

# ASM<sup>®</sup> HANDBOOK

Volume  
**19**

**Fatigue  
and Fracture**



The Materials  
Information Society

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# Foreword

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The publication of this Volume marks the first time that the *ASM Handbook* series has dealt with fatigue and fracture as a distinct topic. Society members and engineers involved in the research, development, application, and analysis of engineering materials have had a long-standing interest and involvement with fatigue and fracture problems, and this reference book is intended to provide practical and comprehensive coverage of all aspects of these subjects.

Publication of *Fatigue and Fracture* also marks over 50 years of continuing progress in the development and application of modern fracture mechanics. Numerous Society members have been actively involved in this progress, which is typified by the seminal work of George Irwin ("Fracture Dynamics," *Fracturing of Metals*, ASM, 1948). Since that time period, fracture mechanics has become a vital engineering discipline that has been integrally involved in helping to prevent the failure of essentially all types of engineered structures.

Likewise, fatigue and crack growth have also become of primary importance to the development and use of advanced structural materials, and this Volume addresses the wide range of fundamental, as well as practical, issues involved with these disciplines.

We believe that our readers will find this Handbook useful, instructive, and informative at all levels. We also are especially grateful to the authors and reviewers who have made this work possible through their generous commitments of time and technical expertise. To these contributors we offer our special thanks.

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# Policy on Units of Measure

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By a resolution of its Board of Trustees, ASM International has adopted the practice of publishing data in both metric and customary U.S. units of measure. In preparing this Handbook, the editors have attempted to present data in metric units based primarily on *Système International d'Unités* (SI), with secondary mention of the corresponding values in customary U.S. units. The decision to use SI as the primary system of units was based on the aforementioned resolution of the Board of Trustees and the widespread use of metric units throughout the world.

For the most part, numerical engineering data in the text and in tables are presented in SI-based units with the customary U.S. equivalents in parentheses (text) or adjoining columns (tables). For example, pressure, stress, and strength are shown both in SI units, which are pascals (Pa) with a suitable prefix, and in customary U.S. units, which are pounds per square inch (psi). To save space, large values of psi have been converted to kips per square inch (ksi), where 1 ksi = 1000 psi. The metric tonne ( $\text{kg} \times 10^3$ ) has sometimes been shown in megagrams (Mg). Some strictly scientific data are presented in SI units only.

To clarify some illustrations, only one set of units is presented on artwork. References in the accompanying text to data in the illustrations are presented in both SI-based and customary U.S. units. On graphs and charts, grids corresponding to SI-based units appear along the left and bottom edges. Where appropriate, corresponding customary U.S. units appear along the top and right edges.

Data pertaining to a specification published by a specification-writing group, may be given in only the units used in that specification or in dual units, depending on the nature of the data. For example, the typical yield strength of steel sheet made to a specification written in customary U.S.

units would be presented in dual units, by the sheet thickness specified in that specification might be presented only in inches.

Data obtained according to standardized test methods for which the standard recommends a particular system of units are presented in the units of that system. Wherever feasible, equivalent units are also presented. Some statistical data may also be presented in only the original units used in the analysis.

Conversions and rounding have been done in accordance with ASTM Standard E 380, with attention given to the number of significant digits in the original data. For example, an annealing temperature of 1570 °F contains three significant digits. In this case, the equivalent temperature would be given as 855 °C; the exact conversion to 854.44 °C would not be appropriate. For an invariant physical phenomenon that occurs at a precise temperature (such as the melting of pure silver), it would be appropriate to report the temperature as 961.93 °C or 1763.5 °F. In some instances (especially in tables and data compilations), temperature values in °C and °F are alternatives rather than conversions.

The policy of units of measure in this Handbook contains several exceptions to strict conformance to ASTM E 380; in each instance, the exception has been made in an effort to improve the clarity of the Handbook. The most notable exception is the use of  $\text{g}/\text{cm}^3$  rather than  $\text{kg}/\text{m}^3$  as the unit of measure for density (mass per unit volume).

SI practice requires that only one virgule (diagonal) appear in units formed by combination of several basic units. Therefore, all of the units preceding the virgule are in the numerator and all units following the virgule are in the denominator of the expression; no parentheses are required to prevent ambiguity.

# Preface

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This volume of the *ASM Handbook* series, *Fatigue and Fracture*, marks the first separate Handbook on an important engineering topic of long-standing and continuing interest for both materials and mechanical engineers at many levels. Fatigue and fracture, like other forms of material degradation such as corrosion and wear, are common engineering concerns that often limit the life of engineering materials. This perhaps is illustrated best by the "Directory of Examples of Failure Analysis" contained in Volume 10 of the 8th Edition *Metals Handbook*. Over a third of all examples listed in that directory are fatigue failures, and well over half of all failures are related to fatigue, brittle fracture, or environmentally-assisted crack growth.

