Elements of Failure Analysis

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Abstract

Failure analysis is conducted to determine the root cause of failure. Sometimes these failures are catastrophic, e.g., Titanic. Other times the failures are a nuisance, e.g., failed o-ring in plastic faucet water valve. In both cases, the component failed unexpectedly, which can result in injury or death, not to mention financial loss due to unscheduled downtime. By using the information presented in the failed component a company could reduce, or eliminate, the possibility of re-occurrence of that type failure. This paper will discuss failure analysis in general terms and provide several case studies. The areas of failure analysis to be presented include typical tools, steps in conducting a failure analysis, theory of crack propagation, typical failure mechanisms, and case studies.

Introduction

It may sound like a bad joke, but what do manufacturers, insurance companies, and lawyers have in common? From an engineering viewpoint the common factor is providing engineering analysis to determine the root cause of why a component failed. Manufacturing companies want to save money, be more efficient, reduce down-time, and have proper preventive maintenance programs. Insurance companies do not want to pay a claim if abuse of the equipment was responsible for the failure and resulting claim. Lawyers need engineering data to assist in proving their case.

Failure analysis is a broad discipline that includes metallurgy and mechanical engineering. Some personal attributes of a good failure analyst include common sense, the willingness to expect the unexpected, and of course, a strong understanding of the engineering theory. Some of the typical tools include various forms of examination, e.g., visual and electronic. There are numerous steps in completing a failure analysis study and they should be performed in the proper sequence.

This paper introduces the above concepts and provides a few case studies showing how engineering knowledge and the ability to apply it work in these problem solving scenarios.

Typical tools

Failure analysis provides insight into failure mechanisms if the analysis is thorough and accurate and all the necessary tests are performed. If the analysis is incomplete, then the wrong conclusions will be reached with possible serious future consequences. This paper only addresses a few of the tools, but they are all inter-related. There are several references the reader can obtain to become familiar with all the possible tools available. (1, 2, 3, 4)

Visual exam

The overall condition of the component is quite important, beyond just looking at the fracture surface. It is important to determine the exposure of the entire component to the environment, which includes temperature, acid, tensile or compressive stresses, impact forces, corrosion, and wear. Just receiving a portion of the failed component, i.e., the fractured surfaces will not allow a fully justifiable conclusion to be determined. The author experienced this very concept a few years ago, which made the investigation quite challenging. (5)

Macroscopic exam

The initial view of the fractured surface provides many clues that will aid the failure analyst in determining the responsible failure mechanism. The presence of oxide on a portion of the fracture surface indicates a long exposure to the atmosphere, a smooth surface could indicate rubbing of the mating surfaces after fracture. Certain features will assist the failure analyst in where to concentrate the area of evaluation, e.g., ratchet marks and beach marks. There are several excellent references that can aid the reader. (1, 6, 7)

Microscopic exam

This examination technique is essential for determining processing history, e.g., heat treatment, exposure to environment, e.g., temperature during use, presence of internal defects, e.g., inclusions, porosity. A certain amount of skill is required during sample preparation and knowledge of the proper etchant is critical to ascertain the presence of certain features, which include ferrite, austenite, Martensite, sigma phase, and carbides for steel and similar features for non-ferrous metals. Knowledge of the microstructure will allow the failure analyst to reach conclusions. (8)

Scanning electron microscopy (SEM)

This inspection tool is able to provide details of the fractured surface! The depth of field makes this technique invaluable to the failure analyst. Many times low magnification is sufficient to document features that are not discernable with macroscopic examination using light. The SEM is routinely used from 20X to 200X, and on rarer occasions from 500X to 3000X. Striations, which indicate fatigue failure, can easily be seen. Ductile failure can be identified by tearing and coalescence of microporosity.

Steps in conducting a failure analysis

Collect and preserve failed components

Preservation of the fractured surfaces is paramount in performing a comprehensive examination; resist all urges to grind the two surfaces together to confirm that, “yes, they do fit together.” Introducing damage to the fractured surfaces damages the very aspect that provides clues as to the failure mechanism. Do not even remove oxides until it is necessary.

