METALLURGICAL FAILURE ANALYSIS—WHAT, WHY AND HOW

by

Edward L. Creamer

Engineering Advisor

Engineering Construction and Services

Shell Oil Company

Houston, Texas

Edward L. Creamer is an Engineering Advisor in Engineering Construction and Services in Shell Oil Company's head office in Houston, Texas. Prior to joining the head office staff in 1980, he spent 24 years on several applied metallurgy assignments at Shell's laboratories. In his present assignment, he provides metallurgical guidance to the oil refining and petrochemical manufacturing functions of the company. He is also active in staff training programs.

Mr. Creamer has a B.S. degree from the University of Missouri-Rolla (formerly Missouri School of Mines) and an M.S. degree from Washington University (St. Louis). He holds memberships in ASM, NACE, and ASME. He is also a member of the ASTM/ASME/MPC Joint Committee J-1 on the Effects of Temperature on the Properties of Metals and its Chemical and Petroleum Panel.

ABSTRACT

When capital expenditures are made for plant equipment, it is routine to anticipate that this equipment will meet reliability and performance expectations and will not experience untimely failure. Being realistic, however, it must be acknowledged that unanticipated equipment failures can and do occur and for a variety of reasons. These events are commonly both costly and disruptive to plant operations and may also have safety implications.

To minimize the frequency and severity of such failures, it is necessary for personnel who have equipment responsibility to understand the failures and to confront their causes. One tool used widely for this purpose is the metallurgical failure analysis, which is explored here in terms of WHAT it is, and WHY it is undertaken and HOW it is executed. The development of the subject includes some metallurgical background information. In defining and describing various damage and failure mechanisms, such as brittle fracture, fatigue, creep, corrosion, erosion, and sulfide cracking, actual field experiences are utilized.

Dual objectives of an in-depth treatment of the metallurgical failure analysis are (1) exposing involved personnel to the numerous modes of equipment damage and failure and (2) achieving improved plant reliability through increased awareness of the causes of failure and the means of prevention.

INTRODUCTION

When commitments are made for major capital outlays for plant equipment, there is a common expectation that this equipment will operate in accordance with applicable performance specifications and will demonstrate an acceptable reliability level. Implicit in this expectation is a pride of ownership and a view that the equipment will operate in a safe and satisfactory manner for a period of time consistent with the design life premises. While long duration, trouble-free performance is, of course, an almost universal goal of owners and operators of such equipment, it is not always possible to achieve this objective. For a variety of reasons, often complex and intertwined, equipment failures occur.

In attempting to prevent failures and to minimize the severity and consequences of those which do occur, it is necessary for causes and contributing factors to be both identified and understood by those having responsibility for equipment integrity. Perhaps the most widely employed approach for accomplishing these tasks is the metallurgical failure analysis. To help place the metallurgical failure analysis in perspective, it is described in terms of WHAT it is, and is not, WHY it is undertaken, and HOW it is executed.

THE METALLURGICAL FAILURE ANALYSIS

What

The metallurgical failure analysis can be defined as a scientifically based systematic laboratory examination of metallurgical evidence and the gathering of background information related to an equipment failure. This leads to establishing the cause of the failure. Because the approach to the failure analysis is usually determined by the nature of the failure, all analyses do not require the same procedure. Laboratory procedures focus on the failed equipment itself and most commonly consist of general and detailed macrophotography, metallographic examination, chemical analysis of the failed part and of any extraneous or foreign materials present, mechanical property determinations, fractographic examination, and others.

Though sometimes not included in the metallurgical failure analysis definition, the gathering of pertinent background information must be regarded as a vital portion of the analysis. Typical useful information that may surface in the collection of background includes: 1) full description of equipment, 2) name of manufacturer, 3) description of service, including any prior service different from the current application, 4) materials of construction, including material specifications and mill test reports, 5) information concerning the failure incident obtained from operations personnel, 6) prior instances of damage or failure, and 7) knowledge concerning performance of equivalent equipment operating elsewhere. By integrating the factual information obtained from the laboratory analysis with the pertinent background information, the metallurgist should be in a position to establish the cause of failure with reasonable certainty. When a systematic approach to metallurgical failure analysis is not employed, there is a greatly increased risk that the exercise will degenerate into an expensive, aimless groping procedure leading, perhaps, to a number of possible explanations, but not likely to a precise conclusion as to the cause of the failure.

