

Handbook of
Materials Failure Analysis
With Case Studies from the Oil
and Gas Industries

Edited by
Abdel Salam Hamdy Makhlouf
Mahmood Aliofkhazraei

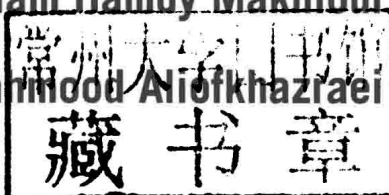


Handbook of Materials Failure Analysis With Case Studies from the Oil and Gas Industry

Edited by

Abdel Salam Hamdy Makhlouf

Mahmood Aliofkhazraei



AMSTERDAM • BOSTON • HEIDELBERG • LONDON
NEW YORK • OXFORD • PARIS • SAN DIEGO
SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO

Butterworth-Heinemann is an imprint of Elsevier



Butterworth Heinemann is an imprint of Elsevier
The Boulevard, Langford Lane, Kidlington, Oxford OX5 1GB, UK
225 Wyman Street, Waltham, MA 02451, USA

Copyright © 2016 Elsevier Ltd. All rights reserved.

No part of this publication may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher. Details on how to seek permission, further information about the Publisher's permissions policies and our arrangements with organizations such as the Copyright Clearance Center and the Copyright Licensing Agency, can be found at our website: www.elsevier.com/permissions.

This book and the individual contributions contained in it are protected under copyright by the Publisher (other than as may be noted herein).

Notices

Knowledge and best practice in this field are constantly changing. As new research and experience broaden our understanding, changes in research methods, professional practices, or medical treatment may become necessary.

Practitioners and researchers must always rely on their own experience and knowledge in evaluating and using any information, methods, compounds, or experiments described herein. In using such information or methods they should be mindful of their own safety and the safety of others, including parties for whom they have a professional responsibility.

To the fullest extent of the law, neither the Publisher nor the authors, contributors, or editors, assume any liability for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions, or ideas contained in the material herein.

British Library Cataloguing in Publication Data

A catalogue record for this book is available from the British Library

Library of Congress Cataloging-in-Publication Data

A catalog record for this book is available from the Library of Congress

ISBN: 978-0-08-100117-2

For information on all Butterworth Heinemann publications
visit our website at <http://store.elsevier.com/>

Printed in the United States of America



Handbook of
Materials Failure
Analysis
With Case Studies
from the Oil and
Gas Industry

Contributors

Mohammed A. Al-Anezi

Saudi Aramco, Dhahran, Saudi Arabia

Tariq A. Al-Ghamdi

Saudi Aramco, Dhahran, Saudi Arabia

Saad M. Al-Muaili

Saudi Aramco, Dhahran, Saudi Arabia

Waleed L. Al-Otaibi

Saudi Aramco, Dhahran, Saudi Arabia

Julien Capelle

ENIM (LaBPS), Metz, France

Guillermina Capiel

Composite Materials, Institute of Materials Science and Technology (INTEMA), University of Mar del Plata and National Research Council, and Chemical Engineering Department, University of Mar del Plata, Mar del Plata, Argentina

Carlos Chastre

Department of Civil Engineering, FCT, Universidade NOVA de Lisboa, Lisboa, Portugal

Joaquim S. Corte

Universidade Federal do Rio de Janeiro, COPPE, Programa de Engenharia Metalúrgica e Materiais, Rio de Janeiro, Brazil

Tito L. da Silveira

TSEC Integridade Estrutural Ltda, Rio de Janeiro, Brasil

Ryuichiro Ebara

Institute of Materials Science and Technology, Fukuoka University, Fukuoka-city, Japan

Ahmed Z. Farahat

Central Metallurgical Research and Development Institute, CMRDI, Helwan, Cairo, Egypt

Pablo Fayó

Composite Materials, Institute of Materials Science and Technology (INTEMA), University of Mar del Plata and National Research Council, Mar del Plata, Argentina

