Techniques of Failure Analysis*

What Is Failure Analysis?

*Failure analysis* is a systematic investigative procedure using the scientific method to identify the causes of a failure. “Forensic engineering” is often used as a synonym, but this term is more appropriate for litigation-based investigations. Analysis of failures is an integral part of design and manufacturing processes. In addition to providing incremental improvements for refinement of successful designs, proper failure analysis can help prevent catastrophic failures. Although failure analysis is essential, it is not typically emphasized as part of most engineering curricula. As a result, failure analysis methods and techniques are not always understood by many engineers.

Figure 1 shows how a failure investigation is the reverse of the design process. During the failure investigation, the failure analyst will revisit and reanalyze all of the service, manufacturing, and design aspects and decisions to identify the cause of failure.

In the study of any failure, the analyst must consider a broad spectrum of possibilities or reasons for the occurrence. Often a large number of factors, frequently interrelated, must be understood to determine the cause of the original, or primary, failure. The analyst is in the position of Sherlock Holmes attempting to solve a baffling case. Like the great detective, the analyst must carefully examine and evaluate all evidence available and then prepare a hypothesis—or possible chain of events—that could have caused the “crime.” The analyst may also be compared to a coroner per-

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forming an autopsy on a person who suffered an unnatural death, except that the failure analyst works on parts or assemblies that have had an unnatural or premature demise. If the failure can be duplicated under controlled simulated service conditions in the laboratory, much can be learned about how the failure actually occurred. If this is not possible, there may be factors about the service of the part or assembly that are not well understood.

Fractures, usually the most serious type of failure, are studied here in some detail. Usually undesired and unexpected by the user, fractures can have disastrous results when a load-bearing member suddenly loses its ability to carry its intended load. Distortion, wear, and corrosion failures also are important and sometimes lead to fractures. However, these types of failure can be reasonably well predicted and prevented.

**Procedure for Failure Analysis**

Reference 1 is a basic guide to follow in various stages of a failure analysis investigation. It must be emphasized that the most important initial step to perform in any failure analysis investigation is to do *nothing* but organize the failure investigation (Ref 2). In this first step, the failure analyst should collect data and information; study the evidence; think about the failed part or parts; ask detailed questions about the parts, the machine itself, and circumstances of the failure; and make accurate notes about the responses. When possible, it is highly desirable to use low-power magnification—up to about 25 or 50×—with carefully controlled lighting to study the failed part or parts.

A failure analyst must also realize that a failure investigation is evaluated using “real” or typical data derived from the failure investigation itself. Design values of mechanical properties taken from books and material certifications are less desirable substitutes for a tensile test and chemical composition analysis of the actual material involved in the failure. In addition, the streamlining and cost-reduction concepts of many industries over the last 20 years have resulted in a reduction of internal qualification testing for materials and processes certification. The testing has been del-
egated to the industrial supplier base, which results in the industrial database becoming pieces of paper that contain very little actual, or useful, technical information. The failure analyst must be prepared to generate the data required.

In addition, in some rare cases, design engineers who may not be well versed in failure investigation may have the unfortunate “Titanic” viewpoint that their design is too good to fail. It can sometimes be a real challenge for the failure analyst to convince these design engineers to rethink their design and “discover” a method to make their design fail.

For a complete evaluation, the sequence of stages in the investigation and analysis of failure, as detailed in Ref 1, is:

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 specimens (and comparison with parts that have not failed)
6. Macroscopic examination and analysis and photographic documentation (fracture surfaces, secondary cracks, and other surface phenomena)
7. Microscopic examination and analysis using various light microscopy and electron microscopy techniques
8. Selection and preparation of metallographic sections
9. Examination and analysis of metallographic specimens
10. Determination of failure mechanism
11. Chemical analysis (bulk, local, surface corrosion products, deposits or coatings, and microprobe analysis)
13. Testing under simulated service conditions (special tests)
14. Analysis of all the evidence, formulation of conclusions, and writing the report (including recommendations). Writing a report may not be necessary in many product litigation cases; it is best to follow the advice of the attorney or client with whom the analyst is working.

