Applied Failure Analysis

Guideline for Examining Failed Parts{1000, 7000}

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SMCS - 1000; 7000

Caterpillar Products: All

Introduction

The Applied Failure Analysis (AFA) Team at the Caterpillar Product Support Center in Peoria, IL provides the following information to assist with initial assessment of failed parts and collecting information relevant to investigation of part failures.

Failure analysis should not be attempted without proper training. Failure analysis training and reference material is available through Caterpillar, Cat Dealers, and the Caterpillar Media system. Assistance with failure analysis is available from trained personnel at Caterpillar Dealers, Caterpillar's Technical Service Reps and the Applied Failure Analysis Team.

Failure Analysis Consulting

Assistance with performing failure analysis is available through the Applied Failure Analysis Team at the Caterpillar Product Support Center. Caterpillar personnel can contact the AFA Team directly for help. Cat dealers should work through their Technical Service Representatives for assistance.

Table 1

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The following topics will be covered in this discussion.

- The Failure Analysis Process
- Disassembly for Failure Analysis
- Visual Inspection Methods

- Analyzing Fractured Parts
- Stress Raisers
- Analyzing Worn Parts
- Additional Information

The Failure Analysis Process

Failure analysis is the "thoughtful review of product and environmental **facts** which leads to the identification of the **root cause** for product problems." The purpose for performing failure analysis is simply to discover the root cause for a failure so the proper steps can be taken to prevent the failure from happening again.

Two key words are highlighted in the definition. The first word is **facts**. Good failure analysis is based solidly on facts. Facts may be found in many places: the failed parts, application, operation, maintenance records, ECM data, and so on.

The second highlighted words are **root cause**. Working with facts and a defined process allows an investigator to arrive at the most probable root cause for a failure and answer three questions: "What happened?", "How did the failure happen?", and "Who was responsible?". With the answers to these questions, a problem can be fixed so the problem does not happen again.

Failure analysis is one of many tools used for problem solving. The appropriate time to use failure analysis is when:

- Parts are broken
- Parts are worn out early or in an unusual way
- Parts are deformed so that the parts can no longer perform the intended function

Adverse indicators such as running hot, unusual noises or odors or other performance problems usually do not call for failure analysis but rather troubleshooting, testing, or adjusting. Use failure analysis at the appropriate time.

The AFA Team teaches an Eight Step process for performing failure analysis. The process starts some time before the failure when the part or system was still operating properly and continues through the failure using facts, events, and a time line. The process concludes when the results of the failure analysis have been communicated to the responsible party, the machine has been fixed and a follow-up call or visit is accomplished to reinforce the customer's trust in us.

Persons using this information will probably be heavily involved in the fact-finding phase of failure analysis. Facts can be gathered not only from the failed parts, but also from application, operation and maintenance information. Actually, anything that has influenced the part from the manufacture until the time the part failed may provide useful facts for the failure analyst. Usually, the more facts that can be collected, the better the results of the failure analysis.

Disassembly for Failure Analysis

There are two key ideas to remember when disassembling parts for failure analysis:

- Parts should be marked

- Do not further damage parts during disassembly

Marking Parts

The best time to mark parts is before and during disassembly. Parts may be marked to show timing, location, orientation, and family grouping.

Illustration 1 g01200676

Part marked prior to disassembly

Parts may be marked in order to document orientation prior to disassembly.

Illustration 2 g01200680

Part marked during disassembly

Parts may be marked in order to document location and family grouping. This marking is especially useful when there are multiple, identical parts in an assembly.

There are various acceptable methods for marking parts including: acid pens, vibrating pens, scribes, paint pens, and permanent markers. Remember the following when marking parts:

- Surfaces to be marked may need to be cleaned prior to marking.

- Make sure that marks will not be removed by cleaning processes, or plan to remark after cleaning.
- Apply marks in areas where the marks will not be worn away by handling.

Do Not Damage Parts During Disassembly

Careless disassembly techniques can damage the failed parts and parts that may be reused. Subsequent damage on fracture surfaces or worn areas will make failure analysis that much more difficult. The most common types of subsequent damage on failed parts are physical damage due to careless disassembly, handling, and shipping practices and corrosion from the atmosphere or handling.

Hammers and impact tools can damage parts during disassembly. For instance, anti-friction bearings are subject to this type of damage. Since bearing races and rolling elements are heat treated to high hardness levels, they are easily chipped and damaged by shock loads. Also, when a failed bearing is removed, care must be taken not to damage the housing or else a subsequent bearing failure may occur.

Illustration 3 g01200708

Dent in the bearing race

Denting a bearing race during removal adds another fact that was not present as a result of the failure.

Illustration 4 g01200711

Housing damage

Housing damage resulting from the removal of a failed bearing can cause the failure of the next bearing.

Various heating methods are used during the disassembly process. If not carefully controlled, heating can further damage failed parts making failure analysis more difficult. Uncontrolled heating can also damage parts that might be reused during repair after failure leading to repeat failures. Remember, any time a part has been hot enough to discolor the surface, metallurgical changes have occurred and the part is no longer as the part was after the failure. Avoid heating during disassembly that discolors parts in the fracture or wear areas that need inspection.

Bearing races and mounting surfaces provide a good example of how parts can be damaged during disassembly. Here are some things to keep in mind during disassembly:

- Do not cut completely through a race to avoid damaging (nicking) or overheating the part under the race.
- Aim the cutting torch tip across the part rather than straight down on the parts to control the depth of heat penetration
- The best practice is to nick the surface of the race with the torch and then carefully finish the break with a chisel and hammer.

Illustration 5 g01200716

Damage caused by excessive heat

Using excessive heat or cutting through a bearing race during disassembly can damage the surface behind the race.

Illustration 6 g01200718

Nick in the underlying surface

Cutting through a bearing race can nick the underlying surface creating a stress raiser. Overheating changes the properties of the material which can also produce stress raising effects.

Corrosion damage on fracture surfaces or wear areas is common. Fracturing parts produces very clean surfaces that are highly reactive. Some types of wear also have a cleaning action that can aggravate corrosion damage. Corrosion can also result from body oils transferred to the surface of parts as the parts are handled. When working with failed parts, always keep in mind the need to protect surfaces from corrosion during storage and handling. Except in the case of abrasive or erosion wear, the best way to handle failed parts is as follows.

- Upon disassembly, make sure that failed parts are immediately protected from corrosion. Coat surfaces with oil, grease, or some other corrosion inhibitor that can be easily removed later. Caterpillar has plastic storage bags that incorporate a corrosion inhibitor to protect the surface of parts. Sometimes small parts can be stored in airtight containers containing a desiccant material to reduce humidity.
- Clean surfaces to be inspected just before inspection and do not allow the parts to be exposed unprotected any longer than necessary.
- Following inspection, immediately reapply corrosion protection or return the part to the protective storage area. Do not expose the parts to corrosive environments until after failure analysis is completed.
- Make sure that part surfaces are properly protected during transportation and shipment. Accidental exposure to corrosive environments is always possible during transportation and shipment.

Illustration 7 g01200725

Corrosion damage

Protect fracture surfaces and worn areas from corrosion damage after failure.

Notice the corrosion on the fracture surface in illustration 7. Fortunately, the area of interest was at the center of the section, not in the corroded area. Still a little corrosion will often obscure the surface and make identification of the facts from the fracture surface difficult. Also, if corrosion was part of the failure process, later corrosion could cover up that fact.

Visual Inspection Methods

Visual inspection is a continuous process during failure analysis. Visual inspection should start prior to disassembly and continue until all facts pertaining to the failure have been discovered and recorded.

Visual inspection prior to disassembly should include the overall condition of the engine or machine and conditions in the area where the failure occurred. Note what seems to be damaged and the extent of the damage. If possible, inspect the work location where the failure occurred and interview the operator and anyone else in the area at the time of the failure. Also, note whether the working conditions were "normal" at the time of the failure. Was there something unusual happening at the time of failure?

Markings

Illustration 8 g01200895

Competitor part

Sometimes non-Caterpillar parts are used. Competitors may use Caterpillar part numbers, but are not allowed to use the Caterpillar trademark.

Illustration 9 g01200901

Genuine Caterpillar bearing

Illustration 9 shows a genuine Caterpillar bearing. Markings include not only the part number, but also the Caterpillar trademark and certain required manufacturing information.

As the components in the area of the failure are disassembled, record as much of the following information as possible (Write down all markings on each component that is removed):

1. Part numbers, engineering change numbers, and manufacturer trademarks
    - Make sure that the parts are correct, up to date and genuine Caterpillar parts
2. Manufacturing or remanufacturing date codes
    - Date codes are forged or stamped on many new parts. Date codes are also stamped, engraved, or acid etched on remanufactured parts to indicate the date of remanufacturing. Date codes are typically specified with the Caterpillar NUMERALKOD system.
3. Identifying marks such as supplier codes, forging die codes, steel heat codes, and so on.
    - The information provided by these markings, when the markings are on the part, may be important if the part fails early in its life or if there is a product watch.

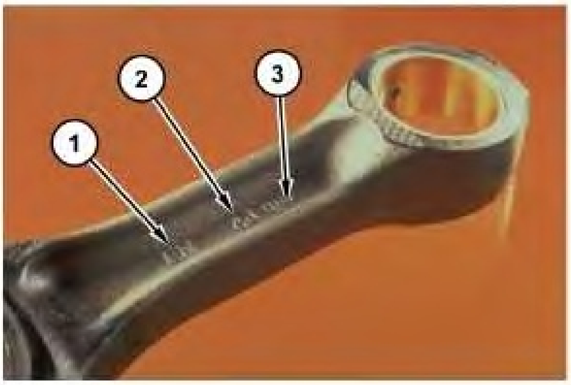

Illustration 10 g01200958

(1) Die code

(2) Supplier code

(3) Steel heat code

Some parts contain several pieces of information in the markings on the part. Record all information because some of the information may be useful later in the investigation.

Illustration 11 g01201236

Number of rebuilds and hours accumulated on each part.

Some parts contain information indicating remanufacturing or reuse. Be sure to consider this information when determining the number of service hours on the part.

When collecting this information, take the opportunity to look at all areas of each part. Pay particular attention to high stress areas and normal stress raisers in order to determine whether closer inspection is needed.

The initial inspection period is the time to determine which parts will require a closer look. Besides parts that are broken, cracked or worn here are some other indicators of parts that should be saved for inspection.

- Abnormal wear or wear patterns

- Abnormal stress raisers such as pits, dents, scratches, cracks, and so on.
- Discoloration not associated with normal operation
- Temper colors not a result of heat treatment
- Plastic deformation or distortion of parts
- Deposits on the surface of parts
- Any evidence of abusive operation or damage
- Any other abnormal or unusual feature

Any parts that are identified as requiring closer inspection should immediately be labeled and set aside for special handling and cleaning. These parts must maintain their identification through cleaning and inspection and should be protected until failure analysis has been completed.

Examining Failed Parts

Good visual examination techniques will reveal much about failed parts. Often it is possible to obtain information about:

- Types of wear and fracture
- Normal and abnormal stress raisers
- Operating environment and temperature
- Loading during operation and failure
- Abusive operation
- Damage during handling or operation
- Evidence of previous repairs

Cleaning

The first step of visual examination is to prepare the surface of the part for inspection. Even thin layers of oil, grease, or other materials may hide important facts. If the surface is painted, removing the paint to inspect the surface underneath may be necessary. Some cleaning methods work much better than others for failure analysis. Generally, aggressive cleaning methods employing harsh chemicals, glass beads, soda blasting, or hand scrubbing should be avoided as these methods can remove facts that aid in determining the type and location of additional testing that may be needed. Even soft cloth and gentle rubbing may be too harsh for some surfaces such as the soft bearing surface on engine bearings.

Illustration 12 g01201256

Soft brushes and mild solvents usually work best for cleaning parts for failure analysis.

