# UNDERSTANDING How Components Fail

THIRD EDITION

Donald J. Wulpi

Edited by Brett Miller

ASM INTERNATIONAL

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The Materials Information Society

ASM International®
Materials Park, Ohio 44073-0002
www.asminternational.org

First printing, October 2013



In writing this book, the author has drawn upon both his personal experience and the available literature. As the text itself makes clear, there is often no single or simple remedy for component failure. The author makes no representation or warranty as to the appropriateness or success of any method or procedure herein suggested.

The terms "fail" and "failure" as used in this book are intended to mean cessation of function or usefulness, and carry no implication of negligence or malfeasance.

Comments, criticisms, and suggestions are invited, and should be forwarded to ASM International.

Prepared under the direction of the ASM International *Technical Books Committee (2012–2013)*, Bradley J. Diak, Chair; and the *Failure Analysis Committee*, Dustin A. Turnquist, Chair, and Larry D. Hanke, Past Chair.

*ASM International staff who worked on this project include Scott Henry, Senior Manager, Content Development and Publishing; Karen Marken, Senior Managing Editor; Madrid Tramble, Manager of Production; and Diane Whitelaw, Production Coordinator.*

Library of Congress Control Number: 2013933056
ISBN-13: 978-1-62708-014-9
ISBN-10: 1-62708-014-7
SAN: 204-7586

ASM International®
Materials Park, OH 44073-0002
www.asminternational.org

Printed in the United States of America

# About the Editor

BRETT MILLER IS A metallurgical engineer with degrees from the Missouri University of Science and Technology and the University of Wisconsin-Milwaukee. He is a registered Professional Engineer in several states. For over 28 years, Brett has worked as a failure analyst, metallurgist, and expert witness, completing thousands of failure analysis investigations. He has authored numerous publications, including book chapters and journal articles. Brett has been active in ASM International since 1984 and is a former chairman of the ASM Failure Analysis Committee. He is also active in NACE International and the American Welding Society. He has experience in aerospace, oil field, and commercial laboratories. Brett is currently the technical director at IMR Metallurgical Services in Louisville, Kentucky.

# About the Author

A METALLURGICAL CONSULTANT in Fort Wayne, Indiana, Donald J. Wulpi studied and analyzed failures of metal parts for more than 45 years. A graduate of Lehigh University, with a degree in metallurgical engineering, he spent most of his working life in several metallurgical laboratories of the International Harvester Company, now Navistar International Corporation. In retirement, Mr. Wulpi devoted himself to teaching the principles of failure analysis at the ASM International headquarters, in Materials Park, Ohio, and at various companies throughout the United States. He testified as an expert witness in product litigation cases for many years.

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# Preface to Third Edition

THE FIRST EDITION of Don Wulpi's *Understanding How Components Fail* was handed to me at my first job, right after it was published. I was told to read it cover to cover because it had so much that I would need to know. It was easy to understand and provided a great deal of insight into failures. The book, and the subsequent second edition, became indispensable to my expanding technical bookshelves. Early in my career I often recommended it to colleagues. Now the book is one of the first reference books I hand to new engineers and technicians. Although it is written primarily for the novice, all technically interested people can learn a great deal from it.

Because I am a proponent of *Understanding How Components Fail*, preparing a new edition was a difficult task. However, as in most things, materials science and failure analysis are constantly changing. This new edition has attempted to add recent technical knowledge and analysis tools to bring the content up-to-date.

Engineering design, materials, and analysis techniques have all advanced significantly since the first edition. A substantial enhancement to this volume is the update to Chapter 10, "Fatigue Fracture." Fatigue striation counting, modeling, and crack rate prediction are now routinely performed for critical components, and this is reflected in this new edition. Corrosion failure analysis (Chapter 13) is updated to reflect the current greater understanding of the processes involved. DNA testing can now be performed to identify organisms responsible for microbiologically influenced corrosion (MIC), a technology that was not widely available in 1985. Chapter 14, "Elevated-Temperature Failures," also reflects our greater understanding of these failures, as engineering materials are used in progressively harsher conditions. Chapter 15, "Fracture Mechanics," was added to the second edition as the field became more prominent. In this edition, the chapter is updated to parallel modern thought and terminology. For younger readers this may sound odd, but most of us did not have computers on our desks in the mid-1980s. The advent of affordable, user-friendly (mostly) computers has been a boon to engineering designers and failure analysts. Complex calculations and computational modeling of huge volumes of data could not be approached before computers.