The title *Fatigue and Fracture* also represents the decision to include fracture mechanics as an integral part in characterizing and understanding not only ultimate fracture but also "subcritical" crack growth processes such as fatigue. The development and application of fracture mechanics has steadily progressed over the last 50 years and is a field of long-standing interest and involvement by ASM members. This perhaps is best typified by the seminal work of George Irwin in *Fracturing of Metals* (ASM, 1948), which is considered by many as the one of the key beginnings of modern fracture mechanics based from the foundations established by Griffith at the start of this century.

This Handbook has been designed as a resource for basic concepts, alloy property data, and the testing and analysis methods used to characterize the fatigue and fracture behavior of structural materials. The overall intent is to provide coverage for three types of readers: i) metallurgists and materials engineers who need general guidelines on the practical implications of fatigue and fracture in the selection, analysis or application structural materials; ii) mechanical engineers who need information on the relative performance and the mechanistic basis of fatigue and fracture resistance in materials; and iii) experts seeking advanced coverage on the scientific and engineering models of fatigue and fracture.

Major emphasis is placed on providing a multipurpose reference book for both materials and mechanical engineers with varying levels of expertise. For example, several articles address the basic concepts for making esti-

mates of fatigue life, which is often necessary when data are not available for a particular alloy condition, product configuration, or stress conditions. This is further complemented with detailed coverage of fatigue and fracture properties of ferrous, nonferrous, and nonmetallic structural materials. Additional attention also is given to the statistical aspects of fatigue data, the planning and evaluation of fatigue tests, and the characterization of fatigue mechanisms and crack growth.

Fracture mechanics is also thoroughly covered in Section 4, from basic concepts to detailed applications for damage tolerance, life assessment, and failure analysis. The basic principles of fracture mechanics are introduced with a minimum of mathematics, followed by practical introductions on the fracture resistance of structural materials and the current methods and requirements for fracture toughness testing. Three authoritative articles further discuss the use of fracture mechanics in fracture control, damage tolerance analysis, and the determination of residual strength in metallic structures. Emphasis is placed on linear-elastic fracture mechanics, although the significance of elastic-plastic fracture mechanics is adequately addressed in these key articles.

Further coverage is devoted to practical applications and examples of fracture control in weldments, process piping, aircraft systems, failure analysis, and more advanced topics such as high-temperature crack growth and thermo-mechanical fatigue. Extensive fatigue and fracture property data are provided in Sections 5 through 7, and the Appendices include a detailed compilation of fatigue strength parameters and an updated summary of commonly used stress-intensity factors.

Once again, completion of this challenging project under the auspices of the Handbook Committee is made possible by the time and patience of authors who have contributed their work. Their efforts are greatly appreciated along with the guidance from reviewers and the Editorial Review Board.

