A Re-Examination of Failure Analysis and Root Cause Determination

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Failure analysis is a complex process applied to all different types of materials. Each class of materials requires special skills and experience to effectively unravel the causes of failure. This is the first in a series of papers focusing on these various subsets of materials. The series will include failures in metallurgy, paints and coatings, plastics and electronics, as well as failure caused by corrosion. Each paper in the series will also include an examination the principles of root cause determination within that particular field. This first paper is primarily concerned with the overall approach to failure analysis and with the applications of that approach to <u>metallurgical failures</u>.

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I. Introduction

The purpose of failure analysis is entirely positive: to prevent further failures. Failures occur when some system or part of a system fails to perform up to the expectations for which it was created. A transmission fails. A pipeline leaks. A cell phone explodes. The concept of failure is easy to understand intuitively. But underneath that intuitive understanding are important conceptual principles which are commonly either misunderstood or not considered at all.

Failure itself is a human concept. Materials do not fail in and of themselves. They follow the laws of nature perfectly. If a part is loaded beyond its tensile strength, it breaks. Until that stress level is reached, it does not break. When a part fails in service, it was under-designed or poorly manufactured for the circumstances in which it was used.

II. Failures Are Caused by Human Errors

That being understood, then all failures are caused by human errors, of which there are three general types:

- a) Errors of knowledge
- b) Errors of performance (which might be caused by negligence), or
- c) Errors of intent (which may come down to acts of greed)

What are often called "acts of God" are more or less widely spaced natural events, such as the flooding associated with unusually large storms, earthquakes, and so forth. In terms of geologic time rather than the very short human experience, these events are certainties, not exceptions. They <u>will</u> happen, given enough time. Failures associated with "acts of God" are, again, the results of under-design for the actual conditions the component or system faces in service.

Errors of knowledge usually involve insufficient knowledge, education, training, and/or experience. Here are a few examples of such errors of knowledge

- Ancient Romans used lead in their wine goblets. Using them over long periods produced lead poisoning and ultimately insanity. 19th century Arctic explorers repeated this failure in their food containers.
- Dendrite growth on metals in conductive ionic environments produces short circuits in electronic components for computers.
- Hydrogen Embrittlement (HE) causes otherwise stable high strength steel components to fail.
- Degassing produces bubbles and ultimately corrosion in coated cast iron pipes.
- Internal and external corrosion of gas lines in the early 20th century caused frequent urban explosions.
- NASA Shuttle disasters involved both O-ring and ceramic insulation failures.

Errors of performance result from lack of sufficient care or from negligence. Negligence involves such things as misreading of drawings, inadequate specifications, and defective manufacturing and workmanship. Some examples are:

- Recent NASA failures in a Mars mission involved the incorrect conversion from the English to the Metric System of measurement in a computer program.
- The Chernobyl Nuclear Power Plant accident involved a major failure in design of the safety system.
- Failures in Human Breast Implants involve an insufficiently durable packaging for the silicone materials of which the implants were made.
- Explosions of natural gas have been caused by the spark from a car's ignition being started next to a leaking pipe line.

Errors of intent very commonly involve greed. Greed leads to actions usually carried out with a conscious or unconscious denial of full knowledge of the potential consequences. In other words, the perpetrators convince themselves that their actions will not have serious impacts. For example:

- Cost reduction driving design of military vehicles causing premature failures.
- Exxon Valdez and many other oil tanker spills were caused by using single hulls in super tankers.
- Aloha stadium superstructure corrosion failures were caused by lack of surface preparation and poor materials and coating selection.
- Failure of bonding of steel belts in Firestone radial tires on Ford SUV's caused many roll-over accidents.

An interesting example of combining various types of errors is found in the production of galvanized steel. Since the 1930s it has been known that introduction of approximately 0.15% of aluminum into a hot-dip galvanizing bath will cause the formation of a thin aluminum-iron-zinc intermetallic layer at the steel surface. This intermetallic layer acts as a barrier to iron migration into the zinc, preventing the formation of brittle iron-zinc intermetallics. With this al-fe-zn layer in place, when the galvanized component is bent during service, the zinc layer deforms plastically, rather than fracturing. When manufacturers experience high rates of cracking in their galvanizing layers, they have often let the aluminum concentration in their galvanizing bath slip out of control.

This failure may be a combination of all three kinds of errors. The manufacturer may simply not know that the aluminum concentration is so vital to the success of his product, he may just be letting his quality control function slip out of negligence, or he may be unwilling to spend the money necessary to mount an effective quality control program in his plant.

We will refer back to this example below when we discuss "root cause" determination in **Section IV** below.

These ideas provide the philosophical underpinnings for a study of failures. It is important to recognize that many failures are preventable if we understand the materials and their intended applications well enough and are willing to pay the required costs for safety and durability.

III. Product Specifications and Failure

The service-life-expectancy of a product is defined by the level of degradation that will be designated as failure. This would ideally be found in a product specification or warranty, a document which summarizes product quality requirements, desired outcomes, and expectations. A product specification may include requirements that the product meet certain accepted standards such as those defined by ASTM, NACE, or other self-regulatory bodies. A well–written specification indicates such characteristics as load-bearing capacity and life expectancy.

Many specifications recognize that perfect materials do not exist. Major construction codes may do the same thing. They make allowance for the presence of defects or corrosion loss by establishing limits on defect type, size, location, and distribution. Imperfections such as surface laps, tears and casting and forging defects are recognized in ASME and AFS materials specifications as acceptable within certain limits. However, in the real world of MATCO's investigations it has been found that specifications or standards have commonly not been put in place prior to putting a product in service. Having such specifications would provide a valuable reference guide should a product fail in service, helping the analyst determine whether the failure was reasonably to be expected.

For example, recently a widely used type of aluminum scaffolding collapsed in service. The owner wanted to know if he had a cause of action against the manufacturer. The product had been in service for over five years, three of which had been under a prior owner. A full failure analysis found no defect in the product and found it fully within the specifications. Apparently the product simply wore out and finally failed. It may have suffered overload under the prior ownership, but that was unknowable. The manufacturer was protected by the load-limit specifications and by the finding of no manufacturing or material defects.

