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26TH VOLUME

Walter G. Reuter,
John H. Underwood and
James C. Newman, editors

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The quality of the papers in this publication reflects not only the obvious efforts of the authors and the technical editor(s), but also the work of these peer reviewers. The ASTM Committee on Publications acknowledges with appreciation their dedication and contribution to time and effort on behalf of ASTM.

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Overview

The ASTM National Symposium on Fracture Mechanics is sponsored by ASTM Committee E08 on Fatigue and Fracture Testing. The original objective of these symposia was to promote technical interchange between researchers from the United States and worldwide in the field of Fracture. This objective was recently expanded to promote technical interchange between researchers in the field of fatigue and fracture. The meeting attracted about 100 researchers covering a broad range of issues in constraint, weldments, advanced materials, and practical applications.

The volume opens with the paper by Merkle who delivered the Fifth Annual Jerry L. Swedlow Memorial Lecture at this symposium. Merkle's presentation provided a brief philosophical and historical overview of applied fracture mechanics, particularly as it pertains to the safety of pressure vessels. The importance of constraint, a fundamental aspect of fracture mechanics in which Jerry Swedlow had a keen interest and made valuable contributions, was presented along with the need for physically realistic analysis. Additional insight into constraint effects on fracture toughness was developed by considering the roles played by the plastic strains, as well as the stresses that develop near a crack tip.

There are 42 papers following the Merkle paper that are broadly grouped in the same categories used to separate the presentation at the symposium. The constraint issue was separated into Crack Initiation with seven papers examining J or CTOD, and Crack Growth with seven papers investigating plane strain or plane stress conditions. Following these papers, there is a section on Weldment with eight papers. These papers are primarily concerned with effects of weld metal mismatch on the fracture process. The remaining papers discuss strain aging and nodular cast iron. The next section on Engineered Materials contains nine papers that cover a variety of topics consisting of monotonic or cyclic loading of ceramics, composites, adhesive joints, graded materials, paper, and an Al-Li alloy. The last three sections consist of Subcritical Crack Growth with five papers that present results of studies on fatigue, creep, or stress corrosion crack growth; Dynamic Loading with two papers; and Applications with four papers.

The technical quality of these papers is due to the authors and to the fine reviews provided by the reviewers. The symposium organizers would like to express our appreciation to all reviewers for a job well done. Because of the large number of papers, camera-ready manuscripts were used to develop the STP. The organizers of the symposium hope that it meets your approval.

The National Symposium on Fracture Mechanics is often used to present ASTM awards to recognize the achievement of current researchers. At the Twenty-Sixth Symposium, the award for the Jerry L. Swedlow Memorial Lecture was presented to Dr. John G. Merkle, Oak Ridge National Laboratory. The Award of Merit was presented to Professor Ashok Saxena, Georgia Institute of Technology. Awards of Appreciation were presented to Dr.

Mark T. Kirk, Dr. James C. Newman, Jr., and to Professor Ad Bakker, Delft University of Technology. The organizing committee would like to congratulate the above award winners as considerable time, effort, and hard work were required to win these awards.

Walter Reuter
EG&G Idaho Ink,
Idaho Falls, ID; symposium
chairman and editor.

John H. Underwood
U.S. Army Armament RD Center
Watervliet, NY; symposium
co-chairman and editor.

James C. Newman, Jr.
NASA Langley Research Center
Hampton, VA; symposium
co-chairman and editor.

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Professor J. L. Swedlow Memorial Lecture

John G. Merkle[1]

PATTERNS AND PERSPECTIVES IN APPLIED FRACTURE MECHANICS

REFERENCE: Merkle, J. G., **"Patterns and Perspectives in Applied Fracture Mechanics,"** Fracture Mechanics: 26th Volume, ASTM STP 1256, Walter G. Reuter, John H. Underwood, and James C. Newman, Jr., Eds., American Society for Testing and Materials, Philadelphia, 1995.

