# METALLURGICAL FAILURE ANALYSIS

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# Metallurgical Failure Analysis

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# Preface

Despite the care taken in their design, installation, and operation, machine and structural components fail. Their failure is such a common occurrence that failure analysis remains an extremely important subject. In general, the main justification for performing a failure analysis lies in the application of the knowledge gained about the failure for the minimization of future problems, and also in the prominent role such analysis usually plays in litigation subsequent to failures.

A treatise on failure analysis can be approached by first covering the general aspects of the failure of materials, then examining the failure of specific classes of materials, such as metallic, polymeric, ceramic, or electronic. However, the majority of machine and structural components are made of metallic materials, and thus we have chosen to limit this book to the failure analysis of metals. Also, since most failures involve the breakage of components, the main thrust of the book is the analysis of fracture failures.

There are many books and special tracts which treat failure analysis of materials, and metallic materials specifically. Most of these cover the results of research related to failures, but these are introductory books. However, we felt that there was no proper balance between introductory material and examples of fracture-surface appearances. The introductory books were weak on fractographs, and handbooks, such as the *Metals Handbooks*, were designed for those already having a rather detailed understanding of metallurgical failure analysis. Thus, in our book we have placed emphasis on the appearance of fracture surfaces, and therefore have included copious fractographs to illustrate the points made in the text. The scope, however, is limited to an introductory range so as not to get bogged down in too much detail. The introductory nature of the book is designed for metallurgists and materials scientists and engineers who are novices in the subject, as well as for those working in this field who desire a refresher. In addition, it will be useful to engineers and scientists who encounter the subject as a peripheral, but important, aspect of their work. It is, furthermore, a useful reference book—for example, as a quick source of definitions and examples of fractographic terms. Also, the book will be helpful in design courses for senior undergraduate and graduate students in materials engineering and mechanical engineering.

In Chapter 1, following an introduction to the methodology of failure analysis, we present a brief treatment of the common tools used as an aid in understanding how the experimental information is obtained, and the advantages, disadvantages, and limitations of them. Included in this chapter is a treatment of sample preparation. In Chapter 2, the relation of the external loading of components to the macroscopic fracture-surface orientation is treated. This is followed, in Chapter 3, by a treatment of the microscopic fracture mechanisms and the common microfractographic features associated with known loading conditions. Chapter 4 covers the macroscopic fracture-surface appearances associated with known loading conditions. Both the macro- and the microfractographic aspects of fracture are illustrated by examples. Finally, several case studies are described in detail with reference to information and fractographs in the preceding chapters to illustrate the use of the introductory concepts.

In the text, we have usually given values of quantities in both U.S. customary and SI units. Commonly used units, such as centimeters, inches, angstroms, and micrometers have been retained. Data in figures are given in the units of the source from which they were taken. However, we have supplied convenient conversion tables in the appendixes.

Understanding the physical metallurgy of metallic materials can be central to a successful metallurgical failure analysis. However, the physical metallurgy involved is too complicated to be reviewed in this book, which is only an introduction to metallurgical failure analysis. There exist many books and articles which can be consulted for information about the metallurgy of specific metals and alloys.

Finally, a word about definitions: A glossary of terms follows Appendix F. Terms not included there can be found by consulting the index. The common terms used in metallurgical failure analysis are defined and described in the text.

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*Ashok Choudhury*

# Contents

# Chapter 1

# Introduction

*The general conclusion is this—Frost does not make either iron (cast or wrought) or steel brittle, and accidents arise from neglect to submit wheels, axles, and all other parts of the rolling stock to a practical and sufficient test before using them.*

JAMES PRESCOTT JOULE
*Philosophical Magazine, 1871*

## 1.1 Objectives

The analysis of failures of metallic components is an extremely important aspect of engineering. Establishing the causes of failures provides information for improvements in design, operating procedures, and the use of components. Also, determining the cause of a failure can play a pivotal role in establishing liability in litigation. Failure analysis is often difficult and frustrating, but understanding how to approach an analysis and how to interpret observations provides a basis for assuring meaningful results.

The objective of this book is to introduce the important aspects associated with the failure analysis of metallic components. Emphasis is placed on the analysis of broken components, where observations of the fracture surface play a key role. Thus a treatment of both macroscopic and microscopic observations of fracture surfaces is given. Since loading conditions are often an important aspect of the possible causes of failures, a simplified treatment of the mechanics involved is presented. It is to be noted that some information about prior loading conditions can often be gleaned from a careful observation of the general macroscopic orientation of the fracture surface. Also included is a section which reviews the common experimental methods used in metallurgical failure analysis. Finally, some case studies of metallurgical failure analyses are introduced, and the approaches taken are related to the information presented in preceding chapters.

