

# ASM Handbook®

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## Volume 11 Failure Analysis and Prevention

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# Foreword

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This 2002 edition of *Failure Analysis and Prevention* is the outcome from the devoted efforts of volunteer editors, authors, and reviewers, who have helped organize and develop this revised Volume 11 of the *ASM Handbook* series. This publication would not have been possible without their vision and dedicated efforts in the ongoing improvement of engineering knowledge and education through the analysis, understanding, and prevention of failure.

As noted in the Preface, the authors and editors assembled this Volume with several broad themes in mind. The nature of failure is complex, varied, and unanticipated. Its prevention can also be multifaceted and varied. In this way, failure analysts are not only specialists, but also educators who help others become aware of the root cause(s) of failure. This requires a clear understanding of the many stages in the life of a part from design and manufacturing to anticipated service, inspection, and maintenance. It also involves a host of tools and techniques for effective planning and implementation of a failure investigation.

Thus, failure analysis and prevention can be a complex multidisciplinary activity that requires broad knowledge in design, manufacturing, mechanics, materials, and testing. The editors and authors have tackled this complex nature of failure analysis and prevention in an updated volume that is, in many respects, an all-new volume. This new edition contains over 50 new articles with expanded coverage on the four basic types of failures (deformation, fracture, corrosion, and wear) and the variety of tools and techniques for effective planning, organization, implementation, and reliable conclusion of a failure investigation through proper interpretation of information.

We would like to extend our thanks to the devoted community of volunteers who have helped organize and develop this 2002 edition of *Failure Analysis and Prevention*. The editors, authors, and reviewers are to be commended for their fine contributions on a vital topic for all engineering disciplines, in the very best of tradition of the Handbook series. We especially thank Bill Becker, Roch Shipley, Debbie Aliya, Dan Benac, Larry Hanke, Jeff Hawk, Steve McDanel, Richard McSwain, Ron Parrington, Jim Scutti, Aaron Tanzer, and Richard Wilson. This publication would not have been possible without their vision, knowledge, and efforts.

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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 usually 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, but 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 IEEE/ASTM SI-10, 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 IEEE/ASTM SI-10; 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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Welcome to the new edition of *ASM Handbook*, Volume 11, *Failure Analysis and Prevention*.

**Theme and Purpose of this Volume.** The authors and editors assembled this Volume with several broad themes in mind. First, the most important goal of failure analysis is to decrease the occurrence of component failures through the understanding of the root cause for failure. Experienced failure analysts are often frustrated when, despite extensive engineering research, investigations, and failure analysis reports, the same types of failures occur again and again. When the root cause has been identified as defective global design rather than abuse or misuse, product quality and reliability is improved.

The failure analyst should strive to uncover the underlying or root (technical) cause of the failure. The fact that a specific component appears to have failed in some way does not automatically mean that the component itself is defective. The problem may lie in the way the component was used, inspected, or maintained. If it is truly defective, then the analysis should determine whether the defect originates in design, manufacture (fabrication and assembly), material selection/processing, or unexpected service environment.

This Volume provides a framework for investigating the above issues. In addition to sections devoted to design and manufacture, there are also sections on failures that occur through fracture, corrosion, and wear, as well as an article on failure through deformation. This Volume is also an attempt to address the principles, tools, techniques, and procedures necessary to plan, organize, and conduct a thorough investigation. Not every failure investigation is the same, and a failure root-cause analysis is more than a microstructural examination, a stress analysis, or a chemical corrosion analysis. All of these disciplines, as well as others, may be required to reach a root cause conclusion.

No single volume, no matter how comprehensive, can present all the information that may potentially be needed. The emphasis of this Volume is on general principles with the widest applicability to situations that the reader is likely to encounter. References and sources of further information are provided throughout. While some common types of components or equipment may be included in some detail, not every type of machine can be treated. The reader is encouraged, and in fact urged, to pursue additional sources of information so as to understand the function and history of the component, machine, or system that is under investigation.

**Audience.** One of the challenges in preparing a work of this type is the diversity of readership. Some readers are students and other novices who may be confronted with a failed part for the first time. They may be looking to the Handbook for guidance on where to start their analysis. Other readers are experienced practitioners, using the Handbook to verify or clarify a critical detail in their analysis. Thus, the contents of this Volume include the essential basics of failure analysis, as well as more advanced discussions from a research perspective.

