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Environment-Induced Cracking of Materials

Chemistry, Mechanics and Mechanisms

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Volume 1: Chemistry, Mechanics and Mechanisms

Proceedings of the Second International Conference on Environment-Induced Cracking of Metals (EICM-2), The Banff Centre, Banff, Alberta, Canada, September 19–23, 2004

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Preface

This volume is the first of two containing most of the papers presented at the Second International Conference on Environment-Induced Cracking of Metals (EICM-2), which was held at The Banff Centre, Banff, Alberta, Canada in September 2004.[1] This conference was the fifth in a series of major international meetings sponsored or co-sponsored by NACE in the area of environment-induced cracking. The previous four conferences, recognized as landmark events, were the:

- International Conference on Fundamental Aspects of Stress Corrosion Cracking held at the Ohio State University, Columbus, OH, USA, 1967
- International Corrosion Fatigue Conference held at the University of Connecticut, Storrs, CT, USA, 1971
- International Conference on Stress Corrosion Cracking and Hydrogen Embrittlement of Iron Base Alloys held in Unieux-Firminy, France, 1973
- First International Conference on Environment-Induced Cracking of Metals held in Kohler, WI, USA, 1988

EICM-2 was jointly sponsored by the Committee TEG 186X on Environmentally Assisted Cracking of NACE International, the Working Party WP5 on Environment Sensitive Fracture of the European Federation of Corrosion and the Joint ASM/TMS Corrosion and Environmental Effects Committee in association with the Technical Committee of Hydrogen Embrittlement and Stress Corrosion of the Chinese Society of Corrosion and Protection and the Technical Committee TC10 on Environmentally Assisted Cracking of the European Structural Integrity Society. This conference was international in scope and attracted a significant number of researchers and professionals. There were 115 participants from countries that included Australia, Japan, China, India, Saudi Arabia, Israel, Russia, Ukraine, Poland, Slovak Republic, Austria, Slovenia, Italy, Sweden, Germany, Belgium, France, the United Kingdom, Brazil, the United States and Canada. The conference provided a forum for dialogue, assessment and critique among researchers committed to different methodologies and actively promoted discussion and cross-fertilization of ideas among established and emerging researchers working in different areas related to the problem of environment-induced cracking in materials.

The technical program consisted of three plenary sessions, 12 technical sessions with 72 oral presentations, a poster session and a luncheon talk. In total, 87 papers that described both fundamental research studies and more practical engineering applications were presented. Topics included but were not limited to: SCC, hydrogen embrittlement, corrosion fatigue, liquid metal embrittlement, localized environment-induced attack, modeling environmental effects, crack growth mechanisms, hydrogen permeation and transport, hydrogen-plasticity interaction, test methods and interpretation of test data, materials degradation in service, failure analysis, life prediction of corrodible structures, and the history of EICM research. Together the papers provided a comprehensive account of advances in research on environment-induced cracking and constituted the most recent fundamental and industrial survey of

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[1] Volume 2 is published under the title "Environment-Induced Cracking of Materials: Prediction, Industrial Developments and Evaluation," S.A. Shipilov, R.H. Jones, J.M. Olive, R.B. Rebak (Editors), Elsevier, Oxford, 2007. 508 pages.

the subject. Plenary lectures were presented by Richard Gangloff, Digby Macdonald, Roger Newman, Roger Staehle, Alan Turnbull and Robert Wei. A luncheon lecture entitled "Growing Old Gracefully? A Perspective on Pipeline Safety" was given by Alan Murray of the National Energy Board Canada. A highlight of the conference was the General Discussion which featured a panel comprising the plenary speakers with John Scully as a moderator. During the discussion, recent developments and a number of key questions in environment-induced cracking research were considered, including how to move from theory to validation to practice, needs and opportunities for mechanistic advances, progress towards life prediction/prognosis/damage evolution, the challenge to mitigate and control EICM, and needs and opportunities for technological and practical progress.

