Analysis of Metallurgical Failures

SECOND EDITION

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Preface

In this era of increasing awareness of product liability, the need for accurate failure analyses has also grown in a corresponding fashion.

The proper analysis of a component failure can provide valuable assistance in determining the validity of a product design. Errors in materials selection and design as well as materials defects and shortcomings in processing can frequently be revealed. These problems can often be detected in prototype testing or early in production, which results in substantial savings in time and money.

Often, failure analysis can also determine whether the failure was the result of misuse or abuse. However, such analysis is often neglected and usually does not consider the effects of particular manufacturing processes on performance. In many small organizations, sophisticated materials and process engineering groups are not available. Too often, the responsibility may fall to an engineer who lacks the experience and background to interpret the available information.

In the course of several years of failure analyses, it has become evident that a text clearly presenting the techniques and approaches of this specialty would be extremely useful to the working engineer. Although much of the information has been published, the material is scattered throughout many sources and does not form a coherent presentation. In this volume, we present a coordinated approach to metallurgical failure analysis. Those destructive and nondestructive evaluation techniques commonly available are described, as are suggestions regarding their advantages, limitations, application, and meaning. Typical problem areas are approached from the viewpoints of physical and mechanical metallurgy. Emphasis is placed on typical types of defects which contribute to failures, which are related to manufacturing processes. An attempt is made to show the interrelation between the practical and the theoretical, so that failures can best be resolved and their recurrence prevented.

Since the publication of the previous edition there have been major advances in the various topical areas covered in the book. We have attempted to include these advances as well as newer and more representative illustrations of the various defect types.

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Introduction

1.1 FUNCTION OF FAILURE ANALYSIS

The primary reasons for conducting an analysis of a metallurgical failure are to determine and describe the factors responsible for the failure of the component or structure. This determination may be motivated by either sound engineering practice or by legal considerations.

From an engineering standpoint, the proper application of failure analysis techniques can provide a valuable feedback to design problems and material limitations. The optimum design is one in which the requirements are slightly exceeded by the capabilities in all circumstances. This aim is seldom realized because of the obvious difficulty in recognizing or defining precisely the various demands that the system must be called upon to meet. This latter aspect of the design requirements is generally met by a sound engineering device, the application of safety factors. However, how much of a safety factor is appropriate? To grossly overdesign the component is economically extravagant and can inadvertently overload other parts of the structure. Underdesigning of the component leads to its premature failure, is economically wasteful, and, most important, could jeopardize life. The role failure analysis plays in the overall design and production of a component is shown in Fig. 1.1. It is in this role, as a design adjunct, that failure analysis can play a maximum part, since the most sophisticated simulation testing can never duplicate the varied and interacting conditions found in actual service.

The legal reasons for failure analysis are equally compelling. The emphasis in product liability laws has shifted from the status of the plaintiff to the nature of defectiveness in a product.[1] Under present day law, regardless of the legal theory that the plaintiff may choose to proceed upon, he must prove that a defect in design or materials exists in the product. Consequently, if the aim is the successful de-

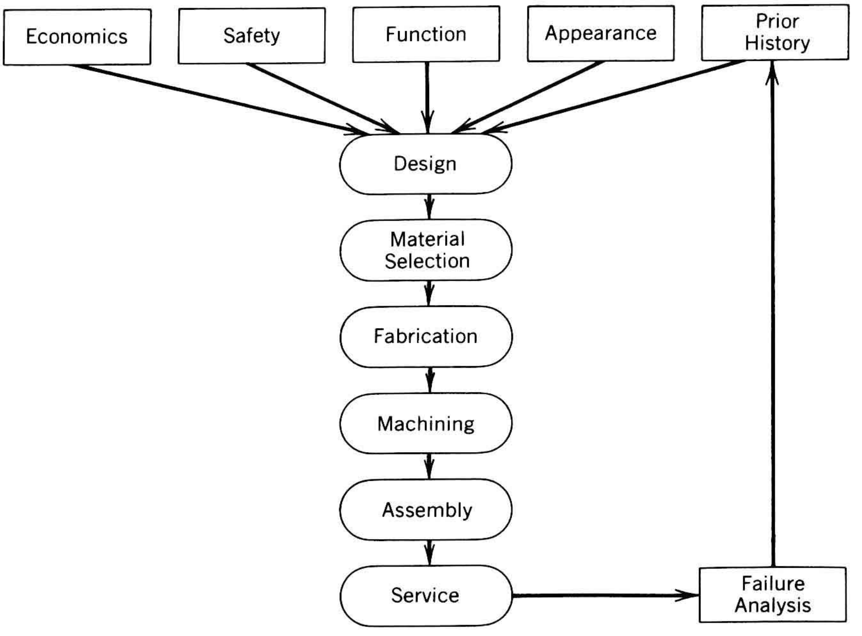

Figure 1.1. The relationship of failure analysis to the design and production of a component.

fense or proof in a product liability case, the question of whether a defect existed must be determined.