S. Lämpman  
Technical Editor

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# Contents

<b>Section 1: Introduction</b> .....	<b>1</b>	<b>Environmental Effects</b>	
Industrial Significance of Fatigue Problems .....	3	Stress Corrosion Cracking and Hydrogen Embrittlement .....	483
Fracture and Structure .....	5	Elevated-Temperature Crack Growth .....	507
Fatigue Properties in Engineering .....	15	High-Temperature Life Assessment .....	520
Alloy Design for Fatigue and Fracture .....	27	Thermal and Thermo-Mechanical Fatigue of Structural Alloys ..	527
Micromechanisms of Monotonic and Cyclic Crack Growth .....	42	<b>Damage Tolerance of Aircraft Systems</b>	
<b>Section 2: Fatigue Mechanisms, Crack Growth, and Testing</b> .....	<b>61</b>	Life Extension and Damage Tolerance of Aging Aircraft .....	557
Fatigue Failure in Metals .....	63	Damage Tolerance Certification of Commercial Aircraft .....	566
Cyclic Stress-Strain Response and Microstructure .....	73	The Air Force Approach to Aircraft Damage Tolerant Design. ...	577
Fatigue Crack Nucleation and Microstructure .....	96	<b>Section 5: Fatigue and Fracture Resistance of Ferrous Alloys</b> ...	<b>589</b>
Fatigue Crack Growth under Variable-Amplitude Loading .....	110	Fracture and Fatigue Properties of Structural Steels .....	591
Fatigue Crack Thresholds .....	134	Fatigue Resistance and Microstructure of Ferrous Alloys .....	605
Behavior of Small Fatigue Cracks .....	153	Fracture Mechanics Properties of Carbon and Alloy Steels .....	614
Effect of Crack Shape on Fatigue Crack Growth .....	159	Fatigue and Fracture Properties of Cast Steels .....	655
Fatigue Crack Growth Testing .....	168	Fatigue and Fracture Properties of Cast Irons .....	665
Appendix: High-Temperature Fatigue Crack Growth Testing ..	181	Bending Fatigue of Carburized Steels .....	680
Mechanisms of Corrosion Fatigue .....	185	Contact Fatigue of Hardened Steels .....	691
Corrosion Fatigue Testing .....	193	Fatigue and Fracture Mechanics of Heat-Resistant (Cr-Mo)	
Detection and Monitoring of Fatigue Cracks .....	210	Ferritic Steels .....	704
<b>Section 3: Fatigue Strength Prediction and Analysis</b> .....	<b>225</b>	Fatigue and Fracture Properties of Stainless Steels .....	712
Fundamentals of Modern Fatigue Analysis for Design .....	227	Fracture Toughness of Austenitic Stainless Steels	
Estimating Fatigue Life .....	250	and Their Welds .....	733
Multiaxial Fatigue Strength .....	263	Fatigue and Fracture Properties of Duplex Stainless Steels .....	757
Factors Influencing Weldment Fatigue .....	274	<b>Section 6: Fatigue and Fracture Resistance</b>	
Fatigue of Mechanically Fastened Joints .....	287	<b>of Nonferrous Alloys</b> .....	<b>769</b>
Statistical Considerations in Fatigue .....	295	Selecting Aluminum Alloys to Resist Failure	
Planning and Evaluation of Fatigue Tests .....	303	by Fracture Mechanisms .....	771
<b>Surface Effects on Fatigue</b>		Fatigue and Fracture Properties of Cast Aluminum Alloys .....	813
Effect of Surface Conditions and Processing		Fatigue Strength of Aluminum Alloy Welds .....	823
on Fatigue Performance .....	314	Fatigue and Fracture Resistance of Titanium Alloys .....	829
Fretting Fatigue .....	321	Fatigue and Fracture Properties of Superalloys .....	854
Contact Fatigue .....	331	Fatigue Properties of Copper Alloys .....	869
<b>Fatigue of Special Forms or Components</b>		Fatigue and Fracture Resistance of Magnesium Alloys .....	874
Fatigue and Fracture Control for Powder		Fatigue of Solders and Electronic Materials .....	882
Metallurgy Components .....	337	<b>Section 7: Fatigue and Fracture of Composites,</b>	
Fatigue and Life Prediction of Gears .....	345	<b>Ceramics, and Glasses.</b> .....	<b>893</b>
Fatigue and Life Prediction of Bearings .....	355	Fracture and Fatigue of DRA Composites .....	895
Fatigue of Springs .....	363	Fatigue of Composite Laminates .....	905
<b>Section 4: Fracture Mechanics, Damage Tolerance,</b>		Residual Strength with Damage in Composite	
<b>and Life Assessment</b> .....	<b>369</b>	Aircraft Structures .....	920
An Introduction to Fracture Mechanics .....	371	Fatigue of Brittle Materials .....	936
Fracture Resistance of Structural Alloys .....	381	Toughening and Strengthening Models for Nominally	
Fracture Toughness Testing .....	393	Brittle Materials .....	946
Concepts of Fracture Control and Damage Tolerance .....	410	Fatigue and Fracture Behavior of Glasses .....	955
The Practice of Damage Tolerance Analysis .....	420	<b>Appendices</b> .....	<b>961</b>
Residual Strength of Metal Structures .....	427	Parameters for Estimating Fatigue Life .....	963
Fatigue and Fracture Control of Weldments .....	434	Stress Intensity Factors .....	980
Fracture Mechanics in Failure Analysis .....	450	<b>Metric Conversion Guide</b> .....	<b>1001</b>
Stress Maps for Failure Control .....	457	<b>Abbreviations and Symbols</b> .....	<b>1003</b>
Failure Control in Process Operations .....	468	<b>Index</b> .....	<b>1005</b>

# Section 1: Introduction

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Industrial Significance of Fatigue Problems .....	3
Fracture and Structure .....	5
Fatigue Properties in Engineering .....	15
Alloy Design for Fatigue and Fracture .....	27
Micromechanisms of Monotonic and Cyclic Crack Growth .....	42



# Industrial Significance of Fatigue Problems

David W. Hoepfner, Department of Mechanical Engineering, The University of Utah

THE DISCOVERY of fatigue occurred in the 1800s when several investigators in Europe observed that bridge and railroad components were cracking when subjected to repeated loading. As the century progressed and the use of metals expanded with the increasing use of machines, more and more failures of components subjected to repeated loads were recorded. By the mid 1800s A. Wohler (Ref 1) had proposed a method by which the failure of components from repeated loads could be mitigated, and in some cases eliminated. This method resulted in the stress-life response diagram approach and the component test model approach to fatigue design.