Obtain pertinent background information regarding operation and environment
The worst case is when a bucket of failed components is delivered and the client requests that the failure mechanism be identified. The best case is when the failure analyst is present when the failed component is extracted from its environment. Then relevant questions can be asked and many small details can be observed that might not have been asked.

Conduct chemistry analysis
This is important to know which alloy is being examined. Then handbook values can be used for comparison in determining expected level of performance. Chemical analysis will provide the details to the failure analyst regarding what material is being evaluated. Many strengthening elements do not appear in the microstructure and are in low composition, such that, Energy Dispersive Spectroscopy (EDS) will not detect. Knowledge of the alloy will permit the failure analyst to know where to look on the phase diagram, which TTT curve to use, what typical mechanical properties are expected.

Develop hypotheses for possible failure mechanisms
After collecting preliminary data the failure analyst should develop several possible scenarios regarding the failure; a good engineer can always come up with at least 3 ideas. Then subsequent pertinent tests can be conducted to verify or refute those ideas.

Perform loading analysis
Use engineering skills to determine order of magnitude of forces on the component; are they tensile, compressive, torsional, bending, shear, etc. This knowledge in combination with knowing if the material is brittle or ductile is quite valuable.

Non-destructive examination
These tools were described in the previous section, “Typical tools”. Many indications can be observed that provide insight into the failure mechanism. SEM is particularly useful as mentioned previously.

Conduct mechanical tests
Tensile, compressive, hardness, microhardness, and impact tests can readily be performed from representative material. Fatigue testing is time consuming and statistical in nature, but can provide tremendous insight into expected performance. Much of this type testing is dependent on the size and configuration of available material.

Theory of crack propagation

Three aspects of crack propagation will be considered in this paper. The reader is encouraged to obtain additional references for further elucidation in this fascinating, complex topic. (2, 9, 10)

Crack size

Critical crack size is a function of applied stress and fracture toughness of the material.

$$K_{IC} = \sigma f (\pi a_c)^{0.5} \qquad \text{EQ \#1}$$

where K is fracture toughness (material property), σ is stress (design property), and a_c is the critical crack size for failure (detection dependent on NDE technique (detection size is inversely related to cost)).

Plastic zone at crack tip

Brittle materials have little ability to plastically deform, therefore the crack readily propagates. Ductile materials can easily deform at the crack tip, which blunts the tip and results in additional energy (force) to advance the crack tip.

Leak-before-break

Wall thickness of pressure vessel is a function of fracture toughness and yield strength

$$t < 2.5 (K_{IC} / \sigma_{YS})^2 \qquad \text{EQ \#2}$$

Thin-walled vessels will allow the crack to penetrate the wall, generating a leak, prior to fracture. A thick-walled vessel will be thicker than the critical crack length, a_c , which means the first visible sign of a crack is after catastrophic failure.

Typical failure mechanisms

There are numerous failure mechanisms that might occur, some appear more often than others, which include various types of corrosion by itself, various types of wear by itself, corrosion in combination with wear, and compression to name a few. There are many publications that cover these mechanisms and the reader is referred to them for additional detail.(1, 2, 4, 11)

Fatigue

Fatigue indications include ratchet marks and beach marks that are visible at 1X. SEM inspection can show striations at high magnification. Fatigue is influenced by notches, scratches, and transition areas where diameter changes occur. Figures 1- 4 show some typical fatigue features.

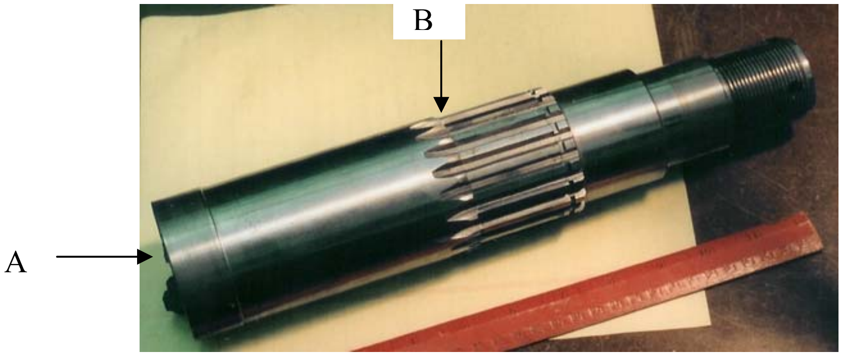

Figure 1. Axle from skid-steer earth mover. Failure occurred at locations A and B.