Cleaning Methods

- ~~Glass Bead~~
- ~~Grit Blast~~
- ~~Wire Brush~~
- ~~Scotchbrite~~
- ~~Aggressive Solvent~~

AVOID!!

Illustration 13 g01201262

These cleaning methods should be avoided on parts that are involved in failure analysis. Surface damage during cleaning is likely.

To summarize cleaning requirements for parts involved in failure analysis, remember that the objective is to not further damage fracture or wear areas before the areas can be inspected for facts. Keep in mind these things when cleaning parts:

- Use a fast drying, mild solvent to soak and/or rinse parts clean
- Do not wipe, scrub, or scratch to clean parts, especially soft parts like engine bearings
- After cleaning, air dry, blow with dry compressed air or blot dry with a paper towel.
- Do not wipe parts with a shop towel to dry.

Lighting for Visual Examination

Sufficient lighting is necessary for proper inspection of failed parts. Without sufficient lighting, overlooking critical facts on failed parts becomes easier.

Illustration 14 g01201273

Bright lighting

Bright, directed lighting is essential to visual inspection of parts. Bright lighting aids in locating and identifying wear types, foreign material deposits, cracks, and other facts that might go unnoticed in dimmer lighting.

Illustration 15 g01201274

Angled lighting

Besides directed lighting, angled lighting is often useful during failure analysis inspection. Angled lighting produces shadows and contrast on the surface of the part which tends to highlight some features that otherwise might remain hidden like wear scratches, cracks, and machining marks. However, angled lighting usually makes the surface look much worse than the surface actually is.

Examine All Areas

Once parts are properly cleaned and there is sufficient light available, begin inspecting parts for facts. During visual examination of failed parts, examine ALL the surfaces of ALL of the parts involved in the failure. This process may require some disassembly. Once apart, hidden mating surfaces may, for example, reveal fretting wear indicating that there was movement in a joint. This may provide a valuable fact about load on the joint or whether a recent repair was performed properly.

Illustration 16 g01201286

Completely disassemble all components.

Completely disassemble all components to be able to look at all of the surfaces of all of the parts for signs of wear, material build-up, or other types of damage. For example, remove the engine bearings to inspect the back side of the bearing and the bore surface, even if the wear surface of the bearing looks good.

If circumstances prevent removal and inspection of some parts, then inspect the surfaces of the parts that are available to determine the next steps. For instance, the crankshaft probably will not be removed during an in-frame procedure so how could a failure analyst get information about the condition of the bearing bore on the block side of the crankshaft?

Illustration 17 g01201289

Fretting on bearing back

Closely inspecting the back or mounting side of the parts that are removed. For example, this engine bearing will indicate the condition of the parts or areas that are not visible. Note the fretting damage on the back of the bearing.

Illustration 18 g01201290

Fretting on bearing bore

Fretting damage on the back of the bearing in the previous photo means that the bearing bore in the block is also fretted and the crankshaft must be removed to clean and/or repair the bore surface in the block.

As parts are carefully examined, determine which facts found on the parts are a result of the failure and therefore important to the failure analysis. Some of the facts on the parts will be a result of the manufacturing processes used to produce the part. Other facts found on the parts may result from normal operation. One good way to determine which facts are significant is to compare the failed part with new parts, good used parts, or information found in Caterpillar Reusability Guidelines. Obviously, fractures are not normal. Scratches, machining marks, and discolored areas may appear on the surface of parts depending on what manufacturing processes were used during production.

Illustration 19 g01201291

Used valve guides

Illustration 19 shows two used valve guides. The valve guide on the left appears to be severely worn compared to the one on the right. Comparing used parts is one way to determine which facts are important in a failure analysis.

Magnification

Some of the facts found on failed parts are small and difficult to see without magnification. Many times, all that is needed is a small hand-held magnifier with 10 – 20X capability such as the Caterpillar eye loupe (similar to what jewelers use to examine precious stones). In other instances, more magnification is required such as when looking for inclusions at fracture initiation sites or small abrasive wear particles. In these situations, a stereomicroscope or a scanning microscope is required.

When examining parts, the best practice is to examine the parts at 1X – look at the parts under good lighting. If there is an area that requires closer inspection, then use magnification. Do not use more magnification than is necessary to find and identify the unknown object or material. As magnification increases, the area that is visible decreases and inspection takes longer.

Another way to magnify an area of a part is to take a digital photograph and electronically enlarge the photograph. The quality and resolution of digital photographs with cameras today makes a viable method for close inspection.

Illustration 20 g01201315

8S-2257 Eye Loupe As

A simple eye loupe magnifier, such as the **8S-2257** Eye Loupe As , is useful for identifying wear types, foreign debris particles and studying abnormal stress raisers. A magnification power of 10-20X will be sufficient for most situations.

Illustration 21 g01201316

Stereomicroscope

Stereomicroscopes give greater magnification and a three-dimensional view. More light is required as the level of magnification increases. The disadvantage of these microscopes is that the part usually has to be brought to the microscope and the size of the part is limited by handling limitations.

Recently, portable microscopes that can be used with laptop computers have been marketed. The laptop computers can be taken into the field and the images screen-captured and emailed. Compared to stereomicroscopes, the cost is reasonable.

Facts

The purpose of visual examination is to find and record facts that will help determine the root cause of a failure. Facts are things found with senses – sight, hearing, touch, and smell. Real facts are not disputable. If there is disagreement about a fact, the fact probably is not a fact. When inspecting parts, make sure to record facts, not interpretation of facts. For instance, abrasive wear and brittle fracture are not facts, but interpretations of facts found on parts. Scratches are a fact that can be seen that indicates that abrasive wear has occurred. A rough surface, chevrons, and no plastic deformation are facts that indicate a brittle fracture has occurred.

Protecting Parts After Examination

The final step in visual examination is to protect the parts from further damage until failure analysis is complete. Any worn or fractured pieces must not be allowed to corrode or suffer mechanical damage. Parts that have been cleaned for visual examination can corrode quickly and seem to attract dirt and dust particles. After visual examination is complete, follow these steps:

1. Coat worn and fractured surfaces with oil or some other moisture barrier coating that can easily be removed if further examination is required.
2. Cover parts to protect from dirt and dust.
3. Smaller parts may be stored in bags or containers to avoid contamination and damage.
4. Store parts in a dry, low humidity area.

Illustration 22 g01201326

Protect fractured surfaces

When failed parts are not being examined, fracture and wear surfaces should be protected from corrosion and mechanical damage. Make sure that the material applied for corrosion protection can be easily removed in case further examination is required.

Analyzing Fractured Parts

Analyzing broken parts should be done in an organized way with two objectives in mind:

1. Obtain all of the facts from the broken parts.
2. Prevent any additional damage to the parts during removal, inspection and afterwards.

The following steps can be followed to make sure that the objectives are met.

1. Do not put mating pieces of a fracture back together unless the surfaces are protected and extreme caution is used.
    - Fracture surfaces are fragile and easily damaged on a microscopic level. Fracture examination can become difficult by carelessly reassembling broken pieces, inadequate protection during shipping and lack of proper protection from corrosion of the fracture surface including protecting from skin oils when handling the pieces.
2. Obtain the failed parts and protect from damage
    - Appropriate methods for obtaining failed parts are covered in the section "Disassembly for Failure Analysis." Failed parts must be removed and handled carefully to avoid further damaging the parts. Once parts have been removed, the parts are susceptible to casual impact damage and corrosion on the fracture surfaces. Wrapping fracture surfaces with cloth or towels and coating with rust inhibitors such as engine oil or grease are good ways to prevent additional damage. Be careful if parts have to be shipped to another location for analysis. Prepare the parts for shipping to prevent impact damage or corrosion on fracture surfaces. If parts must be sectioned prior to moving or shipment, be careful not to do anything that will change the characteristics of the material in the area of the fracture. For instance, cutting with a torch too close to a fracture can overheat the metal and change the properties making failure analysis more difficult.
3. Clean the parts carefully
    - Damaging a fracture surface is easy if overly aggressive cleaning methods are used. When fracture surfaces have been cleaned with a solvent, be careful not to damage the surface when drying. For further information, see the section on "Cleaning" under Visual Inspection Methods.
4. Determine the type of fracture present
    - Once the fracture surface has been cleaned of oil, grease and loose dirt and debris particles the surface can be inspected to determine the type of fracture. Refer to the sections on Brittle, Ductile, and Fatigue fracture for help with identifying the type of fracture.
5. Identify the fracture initiation site
    - Once the type of fracture has been identified, determine exactly where the fracture initiated. Many of the road signs used to identify the type of fracture can also be used to

find the fracture initiation site. Here are some additional principles that may help to locate the fracture initiation site.

a. Smooth to rough

    - Fracture surfaces are smoother near the fracture initiation site because the crack is traveling more slowly in that area. As cracks move away from the fracture initiation site, the cracks move faster and create rougher fracture surfaces. This concept of "smooth to rough" applies regardless of whether the fracture is brittle, ductile, or fatigue. The change from smoother to rougher may not be dramatic, but the change is detectable with careful inspection.

b. Where would an overloaded part fail

    - Most parts have normal stress raisers incorporated in the design. Examples of normal stress raisers include: holes, fillets, thread roots, and so on. If a part is overloaded in service, these normal stress raisers provide convenient fracture initiation sites. Therefore, when fracture initiates from a normal stress raiser, investigate for unusually high loads in service as a root cause of fracture.

c. Look opposite any final fracture areas

    - Many types of loads on parts produce fractures that move across the part from one side to the other. So, if the last area to fracture can be identified, a good place to look for the fracture initiation site is directly across from the final fracture area.

6. Examine the fracture initiation site for normal or abnormal stress raisers

    - Identifying normal or abnormal stress raisers at the fracture initiation site will help to determine whether the fracture resulted from a material or manufacturing flaw, overloading in service, damage during service, and so on. Refer to the section "Stress Raisers" for additional information.

7. Verify that the type of load on the part corresponds to the type of fracture identified

    - The final step in analyzing fractured parts is to make sure that the type of load that the fractured part sees in service is consistent with the type of fracture identified. As a reminder, here is some information on types of load and fractures.

a. Shock or impact loads

    - These are large loads applied fast and are responsible for brittle fracture of parts.

b. Overloads

    - These are large loads applied fast, but not as fast as shock or impact loads. Because the load is applied more slowly, parts have time to plastically deform by twisting, stretching, bending, or necking before fracture. Overloads often produce ductile fracture of parts. However, an overload can also crack the surface of a part without causing the part to fail. This overload provides an abnormal stress raiser from which a fatigue crack can grow. Overloads can also produce brittle fracture if the material of the part is brittle such as cast aluminum or gray cast iron.

c. Cyclic loads

- These are repeated loads on a part during service and are much lower than shock loads or overloads. The repetitive nature of cyclic loads gradually damages the material in a part until a fatigue fracture initiates and grows to part failure. Cyclic loads considered normal for the application can also initiate a fatigue fracture from an abnormal stress raiser. If the cyclic loading is large or if the frequency of loading is high, fatigue cracks can initiate and grow to part failure in a relatively short period.

Brittle Fractures

Brittle fractures typically result from a single, large shock or impact load on a part that exceeds the maximum design strength of the part. Brittle fracture occurs quickly.

