



PDHonline Course M118 (3 PDH)

Introduction to Metallurgical Failure Analysis

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Failure Analysis

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Course Outline

This three hour online course discusses the various types of failure mechanisms and the process of conducting a metallurgical failure analysis. Failure Analysis is one of the most useful techniques for ensuring the safety and reliability of products and plant facilities/components. The main benefits are the prevention of failure in a similar equipment, and improvement in useful service life through design or material modifications. This course includes a multiple-choice quiz at the end.

Learning Objective

At the conclusion of this course, the student will:

Have information about the various factors that needs to be considered in material selection, design and the service environment.

Be able to recognize some of the basic features and characteristics of different failure mechanisms.

Be knowledgeable in the laboratory testing methods and procedures that can help determine the cause of the failures.

Course Introduction

Some of the most typical causes of failures shall be discussed along with the general tools and techniques of failure analysis.

Any one or a combination of these factors can contribute to the failure of a part.

Design deficiencies
Improper material selection
Inadequate or incorrect process specifications
Defective material
Defective manufacturing and/or processing
Improper or insufficient quality control inspection
Service conditions that exceed design limitations

Course Content

Failure analysis is a technique where facts are gathered through investigations and testing and analyzed to determine the root cause of a product failure. The common approach includes:

1. Obtaining background information such as service/operating conditions, manufacturing history, discussions with the end-user and/or eye witness to the failure,
2. Site visit to the scene of failure (if applicable), visual examinations, photo documentation,
3. Nondestructive examination of the parts to identify nature and presence of defects,
4. Fractographic exam to determine failure mode,
5. Destructive tests (chemical, metallurgical, mechanical) to verify conformity to specifications,
6. Evaluation of all data to draw a conclusion about the failure mechanism.

Typically failures can be attributed to any one or a combination of the following mechanisms and may involve improper material selection, design, fabrication, processing and/or operation along with exposure to extreme environments that they are not designed for.

Overload (single load events)

Tension/torsional/shear loads
Ductile versus brittle failure modes

Fatigue

Unidirectional/reverse bending/torsional
Characteristics (low cycle/high cycle)

Corrosion

Several corrosion mechanisms, which will be discussed in detail below, may initiate failures.

Wear

Abrasion or wear is loss of material caused by movement of an abrading material over the surface of a component. Wear failures are challenging to analyze just like the corrosion failures because numerous factors can be contributing to the mechanism at the same time. Furthermore, the material deficiency, which may have resulted in the excessive wear, to begin with (i.e. soft spot due to inadequate heat treating) may no longer be present to analyze. The remaining material may not necessarily be representative of the worn (missing) material

General (uniform) corrosion

Corrosion is an undesired chemical action that attacks materials in such a way as to degrade their properties or render them ineffective. General corrosion may result in excessive material loss that weakens a component until it either deforms or fractures under load. Majority of the corrosion failures do not involve fractures. The resulting failure may be in the form of a leak, such as in piping. Even the so-called corrosion resistant materials such as aluminum, stainless steels and titanium that obtain their resistance from a thin adherent oxide film that develops on their surfaces are susceptible to attack under certain conditions. When they are exposed to chemicals that can break down this passive oxide layer, corrosion initiates and progresses in a relatively short time.

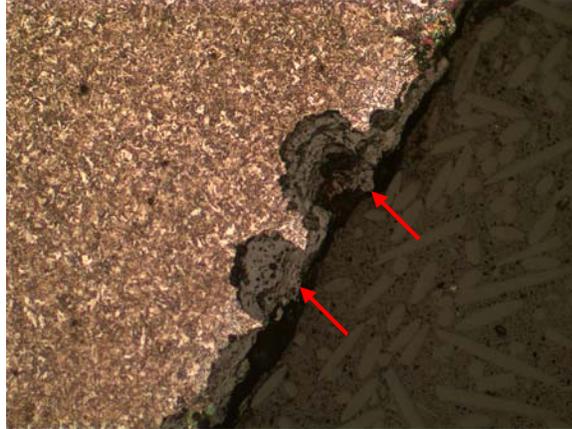


General Corrosion

Localized (pitting, crevice) corrosion

Pitting corrosion is a localized form by which attack can lead to perforations in the material. It is considered to be more dangerous than uniform corrosion because it may be difficult to detect and also design against. A small pit with insignificant overall metal loss can lead to the failure of a complex system. Pitting is usually initiated by the breakdown of a protective film (passive oxide layers or

coatings). Aggressive environments or coating or material defects are the main factors leading to pit formation. Crevice corrosion is usually associated with a stagnant solution in a shielded area between two surfaces such as those formed under washers, fastener heads, gaskets, lap joints, clamps, etc. Changes in local chemistry within the crevice by depletion of oxygen, build up of aggressive species (chlorides) or by shifting to acidic conditions can all help initiate the corrosion process. It may be possible to prevent this type of attack by designing crevice corrosion out of the system. Using welded instead of bolted joints or using solid non-absorbent gaskets are some examples.



Pitting Corrosion

Selective leaching

This type of corrosion is an example of dealloying in which one of the constituents of an alloy is preferentially removed by corrosion. Dezincification in brass (copper zinc alloy) and graphitic corrosion of cast iron are two common examples of this type of attack. Typically brass alloys with zinc content of over 15% are susceptible to this type of attack where zinc selectively leaches out leaving a porous copper-rich structure with little or no strength.

Galvanic corrosion

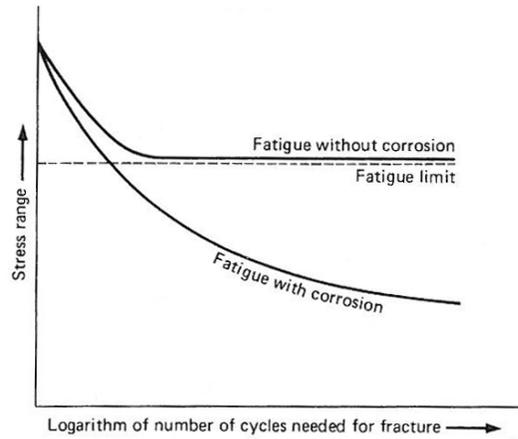
Galvanic corrosion occurs when dissimilar metals, with a potential difference are coupled together in the presence of an electrolyte. The less noble metal becomes the "anode" and preferentially corrodes. For example, aluminum coupled with stainless steel in the presence of moisture will get consumed with time due to galvanic corrosion. The galvanic couples are also used in corrosion prevention; magnesium or aluminum anodes are used on underground pipelines, offshore rigs, and domestic water heater tanks for cathodic protection. In galvanized steel, the zinc coating (i.e. the anodic coating) protects the steel substrate by preferentially corroding. These are sometimes named sacrificial coatings. If dissimilar metals cannot be avoided due to design requirements and when the electrolyte (e.g. moisture) cannot be eliminated, then the solution may be to use an insulator between the two metals. The basic list of materials and their relative locations in a galvanic series is shown below. In a strict sense a galvanic series must be set up for different electrolytes, but the differences are rather minor. The series for seawater is usually considered universal in most applications.