Why

Although the primary reason (determining the cause of failure) for undertaking a metallurgical failure analysis initially may appear obvious, specific circumstances can influence motives. For example, in the simplest case after a failure has occurred in an item of expensive equipment, it is normal for the owner to seek to establish the cause so that corrective action can be taken and a repetition avoided. However, if the equipment were under warranty at the time of failure, the results of the metallurgical failure analysis could be expected to assist in establishing responsibility. In such instances, cooperative efforts in requesting and executing a metallurgical failure analysis are common and sometimes involvement of a third party is appropriate.

In the case of some failures, particularly if they have resulted in serious damage or injury or are technically complex or controversial, the metallurgical failure analysis is undertaken to provide a basis for legal action. Occasionally, however, a metallurgical failure analysis may be performed simply to satisfy technical curiosity or to serve an educational purpose.

How

In describing how the metallurgical failure analysis is accomplished, it is helpful first to review several basic metallurgical fundamentals and to provide illustrations of actual field failures and the steps taken to identify them.

When a metal is cast by pouring it in its liquid form into a mold and then allowing it to cool and solidify, it possesses certain physical properties (density, thermal expansion characteristics, thermal conductivity, etc.) and mechanical properties (tensile strength, yield strength, ductility, impact resistance, etc.). While the physical properties for the material are established, the mechanical properties are subject to significant alteration through manufacturing procedures, such as hot working, cold working, and heat treating. Metallurgists and

design engineers arrive jointly at the desired level of mechanical properties for an item of equipment. Items considered are: 1) yield strength level to prevent deformation (yielding) of components when stressed in service; 2) tensile strength level well above the yield strength, denoting satisfactory ductility; 3) strength low enough to avoid susceptibility to certain types of environmentally assisted cracking; 4) high ductility, consistent with strength requirements; 5) level of impact resistance at all anticipated testing and service temperatures consistent with the avoidance of brittle fracture; 6) fatigue strength level compatible with the level of cyclic loading anticipated; and 7) creep and rupture strengths compatible with high temperature design requirements.

In the light of these characteristics and material properties, it is to be recognized that opportunities exist for equipment to fail when subjected to conditions which exceed the capabilities and properties of the materials of construction. It is also not uncommon for field failures to result from the action of several mechanisms acting in combination.

To illustrate how metallurgical failure analyses are performed, several examples of failure resulting from various causes are described:

Tensile Overstress—Failures resulting from overloading in tension usually result in relatively simple fractures. In a ductile material, the failure is normally a shear fracture and is accompanied by plastic deformation in the failure zone (Figure 1). In a material with very limited ductility, the fracture is accompanied by little, if any, deformation (Figure 2). When examining a metallographic cross section from a ductile tensile overstress failure, the metallurgist normally detects severe localized distortion of the microstructure and a ragged fracture surface where ductility is lacking. Factors expected to be absent in a simple tensile overstress failure are multiple cracks, intergranular cracking, crack networks and/or evidence of enviromentally assisted cracking.
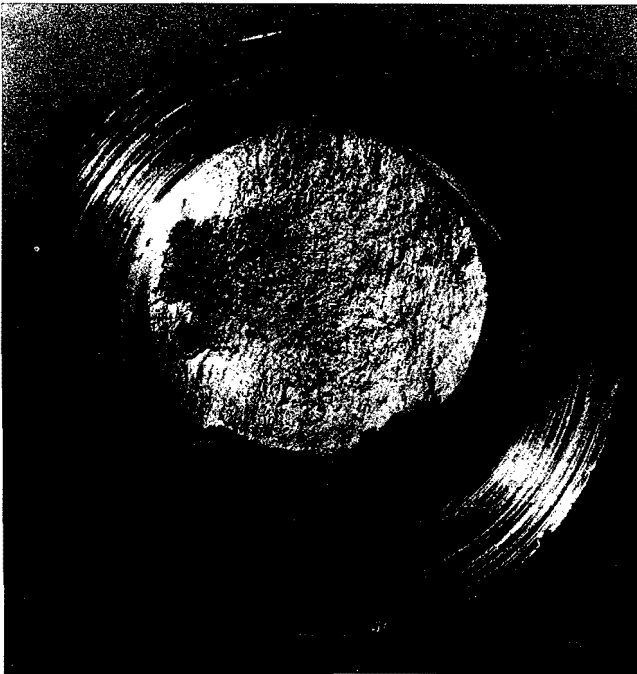

Figure 1. Ductile Fracture in Carbon Steel Resulting from Tension Overstress.

