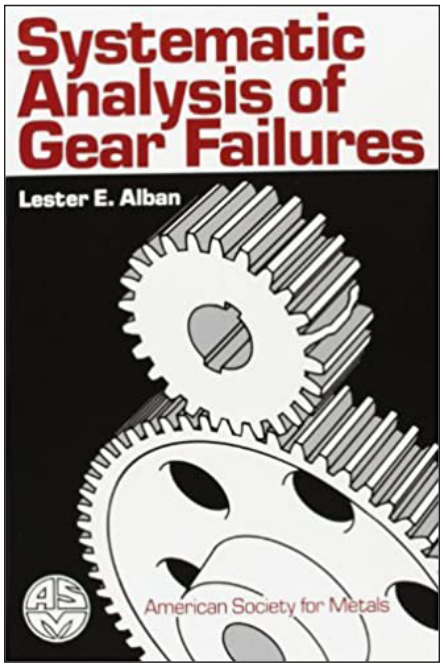
Ten Top Books for Gear Failure Analysis

Robert Errichello

Introduction

The purpose of this article is to provide an overview of proven books or standards dealing with failure analysis. Following you will find a short description of ten books or standards. At the end of the document you will find an overview and a detailed reference list.



1. Systematic Analysis of Gear Failures

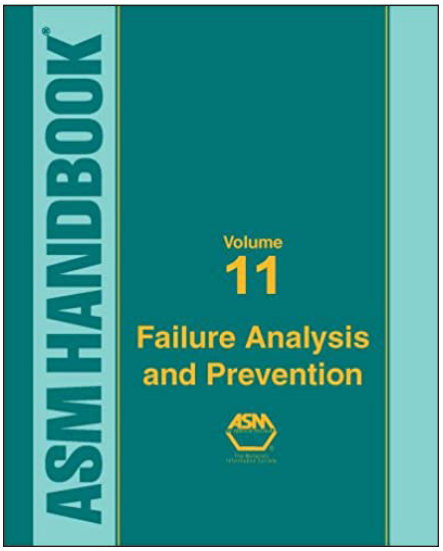
This book, by the metallurgist Lester E. Alban, who retired from Fairfield Gear in 1983, was published in 1985, so it contains some outdated nomenclature, such as "case crushing," which is now called "subcase fatigue." Nevertheless, it contains good practical knowledge from an experienced metallurgist that is helpful in understanding the metallurgical aspects of failures. It emphasizes a systematic approach to investigating failures, which includes careful review of all available background information and documentation, field examination of failed components by visual and physical means, and laboratory examination of all relevant components. It provides reliable guidance on the proper metallurgical properties of carburized gears. The chapter on modes of failure is relatively brief, and it uses outdated nomenclature, but it does contain many good images of failure modes. The chapter on causes of gear failure is a good discussion of microsegregation in forgings and its detrimental effects on diffusion of carbon during carburizing, which causes patchy, retained austenite at the surface of a carburized component. The discussion of case/core separation, which the author calls "internal rupture," is especially valuable because it points out the four factors that aggravate case/core separation:

- Deep case depth
- High core hardness
- Sub-zero treatment
- Shot peening

The author states: "Each factor by itself may be beneficial, but, when these factors exist together, they can be detrimental." The discussion of induction hardening illustrates the important fact that the terminus of a hardened case and unhardened area is an area with a high peak of tensile residual stress, which is a self-induced "metallurgical notch" that often results in fatigue failure.

2. ANSI/AGMA 1010-F14, Appearance of Gear Teeth-Terminology of Wear and Failure

This is AGMA's official nomenclature for failure modes, mechanisms, and root causes of gear failure. Written by the AGMA Nomenclature Committee, it includes recommended remedies for each failure mode. Table 1 is an updated table of the original ANSI/AGMA 1010-F14 Table 1. It shows the latest classification system nomenclature that is currently being considered for the next version of ANSI/AGMA 1010. Although Table 1 is only a draft version of the classification system, and therefore not yet officially adopted by AGMA, it is likely to be approved by AGMA and published in the next version of ANSI/AGMA 1010.