The discussions of fracture mechanisms are an example of this approach to Handbook organization. The articles “Overload Failures” and “Fatigue Failures” are good starting points for readers wishing to begin their study of fracture. Examination of the fracture surface (when failure did result in fracture) at both the macro and micro scale provides considerable information pertinent to a failure investigation. This subject is introduced in

the article “Overload Failures” with some discussion of the mechanisms that may be involved.

For some readers, these may be sufficient, if all they need is to identify the basic fracture mechanism. However, further study can sometimes allow the analyst to learn more about the circumstances of a fracture. Unfortunately, there are few instances in which a single fractographic feature is definitive in identifying a root cause (and to distinguish between abuse and defective design). Casual examination may not distinguish between fine details caused by different fracture processes. Consequently, a detailed study of the fracture surface at both the macroscale and microscale is helpful and may be critical in obtaining a root cause conclusion. The reader who desires a more detailed appreciation and thorough understanding should continue with the article “Fracture Appearance and Mechanisms of Deformation and Fracture” and the article “Stress Analysis and Fracture Mechanics.” These articles introduce quantitative means to relate the fracture process to material properties and, therefore, are critical to distinguishing between abuse or misuse and inadequate quality. Finally, the article “Mechanisms and Appearances of Ductile and Brittle Fracture in Metals” provides a still more in-depth treatment on the detailed appearances at both the macroscale and microscale, with the intent of extracting the maximum possible information for root-cause failure analysis.

**Differences of Opinion.** Controversy is, perhaps, inherent in the very nature of failure analysis. If anything, that is even truer today when real or perceived failures are the subject of litigation. The authors have integrated thoughts on legal considerations into many of the articles. However, nothing here should be taken as legal advice. Those who are concerned regarding legal implications should consult competent counsel.

Furthermore, as every circumstance is somewhat unique, the Handbook should be used with care and should not be the sole source of information when critical decisions are to be made. Most articles include extensive references, which should be reviewed if further information is required.

The authors present analyses and interpretations based on scientific principles and experience. All of the articles have been reviewed and edited. However, there can be and still are differences of opinion among failure analysts regarding some issues. It is up to the reader to determine whether the information presented is applicable and helpful in a particular situation. Experienced analysts should be consulted if there is any doubt. Despite the best efforts of the authors, reviewers, and editors, the reader might find an area that could be improved. If so, please bring this to the attention of the ASM Editors so that your concern can be reviewed and, depending on the consensus of opinion, can be addressed in subsequent printings.

**Collaborative Effort.** This Volume reflects the efforts of many people. Except for ASM staff, all are volunteers. Many of the volunteers are fully employed and contributed their personal time to the project. Neither they nor their employers receive any compensation for their efforts, except for the satisfaction that accrues from being able to share what they have learned, prevent failures, and contribute to safer, more reliable products. The names of the authors, editors, reviewers, and ASM staff are acknowledged individually elsewhere in this Volume and are too numerous to list here. However, ASM Editor Steven Lampman does deserve special mention for his commitment, dedication, and patience, without which this Volume would not have become a reality.

It has been most enjoyable and professionally rewarding to work with all who were involved in this effort. On behalf of ASM and the readers of this Handbook, we express our appreciation to all for the time and effort expended and for their willingness to share their knowledge and lessons derived from experience. Many of the contributors have established national and international reputations in their respective fields. More than any words of appreciation in a Preface such as this, however, it is our hope

that the Handbook itself will be a most fitting tribute to all participants, both now and into the future.