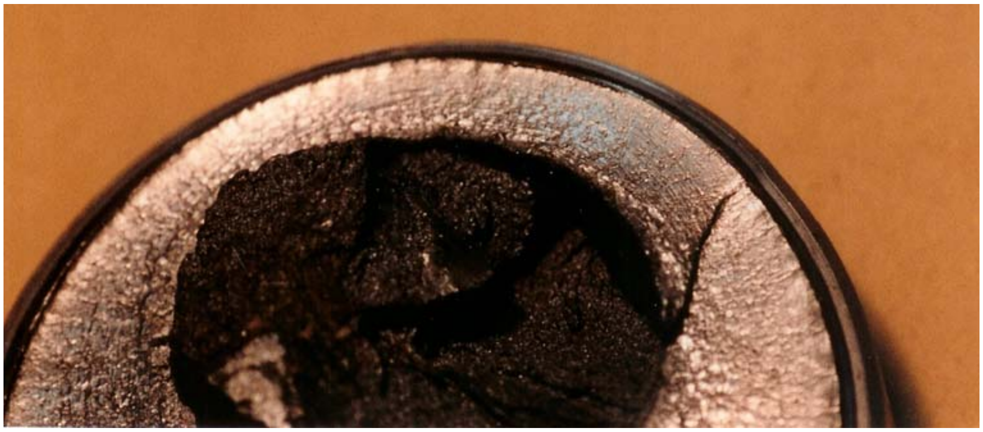

Figure 2. Failure at location “A”. Beach marks are present on fractured surface.

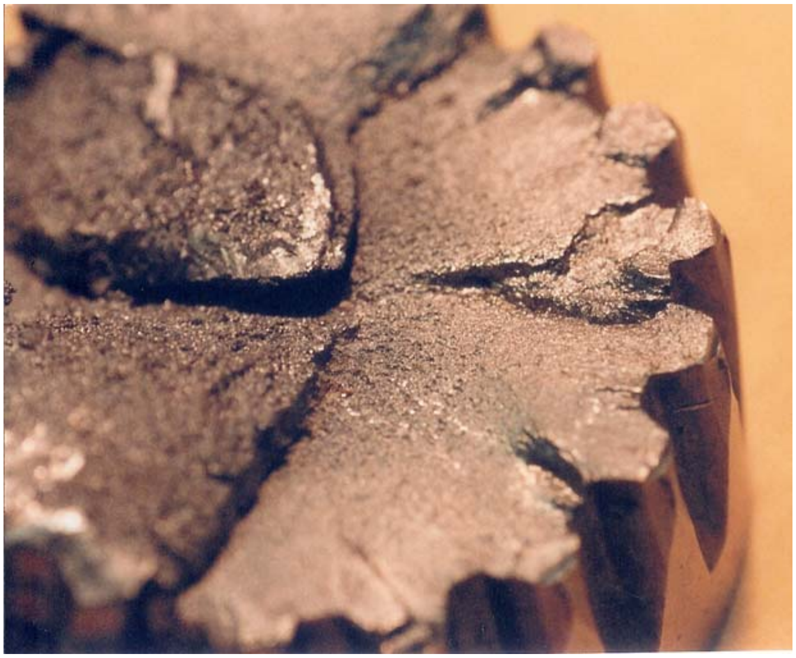

Figure 3. Failure at location “B”. Note ratchet marks at spline roots.