3. ASM Handbook, Vol. 11, Failure Analysis and Prevention

The ASM Handbooks are known for their authoritative quality and content, which is largely due to the devoted efforts of their editors, authors, and reviewers. Unfortunately, Vol. 11 (2002) does not have a separate chapter devoted to gears; rather, it provides the information on gears in separate chapters devoted to failure modes such as macropitting, micropitting, bending fatigue, and so on. The earlier version of Vol. 11 (1986), written by Lester Alban, was better organized and it had a separate chapter on failures of gears. However, the material is essentially the same as Alban's textbook, so one is better off by simply referring to his textbook. A yet-earlier version of the ASM Handbook, Vol. 10 (1975) and written by the ASM Committee on Failures of Gears, also had a separate chapter on failures of gears. However, it is dated and the nomenclature is essentially obsolete. Currently, ASM is planning a new version of Vol. 11, which apparently will have a separate chapter on gear failures.

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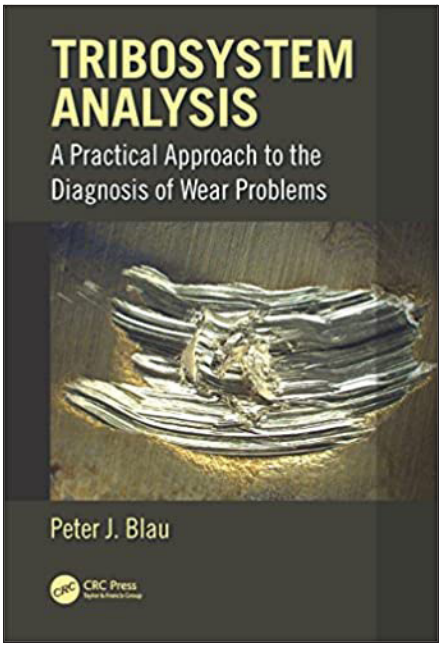
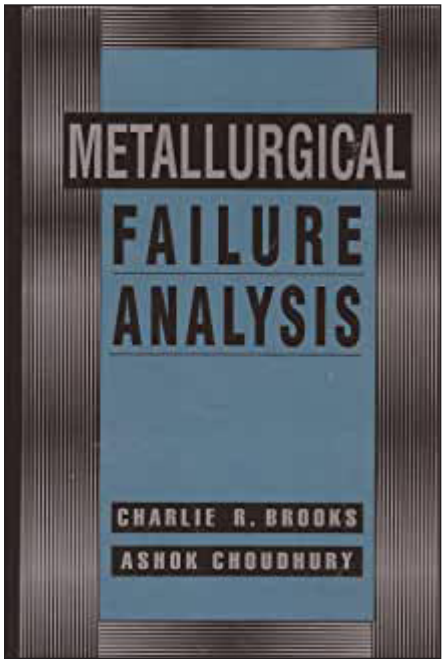


4. Tribosystems Analysis

Peter J. Blau is a renowned tribologist who recently retired from Oak Ridge National Laboratory. He is currently the co-editor-in-chief of the *Wear Journal*, and a consultant in tribology. He contributed to ASTM G40-15 "*Terminology Relating to Wear and Erosion*," ASTM Annual Book of Standards, and has developed a classification system for wear problems in tribosystems. His book, "*Tribosystem Analysis*," features a good overview of the tools a tribologist uses to investigate wear problems, types of surface damage, options for solving wear problems, and tribotesting. The chapter on tools for imaging and characterizing worn surfaces is especially good, and includes discussion of light optical microscopy (LOM), specimen mounting, specimen cleaning, and cross-sectioning, tapersectioning, and transmitted-versus-reflected light illumination. Surface roughness imaging and measurement methodology are also presented in detail, and the capabilities of SEM and TEM microscopy are compared. The book introduces the tribosystem analysis (TSA) form that provides a systematic method to define the characteristics of specific wear problems, which facilitates diagnosis and remedy for wear problems. Overall, this book provides a good overview of failure analysis of wear problems from a tribologist's perspective.



5. Metallurgical Failure Analysis

This book by Professor Charlie R. Brooks and Dr. Ashok Choudhury is an excellent introduction to failure analysis. It emphasizes fractography, i.e. — the study of fracture surfaces. It includes numerous fractographs to illustrate the morphology of fracture surfaces for many modes of crack propagation. The text accompanying each fractograph is the best I've seen.