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# Contents

<b>Engineering Aspects of Failure and Prevention</b> .....	<b>1</b>	<b>Manufacturing Aspects of Failure and Prevention</b> .....	<b>79</b>
<i>Chairperson: James Scutti</i>			
Introduction to Failure Analysis and Prevention .....	3	Failures Related to Metalworking .....	81
Concepts of Failure Analysis and Prevention .....	3	Imperfections in Wrought Forms .....	81
Root-Cause Analysis .....	6	Imperfections from the Ingot .....	82
Primary Physical Root Causes of Failure .....	6	Forging Imperfections .....	90
Charting Methods for RCA .....	14	Workability .....	97
Other Failure Analysis Tools .....	15	Cracking in Bulk Working .....	99
Categories of Failure .....	17	Sheet Forming .....	100
Failure Prevention .....	19	Cold Formed Parts .....	101
Materials Selection for Failure Prevention .....	24	Failures Related to Casting .....	103
Design and Failure Prevention .....	25	Casting Discontinuities .....	103
Materials Selection in Design .....	29	Effect of Casting Discontinuities .....	104
Materials Selection for Failure Prevention .....	34	Permanent-Mold Methods .....	123
Materials Selection and Failure Analysis .....	35	Casting Design .....	133
Design Review for Failure Analysis and Prevention .....	40	Cast Irons .....	137
What Is an Engineering Failure? .....	40	Cast Steels .....	142
The Context of an Engineering Failure .....	40	Cast Aluminum Alloys .....	149
The Engineering Design Process .....	41	Welding .....	152
Preliminary Investigation .....	42	Failures Related to Welding .....	156
Analysis of the Engineering Design Process .....	42	Weld Discontinuities and Service Conditions .....	157
Task Clarification—Defining the Problem .....	43	Joint Design .....	161
Conceptual Design .....	44	Failure Origins in Arc Welds .....	169
Embodiment Design .....	44	Other Welding Processes .....	186
Detail Design .....	46	Failures Related to Heat Treating Operations .....	192
Management Influences .....	46	Phase Transformation during Heating and Cooling .....	192
External Influences .....	47	Tempering .....	195
Design Life-Cycle Issues .....	48	Metallurgical Sources of Stress and Distortion during	
Failure Modes and Effects Analysis .....	50	Reheating and Quenching .....	195
Overview of FMEA .....	50	Effect of Materials and Process Design on Distortion .....	196
The FMEA Process .....	53	Quenching .....	205
Fault Equivalence .....	56	Steel Transformation Products and Properties .....	214
The Failure Cause Model .....	56	Influential Microstructural Features .....	217
Automation .....	57	<b>Structural Life Assessment Methods</b> .....	<b>225</b>
Conclusions .....	58	<i>Chairperson: Dan Benac</i>	
Reliability-Centered Maintenance .....	60	Failure Analysis and Life Assessment of Structural Components	
History of RCM .....	60	and Equipment .....	227
Overview of the RCM Process .....	61	Industry Perspectives on Failure and Life Assessment	
Failure Modes and Effects Analysis .....	62	of Components .....	227
Failure Management Policies and “Technical Feasibility” .....	64	Structural Design Philosophies .....	227
Failure Consequences and “Worth Doing” .....	66	Life-Limiting Factors .....	232
Failure Management Policy Selection .....	67	Role of the Failure Investigator .....	234
Managing and Resourcing the RCM Process .....	68	Role of Nondestructive Inspection .....	238
Conclusions .....	70	Specific Life Assessment Methodologies .....	239
Products Liability and Design .....	71	Conclusions .....	242
Legal Bases for Products Liability .....	71	Failure Assessment Diagrams .....	243
Hazard, Risk, and Danger .....	72	Origin and Description of the Failure Assessment	
Definitions of Defects .....	72	Diagram .....	243
Preventive Measures .....	75	Current R6 Failure Assessment Diagrams .....	244
Paramount Questions .....	77	Current Fracture Criteria of BS 7910 .....	244
Acceptable Level of Risk .....	77		