Undoubtedly, earlier failures from repeated loads had resulted in failures of components such as clay pipes, concrete structures, and wood structures, but the requirement for more machines made from metallic components in the late 1800s stimulated the need to develop design procedures that would prevent failures from repeated loads of all types of equipment. This activity was intensive from the mid-1800s and is still underway today. Even though much progress has been made, developing design procedures to prevent failure from the application of repeated loads is still a daunting task. It involves the interplay of several fields of knowledge, namely materials engineering, manufacturing engineering, structural analysis (including loads, stress, strain, and fracture mechanics analysis), nondestructive inspection and evaluation, reliability engineering, testing technology, field repair and maintenance, and holistic design procedures. All of these must be placed in a consistent design activity that may be referred to as a fatigue design policy. Obviously, if other time-related failure modes occur concomitantly with repeated loads and interact synergistically, then the task becomes even more challenging. Inasmuch as humans always desire to use more goods and place more demands on the things we can design and produce, the challenge of fatigue is always going to be with us.

Until the early part of the 1900s, not a great deal was known about the physical basis of fatigue. However, with the advent of an increased

understanding of materials, which accelerated in the early 1900s, a great deal of knowledge has been developed about repeated load effects on engineering materials. The procedures that have evolved to deal with repeated loads in design can be reduced to four:

- The stress-life approach
- The strain-life approach
- The fatigue-crack propagation approach (part of a larger design activity that has become known as the damage-tolerant approach)
- The component test model approach

## What is Fatigue?

*Fatigue* is a technical term that elicits a degree of curiosity. When citizens read or hear in their media of another fatigue failure, they wonder whether this has something to do with getting tired or "fatigued" as they know it. Such is not the case.

One way to explain fatigue is to refer to the ASTM standard definitions on fatigue, contained in ASTM E 1150. It is difficult, if not impossible, to carry on intelligent conversations if discussions on fatigue do not use a set of standard definitions such as E 1150. Within E 1150, there are over 75 terms defined, including the term *fatigue*: "fatigue (Note 1): the *process of progressive localized permanent structural change* occurring in a material subjected to conditions that produce *fluctuating stresses and strains* at some *point or points* and that may culminate in *cracks or complete fracture* after a sufficient number of fluctuations (Note 2). Note 1—In glass technology static tests of considerable duration are called 'static fatigue' tests, a type of test generally designated as stress-rupture. Note 2—Fluctuations may occur both in load and with time (frequency) as in the case of 'random vibration'." (Ref 2).

The words in italics (emphasis added) are viewed as key words in the definition. These

words are important perspectives on the phenomenon of fatigue:

- Process
- Progressive
- Localized
- Permanent structural change
- Fluctuating stresses and strains
- Point or points
- Cracks or complete fracture

The idea that fatigue is a *process* is critical to dealing with it in design and to the characterization of materials as part of design. In fact, this idea is so critical that the entire conceptual view of fatigue is affected by it! Another critical idea is the idea of *fluctuating stresses and strains*. The need to have fluctuating (repeated or cyclic) stresses acting under either constant amplitude or variable amplitude is critical to fatigue. When a failure is analyzed and attributed to fatigue, the only thing known at that point is that the loads (the stresses/strains) were fluctuating. Nothing is necessarily known about the *nucleation* of damage that forms the origin of fatigue cracks.

## Design for Fatigue Prevention

In design for fatigue and damage tolerance, one of two initial assumptions is often made about the state of the material. Both of these are related to the need to invoke continuum mechanics to make the stress/strain/fracture mechanics analysis tractable:

- The material is an ideal homogeneous, continuous, isotropic continuum that is free of defects or flaws.
- The material is an ideal homogeneous, isotropic continuum but contains an ideal crack-like discontinuity that may or may not be considered a defect or flaw, depending on the entire design approach.

The former assumption leads to either the stress-life or strain-life fatigue design approach.

## 4 / Introduction

These approaches are typically used to design for finite life or "infinite life." Under both assumptions, the material is considered to be free of defects, except insofar as the sampling procedure used to select material test specimens may "capture" the probable "defects" when the specimen locations are selected for fatigue tests. This often has proved to be an unreliable approach and has led, at least in part, to the damage-tolerant approach.