Pablo Fazzini

GIE S.A., Failure Analysis Division, Mar del Plata, Argentina

Heloisa C. Furtado

Electrical Research Center, Rio de Janeiro, Brazil

Yi Gong

Department of Materials Science, Fudan University, Shanghai, China

Shokrollah Hassani

BP America Inc., Houston, TX, USA

Alexander Hudgins

Exponent, Menlo Park, California, USA

Brad James

Exponent, Menlo Park, California, USA

Hernán G. Kunert

University of Mar del Plata, and GIE S.A., Failure Analysis Division, Mar del Plata, Argentina

Chun Q. Li

Royal Melbourne Institute of Technology, Melbourne, Australia

Tan F. Long

UTM-MPRC Institute for Oil and Gas, Universiti Teknologi Malaysia (UTM), Skudai, Johor, Malaysia

Marco Ludovico-Marques

Barreiro School of Technology, Polytechnic Institute of Setúbal, Lavrado, Portugal

Mojtaba Mahmoodian

Royal Melbourne Institute of Technology, Melbourne, Australia

Zulkifli A. Majid

UTM-MPRC Institute for Oil and Gas, Universiti Teknologi Malaysia (UTM), Skudai, Johor, Malaysia

Abdel S.H. Makhoul

Manufacturing and Industrial Engineering Department, College of Engineering and Computer Science, University of Texas Rio Grande Valley

Anibal A. Marquez

University of Mar del Plata, and INTEMA-CONICET, Mar del Plata, Argentina

Iain L. May

Metallurgical Consulting Services Ltd., Saskatoon, SK, Canada

Rahmat Mohsin

UTM-MPRC Institute for Oil and Gas, Universiti Teknologi Malaysia (UTM), Skudai, Johor, Malaysia

Pablo E. Montemartini

Composite Materials, Institute of Materials Science and Technology (INTEMA), University of Mar del Plata and National Research Council, and Chemical Engineering Department, University of Mar del Plata, Mar del Plata, Argentina

Seifollah Nasrazadani

Engineering Technology Department, University of North Texas, Denton, TX, USA

Antonela Orofino

Composite Materials, Institute of Materials Science and Technology (INTEMA), University of Mar del Plata and National Research Council, and Chemical Engineering Department, University of Mar del Plata, Mar del Plata, Argentina

José L. Otegui

Y-TEC (YPF—CONICET), Ensenada, Argentina

Juan M. Pardal

Universidade Federal Fluminense – Escola de Engenharia, Rua Passo da Pátria, Niterói, Rio de Janeiro, Brazil

Guy Pluvinage

ENIM (LaBPS), Metz, France

Iván U. Pérez

Universidad Industrial Santander, Bucaramanga, Colombia

Xudong Qian

Department of Civil and Environmental Engineering, National University of Singapore, Singapore

Carlos Rubio-González

Centro de Ingeniería y Desarrollo Industrial, Querétaro, México

Juan M. Salgado-López

Centro de Ingeniería y Desarrollo Industrial, Querétaro, México

Christian Schmitt

ENIM (LaBPS), Metz, France

Sérgio S.M. Tavares

Universidade Federal Fluminense – Escola de Engenharia, Rua Passo da Pátria, Niterói, Rio de Janeiro, Brazil

Gudimella V.S. Murthy

Materials Science and Technology Division, CSIR-National Metallurgical Laboratory, Jamshedpur, Jharkhand, India

Zhen-Guo Yang

Department of Materials Science, Fudan University, Shanghai, China

Xiao-Hua Zhu

School of Mechanical Engineering, Southwest Petroleum University, Chengdu, China

Preface

Failure analysis and prevention are important issues for all engineering materials and industrial structures. One of the most important engineering fields which plays an essential role in failure analysis is Materials Engineering. Whether the failure happens in service or during the production process (manufacturing defects), failure analysis must be performed in order to prevent it from happening again in future. Another important factor which must be precisely investigated is to determine whether or not the metallic components and structures are being used well.