Considerations in Use .....	246	Analysis of Base Material Composition .....	358
Application Examples .....	247	Metallurgical Samples and Hardness .....	359
Analysis Methods for Probabilistic Life Assessment .....	250	Preparation and Examination of Metallographic Specimens in Failure Analysis .....	361
Introduction to Probabilistic Analysis .....	250	Analysis and Interpretation of Microstructures .....	363
Elements of Probabilistic Analysis .....	252	Evaluation of Polymers in Failure Analysis .....	367
Evaluation of Probability of Failure .....	255	Evaluation of Ceramic Materials in Failure Analysis .....	369
Advanced Concepts .....	262	Modeling and Accident Reconstruction .....	371
Case Histories: Examples of the Use of Probabilistic Analysis .....	264	Accident Reconstruction .....	371
Probabilistic Analysis Software .....	267	Modeling .....	376
Nondestructive Evaluation and Life Assessment .....	269	Finite Element Modeling in Failure Analysis .....	380
Common Measurement Techniques .....	269	General Development of FEA .....	380
Life Assessment Strategies .....	269	General-Purpose Applications .....	381
The Role of NDE .....	270	Special Purpose Applications .....	385
Non-Aerospace Applications .....	273	Design Review in Failure Analysis .....	386
Implementation Guidance .....	274	Case Studies of FEA in Failure Analysis .....	387
Conclusions .....	274	<b>Tools and Techniques in Failure Analysis .....</b>	<b>391</b>
Fatigue-Life Assessment .....	276	Practices in Failure Analysis .....	393
Fatigue Crack Growth Variables .....	276	Stages of a Failure Analysis .....	393
Safe-Life versus Damage-Tolerance Approach .....	281	Collection of Background Data and Samples .....	393
Material Behavior .....	282	Fractures .....	397
Retardation and Spectrum Load Effects .....	282	Corrosion Failures .....	405
Crack Growth Software Packages .....	283	Wear Failures .....	407
Case Studies .....	283	Formulating Conclusions and Report Writing .....	413
Elevated-Temperature Life Assessment for Turbine Components, Piping, and Tubing .....	289	Key Guidelines .....	416
Definition of Damage, Life, and Failure Criteria .....	289	Photography in Failure Analysis .....	418
Life-Limiting Elevated-Temperature Failure Mechanisms .....	289	Visual Examination .....	418
Metallurgical Instabilities .....	291	Field Photographic Documentation .....	418
Gas Turbine Blade Life Assessment .....	295	Laboratory Photographic Documentation .....	419
Life Assessment Methods for Power Plant Piping and Tubing .....	304	Photographic Equipment .....	419
<b>Principles and Practice of Failure Analysis .....</b>	<b>313</b>	Film Photography .....	420
<i>Chairpersons: Debbie Aliya, Aaron Tanzer, and Steve McDanel</i>		Digital Photography .....	420
The Failure Analysis Process: An Overview .....	315	Basics of Photography .....	421
Principles and Approaches in Failure Analysis Work .....	316	Photographic Lighting .....	421
The Objectives of Failure Analysis .....	317	Fracture Surface Photography .....	421
Scope and Planning .....	318	Macrophotography .....	425
Planning and Preparation .....	319	Microscopic Photography .....	425
Practices and Procedures .....	321	Special Methods .....	426
Organization of a Failure Investigation .....	324	Chemical Analysis of Metals in Failure Analysis .....	429
What Is a Failure? .....	324	Bulk Composition Verification .....	429
Why Do Failures Happen? .....	324	Microchemical Analysis in Failure Analysis .....	432
Why Is a Failure Investigation Performed? .....	325	Characterization of Plastics in Failure Analysis .....	437
The Four-Step Problem-Solving Process .....	325	Fourier Transform Infrared Spectroscopy .....	437
Nine Steps of a Failure Investigation .....	325	Differential Scanning Calorimetry .....	439
Summary .....	331	Thermogravimetric Analysis .....	441
Failure Investigation Pitfalls .....	331	Thermomechanical Analysis .....	442
Other Tools .....	331	Dynamic Mechanical Analysis .....	443
Conducting a Failure Examination .....	333	Methods for Molecular Weight Assessment .....	444
Basic Approach to Failure Analysis .....	333	Mechanical Testing .....	445
Failure Analysis Procedures .....	333	Considerations in the Selection and Use of Test Methods .....	446
Conclusions .....	341	Case Studies .....	447
Determination and Classification of Damage .....	343	Stress Analysis and Fracture Mechanics .....	460
Characterization and Identification of Damage and Damage Mechanisms .....	343	Analysis of Applied Stresses .....	461
Determining Primary and Secondary Damage Mechanisms .....	346	Fundamentals of Stress Analysis .....	461
Damage Mechanism Categorization .....	347	Stress Analysis Of Common Geometries .....	468
Conclusions .....	349	Application of Stress Analysis .....	473
Examination of Damage and Material Evaluation .....	351	Fracture Mechanics .....	475
Visual or Macroscopic Examination of Damaged Material .....	351	Fracture Mechanics Concepts .....	475
Interpretation of Damage and Fracture Features .....	352	An Introduction to LEFM .....	476
Corrosion and Wear Damage Features .....	354	Subcritical Fracture Mechanics .....	478
		Elastic-Plastic Fracture Mechanics .....	479
		Applications .....	480
		Appendix: Stress Tensor Decomposition and Transformation of Stress .....	482
		Stress Tensor Decomposition .....	482
		Transformation of Stress .....	482