1.2 FACTORS RELATED TO FAILURE

Over the years several fundamental factors causally related to material failures or shortening of service life have been identified:

1. Design.
2. Improper selection of material.
3. Heat treatment.
4. Fabrication.
5. Improper machining and assembly.

These factors may be related to the occurrence of a failure in various ways. For example, they might be responsible for the causation of a crack, an increased susceptibility to corrosion, or other more subtle effects.

The actual failure may be due to any one of these factors acting independently or to the interaction of several of them. The exact cause is often not easy to ascertain and can only be resolved after an intensive investigation.

Very often management has little understanding of the factors and conditions leading to a failure. Frequently, after a field failure, the component, perhaps greasy or encrusted with dirt and rust, is rushed to the engineering department where an immediate answer about the cause of failure is expected. This attitude is never helpful and can hinder an investigation by creating undue pressure on the investigating team. The only countermeasure is patient education.

1.3 INVESTIGATIVE PROCEDURE

When a metallurgical failure occurs and an investigation is required, it is reasonable to ask, "Where does one begin?" and to use the answer advanced by the King of Hearts in Lewis Caroll's *Alice in Wonderland*—"One begins at the beginning." For the investigating metallurgist, the beginning occurs when he is called in on the case; however, the component was conceived, designed, and fabricated during some previous period. In this section we show the significance of determining the history prior to the failure and outline the subsequent course of action.

1.3.1 Documentary Evidence

The documentary or written evidence in an investigation is just as important as the physical evidence and in many cases, more so.[2] Some of this material is technical, represented by such documents as industrial safety codes and standards, federal regulations and standards, test reports and certifications, engineering and scientific articles and books, design drawings, warranties, and specifications. Pertinent data contained in these records should be abstracted and summarized so that they may be compared with data obtained on the component under investigation. Obviously, these tests and specifications will play a major role in determining whether the product is in conformance with the specification. The original documents should be filed, and if an extensive collection is created, an indexing system should be set up for convenient retrieval.

1.3.1.1 Service Conditions

Information about the actual operating or service conditions is extremely relevant. Data on the temperature level and range should be collected and compared with the design or intended service conditions to determine whether abnormal conditions were produced by improper operation, maintenance, temperatures, and so on. In a design where there has been no change in materials, design, or processing, the failure can often be attributed to a change in usage which created an abnormal service condition.

Equally significant are any data about the environmental conditions—composition of surrounding fluids, relative humidity, contamination, cleanliness conditions, and so on.

1.3.1.2 Materials Handling, Storage, and Identification

Failures can often be attributed not to conditions undergone in service but to deficiencies or errors in handling, identification, or storage. For example, tong marks received in handling can act as nuclei for quench cracks. Identification marks caused by stamping or etching can act as focal points for stress corrosion or fatigue.

A fatigue failure[3] which initiated from a numeral on the surface is shown in Fig. 1.2*a*. The electric etch produced temperatures high enough to austenitize the material, and the subsequent transformation resulted in brittle, untempered martensite. Abrasions are also stress raisers and can create similar problems.

Storage conditions are also important. Welding electrodes used on hydrogen-sensitive materials must be kept dry. Failure to do so can result in hydrogen embrittlement of the weld.

Finished parts should have fingerprints removed and should be lightly oiled prior to storage to avoid corrosion.

Obviously, the failure to correctly identify materials can also result in materials problems. The error may be in the complete omission of any identification or in the incorrect identification of the base metal or weld metal, or equally important, in the strength level.

1.3.1.3 Interviews

No investigation is complete without testimony from persons who have information about the failure—witnesses to the failure or personnel associated with the processing or testing. Such testimony, of course, is subject to bias, either unintentional or deliberate. Thus the failure may be directly or indirectly traced to a noncompliance with a prescribed procedure, and the witness will not care to implicate

