatively characterized by methods of linear elastic fracture mechanics (LEFM), it is sometimes necessary to assess the fracture susceptibility using only conventional transition temperature tests. In order to gain the advantages and best features of each approach, a correlation between the two methods of fracture assessment is needed. The existing correlations between LEFM results and transition temperature test results are reviewed in light of new data on A533B steel. A complete series of tests results obtained by the HSST Program (ORNL) for both LEFM and transition temperature tests in both unirradiated and irradiated conditions permit fracture toughness,  $K_{IC}$  and  $K_{ID}$ , to be correlated with charpy V-notch energy, nil-ductility transition temperature, DT transition temperature, and low temperature cleavage stress. By following fundamentals of LEFM, whenever possible, a consistent pattern of fracture behavior is demonstrated for a class of pressure vessel steels similar to A533B.

Comment:

The authors have considered alternate approaches to linear elastic fracture mechanics for the determination of critical flow size in structural materials. These alternate approaches can save both considerable time as well as cost, if proper consideration is given to the decrease in the reliability of the data. In addition for some of the high toughness structural steels suggested for low temperature service, determination of a valid  $K_{IC}$  could be extremely difficult. As the authors indicate their recommendations are tentative and for the most part empirical and should not be indiscriminately applied.

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Key words: Fracture mechanics, fractures (materials); metallic materials; plane strain fracture toughness; toughness; transition temperature.

#### FRACTURE TOUGHNESS TESTING IN ALLOY DEVELOPMENT

Wei, R. P. (United States Steel Corp., Monroeville, PA)

Fracture Toughness Testing ASTM STP 381, 279-289 (April 1965)

This paper examines fracture mechanics as a basis for the evaluation of the fracture toughness of high strength steels and other high strength alloys. It discusses some of the considerations involved in the selection of plane strain fracture toughness as the most appropriate and significant parameter for ultra-high strength alloy steel development. The contribution of fracture mechanics to steel research and development is illustrated with brief reviews of three investigations: (1) a study of the relationships between microstructure and toughness in quenched and tempered low-alloy ultra-high strength steels, (2) an investigation of the effect of sulfur level on the fracture toughness of AISI 4345 alloy steel, and (3) a study of the influence of banding on fracture toughness anisotropy in a maraging steel.

#### Comment:

The author presents some early fracture toughness results which helped to establish the importance of this parameter in high strength steel development. The data presented in the paper accurately shows trends and transition temperature behavior, although the absolute values of the  $K_{IC}$  were not produced in accordance with the ASTM E399 validity criteria developed several years later.

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3. Sullivan, A. M., New Specimen Design for Fracture Toughness Tests, Mater. Res. Stand. 4, No. 1, 20 (January 1964).

Key words: Biaxial stress; fracture mechanics; fracture strength; fracture tests; high strength alloys; microstructures; plane strain; steels; strain rate; tensile properties.

## VIII.B. THIN SECTION MIXED MODE TOUGHNESS

### THE MEASUREMENTS OF FRACTURE TOUGHNESS OF DUCTILE MATERIALS

Ke, J. S. and Liu, H. W., (Syracuse Univ., NY)  
Eng. Fract. Mech. 5, 187-202 (1973)

Near tip strain is proposed as a ductile fracture criterion. This criterion was used to study the onset of slow growth of surface crack. The data from two batches of fully annealed 2024-0 aluminum alloy and HY-80 steel substantiated the proposed criterion. The measured fracture toughness at the onset of surface crack growth are 280, 110 and 800 ksi-square root inches for these three materials respectively. It was demonstrated that the measurement can be made easily with a small foil resistance strain gage. The near tip strain criterion was compared with both crack surface opening displacement and J-integral criteria.

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6. Rice, J. R., A Path Independent Integral and the Approximate Analysis of Strain Concentration by Notches and Cracks, J. Appl. Mech. 379-386 (June 1968)

Key words: Crack tip plastic zone; ductility; fracture mechanics; fracture strength; metallic materials; structural safety.

### CRACK GROWTH RESISTANCE CHARACTERISTICS OF HIGH STRENGTH SHEET ALLOYS

Freed, C. N., Sullivan, A. M., and Stoop, J. (Naval Research Lab., Washington, DC)  
NRL Report 7374 (January 31, 1972)

Crack propagation in a metal sheet is impeded by the inherent resistance to fracture of the alloy. The resistance is manifested by the requirement that crack growth will occur only under a rising load up to an instability load at

which unstable fracture commences. If the fracture resistance curve which designates the load-crack extension relationship to instability has a unique shape for each material and is independent of most specimen dimension, it can be a valuable tool in failure-safe designs.

The fracture resistance curves (R-curves) have been obtained for six high-strength sheet alloys which fractured under elastic loads. The influence of three specimen geometric variables and yield strength on the shape of the R-curve and the critical stress intensity factor  $K_{IC}$  was investigated. On several alloys a comparison was made between the R-curve and  $K_{IC}$  value generated with a center-cracked tension (CCT) specimen and data derived from a crack-line loaded (CCL) specimen used at Armco Steel Corporation.

The radius of the slit tips in the CCT specimen did not affect the  $K_{IC}$  value for aluminum 7075-T6 in which stable crack growth preceded instability. The R-curves emanating from fatigue-cracked specimens did indicate longer crack growth at lower loads than was evident from the blunter slit tips. Both  $K_{IC}$  and R curves were generally independent of initial slit length for aluminum alloys, although some scatter was observed from one steel and the titanium alloy.

The  $K_{IC}$  value was independent of specimen width  $W$  for high-strength aluminum alloys. The shape of the R-curve for the different CCT specimen widths of 2024-T3 was identical. The inverse relationship between  $K_{IC}$  and yield strength was obvious for the aluminum alloys and for 4130 steel.

A comparison of  $K_{IC}$  values for the CCT specimen and the CCL specimen indicated some differences for alloys which manifest crack growth under constant load. Since the commencement of constant-load crack growth marks the end of structural integrity, its recognition is crucial to a rational interpretation of fracture resistance. This behavior is observable on the CCT specimen test record, and the  $K$  value at initiation of constant load crack growth is designated as  $K_{IC}$ . Because the behavior was not directly observed on the CCL specimen test record, the  $K_{IC}$  criterion applied to these specimens was different. Thus, the differences between the  $K_{IC}$  values reported by CCT and CCL specimens are attributable to interpretation of data and not to the different methods of load application employed by the specimens.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 53).

#### ARTIFICIAL SLOW CRACK GROWTH UNDER CONSTANT STRESS. THE R-CURVE CONCEPT IN PLANE STRESS

Broek, D. (National Aerospace Lab., Amsterdam, Netherlands)  
Eng. Fract. Mech. 5, 45-53 (1973)

Tests were carried out on large center-notched tensile panels in which the crack was extended at both ends by means of sawing under constant load. The critical crack lengths were much longer than in normal residual strength tests. This leads to the conclusions that: 1) the execution of a fail-safe test by means of extending a crack by sawing under constant load leads to an overestimation of the critical crack length; and 2) fracture instability both under

monotonic loading and in case of crack growth under constant load can be considered to be determined by an energy concept. The energy concept (R-curve) is compatible with the fact that crack growth under constant load leads to a larger critical crack length than monotonic loading, but the physical background of the observations is not yet clearly understood.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE ).

#### CRACK GROWTH RESISTANCE IN PLANE STRESS FRACTURE TESTING

Heyer, R. H. and McCabe, D. E. (Armco Steel Corp., Middletown, OH)  
Eng. Fract. Mech. 4, 413-430 (1972)

New developments in crack growth resistance measurement using crack line-wedge loaded specimens include improved fixtures, and a double compliance technique for obtaining both load and effective crack length. The latter results in marked improvement in the accuracy of R-curves for materials having large plastic zones. The CLWL specimen, developed for high strength sheet materials, is now being used for light plates, at intermediate strength levels. Several investigations are reported in which center-cracked-tension (CCT) and CLWL specimens have been used in attempts to determine whether R-curves are specimen independent, and whether  $K_{IC}$  instability stress intensity of CCT specimens can be predicted from CLWL determined R-curves. Systems proposed by Feddersen and Allen for predicting the specimen width and crack length dependency of  $K_{IC}$  in CCT specimens are examined, and R-curves are compared over the wide range of specimen sizes and crack lengths tested by T. W. Orange. Principal stresses along the crack path are determined by strain gauges for CCT and CLWL specimens. The stress patterns are widely different, but the effective combined stresses near the elastic-plastic border are similar, which may account for similarity of R-curve development for the two specimen types, it is concluded from available evidence that R-curves appear to be characteristic of a material, in a given thickness, but the data is not conclusive and more verification is needed.

#### Comment:

The authors have examined the characteristic nature of R-curves in an approach to the plane stress fracture toughness situation. Their efforts in development and analysis of the CLWL specimen have resulted in improved understanding of the elastic-plastic fracture situation. The authors have made a step towards the development of a test technique and materials property to characterize plastic fracture.