**Galvanic series in
seawater at 25 °C (77 °F)**

- Corroded end (anodic, or least noble)**
- Magnesium
 - Magnesium alloys
 - Zinc
 - Galvanized steel or galvanized wrought iron
 - Aluminum alloys
 - 5052, 3004, 3003, 1100, 6053, in this order
 - Cadmium
 - Aluminum alloys
 - 2117, 2017, 2024, in this order
 - Low-carbon steel
 - Wrought iron
 - Cast iron
 - Ni-Resist (high-nickel cast iron)
 - Type 410 stainless steel (active)
 - 50-50 lead-tin solder
 - Type 304 stainless steel (active)
 - Type 316 stainless steel (active)
 - Lead
 - Tin
 - Copper alloy C28000 (Muntz metal, 60% Cu)
 - Copper alloy C67500 (manganese bronze A)
 - Copper alloys C46400, C46500, C46600, C46700
(naval brass)
 - Nickel 200 (active)
 - Inconel alloy 600 (active)
 - Hastelloy alloy B
 - Chlorimet 2
 - Copper alloy C27000 (yellow brass, 65% Cu)
 - Copper alloys C44300, C44400, C44500
(admiralty brass)
 - Copper alloys C60800, C61400 (aluminum bronze)
 - Copper alloy C23000 (red brass, 85% Cu)
 - Copper C11000 (ETP copper)
 - Copper alloys C65100, C65500 (silicon bronze)
 - Copper alloy C71500 (copper nickel, 30% Ni)
 - Copper alloy C92300, cast (leaded tin bronze G)
 - Copper alloy C92200, cast (leaded tin bronze M)
 - Nickel 200 (passive)
 - Inconel alloy 600 (passive)
 - Monel alloy 400
 - Type 410 stainless steel (passive)
 - Type 304 stainless steel (passive)
 - Type 316 stainless steel (passive)
 - Incoloy alloy 825
 - Inconel alloy 625
 - Hastelloy alloy C
 - Chlorimet 3
 - Silver
 - Titanium
 - Graphite
 - Gold
 - Platinum
- Protected end (cathodic, or most noble)**
-

Corrosion fatigue

This is a mechanism where the combined effects of cyclic stress and corrosion are acting on a component. Preventative measures are to reduce the stress level and provide corrosion protection. The general effect of corrosion on fatigue failures may be illustrated as shown in the fatigue curve below. More detailed discussion of the S-N curve (stress versus number of cycles to failure) will be included in the fatigue section.



Stress corrosion cracking (SCC)

SCC is the formation of cracks through the simultaneous action of stress and a corrosive environment. The stresses that lead to SCC may be external or residual stresses from processing. Certain materials are more susceptible to this type of attack when exposed to specific environments. Austenitic stainless steels or aluminum alloys in chloride containing environments and copper alloys in ammonia are a few detrimental alloys/environment combinations.



Micrograph showing transgranular SCC in Stainless Steel



Micrograph showing intergranular attack

Sample handling and preservation

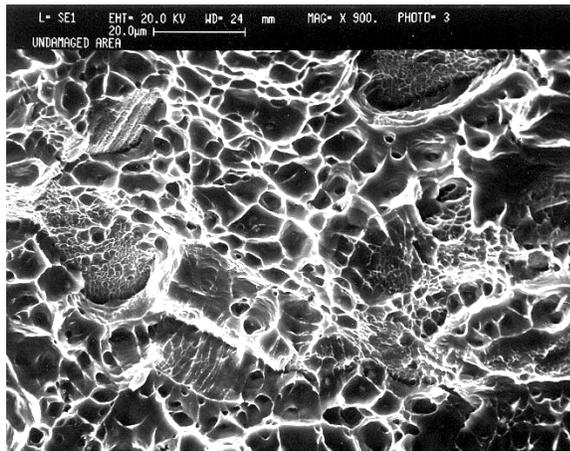
Failed components must be handled very carefully since important evidence can sometimes be destroyed by rough handling or exposure to corrosives before the analyst can observe the failure. For instance, shipping the broken parts in a box, without any protective wrapping where the parts are free to move can make the analysis impossible.

If mechanical failure:

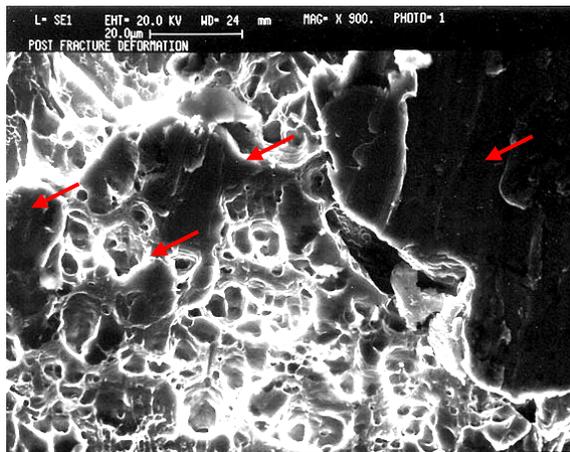
Don't ever fit the two broken halves together, this will damage the surface features that can provide very useful information

If failure is not corrosion related, a rust preventative (such as WD40) may be used on the fracture surfaces to prevent corrosion damage that can destroy surface information. If corrosion is the suspect cause then it is best not to coat the surface with anything.