As the potential audience for the proceedings represents a wide spectrum of professionals, including researchers, engineers, practitioners and consultants with different background and specific research and/or industrial interests, it was found feasible to divide the papers into two volumes, each with a specific focus – as indicated in their titles – which can then be sold and/or used together or separately. This necessitated a different arrangement of the papers in the books than the order in which they were presented at the conference. In each volume, the papers are organized to provide a reasonable reflection of research development in the subject areas. Either volume may be used as an independent reference source that reviews the current state of the fundamental and/or industry-oriented research and provides a comprehensive introduction to the field. Applied researchers and specialists in industry may find volume two highly relevant, especially if they are engaged in the areas related to nuclear power generation, oil and gas transportation, the disposal of radioactive waste, aircraft maintenance, chemical and marine applications, failure analysis in industrial equipment, and assessing the SCC resistance; while volume one may find a ready audience among researchers who focus upon investigating the phenomenological aspects of SCC, hydrogen embrittlement, liquid metal embrittlement and corrosion fatigue, including environmental, microstructural, electrochemical and mechanistic aspects, in high performance steels, nonferrous alloys, ceramics and glasses. Whatever the individual reader's preference, there are synergies and connections across the volumes which make their simultaneous publication an important occasion for researchers and practitioners alike.

Of the 87 papers that were presented at the conference, 81 are offered to the reader across the two volumes. The papers were rigorously peer-reviewed, revised and edited extensively to meet the high standards for scientific publications intended for an international and discerning audience. Volume one contains 43 papers divided into nine sections. These papers provide thorough coverage of the environmental, microstructural, electrochemical and mechanistic aspects of SCC, hydrogen embrittlement, liquid metal embrittlement and corrosion fatigue for a wide range of materials. Section 1 titled "Modeling environmental attack" contains three plenary papers: "Science based probability modeling and life cycle engineering and management" by R.P. Wei and D.G. Harlow, "A model to predict the evolution of pitting corrosion and the pit-to-crack transition incorporating statistically distributed input parameters" by A. Turnbull et al., and "Revisiting the film-induced cleavage model of SCC" by R.C. Newman et al. which review the achievements of the science of EICM during the last decade or so and describe some of the models that simulate damage evaluation and prediction. The remaining seven papers of this section deal with new theoretical and experimental approaches to modeling localized environmental attack that allow researchers to investigate and predict environment-induced cracking in metals. Section 2 titled "Crack growth mechanisms" begins with a plenary paper titled "Critical issues in hydrogen assisted cracking of structural alloys" by R.P. Gangloff, followed by four papers addressing the mechanisms of environment-induced cracking of Al, Fe, Mg, Ni, Ni-Cr and Ti alloys and amorphous $Fe_{80}B_{11}Si_9$ exposed to aqueous solutions, hydrogen gas or liquid metals. Section 3 titled "Hydrogen permeation and transport" contains six papers which deal with the fundamental aspects of the strain-induced permeation and transport of hydrogen and hydrogen interactions with the microstructure of steels and alloys. The four papers in Section 4 titled "Hydrogen-assisted cracking and embrittlement" address hydrogen effects on the properties and fracture of ferrous alloys. New insights into the issues associated with SCC and corrosion fatigue of Al, Cu, Mg, Ni and Ti alloys, HSLA and stainless steels are provided in twelve papers, which are included in Sections 5 and 6 titled "Nonferrous alloys" and "Iron and nickel based alloys" respectively. Section 7, titled "Ceramics and glasses," considers some of the aspects that control corrosion and environment-induced cracking in high performance ceramics and glasses. Recent results on the influence of liquid metals on the mechanical behaviour and fracture of steels and superplastic alloys are presented in Section 8 titled "Liquid metal embrittlement." The final section, titled "History of SCC research," reviews experimental results and mechanistic models for SCC and corrosion fatigue in the century after the first investigation on record was carried out in 1873. As an indication of the scholarly and scientific rigour that characterise these papers, the total number of literature references to the papers in this volume is 1,107.