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Key words: Aluminum alloys; center crack specimens; crack analysis; crack propagation; cracks; fracture mechanics; fracture strength; fracture tests; mechanical properties; plane strain; plane stress; pre-cracked specimens; resistance curves; steels; testing methods; wedge loaded specimens.

#### COMPATIBILITY OF LINEAR ELASTIC $K_{IC}$ AND GENERAL YIELDING (COD) FRACTURE MECHANICS

Egan, G. R. (Welding Inst., Cambridge (England))  
 Eng. Fract. Mech. 5, 167-185 (1973)

An investigation of the applicability of the general yielding fracture mechanics concept of crack opening displacement is made in relation to the well established concepts of linear elastic fracture mechanics. The nature of the relationship between crack opening displacement and stress intensity factor is explored using the concepts of linear elasticity and model analysis proposed by Dugdale.

The test results described in this paper indicated the compatibility of linear elastic ( $K_{IC}$ ) and general yielding (COD) fracture mechanics. As a result of this it is possible for any particular fracture control program to specify a test procedure based on current Standards to determine either  $K_{IC}$  or COD irrespective of the stress conditions at failure. There is no need for a separate test procedure to determine crack opening displacement values although, in the past, a different type of test piece geometry has been used for this purpose.

For the materials and geometries considered, the J at fracture seems to reflect the same order of change with temperature as the COD at fracture, as would be expected from the theoretical relationships of these two parameters. J values at fracture calculated from J calibrations determined by finite element methods indicate that there is only a large increase in the value of J when extensive plasticity is present. With small scale yielding near the crack tip the J values calculated by such methods are the same as those determined from linear elastic fracture mechanics K type analyses, ignoring the fact that these analyses are outside the range of ASTM validity.

(FOR LISTING OF IMPORTANT REFERENCES AND KEYWORDS, AND A DUPLICATE ABSTRACT, SEE PAGE 65 ).

THE SIGNIFICANCE OF MATERIAL DUCTILITY ON THE RELIABILITY AND LOAD CARRYING CAPACITY OF PEAK PERFORMANCE STRUCTURES

Weiss, V., Sengupta, M. and Sanford W. (Syracuse Univ., NY)  
MS-VW-1705-F173, AD-761217 (January 1973)

The relationship between fracture toughness, flow stress and material ductility were studied for the high strength steels, D6AC and 300M, each heat treated to three strength levels. The experimental part of the study was conducted in three phases: 1. Study of the effect of stress state on fracture ductility; 2. Study of the notch strength and ductility characteristics of the materials involved; 3. Determination of the fracture toughness of the materials. In addition, the theoretical studies, to develop an analytical basis for correlations between fracture toughness and flow properties of solids, were continued.

The fracture ductility was found to decrease significantly on going from the uniaxial stress state (tension test) to the plane strain stress state (bend test or clausen-type tension test) to the balanced biaxial condition (bulge test or plunger bulge test). The effective fracture strain is generally reduced to a value of less than half the value of the tensile fracture strain and sometimes to a value of only 12% of the tensile fracture ductility. A strong influence of the surface finish was noted. This gave rise to some scatter, particularly for the bulge tests. More experimentation is planned in the continuing program to clarify this point.

The notch sensitivity decreases with increasing tempering temperature for both materials, with a reduction being somewhat greater for 300M steel. The values of the Neuber micro support effect constant  $\rho^*$ , were determined and found to be between 0.0002 to 0.0014 inches. Measurements of the effective fracture strain at the notch root showed a general trend of decreasing notch root fracture strain with increasing stress concentration factor.

Fracture toughness values were determined for all materials with compact tension specimens. The values determined for 1.0 inch thick specimens met the requirements for plane strain fracture toughness,  $K_{IC}$ .

The analytical studies suggest that the correlation between fracture toughness and ductility should have the general form  $K_{IC} = A_{ei} E \sqrt{\rho^* \epsilon_i}$  where E is the modulus of elasticity, S the shape factor for the plastic zone (approximately 0.54 for  $\eta = 1$ )  $\rho^*$  the Neuber micro support effect constant,  $\epsilon_i$  the effective fracture strain corresponding to the stress state i and  $A_{ei}$  a corresponding constant.

The experimental results were found to be in good agreement with the bulge ductility correlation but in somewhat poor agreement with the bend ductility



correlation. Surface finish effects in the measurements of the bend ductility could be partly responsible for this discrepancy. The analytical correlations were also extended to the plane stress fracture condition. However, reliable estimates of the fracture strain corresponding to the plane stress condition ahead of a crack could not be made. Furthermore an experimental determination of the true plane stress fracture toughness is difficult. Nevertheless, it is anticipated that similar correlations can be established for plane stress conditions or mixed mode fracture.

Comment:

This continuing program is, by careful testing and experiment, developing data on the fracture behavior of these high strength steels. They are employing a measurement of fracture strain to correlate the data. To date this has shown some promise.

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Key words: Ductility; elastic-plastic analysis; fracture strength; fractures (materials); high strength alloys; structural reliability

CONSERVATION LAWS AND ENERGY-RELEASE RATES

Budiansky, B. and Rice, J. R. (Harvard Univ., Cambridge, MA, Brown Univ., Providence, RI)  
J. Appl. Mech., Trans. ASME, 201-203 (March 1973)

New path independent integrals recently discovered by Knowles and Sternberg are related to energy-release rates associated with cavity of crack rotation and

expansion. Complex-variable forms are presented for the conservation laws in the cases of linear, isotropic, plane elasticity. A special point concerning plastic stress distributions around cracks is discussed briefly.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 61).

EFFECT OF SHEET THICKNESS ON THE FRACTURE-RESISTANCE PARAMETER  $K_C$  FOR STEELS  
Sullivan, A. M. and Stoop, J. (Naval Research Lab., Washington, DC)  
NRL Report 7601 (August 1973)

Definition of fracture resistance for thin sheet material in terms of the linear-elastic fracture mechanics plane stress parameter  $K_C$  continues to reveal aspects of its geometrical dependency. The effect of sheet thickness on the  $K_C$  value of three structural steels representing four yield stress levels has been determined over available thickness ranges of 0.794 to 6.350 mm. Within this range, less thickness dependence has been observed than was anticipated. The fact that both economy and convenience would be served if fracture resistance for all sheet thickness could be estimated from a limited number of specimens has given impetus to several models purporting to explain this dependency in terms of the relative contributions of a surface phenomenon, flat fracture, and a volume-sensitive mechanism, shear lip development. Attempts to fit present data to one of the models disclose inadequacies for which there are not apparent immediate solutions.

Comment:

The authors have shed considerable experimental light on the difficult problem of plane stress testing. Their candid admission that the models do not adequately account for the data should stimulate additional efforts in this increasingly important area.

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Key words: Center crack specimens; crack growth rate; crack initiation; crack opening displacement; crack propagation; cracks; fail safe design; fracture strength; geometric effects; high strength alloys; linear elastic fracture mechanics; mechanical properties; metallic materials; plane stress; steels; stress analysis; structural safety; tensile stress.

#### INFLUENCE OF WORK-HARDENING EXPONENT ON THE FRACTURE TOUGHNESS OF HIGH STRENGTH MATERIALS

Steigerwald, E. A. and Hanna, G. L. (TRW Equipment Labs., Cleveland, OH)  
Trans. Met. Soc. AIME 242, 320-328 (February 1968)

The influence of work-hardening exponent on the variation of fracture toughness with material thickness was studied for high-strength steel, aluminum, and titanium alloys. The results indicate that, when materials are compared at similar fracture toughness to yield strength ratios, the material with the lower work-hardening exponent undergoes the transition from flat to slant fracture at a larger thickness than material with a high work-hardening exponent. In the thickness range where complete slant fracture is obtained the reverse is true and a lower work-hardening exponent results in a lower fracture toughness. The influence of work-hardening exponent on fracture toughness is, therefore, dependent on the particular fracture mode. In the transition region a low work-hardening exponent is beneficial for fracture toughness while in the 100% slant region it is detrimental.

#### Comment:

The observations on the influence of the work-hardening exponent on fracture are significant in terms of the microstructure response of the material. It is not unexpected that in those cases (slant fracture) where plastic flow is significant the work-hardening exponent should be a correlatable factor. This is one of the pieces of information employed in developing materials with improved fracture toughness.

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2. Hanna, G. L. and Steigerwald, E. A., Development of Standardized Test Methods to Determine Plane Strain Fracture Toughness, AFML-TR-65-213 (September 1965)

Key words: Center crack specimens; fracture strength; high strength alloys; plane strain fracture toughness; stress intensity factor.