Figure 2. Low Ductility Fracture in Cast Hastelloy C Bolt Resulting from Tension Overstress.

Torsional Overstress—When a component, such as a pump shaft, is overloaded in torsion, a torsional overstress failure occurs (Figure 3).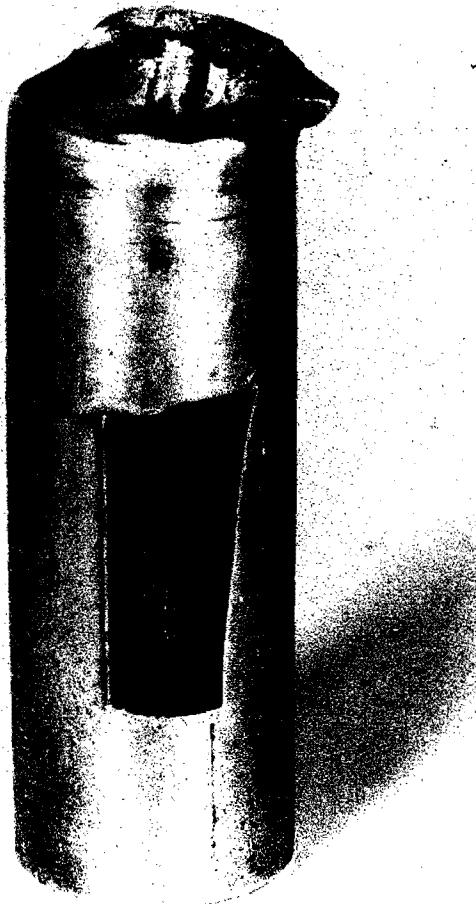 The characteristic appearance of the fracture is of vital importance in identifying the torsional overstress failure. In this example, further evidence of torsional overstress is found in the deformation of the rectangular section machined into the shaft surface.

Brittle Fracture—When a brittle material experiences impact loading in the presence of a notch, a low energy brittle fracture can result (Figure 4). This type of failure can be especially serious because of the potential for releasing large quantities of the contained liquid or gaseous material. Microstructurally, brittle fractures are usually characterized by rough, transgranular fracture surfaces, sometimes exhibiting small secondary cracks (Figure 5). In diagnosing a brittle fracture, it is appropriate to examine not only the failed component for symptomatic evidence, but also to determine the brittle fracture susceptibility of the material by mechanical testing.

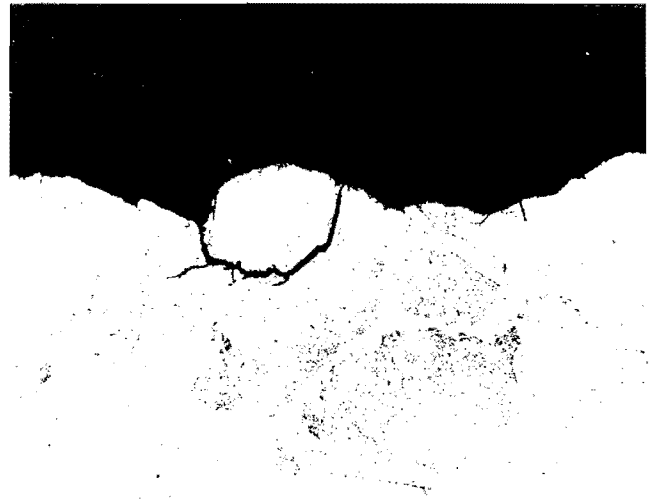Figure 3. Torsional Overstress Failure in Carbon Steel Pump Shaft.