In another example, a small area of discoloration in the paint of an expensive new car may be considered unacceptable because of the desired high quality of appearance. By contrast, pinholes of various sizes through epoxy coatings on gas lines may not be considered unacceptable, because corrosion of the pipeline in service will be prevented by cathodic protection. Corrosion resistance is the issue of greatest importance for the pipeline, not appearance, Thus the criteria for failure are quite different, even though coating quality is an important issue in both cases.

The service-life-expectancy must always be tailored to the product application. For example, most coating specifications are designed for products to be used for aboveground corrosion protection. Few of these specifications are particularly relevant to underground coating applications where cathodic protection may be in place.

IV. Root Cause Determination

The main concern in every business is customer satisfaction. When a product does not live up to its design expectancy, i.e., when it fails either gradually, suddenly, or catastrophically, a method of evaluation must be available to understand why the failure occurred. Root-cause failure analysis provides this understanding. Fully implemented, it seeks not only to solve the immediate problem, but to provide valuable guidance to avoid the problem in the future.

The primary cause is the set of conditions or parameters from which the failure began. The old saying, "For want of a nail the shoe was lost, for want of a shoe the horse was lost, for want of a horse the battle was lost, for want of the battle the kingdom was lost," summarizes a classic primary cause determination. The analyst must discover what it was about this incident that is fundamentally responsible for the failure in performance and determine the sequence of events that led to the final failure.

By contrast, the <u>root cause</u> of a failure is a process or procedure which "went wrong." The finish on a machine part was not as-specified. The heat-treatment on a rail was not uniform. The angle on screw-threads was too steep. Identification of that process is the key to creating a procedure by which future failures can be avoided.

Most failure analysis stops short of this final step. Instead what is presented to the client is the primary cause of failure. The poor finish, the incorrect heat treatment, the shape of the screw threads in the paragraph above are the "primary causes' of those failures, not the root causes. The root causes would be:

- the failure to check the finish after the part was machined,
- the failure to ensure that the heat treatment furnace had sufficient control of changes in temperature to produce the desired microstructure in the rails, or
- The failure to enter the proper information into the thread-cutting process.
- The horse's groom not checking to see that the horse's shoes were properly nailed on before sending him into battle.

All four of these were "process" or "procedure" failures.

In the example presented in Section II on problems in hot-dip galvanizing of steel, the <u>primary cause</u> of cracking of galvanized steel in bending may be the lack of an aluminum-iron-zinc intermetallic layer at the steel surface. But the <u>root cause</u> is the failure to maintain the aluminum level in the galvanizing bath.

To avoid these same failures in the future, to determine the root cause of the failure, the primary cause must be supplemented by intimate understanding of the entire history of the failed system or part, including both its manufacturing and its use. This information is usually most effectively obtained by visiting the manufacturing site for the failed part. From this information a new procedure can be crafted which will prevent repetition of the original failure.

V. How to conduct a failure analysis

A failure analysis is much like the work of a detective. Important clues are discovered throughout the investigation that provide insight into what may have caused the failure and what contributing factors may have been involved. The failure analyst is aided by a broad knowledge of materials in general. Success is more likely if the analyst is aware of the failed material's mechanical and physical properties and its fabrication and historical performance characteristics. The analyst must also possess a working knowledge of structural design and stress behavior.

A component is considered to have failed when it has deteriorated to the point at which it is unsafe or only marginally capable of performing its intended function. For an item to be classified as a failure it need not be completely broken. As an illustration, consider a fracture as a type of failure. Fractures occur in materials when cracks are initiated and propagate to a greater or lesser degree. They may not go to completion. Cracks may be initiated by mechanical stresses or environmental- or chemical-influences, by the effects of heat, by impurities in the material or by a combination of these and many other factors. Understanding the relative importance of those factors in the specific case at hand is the job of the failure analyst.

For the purposes of this paper, the metallurgical aspects of materials will be emphasized in the illustrations. Other types of failures will be considered in later segments of the overall publication.

1. Preliminaries. Determine when, where and how the failure occurred.

Before beginning any failure analysis, it is vital to determine whether or not destructive testing is permitted or if the testing must be limited to non-destructive approaches. If the failure is or may be subject to litigation, opposing counsels must agree on this point before any sampling begins. Witnessed testing (the presence of parties from both sides in a law suit) may be called for.

It is important to visit the failure site in the field if possible. All operators involved in the failure should be interviewed personally. Determine what the conditions were at the time of failure. Were there prior indications suggesting failure was about to occur? Was the failure gradual or catastrophic? Was the part protected after failure? How was the fracture handled? Did the failure involve any fire or other condition which could have altered the microstructure of the base metal or of some part of the sample such as a weld? These and all other appropriate questions should provide a basis for the investigation.

It may be important to obtain documentation on maintenance procedures during the lifetime of the equipment that failed including, if applicable, maintenance personnel, records of scheduled maintenance, and suppliers and products used.

As a part of this preliminary information gathering, it is also important to obtain the physical and chemical specifications for the product which failed, against which performance may be measured.

2. Collect samples for laboratory examination. Samples selected should be characteristic of the material and contain a representation of the failure or corrosive attack. For comparative purposes, a sample should also be taken from a sound and normal section.

Sampling handling is a paramount issue on which the whole remaining analysis depends. Fracture surfaces must be protected from damage during shipment by rigorously careful packaging. Surfaces should not be touched, cleaned or put back together. .Surface chemistry must not be contaminated by careless handling.

Materials specifications and service history reveal much about the nature of failure. If submitting a sample for analysis background information will need to be provided. A sample form that we find helpful is shown on the following page. Take copious notes. Do not rely on memory

Samples can be removed by acetylene torch, air-arc, saw, trepan, or drill. All cuts with an acetylene torch should be made at least six inches and cuts by air-arc at least four inches away from the area to be examined to avoid altering the microstructure or obscuring corrosive attack.

If pipe failures are involved, careful observation of the pipe conditions is important both prior to sample removal and as the cut separates the two ends of the pipe, as those may indicate stress conditions in the pipe at the time of failure. All of these characteristics should be noted and documented photographically. Be careful to include in the samples any failure-related materials such as coatings, soils in which a pipe may have been buried, corrosion deposits, waters, etc.

