Foreword

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 McDanels, 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

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 (kg) 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 g/cm³ rather than kg/m³ 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


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 macro 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.

William T. (Bill) Becker  
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<table>
<thead>
<tr>
<th>Name</th>
<th>Position</th>
<th>Institution/Company</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gordon H. Geiger</td>
<td>President and Trustee</td>
<td>University of Arizona</td>
</tr>
<tr>
<td>Donald R. Muzyka</td>
<td>Vice President and Trustee</td>
<td></td>
</tr>
<tr>
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</tr>
<tr>
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<td></td>
</tr>
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<td>Carus Chemical Company</td>
</tr>
<tr>
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<td>Trustee</td>
<td>Oak Ridge National Laboratory</td>
</tr>
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</tr>
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<td>Buehler Ltd.</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>Name</th>
<th>Position</th>
<th>Institution/Company</th>
</tr>
</thead>
<tbody>
<tr>
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</tr>
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</tr>
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<td>Stress Engineering Services Inc.</td>
</tr>
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</tr>
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<tr>
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<td>Natural Resources Canada</td>
</tr>
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<td>Los Alamos National Laboratory</td>
</tr>
<tr>
<td>George F. Vander Voort</td>
<td>(1997–)</td>
<td>Buehler Ltd.</td>
</tr>
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<td>(2000–)</td>
<td>Borg Warner Morse TEC Corporation</td>
</tr>
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</tr>
</tbody>
</table>

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# Contents

## Engineering Aspects of Failure and Prevention

**Chairperson: James Scutti**

<table>
<thead>
<tr>
<th>Topic</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction to Failure Analysis and Prevention</td>
<td>3</td>
</tr>
<tr>
<td>Concepts of Failure Analysis and Prevention</td>
<td>3</td>
</tr>
<tr>
<td>Root-Cause Analysis</td>
<td>6</td>
</tr>
<tr>
<td>Primary Physical Root Causes of Failure</td>
<td>6</td>
</tr>
<tr>