#### THE EFFECT OF PLASTICITY AND CRACK BLUNTING ON THE STRESS DISTRIBUTION IN ORTHOTROPIC COMPOSITE MATERIALS

Tirosh, J. (Technion - Israel Inst. of Tech., Haifa)  
J. Appl. Mech., Trans ASME, 785-790 (September 1973)

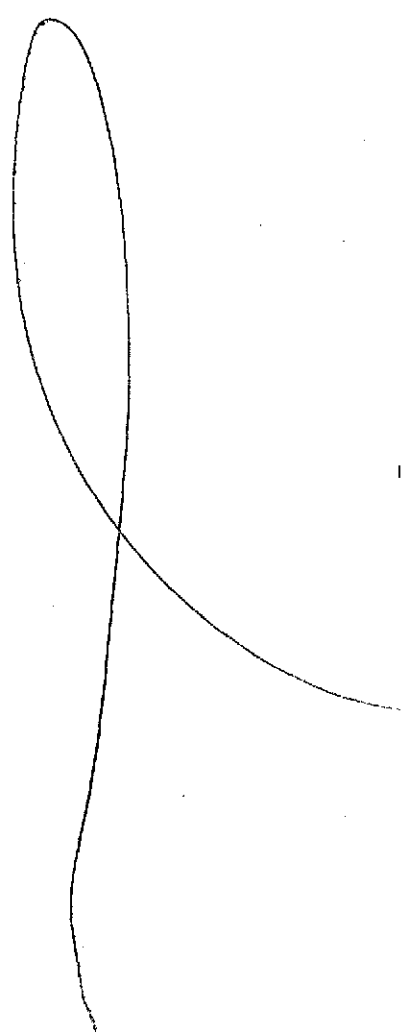
A detailed study of the plasticity and crack-tip blunting effects on toughening materials with rectilinear anisotropy is presented. The most important results are the prediction of the extent of plastic zone and the nature of stress distribution produced by the blunting effect in the tensile mode. The analysis was confirmed experimentally and numerically (finite-element method) on a unidirectional fiber-reinforced composite.

1. The length of the plastic zone in rectilinear anisotropic material is formulated in terms of its pertinent parameters, with the aid of a path-independent integral. The expression has fundamentally the same structure as the familiar solution derived from the antiplane shear mode, and agrees well with experimental and numerical results (finite-element methods).

2. The stress distribution is derived from a mathematical model which stimulates the experimentally observed situation, i.e., the yield zone is a narrow rectilinear strip perpendicular to the crack which transfers a uniform shear traction to the bulk (uncracked) material ahead of the notch. As a result, the elastic tensile stress ahead of a blunted crack obeys a log (1/r) distribution preceded by local stress reduction of known magnitude. The toughening effect of the blunting manifests itself in these circumstances.

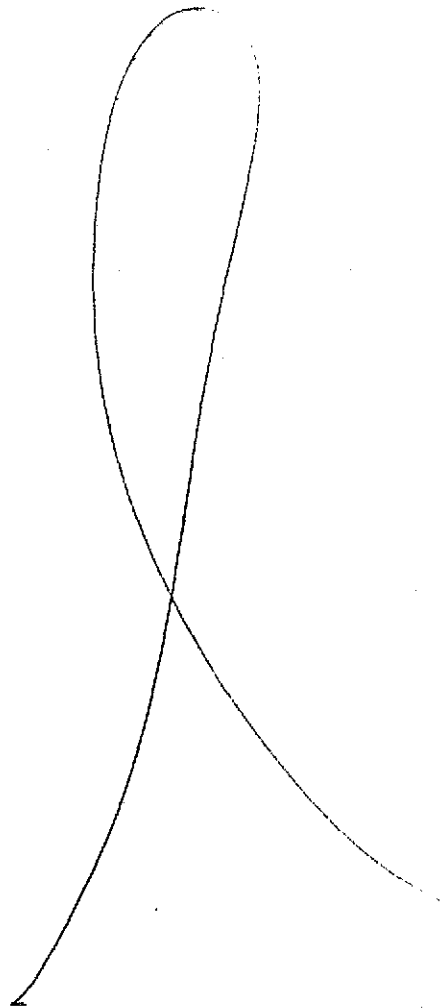
3. The transverse stress, markedly different from the balanced biaxial stress situation ahead of the crack, is much smaller than its longitudinal counterpart (in the present case - by two orders of magnitude) and reaches maximum some distance ahead of the crack. This information casts light on the conditions promoting delamination (fiber/matrix debonding) and/or transverse interlaminar crack propagation.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 46).



IX. NONDESTRUCTIVE EVALUATION

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## IXA. DETERMINATION OF INITIAL CRACK EXTENSION

ULTRASONIC TECHNIQUE FOR DETECTION AND MEASUREMENT OF FATIGUE CRACKS  
Klima, S.J., Lesco, D.J. and Freche, J.C. (National Aeronautics and Space  
Administration, Lewis Research Center, Cleveland, OH)  
NASA-TN-D-3007 (September 1965)

An ultrasonic system was developed and used to observe the formation of fatigue cracks in center-notched sheet specimens while the fatigue tests were in progress. Actual lengths of detected cracks were determined by microscopic examination, S-N curves of life to initial detectable cracks as well as S-N curves of life to fracture were obtained. In the sharply notched specimens utilized in this investigation, cracks were detected within approximately 1 to 3 percent of total life for all the materials. It was possible to detect smaller cracks with the reflection technique than with the through-transmission technique. The instrument output from cracks longer than 0.254 mm, however, was more reproducible when the through-transmission technique was used. Specimens of unalloyed aluminum, aluminum alloy, mild steel, and a nickel alloy were used.

### Important references:

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2. Rasmussen, J.G., Prediction of Fatigue Failure Using Ultrasonic Surface Waves, J. Soc. Non-Destruct. Test. 20, No.2, 103-110 (March-April 1962).
3. Banks, B., Oldfield, G.E. and Rawding, H., Ultrasonic Flaw Detection in Metals, Iliffe Book Ltd., London, England (1962).

Key words: Aluminum alloys; center crack specimens; crack detection; crack initiation; cracks; detection systems; fatigue (materials); fatigue tests; fractures (materials); NDE; NDI; NDT; notched specimens; steels; structural safety; testing methods; ultrasonic tests.

ULTRASONIC DETECTION AND MEASUREMENT OF FATIGUE CRACKS IN NOTCHED SPECIMENS  
Klima, S.J. and Freche, J.C. (National Aeronautics and Space Administration,  
Lewis Research Center, Cleveland, OH)  
Exp. Mech. 9, No. 5, 193-202 (1969)

An ultrasonic technique was developed and used to observe the formation and growth of fatigue cracks in notched cylindrical specimens subjected to reverse axial cyclic loading. Fatigue curves of the life-to-initial detectable cracks as well as life-to-fracture were obtained for an aluminum -, a titanium-, and a cobalt-base alloy, as well as a maraging steel. Depth of initially detectable cracks ranged between approximately 0.01270 and 0.1016 mm. Curves were also obtained relating ultrasonic system output voltage to crack depth



up to 0.762 mm for three materials. These curves were used to demonstrate the capability of the device for monitoring crack growth.

Important References:

1. Feinstein, L. and Hruby, R.J., Surface Crack Detection by Microwave Methods, presented at the Sixth Symposium on Nondestruction Evaluation of Aerospace and Weapons Systems Components and Materials, San Antonio, Texas (17-19 April 1967).
2. Klima, S.J., Lesco, D.J. and Freche, J.C., Application of Ultrasonics to Detection of Fatigue Cracks, Exp. Mech. 6, No.3, 154-161 (1966).
3. Manson, S.S., Interfaces Between Fatigue, Creep, and Fracture, Int. J. Fract. Mech. 2, No. 1, 327-363 (1966).

Key words: Aluminum alloys; analysis methods; crack detection; crack initiation; crack propagation; cracks; cyclic loads; detection systems; fatigue (materials); fatigue tests; fractures (materials); maraging steel; metallic materials; NDE; NDI; NDT; notched specimens; steels; structural safety; titanium alloys; ultrasonic tests.

ULTRASONIC DETECTION OF CRACK EXTENSION IN THE W.O.L. TYPE FRACTURE TOUGHNESS SPECIMEN

Clark, Jr., W.G. (Westinghouse Research Labs., Pittsburgh, PA)  
Mater. Eval., 185-190 (August 1967)

An ultrasonic detection technique has been developed to provide a relatively simple, accurate method of measuring fatigue crack growth within the wedge-opening-loading type fracture toughness specimen. The technique permits:

1. Measurement of the length of the initial fatigue crack in precracked specimens;
2. Automatic control of precracking (fatiguing) operation itself; and
3. Measurement of the extent of slow crack growth under cyclic or tension loading.

The basic technique involves the use of a high-resolution, 10 MHz, contact, pulse-echo ultrasonic inspection system capable of detecting 0.127 mm changes in crack length.

Important references:

1. Davis, R.A. and Quist, W.E., Fracture Toughness, Mater. Des. Eng. 93 (November 1965).
2. Srawley, J.E. and Brown, Jr., W.F., Fracture Toughness Testing Methods, ASTM STP 381, 133-196 (June 1965)

3. Paris, P.C., The Fracture Mechanics Approach to Fatigue, Proc. 1963 Sagamore Conf., Syracuse Univ. Press. PA (1964).
4. Klima, S.J., Lesco, D.J. and Freche, J.C., Ultrasonic Technique for Detection and Measurement of Fatigue Cracks, NASA-TN-D-3007 (September 1965).