It is vital to prevent liquid samples from going septic. If bacterial content is a potentially important issue the samples must be taken in clean containers, refrigerated and delivered to microbiological labs for culturing within 24 hours. If bacterial content is irrelevant to the study, then two drops of household bleach per quart of sample will sterilize the contents. Note that the bleach addition will change the sodium and chlorine contents of the samples. A detailed knowledge of the final purpose for the samples has to control how they are to be handled.

3. Take on-site photographs. Photographs should be taken of the failed piece of equipment including the samples to be removed and their surroundings. These should show the relationship of the questioned area to the remainder of the piece of equipment. Additional photos should be taken of the samples after removal to fully identify them. If more than one sample is to be taken, proper designation of the sample and its location relative to the piece of equipment should be noted. The dimensions of the sample, the date the failure occurred, and the date of the photographs should be noted. Consider the use of video recording if complex disassembly is required

4. Visually examine the sample. Examine the sample with unaided eye, hand lens and/or low magnification field microscopes. Note the condition of the accessible surface documenting all sorts of anomalies, searching for cracks, corrosion damage, the presence of foreign material, erosion or wear damage, or evidence of impact or other distress. Also consider the condition of protective coatings. Manufacturing defects are important.

If pipe failure is involved, it is important to carefully measure wall thicknesses both at the failure site and some distance away from it at four locations 90 degrees apart around the pipe circumference, starting a the failure site. At the same time note the presence of any corrosion and map its general distribution.

5. Identify defects Non-Destructively. Search for material imperfections with radiography, magnetic particle, ultrasonic, liquid/dye penetrant, eddy current, leak, and/or acoustic emissions non-destructive testing procedures. Some photographic examples of these techniques are provided below.



6. Conduct appropriate chemical analyses. Chemical analysis should be conducted on the original material to determine if the material was of proper type and grade, whether it met appropriate standards, and whether deviation from the specifications contributed to the fracture, wear, breaks corrosion and failure. Wet chemical analysis, Atomic Absorption, X-ray Photoelectron, Auger Electron and Secondary Ion Mass Spectroscopies are all potentially suitable methods of chemical analysis, depending on the particular need of the situation. The techniques differ in important ways. Other parts of the failure "system" may also require analysis, including corrosion products, coatings and liquids.



7. Confirm material composition and identify contaminants through EDS analysis. EDS (Energy-Dispersive Spectroscopy) is an analytical method based on the differences in energy of the characteristic x-rays emitted by the various elements. It is used in conjunction with scanning electron microscopy (SEM) to identify the elements present at a particular spot on a sample. Advantages of EDS are that it is easily performed and is reliable as a qualitative method. Limitations are that it is only marginally useful as a quantitative method.

8. Analyze via Fractography, Fractography is used to determine the mode of fracture (intergranular, cleavage, or shear), the origin of fracture, and location and nature of flaws that may have initiated failure. With this information, the answer as to why a part failed can usually be determined. The major use of fractography is to reveal the relationship between physical and mechanical processes involved in the fracture mechanism. The size of fracture characteristics range from gross features, easily seen with the unaided eye, down to minute features just a few micrometers across.

Light and electron microscopy are the two more common techniques used in fractography. An important advantage of electron microscopy over conventional light microscopy is that the depth of field in the SEM is much higher; thus the SEM can focus on all areas of a three-dimensional object identifying characteristic features such as striations or inclusions.

The texture of a fracture surface, that is, the roughness and the color, gives a good indication of the interactions between the fracture path and the microstructure of the alloy. For instance, at low stress a fatigue fracture is typically silky and smooth in appearance. Stress corrosion fractures show extensive corrosion features and corrosion "beach marks." A discontinuous ductile fracture shows some stages of crack tip blunting, crack arrest and "pop-in".

9. Analyze via Metallography. Prepare a laboratory specimen with care not to remove inclusions, erode grain boundaries or compromise the sample in some other way. Study structural characteristics in relation to its physical and mechanical properties at low and

high magnification. Take careful note of grain size, shape, and distribution of secondary phases and nonmetallic inclusions. Segregation and other heterogeneous conditions also influence the mechanical properties and behavior characteristics of metal.



At Far Left: Intergranular Stress Corrosion Cracking (ISCC) in turbine component At Left: Cross-section of copper lance component exposed to excessive temperatures showing grain growth.

Metallography for the analyst may be concerned with pit depth, intergranular corrosion, hydrogen attack and embrittlement, caustic embrittlement, stress corrosion cracking (intergranular or transgranular), and corrosion, mechanical or thermal fatigue. Also, within limits, an almost complete history of the mechanical and thermal treatment received by a metal is reflected in its microstructure.

10. Conduct Appropriate Mechanical and Materials Testing and Analysis as Necessary

1. Physical Testing

It may be necessary to conduct physical tests to determine if the mechanical properties of the materials involved conform to specifications. Hardness, tensile strength, impact, fatigue resistance, wear, flexibility and many other physical tests are relatively common. These tests often compare the material in the failed component with standards. Test specimens for determination of mechanical properties should not be taken from areas of the component that have been plastically deformed during the failure.

In general, structural members and machine parts can fail to perform their intended functions by:

- excessive elastic deformation (deflection under applied loads),
- yielding (permanent material deformation as a result of stress), or
- fracture.

For instance, the deflection of closely mating machine parts due to surface stresses (elastic deformation) can degrade adjacent parts by increasing wear and in certain cases can promote complete failure. A study of the mechanical properties of the parts can provide information on load-bearing capabilities of the system and can minimize such failures.

2. Finite Element Analysis

The finite element method is a powerful numerical tool for analyzing mechanical components and systems. The representation of a component or system mathematically with finite elements generally involves a discretization of the structure into many small pieces, e.g. small brick-like elements (hence the name of the method). The solution to the equations that govern the behavior of the structure is approximated on each and every brick. The collective effect of all the bricks is taken into account during a step that synthesizes the solutions for each brick into one solution valid for the entire structure. This global solution represents the solution to the equations that govern the structure is that govern the structure.