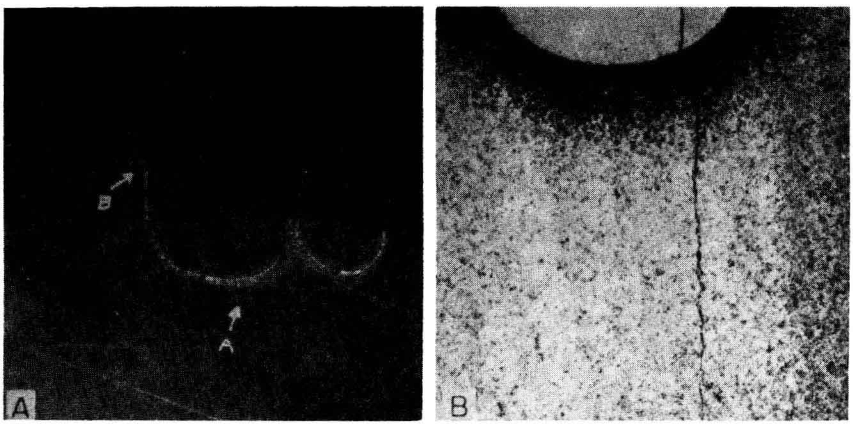

Figure 1.2. Fatigue failure which initiated from electric etch marks. (*a*) Macroscopic view of fracture origin. (*b*) Metallographic section showing crack originating in etch mark.

himself, (for example, the operation of a furnace at too high a temperature or the use of a gauge known to be inaccurate).

This bias may be revealed by other testimony or by test data; or it may remain hidden, which is worse. The important point, however, is that the investigator should use the interview only as a tool; he should not place unreasonable emphasis on these data, but should analyze them judiciously.

1.3.2 Field Investigation

When an engineer or scientist is called upon to perform a failure analysis, he is concerned with determining the origin, the causative factors, and the various responsibilities for the failure. Very often, he is not called in at the time of the occurrence, although this would be the ideal situation. The sequence of the investigation procedure then will vary depending upon when one becomes involved in the action.

Assume for the moment that an engineer is involved in the failure of a piece of machinery operating in the field and is called in shortly after the occurrence. The engineer should approach the failure with an open mind, setting out to collect as much data as possible before attempting to establish the cause.

One of the first steps in this data-collection process is to identify and record any information regarding the manufacturer, size, model number, serial number, date of manufacture, and so forth, of the main component or assembly. Similar information should also be obtained on the pertinent subcomponents.

The scene should then be photographed from several angles showing the location of the unit relative to the general layout, including any damage to the unit or deformation visible from a general inspection. Observations relative to the physical condition of the unit or system should be noted and recorded. If necessary, a sketch of the equipment should be made showing the relative location of any damage discerned as well as the general position of the unit. If movement has occurred, the sketch should show the original location as well as any displacement. Photographs and sketches of the site may also be necessary for certain types of failures—for example, those involving explosions, collapses, or multiple failures.

Close-up photographs of fractured components should be taken before the unit is moved, if this is possible, so that the original condition and position of these fractures may be preserved. Fracture surfaces should be padded for protection against mechanical damage.

If the failed unit is portable, it should be appropriately labeled for subsequent identification and removed for laboratory examination. In some cases the unit will be too large to permit its removal in toto, and decisions must be made on which components to remove and how to remove them. The decisions to be made at this point are difficult and often irreversible and will undoubtedly be subjected to criticism. Nevertheless they must be made, and the more thought that goes into the decision the easier it becomes to defend it. The sketches and photographs described above provide supporting evidence of the condition of the unit right after the event.

1.3.3 Laboratory Analysis

It is important to distinguish between relatively routine failure analyses conducted during the ordinary course of engineering and those made in conjunction with a product liability suit. Although the two have similarities, the product liability analysis differs in that the protocol is more formal, and more detailed records must be kept than for any ordinary in-house investigation.

For units that have been received in a disassembled state, the examination should begin with an inventory of the components. This inventory should include the name of the component, the location of the component in the overall system, and the approximate size of the component. The components should then be tagged or permanently labeled with an identifying number and should be logged into an inventory control system.

A physical description of the components should then be made, keying this description to the identification number previously assigned. The description should include a general discussion of the size and condition of the component together with any unusual features observable by the naked eye. Here one would describe any identifying serial number or logo on the component.

At this point in the investigation, photographs of the specimens should be taken to show the general form and configuration of the component. As many photographs from as many angles as necessary should be taken to provide a complete description of the component. It has happened that a component has been damaged or lost in transit between one office and another, and the photographic record is all that remains as evidence of its original condition. Consequently, this step is very important. Figure 1.3 shows front and side views of a failed component received as part of an overall examination. These photographs, as well as a written description, would comprise the record of the product as it was received. It should be noted that this example is for illustration only; in an actual suit, it would be the usual practice to take photographs from several angles. Ordinarily black-and-white photographs are adequate. If a specimen displays unusual markings, however, such as corrosion products which can be illustrated better by the use of color, then obviously, color photographs should be taken. At this point, you would normally proceed to conduct the more technical aspects of the analysis.