Another possible difficulty with these assumptions is that inspectability and detectability are not inherent parts of the original design approach. Rather, past and current experience guide field maintenance and inspection procedures, if and when they are considered.

The damage-tolerant approach is used to deal with the possibility that a crack-like discontinuity (or multiple ones) will escape detection in either the initial product release or field inspection practices. Therefore, it couples directly to nondestructive inspection (NDI) and evaluation (NDE). In addition, the potential for initiation of crack propagation must be considered an integral part of the design process, and the subcritical crack growth characteristics under monotonic, sustained, and cyclic loads must be incorporated in the design. The final instability parameter, such as plane strain fracture toughness ( $K_{Ic}$ ), also must be incorporated in design. The damage-tolerant approach is based on the ability to track the damage throughout the entire life cycle of the component/system. It therefore requires extensive knowledge of the above issues, and it also requires that fracture (or damage) mechanics models be available to assist in the evaluation of potential behavior. As well, material characterization procedures are needed to ensure that valid evaluation of the required material "property" or response characteristic is made. NDI must be performed to ensure that probability-of-detection determinations are made for the NDI procedure(s) to be used. This approach has proved to be reliable, especially for safety-critical components.

The above approaches often are used in a complementary sense in fatigue design. The details of all three approaches are discussed in this Volume.

The *fatigue process* has proved to be very difficult to study. Nonetheless, extensive progress on understanding the phases of fatigue has been made in the last 100 years or so. It now is gener-

ally agreed that four distinct phases of fatigue may occur (Ref 3, 4):

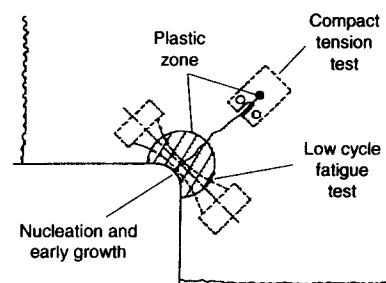
- Nucleation
- Structurally dependent crack propagation (often called the "short crack" or "small crack" phase)
- Crack propagation that is characterizable by either linear elastic fracture mechanics, elastic-plastic fracture mechanics, or fully plastic fracture mechanics
- Final instability

Each of these phases is an extremely complex process (or may involve several processes) in and of itself. For example, the nucleation of "fatigue" cracks is extremely difficult to study, and even "pure fatigue" mechanisms can be very dependent on the intrinsic makeup of the material. Obviously, when one decides to pursue the nucleation of cracks in a material, one has already either assumed that the material is crack-free or has proved it! The assumption is the easier path and the one most often taken. When extraneous influences are involved in nucleation, such as temperature effects (e.g., creep), corrosion of all types, or fretting, the problem of modeling the damage is formidable. In recent years, more research has been done on the latter issues, and models for this phase of life are beginning to emerge.

### Industrial Significance

There is little doubt that fatigue plays a significant role in all industrial design applications. Many components are subjected to some form of fluctuating stress/strain, and thus fatigue potentially plays a role in all such cases. However, it is still imperative that all designs consider those aspects of nucleation processes other than fatigue that may act to nucleate cracks that could propagate under the influence of cyclic loads. The intrinsic state of the material and all potential sources of cracks must also be evaluated.

Nonetheless, fatigue is a significant and often a critical factor in the testing, analysis, and design of engineering materials for machines, structures, aircraft, and power plants. An important engineering advance of this century is also the transfer of the multi-stage fatigue process from the field to the laboratory. In order to study, explain, and qualify component designs, or to conduct failure



**Fig. 1** Laboratory simulation of the multi-stage fatigue process. Source: Ref 5

analyses, a key engineering step is often the simulation of the problem in the laboratory. Any simulation is, of course, a compromise of what is practical to quantify, but the study of the multi-stage fatigue process has been greatly advanced by the combined methods of strain-control testing and the development fracture mechanics of fatigue crack growth rates. This combined approach (Fig. 1) is a key advance that allows better understanding and simulation of both crack nucleation in regions of localized strain and the subsequent crack growth mechanisms outside the plastic zone. This integration of fatigue and fracture mechanics has had important implications in many industrial applications for mechanical and materials engineering.