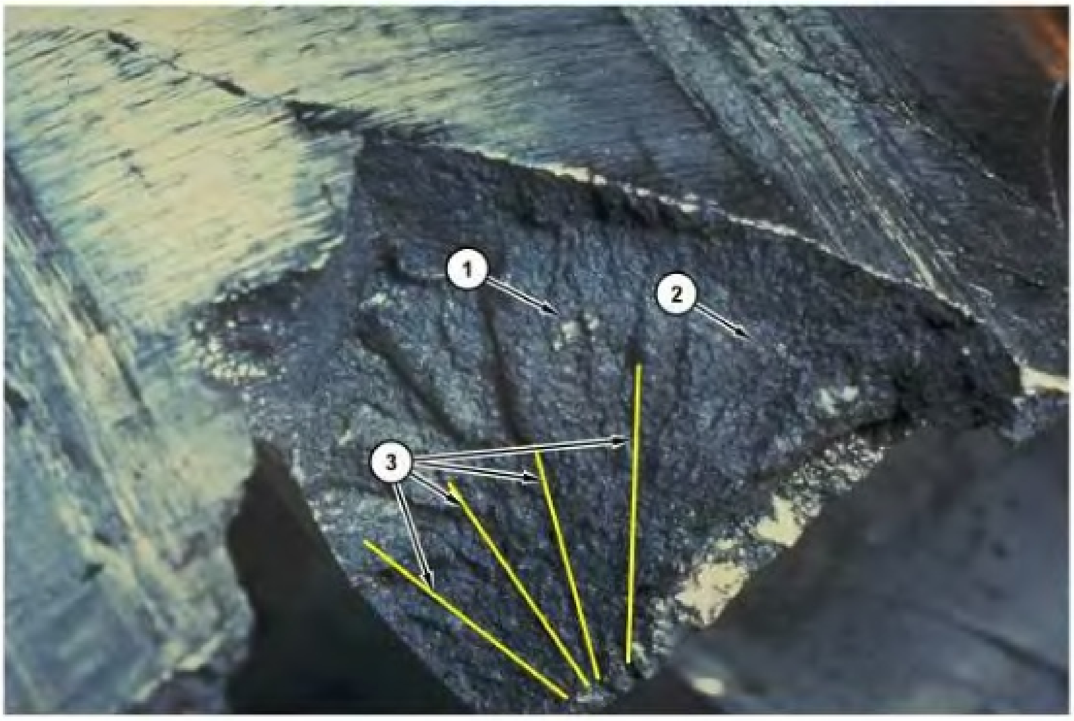

Illustration 23 g01201349

(1) Rough, dark, or dull fracture surface

(2) No plastic deformation

(3) Chevrons

Brittle fractures can be identified by the following characteristics:

1. Rough, dark, or dull looking fracture surface with a grainy or crystalline appearance. In harder metals, the fracture surface may be bright and sparkly due to split, or cleaved, metal grains.
2. No plastic deformation - parts that fail by brittle fracture look like the part simply broke into pieces. The broken sections could be put back together so that the part looks like it did before the part broke. This process is a bad practice since the fracture surface can be damaged by

reassembly. Brittle fractures may have small shear lips at the edges, but shear lips are more common with ductile fractures.

3. Chevrons - lines on the fracture surface. Chevrons may look like lines radiating away from the fracture initiation site. In sections that resemble a flat plate, chevrons may be V-shaped and point toward the fracture initiation site. Cast metal parts may or may not show chevrons depending on the type of metal.

Brittle Fracture Characteristics

There are several features to look for to determine whether a part has broken due to brittle cleavage fracture, which is the most common type of brittle fracture in Caterpillar parts.

Illustration 24 g01201359

Brittle cleavage fracture

Brittle cleavage fracture of harder metals can produce a sparkly appearance on the fracture surface. This appearance is due to the light reflecting off cleaved grain surfaces.

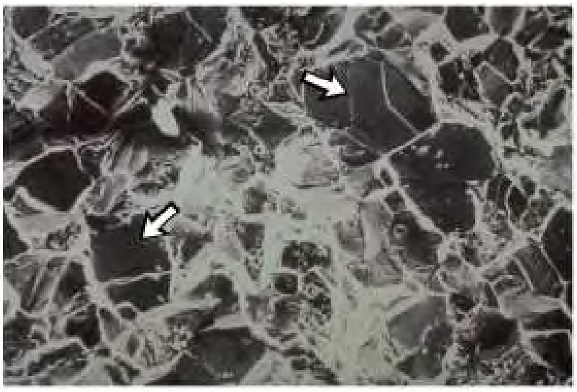

Illustration 25 g01201360

Cleaved grain surface viewed in an electron microscope

This scanning electron micrograph shows cleaved grain surfaces - the large dark areas. Bright areas look dark due to imaging with electrons rather than light rays.

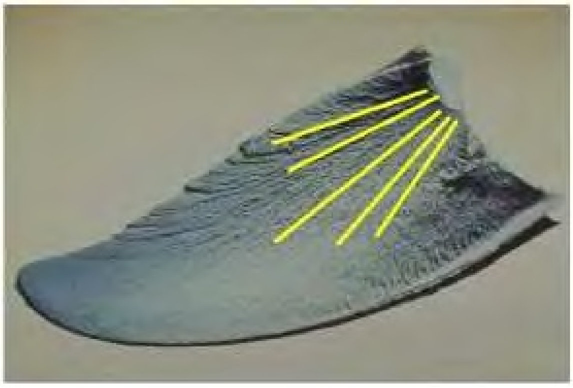

Illustration 26 g01201363

Chevrons on brittle cleavage fracture surface

Sometimes chevrons on brittle cleavage fracture surfaces look like lines radiating away from the fracture initiation site.

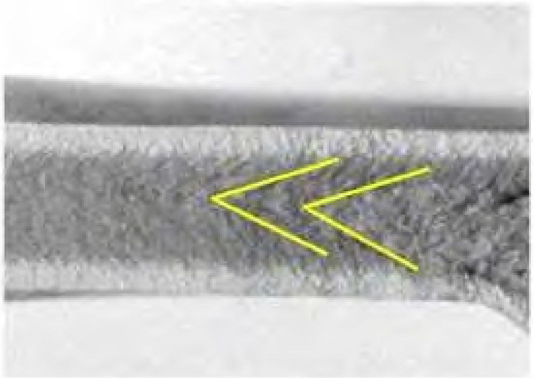

Illustration 27 g01201366

V-shaped chevrons on brittle cleavage fracture

When brittle cleavage fracture goes through a plate-like section, the chevrons often are V-shaped and point toward the fracture initiation site.

Illustration 28 g01201367

Dark surface with pronounced chevrons

Brittle fracture in metals that are not hard often produces a rough, dark surface with pronounced chevrons as in this section.

Intergranular Brittle Fracture Characteristics

There is another brittle fracture that sometimes occurs in Caterpillar parts. It is called intergranular brittle fracture (IGF) because the cracks go between the grains rather than through them. Intergranular fracture usually results from material or processing problems or an adverse reaction with the operating environment. If IGF is suspected, contact the product group for metallurgical inspection of the failed part. IGF also produces a grainy surface appearance, but with fewer sparkles. One good road sign of IGF is brittle fracture in a part that does not experience shock or impact loading in service.

Illustration 29 g01201368

Part that has experienced IGF

This part has experienced IGF. Note the rough grainy looking surface. There are some sparkles, but not nearly as many as when a part fails by brittle cleavage fracture.

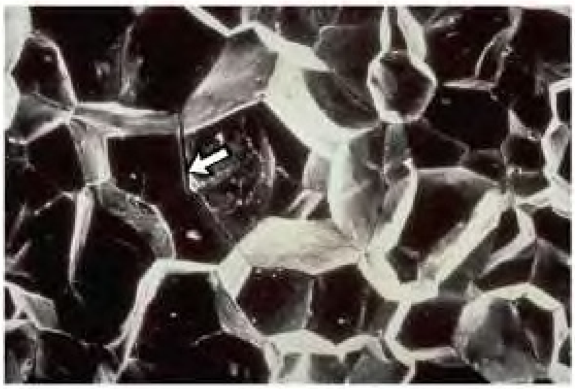

Illustration 30 g01201389

IGF fracture surface viewed in a scanning electron microscope.

This scanning electron micrograph shows the results of IGF. Note the smooth, rounded appearance of the exposed grain boundaries. Cracks at the grain boundaries are also visible.

Significance of Brittle Fractures

When brittle fractures are found in parts, look for the following things:

- Did the part fracture out of a normal or abnormal stress raiser?
- Has the part been loaded beyond maximum design strength so that the part cracked and failed in the area of a normal stress raiser? Normal stress raisers include corners, holes, fillets, threads, spline or gear tooth roots, or any other change in section.
- Does the part contain an abnormal stress raiser such as damage from wear, abusive operation, or a manufacturing flaw that concentrates normal loads excessively?
- Does the part contain a material flaw that concentrates the normal loads excessively?
- Is the part heat-treated and was the heat treatment performed correctly or is the part too hard? Hardness testing and metallurgical analysis can answer this question.
- Was the part operating in a cold environment, much below the normal operating temperature range for the equipment? Low temperatures promote brittle fracture in some materials.
- Is this part the correct part? Is this part a genuine Caterpillar part or an aftermarket part that lacks sufficient properties for the application?
- Evaluate the fracture against the section "Stress Raisers".
- Find the source of the shock or impact on the part.

- If the failure might be an intergranular fracture, note the operating environment of the part and contact the product group for metallurgical analysis of the failed part to verify IGF. A review of material characteristics, processing parameters and operating environment will be necessary.

Ductile Fractures

Ductile fractures typically result from a single, large overload on a part that exceeds the maximum design strength of the part.

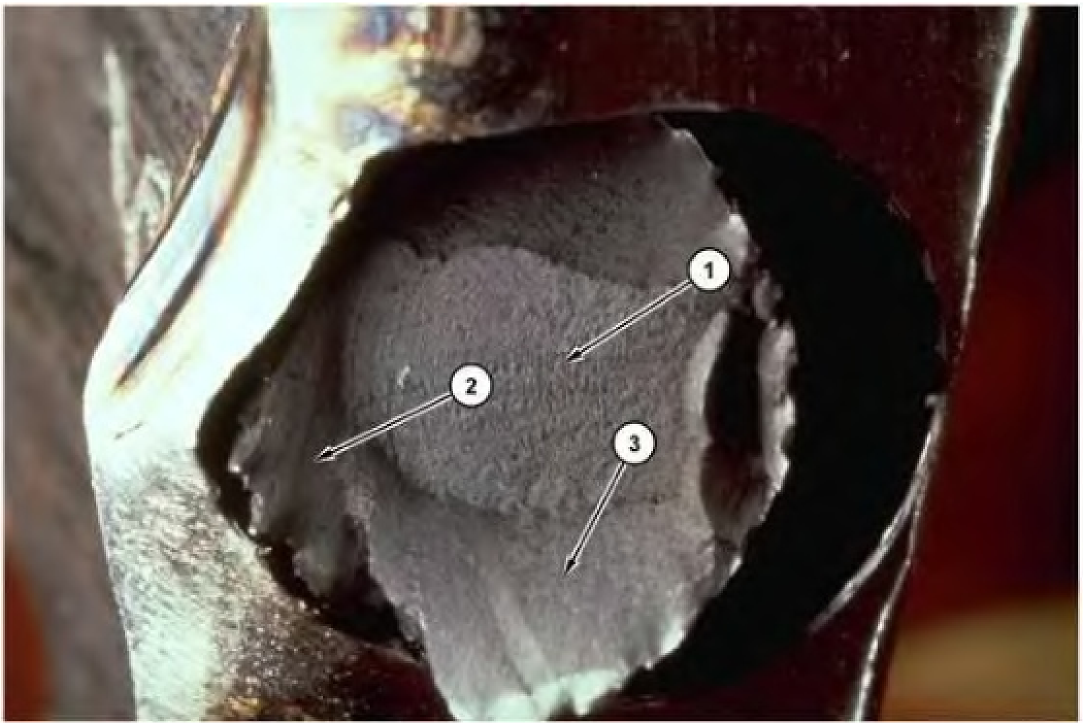

Illustration 31 g01201408

(1) Rough fracture surface

(2) Plastic deformation

(3) Shear lip

Ductile fractures can be identified by the following characteristics:

1. Rough fracture surface with a darker appearance.
    - Rough surfaces do not reflect light as well as smoother ones and so appear darker.
2. Plastic Deformation
    - A permanent change in the shape of a part. Plastic deformation can take the form of bending, stretching, twisting, or necking (reduction of cross section area at the point of fracture). Plastic deformation indicates the part was not capable of carrying the load imposed on the part so that part deformed prior to fracture. Notice in Illustration 31 that as the bolt failed, the bolt bent the side of the hole.