Pack carefully to prevent further damage



SEM micrograph showing undamaged area



SEM micrograph showing post fracture damage due to smearing of the surfaces

If corrosion failure:

Don't touch or otherwise contaminate the sample since chemical analysis of residue or surface deposits can be very instrumental in determining what corrosive species were the culprits

Store in a clean bag or envelope to preserve the evidence and prevent contamination

Identify parts appropriately

Photodocument the part and the surrounding area before it is disturbed in any way

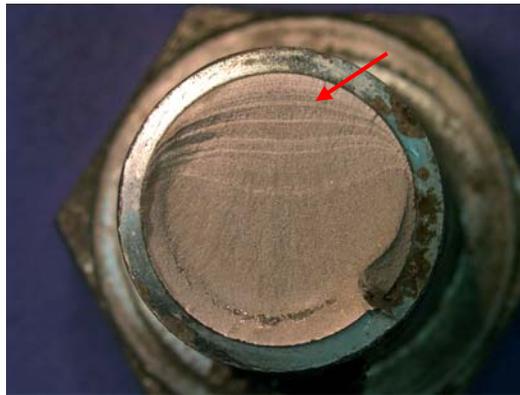
Background Information

Obtain detailed information about part so that proper test procedures can be selected to analyze the cause of the failure. The following information should be gathered as a minimum:

Design drawings, material specifications, manufacturing and fabrication techniques used, codes and specifications governing the manufacturing and inspection of the component, erection or installation procedures, service environment including temperature and pressure, operating parameters (loads, frequency of loading), time in service, maintenance history.

Visual Examination

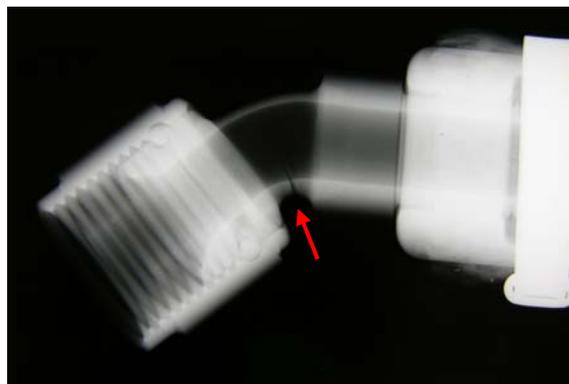
During receipt inspection, the analyst should verify the number of parts, note and photodocument the condition of the parts. As-received photo documentation is very useful especially once the parts are sectioned for testing. Documentation should be conducted throughout the analysis so that the information can later be shared with and described to all concerned parties. Color photography is recommended to illustrate the contaminants and show discoloration or temper marks. Macro examination using stereomicroscopy (5-50X) will allow determination of the failure origin, presence of stress concentrators, direction of crack propagation and other physical data. An example is shown below where a fatigue crack initiated in the fastener (arrow) and progressed until the remaining cross sectional area could no longer support the load and failure occurred via ductile overload.



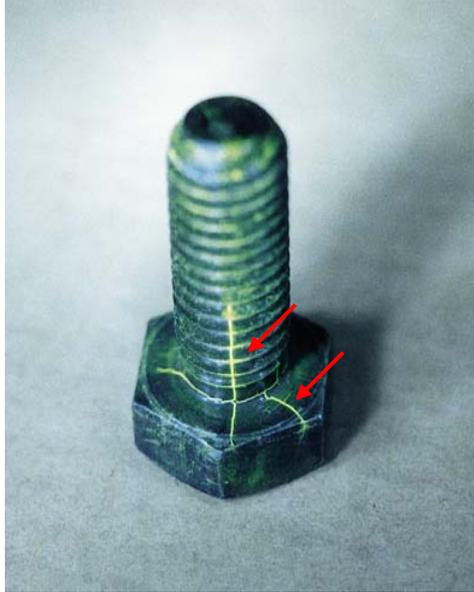
Bolt fracture surface

Nondestructive testing

Nondestructive testing techniques such as Ultrasonic (UT), magnetic particle (MT), radiography (RT), penetrant (PT), eddy current (ET) are very instrumental in detecting surface and internal anomalies in a component. Cracks, hot tears, cold shuts, shrinkage porosity, voids, lack of fusion, delaminations, inclusions and numerous other defects can be detected using these techniques without impairing the parts usefulness. Type of material and the geometry will dictate the best method to use.



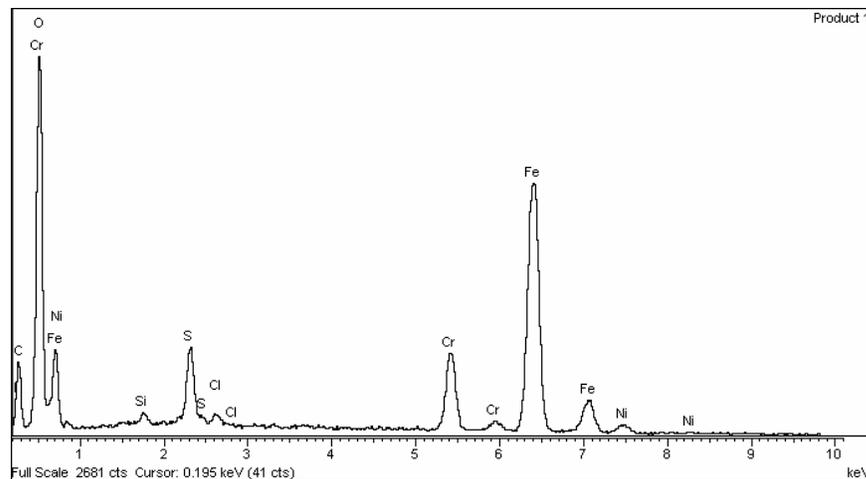
Radiography (x-ray) shows the crack location in tubing



Magnetic particle testing reveals the quench cracks in this high strength steel bolt.