Don Wulpi obviously filled an unfilled niche with this book. Although many years have passed since the original publication, the book remains one of ASM International's best-selling technical books. I think that, beyond the comprehensive information the book provides, its informal manner and conversational tone are what keeps it in demand. Photographs and drawings illustrate concepts that are explained with copious real-world examples. I have spoken to numerous college professors, domestic and foreign, that use *Understanding How Components Fail* as an undergraduate course text. I think the practical, no-nonsense presentation of this book makes it a very good text for all materials and mechanical engineering students.

First, all thanks to Donald Wulpi for creating this book. It contains decades of practical failure analysis knowledge that has helped me throughout my career. In this third edition I believe we have remained faithful to his original intent for the book.

Many thanks to all of the chapter reviewers, who updated the material and tried to make the additions as seamless as possible. The reviewers consisted of engineering professors, industrial failure analysts, commercial failure analysts, and consultants. For many of us there is a compulsion to write in a more formal manner, so most were outside of their comfort zones. I think they were able to maintain the general tone of the book while making the necessary additions. It is a testament to the enduring legacy of this book that I was able to find so many willing and enthusiastic reviewers.

Thanks also to Karen Marken and the other professional staff at ASM International. Karen was able to keep everything moving forward and was a pleasure to work with.

Brett A. Miller, P.E.
Louisville, Kentucky

# Preface to the Second Edition

SINCE THE FIRST publication of this work many years ago, I have been pleased with the reception that it has received. Care has been taken in the preparation of this book to make it as accurate and useful as possible, for analysis of failures is a critical process. Unfortunately, it is impossible to describe or predict every possible combination of type of part, assembly, material, metallurgical condition, service usage, and environment. For this reason, the book had to be written in general terms so that the principles of failure analysis can be applied to a very large number of specific failures. It is highly recommended that the study of any failure not be limited to this book but expanded to encompass many of the references and suggestions for further study. After more than 45 years of studying, writing, and teaching about failures, I am still learning. And so can you.

Again, I am indebted to all of those people who have suggested improvements, particularly J.L. Hess and J.L. Welker. Many suggestions are included in this revision.

Also, I thank E.J. Kubel, Jr., who prepared Chapter 15 on Fracture Mechanics, for his writing on this important subject. Ed is a metallurgical engineer with about 15 years experience in the foundry industry and nearly the same length of time as author and editor for several technical magazines in the areas of materials and manufacturing processes. He made this discussion as elementary as possible in keeping with the theme of this work on the principles of failure analysis and prevention.

Donald J. Wulpi
Fort Wayne, Indiana

# Preface to the First Edition

THIS BOOK IS intended for use primarly by those who have little or no prior knowledge of the principles of metallurgical failures, such as in distortion, fracture, wear, and corrosion. In this sense, it can be considered to be a primer, for many complex technical concepts are explained in relatively simple terms—sometimes oversimplified for ease of understanding.

Failure analysis is a critical first step in identifying a problem that has occurred in a metal component of a mechanism or structure. Once the mode of failure has been identified, appropriate corrective measures may then be taken to try to prevent similar future failures.

Nowhere is the need for accurate failure analysis more dramatically obvious than after an aircraft accident. After a serious crash, trained teams of investigators examine all phases of the aircraft and its operation, seeking clues to the true cause of the accident. Lives literally hang on the accuracy of the failure analysis process.

Failure analysis frequently involves comparing an unexplained failure with examples of failures whose cause has been determined. Identification of fractures, for example, is facilitated by comparing them with photographs of various types of fractures such as those shown in this book. The field of failure analysis is so vast that it encompasses all of metal and metalworking technology. There are many books and articles in the technical literature that deal with all types of failures of virtually all metals. At the end of every chapter in this book are selected references for further study. The serious reader is urged to use these and other references to pursue specific problems beyond the scope of this volume.