The finite element method provides a tool to predict and evaluate component response, elastic or non-linear plastic, subjected to thermal and structural loads. Thermal analyses may include convection, conduction, and radiation heat transfer, as well as various thermal transients and thermal shocks. Structural analyses may include all types of constant or cyclic loads, mechanical or thermal, along with non-linearities, such as opening/closing of contact surfaces, friction, and non-linear material behavior. Finite element analysis can be used during a failure study in such ways as:

- Predicting the response of an existing component or assembly to stress
- Assessment of remaining life of a component or assembly
- Determining the failure mode of a failed component or assembly, e.g. fatigue, creep, and buckling.
- Designing of a new component or assembly as a part of recommendations for remediation of the problem

3. Fracture Mechanics

Using the many analytical techniques above will help to determine how the part in question actually failed, what the mode of failure was and where the failure was initiated. What is missing is a quantitative idea of the stress environment in the failure and the response of the failed part to that stress. The relatively new science of fracture mechanics can provide a quantitative framework within which the failure may be understood.

Fracture mechanics relates the size of flaws in a material, principally cracks, to the applied stresses on those cracks and to the "fracture toughness" of the material, or its resistance to cracking.

Fractures include both initiation and growth phases. After initiation, perhaps at a pit or some other site of stress-concentration, the crack will only grow when the stresses at the crack tip exceed a critical value known as the "fracture toughness" or K_{lc} . If K_{lc} and

the stress conditions are known for a given material, then it is possible to calculate the size of crack that can be tolerated in that material without having the crack grow further. The following equation shows those conditions. A crack will propagate if:

$$\sigma \geq \frac{K_{Ic}}{\beta \sqrt{\pi a}}$$

where σ (sigma) is the fracture stress, β (beta) is a dimensionless shape factor and a is the crack length for a crack with only one tip (i.e., not an internal crack, but one opening at a surface). Handbooks for engineering calculations have tables of values for Beta for different geometries.

If the fracture toughness of the material is known, the fracture stress or critical crack size of a component can be calculated if the stress intensity factor is known.

This calculation will allow

- the determination of "permissible flaw size,"
- the calculation of the stress necessary to cause catastrophic failure
- the determination of the load on a component at the time of failure
- the determination as to whether adequate materials were used in manufacturing
- the determination as to whether a part design was adequate.

If the system that failed is well documented, then operational stresses can be calculated. For example, it can be determined how great the load was on a certain part when it failed. The load history may also be known throughout the time that the part was used. These data can be used to calculate the toughness, given a knowledge of the crack size at the time of final failure. This will show whether the part performed according to the specifications for it.

On the other hand, if the stresses are not known, then toughness still can be estimated from materials handbooks, again knowing the crack size and the area of the remaining sound metal at the time of failure.

If neither toughness nor stresses are known, toughness can be estimated from physical testing, using Charpy-impact tests on pieces of the material. The stresses at failure can be determined by back-calculation and it can then be said if the part failed from overload.

Much can be also done to quantify conditions from fatigue failures. The rate of crackgrowth can be estimated from a knowledge of the number of striations per unit length of crack perpendicular to the crack front. If the stresses are known, the stress intensity can be inferred, and the adequacy of the material for the use conditions can be determined. From a knowledge of the known stresses, the crack size at fracture and the crack growth-rate, estimates may be made as to whether or not the material had been misused. Thus, fracture mechanics can be used to help us understand

- how a particular crack formed at a specific location and
- the stress conditions that caused the crack to propagate.

The design engineer will normally include "factors of safety" in his design to prevent stresses from reaching critical levels .

More detailed examples of the applications of Fracture Mechanics to failure analysis are given in Appendix A.

11. Determine the type of failure

The major types of failures likely to be encountered by metals in service are:

- A. Ductile,
- B. Brittle, and
- C. Fatigue fractures

Wear, Fretting, Elevated Temperature and Corrosion are other important causes of failure which will be covered in a future publication in this series.

A. Ductile Fracture



Ductile fractures are characterized by tearing of metal accompanied by appreciable gross plastic deformation. The microstructure of the fracture surface is quite complex and may include both transgranular and intergranular fracture mechanisms. Ductile fractures in most metals have a gray fibrous appearance and may be flat-faced (tensile overload) or slant-faced (shear). The specimen usually shows considerable elongation and possible reduction of cross-sectional area as well. Whether a part fails in a ductile or brittle fashion depends on the thickness of the part, temperature, strain rate and the presence of stress-raisers. Most commonly seen characteristics of ductile failures are:

- Lateral contraction, or necking;
- Fracture path in the interior following a generally flat plane perpendicular to the principal stress direction, and

• Tensile stress.

Cylindrical specimens will have a "cup and cone" configuration, as shown above on the right, while the fracture surface on thick specimens will be generally perpendicular to the principal stress direction, as seen in the bolt in the illustrations above.

B. Brittle Fracture





Brittle fractures are characterized by rapid crack propagation without appreciable plastic deformation. If brittle fractures occur across particular crystallographic planes they are called Tran crystalline fracture. If along grain boundaries they are called intergranular fracture. Brittle fracture is promoted by:

- thicker section sizes,
- lower service temperatures, and
- increased strain rate.

A material's tendency to fracture in a brittle mode can be determined by measuring its notch ductility. The most common test for this is the Charpy V-notch test. Failure under test condition can exhibit energy and fracture transitions. Shear fracture occurs under the notch and along the free surfaces. Cleavage fracture occurs in the center characterized by a bright, shiny, faceted surface. 50% cleavage is the fracture transition point. Cleavage fracture is caused by inability of the crystal structure to cross-slip. Yield strength loading is required to initiate a brittle fracture; however, only much lower stress may be needed to propagate it. Generally speaking, body-centered cubic metals exhibit a ductile to brittle transition over a relatively narrow temperature range.

The Drop Weight Test defines the nil-ductility transition temperature and is very useful for determining the brittle fracture susceptibility of low-strength steels. Linear elastic fracture mechanics evaluates structural reliability in terms of applied stress, crack length and stress intensity at the crack tip.

C. Fatigue fracture



Fatigue is a progressive localized permanent structural change that occurs in a material subjected to repeated or fluctuating stresses well below the ultimate tensile strength (UTS). Fatigue fractures are caused by the simultaneous action of cyclic stress, tensile stress, and plastic strain, all three of which must be present. Cyclic stress initiates a crack and tensile stress propagates it. Final sudden failure of the remaining cross-section occurs by either shear or brittle fracture. Striations on the crack surface are the classic sign of fatigue fracture.









Fatigue cracks may start because of tool marks, scratches, indentations, corrosion pits and areas of high stress. At the crack tip, the material is plastic. At a small distance from the crack tip, in the material is elastic.