Chemical and Mechanical Testing

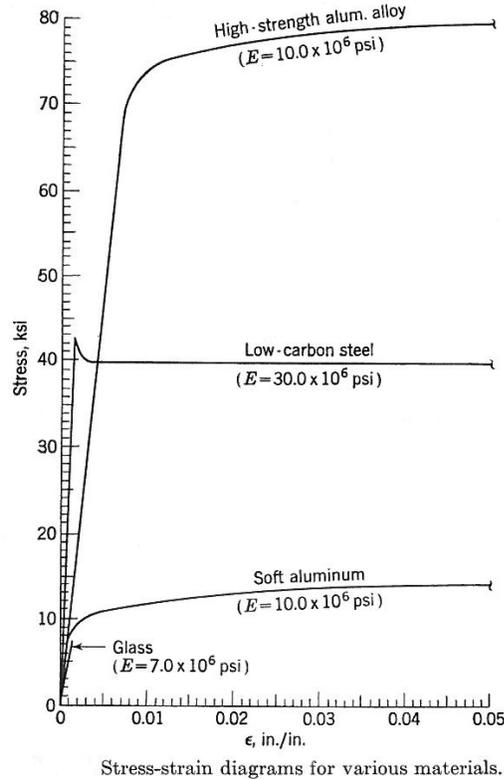
Alloy identification should be performed so that the results can be compared to specified requirements or industry standards. Some failures occur because of material mix-ups at the mill, warehouse or the fabrication stage. In addition to the bulk material analysis using optical emission spectroscopy (OES) or inductively coupled plasma (ICP) techniques, analyze corrosion products, inclusions, surface deposits and platings/coatings if present using energy dispersive x-ray analysis (EDS) during scanning electron microscopy examinations. Additionally, x-ray diffraction (XRD) analysis of corrosion deposits may be utilized for phase identification of crystalline materials and can provide information on unit cell dimensions. The analyzed material is finely ground, homogenized, and average bulk composition is determined. This technique will compliment the EDS results by identifying if the individual elements such as sodium and chlorine detected are actually present in the form of sodium chloride.



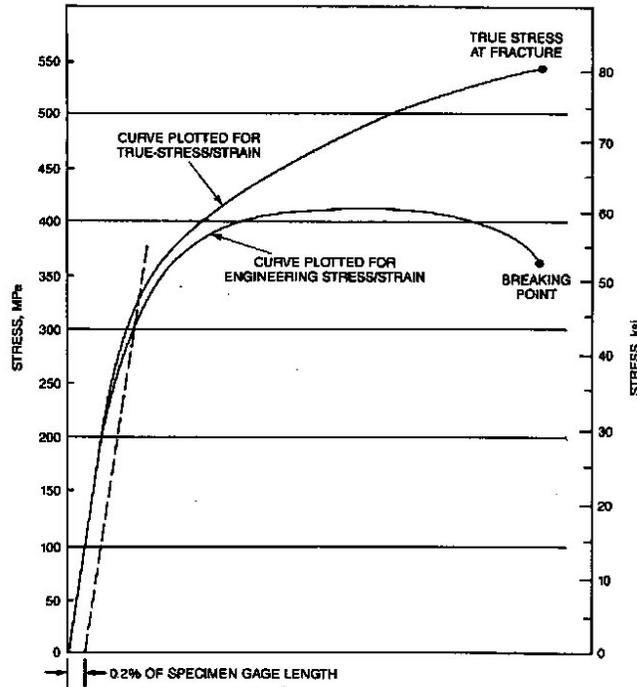
EDS spectrum showing the typical results of the technique, which can provide elemental make up information in a nondestructive manner on limited material or micron size particles. Chart shows presence of iron, chromium, nickel, sulfur and carbon.

Determine mechanical properties and compare with requirements. Material properties such as, strength, hardness, toughness and ductility are usually specified by the design engineer.

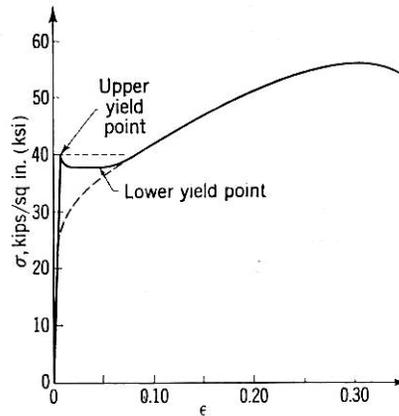
A stress-strain chart obtained through tensile testing can provide information regarding the ultimate tensile strength, yield strength, % elongation, and % reduction in area. The behavior of some common materials and their corresponding modulus of elasticity are shown below.



If the initial portion of the stress-strain graph is linear, as in the case of materials shown above, that is the strain is proportional to stress, then the material can be considered to have a modulus of elasticity (or Young's modulus, E). It is calculated as the ratio of stress to strain, and its unit is psi (pounds per square inch). A very rigid material will have a high E value.



Stress strain diagram showing the behavior of a ductile material during a tensile test. The yield point (the transition from elastic to plastic range) is typically determined using the 0.2% offset method when there is not a sharp transition. Tensile strength corresponds to the break (fracture) point. Percent elongation is usually determined within a gage length (on a standard tensile specimen this is the 2 inch reduced section, which is put back together after the test and the amount of stretch within this gage length is determined as the %E). Reduction in area is another way of expressing the ductility of the material and is determined by comparing the final cross sectional area at the fracture site to the original stress area of the specimen.



Most of the steels used for ordinary structures have carbon contents in the order of 0.25 percent and are often called low-carbon or mild steels. These steels typically display two yield points as shown above. The first yield point (upper yield point) is higher than the second and the yield drops dramatically after the upper yield point. There is practically no plastic strain up to this point, where certain internal restraining effects are abruptly released (e.g. dislocations generated by the initial elastic elongation) and plastic yielding begins, dropping the stress necessary for elongation. The deformation occurring throughout the yield-point elongating is heterogeneous in a way that discrete

localized bands of plastic deformation, often readily visible, appear on the specimen. These bands are generally at approximately 45° to the tensile axis. They are usually called Luder bands, Hartmann lines or stretcher strains. Coincident with the formation of the first band, the load drops to the lower yield point. The yield point gap is followed by plateau in stress-strain curve called yield point elongation when bands propagate along the length of the specimen. Further loading then causes increasing strain and the behavior displayed in the above graph is exhibited.

The yield point behavior depends upon many metallurgical variables: the alloy composition, impurities, prior cold working, time at austenitizing temperature, etc. One factor known to reduce the difference between upper and lower yield point is coarsening of the grain size. The presence of a sharp yield point simplifies certain design problems since it represents a definite upper limit for the general stress level in the structure, because if it were reached a large permanent deflection would occur, if not failure. For all these reasons the lower yield point stress is taken usually as a conservative value, and the term "yield stress" implies the lower yield stress for a material in which an upper yield point exists.