Chapter 1 describes the many tools that failure analysts use for investigating failures — including light optical microscopy (LOM), transmission electron microscopy (TEM), and scanning electron microscopy (SEM). It includes seven appendices that cover all aspects of the handling and cleaning of fracture surfaces.

Chapter 2 explains the macroscopic orientation and features of fracture surface topography, starting with tensile testing and continuing with the effects of 3D principal stresses; material response to stresses; stress concentration; triaxial stress and constraint; plane stress versus plane strain; strain rate and temperature; crack propagation; ductile versus brittle fracture; fracture mechanics; fatigue failure; and ending with creep deformation. The description of ductile versus brittle fracture is the best I've seen on this often complex subject.

Chapter 3 is a very thorough (93 pages) treatment of fracture mechanisms, which includes numerous fractographs that illustrate the many ways that cracks can propagate. Plastic deformation by crystal slip due to shear stress, and by cleavage due to tensile stress, is explained, and examples of ductile void coalescence and quasi-cleavage fracture are given. Fatigue fracture topography including Stage I crack initiation, Stage 2 crack propagation, and Stage 3 fracture, is illustrated with fractographs. Features including microscopic striations and macroscopic beach marks are illustrated and their mechanisms explained. A series of six SEM fractographs at steadily increasing magnification presents excellent views of the morphology of beach marks. The chapter concludes with a treatment of high-temperature fracture topography, environmentally assisted fracture, and stereo examination of fracture surfaces, comparing SEM and TEM fractographs.

Chapter 4 illustrates the fractography of tensile overload, torsion overload, bending overload, and fatigue fracture. The unique morphology of fatigue fractures of rotating shafts in bending is illustrated by charts that show the influence of high and low nominal stress in combination with high and low stress concentrations. Fractographs are used to demonstrate the correlation of micro- and macrofractographic features of fracture surfaces.

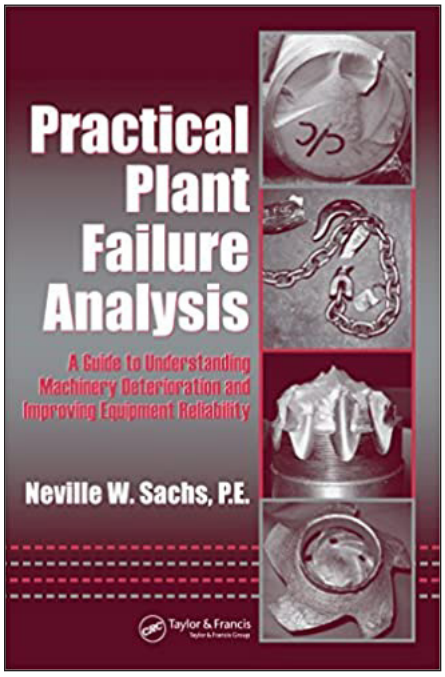
Chapter 5 presents eight case histories that illustrate the application of the principles of metallurgical failure analysis.

Overall, this book is an excellent introduction to failure analysis that emphasizes the principles without getting bogged down in needless detail. It is one of the best resources for understanding fractography.

6.7 ISO DTS-10825-1 and ISO TR- 10825-2

These two ISO documents remain in draft form as of this writing; they were created in cooperation with the AGMA Nomenclature Committee and are very similar — but not exactly the same — as ANSI/AGMA 1010-F12. ISO DTS 10825-1 provides the terminology and definitions including a lot of illustrations

of the appearance of the individual failure modes. ISO DTR 10825-2 provides additional information for finding the cause of a failure mode and mitigation possibilities. Both documents shall replace the ISO TS 10825:1995.



8. Practical Plant Failure Analysis

Neville W. Sachs has written a guide to understanding machinery deterioration and improving equipment reliability. It is a book for engineers and maintenance people, which explains why failures occur and how to prevent them from recurring. It describes how to perform a thorough failure investigation and emphasizes the importance of on-site visual inspection of failed components. It is a primer on failure analysis that is written in a practical, down-to-earth style that would appeal to most mechanical engineers. The text covers many different components, including belt drives, rolling-element bearings, gears, fasteners, chains, lip seals, and flexible couplings.