### REFERENCES

1. A. Wohler, *Z. Bauw*, Vol 10, 1860, p 583
2. ASTM E 1150-1987, Standard Definitions of Fatigue, *1995 Annual Book of Standards*, ASTM, 1995, p 753-762
3. D.W. Hoepfner, Estimation of Component Life by Application of Fatigue Crack Growth Threshold Knowledge, *Fatigue, Creep, and Pressure Vessels for Elevated Temperature Service, MPC-17*, ASME, 1981, p 1-85
4. D.W. Hoepfner, Parameters That Input to Application of Damage Tolerant Concepts to Critical Engine Components invited keynote paper, *Damage Tolerance Concepts for Critical Engine Components*, AGARD-CP-393, NATO-AGARD, 1985
5. L.F. Coffin, *Fatigue in Machines and Structures, Fatigue and Microstructure*, American Society for Metals, 1979

# Fracture and Structure

C. Quinton Bowles, University of Missouri-Columbia/Kansas City

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IT IS DIFFICULT to identify exactly when the problems of failure of structural and mechanical equipment became of critical importance; however, it is clear that failures that cause loss of life have occurred for over 100 years (Ref 1, 2). Throughout the 1800s bridges fell and pressure vessels blew up, and in the late 1800s railroad accidents in the United Kingdom were continually reported as "The most serious railroad accident of the week"! Those in the United States also have heard the hair-raising stories of the Liberty ships built during World War II. Of 4694 ships considered in the final investigation, 24 sustained complete fracture of the strength deck, and 12 ships were either lost or broke in two. In this case, the need for tougher structural steel was even more critical because welded construction was used in shipbuilding instead of riveted plate. In riveted plate construction, a running crack must reinitiate every time it runs out of a plate. In contrast, a continuous path is available for brittle cracking in a welded structure, which is why low notch toughness is a more critical factor for long brittle cracks in welded ships.

Similar long brittle cracks are less likely or rare in riveted ships, which were predominant prior to welded construction. Nonetheless, even riveted ships have provided historical examples of long brittle fracture due, in part, from low toughness. In early 1995, for example, the material world was given the answer to an old question, "What was the ultimate cause of the sinking of the Titanic?" True, the ship hit an iceberg, but it now seems clear that because of brittle steel, "high in sulfur content even for its time" (Ref 3), an impact which would clearly have caused damage, perhaps would not have resulted in the ultimate separation of the Titanic in two pieces where it was found in 1985 by oceanographer Bob Ballard. During the undersea survey of the sunken vessel with Soviet Mir submersibles, a small piece of plate was retrieved from 12,612 feet below the ocean's surface. Examination by spectroscopy revealed a high sulfur content, and a Charpy impact test revealed the very brittle nature of the steel (Ref 3). However, there was some concern that the high sulfur content was, in some way, the result of eighty years on the ocean floor at 6,000 psi pressures. Subsequently, the son of a 1911 shipyard worker remembered a rivet hole

plug which his father had saved as a memento of his work on the Titanic. Analysis of the plug revealed the same level of sulfur exhibited by the plate from the ocean floor. In the years following the loss of the Titanic metallurgists have become well aware of the detrimental effect of high sulfur content on fracture.

There are numerous other historical examples where material toughness was inadequate for design. The failures of cast iron rail steel for engine loads in the 1800s is one example. A large body of scientific folklore has arisen to explain structural material failures, almost certainly caused by a lack of tools to investigate the failures. The author was recently startled to read an article on the building of the Saint Lawrence seaway that described the effect of temperature on equipment: "The crawler pads of shovels and bulldozers subject to stress cracked and crumbled. Drive chains flew apart, cables snapped and fuel lines iced up... And anything made of metal, especially cast metal, was liable to crystallize and break into pieces (Ref 4). It is difficult to realize that there still exists a concept of metal crystallization as a result of deformation that in turn leads to failure. Clearly, the development of fluorescence and diffraction x-ray analysis, transmission and scanning electron microscopes, high-quality optical microscopy, and numerous other analytical instruments in the last 75 years has allowed further development of dislocation theory and clarification of the mechanisms of deformation and fracture at the atomic level.

During the postwar period, predictive models for fracture control also were pursued at the engineering level from the work of Griffith, Orowan, and Irwin. Since the paper of Griffith in 1920 (Ref 5, 6) and the extensions of his basic theory by Irwin (Ref 7) and others, we have come to realize that the design of structures and machines can no longer under all conditions be based on the elastic limit or yield strength. Griffith's basic theory is applicable to all fractures in which the energy required to make the new surfaces can be supplied from the store of energy available as potential energy, in the form of elastic strain energy. The elastic strain energy per unit of volume varies with the square of the stress, and hence increases rapidly with increases in the stress level. One does not need to go to very high stress

levels to store enough energy to drive a crack, even though this crack can be accompanied by considerable plastic deformation, and hence consume considerable energy. Thus, self-sustaining cracks can propagate at fairly low stress levels, a phenomenon that is briefly reviewed in this article along with the microstructural factors that influence toughness.