The exact procedure to be followed in conducting an examination will depend on whether the article is a single component or a complete assembly. However, there is one step which applies universally: do nothing right away. Contemplate the article and determine a plan of action. Ideally this should be done before the article arrives, but often this is not possible. However, even if pressed for time, take a portion of the time available to decide what should be done and in what sequence. A general sequence of tests commonly used in evaluating a product failure is presented in Table 1.1. While this table is certainly not all-inclusive, it does serve as a guide in planning the course of action.

If the article is a complete assembly, a functional test, that is, a test of whether the product is capable of normal operation, is certainly worthy of consideration. A functional test could disclose whether any abnormality in function exists or

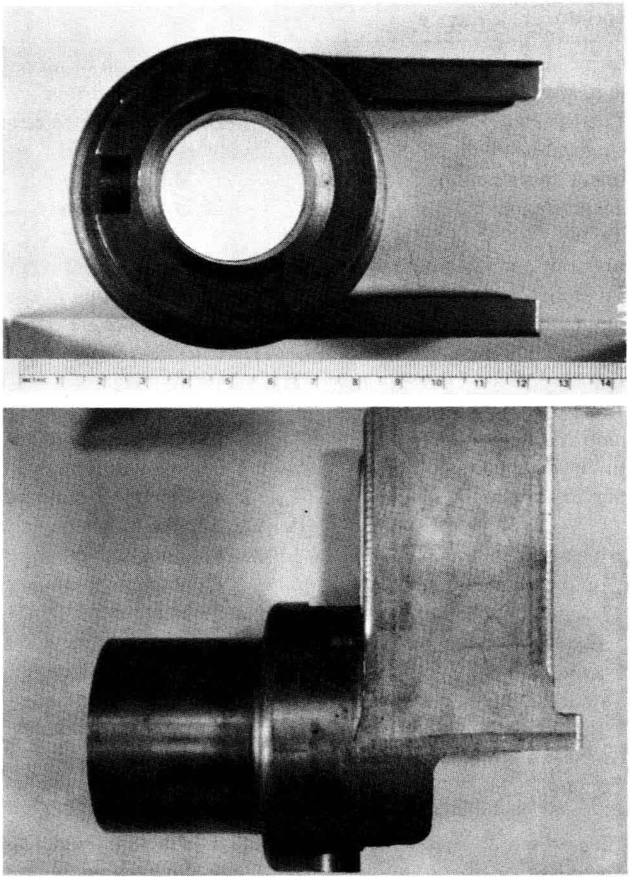

Figure 1.3. General views of a component in the "as-received" condition.

whether the operation appears normal. One might find with a functional test, for example, that a gas control valve exhibits leakage. When disassembly takes place it must be done very carefully. The reason that disassembly of an article must be carefully considered can be illustrated by the example above of a gas control valve that leaked during a functional test. The leak could be caused by a piece of debris lodged in the valve seat. The very act of disassembly could dislodge this debris and render the valve functional. On the other hand, if the leak is caused by porosity through the casting walls, the leak is permanent in nature and disassembly will not affect it. Consequently, the possible results of disassembly should be carefully evaluated before any action is undertaken.

Similar care should be used when the article is a single component. If cutting or sectioning is necessary, then a cutting plan such as the one shown in Fig. 1.4 should be developed to show the location from which the specimens have been

TABLE 1.1 Procedural Sequence

- I. Determine prior history
  - A. Documentary evidence
    1. Test certificates
    2. Mechanical test data
    3. Pertinent specifications
    4. Correspondence
    5. Interviews
    6. Depositions and interrogatories
  - B. Service parameters
    1. Design or intended operating parameters
    2. Actual service conditions
       - a. Temperature data (magnitude and range)
       - b. Environmental conditions
       - c. Service stresses
- II. Cleaning
- III. Nondestructive tests
  - A. Macroscopic examination of fracture surface
    1. Presence of color or texture changes
       - a. Temper colors
       - b. Oxidation
       - c. Corrosion products
       - d. Contaminants
    2. Presence of distinguishing surface features
       - a. Shear lips
       - b. Beach marks
       - c. Chevron markings
       - d. Gross plasticity
       - e. Large voids or exogenous inclusions
       - f. Secondary cracks
    3. Direction of propagation
    4. Fracture origin
  - B. Detection of surface and subsurface defects
    1. Magnaflux
    2. Dye penetrant
    3. Ultrasonics
  - C. Hardness measurements
    1. Macroscopic
    2. Microscopic
  - D. Chemical analysis
    1. Macrochemistry ("wet" analysis)
    2. Spectrographic analysis
    3. X-ray diffraction, fluorescence
    4. Electron beam microprobe
- IV. Destructive
  - A. Metallographic
    1. Macroscopic
    2. Microscopic
       - a. Structure
       - b. Grain size
       - c. Cleanliness
       - d. Microhardness
  - B. Mechanical tests
    1. Tensile
    2. Impact
    3. Fracture toughness
    4. Special
  - C. Corrosion tests
  - D. Wet chemical analysis
- V. Stress analysis
- VI. Storage