Key words: Aluminum alloys; crack analysis; crack growth rate; crack propagation; cyclic loads; fatigue (materials); fracture strength; NDE; NDI; pre-cracked specimens; steels; tensile stress; testing methods; ultrasonic tests; wedge loaded specimens.

#### ACOUSTIC EMISSION TECHNIQUES IN MATERIALS RESEARCH

Liptai, R.G., Harris, D.O., Engle, R.B. and Tatro, C.A. (California Univ., Livermore, Lawrence Radiation Lab.)  
 Int J Nondestruct Test, 3, 215-275 (1971)

A review of the application of emission analysis to evaluate materials properties and defect structure is presented. Topics discussed include fracture toughness and crack propagation, fatigue, plastic deformation, and creep processes in metals, composites, and rock materials. The status of emission techniques as applied to the evaluation of structural integrity is reported. A complete discussion of experimental techniques and data acquisition and processing systems is given. It is concluded that acoustic emission techniques have wide applicability to experimental studies in materials research and to evaluation analysis of structural integrity. Directions of future developments and applications are discussed.

#### Important references:

1. Dunegan, H.L., Harris, D.O. and Tatro, C.A., Fracture Analysis by Use of Acoustic Emission, Eng. Fract. Mech. 1, No. 1, 105 (1968).
2. Engle, R.B. and Dunegan, H.L., Acoustic Emission: Stress Wave Detection as a Tool for Nondestructive Testing and Material Evaluation, Int. J. Nondestruct Test. 1, No. 1, 109 (1969).
3. Dunegan, H. L. and Harris, D.O., Acoustic Emission-A New Non-destructive Testing Tool, Ultrasonics 7, No. 3, 160 (1969).
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5. Dunegan, H.L., Harris, D.O. and Tetelman, A.S., Detection of Fatigue Crack Growth by Acoustic Emission Techniques, Proc. Symp. Nondestruct Eval. Components Mater., Aerosp. Weapons Systems, Nucl. Appl., 7th Amer. Soc. Nondestruct Test and Southwest Research Inst., San Antonio, TX, 20-31 (1969).

6. Harris, D.O., Dunegan, H.L. and Tetelman, A.S., Prediction of Fatigue Lifetime by Combined Fracture Mechanics and Acoustic Emission Techniques, AFFDL TR-70-144, 459-471 (September 1970).

Key words: Crack propagation; detection systems; fatigue (materials); fracture strength; metallic materials; NDT; plastic deformation; structural safety; ultrasonic tests.

ULTRASONIC SURFACE-WAVE DETECTION TECHNIQUES IN FRACTURE MECHANICS  
Ho, C.L., Marcus, H.L. and Buck, O. (Rockwell International Corp., Thousand Oaks, CA).  
Exp. Mech. 42-48 (January 1974).

Recent applications of ultrasonic acoustic waves to characterizing fatigue-crack propagation in part-through-crack specimens is discussed. A simple ultrasonic system recently developed is described in detail. Emphasis of the description is paid to the practical aspects of instrumentation and operation of this system which is based on the interaction of cracks with acoustic surface waves. The received signal contains information of the character of a static or a propagating crack. The sensitivity of the system mainly due to its high-resolution power makes it particularly suitable for studying plasticity effects in fatigue-crack propagations. Of special importance, the present technique provides direct, experimental evidence on the crack-closure phenomenon and convenient means for measuring the amount of this closure, together with its associated crack-tip resistance. The significance of these parameters is discussed in terms of analytic predictions based on the residual deformations at the crack tip. Important fracture mechanics quantities discussed, which are obtainable from the surface-wave test data, include: the instantaneous crack geometry and its variations with changing load conditions; the closure and resistance phenomena at the crack tip due to the material ductility, stress relaxations for sustained loads, and environmental effects on moving cracks. To get more general fracture mechanics information, the present ultrasonic system can be simultaneously coupled to acoustic-emission detectors.

Important references:

1. Rasmussen, J.G., Prediction of Fatigue Failure Using Ultrasonic Surface Waves, Mater. Eval. 20, 103 (1962).
2. Clark, Jr., W.G. and Creschini, L.J., An Ultrasonic Crack Growth Monitor, Mater. Eval. 27, 180 (1969).
3. Clark, Jr., W.G., Ultrasonic Detection of Crack Extension in the W.O.L. Type Fracture Toughness Specimen, Mater. Eval. 25, 185 (1967).
4. Klima, S.J., Lesco, D.J. and Freche, J.C., Ultrasonic Techniques for Detection and Measurement of Fatigue Cracks, NASA-TN-D-3007 (September 1965).

5. Elber, W., The Significance of Fatigue Crack Closure, ASTM STP 486, 230 (1971).

Key words: Aluminum alloys; crack detection; crack growth rate; crack propagation cracks; detection systems; fatigue (materials); fracture mechanics; metallic materials; NDE; NDI; NDT; pre-cracked specimens; steels; stress intensity factor; titanium alloys; ultrasonic tests.

#### ACOUSTIC DETECTION OF CRACK INITIATION IN SHARPLY NOTCHED SPECIMENS

Jones, M.H. and Brown, Jr., W.F. (National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH).

Mater. Res. Stand. 4, No.3, 120-129 (March 1964).

Of the several techniques employed for pop-in load determination, acoustic detection appears to offer the greatest flexibility under a wide variety of testing conditions. This paper describes an acoustic system using an ordinary phonograph pickup and a tape recorder. Both sound and load are recorded on the tape. Results obtained with this technique are described for tests on several sheet alloys using different specimen types, provided with both sharp machined notches and fatigue cracks. In addition, acoustic pop-in data for one alloy are compared with data obtained with a compliance gage.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 84).

## IXB. SENSITIVITY AND RELIABILITY OF FLAW DETECTION

### THE DETECTION OF FATIGUE CRACKS BY NONDESTRUCTIVE TESTING METHODS

Rummel, W.D., Todd, Jr., P. H., Frecska, S.A. and Rathke, R.A.  
(Martin Marietta Corp., Denver, CO).  
NASA-CR-2369 (February 1974).

X-radiography, penetrant, ultrasonic, eddy current, holographic, and acoustic emission techniques were optimized and applied to the evaluation of 2219-T87 aluminum alloy test specimens. 118 specimens containing 328 fatigue cracks were evaluated. The cracks ranged in length from 1.27 cm to 0.018 cm and in depth from 0.451 cm to 0.003 cm. Specimen thicknesses were nominally 0.152 cm and 0.532 cm and surface finishes were nominally 32 and 125 rms and 64 and 200 rms respectively. Specimens were evaluated in the "as milled" surface condition, in the chemically milled surface condition and, after proof loading, in a randomized inspection sequence. Results of the nondestructive test (NDT) evaluations were compared with actual crack size obtained by measurement of the fractured specimens. Inspection data were then analyzed to provide a statistical basis for determining the threshold crack detection sensitivity (the largest crack size that would be missed) for each of the inspection techniques at a 95 percent probability and a 95 percent confidence level.

#### Important References:

1. Erf, R.K., Waters, J.P., Gagosz, R.M., Micheal, R. and Whitney, G.,  
Nondestructive Holographic Techniques for Structural Inspection,  
AFML-TR-72-204 (October 1972).

Key words: Aluminum alloys; analysis methods; crack detection; crack initiation; cracks; critical flaw size; eddy currents; fatigue (materials); NDE; NDT; subcritical crack growth; testing methods; ultrasonic tests.

### DETECTION OF FATIGUE CRACKS BY NONDESTRUCTIVE TESTING METHODS

Anderson, R.T., Delacy, T.J. and Stewart, R.C. (General Dynamics/Convair,  
San Diego, CA)  
NASA-CR-128946 (March 1973)

This program is specifically directed toward the objective of defining the reliability of NDT methods to detect fatigue cracks of various sizes in 2219-T87 aluminum plate and sheet. The performance of these tests was measured by comparing the flaws detected against the flaws present. The principal NDT methods utilized were radiographic, ultrasonic, penetrant, and eddy current. Holographic interferometry, acoustic emission monitoring,

and replication methods were also applied on a reduced number of specimens. Generally, the best performance was shown by eddy current, ultrasonic, penetrant, and holographic tests. Etching provided no measurable improvement, while proof loading improved flaw detectability. Data are shown that quantify the performances of the NDT methods applied.

**Key words:** Aluminum alloys; analysis methods; crack detection; crack initiation; cracks; fatigue (materials); NDE; NDT; reliability; structural safety; testing methods; ultrasonic tests.