X-Ray Diffraction Residual Stress Measurement in Failure Analysis .....	484	Factors Affecting Ductility .....	595
Residual Stress in Failures and XRD Analysis .....	484	Geometric Limits of Ductility .....	595
X-Ray Diffraction Theory and Residual Stress Measurement .....	484	Materials Factors Affecting Ductility .....	597
Analysis of XRD Data .....	485	Fracture Appearances .....	598
Instrument Calibration and Validation of Stress Measurements .....	486	Cylindrical Specimens in Tension .....	598
Sample Selection .....	488	Prismatic Specimens in Tension .....	600
Measurement Location Selection and Location Access .....	488	Compression Failure .....	602
Selecting Measurement Directions and Depths .....	489	Bending .....	603
Specimen Preparation .....	489	Torsion Loading .....	605
Residual-Stress Effects on Components under Quasi-Static Loading .....	490	Fracture Appearances in Cast Materials .....	607
Stress-Corrosion Cracking and Corrosion Fatigue .....	490	Fracture at or near Stress Raisers .....	608
The Importance of Residual Stress in Fatigue .....	491	Macroscale Appearance .....	608
The Effect of Manufacturing Processes on Residual Stress .....	493	Microscale Details of Initiation and Propagation .....	610
The Characterization of Stress Gradients Using XRD .....	494	Fracture from Manufacturing Imperfections .....	612
Effects of Heat Treatment on Residual Stresses .....	494	Case History .....	615
X-Ray Diffraction Stress Measurements in Multiphase Materials and Composites .....	495	Appendix: Modeling of Ductile Plastic Flow .....	616
X-Ray Diffraction Stress Measurements in Locations of Stress Concentration .....	496	Macroscopic Plastic Flow and Instability .....	616
Metallographic Techniques in Failure Analysis .....	498	Strain Localization .....	621
Examination of Fractures .....	499	Void Nucleation Models .....	622
Metallographic Specimen Preparation .....	501	Void Coalescence Microscale Models .....	623
Examination of Microstructures .....	509	Fatigue Fracture Appearances .....	627
Field Metallography .....	513	Fatigue Processes .....	628
Scanning Electron Microscopy .....	516	Macroscopic Appearance of Fatigue Fracture .....	630
Development of SEM Technology .....	516	Microscopic Appearance of Fatigue Fracture in Metals .....	635
Operation .....	516	Fatigue of Polymers and Composites .....	638
Specimen Preparation .....	521	Intergranular Fracture .....	641
Application of SEM in Fractography .....	522	Mechanisms of IG Fracture .....	642
Chemical Characterization of Surfaces .....	527	Intergranular Brittle Cracking .....	642
Overview of Surface Analysis .....	527	Dimpled IG Fracture .....	643