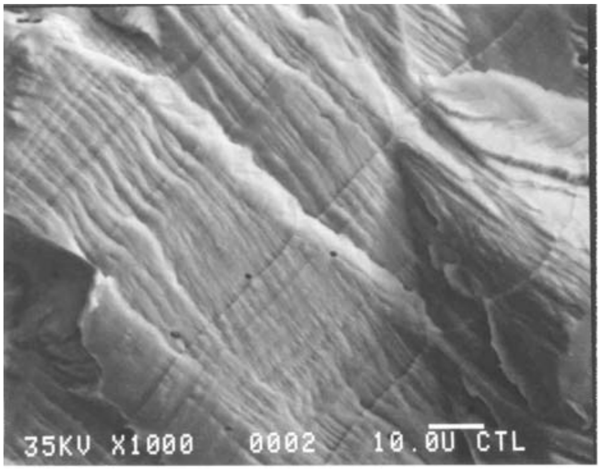

Figure 4. Typical striations.

Tensile overload

Signs of plastic deformation or fractured planes perpendicular to the applied tensile forces are indicative of this type failure. Figure 4 shows some typical tensile and compression failures.

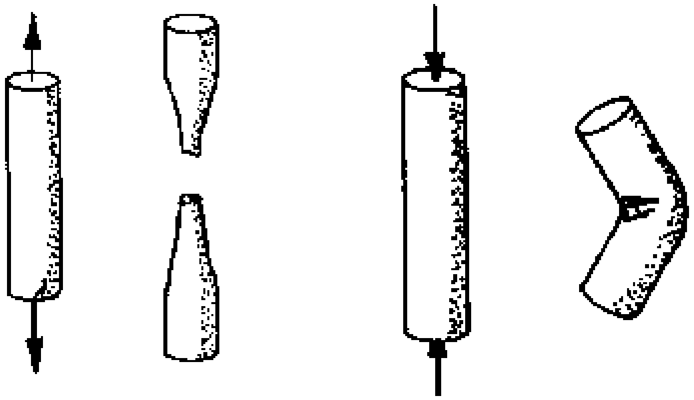

Figure 4. Typical forms of axial overload.

Torsion

Shafts usually fail via this mechanism. Shear occurs and is somewhat opposite in appearance from tensile overloads; brittle fractures are at an angle, while ductile fractures are across the diameter of the shaft. Figure 5 shows some typical torsional failures.

Figure 5. Typical forms of torsion failure, a) ductile, and b) brittle.

Bending

Beams usually encounter this type failure. One outer surface experiences tensile overload, while the opposite outer surface experiences compressive overload. Figure 6 shows a typical failure.

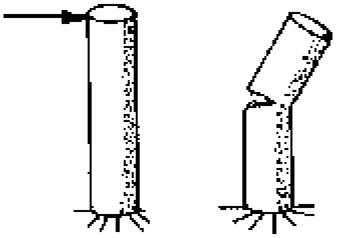

Figure 6. Bending failure.

Corrosion

This type failure has too many aspects to be covered in this paper. The reader is encouraged to read some of the following references, which include theory, data, and case studies. Common types of corrosion include galvanic, uniform, stress corrosion cracking, concentration cells (composition, stress, and crevice). Corrosion protection can readily be accomplished via proper joint design, sacrificial anodes, cathodic protection, and surface coatings.(12, 13, 14, 15, 16)

Wear

Just like corrosion, there are too many aspects to cover in this paper. Please refer to the following references. Common types of wear that exist are abrasive, adhesive, fretting, galling. (11, 17, 18, 19)

Case Studies

Mausoleum bolt – SCC

Fracture surfaces contain many features that help the failure analyst determine the root cause of failure.(4, 5, 6, 7, 20) Inscripted marble slabs were falling off the front of a mausoleum. Some of the slabs were 20 feet in the air; fortunately nobody was injured. The slabs were held in place with brass bolts that did not have any loads from the marble slab; the entire weight was supported by other hardware. Yet, it was these brass bolts that were failing, which merely kept the marble slabs vertical. Figures 7 - 9 depict the failed bolts. Results of the examination showed that SCC had occurred as shown in Figure 9. The bolts were exposed to ammonium via fertilizer, which brass is susceptible to. The source of stress was puzzling. Visiting the site and watching the removal of bolts that would be analyzed, revealed the high levels of torque used during the installation. Residual stress was present due to the heading operation, which was not followed by an anneal. Details of this failure can be found elsewhere. (21) If one of the three criteria for SCC had been removed (1] presence of stress, 2] corrosive environment, and 3] susceptible material), then these failures could have been prevented.