Figure 5. Section of Brittle Fracture Surface in a Medium Carbon Steel (Etchant: 2 percent Nital).

Figure 4. Brittle Fracture in 12 percent Cr Steel Casting.

Creep Rupture—When a material is exposed to stress and elevated temperatures for an extended period of time, deformation (creep) can be expected to occur. The rate at which creep occurs is dependent upon the strength of the material, the stress imposed, and the temperature. If the creep process continues unabated, rupture will occur eventually. Although, theoretically, this form of failure can occur in any stressed high temperature component, it is probably more frequently encountered in process heater and boiler tubes. Long-term creep rupture failures are usually accompanied by less overall deformation than is normally observed in a short-term high temperature tensile overstress failure (Figures 6 and 7).

In metallographic examination, metal that has failed in creep rupture exhibits little or no individual grain deformation in the microstructure. However, microvoids and microcracks are normally present and are in the greatest concentration nearest the rupture itself (Figure 8). By contrast, the microstructure in the rupture zone of a tube failure occurring at high temperature, with short-term tensile overstress, shows no microcracking but extensive grain deformation (Figure 9).

Figure 6. Creep Rupture Failure in Heater Tube.

Figure 8. Microstructure of Heater Tube at Site of Creep Rupture Failure (Etchant: Vilella's Reagent).

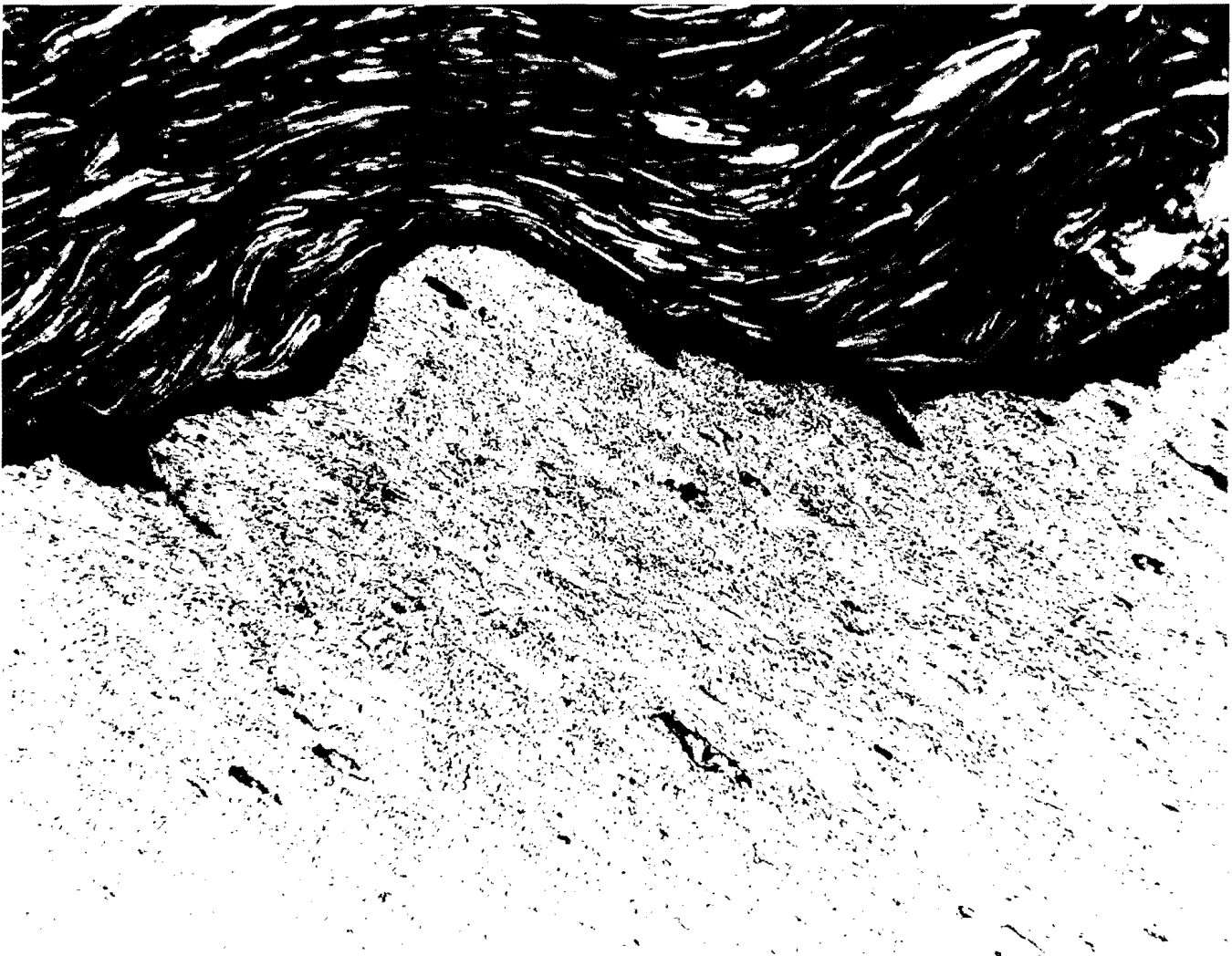*Figure 7. Short-Term High Temperature Tensile Overstress Failure in Boiler Tube.*