There is an infinite variety of types of parts, metals, treatments, conditions, types of loading, applications, environments, and combinations of all of these. Since it is impossible for a single work to cover every conceivable possibility, basic principles are explained with examples using common metals, primarily ferrous. Also, common types of parts are used in the examples, for the principles involved in their analysis may also be applicable to other types of parts not considered.

This work is the distillation of a lifetime of interest in failures and the techniques used to prevent failures, in study of failures, and in teaching others how to identify failures and how to correct them. Failure analysis is a fascinating subject, frequently compared with autopsies in the medical field.

In preparing this book I have had help from many people. Reviewers who read the first draft of each chapter and gave me many valuable suggestions for improvements were F.J. Marcom, J.P. Sheehan, G.H. Walter, and J.L. Welker. E.J. Rusnak and R.W. Morris took many of the photographs that are used. Many other photographs were given to me with the understanding that the contributor not be identified. To all of these persons, and many others who have given assistance, my sincere thanks.

Finally, my wife, Jini, has put up with my erratic schedule and helped me with the proofreading for many months. To her, particularly, my sincere thanks. The effort will have been worth it if this book is able to help many readers understand how components fail.

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Preview for: *Understanding How Components Fail* (Third Edition), by Donald J. Wulpi, edited by Brett Miller, ASM International, 2013
Full digital book available at https://doi.org/10.31399/asm.tb.uhcf3.9781627082709

# Introduction—Why Perform Failure Analysis?*

## Definition of Failure

Before we can understand how components fail, it is necessary to define failure. There is no universal definition for what constitutes a failure. One definition that has been developed by professional failure analysts is:

> *Failure. (1) A general term used to imply that a part in service (a) has become completely inoperable, (b) is still operable but is incapable of satisfactorily performing its intended function, or (c) has deteriorated seriously, to the point that it has become unreliable or unsafe for continued use. (2) Also commonly applied to manufacturing processes that produce components that do not meet specifications. (Ref. 1)*

Simply, failure can be described as the inability of a component to function properly. Failures can occur anywhere: during design, manufacturing, or with the end customer. It is a mistake to assume that the failure of any component is necessarily due to poor design or manufacturing flaws. Failures can be caused by a very large variety of factors, and many failures are the result of multiple related factors.

In a larger, more encompassing context, *failure* can be defined as "the inability of a component, machine, process, or culture/thinking to function properly" (Ref 2). A failure is not just a broken part but can sometimes

*Introduction written by Daniel P. Dennies and Brett A. Miller, IMR Metallurgical Services - Louisville, and Charles V. White, Kettering University encompass all of the factors or attributes that are connected to the failure. In a rigorous and in-depth failure investigation, this may include the humans that are involved with the failure and the latent or overarching corporate and cultural environment that set the operational parameters of a company.

There is no way to eliminate failure entirely. Human ambition tends to outreach engineering, pushing the boundaries of safe, proven design. Designs and materials continue to become more complex, with new technologies developed to create them, and new instruments invented to analyze them. Engineers at all stages of the design and manufacturing process should appreciate the reasons why formal failure analysis is performed. A comprehensive understanding of how components fail is necessary for a proper failure analysis.

## Why Do We Perform a Failure Analysis?

The goal of any failure analysis investigation is to discover the root cause of the failure. Discovering the root cause will identify corrective actions to prevent identical failures. It will also indicate if the failure was a unique situation, or if widespread failures can be anticipated. Proper root-cause investigation will help the judge or jury determine the party at fault in litigation-related failures.

This book focuses on the metallurgical or materials evaluation for failure mode identification. Engineers must realize that the materials analysis may be just a part of a larger root-cause investigation. Full root-cause analysis usually includes many other technical disciplines such as mechanical, civil, and structural engineering. Diverse nonengineering disciplines such as psychology, accounting, and criminal forensics may also be brought to bear.

