Analysis of Metallurgical Failures

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Analysis of Metallurgical Failures

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Preface

The proper analysis of a component failure can provide valuable assistance in determining the validity of a product design. Errors in 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. However, such analysis is often neglected. In many small organizations sophisticated materials and process engineering groups are not available. Too often, the responsibility falls to an engineer who lacks the background to interpret the available information.

In the course of several years of failure analysis it has become evident that a text clearly presenting the techniques and approaches of this specialty would be extremely useful to the working engineer. A comprehenisve work of this type is presently unavailable. Although much of the information has been published, the material is scattered throughout many sources and does not form a coherent presentation. In addition, the present time appears appropriate because of the significant advances that have occurred in the past decade, particularly in the fields of electron microscopy, fracture mechanics, and solidification.

In this volume we present a coordinated approach to 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. An attempt is made to show the interrelation between the practical and the theoretical, so that failure analyses can best be resolved and their recurrence prevented.

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Troy, New York
July 1973

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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. Recently, 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 defense or proof in a

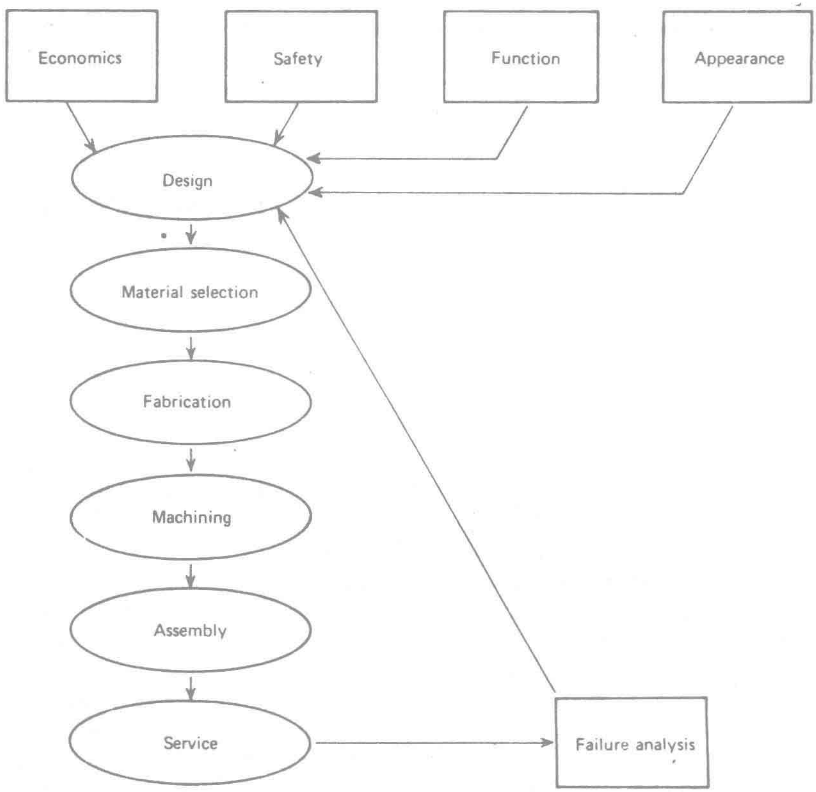

Fig. 1.1 The relationship of failure analysis to the design and production of a component.

product liability case, the question of whether a defect existed must be determined.

1.2 FACTORS RELATED TO FAILURE

Over the years the fundamental factors causally related to failure 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.

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.

Upper management too often 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 Carroll'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

It is advantageous and even necessary to collect documentary evidence, such as test certifications by vendors, mechanical test data, and in-house evaluations and reports. This category of data also includes pertinent specifications and warranties as well as design drawings indicating dimensions and surface finish.

The examination of correspondence, too, can be illuminating, as letters between the producer and consumer or the technician and engineer. The importance of such "technical paper" cannot be overemphasized, since the questions of adherence to a procedure and compliance with a specification can become major points in the investigation, especially a legal one.

1.3.2 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.

1.3.3 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[2] 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 such as those illustrated in Fig. 1.3 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 greased 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

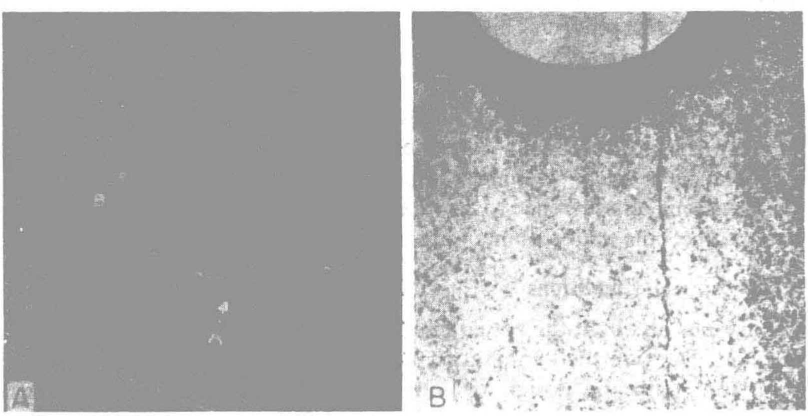

Fig. 1.2 Fatigue failure which initiated from electric etch marks. (*a*) Macroscopic view of fracture origin. (*b*) Metallographic section showing crack originating in etch mark.