3. Shear lips
    - A raised or protruding area along the edge of a fracture. Shear lips are the last area to fracture. Shear lips are formed when a crack traveling under the surface of a part comes to the surface.
4. Woody or fibrous appearance
    - Sometimes when a ductile fracture follows the grain flow in a part, the fracture surface will have a characteristic fibrous looking appearance somewhat like a piece of wood that fractures with the grain.

Types of Ductile Fractures

There are several different ways that parts can be overloaded in service. This leads to different types of ductile fracture.

Illustration 32 g01201420

Tensile overload

Tensile Overload - Over torquing bolts can produce ductile fracture. Note the necked down area near the fracture and the large shear lip.

Illustration 33 g01201422

Torsional shear

Torsional Shear - Results from continuing to twist a bolt or shaft after it has stopped turning. The fracture surface is smooth due to smearing during failure.

Illustration 34 g01201430

Impact shear

Impact Shear - Results from an impact load on a part that cannot move. The result is a "scissoring" action that produces a smooth surface often with some temper colors.

Illustration 35 g01201431

Woody ductile fracture

Woody Ductile Fracture - Fracture of softer metals with the grain flow produces a pronounced fibrous appearance that results from the crack following inclusions.

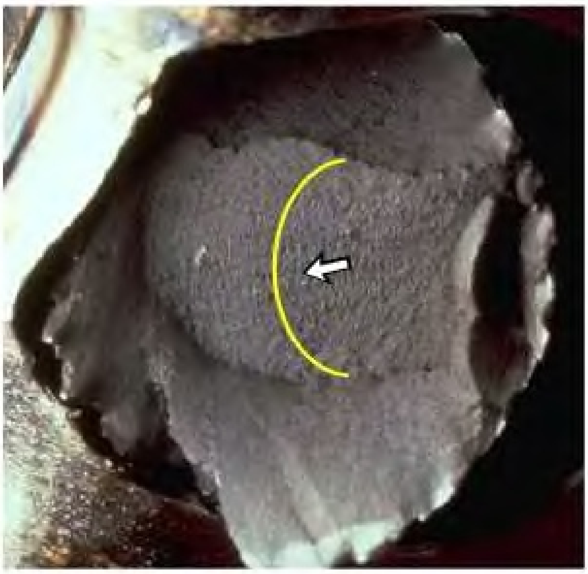

Illustration 36 g01201432

Fibrous tearing

Fibrous Tearing - Intermittent ridges that look similar to beach marks sometimes show up at the center of bolt ductile fractures when the bolt is both stretched and bent. These tear ridges form due to the combination of grain flow and plastic deformation. Do not confuse tear ridges and beach marks. Tear ridges are a road sign of ductile fracture. Beach marks are a road sign of fatigue fracture.

Significance of Ductile Fractures

When ductile fractures are found in parts, look for the following things:

- Did the part fracture out of a normal or abnormal stress raiser?
- Has the part been loaded beyond maximum design strength so that the part cracked and failed in the area of a normal stress raiser? Normal stress raisers include corners, holes, fillets, threads, spline or gear tooth roots, or any other change in section.
- Does the part contain an abnormal stress raiser such as damage from wear, abusive operation, or a manufacturing flaw that concentrates normal loads excessively?
- Does the part contain a material flaw that concentrates the normal loads excessively?
- Is the part heat-treated and was the heat treatment performed correctly so that the part has the necessary strength for the application? Hardness testing and metallurgical analysis can answer this question.
- Are there any discolored areas that indicate overheating which can reduce material strength and result in fracture under normal operating loads?
- Is this part the correct part? Is this part a genuine Caterpillar part or an aftermarket part that lacks sufficient properties for the application?
- Evaluate the fracture against the section "Stress Raisers".
- Find the source of the overload on the part.

Fatigue Fractures

Fatigue fractures typically result from cyclic, or repeated, loads under one of these conditions:

1. A part is loaded beyond maximum design load so that the surface cracks and then continued loading causes the cracks to grow larger until the part fails.
2. A part contains a flaw such as damage from wear, abusive operation, or a manufacturing or material flaw that concentrates normal loads causing the part to grow a crack until the part fails

Fatigue fractures can be identified by the following characteristics:

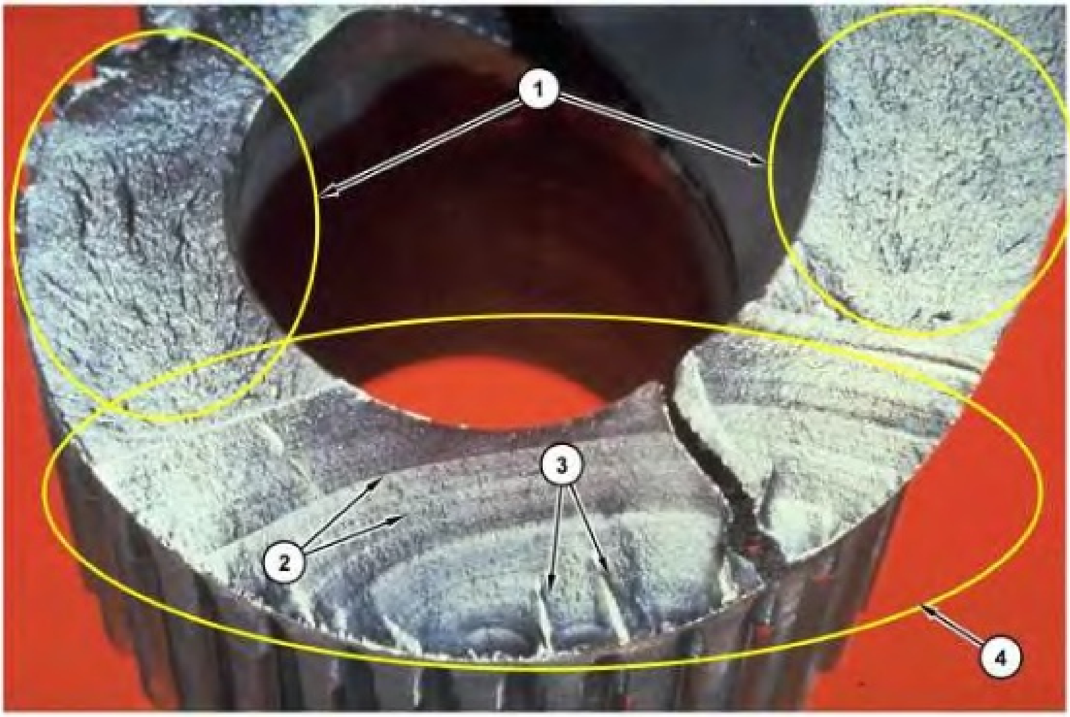

Illustration 37 g01201450

(1) Final fracture area

(2) Beach marks

(3) Ratchet marks

(4) Fatigue fracture area

1. Final fracture area
    - The rougher area on the fracture surface where the part quickly broke apart.
2. Beach marks
    - Continuous lines on the fracture surface that normally curve around the point where the fatigue fracture initiated.

3. Ratchet marks
    - Lines on the fracture surface at the point where several fatigue fractures initiated. Ratchet marks are perpendicular to beach marks.
4. Fatigue fracture area
    - The fatigue fracture area has a relatively smooth fracture surface. The area of the fatigue fracture will generally be much smoother than a ductile or brittle fracture. This area is where the fatigue crack grew slowly.

Types of Fatigue Fractures

Fatigue fractures grow in parts as a result of different types of cyclic loads. Fatigue fractures are named after the type of load that produced the fracture.

Illustration 38 g01201456

Tensile or axial fatigue fracture

Tensile or Axial Fatigue Fracture - Due to tension or stretching type loads. Fracture started at several places on the surface and traveled into the part.

Illustration 39 g01201457

Bending fatigue fracture

Bending Fatigue Fracture - Due to bending loads. Fracture started at the upper left and the final fracture is at the lower right.

Illustration 40 g01201458

Torsional fatigue fracture

Torsional Fatigue Fracture - Due to torsional or twisting loads. Fracture started at a bolt hole and traveled at a 45 degree angle through the part.

Illustration 41 g01201461

Reversed bending fatigue fracture

Reversed Bending Fatigue Fracture - Due to reversed bending loads. Fractures started at about 4 o'clock and 10 o'clock with final fracture at the center of the section.

Illustration 42 g01201462

Rotating bending fatigue fracture

Rotating Bending Fatigue Fracture - Due to a bending load on a part that is rotating, or a "rotating" load on a stationary part. Bending causes one or more cracks at the surface which grow inward and across the section. Final fracture can be anywhere between the center and the surface of the part.

Fatigue fractures can also be classified as "high cycle" or "low cycle". High cycle fatigue fracture produces a smooth fatigue fracture surface, small area of final fracture and takes a long time. High cycle fatigue usually indicates low to normal loads on the part as the part failed. Low cycle fatigue produces a relatively rough fatigue fracture surface, large area of final fracture and progresses quickly. Low cycle fatigue usually indicates higher than normal loads on the part as the part failed.

Note: A large final fracture area can result any time a cracked part receives a load large enough to break the part regardless of how fast the fatigue crack is moving.

Illustration 43 g01201464

High cycle fatigue

High Cycle Fatigue - Implies low to normal loads during the time the part was failing.

Illustration 44 g03399738

Low cycle fatigue

Low Cycle Fatigue - Implies higher than normal loads during the time the part was failing.

Significance of Fatigue Fractures

When fatigue fractures are found in parts, look for the following things:

- Has the part been loaded beyond maximum design load so that the surface cracked in the area of a normal stress raiser? Normal stress raisers include corners, holes, fillets, threads, spline or gear tooth roots, or any other change in section. Machined or as-manufactured surfaces on parts are normal stress raisers when surface roughness meets print requirements.
- Does the part contain an abnormal stress raiser such as damage from wear, abusive operation, or a manufacturing flaw that concentrates normal loads excessively? See the section on "Stress Raisers."
- Does the part contain a material flaw that concentrates the normal loads excessively? See the section on "Stress Raisers."
- Is the part heat-treated and was the heat treatment performed correctly so that the part has the necessary strength for the application? Hardness testing and metallurgical analysis can answer this question.
- Are there any discolored areas that might indicate overheating which can reduce material strength and result in fracture under normal operating loads?
- Is this part the correct part? Is this part a genuine Caterpillar part or an aftermarket part that lacks sufficient properties for the application?

Stress Raisers

For failure analysis, a stress raiser is any physical irregularity in a part that increases the stress in the part. There are two general classifications of stress raisers: normal and abnormal. This section will discuss and illustrate examples of each type of stress raiser.

Normal stress raisers

Normal stress raisers are features of a part that, by the shape or location, tend to increase the stress in a part when the part is loaded. Some examples of normal stress raisers are changes in cross section, holes, sharp edges, fillets, gear tooth and spline roots, keyways, and so on. Normal stress raisers are there by design and as long as operating stresses do not exceed the maximum design stress, the part should perform satisfactorily.

Abnormal stress raisers

Abnormal stress raisers are features found on or in a part that are not intended to be there and result in increased stress in a part. Abnormal stress raisers may result from a number of things such as material flaws, manufacturing problems, careless handling, and abusive operations. A normal stress raiser that was not manufactured properly, such as a fillet with too small a radius, would also be an abnormal stress raiser.

Stress Raisers by Design

It is frequently necessary to incorporate stress raisers in the design of a part for the part to function properly. These stress raisers can be considered "normal" and should be accommodated by the design and manufacturing operations used to produce the part. As long as operating loads are within the expected range, everything is acceptable. If operating loads exceed design limits, failure can initiate out of a normal stress raiser.

Fillets and Corners

Fillets and corners are a common location for fracture initiation if a part is overloaded in service. When examining parts that have failed or been overloaded in service, pay close attention to fillets and corners.