Auger Electron Spectroscopy .....	529	Intergranular Fatigue .....	644
X-Ray Photoelectron Spectroscopy .....	530	Causes of IG Fracture .....	645
Time-of-Flight Secondary Ion Mass Spectrometry .....	532	Intergranular SCC and Hydrogen Embrittlement .....	646
Example: Stainless Steel Analysis .....	533	Example .....	648
Quantitative Fractography .....	538	Fracture of Plastics .....	650
Profilometry-Based Quantitative Fractography .....	539	Deformation and Fracture .....	650
SEM Quantitative Fractography .....	547	Crack Propagation .....	654
Three-Dimensional Fracture Surface Reconstruction .....	551	Fractography .....	655
<b>Fracture .....</b>	<b>557</b>	Case Studies .....	660
<i>Chairperson: William Becker</i>		Fracture Modes and Appearances in Ceramics .....	662
Fracture Appearance and Mechanisms of Deformation and Fracture .....	559	Techniques of Fractography .....	662
General Background on Fractography .....	559	Fracture Markings .....	664
Fracture Surface Information .....	561	Fracture Modes .....	665
Ductile and Brittle Behavior .....	564	Fracture Origins .....	667
Macroscopic Ductile and Brittle Fracture Surfaces .....	566	Overload Failures .....	671
Structure and Behavior .....	568	Fracture Modes and Mechanisms .....	671
Deformation and Fracture .....	568	Ductile Overload Failures .....	671
Brittle Transgranular Fracture (Cleavage) .....	572	Brittle Overload Failures .....	674
Intergranular Fracture .....	574	Mixed-Mode Cracking .....	677
Fatigue Fracture .....	576	Material Factors .....	677
Appendix: Modeling with Fracture Mechanics .....	581	Temperature Effects .....	684
Mechanisms and Appearances of Ductile and Brittle Fracture in Metals .....	587	Effects of Mechanical Loading .....	686
Mechanisms of Deformation and Fracture .....	587	Service Damage or Alteration .....	689
Background .....	588	Embrittlement .....	689
Single-Crystal Cleavage Models .....	588	Environmentally Induced Embrittlement .....	696
Slip, Twinning, and Cleavage in Polycrystals .....	589	Laboratory Fracture Examination .....	699
Ductile Fracture and Microvoid Coalescence .....	591	Fatigue Failures .....	700
		Fatigue Properties and Design Life .....	700
		Infinite-Life Criterion ( <i>S-N</i> Curves) .....	700
		Finite-Life Criterion ( $\epsilon$ - <i>N</i> Curves) .....	702
		Damage Tolerance Criterion .....	702
		Characteristics of Fatigue Fracture .....	706
		Crack Initiation .....	706
		Fatigue Crack Propagation .....	706
		Final Fracture (Stage III) .....	708
		Effect of Loading and Stress Distribution .....	708
		Load Conditions .....	710
		Stress Concentrations .....	715
		Effect of Load Frequency and Temperature .....	718