Low cycle fatigue cracks occur under conditions of high strain amplitude (with failure in less than about 10⁴ cycles) whereas *high cycle fatigue* occurs with low strain amplitude with failure after a large number of load fluctuations. In low cycle fatigue, striations, if visible at all, tend to be rather broad, widely spaced, and discontinuous in places. Areas without striations may appear to be rubbed or may be quite featureless, except for the area of final fracture. In high cycle fatigue, the striations will be well defined and more closely spaced, with propagation evident in many flat plateaus that are joined by narrow regions of tensile tearing. The investigator should be aware, however, that in heat-treated steels striations are absent from fatigue fractures more often than they are observed, and the stronger (harder) the steel, the less likely it is that striations will be observable. Thus, suspected fatigue striations must be studied carefully to ensure that they are not artifacts of some other process. Striations should be parallel to one another along their lengths and perpendicular to the fracture direction at the region being examined.

Thermal Fatigue cracking is caused by cycling the temperature of the part in the presence of mechanical constraint, e.g., rigid mounting of pipe. It could also be caused by temperature gradients in the part.

Contact Fatigue - Elements that roll, or roll and slide against each other under high contact pressure are subject to the development of surface pits or fatigue spalls after many repetitions of load.



Corrosion pit acting as stress concentrator for fatigue crack (on left at low magnification. Higher magnification of crack tip on right.

Corrosion-Fatigue is caused by the combined action of repeated or fluctuating stress and a corrosive environment to produce failure. It frequently initiates at a corrosion pit on the surface. A very aggressive environment may actually slow the fatigue fracture process increasing the number of stress cycles to failure. The environment affects the crack growth rate, or the probability of fatigue crack initiation, or both. Test data show that for high strength steels, the fatigue strength at 10 million cycles in salt water can be reduced to as little as 10% of that in dry air. Carbon steels exhibit transgranular fracture. Copper and its alloys fail by intergranular fracture.

12. Synthesize and summarize the data, determine and report the root-cause of the failure. Proposed root causes of a failure must be based primarily on observed facts. These facts, combined with the experience, skill and knowledge of the analyst will lead to sound conclusions.

All the observed data should be reported, even if some of it seems peripheral. In the future, with additional data, it may turn out to be possible to use what seemed peripheral at first to make an even more sound interpretation.

Part 2: CASE STUDIES IN MATERIALS FAILURE ANALYSIS

The following case histories present a wide range of applications of the techniques for failure analysis outlined in the fore-going protocol. They are selected from the hundreds of cases that have passed through the authors' laboratories over the past thirty years.

Case History #1 On-Site Metallography of Structural Steel

A large crack and several smaller cracks were discovered in one flange of a steel column in a large new stadium. The H-section column was made of ASTM A572 grade 50 high-strength, low-alloy steel, a common structural material in welded, bolted or riveted structures such as buildings and bridges. Such a crack is considered detrimental to the service life of the material and if left untreated, the crack could propagate under adverse conditions.

An on-site metallurgical inspection was carried out to determine the condition of the column. The paint was removed from the area in which the cracking was first detected. The large crack, as well as several smaller vertically aligned cracks were found near the center of the flange face. The widest and most pronounced crack measured 10-15 mils wide with a crack depth of 0.35". The paint was also removed from the opposite flange in the same area for additional metallurgical inspection. A number of short vertical cracks were found that had not been not visible through the paint.

A dry magnetic-particle test was performed on both flange surfaces. When finely divided magnetic particles are applied to the surface of a sufficiently magnetized ferromagnetic material, the particles will concentrate in cracks or other discontinuities in the surface. This procedure makes it possible to inspect a surface for cracks visually without damaging the sample, a vital consideration since the column could not be damaged in any way by sampling.

Concerns about the integrity of the column prompted the investigators to perform on-site hardness testing. Both column flanges were tested in several crack regions. ASTM A572, the specification for the grade 50 steel in the column, does not specify a hardness requirement but it does specify a minimum tensile strength of 65 KSI. This value corresponds to an approximate Rockwell B scale hardness of 74 HRB. The measured values met or exceeded this value.

In-place metallographic analysis was carried out on two of the column's flange areas, the area adjacent to the most pronounced crack and an uncracked area approximately three inches away, to reveal any defects in the microstructure of the steel. Since on-site microscopic analysis is impractical at the magnification necessary to see the important details, the microstructure was recorded using acetate-peel replicas and later examined in the laboratory. The microstructures of the steel at both locations were similar, consisting of dark-etching unresolvable pearlite in a white-etching ferrite matrix. The steel had a fine ferrite grain size of 7.0 as per ASTM E112 plate I specification. There was no evidence of decarburization adjacent to the crack surfaces. The microstructure of the sample is characteristic of a hot rolled steel product. Such findings are

characteristic of ASTM A572 grade 50 high-strength low-alloy steel. This is the normal microstructure for this product

Since the column met hardness requirements and had a normal microstructure, it was concluded that the cracks in the flanges of the steel column were likely to have been produced during hot rolling stage of production of the beams. Because the major crack might propagate under adverse conditions, it was recommended that it be removed by grinding and that the column then be repair welded. The necessary repair work was to be performed by competent welders in accordance with AWS Specification A5.1. It was further recommended that all of the column flanges in the structure be subjected to one hundred percent ultrasonic inspection to determine if any other cracks exist.

IMPORTANT FAILURE ANALYSIS PRINCIPLES REPRESENTED IN THIS CASE HISTORY:

- 1. Applicable specifications were available for the failed part, making conformance determination routine.
- 2. Field metallurgical procedures, including acetate peel replicas, were an important part of the process.
- 3. Non-destructive on-site testing also important
- 4. The source of the problem was determined not to be non-conformance with the specifications but rather production procedures.
- 5. The defect can readily be fixed in place. There was no need for replacement of columns which would have been extremely costly.

Case History #2. Failure Analysis of a Conveyor Drive Shaft

Introduction

A German-made steel coal-conveyor drive shaft was submitted for root-cause failure analysis. The shaft had cracked in service.

