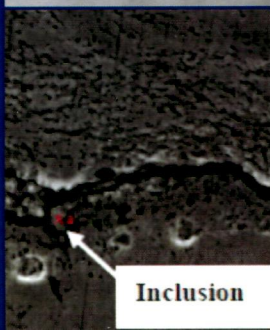
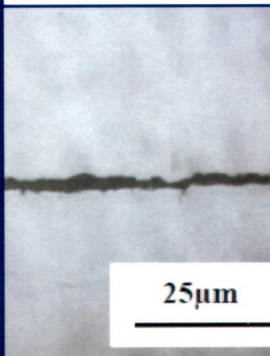
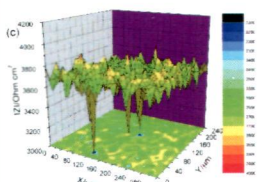
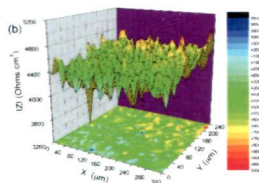
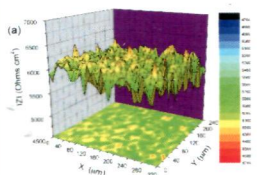


Wiley Series in Corrosion
R. Winston Revie, Series Editor

Stress Corrosion Cracking of Pipelines

Y. FRANK CHENG

WILEY



Stress Corrosion Cracking of Pipelines

Y. Frank Cheng

Professor and Canada Research Chair
in Pipeline Engineering
University of Calgary

 **WILEY**

A John Wiley & Sons, Inc., Publication

Copyright © 2013 by John Wiley & Sons, Inc. All rights reserved.

Published by John Wiley & Sons, Inc., Hoboken, New Jersey.
Published simultaneously in Canada.

No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning, or otherwise, except as permitted under Section 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, (978) 750-8400, fax (978) 750-4470, or on the web at www.copyright.com. Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, (201) 748-6011, fax (201) 748-6008, or online at <http://www.wiley.com/go/permission>.

Limit of Liability/Disclaimer of Warranty: While the publisher and author have used their best efforts in preparing this book, they make no representations or warranties with respect to the accuracy or completeness of the contents of this book and specifically disclaim any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives or written sales materials. The advice and strategies contained herein may not be suitable for your situation. You should consult with a professional where appropriate. Neither the publisher nor author shall be liable for any loss of profit or any other commercial damages, including but not limited to special, incidental, consequential, or other damages.

For general information on our other products and services or for technical support, please contact our Customer Care Department within the United States at (800) 762-2974, outside the United States at (317) 572-3993 or fax (317) 572-4002.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books. For more information about Wiley products, visit our web site at www.wiley.com.

Library of Congress Cataloging-in-Publication Data

Cheng, Y. Frank, 1969–

Stress corrosion cracking of pipelines / Y. Frank Cheng,

pages cm

Includes bibliographical references and index.

ISBN 978-1-118-02267-2 (cloth)

1. Pipelines--Corrosion. 2. Pipelines--Cracking. 3. Steel--Corrosion. I. Title.

TJ930.C545 2013

621.8'672--dc23

2012035723

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

Contents

Foreword	xiii
Preface	xv
List of Abbreviations and Symbols	xix
1 Introduction	1
1.1 Pipelines as “Energy Highways” / 2	
1.2 Pipeline Safety and Integrity Management / 3	
1.3 Pipeline Stress Corrosion Cracking / 3	
References / 5	
2 Fundamentals of Stress Corrosion Cracking	7
2.1 Definition of Stress Corrosion Cracking / 7	
2.2 Specific Metal–Environment Combinations / 9	
2.3 Metallurgical Aspects of SCC / 11	
2.3.1 Effect of Strength of Materials on SCC / 11	
2.3.2 Effect of Alloying Composition on SCC / 11	
2.3.3 Effect of Heat Treatment on SCC / 11	
2.3.4 Grain Boundary Precipitation / 12	
2.3.5 Grain Boundary Segregation / 12	