Figure 9. Microstructure of Heater Tube at Site of Short-Term High Temperature Tensile Overstress Failure (Etchant: Vilella's Reagent).

Fatigue—Fatigue failures are fractures resulting from the repeated imposition of a stress at a level lower than the yield strength of the material. Because of the very large number of stress cycles normally experienced by components in rotating mechanical equipment, fatigue failures are not uncommon in these applications.

Fatigue failures usually exhibit both characteristic macroscopic and microscopic features. The appearance of a fracture surface in a shaft failed by fatigue (Figure 10) shows an extensive pattern of wave-like lines which reflect the cyclic nature of the loading that has occurred. After the fracture propagates by fatigue to a point at which the remaining intact section can no longer sustain the load, the fracture progresses to completion in either a ductile or brittle fashion, depending upon the properties and condition of the material. Metallographically, fatigue cracks are usually single rather than branched or filamentous and they often exhibit a step-wise appearance signifying several changes in direction (Figure 11). In scanning electron microscopic examinations of the fracture surfaces of fatigue failures, characteristic striations denoting cyclic stress are normally found (Figure 12). Fatigue cracks can occur in a wide variety of components, for example, a turbine blade (Figure 13), and a turbine hub, in this case drilled to arrest the cracks (Figure 14).
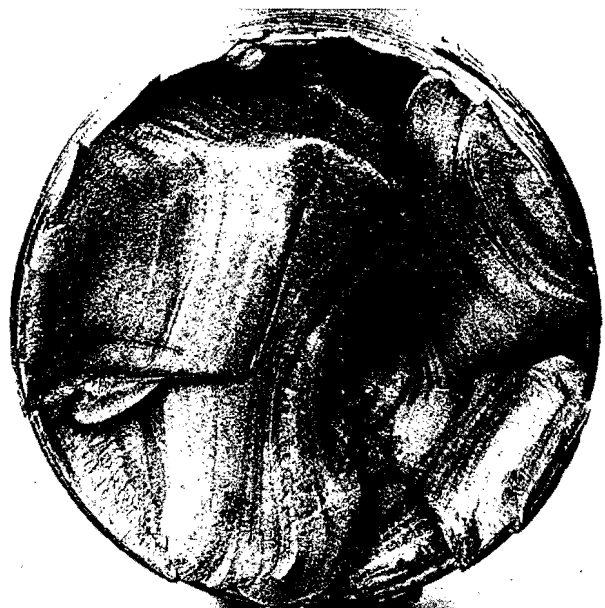

Figure 10. Fracture Surface of Pump Shaft Failed in Fatigue.

Figure 11. Characteristic Appearance of Cracks in Pump Shaft Failed in Fatigue (Etchant: 2 percent Nital).