Visual Examination

The as-received drive shaft is shown in figure 1. A transverse crack had passed through the right keyway near the center of the keyway length, at the red arrow, on line A-A'. The shaft was cut so that the crack could be opened to expose the mating fracture surfaces. The fracture surfaces were found to be corroded; They

were cleaned using a hydrochloric acid solution to enable them to be examined more closely. The fracture surfaces were relatively smooth-textured, flat and perpendicular to the axis of the shaft and the keyway. Two sets of concentric crack arrest marks were found on the fracture surface. One set of crack arrest marks was concentric to each corner of the keyway as shown in figure 2.



Chemical Analysis

A quantitative chemical analysis was performed on the broken shaft material and the results are given in the table below. The shaft conformed to the chemical requirements of the German grade 30 Ni Mo Cr8 alloy steel called for in the shaft specifications.

Element	Shaft	30 NiMoCr8
Carbon	0.28	0.26-0.34
Manganese	0.45	0.3-0.6
Phosphorus	0.017	0.035 Max
Sulfur	0.009	0.035 Max
Silicon	0.30	0.4 Max
Chromium	1.84	1.8-2.2
Nickel	1.86	1.8-2.2
Molybdenum	0.32	0.3-0.5
Vanadium	0.010	-
Copper	0.22	-
Aluminum	0.006	-

Analysis (wt%)

Tensile Property Testing

A tensile test specimen was machined from the broken shaft and tested in accordance with the methods of ASTM A 370. The results are given below. The yield strength was determined at 0.2% offset. The shaft conformed to the tensile property requirements for the German grade 30 NiMoCr8 steel for a section size between 160 and 250 mm.

			30 NiMoCr8
	Shaft(PSI)	Shaft (^N /mm ²)	<u>160-250mm</u>
Yield Strength	134,100	924.5	700 ^N / _{mm} ² MIN
Tensile Strength	151,800	1046.6	900-1100 ^N / _{mm} ²
% Elongation in 2 Inches	17.5	17.5	12.0 MIN
% Reduction of area	60.0	60.0	50.0 MIN

TENSILE PROPERTIES

Rockwell Hardness Survey

A cross section through the shaft diameter was cut adjacent to the crack and surface ground to provide flat, parallel surfaces. Rockwell C scale hardness measurements were made at $^{1}/_{8}$ inch intervals across the shaft diameter. The results are plotted below. They show the hardness to be quite consistent across the shaft section.



Impact Property Testing

A set of U notch impact test specimens were machined from the shaft and tested at +73°F. The results are given in the table below.

Specimen No.	%Shear	%Cleavage	Lateral Expansion (mils)	Impact Strength (Ft. Ibs.)
1	10	90	12	25
2	15	85	13	24
3	15	85	12	24

Impact Properties

- These results show that the material is not brittle and
- that it conforms to the specifications.



Metallographic Examination

Transverse cross sections through each corner of the keyway were prepared for metallographic examination. Secondary cracks were found in each corner of the keyway in the as-polished condition as shown in Figure 3 (approx. 50X).

Secondary cracks were also found at the exterior surface adjacent to the intersection of the keyway and the exterior surface as shown in Figure 4 (approx. 50X). The surfaces of the shaft were rough in texture because of corrosion. In addition many of the secondary fatigue cracks were found to be wide and wedge shaped which is characteristic of corrosion fatigue. The microstructure consists of dark-etching tempered martensite. No surface decarburization was found.

Conclusion

The conveyor drive shaft failed as a result of corrosion fatigue in bending. Failure was initiated at both corners of the keyway. Numerous secondary fatigue cracks were observed and indicate the presence of a large number of stress concentration sites caused by corrosion pitting of the surface. Fatigue is the progressive failure of a component subjected to repeated or fluctuating strains at stress levels below the yield strength of the material. Fatigue cracks initiate at locations of maximum local stress and/or minimum local strength. The shaft conformed to the specified chemical and

tensile properties for the material. The use of protective coatings or shielding the shaft from the corrosive environment should prolong the service life of the drive shaft.

IMPORTANT FAILURE ANALYSIS PRINCIPLES REPRESENTED IN THIS CASE HISTORY

1. The analysis showed that the product involved failed because it could not withstand the environment in which it was used. Thus the materials specification for the product should have included either:

- surface corrosive prevention by a protective coating or
- selection of a material which would be resistant to the corrosive environment.
- 2. Corrosion fatigue can cause failure below the yield strength.
- 3. Corrosion fatigue should be distinguished from fatigue initiating from pits. In corrosion fatigue the corrosion activity is in the crack.

Case History #3. Metallurgical Failure Analysis of A Welded Hydraulic Cylinder

INTRODUCTION

A failed hydraulic cylinder was submitted for examination along with a working drawing giving the dimensions of the cylinder. The failure had occurred at the circumferential weld at the closed end of the cylinder (red arrow, Figure 1). The cylindrical barrel was specified to be grade 1026 and the end cap to be grade 1045, both plain carbon steel. The cylinder assembly had been fabricated by stick welding using a 7018 electrode. We were requested to determine the cause of failure.



Figure



Figure 2, end of cylinder with cap off. Figure 3, cap with fracture through weld on

chamfer

VISUAL EXAMINATION

The as-received sections of the failed hydraulic cylinder are shown in Figures 1, overall about 3 feet long and 4 inches in diameter. The failure occurred through the circumferential weld at the closed end of the cylinder (red arrow, Figure 2). The mating fracture on the end cap section was examined at moderate magnifications using a stereomicroscope. The failure was a shear tensile fracture. The fracture had propagated through the weld metal as shown. The fracture was initiated simultaneously at all locations around the circumference with no preferential sites of fracture initiation. Gas porosity was found at only one location as shown in Figure 8. There were no fracture surface features to indicate that the fracture had preferentially initiated at this point.

The end cap on the cylinder was measured to be 0.502 inches thick. The remains of an approximately-45-degree-chamfer were found around the entire circumference of the end cap as shown between the red lines in **Case History #4.** Aircraft Component **Failure Analysis** Figure 3. This chamfer was 0.157 inches deep, measuring from the exterior side of the end cap to the bottom of the chamfer. The fact that this chamfer is still visible after welding indicates insufficient weld penetration at the weld root, thereby decreasing the size and thus the strength of the weld. The weld deposit, measured at the fracture surface, ranged from 0.046 and 0.156 inches thick.