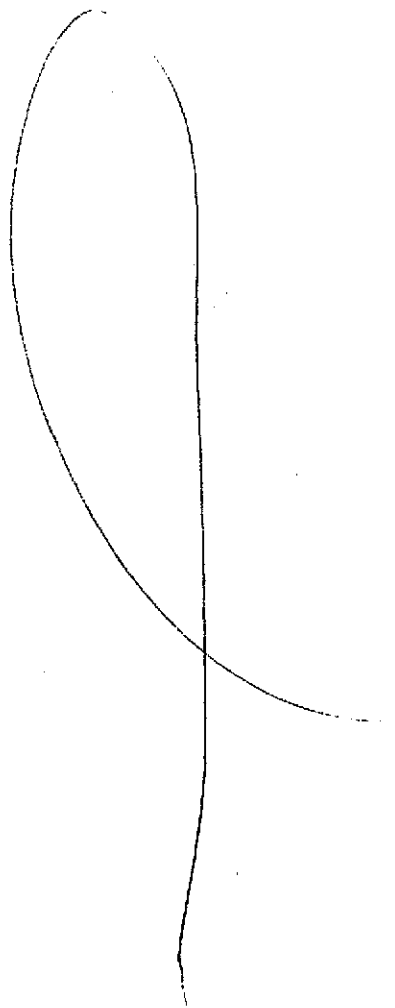
#### FRACTURE TOUGHNESS AND NDT REQUIREMENTS FOR AIRCRAFT DESIGN

Packman, P.F. (Vanderbilt Univ., Nashville, TN).

J. Non-Destruct. Test (Guilford, Engl). 314-324 (December 1973).

This paper reviews current design concepts of fracture toughness and NDT in fracture control programs for advanced aircraft. The dual role of fracture toughness for materials selection and for design where fatigue-crack growth is analyzed under constant-amplitude and spectrum loading. It is essential that the lower limit of detection be known with confidence. The materials are then chosen so that the critical flaw size is above this limit. From this knowledge the life of a particular design may be forecast for different conditions of service. The lifetime is influenced by both detection capabilities and changes in service conditions.

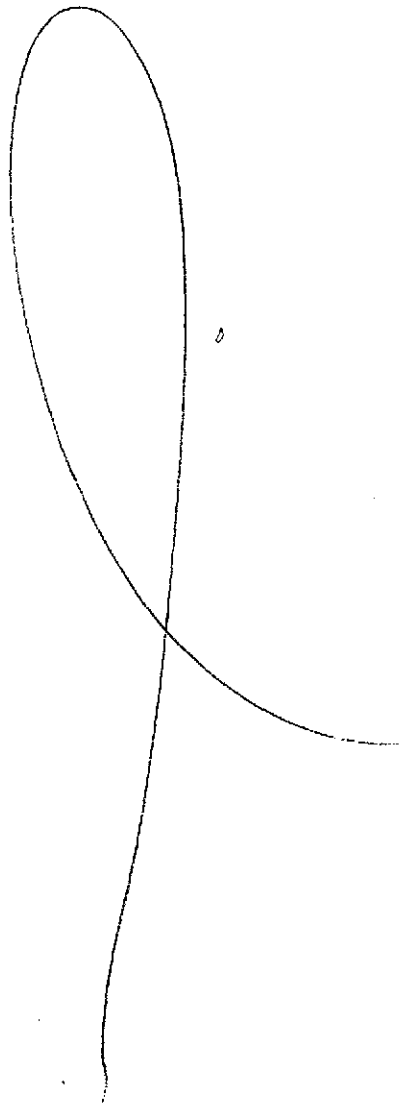
(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 151).



X. APPLICATIONS

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## XA. TECHNOLOGY

### A CASE STUDY IN TECHNOLOGY UTILIZATION: FRACTURE MECHANICS

Industrial Economics Division, Denver Research Institute, University of Denver  
(Denver Research Inst., Denver, CO)  
NASA-CR-127779 (May 1972)

#### Comments:

This case study reviews the role of NASA in the development, dissemination, diffusion and implementation of the technology of fracture mechanics with a particular focus on plane strain fracture toughness. The first two sections (Overview and NASA Contributions to Fracture Mechanics) present a brief history of the development of this technology. It is shown that the phenomena of brittle fracture was recognized as being responsible for significant decreases in the load carrying capability of structures and that the NASA Lewis personnel were instrumental in synthesizing the practical service experience and the basic concepts of Griffith and Irwin into the concept of plane strain fracture toughness. The third section discusses the cooperative efforts, spearheaded by the NASA Lewis group, operating principally within the structure of the American Society for Testing and Materials (ASTM) in the Committee E-24 on fracture to develop a viable testing standard. This cooperation took several forms. These included organizing symposia, round robin testing of proposed standards and extensive publication of results, particularly in ASTM Special Technical Publications. The four sections detail the awakening interest throughout the industrial community in the concepts and employment of the property of plane strain fracture toughness.

#### Important References:

1. Brown, Jr., W. F. and Srawley, J. E., Plane Strain Crack Toughness Testing of High Strength Metallic Materials, ASTM STP 410, Philadelphia, PA (1966).
2. Kaufman, J. G., Progress in Fracture Testing of Metallic Materials, Review of Developments in Plane Strain Fracture Toughness Testing, ASTM STP 463, Philadelphia, PA, 3-21 (1970).

Key words: Fracture mechanics; fracture strength; life (durability); plane strain; stress intensity factor; structural reliability; testing methods; testing standards.

#### FRACTURE MECHANICS

Hardrath, H. F. (National Aeronautics and Space Administration, Langley Research Center, Langley Station, VA)  
AIAA 74-230 (AIAA 12th Aerospace Sciences Meeting, Washington, DC, 30 January - 1 February 1974)

Some applications of fracture mechanics in the design of efficient and safe aerospace structures have been reviewed. The underlying rationale appears capable of dealing with material selection for residual strength, resistance to fatigue and

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stress corrosion cracking, the optimum deployment of structural parts for best residual strength and crack life and the prediction of life under variable amplitude loadings. The discipline is developing rapidly toward providing quantitative predictions for each of these behaviors.

Extensions are needed to account for fracture under other than plane-strain conditions and to provide a practical means for predicting life under complex time histories of loadings. Even without these extensions, designers should be able to profit from comparisons of basic behaviors of candidate materials and structural configurations. Very large improvements in structural reliability are possible by employing redundant structure and controlling the deleterious effects of aggressive environments with modest weight increases. For cases where a structure must be protected against failure due to significant flaws, the limiting stress level can be established with reasonable accuracy.

Because the U. S. Air Force is considering a strong new damage tolerance criterion, research activity in this structural discipline likely to be accelerated dramatically in the next decade.

Important References:

1. Wood, H. A., The Use of Fracture Mechanics Principles in the Design and Analysis of Damage Tolerant Aircraft Structures, Fatigue Life Prediction for Aircraft Structures and Materials, AGARD-LS-62 (May 1973).
2. Erdogan, F., Crack Propagation Theories, NASA-CR-901 (1967).
3. Elber, W., Fatigue Crack Closure Under Cyclic Tension, Eng. Fract. Mech. 2 (1970).
4. Willenborg, J., Engle, R. M. and Wood, H. A., A Crack Growth Retardation Model Using an Effective Stress Concept, AFFDL-TM-71-1-FBR (January 1971).
5. Elber, W. and Davidson, J. R., A Material Selection Method Based on Material Properties and Operating Parameters, NASA-TN-D-7221 (April 1973).
5. Packman, P. F., Pearson, H. S., Owens, J. S. and Marchese, G. B., The Applicability of a Fracture Mechanics - Nondestructive Testing Design Criterion, AFML-TR-68-32 (May 1968).

Key words: Aircraft structures; analysis methods; crack propagation; critical flaw size; design criteria; fatigue (materials); fracture mechanics; fractures (materials); life prediction; materials selection; metallic materials; stress corrosion; stress intensity factor.

#### BASIC ASPECTS OF CRACK GROWTH AND FRACTURE

Irwin, G. R., Krafft, J. M., Paris, P. C. and Wells, A. A. (Naval Research Lab., Washington, DC, Lehigh University, Bethlehem, PA, Queens University, Belfast, Northern Ireland)

Naval Research Laboratory Report 6598 (November 1967)

A near approach to absolute fracture safety in boiling water (BW) and pressurized water (PW) nuclear reactor pressure vessels requires a very conservative fracture control plan. Such a plan must assume that any plausible cracklike defect, which has not been proved absent by inspection, may exist in the vessel. Requirements for design, materials, and inspection may then be established in a conservative way relative to estimates of progressive crack extension behavior. These estimates are assisted by elastic and plastic methods of analysis of cracks in tension. Approximate methods of assigning  $K_{IC}$  values to measurements of crack toughness in terms of a brittle-ductile transition temperature are valuable in reviewing methods of fracture control which have received trial in the past, such as the NRL fracture analysis diagram and the leak-before-break toughness criterion.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 13).