## 1.2 Approach to Metallurgical Failure Analysis

Metallurgical failure analysis deals with the determination of the causes of the failure of metallic parts or components. In the broad, and correct, sense, *failure* can be defined as the inability of a component to function properly, and this definition does not imply fracture. *Failure analysis* can be defined as the examination of a failed component and of the failure situation in order to determine the causes of the failure. The purpose of a failure analysis is to define the mechanism and causes of the failure and usually to recommend a solution to the problem.

The causes of failures can be broken down into the following categories:

1. *Misuse:* The component is placed under conditions for which it was not designed. This is a common cause of failure, and its establishment sometimes relies on determining that the assembly of the component and the design were correct, leaving misuse as a suspected cause.
2. *Assembly errors and improper maintenance:* Assembly errors involve such factors as leaving off a bolt or using incorrect lubricant. Maintenance of equipment ranges from painting surfaces to cleaning and lubrication, and its neglect may lead to failure. It is also pointed out that a failure may be caused by some other part of the system not functioning properly, thereby placing the component which failed under conditions for which it was not designed. Thus failure of a component may point to a problem elsewhere in the system.
3. *Design errors:* This is a very common cause of failure. In this category the following items are considered to be specified by the design process:
   *a.* Size and shape of the part. This is usually determined by stress analysis or geometric constraints.
   *b.* Material. This refers to the chemical composition *and* the treatment (for example, heat treatment) necessary to achieve the required properties.
   *c.* Properties. This is related to stress analysis, but other properties such as corrosion resistance must also be considered.

It is interesting to examine some information about the causes of failures and compare it to the preceding list.

**TABLE 1.1 Frequency of Causes of Failure in Some Engineering Industry Investigations**

| Origin | % |
|---|---|
| Improper material selection | 38 |
| Fabrication defects | 15 |
| Faulty heat treatments | 15 |
| Mechanical design fault | 11 |
| Unforeseen operating conditions | 8 |
| Inadequate environment control | 6 |
| Improper or lack of inspection and quality control | 5 |
| Material mixup | 2 |

SOURCE: Adapted from Davies.[1]

1. *Improper material selection:* Table 1.1 shows that improper material selection is a common problem.
2. *Improper maintenance:* The data in Table 1.2 show that improper maintenance is the main problem in failed aircraft components.
3. *Faulty design considerations:* Causes of failures due to faulty design considerations or misapplication of material include the following (adapted from Dolan[2]):
   *a.* Ductile failure (excess deformation, elastic or plastic; tearing or shear fracture)
   *b.* Brittle fracture (from flaw or stress raiser of critical size)
   *c.* Fatigue failure (load cycling, strain cycling, thermal cycling, corrosion fatigue, rolling contact fatigue, fretting fatigue)
   *d.* High-temperature failure (creep, oxidation, local melting, warping)
   *e.* Static delayed fractures (hydrogen embrittlement, caustic embrittlement, environmentally stimulated slow growth of flaws)
   *f.* Excessively severe stress raisers inherent in the design

**TABLE 1.2 Frequency of Causes of Failure of Aircraft Components (Laboratory Data)**

| Origin | % |
|---|---|
| Improper maintenance | 44 |
| Fabrication defects | 17 |
| Design deficiencies | 16 |
| Abnormal service damage | 10 |
| Defective material | 7 |
| Undetermined cause | 6 |

SOURCE: Adapted from Davies.[1]