<td>Charting Methods for RCA</td>
<td>14</td>
</tr>
<tr>
<td>Other Failure Analysis Tools</td>
<td>15</td>
</tr>
<tr>
<td>Categories of Failure</td>
<td>17</td>
</tr>
<tr>
<td>Failure Prevention</td>
<td>19</td>
</tr>
<tr>
<td>Materials Selection for Failure Prevention</td>
<td>24</td>
</tr>
<tr>
<td>Design and Failure Prevention</td>
<td>25</td>
</tr>
<tr>
<td>Materials Selection in Design</td>
<td>29</td>
</tr>
<tr>
<td>Materials Selection for Failure Prevention</td>
<td>34</td>
</tr>
<tr>
<td>Materials Selection and Failure Analysis</td>
<td>35</td>
</tr>
<tr>
<td>Design Review for Failure Analysis and Prevention</td>
<td>40</td>
</tr>
<tr>
<td>What Is an Engineering Failure?</td>
<td>40</td>
</tr>
<tr>
<td>The Context of an Engineering Failure</td>
<td>40</td>
</tr>
<tr>
<td>The Engineering Design Process</td>
<td>41</td>
</tr>
<tr>
<td>Preliminary Investigation</td>
<td>42</td>
</tr>
<tr>
<td>Analysis of the Engineering Design Process</td>
<td>42</td>
</tr>
<tr>
<td>Task Clarification—Defining the Problem</td>
<td>43</td>
</tr>
<tr>
<td>Conceptual Design</td>
<td>44</td>
</tr>
<tr>
<td>Embodiment Design</td>
<td>44</td>
</tr>
<tr>
<td>Detail Design</td>
<td>46</td>
</tr>
<tr>
<td>Management Influences</td>
<td>46</td>
</tr>
<tr>
<td>External Influences</td>
<td>47</td>
</tr>
<tr>
<td>Design Life-Cycle Issues</td>
<td>48</td>
</tr>
<tr>
<td>Failure Modes and Effects Analysis</td>
<td>50</td>
</tr>
<tr>
<td>Overview of FMEA</td>
<td>50</td>
</tr>
<tr>
<td>The FMEA Process</td>
<td>53</td>
</tr>
<tr>
<td>Fault Equivalence</td>
<td>56</td>
</tr>
<tr>
<td>The Failure Cause Model</td>
<td>56</td>
</tr>
<tr>
<td>Automation</td>
<td>57</td>
</tr>
<tr>
<td>Conclusions</td>
<td>58</td>
</tr>
<tr>
<td>Reliability-Centered Maintenance</td>
<td>60</td>
</tr>
<tr>
<td>History of RCM</td>
<td>60</td>
</tr>
<tr>
<td>Overview of the RCM Process</td>
<td>61</td>
</tr>
<tr>
<td>Failure Modes and Effects Analysis</td>
<td>62</td>
</tr>
<tr>
<td>Failure Management Policies and &quot;Technical Feasibility&quot;</td>
<td>64</td>
</tr>
<tr>
<td>Failure Consequences and &quot;Worth Doing&quot;</td>
<td>66</td>
</tr>
<tr>
<td>Failure Management Policy Selection</td>
<td>67</td>
</tr>
<tr>
<td>Managing and Resourcing the RCM Process</td>
<td>68</td>
</tr>
<tr>
<td>Conclusions</td>
<td>70</td>
</tr>
<tr>
<td>Products Liability and Design</td>
<td>71</td>
</tr>
<tr>
<td>Legal Bases for Products Liability</td>
<td>71</td>
</tr>
<tr>
<td>Hazard, Risk, and Danger</td>
<td>72</td>
</tr>
<tr>
<td>Definitions of Defects</td>
<td>72</td>
</tr>
<tr>
<td>Preventive Measures</td>
<td>75</td>
</tr>
<tr>
<td>Paramount Questions</td>
<td>77</td>
</tr>
<tr>
<td>Acceptable Level of Risk</td>
<td>77</td>
</tr>
</tbody>
</table>