Effect of Material Condition .....	718	Selective Leaching .....	785
Strengthening and Heat Treatments .....	718	Dealloying Mechanisms .....	785
Subsurface Discontinuities .....	719	Dezincification .....	785
Manufacturing Practices on Fatigue Strength .....	720	Graphitic Corrosion .....	786
Corrosion Fatigue .....	721	Dealuminification .....	787
Appearances .....	721	Denickelification .....	788
Examination .....	721	Destannification and Desiliconification .....	788
Contact Fatigue .....	722	Dealloying of Noble Metals .....	788
Macropitting .....	723	Velocity-Affected Corrosion .....	788
Micropitting .....	724	Low-Velocity Effects .....	788
Subcase Fatigue .....	725	High-Velocity Effects .....	791
Thermal Fatigue .....	726	Effect of Environment on the Performance of Plastics .....	796
Identification .....	726	Plasticization, Solvation and Swelling .....	796
Creep and Stress Rupture Failures .....	728	Environmental Stress Cracking .....	797
Bulk Creep Behavior .....	728	Polymer Degradation by Chemical Reaction .....	797
Stress Rupture .....	731	Surface Embrittlement .....	798
Stress-Rupture Fractures .....	733	Temperature Effects .....	798
Metallurgical Instabilities .....	734	Conclusions .....	799
Thermal Fatigue and Creep Fatigue .....	736	Corrosion Failures of Industrial Refractories and Technical	
Thermomechanical Fatigue: Mechanisms and Practical Life		Ceramics .....	800
Analysis .....	738	Basic Principles .....	801
Basic Descriptions of TMF .....	738	Corrosion of Specific Classes of Refractories	
TMF Mechanisms .....	739	and Technical Ceramics .....	803
Experimental Techniques .....	741	Strategies for Analysis and Prevention of Failures .....	805
Case Study: Prediction of Residual Life in a Turbine		Hydrogen Damage and Embrittlement .....	809
Casing .....	741	Overview of Hydrogen Damage Processes .....	809
<b>Corrosion-Related Failures .....</b>	<b>747</b>	Hydrogen Embrittlement .....	810
<i>Chairperson: Ron Parrington</i>		Hydrogen Environmental Embrittlement .....	811
Analysis and Prevention of Corrosion-Related Failures .....	749	Fracture Characteristics .....	813
Electrochemical Nature of Corrosion .....	749	Hydrogen Reaction Embrittlement .....	814
Analysis of Corrosion-Related Failures .....	751	Susceptibility of Various Metals .....	816
Examples of Corrosion Failure Analysis .....	753	Stainless Steels .....	816
Prevention of Corrosion-Related Failures of Metals .....	755	Nickel-Base Alloys .....	816
Forms of Corrosion .....	761	Aluminum and Aluminum Alloys .....	817
Galvanic Corrosion .....	761	Copper and Copper Alloys .....	817
Factors Affecting Galvanic Corrosion .....	762	Titanium and Titanium Alloys .....	817
Combating Circumstances That Promote Galvanic		Transition and Refractory Metals .....	818
Action .....	764	Analysis of Hydrogen Embrittlement in Commodity-Grade	
Evaluation of Galvanic Corrosion .....	764	Steels .....	818
Examples of Factors Contributing to Galvanic		Preservice and Early-Service Failures .....	818
Corrosion .....	766	Factors Affecting Delayed Hydrogen Stress Cracking .....	819
Performance of Alloy Groupings .....	766	Diagnosing Hydrogen Embrittlement .....	820
Uniform Corrosion .....	767	Stress-Corrosion Cracking .....	823
Surface Conditions .....	768	General Characteristics of SCC .....	823
Classification of Uniform Corrosion .....	768	Crack Initiation and Propagation .....	824
Materials Selection .....	769	Mechanisms of SCC .....	826
Effect of Corrosion Products .....	769	Manufacturing Sources of Stress .....	826
Effect of Concentration .....	769	Sources of Stresses in Service .....	830
Effect of Temperature .....	770	Metal Susceptibility .....	831
Evaluation Factors .....	770	Environmental Effects .....	832
Design Considerations .....	771	Analysis of SCC Failures .....	834
Pitting and Crevice Corrosion .....	771	Carbon and Low-Alloy Steels .....	838
Pitting .....	771	Maraging Steels .....	843
Crevice Corrosion .....	775	Austenitic Stainless Steels .....	843
Reducing Failures Due to Pitting and Crevice Corrosion ..	777	Ferritic and Duplex Stainless Steels .....	846
Intergranular Corrosion .....	777	Martensitic and Precipitation-Hardening Stainless Steels ..	847
Development of Intergranular Corrosion .....	777	Nickel-Base Alloys .....	848
Alloy Susceptibility .....	778	Aluminum Alloys .....	850
Evaluation of Intergranular Corrosion .....	779	Copper and Copper Alloys .....	853
Intergranular Corrosion of Stainless Steels .....	779	Magnesium Alloys .....	856
Intergranular Corrosion of Nickel Alloys .....	783	Titanium and Titanium Alloys .....	857
Intergranular Corrosion of Aluminum Alloys .....	784	Liquid Metal and Solid Metal Induced Embrittlement .....	861
Intergranular Corrosion of Copper Alloys .....	784	Characteristics of SMIE and LMIE .....	861
Intergranular Corrosion of Zinc .....	785	Occurrence of SMIE and LMIE .....	862
		Failure Analysis of SMIE and LMIE .....	862
		LMIE and SMIE Service Failures .....	863
		High-Temperature Corrosion-Related Failures .....	868
		High-Temperature Corrosion Mechanisms .....	868
		Protective Coatings .....	876