Each of these stages is considered in greater detail in Ref 1, and they are not discussed here. However, it must be emphasized that three principles be carefully followed:

- **Locate the origin(s) of the fracture.** No laboratory procedure should hinder the effort to find the location(s) where the fracture originated. Also, it is most desirable, if possible, to have both fracture surfaces in an undamaged condition.
• Do not put the mating pieces of a fracture back together, except with considerable care and protection. Even in the best circumstances, fracture surfaces are extremely delicate and fragile and are damaged easily, from a microscopic standpoint. Protection of the surfaces is particularly important if electron microscopic examination is to be part of the procedure. Many such examinations have been frustrated by careless repositioning of the parts, by careless packaging and shipping, and by inadequate protection from corrosion, including contact with fingers. If parts must be repositioned to determine deformation of the total part, fracture surfaces must be protected by paper or tape that will not contaminate the surface. Also, protect fracture surfaces and other critical surfaces from damage during shipping by using padding, such as an adhesive strip bandage for small parts.

• Do no destructive testing without considerable thought. Alterations such as cutting, drilling, and grinding can ruin an investigation if performed prematurely. Do nothing that cannot be undone. Once a part is cut, it cannot be uncut; once drilled, it cannot be undrilled; once ground, it cannot be unground. In general, destructive testing must be performed—if done at all—only after all possible information has been extracted from the part in the original condition and after all significant features have been carefully documented by photography. Caution is particularly necessary in product litigation cases because the details of destructive testing should be agreed upon by all parties in the lawsuit. Consult the attorney with whom the analyst is working.

If there are several fractures from one mechanism (a “basket case”), one should determine if any of the fractures is a fatigue fracture. If definite evidence of a fatigue fracture can be found, this is usually the source of the problem—the primary fracture. Fatigue fracture is the normal, or expected, type of fracture of a machine element after long service. However, there are many possible reasons for fatigue fracture and many different appearances of fatigue fractures, as described in this book. Fatigue fractures are quite common in mechanisms unless specific actions have been taken to prevent them during design, manufacture, and service.

Investigative Techniques

While not all failures require the same degree of effort needed to investigate a product litigation matter, it is imperative that the investigator follow a specific and organized plan during the analysis. The use of checklists and flow charts to keep the investigation on track is very effective to ensure that all elements of the analysis have been performed and properly documented.

The initial stages of the investigation are the most critical. This is the phase where information surrounding the failure is collected and docu-
mented. Without following an organized and well-developed plan, some vital piece of evidence may be overlooked (Ref 2). With the passage of time it may become difficult, if not impossible, to recall or obtain evidence that may prove to be the missing piece of the puzzle (Ref 2, 3).

**Normal Location of Fracture**

The analyst must be aware of the normal, or expected, location for fracture in any type of part, because any deviation from the normal, or expected, location must have been caused by certain abnormal factors or conditions that need to be discovered. In very simple relative terms, this type of failure might be considered a “good” failure because it occurred in the manner and time frame expected by the design.

An all-too-familiar type of fracture is that of the ordinary shoelace. A shoelace will inevitably fail at one of the two top eyelets, adjacent to the bowknot, as shown in Fig. 2. There are several logical engineering reasons that this is the normal location of fracture:

- When the knot is tied, the lace is pulled tightest at the upper eyelets; therefore, the service stress is highest at this location.
- Most of the sliding motion during tightening occurs at the lace as it goes through the upper eyelets. Therefore, the metal eyelets tend to wear, or abrade, the fibers of the lace.

*Fig. 2  Normal location of fracture for a shoelace*
• Since the shoelace presumably has uniform mechanical properties along its length, it will eventually wear—and ultimately tear, or fracture—at the location where conditions are most severe, that is, at an upper eyelet.

