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17 FAILURE ANALYSIS

17·1 Introduction When one considers the many millions of metallic parts that are fabricated and placed in service, it is not unusual that some will fail prematurely. Simply from a statistical viewpoint it is not reasonable, with present engineering practice, to expect no failures. However, even though the number of failures of a particular component may be small, they are important because they may affect the manufacturer's reputation for reliability. In some cases, particularly when the failure results in personal injury or death, it will lead to expensive lawsuits. It is not unusual for automotive manufacturers under prodding and publicity from consumer watchdogs to recall millions of cars to correct a design or heat-treating defect even though the actual number of failures was very small.

The purpose of this chapter is to briefly explain the basic causes for metal failure and to illustrate some of the failures by case histories. Most of the illustrations in this chapter were taken from two excellent books on metal failure—"How Components Fail" by Donald J. Wulpi (American Society for Metals, 1966) and "Why Metals Fail" by R. D. Barer and B. F. Peters (Gordon and Breach Science Publishers, 1970).

17·2 Procedure In any failure analysis it is important to get as much information as possible from the failed part itself along with an investigation of the conditions at the time of failure. Some of the questions to be asked are:

1. How long was the part in service?
2. What was the nature of the stresses at the time of failure?
3. Was the part subjected to an overload?
4. Was the part properly installed?
5. Was it subjected to service abuse?
6. Were there any changes in the environment?
7. Was the part properly maintained?

A study of the fractured surface should answer the following questions:

1. Was the fracture ductile, brittle, or a combination of the two?
2. Did failure start at or below the surface?

3. Did the failure start at one point, or did it originate at several points?
4. Did the crack start recently or had it been growing for a long time?

It should be apparent that no suitable solution may be prescribed unless information regarding how the part performed and failed is available.

Laboratory and field testing permit the evaluation of the effects of material, design, and fabrication variables on performance of the part under controlled conditions. Failure analysis, on the other hand, is concerned with parts returned from service and thus gives results of actual operating conditions. By combining the information from tests with the results from analysis, a clear picture of the causes of failure can be obtained. Rarely are failures assigned to a single cause. Usually they result from the combined effects of two or more factors that are deterimental to the life of the part or structure.

When studying a failure, care must be used to avoid destroying important evidence. Detailed studies usually require documentation of the service history (time, temperature, loading, environment, etc.) along with chemical analysis, photomicrographs, and the like. Further study of the sequence of events leading up to the failure, plus knowledge of the location, markings, and condition of all adjacent parts at the time of failure, is necessary to confirm analysis. There always exists the possibility of unforeseen loading, unreported collision, or unanticipated vibration that may have contributed to premature failure.

The procedure for investigating a failure covers four areas as follows:

1 Initial observations. A detailed visual study of the actual component that failed should be made as soon after the failure as possible. Record all details by many photographs for later review. Interpretation must be made of deformation markings, fracture appearance, deterioration, contaminants, and other factors.

2 Background data. Collect all available data concerned with specifications and drawings, component design, fabrication, repairs, maintenance, and service use.

3 Laboratory studies. Verify that the chemical composition of the material is within specified limits. Check dimensions and properties of the component. Supplementary tests may be made as needed—for example, hardness and determination of microstructure to check heat treatment, nondestructive tests to check for processing defects or existing cracks, composition of corrosion products, a free-bend test to check ductility, etc. Very often, examination of a fracture surface with a low-power binocular microscope can reveal the type and cause of failure.

4 Synthesis of failure. Study all the facts and evidence, both positive and negative, and answers to the typical questions given earlier. This, combined with theoretical analysis, should indicate a solution to the problem of failure.

Extensive studies of carburized and hardened gears for heavy-duty trucks, machine tools, mining machines, diesel engines, etc. showed that 38 percent of the failures resulted from surface problems (pitting, spalling, crushing, and scoring), 24 percent from bending fatigue, 15 percent from impact, and 23 percent from miscellaneous causes. From a detailed analysis of

failures by steel companies, auto manufacturers, and electrical equipment manufacturers, nearly 50 percent of all failures can be attributed to faulty design, the rest being distributed between production and service problems.

17·3 Modes of Fracture As was pointed out earlier, proper analysis of the fracture often yields much information on the contributing factors and helps to identify the type of failure. Ductile and brittle fractures were discussed in Sec. 3·7, but it will be useful to review the fracture modes.

Ductile fractures are the result of shear forces that produce plastic deformation (slip or twinning) along certain crystallographic planes, whereas brittle fractures are due to tensile forces that produce cleavage. In most fractures, both types are present in varying degrees. Identification of the basic mechanism often determines the type of load that initiated fracture. By the same token, a knowledge of load application can help in determining whether a particular failure was ductile (shear) or brittle (cleavage) in nature.

Figure 17·1 shows two bolts pulled to fracture in tension to illustrate ductile and brittle behavior. The one on the right was soft (Rockwell C 15); it failed in a ductile manner by shear, resulting in extensive plastic deformation. The bolt on the left was relatively hard (Rockwell C 57) and failed in a brittle fashion, with no apparent plastic flow. Shear fractures caused by a single load are dull gray and fibrous, with edges which are usually deformed plastically. Small cavities are initially formed by slip. They join together and eventually grow to form a crack under continued loading. The crack spreads with the aid of stress concentration at the tip of the crack, generally moving perpendicular to the tensile force and eventually forming a "shear lip" at the surface (see Fig. 3·14).