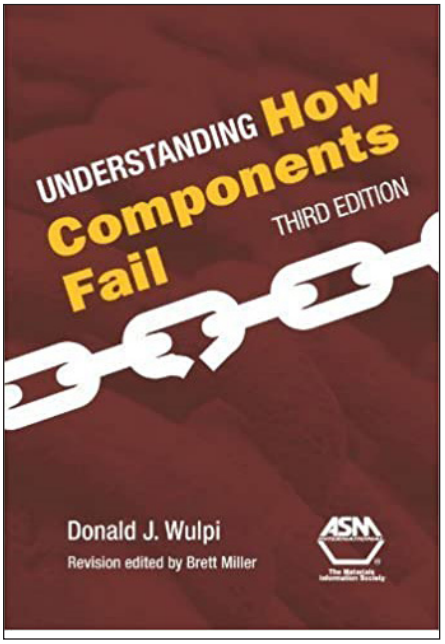
9. Failure Atlas for Hertz Contact Machine Elements

Tibor E. Tallian created the comprehensive "*Failure Atlas for Hertz Contact Machine Elements*;" the *Atlas* consists of parts I and II:

Part I has 1-Introduction, 2-Failure Classification, and 3-Appearance Classification. Readers should read Part I to understand how to navigate and interpret the *Atlas* before proceeding to actually using it.

Part II consists of plates (images) that illustrate the morphology of the failure mode. Each chapter of Part II is introduced by a description of the definition, failure process, morphology, causes and effects of the failure mode(s) covered. Sixteen failure modes are discussed (chapters 4 through 19). The Annex gives titles of the failure modes (plates). Examples include: rolling element bearings, gears, and cams. Each image is fully described by type, scale, component, speed, load, lubrication, and failure code. Following the image data, the failure description, image description, and suspected causes are listed.

Overall, Tallian's *Atlas* is a very comprehensive treatise on Hertzian contact failure modes. Unfortunately, some of the images have relatively poor resolution (due to publishing problems). The publisher provided a supplement of enhanced printing of a few of the problematic images. However, the enhanced images were not much improved over the original images. Nevertheless, Tallian's *Atlas* remains a classic work.



10. Understanding How Components Fail

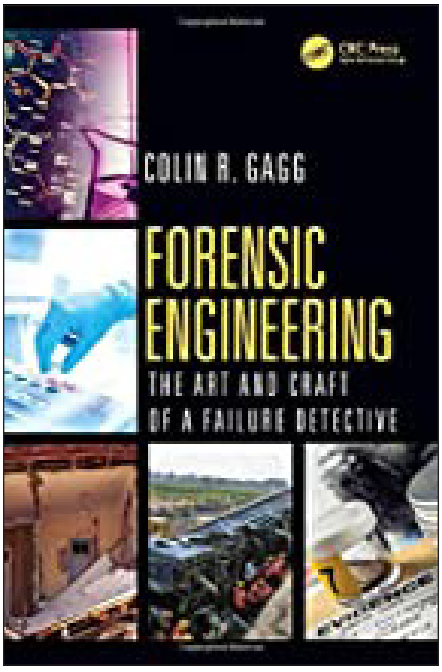
Donald J. Wulpi is a great teacher, which makes *Understanding How Components Fail* an easy read. It is ASM's classic best-seller and is a must-read for any person interested in becoming a failure analyst. Wulpi has a knack for relating component failure to everyday examples that make complex metallurgical subjects easy to understand. There are 14 chapters:

1. Techniques of Failure Analysis
2. Distortion Failures
3. Basic Single-Load Fracture Modes
4. Stress Systems Related to Single-Load Fracture of Ductile and Brittle Metals
5. Mechanical Properties
6. Stress versus Strength
7. Residual Stresses
8. Brittle Fracture
9. Ductile Fracture
10. Fatigue Fracture
11. Wear I
12. Wear II
13. Corrosion
14. Elevated-Temperature Failures

Each chapter illustrates the subject matter with large drawings and large images of the failed components and their fractographs. The many sketches, analogies, photographs, and examples make for a very thorough, yet easy to understand presentation of the basics of failure analysis.