If the shoelace were to fracture at any other location, such as at the lower eyelets or near the free ends, one would have to suspect that, for some reason, the shoelace had substandard mechanical properties at the location of failure. Or, alternatively, the lace could have been damaged, such as by burning from dropped cigarette ashes, thus causing it to be weakened and fractured at an abnormal location.

This familiar example of the normal location of fracture is easy to understand. The situation becomes considerably more complex in metal components that may have been manufactured—intentionally or unintentionally—with different mechanical properties at different locations in the part.

A metal part, however, can be expected to fail, or fracture, at any location where the stress first exceeds the strength, unlike the shoelace, which is expected to have uniform strength throughout its length and will fail at the location of greatest “wear and tear.” Metal parts fracture in a much more complex version of the weakest-link principle: the weakest location in a part will not originate a fracture if the stress is below the strength at that location. On the other hand, a high-strength location in a part may suffer fracture if the stress is concentrated at that location. The point is that stress and strength are inseparably intertwined and must be considered together.

Other locations of normal fracture in metal parts are at geometric stress concentrations, such as the first engaged thread of a bolt within a nut or other tapped hole, or at a sharp-cornered fillet in a rotating shaft, or at the root fillet of a gear tooth. These represent some of the normal locations of fatigue fractures that may occur after long service. Fractures caused by abnormal events, such as accidents, may occur at locations other than those noted because of the unpredictable forces in an accident. The insidious problem with notches is that they concentrate the stress at specific locations; thus, the metal strength at a given location may not be able to survive the geometrical form that concentrates the stress at that location, no matter how high the strength level.

Note: The above discussion is considerably oversimplified. It ignores the different types of stress and strength; however, it is intended to point out, in general terms, the principles involved.

Questions to Ask about Fractures

The broad spectrum of considerations in any fracture investigation can be grouped into ten general areas of inquiry that may be answered with
careful observation and study of a given fractured part. The sequence in which these interrelated areas are considered is unimportant; any one area may be the key in a particular situation. Some of the questions to ask and answer are:

1. **Surface of the Fracture**
   What is the fracture mode? The fracture surface can tell a story if enough careful attention is given to it in conjunction with other information to be learned. One must not make snap judgments about the fracture; all information must be evaluated before making a decision that is crucial. Examination of all regions of the part is necessary before this question can be answered.
   a. Is the origin (or origins) of the fracture visible? If so, is it (are they) located at the surface or below the surface? The location of the origin(s) depends on the relative stress and strength gradients, which are discussed in later chapters of this book.
   b. What is the relation of the fracture direction to the normal or expected fracture directions? The direction of a fracture usually has a specific relation to the direction of the stress that caused the fracture to occur.
   c. How many fracture origins are there? The answer concerns the relative magnitude of the actual stress to the actual strength of the part at the locations of failure.
   d. Is there evidence of corrosion, paint, plating, or some other foreign material on the fracture surface? This may indicate the presence of a preexisting crack, prior to fracture.
   e. Is the stress unidirectional, or is it reversed in direction? If the part is thought to be stressed in only one direction but the fracture indicates that it was stressed also in other directions, the assumed operation of the mechanism is not completely correct.

2. **Surface of the Part**
   a. What is the contact pattern on the surface of the part? This knowledge is extremely important because these “witness marks” of contact with the mating parts reveal how the part was loaded in service. These marks may be only slight polishing, or they may be severe wear or indentations from heavy contact with other parts of the assembly or from outside the assembly. The mating parts usually have corresponding indications of contact that should be matched. For example, rolling elements, such as balls, rollers, and needles in antifriction bearings, may leave indentations on the raceways that can aid in identifying the direction of the forces that caused the damage.
   b. Has the surface of the part been deformed by loading during service or by damage after fracture? The location and direction of deformation are very important in any examination of fractured parts.
The degree of deformation depends on the mechanical properties of the metal involved, as well as on the magnitude and type of force causing the deformation.

c. Is there evidence of damage on the surface of the part from manufacture, assembly, repair, or service? Tool marks, grinding damage, poor welding or plating, arc strikes, corrosion, wear, pitting fatigue, or fretting are possibilities. There are many ways in which the surface of the part can influence a fracture, because many fractures originate at the surface.