ABSTRACT: This fifth Jerry L. Swedlow Memorial Lecture begins with a brief philosophical and historical overview of applied fracture mechanics, particularly as it pertains to the safety of pressure vessels. It then progresses to a more-or-less chronological panorama of experimental and analytical results pertaining to the important subject of constraint, a fundamental aspect of fracture mechanics in which Jerry Swedlow had a keen interest and to which he made valuable contributions. To be truly useful and dependable in application to the safety analysis of real structures, new analysis developments must be physically realistic. That means that they must accurately describe physical cause and effect. Consequently, before useful mathematical modeling can begin, a pattern of cause and effect must be established from experimental data. This can be a difficult and time consuming process, but it is worth the effort. Accordingly, a central theme of this paper is that, consistent with the scientific method, the search for patterns is constant and vital. This theme is well illustrated historically by the development of small, single-specimen, fracture toughness testing techniques. It is also illustrated, at the end of the present paper, by the development, based on two different published large-strain, elastic-plastic, three-dimensional finite-element analyses, of a hypothesis concerning three-dimensional loss of constraint. Specifically, it appears that, at least in standard compact specimens, when a generalization of Irwin's thickness-normalized plastic-zone parameter, β, reaches a value close to 2π, the through-thickness contraction strain at the apex of the near-tip logarithmic-spiral slip-line region becomes the dominant negative strain accommodating crack opening. Because slip lines passing from the midplane to the stress-free side surfaces do not have to curve, once these slip lines are established, stresses near the crack tip are only elevated by strain hardening and constraint becomes significantly relaxed. This hypothesis, based on published three-dimensional elastic-plastic analyses, provides a potentially valuable means for gaining additional insight into constraint effects on fracture toughness by considering the roles played by the plastic strains as well as the stresses that develop near a crack tip.

Keywords: Fracture mechanics, pressure vessels, fracture toughness, small specimen testing, flawed structural components, thickness effects, constraint.

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It is an honor to be invited to present the Fifth Professor Jerry L. Swedlow Memorial Lecture. Jerry Swedlow set a personal example of insight and quality in research, as well as an example of professional service, that we can all admire. I've tried to prepare this paper with these two examples in mind. By fortunate circumstance, this paper develops a focus on one of the very subjects that attracted Jerry's keen interest as a graduate student and held it throughout his career, that of the effects of thickness on fracture toughness, or slightly more generally, the three-dimensional aspects of constraint. This paper begins with some overall philosophy about fracture mechanics. It then progresses to a brief historical overview of some of the important experimental and analytical developments in fracture mechanics, especially as they relate to pressure vessels. Next a more or less chronologically based chain of evidence about what have come to be called constraint effects on fracture toughness is developed. Finally, the paper concludes with some recent evidence, and a hypothesis, about three-dimensional loss of constraint, especially in standard compact specimens.

It is easy to be positive and enthusiastic about fracture mechanics because it is an important and challenging field for several good reasons. It deals with an important real problem, the imperfection of real structures. By means of fracture toughness, it does what stress analysis alone cannot do; it enables the quantification of safety margins against fracture for real, imperfect structures. It makes full use of material science, nondestructive examination, thermal analysis, stress analysis, and probabilistic information. Nothing is overlooked. Interdisciplinary teamwork is essential. An important aspect of the behavior of structural metals is that crack-tip yielding precedes fracture. Therefore, a basic understanding of elastic-plastic metal behavior is required. Furthermore, fracture toughness is a unique material property. Its value cannot be reliably synthesized from other material properties. It must be calculated from sharp-cracked specimen data. With respect to analysis methods, some relationships in fracture mechanics exist in algebraic closed form. Others can only be obtained numerically. A partnership between algebraically direct and iterative numerical analysis is required. Finally, development and application of fracture mechanics requires proper use of the scientific method. Experiments and analyses must be coupled. *The search for patterns is constant and vital.*

To establish a perspective on applied fracture mechanics as it now exists, a look at its history is helpful. Table 1 lists some historically key issues and developments in fracture mechanics, emphasizing those that have been particularly significant with regard to quantifying the safety margins of pressure vessels. There was a time when brittle fracture was described simply in terms of catastrophic failure without warning, due to what was believed to be the reaching of a cleavage stress before yielding, a condition caused by triaxial stress concentration. The realization that, in structural metals, macroscopic cracks are a necessary cause of brittle failure was the key to modern fracture mechanics. From that realization flowed the concepts of elastic strain energy release rate [1], G_I, and the linear-elastic stress-intensity factor [2], K_I, as well as their critical values. In some structural metals, loading rate and crack-front-motion induced strain-rate effects were observed and appropriate analyses were developed [3, 4]. Effects of specimen size, especially thickness, on fracture toughness were observed and provisions made to deal conservatively with these effects [5]. Pressure vessel steels were characterized, first in terms of their thick-section dynamic impact

TABLE 1--Some historically key issues and developments in fracture mechanics for pressure vessels