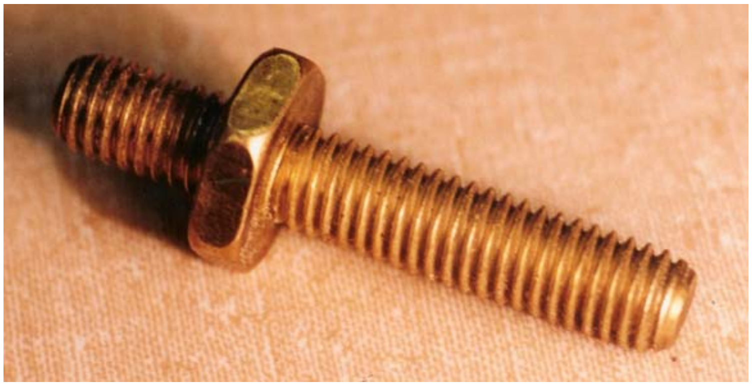

Figure 7. Brass Bolt.

Figure 8. Failure of Brass bolt.

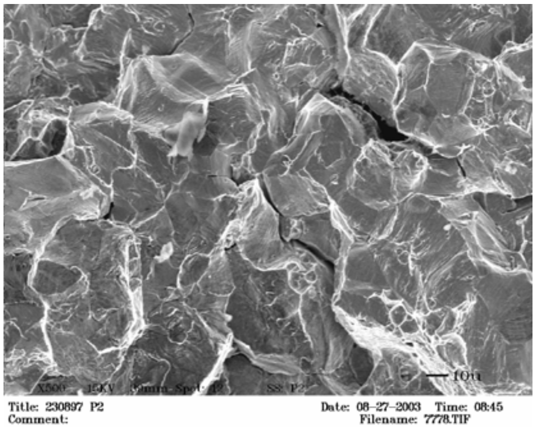

Figure 9. SCC of failed brass bolt.

RV fire – melting temperature versus location

An RV caught on fire while parked in a camping area. Two people were injured and one later died. The fire was suspected to have originated at the LP gas line that passed through the passenger side front wheel well. It was opined that constant impact from road debris (propelled from the tire) penetrated the gas line tube; the leak that then ignited.

The approach in this case was to use metallurgical knowledge of melting temperatures and phase diagrams (8) to show the temperatures experienced in various locations throughout the RV. By examining the surface of various metals (steel, copper, and aluminum) located in the engine compartment, the temperatures could be bracketed. Melting of aluminum (T_M = 1220°F, 660°C) dripped onto copper tubing. Copper melts at 1985°F (1085°C), whereas eutectic melting of Cu + Al can occur as low as 1018°F (548°C). Examination of various components retrieved from the RV was conducted and Figure 10 shows the results of this analysis.

Figure 10. Temperature profile of engine area.

Weld parameters – HAZ cracking

A manufacturing company was having difficulty with cracking in their welds on stainless steel (Ferritic SS with austenitic filler metal). They submitted four samples with different weld parameters for metallurgical evaluation that consisted of microstructure and microhardness testing. Knowledge of microstructures is essential to understanding the relationship between processing, alloy, performance, and structure. (21) Figures 11 - 14 show the some of the samples and results. Some of the conclusions were: 1) Cool the weldments at a faster rate, perhaps by using a backplate to prevent sensitization and formation of Martensite, 2) Employ a cover gas for the top and bottom of the weld to minimize Nitrogen pickup and the ensuing formation of Martensite, and 3) Develop a consistent bend test to characterize the ductility of the welds.