taken. Even after the tests have been completed the specimens should be identified and stored—for example, a chemical analysis specimen that has been reduced to chips. The authors have learned to their chagrin that an overzealous attorney can assign devious motives to the discarding of even a routine specimen or fragment of the component, even one that has no special significance.

1.3.4 Dimensional Analysis

Often, in order to provide data regarding the condition of a component, it is necessary to conduct detailed dimensional evaluations. This is particularly true when

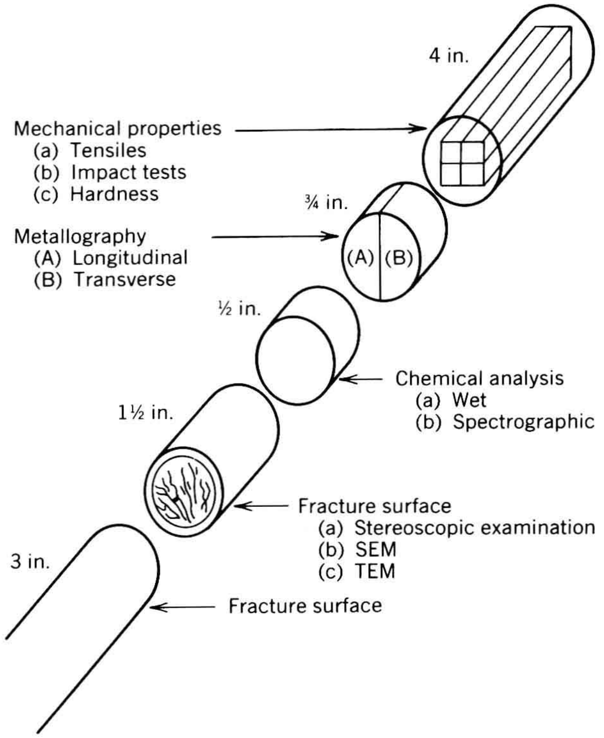

Figure 1.4. Typical cutting plan showing location of test specimens.

the component that has failed is part of a precisely dimensioned machine assembly. A frequently encountered situation where dimensional information is required occurs when one desires to known the degree of straightness of a rotating shaft, either because of bearing damage or because the shaft has failed.

The methodology required in this instance is that consistent with the practice of a good metrology laboratory. The metrology instruments, micrometers, calipers, and gauges should be calibrated frequently so that their accuracy cannot be called into question. Similarly, the technique used in the procedure should be recorded and, if necessary, diagrams should be made. The results obtained should be recorded on a drawing of the component, showing the exact location where the dimensional value was obtained.

1.4 EVALUATION OF DATA

The value of information gathered from macroscopic and microscopic examination and from the physical, chemical, and mechanical tests performed depends as much on the interpretation of the data as on the raw data themselves. Seldom are the raw data alone completely self-sustaining and sufficient to support the conclusions drawn. In the majority of failures, the true cause is revealed only by a systematic examination of *all* the facts related to the case. The investigator frequently must draw on prior experience in his background, which may be only casually related to the failure. Every item of data must be scrutinized and evaluated for its source, accuracy, and relevance to the entire investigation. The implication of each item and the conclusion that it warrants must be logically analyzed and evaluated to establish whether it is reasonable and consistent with the balance of the information generated. Apparent conflicts created by incompatible data should be resolved by determining whether the datum was erroneous or true with the differences created by time, location of the test, or an abnormality. Seemingly incompatible data should not be arbitrarily rejected. These data may be indicative of some abnormality, and additional testing may be required to form a sound conclusion.

The unsuccessful performance of a structure or component can, in general, be traced to the following modes of failure: ductile or brittle fracture, fatigue, creep, corrosion, or wear. Failure may result via the independent action of any of these modes; however, the final failure is often caused by the simultaneous or sequential activity of several mechanisms.

One mechanism may create stress raisers while another may promote the initiation of a crack and its subsequent growth. Thus, although there may be one primary mechanism, contributory mechanisms also exist. The role of each of these failure modes is examined in later chapters with the aim of developing a proficiency in the identification of the primary and secondary causes of failures.

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