  g. Inadequate stress analysis, or impossibility of a rational stress calculation in a complex part
  h. Mistake in designing on the basis of static tensile properties, instead of the significant material properties that measure the resistance of the material to each possible failure mode
4. *Faulty processing:* Causes of failures due to faulty processing include the following (adapted from Dolan[2]):
  a. Flaws due to faulty composition (inclusions, embrittling impurities, wrong material)
  b. Defects originating in ingot making and casting (segregation, unsoundness, porosity, pipes, nonmetallic inclusions)
  c. Defects due to working (laps, seams, shatter cracks, hot-short splits, delamination, excess local plastic deformation)
  d. Irregularities and mistakes due to machining, grinding, or stamping (gouges, burns, tearing, fins, cracks, embrittlement)
  e. Defects due to welding (porosity, undercuts, cracks, residual stress, lack of penetration, underbead cracking, heat-affected zone)
  f. Abnormalities due to heat treating (overheating, burning, quench cracking, grain growth, excessive retained austenite, decarburization, precipitation)
  g. Flaws due to case hardening (intergranular carbides, soft core, wrong heat cycles)
  h. Careless assembly (such as mismatch of mating parts, entrained dirt or abrasive, residual stress, gouges or injury to parts)
  i. Parting-line failures in forging due to poor transverse properties
5. *Deterioration in service:* Causes of failures due to deterioration during service conditions include the following (adapted from Dolan[2]):
  a. Overload or unforeseen loading conditions
  b. Wear (erosion, galling, seizing, gouging, cavitation)
  c. Corrosion (including chemical attack, stress corrosion, corrosion fatigue, dezincification, graphitization of cast iron, contamination by atmosphere)
  d. Inadequate or misdirected maintenance or improper repair (such as welding, grinding, punching holes, cold straightening)
  e. Disintegration due to chemical attack or attack by liquid metals or platings at elevated temperatures
  f. Radiation damage (sometimes must decontaminate for examination, which may destroy vital evidence of cause of failure); varies with time, temperature, environment, and dosage
  g. Accidental conditions (such as abnormal operating temperatures, severe vibration, sonic vibrations, impact or unforeseen collisions, ablation, thermal shock)

Most metallurgical failures involve fracture of the component, and thus most failure analyses involve examination of the mechanical loading situation. In this book, the term *mode* of fracture will be used to reflect the type of loading involved, such as tensile overload, fatigue, or creep, and is covered in Chapter 4. The term fracture *mechanism* will be used to define the type of microscopic process whereby the material fractured. This refers to processes such as cleavage or void coalesence, which are covered in detail in Chapter 3. The frequencies of the various types of fracture modes which have been identified are illustrated by the data in Tables 1.3 and 1.4.

The steps involved in conducting a failure analysis and their sequence depend upon the failure. One sequence to do this includes the following eight steps:

1. *Description of the failure situation:* Here the history of the failure should be documented. Any information pertaining to the failure, such as the design of the component (including the material and properties), and how the component was being used, is important to obtain. Especially useful are photographs of the part and of associated components.
2. *Visual examination:* Here the general appearance of the part should be documented. Care should be exercised in handling the part so as not to damage any of the fracture surfaces or other important features.
3. *Mechanical design analysis (stress analysis):* When the part clearly involved mechanical design as a major design component, a stress analysis should be carried out. This will help to establish whether the part was of sufficient size and of proper shape, and what mechanical properties were required. In some cases this analysis may establish the cause of failure. For example, if the load on a part can be determined and estimates of the mechanical properties made, then it may be possible to establish that the part is too small for this load.

**TABLE 1.3 Frequency of Causes of Failure in Some Engineering Industry Investigations**

| Cause | % |
|---|---|
| Corrosion | 29 |
| Fatigue | 25 |
| Brittle fracture | 16 |
| Overload | 11 |
| High-temperature corrosion | 7 |
| Stress corrosion/corrosion fatigue/hydrogen embrittlement | 6 |
| Creep | 3 |
| Wear, abrasion, and erosion | 3 |

SOURCE: Adapted from Davies.[1]

**TABLE 1.4 Frequency of Causes of Failure of Aircraft Components**

| Cause | % |
|---|---|
| Fatigue | 61 |
| Overload | 18 |
| Stress corrosion | 8 |
| Excessive wear | 7 |
| Corrosion | 3 |
| High-temperature oxidation | 2 |
| Stress rupture | 1 |

SOURCE: Adapted from Davies.[1]

4. *Chemical design analysis:* This step refers to an examination of the suitability of the material from the standpoint of corrosion resistance.
5. *Fractography:* Examination of the fracture surface with the unaided eye, with optical microscopes, and with electron microscopes should be carried out in order to establish the mechanism of fracture.
6. *Metallographic examination:* This requires sectioning and metallographic preparation. It may require agreement between all parties involved before sectioning. This step will help to establish such facts as whether the part had the correct heat treatment.
7. *Properties:* The properties pertinent to the design should be determined. This is not always possible because the test to determine a property may destroy the part. In terms of mechanical properties, hardness is especially important. Hardness will frequently correlate with many other mechanical properties (such as yield strength). It is a simple test to perform, and it usually will not damage the part.
8. *Failure simulation:* A very useful approach is to take an identical (supposedly) part and subject it to the exact condition under which it is designed to operate. This may be too expensive to carry out and is not done frequently.