## Manufacturing Aspects of Failure and Prevention

<table>
<thead>
<tr>
<th>Topic</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturing Aspects of Failure and Prevention</td>
<td>79</td>
</tr>
<tr>
<td>Failures Related to Metalworking</td>
<td>81</td>
</tr>
<tr>
<td>Imperfections in Wrought Forms</td>
<td>81</td>
</tr>
<tr>
<td>Imperfections from the Ingot</td>
<td>82</td>
</tr>
<tr>
<td>Forging Imperfections</td>
<td>90</td>
</tr>
<tr>
<td>Workability</td>
<td>97</td>
</tr>
<tr>
<td>Cracking in Bulk Working</td>
<td>99</td>
</tr>
<tr>
<td>Sheet Forming</td>
<td>100</td>
</tr>
<tr>
<td>Cold Formed Parts</td>
<td>101</td>
</tr>
<tr>
<td>Failures Related to Casting</td>
<td>103</td>
</tr>
<tr>
<td>Casting Discontinuities</td>
<td>103</td>
</tr>
<tr>
<td>Effect of Casting Discontinuities</td>
<td>104</td>
</tr>
<tr>
<td>Permanent-Mold Methods</td>
<td>123</td>
</tr>
<tr>
<td>Casting Design</td>
<td>133</td>
</tr>
<tr>
<td>Cast Irons</td>
<td>137</td>
</tr>
<tr>
<td>Cast Steels</td>
<td>142</td>
</tr>
<tr>
<td>Cast Aluminum Alloys</td>
<td>149</td>
</tr>
<tr>
<td>Welding</td>
<td>152</td>
</tr>
<tr>
<td>Failures Related to Welding</td>
<td>156</td>
</tr>
<tr>
<td>Weld Discontinuities and Service Conditions</td>
<td>157</td>
</tr>
<tr>
<td>Joint Design</td>
<td>161</td>
</tr>
<tr>
<td>Failure Origins in Arc Welds</td>
<td>169</td>
</tr>
<tr>
<td>Other Welding Processes</td>
<td>186</td>
</tr>
<tr>
<td>Failures Related to Heat Treating Operations</td>
<td>192</td>
</tr>
<tr>
<td>Phase Transformation during Heating and Cooling</td>
<td>192</td>
</tr>
<tr>
<td>Tempering</td>
<td>195</td>
</tr>
<tr>
<td>Metallurgical Sources of Stress and Distortion</td>
<td>195</td>
</tr>
<tr>
<td>Reheating and Quenching</td>
<td>195</td>
</tr>
<tr>
<td>Effect of Materials and Process Design on Distortion</td>
<td>196</td>
</tr>
<tr>
<td>Quenching</td>
<td>205</td>
</tr>
<tr>
<td>Steel Transformation Products and Properties</td>
<td>214</td>
</tr>
<tr>
<td>Influential Microstructural Features</td>
<td>217</td>
</tr>
<tr>
<td>Structural Life Assessment Methods</td>
<td>225</td>
</tr>
<tr>
<td>Failure Analysis and Life Assessment of Structural Components and Equipment</td>
<td>227</td>
</tr>
<tr>
<td>Industry Perspectives on Failure and Life Assessment of Components</td>
<td>227</td>
</tr>
<tr>
<td>Structural Design Philosophies</td>
<td>227</td>
</tr>
<tr>
<td>Life-Limiting Factors</td>
<td>232</td>
</tr>
<tr>
<td>Role of the Failure Investigator</td>
<td>234</td>
</tr>
<tr>
<td>Role of Nondestructive Inspection</td>
<td>238</td>
</tr>
<tr>
<td>Specific Life Assessment Methodologies</td>
<td>239</td>
</tr>
<tr>
<td>Conclusions</td>
<td>242</td>
</tr>
<tr>
<td>Failure Assessment Diagrams</td>
<td>243</td>
</tr>
<tr>
<td>Origin and Description of the Failure Assessment Diagram</td>
<td>243</td>
</tr>
<tr>
<td>Current R6 Failure Assessment Diagrams</td>
<td>244</td>
</tr>
<tr>
<td>Current Fracture Criteria of BS 7910</td>
<td>244</td>
</tr>
</tbody>
</table>
Considerations in Use ........................................... 246
Application Examples ........................................... 247
Analysis Methods for Probabilistic Life Assessment ........ 250
Introduction to Probabilistic Analysis ......................... 250
Elements of Probabilistic Analysis ............................ 252
Evaluation of Probability of Failure ............................ 255
Advanced Concepts ............................................... 262
Case Histories: Examples of the Use of Probabilistic Analysis 264
Probabilistic Analysis Software .................................. 267
Nondestructive Evaluation and Life Assessment .......... 269
Common Measurement Techniques .......................... 269
Life Assessment Strategies ..................................... 269
The Role of NDE .................................................. 270
Non-Aerospace Applications ................................... 273
Implementation Guidance ......................................... 274
Conclusions ....................................................... 274
Fatigue-Life Assessment ........................................... 276
Fatigue Crack Growth Variables ............................... 276
Safe-Life versus Damage-Tolerance Approach .......... 281
Material Behavior ............................................... 282
Retardation and Spectrum Load Effects .................... 282
Crack Growth Software Packages ............................. 283
Case Studies ....................................................... 283
Elevated-Temperature Life Assessment for Turbine Components, Piping, and Tubing 289
Definition of Damage, Life, and Failure Criteria .......... 289
Life-Limiting Elevated-Temperature Failure Mechanisms .................................................. 289
Metallurgical Instabilities ..................................... 291
Gas Turbine Blade Life Assessment .......................... 295
Life Assessment Methods for Power Plant Piping and Tubing .................................................. 304
Principles and Practice of Failure Analysis ................. 313
Chairpersons: Debbie Aliya, Aaron Tanzer, and Steve McDaniel