There have been several reports of catastrophic accidents in the Oil and Gas industry in countries including the United Kingdom, Kuwait, the United States of America, Venezuela, etc. Most, if not all of these accidents, were due to materials failure and were thought to be the cause of a number of workers being killed, in addition to the environmental crises. For instance, in 1993, a natural gas pipeline running along a highway in Venezuela, exploded. The rapid combustion of the spreading gas caused a hellish situation that led to the deaths of at least 50 people. It should be noted that a lot of factors, including bad design, improper manufacturing, low-grade raw materials in the pipe production, improper joining of the pipes and/or corrosion, can be the cause of such incidents.

This handbook covers analysis of materials failure in the Oil and Gas industry, where a single failure can result in devastating consequences for people, wildlife, the environment, and the economy of a region. The book combines introductory sections on failure analysis with numerous real-world case studies of pipelines and other types of materials failure in the Oil and Gas industry, including joint failure, leakage in crude oil storage tanks, failure of glass fiber-reinforced epoxy pipes, and failure of stainless steel components in offshore platforms, amongst others.

This handbook contains many failure real-world cases and case studies covering a wide spectrum of materials failure related to petroleum, petrochemicals, oil, and gas applications. The editors thank all the contributors for their excellent chapter contributions to this handbook, and for their hard work and patience during preparation, and production of the handbook. We sincerely hope that the publication of this handbook will help people from Industry and Academia to get the maximum benefits from the experience contained in the published chapters.

Summer 2015

**Abdel Salam Hamdy Makhlouf
Mahmood Aliofkhazraei**

Contents

Contributors	xv
Preface	xix

CHAPTER 1	Failure Analysis of Oil and Gas Transmission Pipelines	1
	Brad James, Alexander Hudgins	
1	Introduction.....	1
2	Mechanical Damage	3
3	Longitudinal Seam-Weld Defects	6
	3.1 Lap-Weld Defects.....	8
	3.2 Lap-Weld Case Study.....	9
	3.3 ERW Defects	12
	3.4 Flash Weld Defects	14
	3.5 Submerged-Arc Weld Defects.....	14
	3.6 Submerged-Arc Weld Defect Case Study.....	15
	3.7 Shielded Metal Arc Weld Defects	20
4	Corrosion.....	21
	4.1 General Corrosion.....	22
	4.2 Stress Corrosion Cracking.....	22
	4.3 High-pH SCC Case Study	23
	4.4 Near-Neutral pH SCC Case Study	24
	4.5 Hydrogen-Stress Cracking.....	24
	4.6 HSC Case Study	28
	4.7 Grooving Corrosion	31
5	Fatigue.....	33
6	Conclusion	36
	References.....	36

CHAPTER 2	Modern Analytical Techniques in Failure Analysis of Aerospace, Chemical, and Oil and Gas Industries	39
	Seifollah Nasrazadani, Shokrollah Hassani	
1	Microscopy Techniques.....	39
	1.1 Optical Microscopy	39
	1.2 Scanning Electron Microscopy	40
	1.3 Focused Ion Beam	41
2	Chemical and Radiographic Analysis.....	42
	2.1 Energy Dispersive Spectroscopy.....	42
	2.2 X-Ray Fluorescence	44

2.3	X-Ray Diffraction	45
2.4	Fourier Transform Infrared Spectrophotometry	46
2.5	X-Ray Photoelectron Spectroscopy	47
2.6	Radiography	49
2.7	Neutron Radiography	50
2.8	X-Ray Radiography	51
2.9	Gamma-Ray Radiography	52
2.10	Fluoroscopic Radiography	53
3	Conclusion and Future Outlook	53
	References	53