- 2.4 Electrochemistry of SCC / 13
 - 2.4.1 SCC Thermodynamics / 13
 - 2.4.2 SCC Kinetics / 14
- 2.5 SCC Mechanisms / 15
 - 2.5.1 SCC Initiation Mechanisms / 15
 - 2.5.2 Dissolution-Based SCC Propagation / 16
 - 2.5.3 Mechanical Fracture-Based SCC Propagation / 18
- 2.6 Effects of Hydrogen on SCC and Hydrogen Damage / 20
 - 2.6.1 Sources of Hydrogen / 20
 - 2.6.2 Characteristics of Hydrogen in Metals / 21
 - 2.6.3 The Hydrogen Effect / 21
 - 2.6.4 Mechanisms of Hydrogen Damage / 25
- 2.7 Role of Microorganisms in SCC / 27
 - 2.7.1 Microbially Influenced Corrosion / 27
 - 2.7.2 Microorganisms Involved in MIC / 29
 - 2.7.3 Role of MIC in SCC Processes / 31
- 2.8 Corrosion Fatigue / 32
 - 2.8.1 Features of Fatigue Failure / 33
 - 2.8.2 Features of Corrosion Fatigue / 34
 - 2.8.3 Factors Affecting CF and CF Management / 35
- 2.9 Comparison of SCC, HIC, and CF / 35
- References / 37

3 Understanding Pipeline Stress Corrosion Cracking

43

- 3.1 Introduction / 43
- 3.2 Practical Case History of SCC in Pipelines / 44
 - 3.2.1 Case 1: SCC of Enbridge Glenavon Pipelines (SCC in an Oil Pipeline) / 45
 - 3.2.2 Case 2: SCC of Williams Lake Pipelines (SCC in a Gas Pipeline) / 46
- 3.3 General Features of Pipeline SCC / 46
 - 3.3.1 High-pH SCC of Pipelines / 47
 - 3.3.2 Nearly Neutral-pH SCC of Pipelines / 48
 - 3.3.3 Cracking Characteristics / 48
- 3.4 Conditions for Pipeline SCC / 50
 - 3.4.1 Corrosive Environments / 50
 - 3.4.2 Susceptible Line Pipe Steels / 53
 - 3.4.3 Stress / 58

3.5 Role of Pressure Fluctuation in Pipelines: SCC or Corrosion Fatigue? / 62

References / 68

4 Nearly Neutral-pH Stress Corrosion Cracking of Pipelines

73

4.1 Introduction / 73

4.2 Primary Characteristics / 73

4.3 Contributing Factors / 75

4.3.1 Coatings / 75

4.3.2 Cathodic Protection / 79

4.3.3 Soil Characteristics / 81

4.3.4 Microorganisms / 83

4.3.5 Temperature / 85

4.3.6 Stress / 85

4.3.7 Steel Metallurgy / 88

4.4 Initiation of Stress Corrosion Cracks from Corrosion Pits / 89

4.5 Stress Corrosion Crack Propagation Mechanism / 96

4.5.1 Role of Hydrogen in Enhanced Corrosion of Steels / 96

4.5.2 Potential-Dependent Nearly Neutral-pH SCC of Pipelines / 99

4.5.3 Pipeline Steels in Nearly Neutral-pH Solutions: Always Active Dissolution? / 101

4.6 Models for Prediction of Nearly Neutral-pH SCC Propagation / 104

References / 111

5 High-pH Stress Corrosion Cracking of Pipelines

117

5.1 Introduction / 117

5.2 Primary Characteristics / 117

5.3 Contributing Factors / 118

5.3.1 Coatings / 118

5.3.2 Cathodic Protection / 119

5.3.3 Soil Characteristics / 123

5.3.4 Microorganisms / 125

5.3.5 Temperature / 125

5.3.6 Stress / 125

5.3.7 Metallurgies / 128

- 5.4 Mechanisms for Stress Corrosion Crack Initiation / 128
 - 5.4.1 Electrochemical Corrosion Mechanism of Pipeline Steels in a Thin Layer of Carbonate–Bicarbonate Electrolyte Trapped Under a Disbonded Coating / 128
 - 5.4.2 Conceptual Model for Initiation of Stress Corrosion Cracks in a High-pH Carbonate–Bicarbonate Electrolyte Under a Disbonded Coating / 133
- 5.5 Mechanisms for Stress Corrosion Crack Propagation / 137
 - 5.5.1 Enhanced Anodic Dissolution at a Crack Tip / 137
 - 5.5.2 Enhanced Pitting Corrosion at a Crack Tip / 143
 - 5.5.3 Relevance to Grain Boundary Structure / 144
- 5.6 Models for the Prediction of a High-pH Stress Corrosion Crack Growth Rate / 144
- References / 145

6 Stress Corrosion Cracking of Pipelines in Acidic Soil Environments 149

- 6.1 Introduction / 149
- 6.2 Primary Characteristics / 150
- 6.3 Electrochemical Corrosion Mechanism of Pipeline Steels in Acidic Soil Solutions / 151
- 6.4 Mechanisms for Initiation and Propagation of Stress Corrosion Cracks / 151
- 6.5 Effect of Strain Rate on the SCC of Pipelines in Acidic Soils / 154
- References / 157