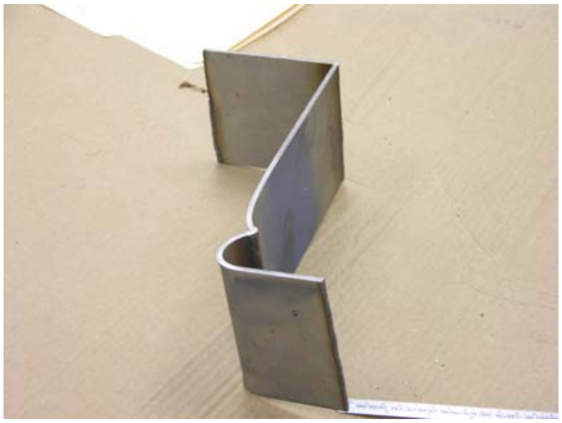

Figure 11. Successfully welded component; ductile weld.

Figure 12. Failed weld; no ductility.

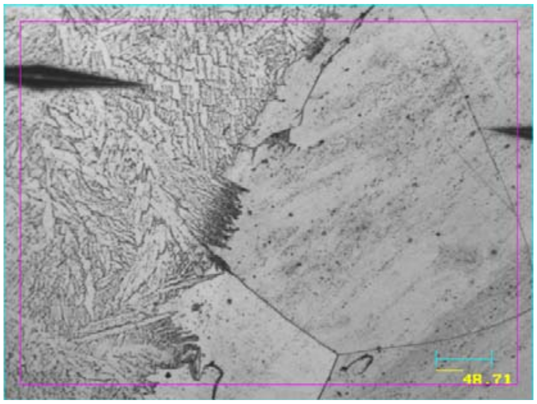

Figure 13. Microstructure of fusion zone and base metal that exhibits grain growth. Good interface between these two zones.

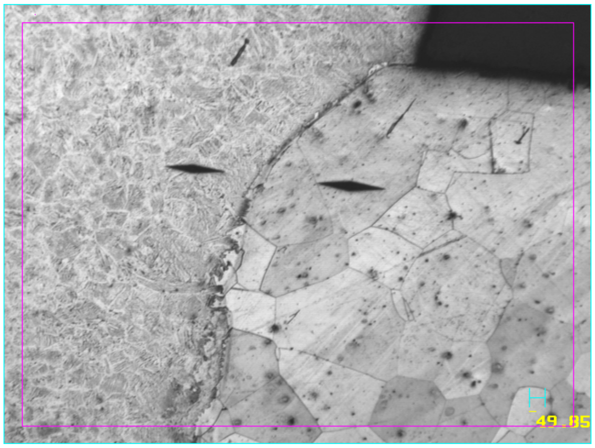

Figure 14. Microstructure of fusion zone and base metal. Note poor interface quality. Diamond shapes are microhardness indentations.

Conclusions

1. Preserving failed components for future evaluation is paramount in conducting a successful failure analysis.
2. Developing hypotheses and using the proper tools validates or eliminates the possible failure mechanisms.
3. Visual, microscopic and SEM results along with chemistry and mechanical data allow the metallurgist to formulate a reasonable failure scenario.
4. The metallurgist can make recommendations regarding design, material selection, material processing, or presence of abuse to minimize future failures.
5. Manufacturing companies can schedule preventive maintenance, insurance companies can pay valid claims, and lawyers can be justifiable.

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Credits:
Website for Figure 4

http://images.google.com/imgres?imgurl=http://www.corrosionlab.com/Failure-Analysis-Studies/Failure-Analysis-Images/28186.mechanical-fatigue.ss-bolts/figure02-beachmarks.jpg&imgrefurl=http://www.corrosionlab.com/Failure-Analysis-Studies/28186.mechanical-fatigue.ss-bolts.htm&h=1536&w=2048&sz=68&tbnid=ueN454j5ccUJ:&tbnh=112&tbnw=150&hl=en&start=2&prev=/images%3Fq%3Dfatigue%2Bfailure%26svnum%3D10%26hl%3Den%26lr%3D

Website for figures 4, 5, 6
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