The other most common test, especially if the component is too small and not suitable for tensile testing, is the hardness test. These results may also be used to estimate approximate tensile strengths. Typical methods include: Brinell, Rockwell (e.g. HRC, HRB, HRF), superficial Rockwell (e.g. HR30T, HR15N). These techniques employ various test load and indenter combinations. For hard materials the most common scale is the Rockwell C scale using a diamond tip and a 150 kg load. Softer materials may be tested using the Rockwell B scale (using a 1/16" diameter ball and 100 kg load). Brinell may be used for both hard and soft materials with either a 3,000kg or a 500kg load with a 10 mm carbide ball. This is the preferred scale for cast irons since the structure of the cast iron contains soft graphite (in the form of flakes or nodules) and a relatively hard matrix; the large indenter utilized in Brinell testing allows sort of an average hardness to be determined. Smaller tips or lighter loads may give inconsistent or nonuniform values. For extremely thin sections or case hardened parts Microhardness (e.g. Knoop, Vickers using diamond tips and typically loads around 500 grams) are utilized. Besides the small or very thin samples microhardness testing –which has to be conducted on polished specimens- is also used to determine case depths, evaluate cold working effects and properties of heat affected zones (HAZ) of weldments.

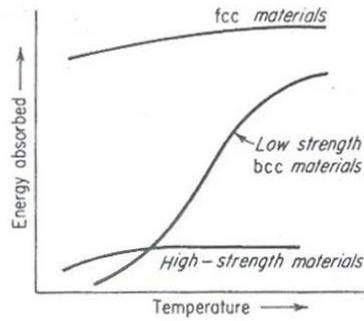


Rockwell hardness testers

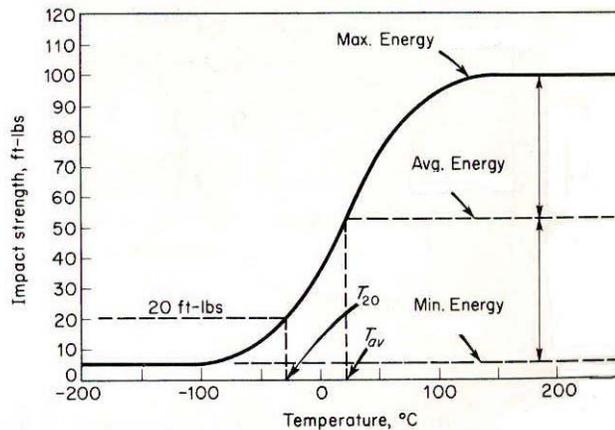


Microhardness testers

Charpy impact testing is one the most common ways of determining the toughness of a material. It is also one of the most revealing tests for detecting the low temperature brittleness in otherwise ductile materials. Charpy test uses a small specimen, typically with a v-notch in it. The specimen is supported horizontally at its ends in the impact machine and struck on the side opposite to the notch by a swinging pendulum type hammer. The energy dissipated by fracturing the specimen is measured in ft-lbs and can be plotted against the test temperature. As shown in the graph below carbon and alloy steels behave in a unique manner compared to other materials (e.g. aluminum or stainless steels) and can fail in a brittle manner when subjected to low temperatures. This ductile to brittle transition occurs abruptly when certain temperatures are reached.

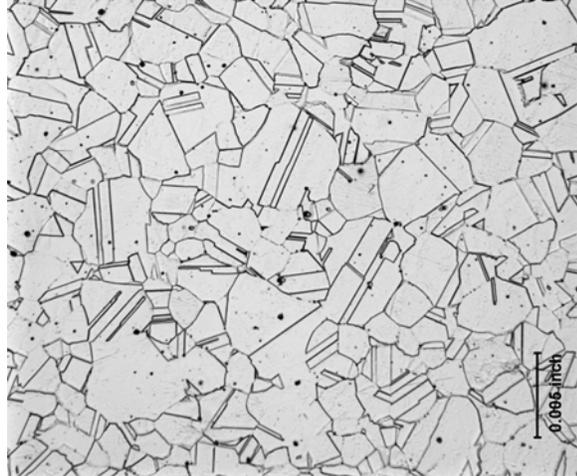


For some heats of steel this transition may take place at around ambient temperature. If the failure is determined to be brittle then the impact properties of the material at the expected service temperature should be determined. Series of Charpy impact tests may also be conducted over a temperature range to determine the ductile-to-brittle transition temperature. The graph below illustrates this phenomenon and the various ways of determining the transition temperature. The most common ways are either by establishing the temperature that corresponds to a minimum energy value such as 15 or 20 ft-lbs, or the mid-point (average energy) value between the lower and upper energy shelves of the energy curve that is developed by testing a series of impact specimens over a wide temperature range.

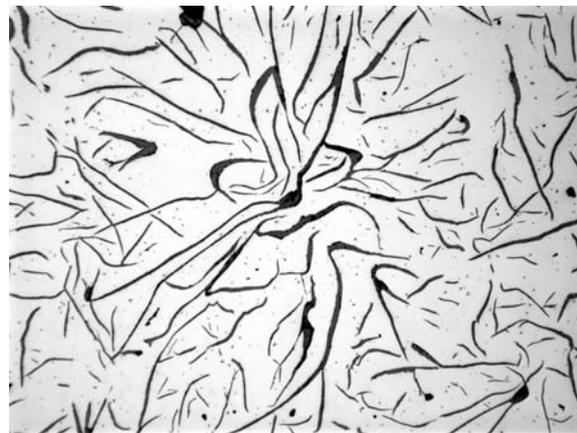


Microscopic examinations

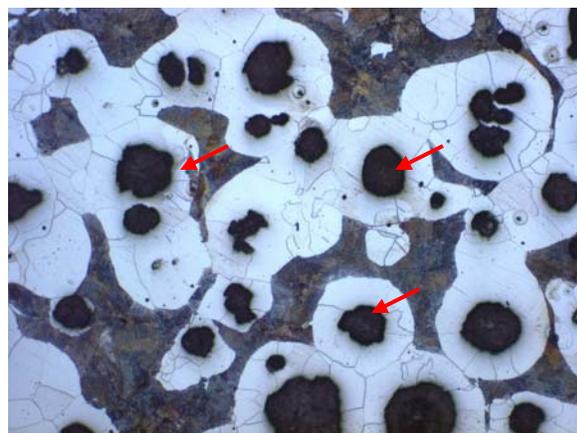
Metallographic examinations are conducted to determine the actual processing/heat treat conditions or if the scheduled processing steps were inadvertently omitted or incorrectly performed. Sample preparation for this type of analysis is critical. The failure area should be preserved and any cutting or sectioning should be done well away from the fracture initiation area. Since the original heat treat condition (microstructure) may be altered by the heat generated during the cutting process, abrasive cutting using coolants should be utilized to avoid overheating. If the failure mechanism is corrosion related then adequate sample collection should be performed before sectioning since cutting fluids may introduce contaminants. Sample preparation steps such as mounting, grinding, sanding and final polishing should be carried out following standard metallographic techniques. Usually samples in as-polished condition contain very little information but they should still be examined because etching may obliterate fine details such as microcracks, features in corroded specimens or plating layers. Etching with a suitable chemical reveals grain boundaries and phases and allows you to view the microstructure. The part's processing history (cast, forged or wrought material), heat treat condition, presence of inclusions, secondary phases, chemical variations (segregation), grain deformations, weld joints can all be revealed.