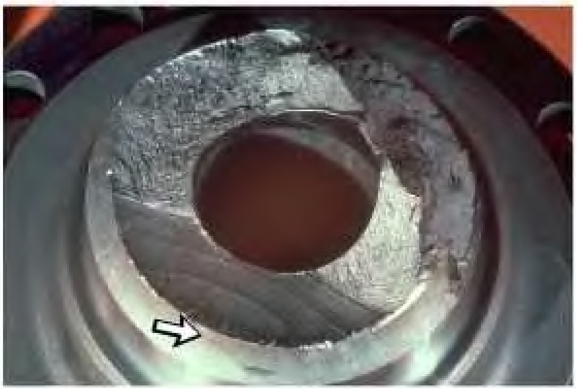

Illustration 45 g01201490

Fracture initiated at the bottom side of the fillet in this spindle.

Illustration 46 g01201492

Fracture initiated in the fillet of this shaft.

Illustration 47 g01201493

Fracture can initiate at the fillet between the stem and head of an engine valve.

Illustration 48 g01201495

Fracture can initiate at the bolt head seat and nut seat on a connecting rod and cap.

Illustration 49 g01201498

The underhead fillet is a common location for fractures to initiate in bolts.

Illustration 50 g01201501

Fracture initiated at all four fillets on this universal joint cross.

Thread Roots

Fasteners that are overloaded in service often fail in the thread roots. The exact location of the fracture and the type of fracture depend on the loading conditions prior to, and at the time of, failure.

Illustration 51 g01201707

The first exposed thread and the first thread after the shank are common failure locations.

Illustration 52 g01201708

Overloading this bolt by over torquing resulted in ductile fracture through the threads.

Illustration 53 g01201710

Single direction cyclic loading resulted in fatigue fracture through the threads of this bolt.

Illustration 54 g01201713

Reversed cyclic loading resulted in reversed bending fatigue fracture through the threads of the bolt.

Illustration 55 g01201715

Over twisting a seized bolt produced a torsional shear fracture that initiated all around the threads in this bolt.

Grooves

Like fillets and corners, grooves are another common location for fracture initiation if a part is overloaded in service. So, when examining parts that have failed or been overloaded in service, pay close attention to any grooves in the part.

Illustration 56 g01201726

The keeper grooves on valve stems may fret and fail if a valve is overloaded in service.

Illustration 57 g01201728

The fracture in a gear pump flange followed the seal ring groove.

Illustration 58 g01201730

This hydraulic vane pump shaft failed through a snap ring groove.

Illustration 59 g01201733

This hydraulic vane pump shaft failed through a snap ring groove.

Illustration 60 g01201734

This shaft failed through a groove at the base of the splines.

Spline Tooth Roots

Spline tooth roots can be a location for fracture initiation if the splines are overloaded in service. In shafts, the fracture may initiate in the longitudinal direction parallel to the splines or at 45 degrees to the longitudinal direction.

Illustration 61

g01202063

Spline tooth roots that are sharp corners can initiate fracture in overloaded shafts.

Illustration 62

g01202066

This shaft fracture initiated in the longitudinal direction at the root of a spline tooth.

Corners

Corners of parts concentrate the stress in a part and provide locations from which cracks can start.

Illustration 63 g01202068

A sudden shock load resulted in multiple fractures initiating at various corners in this plate.

Illustration 64 g01202069

This corner has been reinforced in order to reduce stresses at a normal stress raiser.

Holes

Holes in a part concentrate the stress in the part and provide locations from which cracks can start.

Illustration 65 g01202071

The vane pump cam ring failed through a hole in the high-pressure area.

Illustration 66 g01202072

This shaft failed when the point at the bottom of a drilled hole was overloaded in service.

Keyways

Keyways in a part concentrate the stress in the part and provide locations from which cracks can start.

Illustration 67 g01202073

Keyways not designed to carry loads can initiate fractures if overloaded in service.

Illustration 68 g01202075

This pump shaft failed out of a keyway when overloaded in service.

Gear Tooth Roots

Like spline tooth roots, gear tooth roots can concentrate the stress in a gear and provide a location from which cracks can start.
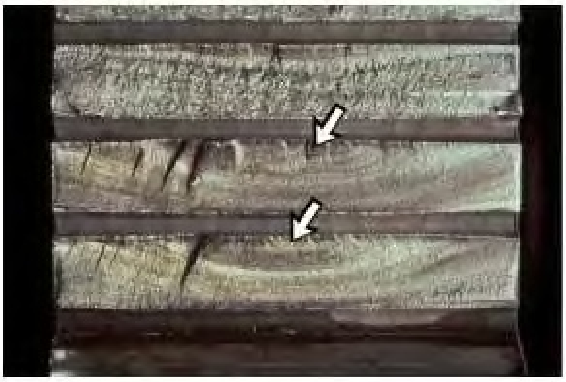
Illustration 69 g01202080

Gear tooth roots can initiate fractures if overloaded in service.

Surface Finish

No surfaces on a part are perfectly smooth. The roughness on a surface of a part can be the stress raiser that initiates fracture if overloading in service is severe.

Illustration 70 g01202082

If loading is severe, fractures can initiate from the machining marks on the surface of a part.

Structural Stiffness

If a structure becomes too stiff, stress from operating loads will be too high and cause fractures to initiate. Structures that have been repaired with reinforcing plates can fail this way.

Illustration 71 g01202085

The mounting plate over-stiffened the frame and contributed to fracture.

Illustration 72 g01202086

A heavy plate that was added to modify a structure may have been one of the factors leading to sudden fracture.

Markings

When part markings are placed in high stress areas on the surface of parts, the marking can provide the initiation site for fractures.

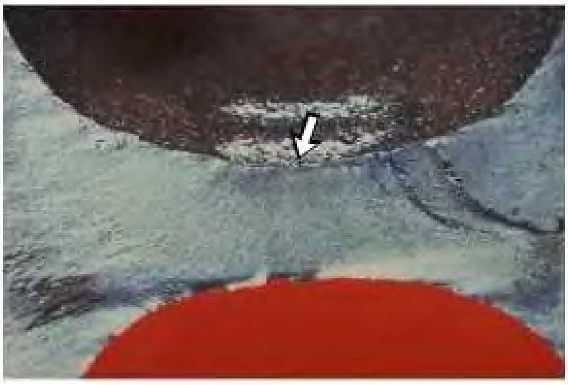

Illustration 73 g01202102

Raised markings were the initiation site on a highly loaded surface on a connecting rod

Illustration 74 g01202110

Depressed markings were the initiation site on a highly loaded surface on a ripper tip.

Material Stress Raisers

Some stress raisers are material flaws or defects. Material stress raisers are not a common cause of failure. There are a few other material stress raisers not illustrated here that can cause failure, but it takes the expertise and equipment of a metallurgical laboratory to detect them.

Inclusions

Inclusions in metals are bits and pieces of non-metallic materials left over from the production and processing of the metal. All of the metals that Caterpillar uses contain inclusions, so the metals normally are not a problem. However, when inclusions are too large or in a high stress area, the inclusions can provide the initiation site for fracture.

Illustration 75 g01202620

An inclusion just below the fillet surface of a crankshaft that initiated a fatigue fracture. The light-colored area is commonly called a "Bulls Eye" and often indicates a subsurface crack initiation from a material flaw.

Illustration 76 g01202621

An inclusion at the inside corner of a single piece piston pin bore initiated a fatigue fracture.

Illustration 77 g01202622

An elongated inclusion (called a stringer) initiated a fatigue fracture in a piston pin.

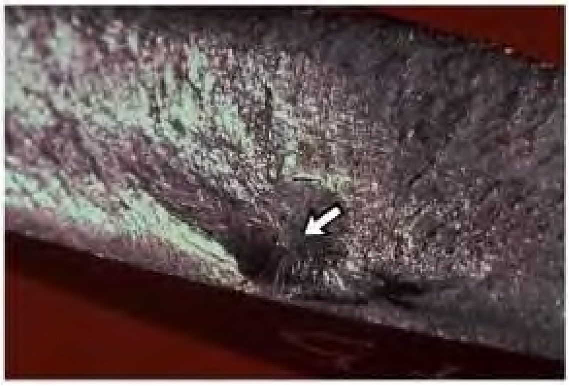

Illustration 78

g01202623

A subsurface inclusion in a gear tooth initiated a fatigue fracture due to cyclic loading of the tooth. Note the presence of the circular bulls eye.

Grain Flow

Parts that are formed by rolling, forging, drawing, or extruding have grain flow. Proper forming methods orient grain flow so the flow is parallel to the surface of the part providing extra strength because the part is more difficult to fracture across grain flow than in the direction of grain flow. If the loading direction is in the direction of grain flow, the grain flow can be a "weak link" initiating fracture of the part.

Illustration 79

g01202624

Grain flow direction in the pin bore of a connecting rod provides an area of potential fracture initiation.

Illustration 80 g01202625

The loading on this shaft produced a fracture in the direction of the grain flow in the part.

Forging Burns

"Burned forgings" have been heated so hot in the forging process that the metal melts at the grain boundaries and then resolidifies leaving micro cracks at the grain boundaries.

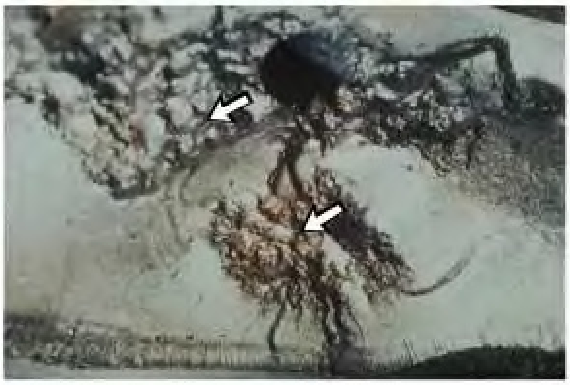

Illustration 81 g01202626

This forging fracture surface shows grainy-looking areas of burning where remelting during forging occurred.

Pipe

Pipe defects, found in ingot cast steel, result from improper processing at the steel mill. These defects are not common in Caterpillar parts.

Illustration 82 g01202627

The fracture of this part initiated at a pipe defect.

Hydrogen Flakes

Steel that is not processed properly after pouring can contain internal cracks known as hydrogen flakes that appear as silvery looking spots on a fracture surface. Hydrogen flakes are rare in Caterpillar parts.

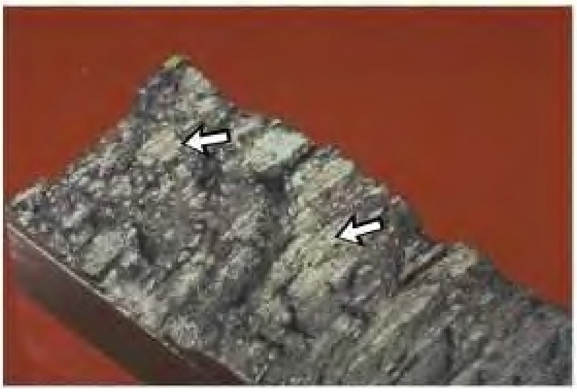

Illustration 83 g01202647

Fractured part showing hydrogen flakes on the fracture surface.

Illustration 84 g01202649

Failed crankshaft showing fracture initiation at a hydrogen flake inside the part.

Casting Shrinkage

Castings with insufficient hot metal available to compensate for shrinkage during solidification can develop internal voids known as shrinkage. Shrinkage areas may look like internal holes or may have a spongy appearance.

Illustration 85 g01202651

Fracture of a cast steel wheel loader lift arm initiated at an area of shrinkage inside the part.

Illustration 86 g01202656

Fracture of a cast steel swivel initiated at an area of shrinkage within the part.

Microstructure

Sometimes normal or abnormal features in the microstructure of the part material can act as stress raisers and initiate fractures. For instance, the graphite flakes (natural "cracks") in the normal gray cast iron microstructure often initiate fracture if the part is overloaded in service.