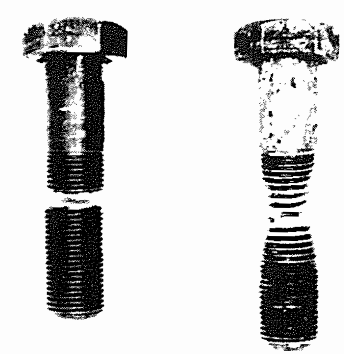

Fig. 17·1 Two bolts intentionally pulled to failure in tension to demonstrate brittle and ductile behavior. The brittle bolt, left, was hard, Rockwell C 57; the ductile bolt was soft, Rockwell C 15. (Courtesy of D. J. Wulpi, International Harvester Company.)

Brittle (cleavage) fractures generally appear bright and crystalline. Each crystal tends to fracture on a single cleavage plane, and this plane varies only slightly from one crystal to the next in the aggregate. For this reason it follows that a cleavage fracture *in* a polycrystalline specimen will generally sparkle in the light when rotated in the hand. Surfaces of brittle fractures sometimes have distinctive appearances. From the origin of fracture, a characteristic "chevron" or "herringbone" pattern is formed which points to the fracture origin (Fig. 17·2). Since (as pointed out in Chap. 3) slip and cleavage occur on a different set of crystallographic planes, the nature of individual fractures can often be determined by metallographic examination in the laboratory.

Fractures are rarely either cleavage or shear. The variable stresses that usually exist in a structure, the changing of stress patterns during the progress of fracture, or the microscopic differences in orientation of grains produce fractures composed of both shear and cleavage areas. Consideration of combinations of fracture modes can often give information regarding the nature of the fracture. Figure 17·3 shows three samples of the same material as they reacted to notched-impact tests at different temperatures. On the left, the fracture surface is mainly dull gray and fibrous; the edges are curved, indicating plastic deformation, so that the fracture mode is mostly shear. In the center the mode was mixed shear and cleavage, since the surface is both shiny and dull with some evidence of plastic deformation at the edges. The fracture on the right is by cleavage alone.

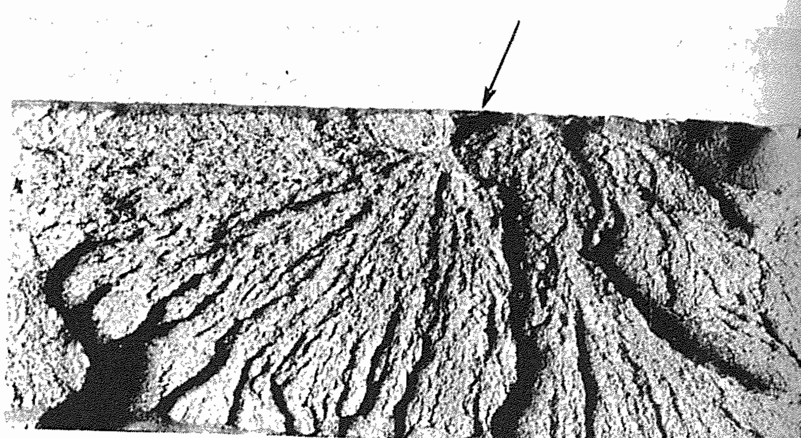

Fig. 17·2 "Chevron" pattern points to the origin of the brittle fracture (arrow) in this specimen. A fatigue fracture is also apparent in the upper right-hand corner. (Courtesy of D. J. Wulpi, International Harvester Company.)

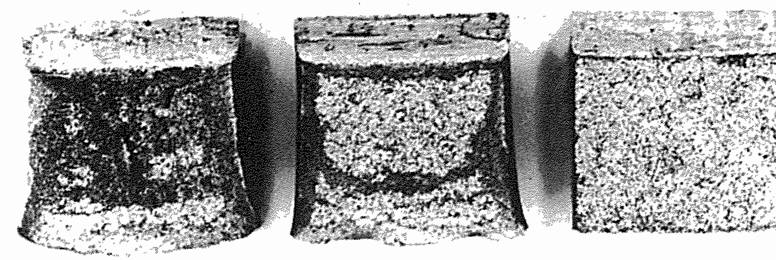

Fig. 17·3 Combinations of fracture modes are shown by fracture surfaces of three impact test specimens which were broken at different temperatures. On the left, fracture is mostly shear; in the center, combined shear and cleavage; and on the right, cleavage. (Courtesy of D. J. Wulpi, International Harvester Company.)

The entire surface is bright and the edges are straight, showing no evidence of plastic deformation.

17·4 Stress and Strength The solution to failure problems resulting from overstressing of parts depends on the determination of two factors: the stress on the part and the strength required to support that stress. Depending on the type of load and the geometry of the part, there may be simple axial stress or a complex system of multiaxial stresses. The total stress can include internal residual stresses from fabrication or heat treatment as well as stresses from external loads.

The basic stresses in a part under external load were discussed in Sec. 3·2. The most important are the normal stresses (those perpendicular to the plane of the cross section) and shear stresses (those in the plane of the cross section). Normal stresses tend to produce separation, while shear stresses tend to produce plastic flow. It was pointed out that the maximum shear stress occurs at a 45° angle to the initiating tensile stress. When a part is under load, yielding will occur when the shear stress is greater than the shear yield strength; ductile or shear fractures develop when the shear strength is overcome by the shear stress; and brittle fractures occur when the tensile (cohesive) strength is exceeded by the tensile stress.

Consideration should be given to the significant stresses when investigating a particular mode of failure. For example, if failure is due to a fatigue fracture at a gear tooth root, the significant stress would be the repeated bending stress at that location. Contact stress acting on the gear face would not be significant in this case. For a pitting or wear-type failure of the gear tooth, the reverse would be true.

17·5 Types of Loading In many cases, the type of load is a contributing factor to failure. There are essentially five types of loads illustrated in Table 17·1—