Biological Corrosion Failures .....	881	Effect of Environmental Factors on Corrosive Wear .....	990
Microbial Involvement in Corrosion .....	881	Grinding Wear: Impact and Three-Body	
Degradation of Protective Systems .....	884	Abrasive-Corrosive Wear .....	991
Failure Analysis .....	885	Means for Combating Corrosive Wear .....	992
Monitoring Industrial Systems .....	891	Erosive Wear Failures .....	995
Prevention and Control Strategies .....	893	Erosion of Ductile Materials .....	995
Conclusions .....	894	Erosion of Brittle Materials .....	997
		Examples of Erosive Wear Failures .....	997
<b>Wear Failures .....</b>	<b>899</b>	Cavitation Erosion .....	1002
<i>Chairpersons: Jeff Hawk and Richard Wilson</i>		Cavitation Mechanisms .....	1002
Fundamentals of Wear Failures .....	901	Cavitation Erosion Analysis .....	1002
Examination and Characterization of the Tribosystem .....	901	Industry Examples of Cavitation Failure .....	1004
Characterization and Modeling of the Wear Situation .....	902	Cavitation Resistance of Materials .....	1005
Obtaining and Evaluating Wear Data .....	903	Other Prevention Parameters .....	1007
Evaluation and Verification of Solutions .....	904	Cavitation Tests .....	1007
Avoiding Wear Failures .....	904	Liquid-Impact Erosion .....	1013
Abrasive Wear Failures .....	906	Cavitation Erosion .....	1013
General Classification of Wear .....	907	Liquid-Droplet Erosion .....	1014
Abrasive Wear Mechanisms .....	909	Materials Issues in Liquid Impact .....	1015
Wear Failure Analysis .....	914	Mitigation and Repair of Liquid-Impact Damage .....	1016
Examples of Abrasive Wear .....	915	Wear Failures of Plastics .....	1019
Fretting Wear Failures .....	922	Interfacial Wear .....	1019
Fretting Wear .....	922	Cohesive Wear .....	1022
Examples of Fretting Failures .....	934	Elastomers .....	1022
Rolling Contact Fatigue .....	941	Thermosets .....	1023
General Principles of RCF .....	941	Glassy Thermoplastics .....	1023
Rolling-Contact Fatigue of Vapor-Deposited Coatings .....	945	Semicrystalline Thermoplastics .....	1023
Rolling-Contact Fatigue of TS Coatings .....	949	Environmental and Lubricant Effects on the Wear	
Rolling-Contact Fatigue of Ceramics .....	957	Failures of Polymers .....	1024
Surface Crack Defects .....	957	Summary and Case Study .....	1025
Fatigue Crack Propagation in Rolling Contact .....	958	Failure Examples .....	1026
Rolling Contact Fatigue Test Machine .....	959	Wear Failures of Reinforced Polymers .....	1028
Failure Modes of RCF .....	960	Abrasive Wear Failure of Reinforced Polymers .....	1029
Impact Wear Failures .....	965	Sliding (Adhesive) Wear Failure of Polymer	
Impact Wear Modes .....	965	Composites .....	1035
Impact Wear of Metals .....	965	<b>Distortion .....</b>	<b>1045</b>
Impact Wear of Ceramics .....	968	Analysis of Distortion and Deformation .....	1047
Impact Wear of Polymers .....	970	Overloading .....	1047
Impact Wear Testing .....	970	Inappropriate Specifications .....	1050
Impact Wear Modelling .....	971	Failure to Meet Specifications .....	1051
Impact Wear Failure Case Study: Automotive Engine Inlet		Analyzing Distortion Failures .....	1054
Valve and Seat Wear .....	971	Special Types of Distortion Failure .....	1055
Spalling from Impact Events .....	975	Deformation Related to Other Types of Failure .....	1056
Development of Testing and Analysis Methods		Deformation by Design .....	1057
for Spalling of Striking Tools .....	975	<b>Reference Information .....</b>	<b>1059</b>
Conclusions Drawn by Spalling Studies .....	978	Glossary .....	1061
Metallography and Fractography of Spalling .....	982	Metric Conversion Guide .....	1077
Comments on Specifications for Striking/Struck Tools .....	985	Abbreviations and Symbols .....	1081
New Materials for More Spall-Resistant Tools .....	987	Directory of Examples of Failure Analysis .....	1084
Conclusions .....	988	Index .....	1090
Corrosive Wear Failures .....	989		
Occurrences in Practice .....	989		



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