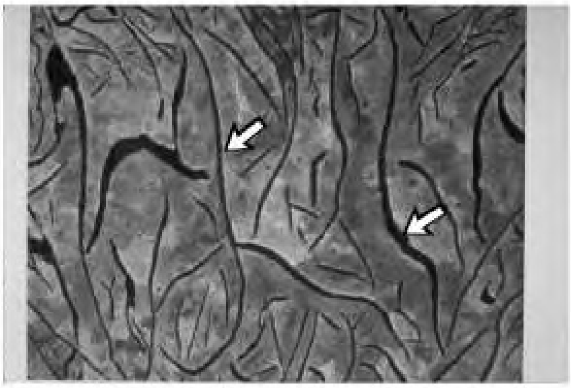

Illustration 87 g01202658

Graphite flakes in the microstructure of gray cast iron will initiate fracture if the part is overloaded.

Stress Raisers from Manufacturing Processes

Manufacturing processes can produce stress raisers in parts. Some of the stress raisers are normal and were covered under "Stress Raisers by Design." When manufacturing processes go out of control, abnormal stress raisers that can lead to failure may result.

Heat Treatment

Many parts require heat treatment to develop the strength and wear characteristics necessary for the application. When done improperly, thermal stresses from heat treatment can crack parts. Heat treatment can warp parts. Insufficient or excessive heat treatment can also cause problems.

Illustration 88 g01202674

This connecting rod fractured from a quench crack that was produced by thermal shock during heat treatment.

Illustration 89 g01202675

A small quench crack at the corner of a journal oil hole initiated the fracture of this crankshaft.

Illustration 90 g01202680

The dark areas in the fillet are quench cracks from improper heat treatment of the part.

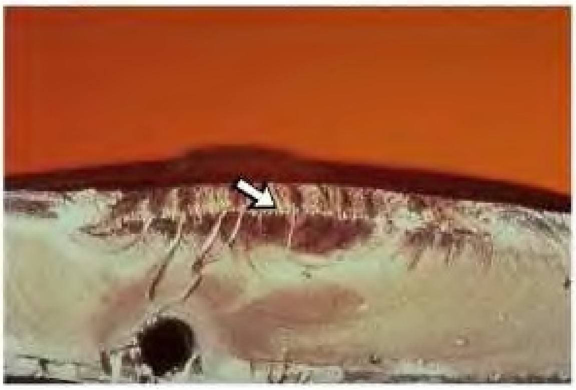

Illustration 91 g01202683

The rough area is a straightening crack from trying to straighten a part that warped during heat treatment.

Illustration 92 g01202685

This bearing race missed heat treatment leaving the part soft so the part failed rapidly under normal service loads.

Illustration 93 g01202689

Excessive hardened depth caused this shaft to fracture internally from residual tensile stress.

Forming Cracks

When steel does not flow properly during forging and rolling, flaws called forging laps or seams can result. Laps and seams can act like cracks on the surface of a part and initiate fracture when loading is sufficient. Forming can also produce internal rupture or other types of cracking in parts

Illustration 94 g01202691

Part of the connecting rod broke away due to a forging lap at the corner of the connecting rod.

Illustration 95 g01202692

A forging lap at the surface of a connecting rod initiated a fatigue fracture in the part.

Illustration 96 g01202693

A seam in the wire from which the bolt was formed produced a burst in the head of the bolt.

Illustration 97 g01202696

This bolt ruptured internally during an extrusion operation. The bolt failed completely during installation.

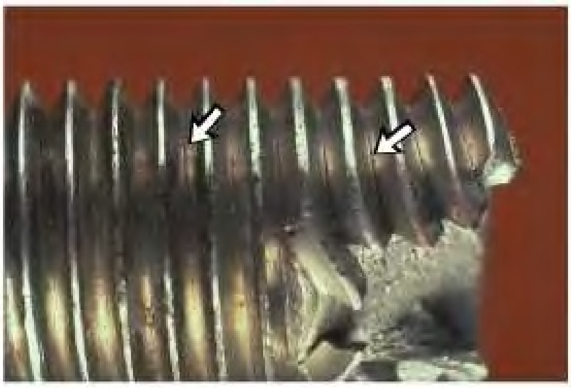

Illustration 98 g01202699

Thermal shock from an improper machining practice cracked the roots of the threads leading to failure.

Illustration 99 g01202700

Forming metal parts can produce residual stresses that adversely affect part performance.

Precracks

If a part is cracked before the part enters service, the part is said to be precracked. When a crack has existed for a while, there may be things like rust, paint, discoloration, or oxides on the area of the precrack surface that was there before the part finally broke.

Illustration 100 g01202702

Part of the fracture surface is rusted indicating a precrack was present before the part broke.

Illustration 101 g01202704

Improper hardness testing (too close to an edge) precracked this part and initiated failure.

Improper Machining

The surface finish left from machining can initiate fracture when a part is severely overloaded. As surface roughness increases, the load to initiate fracture decreases. Grooves or fillets machined with too small a radius can also initiate fracture.

Illustration 102 g01202705

The surface roughness produced by improper machining setups can initiate fractures if the loading is severe enough.

Illustration 103 g01202707

Improperly machined grooves with too small a radius can initiate fracture in parts.

Welding Flaws

Welding can produce several types of flaws that may initiate fracture in welded components and structures. Many of the flaws are notch or crack-like and thus are severe stress raisers.

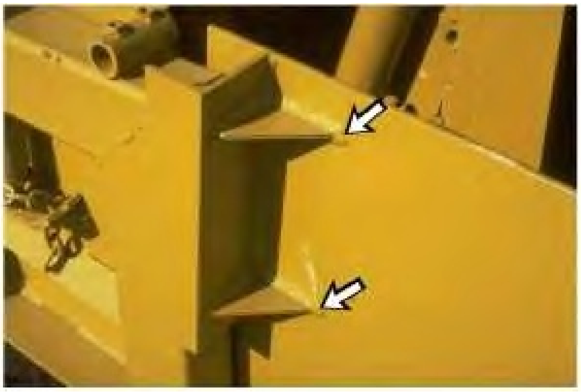

Illustration 104 g01202723

Weld start/stops should not be in high stress areas or at locations where there is a change in stiffness.

Illustration 105 g01202724

Weld toes often form notches that can concentrate stress and initiate fractures.

Illustration 106 g01202726

Undercut weld toes produce notches that can initiate fractures.

Illustration 107 g01202728

Rough welds produce notches that can initiate fractures.

Illustration 108 g01202729

Welds that are not properly tied together produce notches that can initiate fractures.

Illustration 109 g01202731

Overlap at weld toes produces notches that can initiate fractures.

Illustration 110 g01202733

Insufficient crater fill produces a stress raiser that can initiate fractures.

Illustration 111 g01202734

Improper weld processes can produce porosity - an internal stress raiser in the weld

Illustration 112 g01202736

Improper fit-up between parts may produce notches and undersized welds that can result in fractures.

Debonding

If bonded parts debond prior to service, failure results. Debonding can produce a crack-like stress raiser that initiates fracture.

Illustration 113 g01202737

The ring carrier insert debonded from the piston after which the piston cracked and failed.

Stress Raisers from Operation

Normal or abnormal operation can produce stress raisers on parts. This section illustrates some stress raisers that can result during atypical engine or machine operation.

Contact Stress Fatigue

Overloading the surface of parts that roll on or slide against one another can lead to contact stress fatigue damage. The pits that are produced act as stress raisers and can initiate fractures.

Illustration 114 g01203170

Bearing rollers have spalled due to rolling contact stress fatigue. Pits are stress raisers.

Illustration 115 g01203173

Bearing race with rolling contact stress fatigue. Pits are stress raisers.

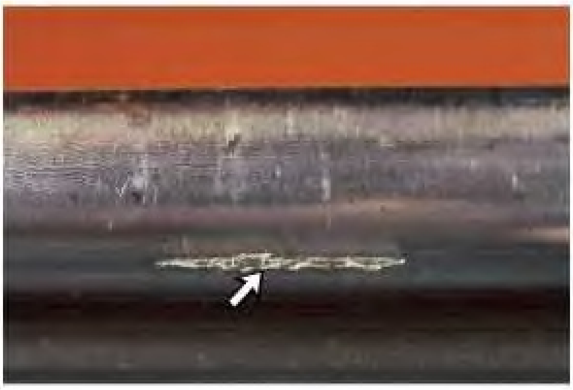

Illustration 116 g01203175

Gear tooth with sliding contact stress fatigue pits. This stress raiser may lead to tooth fracture.

Illustration 117 g01203176

Sliding contact stress fatigue on an engine bearing produces transverse cracking and pitting.

Cavitation Erosion

Cavitation erosion results from a combination of bubbles in a fluid and a pressure change. Cavitation erosion pits a surface creating stress raisers that may initiate fractures.

Illustration 118 g01203177

Bright, shiny pits from cavitation erosion are a stress raiser that can initiate fracture.

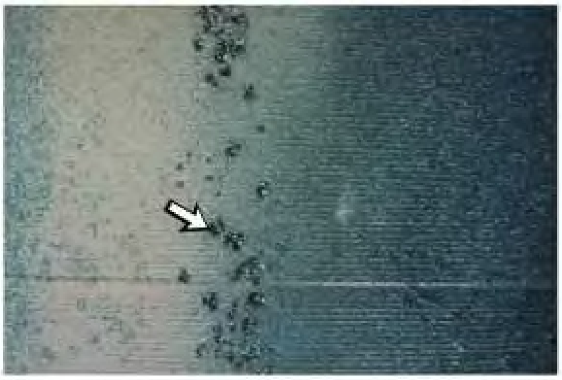

Illustration 119 g01203179

Cavitation erosion can create pits that go completely through the wall of a part.

Corrosion

Corrosion during service removes material from the surface of parts. Sometimes the material is removed uniformly, but more often corrosion is localized producing pits on the surface. The pits are stress raisers and can be the initiation site for fractures if the pits are in highly loaded areas of the part.

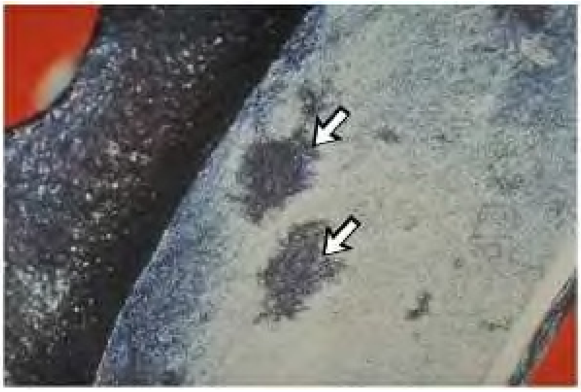

Illustration 120 g01203182

Discoloration and pitting resulting from corrosion. Corrosion pits are stress raisers.

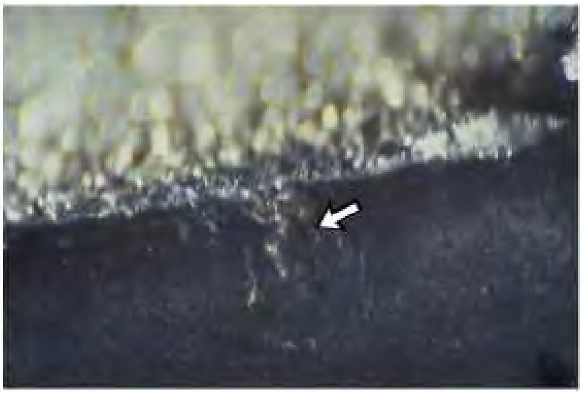

Illustration 121 g01203183

Magnified view of corrosion pit at the initiation site of a fracture.

Fretting (Fretting Corrosion)

Fretting or fretting corrosion from movement in tight joints produces pits on the moving surfaces. The pits are stress raisers that can initiate fractures.

Illustration 122 g01203185

Fretting corrosion and pitting on a bolt shank can lead to early failure.