- Brittle fracture: catastrophic failure without warning (up to early 1950's).
- Basic material behavior; is that all there is to it (up to early 1950's)?
- The involvement of cracks (starting in late 1940's).
- Elastic strain energy release rate; G and G_{Ic} (1954).
- The elastic stress intensity factor; K_I and K_{Ic} (1957).
- Loading rate and strain rate effects (1960's).
- Effects of size, especially thickness, on toughness (1970's).
- Characterizing pressure vessel steels (1970's).
- Initial codes, standards and technical basis documents; ASTM E399, WRC-175, ASME Section III Appendix G (1970's).
- Measuring toughness with reasonably sized specimens (1970's).
- CTOD and the J Integral (1965 and 1970).
- Determining the behavior of cracked structural components (1970's).
- ASME Section XI Appendix A (1974).
- Size and geometry effects (1980's).
- Ductile crack growth (1980's).
- E561, E813, E1152, E1221, and E1290 (1980's).
- ASME Section XI appendices for piping (1990's).
- Computers come of age (1990's).
- Constraint (1990's).
- Shallow cracks (1990's).
- Ductile hole growth and cleavage initiation sites (1990's).
- Statistical variability of cleavage toughness (1990's).

energy [6] and then in terms of their static [7], dynamic [8] and crack arrest [9] fracture toughness values. Initial versions of American Society of Mechanical Engineers (ASME) codes, American Society for Testing and Materials (ASTM) standards, and Welding Research Council (WRC) technical basis documents were written and published, as mentioned in Table 1. It soon became apparent that developing the experimental and analytical methods for measuring fracture toughness with reasonably sized specimens was going to be a major long-term challenge. The crack-tip-opening displacement (CTOD) and J-Integral parameters became prime candidates for this job. As single specimen J-Integral testing techniques were being developed, attention also became focused on determining the performance of cracked structural components, which display various unique behavioral characteristics of their own. Once linear-elastic fracture mechanics (LEFM) had reached a sufficient level of maturity, its essentials were incorporated into Appendix A of Section XI of the ASME Code [10], for the purpose of evaluating flaw indications discovered by nondestructive inspection. The J Integral was used to characterize ductile crack growth, and once again size and geometry effects became apparent [11]. Several more ASTM standards were completed and published, three relating to tearing resistance curves, one for crack arrest and one for CTOD testing. Appendices to the ASME Code were written to describe acceptable methods for performing ductile tearing instability analyses for flawed piping, as well as safety margin calculations for vessels containing materials with relatively low ductile tearing resistance. Then as computers and their software grew in capability, attention focused anew on the details of crack-tip deformation and stress distributions, creating the prospect of finally understanding the subject of constraint. Specimens with shallow cracks were tested and analyzed [12, 13] and the detailed modeling of ductile hole growth began in earnest [14]. Modeling the onset of unstable cleavage may not be far behind. The statistical variability of cleavage fracture toughness has already become a subject in its own right [15] despite the present lack of certainty concerning the exact sequence of events that leads to unstable cleavage.

Because fracture mechanics is a relatively new branch of knowledge within the field of structural engineering, opportunities for the development of new problem solutions and analysis procedures have abounded. However, to be truly useful and dependable in application to the safety analysis of real structures, these new problem solutions must be more than just mathematically or computationally ingenious. They must also be physically realistic. That means that they must accurately describe physical cause and effect. Consequently, before useful mathematical modeling can begin, a pattern of cause and effect must be established from experimental data. This can be a difficult and time consuming process, but it is worth the effort. Table 2 lists some of the analytical aspects of fracture mechanics that have been particularly dependent upon experimental data for their development. The remainder of this paper focuses on a selection of subjects from Table 2, particularly those related to size, geometry and rate effects on fracture toughness.

SMALL SPECIMEN TESTING

In the course of performing the static and dynamic fracture toughness testing of pressure vessel steels described in Refs. 7 and 8, some important fundamental facts about such testing soon became apparent. Because of the crack size dependence of all crack-tip stress

TABLE 2--Analytical aspects of fracture mechanics particularly dependent upon experimental data for their development

- Effects of yielding
  - Small specimen toughness testing
  - Cracks in structural members
  - Warm prestressing
- Constraint
- Stable ductile crack growth
  - Upper shelf
  - Before cleavage
- Strain rate effects, including crack arrest
- Effects of temperature and irradiation
- Effects of environment
- Fatigue
- Calculated versus measured strains and displacements
- Statistical effects of crack length
- Interactions between fracture and plastic collapse