The reason the failure analyst must strive to discover the root cause of the failure has many possible answers, as demonstrated in Fig. 1. Discovering the root cause will determine a definitive corrective action and prevent future occurrences of the same failure. Additionally, in failures that involve litigation, discovering the root cause will help decide the fault, or innocence, of the parties involved.

The benefits to a company or customer of a well-run and organized failure investigation are many. Failure investigation is an integral part of any company's Quality System, including such programs as Lean, Attention to Detail, Six Sigma, Total Quality Management, Continuous Improvement, and various other quality system concepts. A failure investigation can also assist in the redesign of a failed component that results in a better, more elegant, forgiving, and resilient engineering solution. It can solve a manufacturing problem that can save money and save time. In the end, a well-run and organized failure investigation can even save lives.

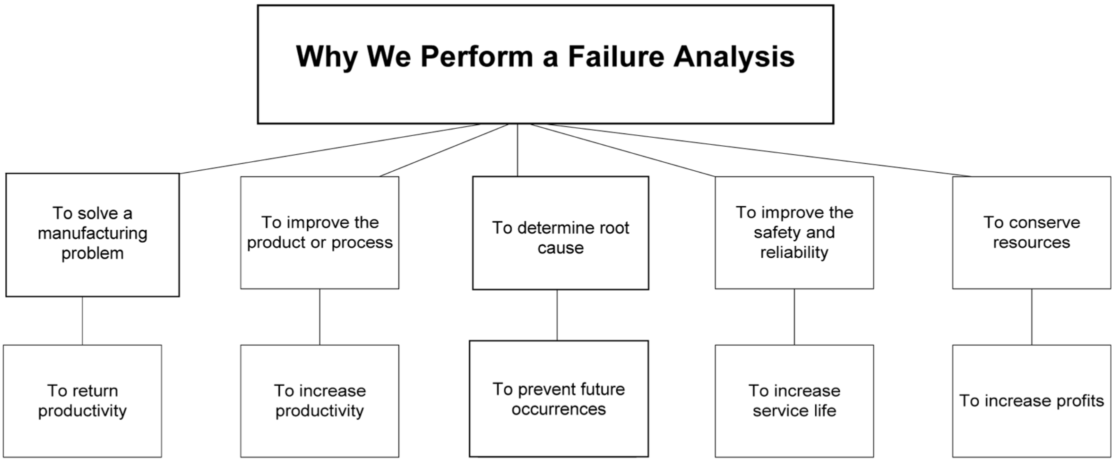


**Fig. 1** Some of the reasons we perform failure analysis

## The Responsibilities of the Failure Analyst

Failure analysts wield great power. Companies depend upon them to perform the task to the utmost of their capabilities, with due care, and with due diligence. Failure analysts must always remember the words of Voltaire, "With great power comes great responsibility."

Failure analysts must also always remember that failures can be associated with things that can be touched, like a broken component, or things that cannot be touched, like a process specification with conflicting or erroneous criteria. Pursuant to that goal, failure analysts must always strive to look at each and every failure as unique and different. They must not allow themselves to quickly dismiss a failure as "the same as all the others." A sound technical opinion must be developed to a reasonable degree of engineering certainty based on engineering principles, data, testing, and/or published literature for each failure. As failure analysts gain experience and expertise practicing this scientific art, they must use that intelligence and experience to enhance and sharpen the technical assessment and analysis, not abandon them. Lastly, failure analysts must consider that each failure is relative to the industry and requirements of a particular program or part. Many industries use the same material or processes but have radically different acceptance criteria or expectations. A good first question for any failure by the failure analyst is simply, "What is the failure?"

In the industrial world, failure analysts are often requested by their management or customer to "make the problem go away." Many times this type of directive may not appear to be asking the failure analyst to determine root cause. However, experience and time will teach the failure analyst that the best way to "make a problem go away" is to discover root cause.

This book may be the first of many books, papers, and articles you will read on the subject of failure analysis. However, there are many other books, papers, and articles that will assist you to hone your craft and expertise. Some are listed as references for your convenience.

# Introduction: Why Perform Failure Analysis?

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