Illustration 123 g01203186

Pits from fretting on the ball stud surface initiated a reverse bending fatigue fracture.

Excessive Operating Temperature

Operating parts at excessively high temperatures can have two bad effects. First, high temperature can reduce the strength of parts so that a normal load can become an overload leading to failure. Second, high temperature oxidation can pit surfaces producing stress raisers.

Illustration 124 g01203189

High temperature operation weakened the connecting rod allowing the rod to deform and fail.

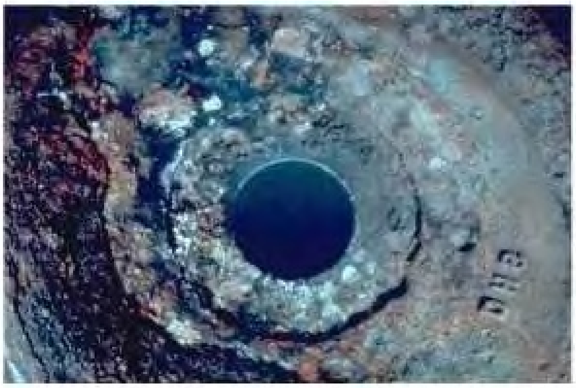

Illustration 125 g01203191

High temperature operation pitted the surface of this part producing stress raisers.

Abrasive Wear

Abrasive wear can weaken a part by removing enough material that the part is no longer capable of carrying the loads the part was designed to carry. Abrasive wear can also produce notches and grooves, stress raisers that can initiate fractures.

Illustration 126 g01203194

Wear on the face of the valve can lead to fractured edges during operation.

Plastic Deformation

Parts that are plastically deformed can concentrate applied loads (such as trying to straighten a bent shaft) and may thus fail early.

Illustration 127 g01203196

This bent link failed when the link was overloaded by operating stresses attempting to straighten the link.

Debonding

Abusive operation that produces excessive loads can cause bonds in parts to separate and lead to failure of the part.

Illustration 128 g01203197

When the piston ring insert bond failed in the piston, a "corner" was created that concentrated applied loads so that the piston failed.

Electrical Damage

Stray currents passing through parts can cause surface damage. The damage can result in pits and rough surfaces that can damage other mating parts during operation. Pits are stress raisers from which fractures can initiate.

Sources for damaging electric currents include: faulty grounds, improper welding on machinery, lightning strikes and inadvertent contact with power lines or other power sources.

High Current Damage

When high current arcs between parts the current acts like a miniature lightning bolt. Electric arcs result in high surface temperature that melts the surface and forms pits. When magnified, the pits show evidence of melting and flow of the material. (Photo courtesy of Timken Company)

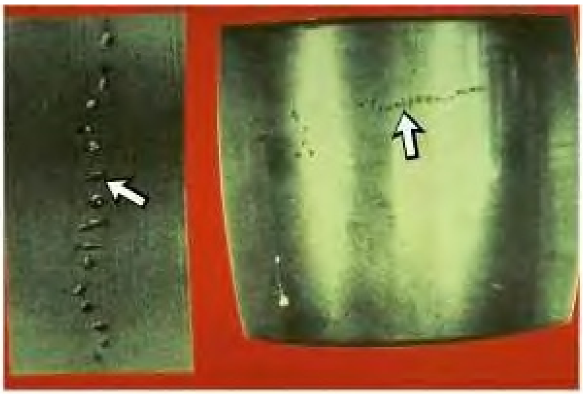

Illustration 129 g01203198

This bearing surface was pitted by high current arcs while the bearing was not rotating.

Low Current Damage

Low current arcs can damage the surface of parts. The pits formed by a low current arc are small but, collectively over time, serious surface damage is possible. The following photo shows the surface of a ball bearing from an electrical generator.

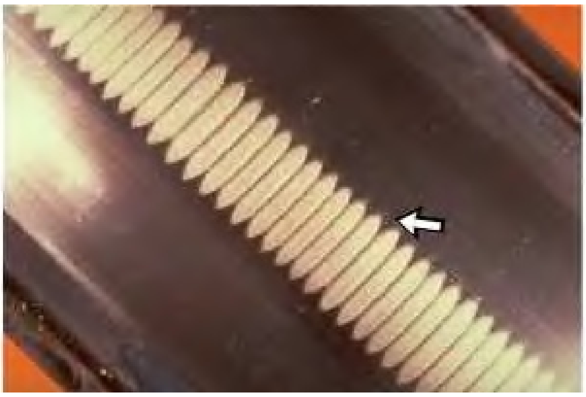

Illustration 130 g01203201

This bearing surface was pitted by low current arcs while the bearing was rotating. This type of damage is called "fluting"

Stress Raisers from Handling, Assembly, Disassembly, and Repair

Careless handling, assembly, and disassembly or repair can produce stress raisers on parts. Some parts are made from materials like cast iron or cast aluminum that are more sensitive to shock loads.

Handling

Careless handling can crack or dent parts producing stress raisers that may reduce the service life of a part.

Illustration 131 g01203227

Cast iron parts can crack if shock loaded. Even a small drop can produce a crack that may grow under service loads.

Illustration 132 g01203229

This bolt was dented by careless handling which later resulted in an expensive engine failure.

Improper Weld Repair

Welding can produce adverse residual tensile stresses, a bad surface profile, and a weakened heat affected zone near the weld. These defects can result in early failure if welding is not done properly.

Illustration 133 g01203230

Improper weld repair on a crankshaft produced stress raisers that drastically shortened the life of the crankshaft.

Assembly and Disassembly

Methods used to assemble and disassemble parts can result in stress raisers that may shorten part life.

Illustration 134 g01203233

Chipped bearing races during installation can affect bearing life.

Illustration 135 g01203235

Housing damage during bearing removal may shorten bearing life or cause the new bearing to fail.

Illustration 136 g01203238

Torch marks from bearing race removal are stress raisers. Here the surface damage resulted in shaft failure.

Analyzing Worn Parts

Analyzing worn parts should be done in an organized way with two objectives in mind:

1. Obtain all of the facts from the worn parts.
2. Prevent any additional damage to the parts during removal, inspection and afterwards.

The following steps can be followed to make sure that the objectives are met.

1. Obtain the failed parts and protect from damage

   Appropriate methods for obtaining failed parts are covered in the section "Disassembly for Failure Analysis." Failed parts must be removed and handled carefully to avoid further damage. Once parts have been removed, the parts are susceptible to casual impact damage and corrosion on the worn surfaces. Wrapping worn surfaces with cloth or towels and coating with rust inhibitors such as engine oil or grease are good ways to prevent additional damage. Be careful if parts have to be shipped to another location for analysis. Prepare the parts for shipping to prevent impact damage or corrosion on worn surfaces. If parts must be sectioned prior to moving or shipment, be careful not to do anything that will change the characteristics of the material in the worn area. For instance, cutting with a torch too close to a worn area can overheat the metal and change the properties making failure analysis more difficult.

2. Clean the parts carefully

   Damaging a worn surface is easy if overly aggressive cleaning methods are used. The best methods for cleaning fracture surfaces involve mild solvents, soft bristle brushes, and forced air -drying as illustrated below. Cleaning processes using glass beads, grit blasting, wire brushing, Scotchbrite pads, or aggressive solvents are not suitable for cleaning failed parts prior to inspection.

   If the damage on a part may have been due to abrasive or erosive wear, cleaning becomes a critical step. Both abrasive and erosive wear damage result from the actions of particles on the part surface. Analysis of the root cause for abrasive or erosive wear involves finding examples of the particles to determine what the particles are and where the particles came from. Improper cleaning methods can remove the particles that did the damage and make the failure analysis job much more difficult. If rough cleaning damages the surface of the part, the wear tracks left by the particles may be obscured covering up road signs critical to identifying the wear particles.

   So, if abrasive or erosive wear is suspected, rinse the part first and then collect and filter the rinse solution to collect any loose particles on the surfaces or in holes in the part.

3. Determine the type of wear present

   Once the worn surface has been cleaned of oil, grease and loose dirt and debris particles, inspect the surface to determine the type of wear. Refer to the sections on Abrasive, Adhesive, Corrosion, Erosion, Cavitation Erosion, Contact Stress Fatigue, and Fretting Corrosion for help with identifying the type of wear.

   It is not unusual for more than one type of wear to be present on a failed part. For instance, adhesive wear can easily lead to abrasive wear and vice versa. Several of the wear processes produce particles that can lead to secondary abrasive wear. When multiple types of wear are present, determine the order of wear. For instance, did abrasive wear lead to adhesive wear or was the adhesive wear present before the abrasive wear began? Finding the order of wear damage requires close inspection of the worn surfaces usually with magnification to clearly see small details. Be sure to take enough time to find all of the facts on the worn surfaces.

4. Identify the environment that caused the wear damage

   Just as each type of fracture is associated with a particular type of load, each type of wear is associated with a particular type of environment. Collect information about the operating environment at the time that the wear damage occurred. In fact, when parts are both worn and broken, wear facts may assist in fracture analysis by indicating the operating environment at the time of failure. Here is the environment for each type of wear.

Table 2

Wear Type	Environment
Abrasion	2-body: one rough surface rubbing against another
	3-body: particles between moving surfaces
Adhesion	Metal to metal contact
Corrosion	General & galvanic: anode, cathode, and electrolyte
Erosion	Moving particles impacting a surface
Cavitation erosion	Bubbles and an area of high pressure
Contact stress fatigue	Overload on sliding or rolling surfaces
Fretting corrosion	Movement in a tight joint

   The first step in determining the operating environment is to understand how the customer is using the equipment. What is the application of the equipment? Is the application typical or atypical? How is the equipment operated and are the operators experienced? What is known about equipment maintenance? Who performs maintenance, how often is maintenance done and what parts and materials are used?

   System facts such as the materials involved and operating temperatures may be significant when analyzing some types of wear. If corrosion is involved, fluid samples may be necessary to identify electrolytes. Lubrication facts may also be key when analyzing wear failures. Collect facts that document the quality and quantity of lubricant in the system and whether the lubricant was being delivered properly to the parts. Determine whether there is a history of lubricant analysis results and sample the lubricant at the time of failure.

5. Putting the facts together

   Facts gathered while analyzing worn parts provide evidence about the type of wear, location of the wear and loads that might have been involved. For instance, off center wear may indicate misalignment or bent parts. Wear that occurred later in the failure may be on top of earlier wear that caused the failure. Fretting damage indicates that surfaces in a tight joint have been moving.

   Loading on parts affects the type of wear that is produced, so abnormal wear patterns are often an indication of hostile loading conditions.

   When analyzing worn parts, make sure to identify all of the wear types present, the environmental conditions that produced the wear and any abnormal loading that might have been involved.

Finally, although not too common, abnormal wear may result from parts that do not conform to print requirements. If the facts indicate a possible parts problem (such as abnormally rapid wear under normal operating conditions) then make sure to check the parts for conformance to print material and processing requirements.

Abrasive Wear

Caterpillar parts can exhibit two types of abrasive wear: 2-body and 3-body. Two-body abrasive wear occurs when a hard rough surface moves across a softer surface and cuts material away. An example of 2-body abrasive wear would be removing metal with a grinding wheel. Three-body abrasive wear can occur when hard particles that are larger than the lubricant film thickness get between two moving surfaces. Soft surfaces are cut leaving deep scratches and producing debris. Harder surfaces do not cut as easily but some frictional heat is generated as the hard particles rub against the hard surface. If the supply of lubricant is adequate, the frictional heat will be carried away.

The key thing when analyzing 3-body abrasive wear is to identify the particles doing the damage. If the particles can be identified and the source of the particles determined, then the abrasive wear problem can be fixed so the problem will not happen again. For instance, if dirt particles are entering an engine due to a damaged air filter housing, just replacing the filter will not cure the wear. Repairing or replacing the damaged housing is necessary to prevent further abrasive wear damage.