3. Geometry and Design
   a. Are there any stress concentrations related to the fracture? This refers to such common design features as fillets, oil holes or other holes, threads, keyways, splines, stamped identification marks, and any other intentional geometric notches.
   b. Is the part intended to be relatively rigid, or is it intended to be flexible, like a spring? The intent must be understood by the failure analyst.
   c. Does the part have a basically sound design? Occasionally, a part (or assembly) is found that seems to have been designed to fail: no amount of metallurgical help will be able to make it succeed. Parts of this type should have been recognized and corrected prior to serious problems, but occasionally this does not occur.
   d. How does the part—and its assembly—work? The function and operation must be thoroughly understood before analysis is undertaken.
   e. Is the part dimensionally correct? If possible, check the part against the drawing from which it was made, for it may be dimensionally inaccurate. If metal has been lost by wear or corrosion, however, dimensional checks may not be possible.

4. Manufacturing and Processing
   a. Are there internal discontinuities or stress concentrations that could cause a problem? All commercial metals contain microdiscontinuities that are unavoidable and are innocuous in normal service. However, a more serious problem that could interfere with normal service is a possibility.
   b. If it is a wrought metal, does it contain serious seams, inclusions, or forging problems, such as adiabatic overheating, end grain, laps, or other discontinuities, that could have had an effect on performance?
   c. If it is a casting, does it contain shrinkage cavities, cold shuts, gas porosity, or other discontinuities, particularly near the surface of the part? Frequently these are deep within the casting where the stress is often low, and they are harmless. However, machining may bring them near the final surface. Each case must be studied individually.
   d. If a weldment was involved, was the fracture through the weld itself or through the heat-affected zone in the parent metal adjacent
to the weld? If through the weld, were there problems such as gas porosity, undercutting, under-bead cracking, or lack of penetration? If through the heat-affected zone adjacent to the weld, how were the properties of the parent metal affected by the heat of welding?

e. If the part was heat treated, was the treatment properly performed? Many problems can be caused by inadequate heat treatment, including too shallow or too deep a case depth, excessive decarburization, very coarse grain size, overtempering, undertempering, and improper microstructure.

5. **Properties of the Material**
   a. Are the mechanical properties of the metal within the specified range and comparable to the typical properties of the metal, if this can be ascertained? If so, are the specifications proper for the application? The simplest mechanical property to measure is usually hardness; this test gives an approximation of tensile strength and is widely used for specification purposes. Measurement of other mechanical properties—tensile strength, yield strength, elongation, reduction of area, and modulus of elasticity—involves destructive testing and may not be possible in a fractured part.

   b. Are the physical properties of the metal proper for the application? These are considered to be physical constants, but they are critical in many applications. In some instances, such as close-fitting pistons and other precision parts, the coefficient of thermal expansion of both the piston and the cylinder is critical to the dimensions. Density, melting temperature, and thermal and electrical conductivity are other physical properties to be considered.

6. **Residual and Applied Stress Relationship**
   The residual stress system that was within the part prior to fracture can have a powerful effect—good or bad—on the performance of a part. Residual stresses cannot be determined by simple examination but may be deduced by an analyst familiar with residual stresses. See Chapter 4, “Residual Stresses,” in this book for information on how to deduce their pattern. Applied stresses are more obvious than residual stresses. The magnitudes of both are algebraically additive.