7 Stress Corrosion Cracking at Pipeline Welds 159

- 7.1 Introduction / 159
- 7.2 Fundamentals of Welding Metallurgy / 160
 - 7.2.1 Welding Processes / 160
 - 7.2.2 Welding Solidification and Microstructure / 160
 - 7.2.3 Parameters Affecting the Welding Process / 162
 - 7.2.4 Defects at the Weld / 162
- 7.3 Pipeline Welding: Metallurgical Aspects / 163
 - 7.3.1 X70 Steel Weld / 163
 - 7.3.2 X80 Steel Weld / 163
 - 7.3.3 X100 Steel Weld / 164
- 7.4 Pipeline Welding: Mechanical Aspects / 164
 - 7.4.1 Residual Stress / 164
 - 7.4.2 Hardness of the Weld / 166

- 7.5 Pipeline Welding: Environmental Aspects / 170
 - 7.5.1 Introduction of Hydrogen into Welds / 170
 - 7.5.2 Corrosion at Welds / 172
 - 7.5.3 Electrochemistry of Localized Corrosion at Pipeline Welds / 173
- 7.6 SCC at Pipeline Welds / 178
 - 7.6.1 Effects of Material Properties and Microstructure / 178
 - 7.6.2 Effects of the Welding Process / 179
 - 7.6.3 Hydrogen Sulfide SCC of Pipeline Welds / 179
- References / 180

8 Stress Corrosion Cracking of High-Strength Pipeline Steels 185

- 8.1 Introduction / 185
- 8.2 Development of High-Strength Steel Pipeline Technology / 186
 - 8.2.1 Evolution of Pipeline Steels / 186
 - 8.2.2 High-Strength Steels in a Global Pipeline Application / 187
- 8.3 Metallurgy of High-Strength Pipeline Steels / 189
 - 8.3.1 Thermomechanical Controlled Processing / 189
 - 8.3.2 Alloying Treatment / 189
 - 8.3.3 Microstructure of High-Strength Steels / 190
 - 8.3.4 Metallurgical Defects / 192
- 8.4 Susceptibility of High-Strength Steels to Hydrogen Damage / 193
 - 8.4.1 Hydrogen Blistering and HIC of High-Strength Pipeline Steels / 193
 - 8.4.2 Hydrogen Permeation Behavior of High-Strength Pipeline Steels / 196
- 8.5 Metallurgical Microelectrochemistry of High-Strength Pipeline Steels / 199
 - 8.5.1 Microelectrochemical Activity at Metallurgical Defects / 199
 - 8.5.2 Preferential Dissolution and Pitting Corrosion Around Inclusions / 203
- 8.6 Strain Aging of High-Strength Steels and Its Implication on Pipeline SCC / 207
 - 8.6.1 Basics of Strain Aging / 208
 - 8.6.2 Strain Aging of High-Strength Pipeline Steels / 212
 - 8.6.3 Effect of Strain Aging on SCC of High-Strength Pipeline Steels / 214

- 8.7 Strain-Based Design of High-Strength Steel Pipelines / 216
 - 8.7.1 Strain Due to Pipe–Ground Movement / 217
 - 8.7.2 Parametric Effects on Cracking of Pipelines Under SBD / 218
- 8.8 Mechanochemical Effect of Corrosion of Pipelines Under Strain / 219
- References / 225

9 Management of Pipeline Stress Corrosion Cracking **231**

- 9.1 SCC in Pipeline Integrity Management / 231
 - 9.1.1 Elements of Pipeline Integrity Management / 231
 - 9.1.2 Initial Assessment and Investigation of SCC Susceptibility / 234
 - 9.1.3 Classification of SCC Severity and Postassessment / 235
 - 9.1.4 SCC Site Selection / 236
 - 9.1.5 SCC Risk Assessment / 238
- 9.2 Prevention of Pipeline SCC / 240
 - 9.2.1 Selection and Control of Materials / 241
 - 9.2.2 Control of Stress / 242
 - 9.2.3 Control of Environments / 243
- 9.3 Monitoring and Detection of Pipeline SCC / 244
 - 9.3.1 In-Line Inspections / 244
 - 9.3.2 Intelligent Pigs / 247
 - 9.3.3 Hydrostatic Inspection / 248
 - 9.3.4 Pipeline Patrolling / 249
- 9.4 Mitigation of Pipeline SCC / 249
- References / 251