Many individuals and organizations contributed to the success of EICM-2 and these volumes, and I would like to acknowledge their assistance. The conference and its proceedings would not have been possible without the generous support of my co-editors, Russ Jones, Jean-Marc Olive and Raúl Rebak. These dedicated individuals contributed greatly of their time and skills to arrange various aspects of the meeting. They were instrumental in helping to develop the program, with organizing sessions and assisting with reviewing the manuscripts. I also wish to thank Winston Revie for his assistance at the early stage of the planning of the conference. Special acknowledgments are extended to chairs of sponsoring committees for helping to organize international participation: Jorge Perdomo, Jean-Marc Olive, Raúl Rebak, Lijie Qiao and Wolfgang Dietzel. Pierre Crevolin, President of NACE in 2003/2004 and Interim Executive Director in 2004, his staff and especially Gretchen Jacobson, Publishing Director, provided invaluable assistance in publicizing EICM-2. Special thanks go to my students, Don Boll, Vicky Carathanassis, Christie Millington, Enoch Ng, Krishna Panchalingam, Feng Wang and Hong Wang, who helped with registration and assisted me through all stages of the conference, including the preparation of several graphs for this publication. Sincere thanks also to Kim Allan for providing technical support for the conference website. I would like to extend my special thanks to the session chairs, Jenny Been, Anne-Marie Brass, Steve Bruemmer, Jacques Chêne, Wolfgang Dietzel, Noam Eliaz, Russ Jones, Rob Kelly, Fraser King, Amar Kumar, Graham Lobley, Stan Lynch, Jean-Marc Olive, Alan Plumtree, Raúl Rebak, John Scully, Raman Singh, Brian Somerday, Bob Sutherby, Mirna Urquidi-Macdonald and Marc Vankeerberghen, who worked very effectively to keep the program organized and the floor discussions effective. I greatly appreciate the work of the technical experts who joined in reviewing the manuscripts for these volumes, and who approached the

manuscript reviews with the detail and exacting standards that mark the review process at technical journals. The names of these reviewers are listed on the next page. Without the generosity of our financial sponsors, and the individuals who secured sponsorship funds, the conference would not have happened and these papers would not have seen the light of day. Hence, my heartfelt thanks to NACE International (Pierre Crevolin), National Energy Board Canada (Alan Murray), Metallurgical Consulting Services Ltd. (Iain Le May), the University of Calgary (Ron Bond), Canadian Energy Pipeline Association (Jake Abes), NOVA Chemicals Corporation (Fraser King), ASM Canada Council (Steve Yue), ASM Calgary Chapter (Sammy Tang), and Broadsword Corrosion Engineering Ltd. (Pat Teevens). During the preparation of the proceedings, I was very ably assisted by Michael Aleksiuk who provided diligent and insightful proofreading of several of the manuscripts, and by Lucy Dickinson, Nicola Jones and Kristi Green of Elsevier Ltd. for their kind co-operation at all stages of the work. My sincere thanks go to the authors of the papers for making time in their busy lives to put their work in the public domain. To all those who have helped, I express my sincere "Thanks!"

Last, but certainly not least, I would like to acknowledge my thanks and appreciation to my wife, Hyacinth, whose support, encouragement and companionship sustained me through both the organizing of EICM-2 and the preparation of this publication.

Sergei Shipilov
Editor and Conference Chair

List of Reviewers

The quality of the papers that appear in this volume reflects not only the obvious efforts of the authors but also the unheralded, though essential, work of the reviewers who joined with the editors in reviewing the manuscripts for the proceedings. The editors sincerely acknowledge the following reviewers who provided comments and constructive suggestions for the revision of manuscripts.

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Section 1

MODELING ENVIRONMENTAL ATTACK

Science based probability modeling and life cycle engineering and management

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Abstract

Life cycle engineering and management (LCEM) of modern, high value-added engineered systems demands the formulation and use of science based probability models (SBPM) for predicting the evolution and distribution of damage, and their impact on structural reliability. In this paper, the need for SBPM is discussed within the context of LCEM. The approach and its efficacy are illustrated and demonstrated through selected examples on the formulation and use of these models. They include modeling of corrosion and corrosion fatigue of aluminum alloys, and its application to aging aircraft, and the impact of residual stress/environment on fatigue (*S-N*) response into the very high cycle (up to 10^{10} cycles) domain.