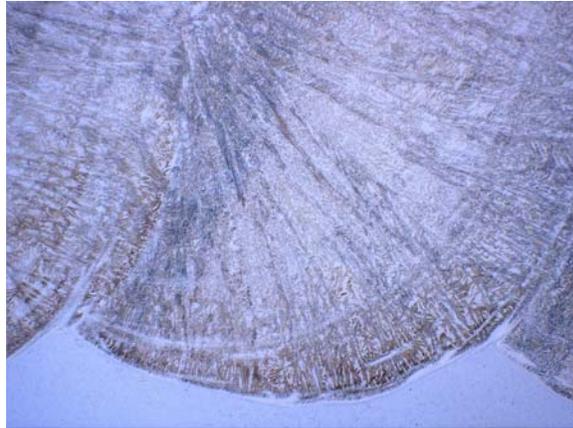
Micrograph showing annealed grains in a stainless steel part.



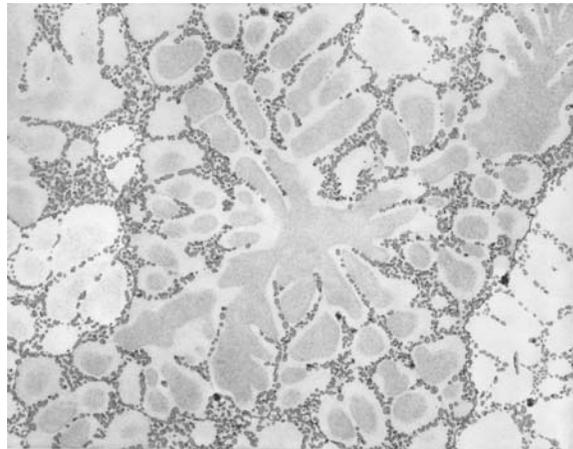
Micrograph showing the graphite flakes in a gray cast iron part (unetched condition)



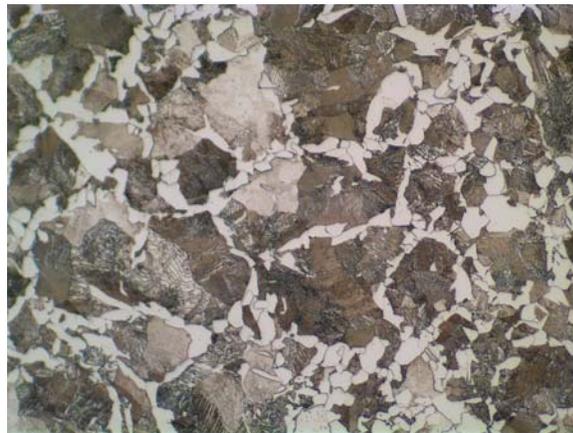
Micrograph showing the graphite nodules in a ductile cast iron part (etched condition)



Micrograph showing the weld microstructure on a steel sample



Micrograph showing the cast structure of a brass alloy



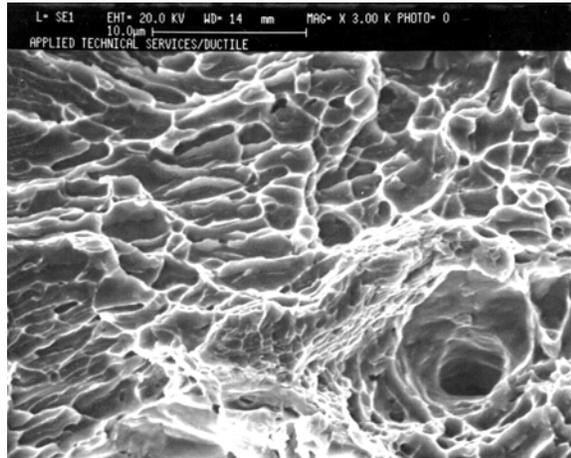
Micrograph showing the pearlitic (dark, carbon-rich) and ferritic (light, carbon-free) microstructure of a steel sample

Fractography

High magnification examination of the fracture surfaces using the electron microscope (SEM) is very instrumental in failure investigations. Analysis of the fracture features and relating the topography to the causes or basic mechanisms of failure allows the analyst to determine the failure mode of the component. SEM offers greater depth of focus than optical microscopes and allows rough fracture surface examination possible at very high magnifications.

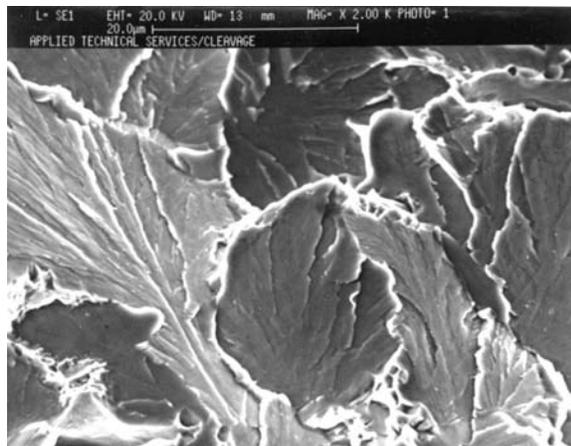
Various modes of failure that are commonly experienced are given below:

Ductile rupture: Typically the main difference between ductile and brittle fracture is the amount of plastic deformation that the material experiences before the fracture. Ductile materials exhibit significant amount of deformation while brittle materials show very little or no appreciable deformation before fracture. Ductile failures initiate with microvoids. When deformation continues and these microvoids enlarge to form a crack, the separation is said to have occurred due to microvoid coalescence.