#### FRACTURE TOUGHNESS - AN ENGINEERING DESIGN PARAMETER

Lange, E. A. (Naval Research Lab, Washington DC )

Metals Eng. Quart. 11, 31-39 (November 1971)

A brief outline of general principles related to the mechanical aspects of fracture is presented. Three general types of fracture instability are described:

1. Sharp instability, which corresponds to a sharp, plane strain type fracture, where the initial crack movement signifies complete fracture of the section;
2. Pop-in, which occurs after a small but significant deviation from linearity in the load-displacement relationship; and
3. Fully plastic fracture, in which terminal fracture occurs after a gross plastic strain reduces the net section enough to force an instability condition.

Coupling between engineering fracture tests for measurement of fracture toughness and linear elastic fracture mechanics theory is achieved. Fracture analysis and ratio analysis diagrams are used to couple the fracture toughness values from engineering fracture tests to the analytical capability of fracture mechanics. The dynamic tear test has the capability for measuring fracture toughness, ranging from the low energy region pertaining to elastic fracture to the high energy region pertaining to fully plastic fracture.

**Important References:**

1. Pellini, W. S., Evaluation of Engineering Principles for Fracture-Safe Design, NRL Report 6957 (22 September 1969).
2. Pellini, W. S., Advances in Fracture Toughness Characterization Procedures and in Quantitative Interpretations to Fracture-Safe Design for Structural Steels, NRL Report 6713 (3 April 1968).
3. Pellini, W. S. and Loss, F. J., Integration of Metallurgical and Fracture Mechanics Concepts of Transition Temperature Factors Relating to Fracture-Safe Design for Structural Steels, NRL Report 6900 (22 April 1969).
4. Tetelman, A. S. and McEvily, Jr., A. J., Fracture of Structural Metals, John Wiley Press, New York, NY (1967).
5. Brown, Jr., W. F. and Srawley, J. E., Plane Strain Crack Toughness Testing of High Strength Metallic Materials, ASTM STP 410 (1966).

**Key words:** Analysis methods; crack tip plastic zone; critical flaw size; dynamic tear tests; fracture mechanics; fracture strength; fractures (materials); high strength; linear elastic fracture mechanics; metallic materials; plane strain; plane strain fracture toughness; steels; stress intensity factor; yield strength.

XB. AIRCRAFT

FRACTURE MECHANICS GUIDELINES FOR AIRCRAFT STRUCTURAL APPLICATIONS

Wilhem, D. P. (Northrop Corporation, Hawthorne, CA)

AFFDL-TR-69-111 (February 1970)

This document provides the guidelines, limitations, and modifications required to perform a structural, fracture analysis using Griffith-Irwin fracture mechanics principles. It serves as an introduction to fracture mechanics principles for those personnel who are concerned with fracture strength estimates for aerospace structural applications. Illustrations and hypothetical examples are included which show how engineering solutions for critical crack size and fracture stress may be made. The critical stress intensity (fracture toughness) concept is used as a basic factor for the fracture analysis of materials. For most crack situations, a stress intensity factor can be computed which can be related to critical conditions and estimates made of critical crack lengths, stresses, and crack propagation behaviors.

Important References:

1. Irwin, G. R., Exploratory Aspects of Fracture Mechanics, Fracture Mechanics Workshop Notes (August 1965).
2. Timoshenko, S. and Goodier, J. N., Theory of Elasticity, Mc Graw-Hill, 2nd Edition (1951).
3. Westergaard, D. H., Bearing Pressures and Cracks, Trans, ASME, J. Appl. Mech. (1939).
4. Paris, P. C. and Sih, G. C., Stress Analysis of Cracks, ASTM STP 381 30-81 (1965).
5. Dugdale, D. S., Yielding of Steel Sheets Containing Slits, J. Mech. and Physics of Solids 8 (1960).

Key words: Aluminum alloys; bending loads; biaxial stress; crack analysis; crack tip plastic zone; cracks; cyclic loads; fracture analysis; fracture mechanics; fracture strength; fracture tests; fractures (materials); plastic zone; residual strength; strain; strain rate; stress; stress analysis; stress concentration; stress intensity factor; structural safety; yield strength.

## FRACTURE MECHANICS OF AIRCRAFT STRUCTURES

Liebowitz, H. (George Washington University, Washington, DC)  
AGARD AG-176

The first chapter of this book is an introduction by Liebowitz. The six succeeding chapters are a fracture mechanics survey presenting the following information: Chapter 2 presents a summary of airframe service loadings particularly related to that portion of life following the initiation of a crack; Chapter 3 reviews current trends in the usage of high strength structural materials for aerospace applications and illustrates the manner in which fracture control procedures may be implemented to achieve a high degree of damage tolerance; Chapter 4 presents a technical review of fracture mechanics including several appendices which discuss the application of some analysis methods to the fracture process; Chapter 5 treats the importance of fail safe design and its basic design concepts; Chapter 6 describes two standard methods, test for plane strain fracture toughness of metallic materials and sharp notch tension testing of high strength sheet materials; Chapter 7 discusses to present reliability of crack detection methods and the means for determining crack size. The appendices contain detailed information on typical plane strain fracture toughness of aircraft materials; fracture toughness test results; references of approximately 140 configurations for which stress intensity factors have been determined. A list of selected references completes the survey.

Key words: Aircraft structures; aluminum alloys; analysis methods; crack detection; crack initiation; crack opening displacement; critical flaw size; data; environmental effects; fail-safe design; failures (materials); fatigue (materials); fracture analysis; fracture mechanics; fracture strength; fractures (materials); high strength alloys; J-integral; life prediction; metallic materials; NDE; NDI; NDT; notched specimens; plane strain fracture toughness; pressure vessels; residual strength; steels; stress intensity factor; structural design; structural safety; tensile tests; tests; titanium alloys; utilization.

## APPLICATION OF FRACTURE PREVENTION PRINCIPLES TO AIRCRAFT

Committee on Application of Fracture Prevention Principles to Aircraft (National Materials Advisory Board, Washington, DC)  
NMAB-302 (February 1973)

The elements of current fracture control plans and associated technologies were reviewed. After reviewing the status, applicability, and potential of the elements and technologies, it was concluded that fracture control plans and development of related technologies not only afford an opportunity to reduce catastrophic failures of aircraft structures and structural maintenance but also can help to quantify many structural material, design, NDE, and maintenance decisions that now are made on a relatively qualitative basis. The committee recommended careful trade studies, together with caution and flexibility, in the use of existing criteria and prior to the issuance of new criteria. Assumptions regarding initial flaw size and

requirements for analysis, testing, and NDE can have particularly serious impact. Required technologies to implement fracture control plans need extensive development, particularly fracture toughness characterization of structural sections that are too thin for plane strain to apply. Specific recommendations and needs for research and development for the fracture-related technologies and design applications are summarized.

Important References:

1. Hahn, G. T. and Simon, R., Metallurgical Control of Fatigue Crack Growth in High Strength Aluminum, AFML-TR-72-48 (February 1972).
2. Hartman, A. and Schijve, J., The Effect of Environment and Load Frequency on the Crack Propagation Law for Macro Fatigue Crack Growth in Aluminum Alloys, Eng. Fract. Mech. 1, No. 4, 615 (April 1970).
3. Packman, P. F., Pearson, H. S., Owens, J. S. and Young, G., Definition of Fatigue Cracks Through Nondestructive Testing, J. Mater. 666 (September 1969).
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5. Wilhem, D. P., Fracture Mechanics Guidelines for Structural Applications, AFFDL-TR-69-111 (February 1970).
6. Wood, H. A., Fracture Control Procedures for Aircraft Structural Integrity, AFFDL-TR-71-89 (July 1971).

Key words: Aircraft structures; analysis methods; fatigue (materials); fracture analysis; fracture mechanics; fractures (materials); metallic materials; NDI; plane strain fracture toughness; structural safety; subcritical crack growth.

CRACK BEHAVIOR IN D6AC STEEL: AN EVALUATION OF FRACTURE MECHANICS DATA FOR THE F-111 AIRCRAFT

Feddersen, C. E., Moon, D. P. and Hyler, W. S. (Battelle Memorial Institute, Columbus, OH)

MCIC Report No. MCIC-72-04 (January 1972)

The fracture-toughness tests accomplished on this multilaboratory program demonstrate the quench-rate sensitivity of the D6AC steel plate and forging materials used in the F-111 aircraft. The quench-rate sensitivity reflects the dependency of fracture toughness on the heat-treat process for these materials. The data indicated that part-size and heat-treat variables overshadow the influence of product form and chemistry variations. Since heat-treat process and basic chemistry interact very subtly, microstructure studies would be an important element in quantifying these influences.



In general, the results of the compact tension, surface flaw and double cantilever beam specimen types appear to agree quite well. However, because there was a significant thickness disparity, a rigorous correlation could not be confirmed or denied in a positive fashion. The test methods appear to be consistent within themselves, each providing reproducible results.

In general, the fatigue-crack propagation behavior of these materials appears to be influenced more by the test conditions (i.e., loading, environment, and frequency) than by product form or heat-treat parameters.