7. **Adjacent Parts**
   a. What was the influence of adjacent parts on the failed part? One must always be aware that the fractured part may not be the primary, or original, failure. It may be damaged because of malfunction of some other part in the assembly.

   b. Were fasteners tight? A loose fastener can put an abnormal load on another part, causing the other part to fail. In this case, the loose fastener is the primary failure, while the other part is damaged, or a secondary failure.
8. **Assembly**
   a. Is there evidence of misalignment of the assembly that could have had an effect on the fractured part?
   b. Is there evidence of inaccurate machining, forming, or accumulation of tolerances? These could cause interference and abnormal stresses in the part.
   c. Did the assembly deflect excessively under stress? Long, thin shafts under torsional and bending forces, as in a transmission, may deflect excessively during operation, causing poor contact on the gear teeth and resultant failure by fracture or pitting of the teeth.

9. **Service Conditions**
   This is a difficult area to investigate because people are involved, and people may become defensive. But it is extremely important to question the operator of a mechanism and other witnesses to a fracture or accident to determine if there were any unusual occurrences, such as strange noises, smells, fumes, or other happenings that could help explain the problem. Also, these questions should be considered:
   a. Is there evidence that the mechanism was overspeeded or overloaded? Every type of mechanism has a design capacity or rated load; if that limit is exceeded, problems frequently arise.
   b. Is there evidence that the mechanism was abused during service or used under conditions for which it was not intended?
   c. Did the mechanism or structure receive normal maintenance with the recommended materials? This is particularly important when lubricants are involved in the failure, because use of improper lubricants can be extremely damaging to certain mechanisms, as well as to the seals and gaskets that are intended to keep them from leaking.
   d. What is the general condition of the mechanism? If it is a candidate for the scrap pile, it is more likely to have problems than if it is relatively new.

10. **Environmental Reactions**
    Every part in every assembly in every mechanism has been exposed to several environments during its history. The reaction of those environments with the part is an extremely important factor that may be overlooked in failure analyses. The problems relating to the environment can arise anywhere in the history of the part: manufacturing, shipping, storage, assembly, maintenance, and service. None of these stages should be overlooked in a thorough investigation.
    a. What chemical reactions could have taken place with the part during its history? These include the many varieties of corrosion and possible exposure to hydrogen (such as during acid pickling, electroplating, and certain types of service). Hydrogen exposure can, under certain conditions, result in fracture due to hydrogen em-
brittlement or formation of blisters. Another situation sometimes encountered is stress-corrosion cracking, in which exposure to a critical corrosive environment can cause cracking while the surface of the part carries a tensile stress—applied and/or residual.

b. To what thermal conditions has the part been subjected during its existence? This can involve abnormally high temperatures, which may cause melting and/or heat treatment of a very small area of the surface. Such accidental and uncontrolled heat treatment can have disastrous results. Problems frequently arise as a result of localized electrical arcing, grinding damage, adhesive wear, or other instances where frictional heat is encountered. Similarly, relatively low temperatures for the metal can result in brittle fracture of normally ductile metals with no change in microstructure. Also, low temperatures may initiate uncontrolled phase changes that may cause such problems as the temperature-induced transformation of retained austenite to untempered martensite in steels.

Following study of the fractured part or parts with consideration of these questions—along with others that inevitably arise—it is necessary to reach a conclusion about the reason for the observed fracture. This involves formulating a hypothesis of the sequence of events that culminated in fracture, along with recommendations to prevent the observed type of fracture in the future. Occasionally this process is quite simple; more often it is frustratingly difficult. In either instance, the facts of the situation must be set forth, either orally or in a carefully written report to the appropriate persons. All pertinent information must be documented thoroughly with carefully prepared photographs and other records that should be retained for a number of years. If a similar situation arises in the future, the previous work will serve as a guide.

Summary

Failure analysis is an extremely complex subject and involves areas of mechanics, physics, metallurgy, chemistry and electrochemistry, manufacturing processes, stress analysis, design analysis, and fracture mechanics, to name a few specialties. Because it is nearly impossible for any one person to be an expert in all these fields, it is extremely important to be organized and to know when to seek help. In any situation, it is very important not to leap to conclusions, for a misstep can be extremely hazardous for all concerned.

REFERENCES

**SELECTED REFERENCES**

- *Case Histories in Failure Analysis*, American Society for Metals, 1979