## Fracture Behavior

In most structural failures, final fracture is usually abrupt after some sort of material or design flaw (such as a material defect, improper condition, or poor design detail) that is aggravated by a crack growth process that causes the crack to reach a critical size for final fracture. The cracking process occurs slowly over the service life from various crack growth mechanisms such as fatigue, stress-corrosion cracking, creep, and hydrogen-induced cracking. Each of these cracking mechanisms has certain characteristic features that are used in failure analysis to determine the cause of cracking or crack growth.

In contrast, the final fracture is usually abrupt and occurs from cleavage, rupture, or intergranular fracture (which may involve a combination of rupture and cleavage). Fracture mechanisms also are termed "ductile," although these terms must be defined on either a macroscopic or microscopic level. This distinction is important, because a fracture may be termed "brittle" from an engineering (macroscopic) perspective, while the underlying metallurgical (microscopic) mechanism could be termed either ductile or brittle. For metallurgists, cleavage is often referred to as brittle fracture and dimple rupture is considered ductile fracture. However, these terms must be used with caution, because many service failures occur by dimple rupture, even though most of these failures undergo very little overall (macroscopic) plastic deformation from an engineering point of view.

The majority of structural failures are of the more worrisome type, brittle fracture, and these almost invariably initiate at defects, notches, or discontinuities. Cracks resulting from machining, quenching, fatigue, hydrogen embrittlement, liquid-metal embrittlement, or stress corrosion also



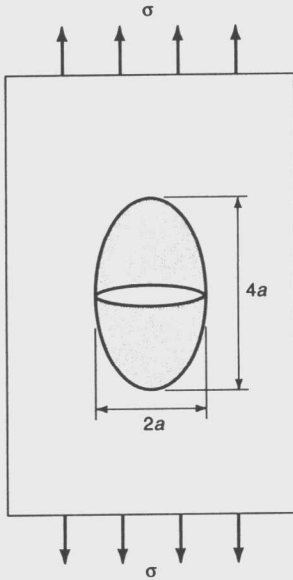


Fig. 1 Schematic illustration of the concept of energy release around a center crack in a loaded plate

lead to brittle fracture. In fact, the single most prevalent initiator of brittle fracture is the fatigue crack, which conservatively accounts for at least 50% of all brittle fractures in manufactured products by one account (Ref 8).

In contrast, service failure by macroscopic ductile failure is relatively infrequent (although the microscopic mechanisms of ductile fracture can ultimately lead to macroscopic brittle fracture). Typically, macroscopic ductile fracture occurs from overloads as a result of the part having been underdesigned (a term that includes the selection and heat treatment of the materials) for a specific set of service conditions, improperly fabricated, or fabricated from defective materials. Ductile fracture may also be the result of the part having been abused (that is, subjected to conditions of load and environment that exceeded those of the intended use).

This section briefly introduces the macroscopic and microscopic basis of understanding and modeling fracture resistance, while other articles in this Volume expand upon the microscopic and macroscopic basis of fatigue and fracture in engineering research and practice. More detailed information on the mechanisms of ductile and brittle fracture is given in the article "Micromechanisms of Monotonic and Cyclic Crack Growth" in this Volume.

**Griffith Theory and the Specific Work of Fracture.** The origins of modern fracture mechanics for engineering practice may be traced to Griffith (Ref 5, 6), who established an energy-release-rate criterion for brittle materials. Observations of the fracture strength of glass rods had shown that the longer the rod, the lower the strength. Thus the idea of a distribution of flaw sizes evolved, and it was discovered that the longer the rod, the larger the chance of finding a large natural flaw. This physical insight led to an instability criterion that considered the elastic en-