The Failure Analysis Process: An Overview ............... 315
Principles and Approaches in Failure Analysis Work .... 316
The Objectives of Failure Analysis ............................. 317
Scope and Planning ............................................... 318
Planning and Preparation ....................................... 319
Practices and Procedures ........................................ 321
Organization of a Failure Investigation ..................... 324
What Is a Failure? ............................................... 324
Why Do Failures Happen? ...................................... 324
Why Is a Failure Investigation Performed? ................. 325
The Four-Step Problem-Solving Process .................... 325
Nine Steps of a Failure Investigation ......................... 325
Summary ........................................................... 331
Failure Investigation Pitfalls ................................... 331
Other Tools ........................................................ 331
Conducting a Failure Examination .......................... 333
Basic Approach to Failure Analysis ......................... 333
Failure Analysis Procedures ................................... 333
Conclusions ....................................................... 341
Determination and Classification of Damage ............... 343
Characterization and Identification of Damage and Damage Mechanisms ........................................... 343
Determining Primary and Secondary Damage Mechanisms .................................................. 346
Damage Mechanism Categorization .......................... 347
Conclusions ....................................................... 349
Examination of Damage and Material Evaluation ......... 351
Visual or Macroscopic Examination of Damaged Material .................................................. 351
Interpretation of Damage and Fracture Features ........ 352
Corrosion and Wear Damage Features ..................... 354
Analysis of Base Material Composition ..................... 358
Metallurgical Samples and Hardness ......................... 359
Preparation and Examination of Metallographic Specimens in Failure Analysis ....................... 361
Analysis and Interpretation of Micrographic Specimens 363
Evaluation of Polymers in Failure Analysis .................. 367
Evaluation of Ceramic Materials in Failure Analysis .... 369
Modeling and Accident Reconstruction ..................... 371
Accident Reconstruction ......................................... 371
Modeling .......................................................... 376
Finite Element Modeling in Failure Analysis ............... 380
General Development of FEA .................................. 380
General-Purpose Applications ................................ 381
Special Purpose Applications .................................. 385
Design Review in Failure Analysis ............................ 386
Case Studies of FEA in Failure Analysis ...................... 387
Tools and Techniques in Failure Analysis ................. 391
Practices in Failure Analysis .................................. 393
Stages of a Failure Analysis ................................... 393
Collection of Background Data and Samples ............. 393
Fractures ........................................................... 397
Corrosion Failures ............................................... 405
Wear Failures ..................................................... 407
Formulating Conclusions and Report Writing .............. 413
Key Guidelines ................................................... 416
Photography in Failure Analysis ............................. 418
Visual Examination ............................................. 418
Field Photographic Documentation ......................... 418
Laboratory Photographic Documentation ................. 419
Photographic Equipment ....................................... 419
Film Photography ............................................... 420
Digital Photography ............................................ 420
Basics of Photography ........................................... 421
Photographic Lighting ........................................... 421
Fracture Surface Photography ................................ 421
Macrophotography .............................................. 425
Microscopic Photography ..................................... 425
Special Methods .................................................. 426
Chemical Analysis of Metals in Failure Analysis ......... 429
Bulk Composition Verification ................................ 429
Microchemical Analysis in Failure Analysis ............... 432
Characterization of Plastics in Failure Analysis ........... 437
Fourier Transform Infrared Spectroscopy ................... 437
Differential Scanning Calorimetry ............................ 439
Thermogravimetric Analysis ................................... 441
Thermomechanical Analysis ................................... 442
Dynamic Mechanical Analysis ................................ 443
Methods for Molecular Weight Assessment ............... 444
Mechanical Testing .............................................. 445
Considerations in the Selection and Use of Test Methods .................................................. 446
Case Studies ....................................................... 447
Stress Analysis and Fracture Mechanics ................. 460
Analysis of Applied Stresses .................................. 461
Fundamentals of Stress Analysis ............................. 461
Stress Analysis Of Common Geometries .................... 468
Application of Stress Analysis ................................ 473
Fracture Mechanics .............................................. 475
Fracture Mechanics Concepts ................................ 475
An Introduction to LEFM ...................................... 476
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
Residual Stress in Failures and XRD Analysis .......... 484
X-Ray Diffraction Theory and Residual Stress Measurement ......................................................... 484
Analysis of XRD Data ................................................... 485
Instrument Calibration and Validation of Stress Measurements ................................................... 486
Sample Selection ....................................................... 488
Measurement Location Selection and Location Access ................................................................. 488
Selecting Measurement Directions and Depths .......... 489
Specimen Preparation ................................................ 489
Residual-Stress Effects on Components under Quasi-Static Loading ............................................. 490
Stress-Corrosion Cracking and Corrosion Fatigue .... 490
The Importance of Residual Stress in Fatigue ......... 491
The Effect of Manufacturing Processes on Residual Stress ......................................................... 493