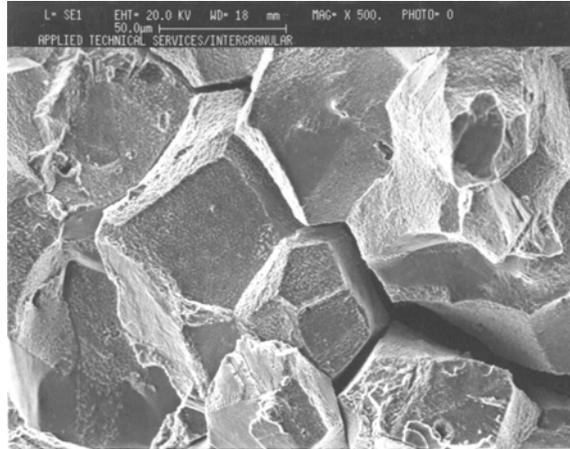


SEM micrograph showing typical ductile fracture features.

Brittle fractures can occur in two distinct modes, transgranular cleavage and intergranular separation. Cleavage fracture progresses along crystallographic planes of a material and leaves ledges or steps behind. Some also include river patterns. Intergranular fracture, also known as "rock candy" in materials with coarse grain size (i.e. castings) is another form of low energy failure that usually indicates a service environment or processing problem. Typical causes are quench cracking, temper embrittlement, hydrogen embrittlement, liquid metal embrittlement, precipitation or transformation of detrimental phases due to high temperature exposures or stress corrosion cracking.

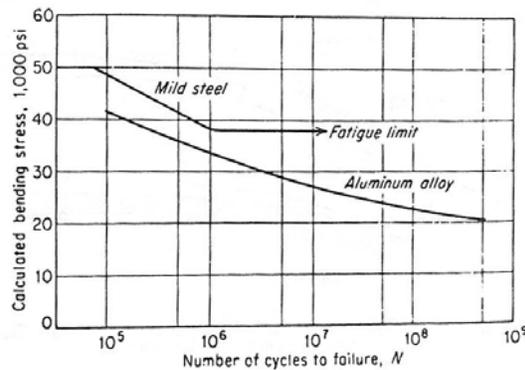


SEM micrograph showing typical brittle-cleavage fracture features.



SEM micrograph showing intergranular fracture features.

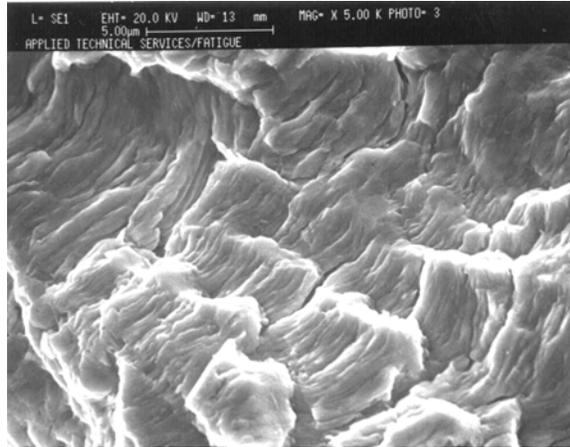
Fatigue fractures occur at stress levels below the yield stress of the material. They are produced by stresses repeated thousands or millions times (caused by cyclic loading). They are found in shafts, gear teeth, fasteners, vehicle frames, and various machine components. The crack propagates in a progressive manner due to fluctuating stresses. Cracks initiate at either metallurgical (e.g. porosity, inclusion, hard or soft spots) or geometrical (sharp change in cross section, toe of a weld, corrosion pits, etc.) stress concentration points. The fatigue process consists of the following stages: crack initiation, crack propagation and final sudden fracture of the remaining cross section. The maximum cyclic stress that can be applied indefinitely under fatigue conditions is called the endurance limit of the material as illustrated in the S-N curve below. For steels, the endurance limit is approximately 40% of the tensile strength.



Typical bending fatigue curves comparing the fatigue characteristics of mild steel versus aluminum alloys

Note the lack of the “knee” for the aluminum alloy, compared to mild steel. Fatigue or Endurance limit is defined as this point on the curve where the number of cycles to failure becomes a straight line (infinite) at this stress level.

Typical features that are observed on the fracture surfaces in most cases are "striations" which correspond to the growing crack with alternating load cycles. Fracture surfaces may also exhibit beach marks (sometimes referred to as clamshell marks), which are macroscopic fatigue features marking the interruption/succession cycles of the progressive crack front.



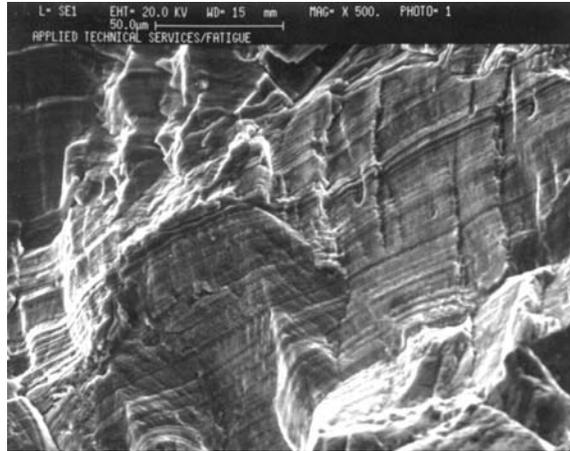
SEM micrograph showing fatigue striations.

Case study 1

Background: A rebuilt motor shaft failed in the keyway near the end of the slot. The original shaft was manufactured from 1045 carbon steel, but was replaced by the present shaft made from 1144 resulfurized steel. The shaft failed within two years of being rebuilt.

Analysis/Cause of Failure: SEM examination of the fracture surface revealed the fracture mode to consist mainly of fatigue. A metallurgical cross-section below the fracture plane revealed a weld overlay on the shaft with a weld metal filled original keyway. The interface between the weld metal and the shaft material in the keyway contained areas with porosity and lack of fusion. Microhardness measurements indicated that the heat-affected zone (HAZ) was much harder than either the weld metal or the base metal. These defects provided the initiation site for the fatigue crack that led to the failure of the shaft due to cyclic loading.