SEM EXAMINATION

Part of the fracture surface was removed from the cap and examined at higher magnification using a scanning electron microscope (SEM). The fracture surface features are similar at all locations examined. They consisted of numerous elongated dimples as shown in Figure 4. The elongation of these dimples is characteristic of a tensile shear failure.





Figure 4. Elongated dimples Figure 5. Localized plastic deformation in fracture surface. during fracture of weld surface (red arrow)

METALLOGRAPHIC EXAMINATION

A transverse cross section through the failed weld was prepared for metallographic examination. The microstructure of the end cap consisted of dark-etching pearlite plus white-etching ferrite. This microstructure is consistent with a grade 1045 carbon steel. The microstructure of the host-affected zone (HAZ) consisted of dark-etching tempered martensite plus white-etching grain boundary ferrite. The weld was made with a single pass. At the fracture surface the weld metal exhibited localized plastic deformation as shown in Figure 5.

MICROHARDNESS INSPECTION

In the as-polished condition a Knoop microhardness inspection was performed in both the weld metal and in the heat affected zone using a 500-gram load. The results are given in the accompanying table. The approximate ultimate tensile strength of the weld metal deposit is above the minimum required value of 70,000 psi, as determined by conversion from Knoop hardness to tensile strength using Table 2 of the AWS A 5.1.

LOCATION	KHN	Approx. HRB	Approx.	Approx.
(inches from interface)			HRC	TS (KSI)
Weld 0.010	227	95.2		
Weld 0.030	214	92.6		
Weld 0.050	227	<u>95.2</u>		
		average 94.3		98.6
HAZ 0.004	368		36.8	
HAZ 0.008	302		28.7	
HAZ 0.012	298		28.1	
HAZ 0.016	272		24.0	
HAZ 0.020	291		27.1	
HAZ 0.024	285		26.2	
HAZ 0.028	282		25.7	
HAZ 0.032	291		27.1	
HAZ 0.036	306		29.3	
HAZ 0.040	305		29.1	
BASE METAL	235	96.8		
BASE METAL	268		23.3	
BASE METAL	270		23.7	

Knoop Microhardness

CHEMICAL ANALYSIS

A chemical analysis was performed on chips machined from the weld crown. The results are given in the table below. The weld metal conforms to the chemical composition requirements for grade E7018 welding electrode as specified in AWS A 5.1 Table 7. The weld metal also conforms to the chemical composition requirements for several other grade E70xx welding electrodes.

ELEMENT	WELD METAL	AWS A 5.1 E 7018
Carbon	0.164	NS
Manganese	1.01	1.60 MAX
Phosphorus	0.015	NS
Sulfur	0.013	NS
Silicon	0.48	0.75 MAX
Chromium	0.06	0.20 MAX
Nickel	0.04	0.30 MAX
Molybdenum	<0.1	0.30 MAX
Vanadium	0.04	0.08 MAX

Chemical Analysis (wt%)

NS = Not Specified

CALCULATION OF WELD SIZE

The required thickness for the weld under static loading conditions was calculated as follows:

Given an end cap diameter of D=4.25 inches

Given an average fractured weld thickness of t=0.0625 inches Given an operating hydraulic pressure of 1250 lbs./inch²

Force = $(1250 \text{ lbs./in}^2) \pi (D/2)^2 = 35,470 \text{ lbs.}$

Area of fractured weld = π Dt = 0.834 in.²

Stress = $F/A = 17,735 \text{ lbs./in}^2$

Ultimate strength = 70,000 lbs./in² minimum for E7018 electrodes.

As per ASME Section 8 Division I the allowable stress (Sm) should be 1/4 of the ultimate strength. Furthermore, since the weld failed in shear an additional factor of 1/2 should be applied as follows:

 $Sm = 70,000 \text{ lbs/in}^2/(4)(2) = 8750 \text{ lbs/in}^2$

The ratio of the actual stress to the allowable stress = $S/Sm = 17,735 \text{ lbs/in}^2/8,750 \text{ lbs/in}^2 = 2.430$

Therefore the design weld thickness should be approximately 2.5 times the actual average weld thickness of 0.0625 inches or

(2.5) (0.0625 inches) = 0.156 inches (ie 5/32 inch)

The actual chamfer was measured to be 0.157 inches deep. This should also be the weld depth for static loading conditions.

CONCLUSION

The failure of the hydraulic cylinder occurred as a tensile shear fracture solely within the circumferential weld at the end cap. The weld did not have enough strength to support the applied loads. The failure occurred as a single event with fracture occurring at all locations around the circumference of the cap simultaneously. The failure is attributed to insufficient depth of weld penetration. The reduced cross-sectional area at the weld was unable to support the applied load. This conclusion is corroborated by the continued presence of the machined chamfer at the weld root. The chamfer should have been covered by the weld. It is recommended that during manufacturing of the part that the weld be completed in two passes to ensure that sufficient penetration is achieved at the weld root.

IMPORTANT FAILURE ANALYSIS PRINCIPLES REPRESENTED IN THIS CASE HISTORY

The root-cause of this failure was identified as an incorrectly applied process, so a change in the process was recommended. The process specified for welding the top of a hydraulic cylinder was inadequate to create a good weld. Changing the process would change the outcome and eliminate the failure. This is a sound root-cause determination.

Case History #4. Aircraft Component Failure Analysis

Introduction

Both halves of a broken steel pin were submitted for examination. The sample was identified as Left Hand Main Landing Gear, AC 809. At a later date an unbroken pin identified as Right Hand Main Landing Gear, AC 809 was also submitted. We were asked to determine the mode, not the cause, of failure.



Visual Examination

The two as-received pins are shown in figure 1 where an arrow shows the location of failure. The failure occurred in a 1.230-inch-diameter cylindrical part of the pin which was corroded on the outer surface. One side of the fracture surface is shown in figure 2, below.





Convergent chevron patterns identified the fracture initiation site on the outside surface. The fracture initiation site is marked by a red arrow in figure 2. Most of the fracture surface had been darkened by corrosion. A series of coarse low cycle fatigue crack arrest marks was identified at the ends of the two discolored crack-propagation fronts. The exterior surface of the 1.230 inch diameter cylindrical part of the pin contained corrosion pits. Corrosion pitting was also visible at the fracture initiation site. The fracture surface profile is shown in figure 3.