The interaction of environment and cyclic frequency is the most dominant parameter evident in these data. Although stress ratio effects can be distinguished,  $\Delta K$  appears to consolidate the data quite well. Hence, it is implied that loading effects and flaw severity are coupled usefully in  $\Delta K$ .

An important observation made from among these data is that fatigue-crack propagation rates, when compared directly on a  $da/dN$  basis for given environmental conditions, agree amazingly well, irrespective of the specimen configuration. Specifically, it was noted in the analysis of surface flaw data that the accommodation of the  $Q$  factor within the rate variable, i.e., and  $d(a/Q)dN$ , tended to distort data correlation which was achievable with  $da/dN$  directly. This implies that the configuration effect for surface flaws is accommodated completely in the independent variable  $\Delta K$ .

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1. Masters, J. N and White, J. L., Development of Fracture Toughness Properties of D6AC Steel for F-111 Applications, AFML-TR-70-130, The Boeing Company (January 1971).
2. Mostovoy, S., Crosley, P. B. and Ripling, E. J., Use of Crack-Line Loaded Specimens for Measuring Plane Strain Fracture Toughness, J. Mater. 2, No. 4 (1967).
3. Gunderson, A. W., Preliminary Mechanical Property Evaluation of D6AC Steel in Support of the F-111 Recovery Program, Technical Memorandum MAA 70-6, Air Force Materials Laboratory (July 1970).
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Key words: Aircraft structures; crack initiation; crack propagation; cracks; critical flaw size; data; environmental effects; fatigue (materials); fracture analysis; fracture mechanics; fracture strength; fractures (materials); high strength alloys; plane strain fracture toughness; steels; stress intensity factor; subcritical crack growth.

FRACTURE TOUGHNESS AND NDT REQUIREMENTS FOR AIRCRAFT DESIGN  
Packman, P. F. (Vanderbilt Univ., Nashville, TN)  
Non-Destruct Test (Guilford, England), 314-324 (December 1973)

This paper reviews current design concepts of fracture toughness for materials selection and for design where fatigue-crack growth is analyzed under constant amplitude and spectrum loading. It is essential that the lower limit of detection be known with confidence. The materials are then chosen so that the critical flaw size is above this limit. From this knowledge the life of a particular design may be forecast for different conditions of service. The lifetime is influenced by both detection capabilities and changes in service conditions.

Comment:

This paper is particularly useful as a summary of NDT information. It includes tables on the surface flaw size to cause failure in materials of different strength and thicknesses and of detection sensitivities for commercial NDT processes.

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2. Paris, P. C. and Sih, G. C., Stress Analysis of Cracks, ASTM STP 381, 30-83 (April 1965).
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Key words: Aircraft structures; crack propagation; critical flaw size; fatigue (materials); fracture mechanics; fracture strength; life prediction; materials selection; NDE; NDI; NDT.

## XC. MATERIALS DEVELOPMENT

### FRACTURE MECHANICS IN MATERIALS SELECTION AND DESIGN

Begley, J. A. (Westinghouse Research Lab., Pittsburgh, PA)  
ASME Fracture and Flaws Symposium, 3-12 (1973)

A simplified linear elastic fracture mechanics design approach is presented. The end point is a quantitative treatment of the flaw tolerance of a structure. This is made possible by information in three areas, material properties, stress analysis and nondestructive testing. Some practical difficulties are described in the application of a fracture mechanics design approach. Finally rules of thumb are proposed for a quick evaluation of the severity of fracture and fatigue crack growth problems. These approximations can help in material selection and in evaluating the need for a sophisticated fracture mechanics analysis.

#### Comment:

The simplified design approach presented in this paper could be a valuable tool - if used only as intended, i.e., as a guide in narrowing the field for materials selection and in determining if additional sophisticated analysis is necessary. The temptation on the part of the designer to employ the simplified approaches and rules of thumb must be avoided because of the serious consequence of brittle fracture failure.

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2. Johnson, H. H. and Paris, P. C., Sub-Critical Flaw Growth, Eng. Fract. Mech. 1, No. 1 (June 1968).
3. Clark, Jr., W. G. and Wessel, E. T., Application of Fracture Mechanics Technology to Medium Strength Steels, in Review of Development in Plane Strain Fracture Toughness Testing, ASTM STP 463, 160-190 (1970).
4. Pellini, W. S., Advances in Fracture Toughness Characterization Procedures and in Quantitative Interpretations to Fracture-Safe for Structural Steels, NRL Report 6713 (April 1968).
5. Heyer, R. H. and McCabe, D. E., Evaluation of a Method of Test for Plane Strain Fracture Toughness Testing Using a Bend Specimen, ASTM STP 463, 22-41 (1970).
6. Roberts, R. and Kibler, J. J., Some Aspects of Fatigue Crack Propagation, Eng. Fract. Mech. 2, No. 3 (May 1971).

Key words: Crack initiation; crack propagation; design criteria; fatigue (materials); fracture mechanics; fracture strength; linear elastic fracture mechanics; materials selection; NDT; plane strain; stress intensity factor; subcritical crack growth.

## SELECTING METALS FOR FRACTURE TOUGHNESS

Steigerwald, E. A. (TW Equipment Labs, Cleveland, OH)  
ASME Paper No. 69-DE-10, presented at the American Society of Mechanical Engineers,  
Design Engineering Conference and Show, New York, NY (May 5-8 1969)

In selecting materials for high strength-to-weight ratio applications the designer must give considerable attention to the crack propagation resistance in order to ensure reliable performance. The current linear elastic fracture mechanics concept have provided a material dependent parameter, plane strain fracture toughness ( $K_{IC}$ ), which can serve as both a material rating parameter and a method of predicting component performance. Representative ( $K_{IC}$ ) values are presented for a variety of high strength steels and several examples are given which indicate possible methods of employing fracture toughness values to make engineering decisions.

### Comment:

This paper gives several examples of how the plane strain fracture toughness ( $K_{IC}$ ) materials property is the critical materials selection factor for high strength applications. This is particularly true for multiaxial applications such as pressure vessels. In addition, several graphical techniques for displaying the data to aid in materials selection are presented such as fracture toughness as a function of temperature and as a function of tensile strength. The use of tensile strength as graphical parameter may be misleading as almost all design criteria involving strength are based on yield rather than tensile strength.

### Important References:

1. Tiffany, C. F. and Masters, J. N., Applied Fracture Mechanics, ASTM STP 381, 249-278 (1965).
2. Srawley, J. E. and Brown, Jr., W. F., Fracture Toughness Testing Methods, ASTM STP 381, 133-198 (1965).
3. Paris, P. C. and Sih, G. C., Stress Analysis of Cracks, ASTM STP 381, 30-83 (1965).

Key words: Design criteria; fractures (materials); high strength alloys; linear elastic fracture mechanics; plane strain fracture toughness; stress intensity factor; structural safety.

## FRACTURE TOUGHNESS TESTING IN ALLOY DEVELOPMENT

Wei, R. P. (United States Steel Corp., Monroeville, PA)  
Fracture Toughness Testing and Its Applications, ASTM STP 381, 279-289 (April 1965)

This paper examines fracture mechanics as a basis for the evaluation of the fracture toughness of high strength steels and other high strength alloys. It discusses some of the considerations involved in the selection of plane strain fracture toughness as the most appropriate and significant parameter for ultra-high strength alloy steel development. The contribution of fracture mechanics

to steel research and development is illustrated with brief reviews of three investigations: (1) a study of the relationships between microstructure and toughness in quenched and tempered low-alloy ultra-high strength steels; (2) an investigation of the effect of sulfur level on the fracture toughness of AISI 4345 alloy steel; and (3) a study of the influence of banding on fracture toughness anisotropy in a maraging steel.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 120).

ENHANCEMENT OF FRACTURE TOUGHNESS IN HIGH STRENGTH STEEL BY MICROSTRUCTURAL CONTROL  
Parker, E. R. and Zackay, V. F. (California, Univ., Berkeley, CA)  
Eng. Fract. Mech. 5, No. 1, 147-165 (1973)

The development of new alloys with improved mechanical properties has been seriously hampered in the past by the inability of a metallurgist to relate quantitatively the variables of microstructure and fracture toughness. The emergence of a unified theory of fracture toughness in the past decade has done much to alleviate this difficulty. As a consequence of a recent interdisciplinary research effort involving both the disciplines of physical metallurgy and experimental fracture mechanics, we have been able to develop alloys with engineering properties superior to those of commercially available materials. This research has required the creation of new and unusual microstructures, utilizing a variety of thermomechanical processes.

The quantitative relationships of mechanical properties (strength, ductility, work hardening, and fracture toughness) with composition and microstructure are discussed in detail for the newly developed TRIP (transformation induced plasticity) steels. In the report of another development, it is shown how the fracture toughness of low alloy quenched and tempered steels with yield strengths over 200,000 psi can be improved by as much as 70 percent by microstructural control. Lastly, the initial results of research on alloys intended for cryogenic service are described. The composition, heat treatment, microstructure and properties of an alloy having more than three times the toughness of the presently used alloys are discussed.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 35).