CHAPTER 3 Methods for Assessing Defects Leading to Gas Pipe Failure..... 55

Guy Pluvinage, Julien Capelle, Christian Schmitt

1	Introduction	56
2	Macroscopic and Microscopic Aspects of Pipe Failure	58
3	Brittle Fracture in a Pipe Emanating from a Crack	59
3.1	Cracks in a Pipe	59
3.2	Fracture Condition of a Cracked Pipe	60
3.3	Failure Assessment Diagram	61
3.4	Defect Assessment in a Brittle Cast Iron Pipe	64
4	Assessment of Gouges Using Notch Fracture Mechanics	65
4.1	Gouges in Pipes	65
4.2	Notch Fracture Mechanics	66
4.3	Notch Failure Assessment Diagram	68
4.4	Safety Factor Associated with Defect in Pipe Under Service Pressure	68
4.5	Two-Parameter Fracture Mechanics	70
5	Pipe Failure Emanating from Corrosion Defect	71
5.1	Burst Pressure Predicted by Plastic Collapse	73
5.2	Domain Failure Assessment Diagram	76
5.3	Application to Corrosion Defect in a Gas Pipe	77
6	Pipe Failure Emanating from Dents	78
6.1	Dent: Origin and Description	78
6.2	Limit of Acceptability of Dent Depth	79
6.3	Methods to Estimate and Control Dent	80
6.4	Methods to Estimate and Control Dent+Gouge Defect	83
7	Conclusion	86
	References	88

CHAPTER 4	Failure of Glass Fiber-Reinforced Epoxy Pipes in Oil Fields	91
	Guillermina Capiel, Pablo Fayó, Antonela Orofino, Pablo E. Montemartini	
1	Introduction	91
2	In-Lab Studies	93
3	In-Service Degradation and Failure	98
4	Conclusion	101
	References	102
CHAPTER 5	Failures and Integrity of Pipelines Subjected to Soil Movements	105
	Hernán G. Kunert, Anibal A. Marquez, Pablo Fazzini, José L. Otegui	
1	Introduction	105
2	Recent Failures and Lessons Learned	108
3	Mitigation Measures During Operation	113
4	Prevention Measures at the Design Stage	119
5	Conclusion	120
	Acknowledgment	121
	References	121
CHAPTER 6	Oil Field Drill Pipes Failure	123
	Gudimella V.S. Murthy	
1	Introduction	124
2	Case 1: In-Service Pitting	124
	2.1 Experimental	126
	2.2 Discussion	130
	2.3 Conclusion and Recommendations	131
3	Case 2: Surface Oxide Cracking	131
	3.1 Experimental	132
	3.2 Discussion	137
	3.3 Conclusion and Recommendations	139
4	Case 3: Hardbanding Failure	139
	4.1 Experimental	140
	4.2 Discussion	151
	4.3 Conclusion and Recommendations	151
	Acknowledgments	151
	References	152

CHAPTER 7	Failure Analysis and Solution Studies on Drill Pipe Thread Gluing at the Exit Side of Horizontal Directional Drilling	153
	Xiao-Hua Zhu	
1	Introduction.....	153
2	Methodology and Model	155
2.1	Analysis of Construction Conditions	155
2.2	Material Tensioning and Make-Up and Break-Out Tests	157
3	Results and Discussion	161
3.1	FEM Verification.....	161
3.2	Effects of Insufficient Make-Up Torque.....	162
3.3	Effect Analysis of Bending Moment	162
3.4	Improvement Measures	166
3.5	New Drill Pipe Thread Design.....	167
3.6	Comparison of Bending Strength.....	168
3.7	Comparison of Flexural Rigidity	168
3.8	Comparison of the Shoulder Sealing	170
4	Conclusion and Recommendations	172
	Acknowledgments	172
	References.....	172
 CHAPTER 8	 Causes and Conditions for Reamer Blade Balling During Hole Enlargement While Drilling.....	 175
	Xiao-Hua Zhu	
1	Introduction.....	175
2	Methodology and Model	177
2.1	Physical Model	177
2.2	Mathematical Model.....	178
2.3	Simulation Conditions	182
2.4	Numerical Model and Computation.....	182
2.5	Restrictive Conditions	183
3	Results and Discussion	184
3.1	Flow Pattern Discussion	184
3.2	Discussion of the Causes of Reamer Blade Balling	186
3.3	Measures to Reduce Balling.....	186
3.4	Optimizing the Reamer Blade Hydraulic Structure.....	187
3.5	The Influence of Nozzle Type and Angle	190
3.6	Parameter Optimization.....	192
4	Conclusion and Recommendations	195
	Acknowledgments	197
	References.....	197