Summary and Conclusion

Ref. No.	Strength	Weakness
1	Good, practical, metallurgical guidance on failure analysis. Especially good for carburized gears. Best description of case/core separation.	Outdated nomenclature. Only for gear failures.
2	Most comprehensive classification system for gears. Best resource for morphology, mechanism, and root cause of failure.	Only for gear failures.
3	Most authoritative and best writing style. Best resource for all aspects of failure analysis including how to manage a failure investigation.	Poorly organized, which makes it difficult to find information on gears.
4	Highly systematic nomenclature for wear failure modes. Good description of tools used by tribologists.	Some nomenclature conflicts with reference 2. Only for wear failures.
5	Best resource for microscopy and fractography. Excellent text accompanies each fractograph. Best description of ductile versus brittle behavior.	Limited information on gears.
6	Similar to reference 2. A work in progress.	Some outdated nomenclature.
7	Similar to reference 2. A work in progress.	Some outdated nomenclature.
8	Best description for how to conduct a failure investigation. Good practical information for industry. Good description of morphology of shaft failures.	Some outdated nomenclature. Information on gears limited.
9	Classic Atlas for Hertzian contact failures. Good writing style by a renowned bearing expert. Good description of morphology and mechanism.	Images have poor resolution due to reproduction problems. Only for Hertzian failures.
10	Good writing style and best introduction to the basics of failure analysis. Many everyday examples of failures enhance learning.	None.



Room for One More—Addendum to "Ten Top Books for Gear Failure Analysis". Shortly after I submitted the manuscript: "Ten Top Books for Gear Failure Analysis" to *Gear Technology*, I discovered a new book on failure analysis (Ref. 11), i.e.—***Forensic Engineering—the Art and Craft of a Failure***. The book, by Colin R. Gagg, is for anyone interested in learning what it is that a failure investigator does, what the responsibilities are, and what tools and methodology are used to discover failure modes and root causes. Although the book is not specifically for gear failure analysis, it will appeal to all professionals that are interested in failure analysis.

Dr. Gagg, now retired from academia, has taught the postgraduate forensic engineering course at the UK Open University for 30 years. He is now an independent failure analyst with over 800 forensic investigations to his credit. His book contains a multitude of case histories that demonstrate the principles of failure analysis. His teaching experience has shown him that case studies are effective teaching tools. As Confucius said:

I Hear, and I Forget
I See, and I Remember
I Do, and I Understand

The moral: tell me and I will forget. Show me and I will remember. Involve me and I will understand. In other words, we learn best by doing. After teaching the AGMA Gear Failure Analysis Seminar for over 25 years, I wholeheartedly agree that case studies are effective teaching tools.

Dr. Gagg's book contains over 400 high-resolution, color images of failed components that illustrate a wide variety of product failures and serve as a working manual for practitioners of forensic engineering. His well-written case histories are a joy to read, and I guarantee you will obtain a good background in the art and craft of a failure detective.

For more information.
Questions or comments regarding this paper? Contact Robert Errichello—*rlgears@mt.net.*

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Robert Errichello, PE, heads his own gear consulting firm—GEARTECH (*rlegears@mt.net*)—and is a founder of GEARTECH Software, Inc. A graduate of the University of California at Berkeley, he holds B.S. and M.S. degrees in mechanical engineering and a master of engineering degree in structural dynamics. In his more than 30 years of industrial experience, Errichello worked for several gear companies; he has also been a consultant to the gear industry for more than 20 years and has taught courses in material science, fracture mechanics, vibration and machine design at San Francisco State University and the University of California at Berkeley. He is also a member of ASM International, STLE, ASME Power Transmission and Gearing Committee, AGMA Gear Rating Committee and the AGMA/AWEA Wind Turbine Committee. Errichello has published dozens of articles on design, analysis and the application of gears, and is the author of three widely used computer programs for the design and analysis of gears. He is also a longtime technical editor for Gear Technology magazine and STLE Tribology Transactions, and has presented numerous seminars on design, analysis, lubrication and failure analysis of gears.