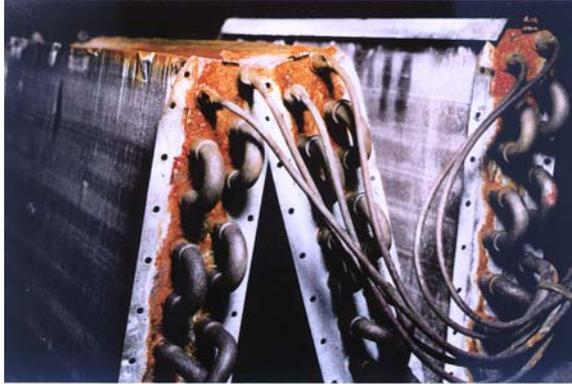
SEM showing fatigue striations

Case study 2

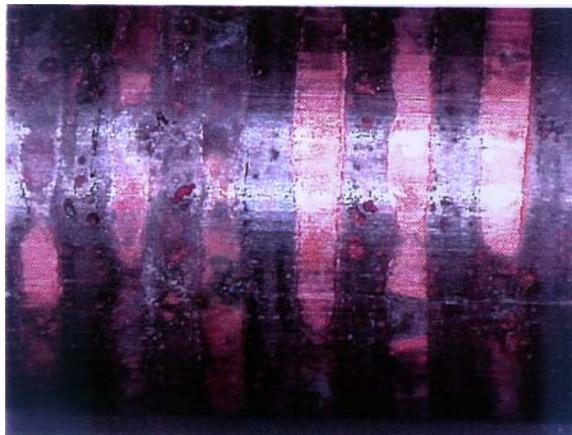
Background:

Evaporator coils failed when leaks developed after 16 months of service.

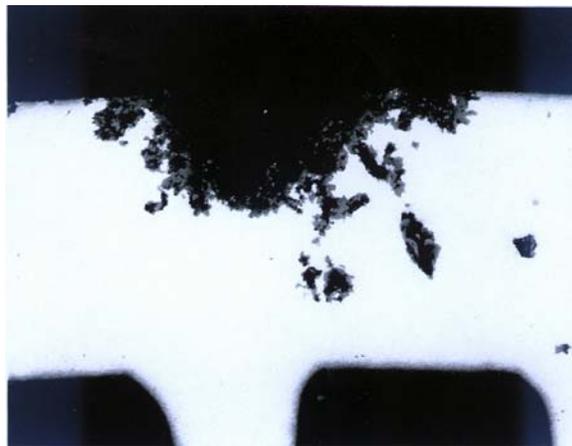
Analysis/Cause of Failure: Pitting corrosion between the cooling fins and the copper tubing was determined to be the cause of failure. No evidence of corrosive species was found through EDS analysis. Metallographic examination of pits revealed features characteristic of formicary corrosion. Formicary, which is also known as ant-nest corrosion due to the unique appearance of the microscopic interconnected pits and cavities, mainly occurs in the HVAC industry. The residual organic drawing fluids used in fabrication decompose into acids when exposed to moisture and air during service and cause this type of corrosion. Thorough cleaning of the coils is required after fabrication to eliminate this type of attack in service.



Overall view showing corrosion



Condition of tube surface



Micrograph showing pit "network"

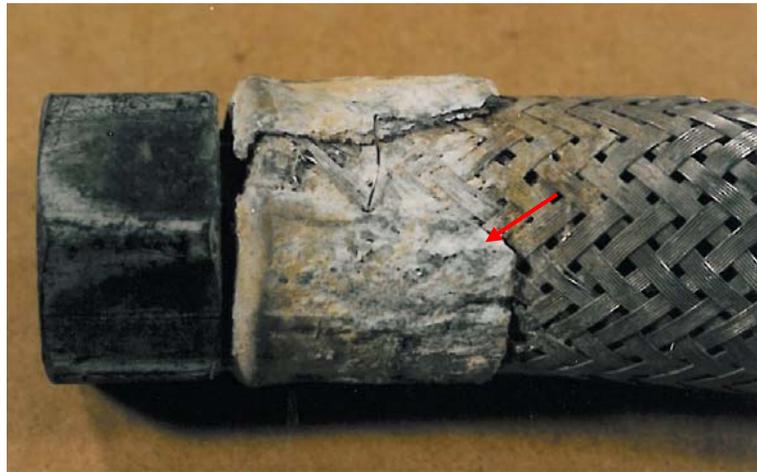
Case study 3

Background:

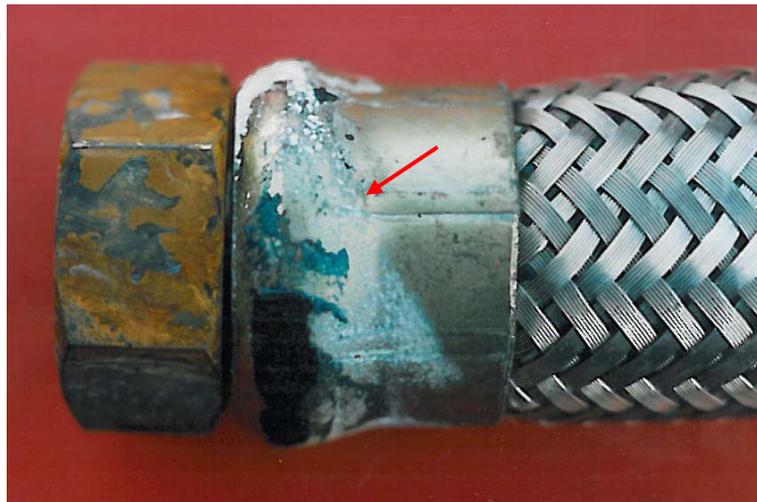
Stainless steel braided rubber hose used in a chilled water line leaked after approximately 3 years in service.

Analysis/Cause of Failure: Evaluation of the two different types of hoses that were used in the system revealed that both types were experiencing corrosion as shown in the below photographs. However, the leaks were confined to the ones with aluminum ferrules not steel. Energy dispersive x-ray analysis (EDS) of the corrosion products did not show evidence of any corrosive species (i.e. chlorides) that were suspected to have leached out of the insulation and accelerated the attack. The corrosion appeared to be as a result of condensation and entrapment of moisture between the hose and the pipe insulation. Metallographic examination of the ferrules revealed attack on both the exterior and the interior surfaces of the aluminum ferrule that was in contact with the stainless steel braid.

The primary corrosion mechanism was determined to be galvanic attack between the ferrule and the braid due to dissimilar metals being in contact with each other. This condition, in the presence of an electrolyte (i.e. water) causes corrosion of the less noble metal, which was aluminum in this case. Assuming water/moisture cannot be avoided, replacing the aluminum ferrule with one made from the same type of stainless steel material as the braid is recommended to eliminate the galvanic corrosion.



The corroded aluminum ferrule



The corroded carbon steel ferrule