An alternative procedure for metallurgical failure analysis as adapted from Ryder et al.[3] follows these steps:

1. Collection of background data and selection of samples
2. Preliminary examination of the failed part (visual examination and record keeping)
3. Nondestructive testing
4. Mechanical testing (including hardness and toughness testing)

5. Selection, identification, preservation, and/or cleaning of all specimens
6. Macroscopic examination and analysis (fracture surfaces, secondary cracks, and other surface phenomena)
7. Microscopic examination and analysis
8. Selection and preparation of metallographic sections
9. Examination and analysis of metallographic sections
10. Determination of failure mechanism
11. Chemical analyses (bulk, local, surface corrosion products, deposits or coatings, and microprobe analysis)
12. Analysis of fracture mechanics
13. Testing under simulated service conditions (special tests)
14. Analysis of all the evidence, formulation of conclusions, and writing the report (including recommendations)

The importance of obtaining background information cannot be overemphasized. Also, prior to the physical destruction of any broken components and the assembly of which they are a part, it is important to document, usually in pictures, their external features. In cases that may involve litigation it is recommended that all parties involved agree on any testing in which physical destruction may occur. Determination of the mechanical properties frequently plays a prominent role in failure analysis, and these properties can often be estimated from hardness measurements. This procedure is essentially nondestructive. Thus consideration of hardness measurements usually occurs as an early step.

A critical step is examination of the fracture surface. This usually is best made by sectioning the broken component for ease of handling. However, it is possible to reproduce the fracture surface topology by preparing a replica and making the observations on the replica. This can be very useful, and perhaps necessary, since it is nondestructive. Another critical step is usually microstructural analysis, which gives information about the processing and properties of the material. However, this nearly always requires sectioning.

A very useful step is failure simulation. Here a part identical to the one that broke is subjected to an opération that simulates what occurred during service. However, such a simulation may be too difficult or expensive to conduct.

Another feature of failure analysis is interaction with people. It is important to be able to obtain information from those involved in the failure, and to be able to interpret their statements correctly.

The type of background information that may be required for a fail-

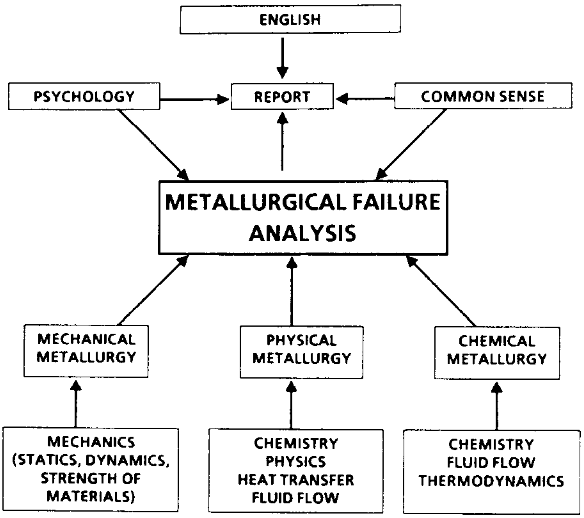


**Figure 1.1** Disciplines and subjects involved in metallurgical failure analysis.

ure analysis is depicted in Fig. 1.1. The results of an analysis usually culminate in a report, which contains the findings and recommendations. Thus careful writing is very important.

## 1.3 Tools of Metallurgical Failure Analysis

Characterization of the microstructure and of the fracture surface topology plays a prominent role in metallurgical failure analysis. The most common tools for this are the eye and the optical microscope, the scanning electron microscope, and the transmission electron microscope. Their utilization is reviewed in this section. Less commonly used techniques are covered in the volume in the 9th edition of the *Metals Handbook* on materials characterization.[4]

### 1.3.1 Optical microscopy

In an optical microscope (OM) utilized in fractography (and in metallography), a light source passes through an objective lens which, if at the proper distance from the surface, will form an image of the surface. To further magnify this image, this light passes through another lens (the eyepiece) and is then focused on the retina of the eye. The general scheme for an inverted-stage metallurgical microscope is shown in Fig. 1.2. The light from the source passes through a condenser lens to collimate the beam. There is also an adjustable aper-