CHAPTER 9	Analysis of Reamer Failure Based on Vibration Analysis of the Rock Breaking in Horizontal Directional Drilling	199
	Xiao-Hua Zhu	
1	Introduction.....	199
2	Methodology and Model	202
2.1	Reamer-Rock Contact with Mathematical Model	202
2.2	Drucker-Prager Rock Strength Criterion	202
2.3	Basic Assumptions.....	203
2.4	Petrophysical Parameters.....	203
2.5	Meshing and Boundary Conditions.....	203
3	Results and Discussion	204
3.1	Reamer Lateral, Axial, and Torsional Vibration Characteristics.....	204
3.2	Pullback Force on the Reamer Lateral Vibration.....	207
3.3	RPM on the Reamer Lateral Vibration.....	208
3.4	Selection of Reasonable Construction Parameters	209
3.5	Engineering Applications	211
4	Conclusion and Recommendations	212
	Acknowledgments	213
	References.....	214
CHAPTER 10	Effect of Artificial Accelerated Salt Weathering on Physical and Mechanical Behavior of Sandstone Samples from Surface Reservoirs	215
	Marco Ludovico-Marques, Carlos Chastre	
1	Introduction.....	215
1.1	Geological Setting	215
1.2	Salt Weathering Effect	217
2	Experimental Program	217
2.1	Mineralogical Characterization	217
2.2	Experimental Procedures for Artificial Accelerated Salt Weathering Tests	219
2.3	Experimental Procedures for Physical Tests.....	221
2.4	Experimental Procedures for Mechanical Tests	222
3	Analysis of Results of the Experimental Program.....	223
3.1	Physical Behavior	223
3.2	Mechanical Behavior.....	225
4	Conclusion	231
	References.....	232

CHAPTER 11 Stochastic Failure Analysis of Defected Oil and Gas Pipelines	235
Mojtaba Mahmoodian, Chun Q. Li	
1 Introduction.....	235
2 Research Significance.....	237
3 Time-Dependent Reliability Analysis.....	238
3.1 Background.....	238
3.2 Methods for Time-Dependent Reliability Analysis.....	239
3.3 Gamma Process Model.....	243
3.4 Comparison of Reliability Analysis Methods.....	246
4 Worked Example	247
5 Conclusion	252
References.....	253
 CHAPTER 12 Determining the Cause of a Carbon Steel Joint Failure in a Gas Flow Pipeline Production Facility	 257
Abdel S.H. Makhlof, Ahmed Z. Farahat	
1 History and Visual Examination	257
2 Laboratory Evaluation of the Failed “T” Joint	259
3 Failure Analysis Summary	260
3.1 Physical Evaluation of the Cracked Site of the “T” Joint	260
3.2 Chemical Composition Examination	261
3.3 The Metallographic Examination.....	263
3.4 Surface Examination Using SEM-EDS and Macrograph Images	263
4 Conclusion	264
5 Recommendations.....	264
References.....	266
 CHAPTER 13 Experimental and Numerical Investigation of High-Pressure Water Jetting Effect Toward NPS8 Natural Gas Pipeline Integrity—Establishing Safety Distance Perimeter	 267
Zulkifli A. Majid, Rahmat Mohsin, Tan F. Long	
1 Introduction.....	268
2 Description of the Ruptures Pipe Incident.....	270
3 Methodology	272
4 Results and Discussion	275
4.1 Experimental Study	275