1. Introduction

Material aging, through the evolution and distribution of damage (for example, by localized corrosion and corrosion fatigue), is one of the principal causes for the reduction in the reliability and margin of safety of engineered systems. It can contribute significantly to the cost of maintenance and operation and, thereby, their overall life cycle cost. To quantify materials aging and facilitate the overall optimization of the performance, reliability, and life cycle costs of these systems (i.e., for life cycle engineering and management, LCEM) new modeling approaches are needed. Traditional (and current) approaches to engineering design are no longer adequate. The reason lies in the fact that these approaches are based largely on the use of experientially based statistical methodologies and accelerated testing over periods that are well short of those of the intend service. The models developed from them are essentially parametric representation of statistical fits to the experimental data, and are effective only over the range of the underlying data. They capture, at best, the influences of the limited number of controlled (*external*) variables used in testing. Furthermore, variability associated with measurement errors (which cannot be separated from the experimental data) are incorporated into the statistical analyses, and can lead to overestimations of the uncertainty bounds. As such, simple application of known statistical techniques cannot provide the necessary tools for LCEM of engineered systems, and a different approach needs to be adopted. In this paper, a science (mechanistically) based probability modeling approach that has been used successfully over the past decade [1–7] is presented to illustrate the modeling process and its efficacy. The overall framework and approach are described. Its use and efficacy are illustrated through two examples: the first, on modeling of pitting corrosion and fatigue crack growth in aluminum alloys and its application to aging aircraft, and the second, in considering the fatigue (*S-N*) response of a bearing steel into the very high cycle domain (i.e., up to 10^{10} cycles).

2. Framework

Materials aging is considered in the context of its influence on the assessments of reliability, safety, availability and maintenance of engineered systems. The framework for these assessments is depicted in Fig. 1. Within it, the materials aging process is reflected specifically in the evolution and distribution of *damage* that compromise *functionality, reliability* and *safety*. The key issues, therefore, pertain to the assessment of such a system under given sets of projected operating conditions (i.e., in terms of forcing functions and environmental conditions) in relation to its *current state* or its *initial state* (either new, or after major maintenance service) and its *future state*. Such assessments are typically made through the use of a set of analysis tools, in conjunction with a comprehensive suite of diagnostic or nondestructive evaluation (NDE) tools that provide information on the current state (sizes and distribution) of damage in the system.

Assurance of reliability and continued safety, and availability, requires a quantitative assessment of the system in its *'projected future state'*. For this assessment, appropriate quantitative models are needed for estimating the accumulation of damage (in size and distribution) over its projected period of operation. The outcome of this assessment then serves as the basis for decisions on its suitability for *continued service* as reflected in Fig. 1 by the labels *Reliable*, *Conditioned Reliability*, and *Not Reliable*. A system judged to be reliable would be accepted for unrestricted operation until the

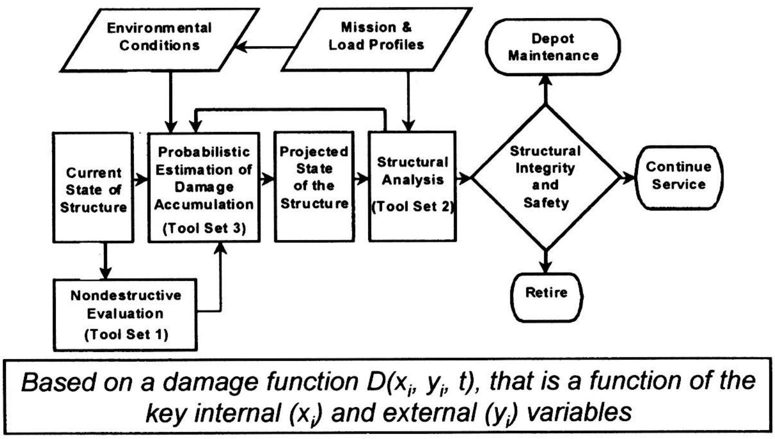

Fig. 1. A simplified flow diagram for life prediction, reliability assessment and management of engineered systems [6].