Additional Information -

Techniques of Failure Analysis

When the problem of determining the cause of a failure and proposing corrective action must be faced, there is a definite procedure for conducting the failure analysis.[1] Often a failure analysis requires the efforts of a team, including experts in materials behavior, stress analysis and vibration, and modeling. Very sophisticated methods of analyzing the structure of materials are often employed. The sections that follow list the main steps in a major failure investigation. Space precludes going into much detail, but *ASM Handbook,* Vol. 11, *Failure Analysis and Prevention,* 2002 gives much valuable information, including many case studies and photographs of material microstructures and fracture surfaces. Many references to this valuable resource, which appear in the form (ASM, pp. xx), are given in the, discussion.

Inspect the Failure in the Field

The first approach is to inspect the site of the failure as soon as possible after the failure occurs. This site visit should be lavishly documented with photographs, for very soon the site will be cleared away and repair begun. Careful sketches and detailed notes help to orient the photographs and allow you to completely reconstruct the scene months or years later when you are in a design review or a courtroom.

41. Extensive information on conducting a failure analysis can be found in *ASM Handbook,* Vol 11: *Failure Analysis and Prevention,* 2002, pp. 315–556

The following critical pieces of information should be obtained during the field inspection (ASM, pp. 315–42).

- Location of all broken pieces relative to each other.
- Interview any witnesses, as well as operations and maintenance people, to learn about the history of failures for the equipment or component.
- Determine the orientation and magnitude of the forces that caused the failure.
- Observe the presence of any obvious material defects, stress concentrations, corrosion, oxidation, or wear.
- Whenever possible, samples should be obtained from identical material or components that did not fail. Samples of process fluids, and lubricants should be obtained for corrosion-related failures. Be sure to label all pieces and key their identification to your notes.
- Great care should be exercised in preserving the fracture surface. Never touch the fractured surfaces, and do not attempt to fit them back together.

Background History and Information

A complete case history on the component that failed should be developed as soon as possible. Ideally, most of this information should be obtained before making the site visit, since more intelligent questions and observations will result. The following is a list of data that need to be assembled.

- Name of item, identifying numbers, owner, user, manufacturer or fabricator
- Function of item
- Data on service history, including inspection of operating logs and records
- Documentation on materials used in the failed component
- Information on manufacturing and fabrication methods used, including any codes or standards that must be adhered to
- Documentation on inspection standards and techniques that were applied
- Date and time of failure; temperature and environmental conditions
- Documentation on design standards and calculations performed in the design
- A set of shop drawings, including any modifications made to the design during manufacturing or installation

Detailed Examination of the Failure

A detailed examination of the failed component should be done in the laboratory to determine the root case of the failure (ASM, pp. 351–70). Typically this starts with a thorough examination at the macro level, from 1× to 100×, to observe the gross features of the fracture, the presence or absence of cracks, the presence of any gross defects, and the presence of corrosion or oxidation. Next, microscopic examination with the optical microscope, up to 1000×, and the scanning electron microscope (SEM) from 10× to 100,000× are conducted.

Metallographic examination with the optical microscope requires a small section of material to be cut out, mounted, polished, and etched (ASM, pp. 498–515). This type of examination is used to determine the microstructure of the material. The presence, size, and arrangement of phases is important documentation of the thermal and mechanical history of the metal. Microstructural analysis will identify such structural features as grain size, inclusion size, and distribution of second phases. The technique also can be used to follow crack growth through the microstructure. For example, it can be used to determine whether a crack propagates in a transgranular or intergranular manner, whether a hard brittle phase cracks to initiate the fracture, or whether some microconstituent serves to impede crack propagation.

The scanning electron microscope (SEM) examines the actual surface of the fracture with a beam of electrons in an evacuated chamber (typically 1 by 2 by 5 in.). A back-scattered image is recorded on an electronic display. Magnifications from 1000× to 40,000× are routinely available. The image has great depth of field and a three-dimensional character. This makes SEM outstandingly useful for the examination of fractures (ASM, pp. 516–526). The crack propagation associated with a particular fracture mode leaves a characteristic appearance on the fracture surface. These *fractographs* are directly revealed by the SEM and provide an identification of the fracture mode mode.[2]

Examination of fractures with the SEM has had a major influence on the engineer's ability to clearly identify the mode of failure, and thus find the root cause of a failure. In the hands of an experienced practitioner, fractography can determine whether the material was used above its design stress or whether it had critical defects that caused the failure.[3]

Each mode of fracture has different mechanisms that lead to a different fracture appearance. These are described in considerable detail in *ASM Handbook,* Vol.11, *Failure Analysis and Prevention,* 2002.

- Ductile and brittle fracture in metals — pp. 587–626; 671–99
- Fatigue fracture — pp. 627–40; 700–727
- Intergranular fracture — pp. 641–49
- Creep and stress rupture — pp. 728–37
- Corrosion-related fracture — pp. 749–898
- Wear-related fracture — pp. 901–1043
- Fracture of plastics — pp. 650–6l
- Fracture of ceramics — pp. 662–70

Other sophisticated observations in addition to microscopy of the fracture surface often are helpful in fracture analysis. Chemical analysis on a micro scale is required to determine the composition of surface layers, precipitates, segregated regions, etc. (ASM, pp. 429–459). This often employs techniques that are based on bombarding the surface to be studied with protons, x-rays, ions, or electrons and analyzing the radia-

2. An extensive collection of fractographs has been assembled in *Metals Handbook,* 9th ed., Vol. 12, Fractography, 1987.
3. W.T. Becker and S. Lampman, "Fracture Appearance and Mechanisms of Deformation and Fracture," *ASM Handbook,* Vol. 11, pp. 559–86, 2002.

tion that is either emitted or reflected from the surface (ASM, pp. 526–37). The most common methods are Auger electron spectroscopy (AES), photoelectron spectroscopy (XPS), and time-of-flight secondary ion mass spectroscopy (TOF-SIMS). Chemical characterization of a surface by energy dispersive spectroscopy (EDS) is commonly used because it is a module often integrated with a scanning electron microscope.