A circumferential ridge and depression were found in the cylindrical surface. A similar ridge and depression were seen in the unbroken pin. By comparing the cylindrical parts of the two pins it was found that the fracture of the broken pin had initiated at the circumferential depression.

The part of the fracture surface containing the fracture initiation site was macroetched for 30 seconds in a hot aqueous 50 percent hydrochloric acid solution to remove the corrosion products. The clean surface showed the fracture initiation site, as seen in figure 3.



Metallographic Examination

A transverse cross section through the fracture initiation site was prepared for metallographic examination. The fracture surface profile is relatively flat. No crack branching was seen. The microstructure consists of dark-etching tempered martensite. No gross plastic deformation was observed at the fracture initiation site.

Conclusion

The pin failed as a result of fatigue which initiated at the outside cylindrical surface. This surface exhibited wear and corrosion pitting. The fracture initiated at a shallow circumferential groove. The corrosion of the fracture surface appears to have occurred subsequent to the fracture. No evidence of stress corrosion cracking was observed

IMPORTANT FAILURE ANALYSIS PRINCIPLES REPRESENTED IN THIS CASE HISTORY

- 1. In this case, examination of the fracture surface and the microstructure were sufficient to reveal the mode of failure. Determination of the cause of failure would require a knowledge of the use conditions.
- 2. Fatigue failures are sometimes quite subtle. The materials used in the parts that fail may be completely as-specified, but the service conditions exceed their long-term ability to resist the stresses applied during use.

Case Hstory #5. Cap Screw Assembly Failure



Cap screws in a robot designed for the removal of parts after they are molded in an injection-molding machine failed as a result of cyclic loading and possible vibrations in the system. Redesigning the system to minimize fatigue sensitivity was recommended. Some of the failed screws are shown at left, above.





A side view of the

system is depicted to the left, below. The robot has a horizontal beam (teal color in drawing), along which a mobile device traverses to move the parts from the molding machine to conveyor belts or stacking devices. The entire robot is secured to the injection-molding machine on the stationary platen (blue plate below left end of beam) by grade 8 socket cap screws. Similar screws are used to connect the top of the riser to the robot beam. Several of these cap screws were failing during normal operations.

Before the system was to be redesigned non-linear finite element analysis was performed using three dimensional models of the main components of the robot assembly. See below. These models were subjected to static and dynamic loads. The dynamic reaction load of the robot operation was applied to the models to determine the cyclic stresses in the cap screws connecting the riser to the beam. The motor assembly weight, the mobile weight and the moving weight were applied as individual forces.

Two finite element models were constructed to simulate normal operations. One model simulated a fully extended robot arm for removing the part in normal operations. The second model simulated conditions when the arm was closest to the riser for delivering the part.



Results

The simulation found that preloading (torquing, putting the screws on tightly) the cap screws increased the stress resistance of the system and consequently, the service life of the system would lengthen. The table on the following page shows the stress resistance of the 8 cap screws assuming preloading conditions. The best result was with 90 ksi preloading. The difference can be explained by alternating stresses that are present with and without preloading. Sufficient contact pressure prevents alternating stress and thus, a higher preload can withstand greater stress.



IMPORTANT FAILURE ANALYSIS PRINCIPLES REPRESENTED IN THIS CASE HISTORY

Finite element analysis showed that a very simple adjustment (tightening the screws in the assembly) would solve a vexing problem without a major redesign of the system.

Case History #6. Aircraft Engine Failure



The fan section of a turbine aircraft engine contains fan blade separators known as annulus fillers, or simply as spacers. The material specification of an annulus filler is usually 7075 T56 aluminum alloy with a painted coating. The highlighted area in the drawing at left represents the annulus filler component, of which there are 22 in this engine. Annulus fillers are attached to an outer rim (rotor disc) by means of insertion.

A B757-200 experienced failure of its right engine during takeoff. The engine was shut down and the aircraft returned for investigation. Inspection revealed that one of the fan section annulus fillers had detached into the fan case area causing the right engine failure. An ultrasonic inspection six months earlier had not detected cracks on the fillers.

The fractured lug section was removed from the damaged engine and sent to Matco to perform failure analysis. The analysis found low cycle fatigue as the failure mode in combination with tensile overloading occurring during the intergranular propagation of the crack. This irregularity resulted in an atypical crack surface topography with non-parallel fatigue striations intermixed with brittle overload regions. As the photograph at right illustrates, fatigue striations in the annulus filler point in several different directions (the arrows illustrate the direction of fatigue striations). Typical fatigue striations for annulus fillers more closely resemble the photograph below with parallel striations.





Ultrasonic inspection will normally recognize fatigue cracks having parallel striation patterns, but highly irregular patterns will not be recognized without special effort. The failed annulus filler contained a cup pattern fatigue crack, an atypical crack. Such a crack can only be detected at a 45 degree angle. This is because the exploratory beam is diverted away from the jagged crack allowing the return beam to register a location away from the target area, away from the fatigue crack. The fracture surfaces of two annulus fillers illustrate this point. Both showed fatigue cracking but the cup shaped pattern crack to the left went undetected by ultrasonic detection because although the exploratory beam (yellow arrow) was in the appropriate detection area, the return arrow (green) had been displaced. A flat fatigue crack is easily detectable by ultrasonics as shown below, at right.



In addition to an undetectable fatigue crack, loading conditions on the annulus filler were not well understood by part designers. Not only were there centripetal forces associated with the engine acting on the filler during take off and anticipated downward loading, but an additional loading condition was present. The presence of brittle overload surfaces on the fracture indicates this. Stress concentration would be especially great at the area of fracture (the mating end of the annulus filler). Dynamic modeling could have discovered this design error.

IMPORTANT FAILURE ANALYSIS PRINCIPLES REPRESENTED IN THIS CASE HISTORY

This failure analysis shows the importance of integrating modeling and stress analysis in component design long before the component is put into service. Proper choice of materials cannot overcome design deficiencies.

Another lesson Learned from this analysis is that although ultrasonic inspection will normally recognize fatigue cracks having parallel striation patterns, but highly irregular patterns may not be recognized without special effort. The failed annulus filler contained a cup pattern fatigue crack, a typical crack. Such a crack can only be detected at a 45 degree angle.