Effects of Heat Treatment on Residual Stresses ...... 494
X-Ray Diffraction Stress Measurements in Multiphase Materials and Composites ............. 495
X-Ray Diffraction Stress Measurements in Locations of Stress Concentration ...................... 496
Metallographic Techniques in Failure Analysis ................................................................. 498
Examination of Fractures ......................................... 499
Metallographic Specimen Preparation ...................... 501
Examination of Microstructures ............................ 509
Field Metallography .................................................. 513
Scanning Electron Microscopy ................................ 516
Development of SEM Technology ......................... 516
Operation .......................................................... 516
Specimen Preparation .............................................. 521
Application of SEM in Fractography ....................... 522
Chemical Characterization of Surfaces .................... 527
Overview of Surface Analysis ................................. 527
Auger Electron Spectroscopy .................................... 529
X-Ray Photoelectron Spectroscopy ........................ 530
Time-of-Flight Secondary Ion Mass Spectrometry .... 532
Example: Stainless Steel Analysis ......................... 533
Quantitative Fractography ....................................... 538
Profilometry-Based Quantitative Fractography ........ 539
SEM Quantitative Fractography ............................... 547
Three-Dimensional Fracture Surface Reconstruction .... 551
Fracture ................................................................ 557
Chairperson: William Becker
Fracture Appearance and Mechanisms of Deformation and Fracture ............................................. 559
General Background on Fractography ...................... 559
Fracture Surface Information ..................................... 561
Ductile and Brittle Behavior ..................................... 564
Macroscopic Ductile and Brittle Fracture Surfaces .... 566
Structure and Behavior ............................................. 568
Deformation and Fracture .......................................... 568
Brittle Transgranular Fracture (Cleavage) ................. 572
Intergranular Fracture ............................................. 574
Fatigue Fracture ..................................................... 576
Appendix: Modeling with Fracture Mechanics ........ 581
Mechanisms and Appearances of Ductile and Brittle Fracture in Metals .................................... 587
Mechanisms of Deformation and Fracture .............. 587
Background .......................................................... 588
Single-Crystal Cleavage Models .............................. 588
Slip, Twinning, and Cleavage in Polycrystals .......... 589
Ductile Fracture and Microvoid Coalescence .......... 591
Factors Affecting Ductility ........................................ 595
Geometric Limits of Ductility ................................. 595
Materials Factors Affecting Ductility ................. 597
Fracture Appearances ............................................ 598
Cylindrical Specimens in Tension ......................... 598
Prismatic Specimens in Tension ........................... 600
Compression Failure ............................................. 602
Bending ........................................................... 603
Torsion Loading .................................................... 605
Fracture Appearances in Cast Materials ................. 607
Fracture at or near Stress Raisers ......................... 608
Macroseal Appearance .......................................... 608
Microseal Details of Initiation and Propagation ...... 610
Fracture from Manufacturing Imperfections .......... 612
Case History ....................................................... 615
Appendix: Modeling of Ductile Plastic Flow ............ 616
Macroscopic Plastic Flow and Instability .............. 616
Strain Localization ................................................. 621
Void Nucleation Models ......................................... 622
Void Coalescence Microscale Models ................. 623
Fatigue Fracture Appearances ............................... 627
Fatigue Processes .................................................. 628
Macroscopic Appearance of Fatigue Fracture .......... 630
Microscopic Appearance of Fatigue Fracture in Metals 635
Fatigue of Polymers and Composites ...................... 638
Intergranular Fracture ............................................. 641
Mechanisms of IG Fracture .................................... 642
Intergranular Brittle Cracking ............................... 642
Dimples IG Fracture ............................................. 643
Intergranular Fatigue ............................................. 644
Causes of IG Fracture ............................................ 645
Intergranular SCC and Hydrogen Embrittlement .... 646
Example ........................................................... 648
Fracture of Plastics ................................................ 650
Deformation and Fracture .................................... 650
Crack Propagation ................................................. 654
Fractography ........................................................ 655
Case Studies ........................................................ 660
Fracture Modes and Appearances in Ceramics ......... 662
Techniques of Fractography ................................. 662
Fracture Markings ................................................. 664
Fracture Modes ..................................................... 665
Fracture Origins .................................................... 667
Overload Failures .................................................. 671
Fracture Modes and Mechanisms ......................... 671
Ductile Overload Failures ...................................... 671
Brittle Overload Failures ........................................ 674
Mixed-Mode Cracking .......................................... 677
Material Factors .................................................... 677
Temperature Effects .............................................. 684
Effects of Mechanical Loading .............................. 686
Service Damage or Alteration ............................... 689
Embrittlement ....................................................... 689
Environmentally Induced Embrittlement ................. 696
Laboratory Fracture Examination ......................... 699
Fatigue Failures .................................................... 700
Fatigue Properties and Design Life ....................... 700
Infinite-Life Criterion (S-N Curves) ......................... 700
Finite-Life Criterion (c-N 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
<table>
<thead>
<tr>
<th>Corrosion-Related Failures</th>
<th>747</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chairperson: Ron Parrington</td>
<td></td>
</tr>
</tbody>
</table>