#### STEELS FOR SEAMLESS HYDROGEN PRESSURE VESSELS

Loginow, A. W. and Phelps, E. H. (United States Steel Corp., Monroeville, PA)  
Presented at Materials Symp. 1974 Petroleum Mechanical Eng. Conf., Dallas, TX)  
(14-18 September 1973)

To provide engineering data useful in the design, manufacture and operation of seamless pressure vessels, extensive tests have been conducted in hydrogen at pressures ranging from 21 to 97 MN/m<sup>2</sup> with precracked specimens of steels having a wide range of mechanical properties. The critical stress intensity level at which crack propagation spontaneously arrests,  $K_{IH}$ , was determined. The values of  $K_{IH}$  were used in an illustrative calculation to estimate the critical flaw size at which hydrogen crack propagation would be expected in thick members loaded in bending. In general, the susceptibility of steels tested increased with yield strength. For the steels with intermediate yield strengths (586 to 770 MN/m<sup>2</sup>),  $K_{IH}$  tended to decrease as pressure was increased from 21 to 97 MN/m<sup>2</sup>. The crack path was analyzed, and a sequence of events is described involving the initiation, growth, and arrest of cracking induced by gaseous hydrogen.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT,  
SEE PAGE ).

#### USING FRACTURE MECHANICS WITH ALUMINUM ALLOY STRUCTURES

Kaufman, J. G., Clark, J. W. and Holt, M. (Aluminum Co. of America, New Kensington, PA)  
Metals. Eng. Quart. 4-11 (February 1973).

Examples demonstrate the applicability of fracture mechanics to the estimation of fracture conditions in high-strength aluminum alloys, ranging from the direct calculation of fracture instability conditions from  $K_{IC}$  values to the indirect estimates of fracture strengths of structure members. Specifically, those examples include: (1) calculation of fracture instability conditions in pressure vessels under cyclic internal pressure, and the relationship to  $K_{IC}$ ; (2) prediction of total service life from initial discontinuity size, fatigue crack growth data, stress-corrosion resistance, and fracture toughness; (3) analysis of ballistic damage through the use of fracture toughness parameters; and (4) estimation of the strengths of single and double-angle structural members from correlations of  $K_{IC}$  with data from small-scale structural tests.

#### Comment:

The authors have shown by example the applicability of fracture mechanics to a number of conditions experienced in the structural application of high strength alloys. Papers of this type, which demonstrate the applicability of fracture mechanics should become more common in the near future and will constitute a significant factor in the further dissemination and application of the technology.

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Key words: Aluminum alloys; crack growth rate; cyclic loads; fracture mechanics; fracture strength; plane strain; pressure vessels; stress intensity factor.

### THE SIGNIFICANCE OF MATERIAL DUCTILITY TO THE RELIABILITY AND LOAD CARRYING CAPACITY OF PEAK PERFORMANCE STRUCTURES

Weiss, V., Sengupta, M. and Sanford, W. (Syracuse University, Syracuse, NY) AD-761217 (January 1973)

The relationships between fracture toughness, flow stress and material ductility were studied for the high strength steels, D6AC and 300M, each heat treated to three strength levels. The experimental part of the study was conducted in three phases: 1. study of the effect of stress state on fracture ductility; 2. study of the notch strength and ductility characteristics of the materials involved; and 3. determination of the fracture toughness of the materials. In addition, the theoretical studies, to develop an analytical basis for correlations between fracture toughness and flow properties of solids, were continued.

The fracture ductility was found to decrease significantly on going from the uniaxial stress state (tension test) to the plane strain stress state (bend test or clausen-type tension test) to the balanced biaxial condition (bulge test or plunger bulge test). The effective fracture strain was generally reduced to a value of less than half the value of the tensile fracture strain and sometimes to a value of only 12 percent of the tensile fracture ductility. A strong influence of the surface finish was noted. This gave rise to some scatter, particularly for the bulge tests. More experimentation is planned in the continuing program to clarify this point.

The notch sensitivity decreased with increasing tempering temperature for both materials, with a reduction being somewhat greater for 300M steels. The values of the Neuber micro support effect constant  $\rho^*$ , were determined and found to be between 0.0002 to 0.0014 inches. Measurements of the effective fracture strain at the notch root showed a general trend of decreasing notch root fracture strain with increasing stress concentration factor. In general, the minimum values of a notch root effective fracture strain lie close to the plunger ductility for 300M steel (hardness  $R_c$  51.5 and  $R_c$  47.5), high for D6AC (hardness  $R_c$  50) and between the bend the plunger ductility for D6AC steel (hardness  $R_c$  46.5 and  $R_c$  42.5). For 300M steel ( $R_c$  39), the scatter in the data was too large to identify a trend.

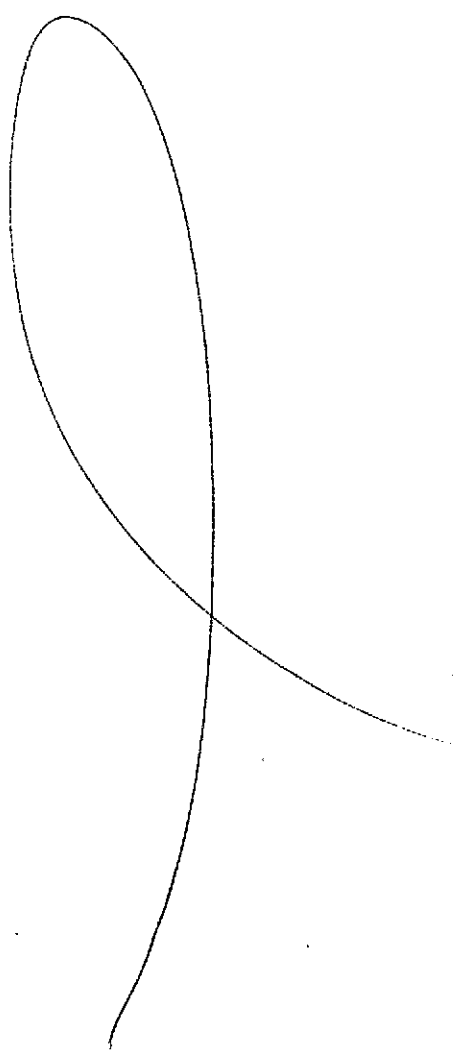
Fracture toughness values were determined for all materials with compact tension specimens. The values determined for 1.0 inch thick specimens met the requirements for plane strain fracture toughness,  $K_{IC}$ .

The analytical studies suggest that the correlation between fracture toughness and ductility should have the general form  $K_{IC} = A_{\epsilon_i} E s \rho^* \epsilon_i$  where  $E$  is the modulus of elasticity,  $s$  the shape factor for the plastic zone (approximately 0.54 for  $n = 1$ )  $\rho^*$  the Neuber micro support effect constant,  $\epsilon_i$  the effective fracture strain corresponding to the stress state  $i$  and  $A_{\epsilon_i}$  a corresponding constant.

The experimental results were found to be in good agreement with the bulge ductility correlation but in somewhat poor agreement with the bend ductility correlation. Surface finish effects in the measurements of the bend ductility could be partly responsible for this discrepancy. The analytical correlations were also extended to the plane stress fracture condition. However, reliable estimates of the fracture strain corresponding to the plane stress condition ahead of a crack could not be made. Furthermore an experimental determination of the true plane stress fracture toughness is difficult. Nevertheless, it is anticipated that similar correlations can be established for plane stress conditions or mixed mode fracture.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT,  
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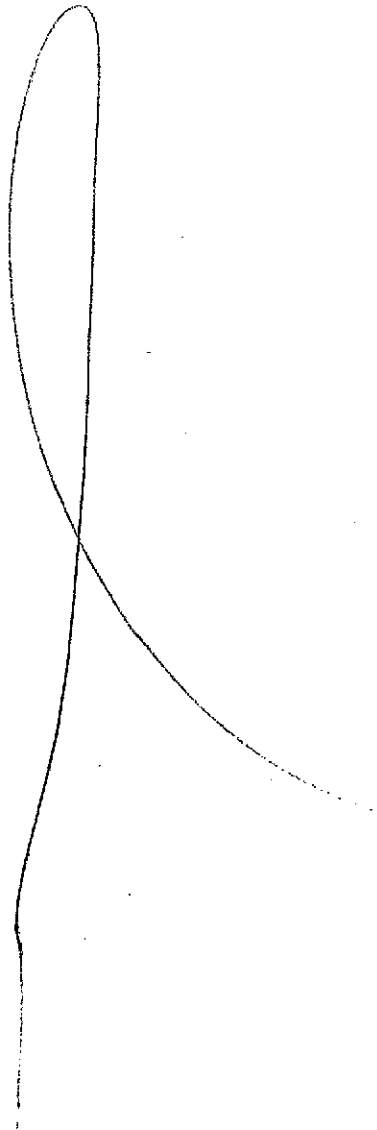
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