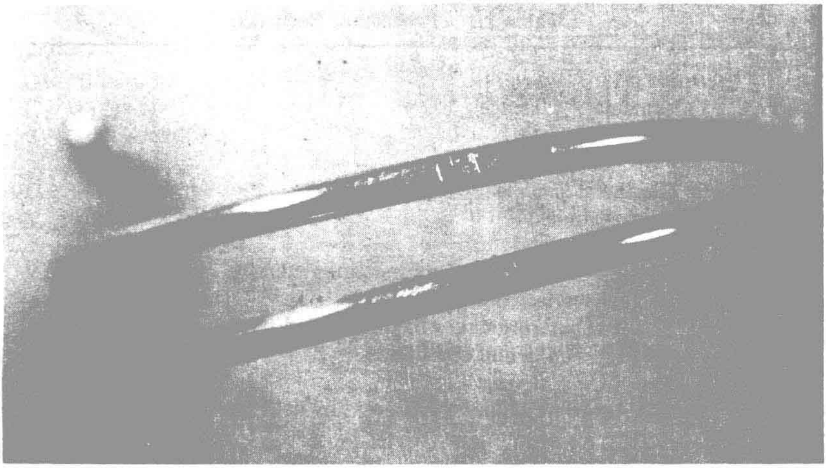

Fig. 1.3 Abrasions and gouges that can act as stress raisers.

identification or in the incorrect identification of the base metal or weld metal, or equally important, in the strength level.

1.3.4 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 himself, (e.g., 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.

1.3.5 Testing

The balance of the investigation should be concerned with various types of testing, both nondestructive and destructive. The test procedures are outlined in Table 1.1. The details of testing and the information obtainable are discussed in subsequent chapters.

Table 1.1 Procedural Sequence

I. Determine prior history
  A. Documentary evidence
    1. Test certificates
    2. Mechanical test data
    3. Pertinent specifications
    4. Correspondence
  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
  C. Details regarding failure as reported by field personnel
II. Nondestructive tests
  A. Macroscopic examination of fracture surface
    1. Presence of color or texture changes
      a. Temper colors
      b. Oxidation
      c. Corrosion products
    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

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

Table 1.1—Continued

- 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. Spectrographic
  - 2. Spot tests

III. 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

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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2

Mechanical Testing

A wide variety of material mechanical tests are available. In this chapter the more common ones are considered, such as tensile testing, impact testing, fracture toughness testing, and hardness testing.

2.1 TENSILE TESTING

A tensile test is performed by applying a uniaxial tensile load to a test bar. The load is gradually increased until the bar breaks. The increasing load is measured against the increasing elongation using an extensometer (Fig. 2.1). Usually, the tensile test bar has a round cross section, although flat plate specimens are also used. Figure 2.2 illustrates the various types of specimens.[1]

2.1.1 Engineering Stress-Strain

Tensile test data can be considered based on the engineering stress-strain or true stress-strain analyses. The main difference is that the former uses the original area and length, whereas the latter considers instantaneous values of area and length. Since the true stress-strain analysis is of little significance in a failure, it is not considered here. The engineering stress-strain analysis is used to determine the various mechanical properties cited in specifications. A typical stress-strain curve is shown in Fig. 2.3. Such curves are obtained from load-elongation diagrams by the following relations:

$$S = \frac{P}{A_0}$$

$$e = \frac{\Delta l}{l_0}$$

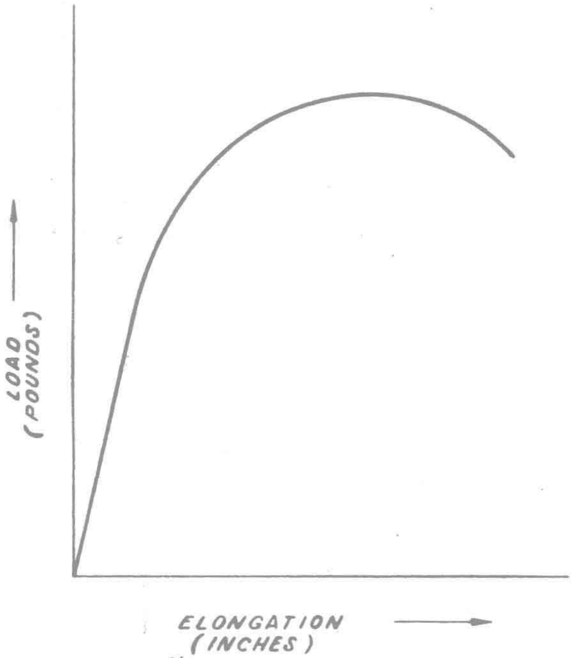

Fig. 2.1 Typical tensile load-elongation curve.

where

S = stress
P = load
A_0 = original area
e = strain
Δl = elongation
l_0 = original gauge length

In the elastic strain region, stress is proportional to strain according to Hooke's law:
where

$$S = Ee$$

E = Young's modulus, elastic modulus, or modulus of elasticity.

At the proportional limit, the stress-strain relation deviates from linearity. At a slightly higher stress, the elastic limit, the strain becomes