### Analysis and Prevention of Corrosion-Related Failures

- Electrochemical Nature of Corrosion ........................................................................ 749
- Analysis of Corrosion-Related Failures ................................................................... 751
- Examples of Corrosion Failure Analysis ..................................................................... 753
- Prevention of Corrosion-Related Failures of Metals .............................................. 755

### Forms of Corrosion

- Galvanic Corrosion .................................................................................................... 761
  - Factors Affecting Galvanic Corrosion ..................................................................... 762
  - Combating Circumstances That Promote Galvanic Action ...................................... 764
  - Evaluation of Galvanic Corrosion .......................................................................... 764
  - Examples of Factors Contributing to Galvanic Corrosion .................................... 766
  - Performance of Alloy Groupings ........................................................................... 766
- Uniform Corrosion ....................................................................................................... 767
  - Surface Conditions ................................................................................................. 768
  - Classification of Uniform Corrosion ....................................................................... 768
  - Materials Selection ................................................................................................. 769
  - Effect of Corrosion Products .................................................................................. 769
  - Effect of Concentration ............................................................................................ 769
  - Effect of Temperature ............................................................................................... 770
  - Evaluation Factors .................................................................................................... 770
  - Design Considerations ............................................................................................... 771
- Pitting and Crevice Corrosion ....................................................................................... 771
  - Pitting ....................................................................................................................... 771
  - Crevice Corrosion ..................................................................................................... 775
  - Reducing Failures Due to Pitting and Crevice Corrosion ........................................ 777
- Intergranular Corrosion ............................................................................................... 777
  - Development of Intergranular Corrosion .................................................................. 777
  - Alloy Susceptibility .................................................................................................. 778
  - Evaluation of Intergranular Corrosion ...................................................................... 779
  - Intergranular Corrosion of Stainless Steels ......................................................... 779
  - Intergranular Corrosion of Nickel Alloys ............................................................... 783
  - Intergranular Corrosion of Aluminum Alloys ......................................................... 784
  - Intergranular Corrosion of Copper Alloys .............................................................. 784
  - Intergranular Corrosion of Zinc ............................................................................... 785

### Selective Leaching

- Dealing of Metals ......................................................................................................... 785
- Dealing of Metals ......................................................................................................... 785
- Dealing of Metals ......................................................................................................... 785
- Dealing of Metals ......................................................................................................... 785
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Extensive mechanical twinning was observed in high-purity, electron-beam-melted zirconium.