X-ray diffraction techniques also may be useful in fracture analysis. X-ray methods can be used for the qualitative and quantitative identification of phases, the determination of crystallographic orientation, the characterization of texture or preferred orientation, and the measurement of residual stresses (ASM, pp. 484–97).

Additional Types of Analysis

A failure analysis investigation does not just involve a study of the material. It is also concerned with a review of the technical analysis made in the product design. Because determination of stresses is an important consideration, FEA is often part of the investigation (ASM, pp. 380–389). For example, a materials investigation might find that failure was due to the propagation of a fatigue crack that initiated at the root of a screw thread that was machined into the part. This is important information about the mechanism of failure, but it is not necessarily the root cause. We need a design analysis to determine what led to the fatigue condition.

The design review might conclude that no stress analysis was performed and the strength of the part was not adequate for the intended use. The solution is to do a proper analysis in a redesign. The review could also find that an error had been made in the original design and this needs to be corrected by redesign. However, the review might find no fault with the original design analysis and suggest that the original analysis underestimated the actual applied loads, or that unanticipated loading conditions occurred. Here, FEA can be used to great advantage in failure analysis. Starting with the known mechanical properties of the material, a FEA model can be run under a variety of loading conditions until the loads are found that will cause failure. Then further study may give clues that can rule out one or more of the overload hypotheses. For example, more detailed metallurgical analysis might find corrosion pits in the root of the screw threads, indicating that a gasket intended to keep out water intrusion had failed to perform its function.

Other types of modeling that might be done in failure analysis are dynamic simulations, as in motor vehicle accident reconstruction, aircraft flight simulation, and virtual reality simulations.

A Process for Finding Root Causes and Corrective Actions

The critical step is assembling the facts and pieces of data into a coherent picture of the root cause of the failure. The goal should be: to objectively identify all possible root causes.[4]

4. D.P. Dennies, "Organization of a Failure Analysis," *ASM Handbook,* Vol. 11, ASM International, Materials Park, OH, pp. 324–332, 2002.

- This can be assisted with a fault tree diagram (ASM, pp.56-58) or a why-why diagram (Sec. 4.7). Use brainstorming to ask why,why,why, being careful that you arrange the possible causes in proper hierarchical order from the most general at the top to the least general at the bottom.
- Next, objectively evaluate the likelihood of each root cause. To do this use a Failure Mode Assessment (FMA) chart. Use a spreadsheet with five columns labeled: (1) Potential root cause; (2) Probability, on the scale Likely, Possible, Not likely; (3) Priority, 1 top priority to 3 least; (4) Rationale for the probability rating, and (5) Technical Plan for Resolution. Column (4) is a written justification for the probability rating of the likelihood of the cause being a root cause. Column (5) briefly lists the actions that will be taken, such as testing or computer modeling, to decide whether each possible root cause should be considered further.
- This step develops the Technical Plan for Resolution (TPR). The TPR is a spreadsheet that takes the actions listed in column (5) of the FMA and develops them into a detailed roadmap of the work needed to prove or disprove each cause. The TPR spreadsheet has six columns: (1) Potential root cause, (2) Priority, (3) Technical approach to resolution, (4) Who in the organization will take on the assignment, (5) Completion date for assignment, and (6) Results.

The technical approach to resolution can take the form of testing or analysis of failed components or of similar components to demonstrate that the failure mode is possible. It may involve detailed analysis of operational data, stress analyses, literature searches, or contacts with consultants and other companies that might have a similar problem.

Early in the failure analysis process it is common to develop a hypothesis of the root cause. All data should be cross-checked against the hypothesis, and any contradictions should be run down and either confirmed or discarded as spurious. The process outlined above is a great help in making this happen. The results column (6) in the TPR is the place where affirmations and contradictions are recorded. When firm contradictions exist, they require refining the hypothesis until gradually all pieces fit together. An experienced failure analyst not only considers the available data but will also take note of the absence of features that experience suggests should be present. It is common for a failure to be caused by more than one root cause. Therefore, developing a defensible hypothesis usually is not a straightforward procedure.

If the failure analysis is initiated to provide support for a legal case for a product liability suit (see Sec. 17.6), then finding a well-documented root cause represents an achieved goal. However, if the failure analysis has been undertaken to redesign and improve a product, then the task is not finished with the root cause analysis. Now the analysis turns to determining the corrective action(s) that will prevent failure from occurring again.

The process for finding corrective actions is the same as that used to find root causes, only now we focus on finding the corrective actions to prevent the failure from occurring again.

- Brainstorm and use the results to create a How-How diagram or corrective action tree.
- Assess the probability of achieving each corrective action with a Corrective Action Assessment (CAA) chart.

- Use one of the concept evaluation methods from Chap.7 to evaluate the likely effectiveness of the highest ranking CAs.

Report of Failure Analysis

The report of the analysis of a failure is one of the most difficult written technical communications because a failure is often a matter of great sensitivity that may be fraught with legal implications. The best procedure is to stick to the hard facts, refrain from conjecture, and keep the technical jargon to a minimum.