Figure 12. Characteristic Striations on Fracture Surface of Component Failed in Fatigue (Scanning Electron Micrograph).
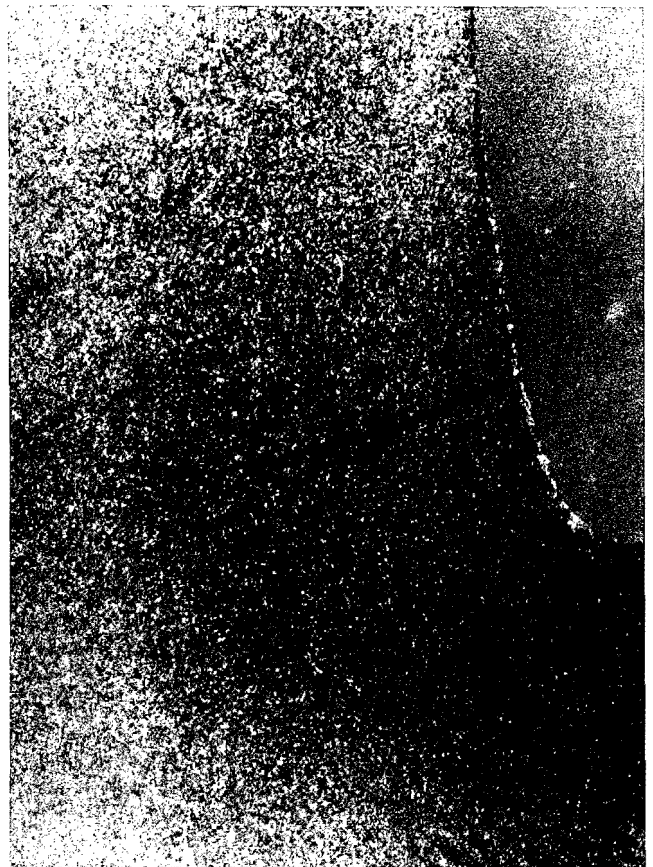

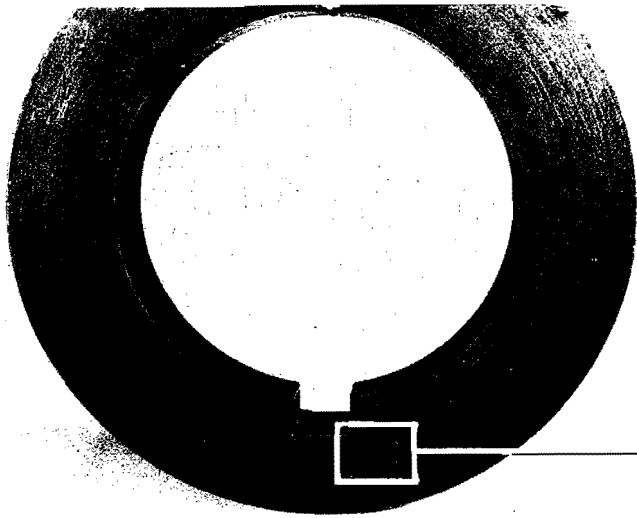*Figure 13. Fatigue Crack in Erosion-Thinned Turbine Blade.*

Figure 14. Section of Turbine Hub Cracked by Fatigue at Keyway Corners. The drilled holes are intended to prevent the propagation of the cracks.

Corrosion—Broadly defined, corrosion is a destructive process in which a metal losses its useful properties because it has reacted chemically with one or more components in its environment. Corrosion damage may exist in a variety of forms, such as the general attack of a corrosion-susceptible alloy (Figure 15), pitting (Figure 16), high temperature nonaqueous forms and often other more complex forms.

When mechanisms (more than one) act jointly to produce failure in a metal, the diagnostic process can be expected to become more complex. Some examples of failures by mechanism combinations are:

Erosion/Fatigue—Erosion of a turbine blade by solid particles entraind in a gas stream eventually led to a degree of metal loss which altered its geometry significantly. One result of this damage was the increased stress level in the thinned

Figure 16. Section of Austenitic Stainless Steel Tube Wall Severely Damaged by Pitting (Etchant: 10 percent Chromic Acid, Electrolytic).

portion of the blade and the subsequent initiation and propagation of a fatigue crack (Figure 13). If the erosion damage had not occurred, there was no reason to suspect that a fatigue failure was likely.