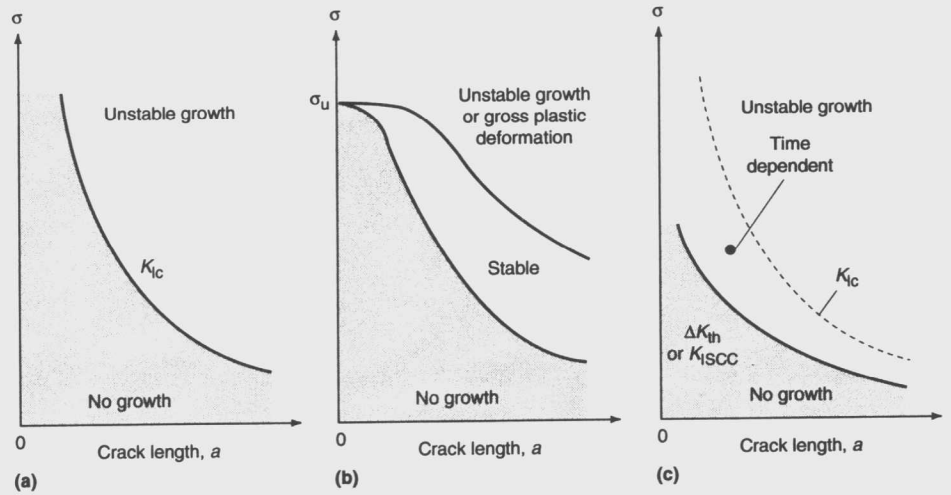


Fig. 2 Relationships between stress and crack length, showing regions and types of crack growth. (a) Linear-elastic. (b) Elastic-plastic. (c) Subcritical

ergy released in a solid at the time a flaw grew catastrophically under an applied stress.

From the theory of elasticity comes the concept that the strain energy contained in an elastic body per unit volume is simply the area under the stress-strain curve, or:

$$U_0 = \frac{\sigma^2}{2E} \quad (\text{Eq 1})$$

where  $\sigma$  is the applied stress and  $E$  is Young's modulus. However, there is a reduction (that is, a release) of energy in an elastic body containing a flaw or a crack because of the inability of the unloaded crack surfaces to support a load. We shall assume that the volume of material whose energy is released is the area of an elliptical region around the crack (as shown in Fig. 1) times the plate thickness,  $B$ ; the volume is  $\pi(2a) \cdot (a)B$ . This is based on the area of an ellipse being  $\pi r_a r_b$ , where  $r_a$  and  $r_b$  are the major and minor radii of the ellipse. Then, the total energy released from the body due to the crack is the energy per unit volume times the volume, which is:

$$U = \pi(2a)(a)B \frac{\sigma^2}{2E} = \frac{\pi\sigma^2 a^2 B}{E} \quad (\text{Eq 2})$$

In ideally brittle solids, the released energy can be offset only by the surface energy absorbed, which is:

$$W = (2aB)(2\gamma_s) = 4aB\gamma_s \quad (\text{Eq 3})$$

where  $2aB$  is the area of the crack and  $2\gamma_s$  is twice the surface energy per unit area (because there are two crack surfaces).

Griffith's energy-balance criterion, in the simplest sense, is that crack growth will occur when the amount of energy released due to an increment of crack advance is larger than the amount of energy absorbed:

$$\frac{dU}{da} \geq \frac{dW}{da} \quad (\text{Eq 4})$$

Performing the derivatives indicated in Eq 4 and rearranging gives the Griffith criterion for crack growth:

$$\sigma\sqrt{\pi a} = \sqrt{2E\gamma_s} \quad (\text{Eq 5})$$

Fracture theory was built upon this criterion in the early 1940s by considering that the critical strain energy release rate,  $G_c$ , required for crack growth was equal to twice an effective surface energy,  $\gamma_{\text{eff}}$ :

$$G_c = 2\gamma_{\text{eff}} \quad (\text{Eq 6})$$

This  $\gamma_{\text{eff}}$  is predominantly the plastic energy absorption around the crack tip, with only a small part due to the surface energy of the crack surfaces. Then, with the development of complex variable and numerical techniques to define the stress fields near cracks, this energy view was supplemented by stress concepts (i.e., the stress-intensity factor,  $K$ , and a critical value of  $K$  for crack growth,  $K_c$ ). Replacing  $\gamma_s$  with  $\gamma_{\text{eff}}$  in Eq 5 and noting that the energy and stress concepts are essentially identical (that is,  $K = \sqrt{EG}$ ) gives:

$$K_c = \sqrt{EG_c} = \sigma\sqrt{\pi a} \quad (\text{Eq 7})$$

which is the crack-growth-criterion equivalent of Eq 1. Thus,  $K_c$  is the critical value of  $K$  that, when it is exceeded by a combination of applied stress and crack length, will lead to crack growth. For thick-plate plane-strain conditions, this critical value became known as the plane-strain fracture toughness,  $K_{Ic}$ , and any combination of applied stress and crack length that exceeds this value could produce unstable crack growth, as indicated schematically in Fig. 2(a) (linear-elastic). This forms the basis for understanding the relation between flaw size and fracture stress, which can be significantly lower than yield strengths, depending on crack length and geometry (Fig. 3).

In work with tougher, lower-strength materials, it was later noted that stable slow crack growth could occur even though accompanied by consid-