Corrosion/Fatigue—When conditions which promote fatigue exist in the presence of a medium which is corrosive to the metal involved, the susceptibility to failure normally increases significantly. For example, a steel component subjected to cyclic stress, while immersed in salt water, is more

Figure 15. Severely Corroded Pipe Section Containing Four Uncorroded Welded Nozzles of a Corrosion-Resistant Alloy.

susceptible to fatigue failure than if it were exposed to dry air only.

Stress Corrosion Cracking—When a susceptible material, such as an austenitic stainless steel, is subjected to residual or applied stress in the presence of a suitable corrosive medium, such as an aqueous chloride solution, failure by stress corrosion cracking can occur. Damage by this complex mechanism is usually severe. The cracking may be widespread, both macroscopically (Figure 17) and microscopically (Figure 18).
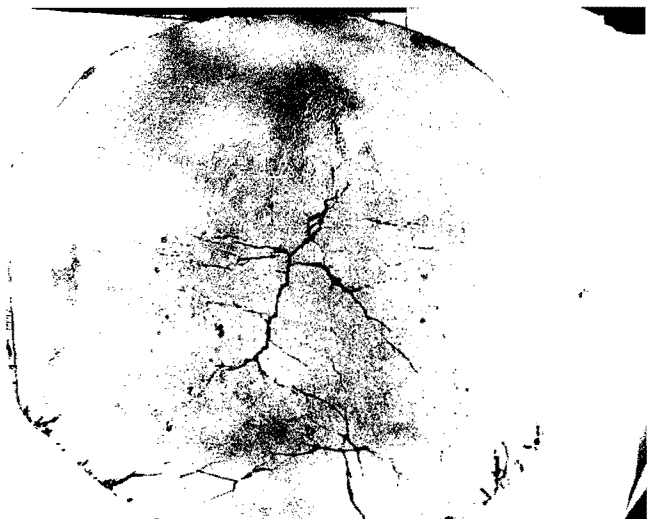

Figure 17. Chloride Stress Corrosion Cracking in Austenitic Stainless Steel Vessel Plate.

Figure 18. Section of Austenitic Stainless Steel Vessel Section Damaged by Severe Chloride Stress Corrosion Cracking (Etchant: Glyceregia).

Sulfide Corrosion Cracking—When steels are contacted by aqueous hydrogen sulfide, the resulting corrosion reaction produces atomic hydrogen. Some of this hydrogen diffuses into the steel and can result in a failure, depending upon the strength of the steel and the stress level present. Although this failure mechanism is termed sulfide corrosion cracking and sometimes sulfide stress cracking or other similar terms, the mechanism actually depends upon the presence of atomic hydrogen in a metal having relatively high strength and correspondingly limited ductility. Failures produced by this mechanism macroscopically exhibit no deformation (Figure 19). Metallographically, the cracking is usually multiple, fine, and predominantly intergranular (Figure 20).

Figure 19. Sulfide Corrosion Cracking Failure of Alloy Steel Bolt.

There are additional damage and failure mechanisms which more or less regularly surface and which also must be dealt with by diagnosis and correction. These are sigma phase embrittlement in high chromium and chromium-nickel stainless steels, 885°F embrittlement in high chromium steels, liquid metal embrittlement, wear, irreversible high temperature hydrogen attack, caustic embrittlement, sensitization of austenitic materials, and so on. Each of these mechanisms also produces characteristic tell-tale evidence which enable the metallurgical diagnostician to identify the root cause.

Figure 20. Section of Alloy Steel Bolt Failed by Sulfide Corrosion Cracking (Etchant: 2 percent Nital).

CONCLUSION

When conducting metallurgical failure analyses, the trained and experienced metallurgist can recognize certain characteristic features symptomatic of the mechanisms by which equipment failed. In real life situations these mechanisms have been found to operate either singly or in various combinations. As a result, the metallurgical diagnostician is challenged routinely to draw upon all available metallurgical evidence and other information in arriving at his conclusions.

Through the performance of competent metallurgical failure analyses, causes of equipment failure can be identified and corrective actions can be formulated and implemented. In this way the overall objective of the owner of equipment—to operate it in a safe, reliable, and economically attractive manner—can be better realized.