A common side effect of abrasive wear is that as abraded surfaces are roughened, the surfaces begin to make contact through the lubricant film and generate more heat than the lubricant can carry away. This leads to secondary adhesive wear and further surface damage. When analyzing worn surfaces, watch for this situation and be careful to separate secondary adhesive wear from the original abrasive wear.

Abrasive wear damage can be identified by the following characteristics:

1. The surface of the parts is scratched, cut, gouged, or grooved.
2. There is little discoloration in the damaged areas indicating cool temperatures.
3. Self-generated, secondary debris particles from the scratched surfaces are present.

Illustration 137 g01203261

Piston skirt cut by abrasive wear particles

Soft surfaces, such as this piston skirt, are easily cut by abrasive wear particles. There may be many scratches in the damaged area as on this piston skirt. Soft surfaces can easily embed some of the particles. So, the wear surface is one good area to look for examples of the particles doing the damage.

Illustration 138 g01203269

Scratches on a gear tooth

Hard surfaces, such as this gear tooth, are not so easily cut by abrasive wear particles. The scratches, if present, will be much smaller and more difficult to see. Look elsewhere in the system, for instance in the lubricant filters, for examples of wear particles.

Illustration 139 g01203282

Scratches on a vane pump flex plate

If abrasive particles are small enough, the particles will polish a surface. Larger particles, such as dirt, leave more distinctive scratches like those scratches on this vane pump flex plate.

Illustration 140 g01203286

Vane pump flex plate with large gouges

Large particles or pieces of other broken parts will leave large gouges in the surfaces of softer parts as on this vane pump flex plate.

Illustration 141 g01203290

Machining chips

Abrasive wear particles come in many shapes and sizes. These machining chips would produce irregular shaped scratches and dents in a surface. Dirt particles are also irregular and produce sharp scratches and irregular shaped dents.

Illustration 142 g01203293

Steel shot and glass beads

Man-made particles such as steel shot and glass beads are nearly spherical and so leave round dents and round-bottomed grooves for scratches. Abrasive wear due to round particles usually indicates contamination with some cleaning media. Note that glass particles can shatter into irregular shapes that will then produce sharper scratches.

Significance of Abrasive Wear

Abrasive wear found on parts indicates that either one rough, hard surface has rubbed over another softer surface (2-body wear) or particles larger than lubricant film thickness have contaminated a system (3-body wear). Look for the following things:

1. What are the primary wear particles?
    a. What is the shape of the particles?
    b. What is the size of the particles?
    c. Is the size of the particles uniform?
    d. What is the color of the particles?
    e. Are the particles opaque or transparent?
    f. What is the size and shape of the scratches the particles produced?
    g. How hard is the surface that the particles scratched?
    h. Are the particles magnetic?
    i. Are any fluid analysis results available?
    j. Are there any marks on the wear particles?
    k. Have soft surfaces been examined for embedded particles?
    l. Have the filters been checked for particles?
    m. Have any low flow areas in the lubricant system (tank, sump) been examined?

    n. Is there any evidence to indicate whether the particles are natural or man-made?

2. What is the source of the wear particles?

    a. Are all filters and housings intact and operating properly?

    b. Are all seals intact and operating properly?

    c. Are all lubricants properly filtered before use?

    d. Are good housekeeping procedures followed during maintenance?

    e. Is there any evidence of leaks that would allow particles to enter?

    f. Has there been any recent maintenance or repairs?

    g. What is the operating environment of the equipment?

    h. Are there samples of particles the equipment routinely encounters during operation?

    Here are some possible sources for particles:

    Built in: Burrs, core sand, weld spatter, paint chips, rust particles, machining chips, pieces of sealant, lint, or fabric threads and scale.

    Ingested: Any particles in the environment that an engine or machine is operated in can enter through breather caps, access plates, faulty cylinder seals and poor maintenance procedures.

    Self-generated contaminants: Operating mechanical systems constantly generate particles including wear particles, corrosion products, cavitation particles, fluid breakdown products (from decomposition or oxidation), pieces of seals and gaskets, additive reaction products and rust particles.

3. Why is the worn part exposed to a rough surface (2-body wear)? What produced the rough surface?

Adhesive Wear

Adhesive wear results when two moving surfaces make contact without adequate lubrication and/or cooling. When the moving surfaces contact and rub, heat is produced through friction. The heat first softens, and then melts the surfaces so the surfaces melt and adhere (weld) together.

Unless the contacting surfaces can be separated, adhesive wear will often proceed rapidly and result in destruction of the parts. When the surfaces of parts begin to heat due to friction from contact, the part begins to grow larger reducing clearances and any lubricant present will begin to thin (reduce viscosity). The net result is increased contact, more frictional heating, and the cycle continues until destruction.

There are two general reasons that moving surfaces make contact during operation. First, the lubricating film between the parts was lost. Second, the parts were forced together through the lubricating film. There is any number of reasons for either of these conditions. The first step in analyzing adhesive wear problems is to identify which general reason was responsible for the damage.

Adhesive wear damage can be identified by the following characteristics:

1. The surface of the part is smeared.
2. The surface of the part is discolored due to frictional heating.
3. The surfaces appear to have melted and stuck together.
4. There is evidence that material from the weaker surface has welded to the stronger surface.
5. There is secondary wear on the weaker surface resulting from the material transfer.

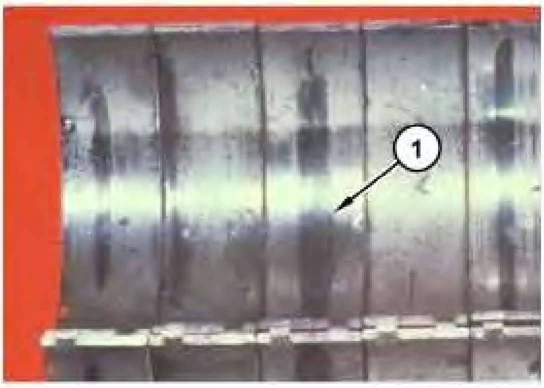

Illustration 143 g01203517

(1) Polishing or smearing is the first road sign of adhesive wear

The first road sign of adhesive wear is polishing or smearing of the weaker surface. Smearing indicates the surface temperature has reached the melting point. Damage will be limited to the surface because heat conduction rapidly lowers the temperature below the surface of the part in this stage of adhesive wear.

When several parts show signs of adhesive wear, look for more facts in common systems. Here, several engine bearings have smeared, so check the lubrication system.

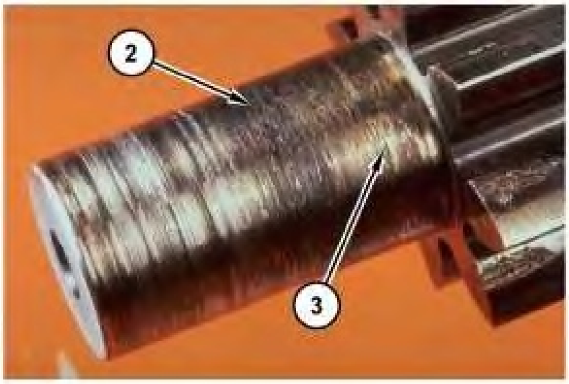

Illustration 144 g01203525

(2) Discolored surface due to frictional heating.

(3) Surface appears to be melted

As adhesive wear continues and temperature increases, surfaces begin to discolor, melt, and adhere together. This results in rough, dark-colored surfaces. Surfaces with adhesive wear often show signs of 2-body abrasive wear due to material transfer from one surface to the other.

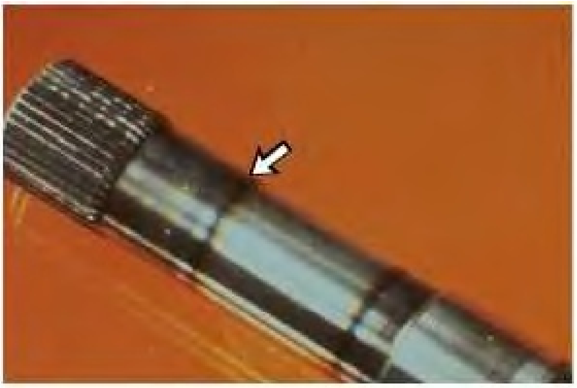

Illustration 145 g01203532

Shaft showing temper colors from induction hardening

When examining worn parts, be careful not to confuse temper colors from heat treatment with heating due to adhesive wear. The spline end of this shaft was induction hardened which left temper colors on the surface of the part. If unsure about the origin of discoloration on the surface of a part, check the processing of the part.

Illustration 146 g01203537

Piston operated to destruction without coolant.

Ultimately, if operation with adhesive wear continues, the temperature of the part approaches the melting temperature, the part loses strength, and breaks apart into pieces. If the pieces are carefully cleaned and organized, examination will often reveal what has happened. This piston operated to destruction without coolant.

Significance of Adhesive Wear

Adhesive wear found on parts indicates that moving surfaces have contacted without adequate lubrication or cooling.

1. Was the load sufficient during operation to force the surfaces together?
    a. Was there abusive operation during service?
    b. Were the parts assembled correctly?
    c. Were any of the parts misaligned?
    d. Did any other parts fail that would allow contact during operation?
    e. Is there any evidence of excessive operating temperatures?
2. Was the lubrication adequate during operation?
    a. What type and viscosity of lubricant was used in the system?
    b. Did the lubricant meet Caterpillar specifications?
    c. Was the quantity of lubrication adequate?
    d. Are any of the lubricant passages blocked?
    e. Was maintenance performed at the specified intervals?
    f. Is there any damage that would interfere with lubrication?
    g. Is there any evidence that the adhesive wear was preceded by abrasive wear?
3. What was the operating temperature of the affected components?
    a. High temperature operation lowers oil viscosity producing thinner oil films and reducing load carrying capability.
    b. Low temperature operation increases oil viscosity resulting in thicker oil that may not flow through small clearances properly.
    c. Parts experience thermal growth in dimensions as temperature increases leading to reduction in lubricating clearances between parts.
4. Was there any other type of wear present prior to the adhesive wear that would have affected the ability to maintain a lubricating film between components?

Corrosion Wear

Corrosion wear typically occurs as a result of chemical change, deterioration, and removal of material from the surface of a part. Corrosion is an electrochemical process meaning that it includes both chemical reactions and the flow of electrons (electricity). For corrosion to occur, there must be a cathode (less active metal area) and an anode (more active metal area) in contact through an electrolyte (a nonmetallic electric conductor in which current is carried by the movement of ions). Remove any one of these three elements, and corrosion stops. During the corrosion process, the more active metal anode area is attacked and material is removed, often producing pits.

Two types of corrosion are common: general corrosion and galvanic corrosion. General corrosion requires an anode, cathode, and electrolyte. The corrosive attack may be over an entire surface or a localized pitting type of attack. The exact nature of the corrosive attack depends on the material being corroded and the nature of the environment surrounding the part. With general corrosion, different areas of a part or even different grains of metal in the part can act as the anode and cathode.

Galvanic corrosion involves two different metals and an electrolyte. One of the metals acts as the anode and the other metal acts as a cathode. When the two metals are connected through an electrolyte, corrosion occurs. The electrolyte in the system and other environmental conditions will determine which metal acts as the anode in any particular case. Metals are rated in "galvanic series" depending on specific electrolytes and environmental conditions. Tables of galvanic series are available in corrosion reference books.

There are many variables that determine whether corrosion will occur and the type of corrosion that occurs. For this reason, involve a corrosion specialist to identify the cause and potential remedy for a particular case of corrosion damage.

General and galvanic corrosion wear damage can be identified by the following characteristics:

1. The surface of the parts is rusting, discolored, scaling, or has crystalline looking deposits.
2. The surface of the part in contact with the electrolyte is rough or pitted.
3. The surface of the part in contact with the electrolyte has irregularly shaped holes.

Illustration 147 g01203554

Bearing failure due to corrosion

Rusting is one of the most common types of corrosion. Metal grains are the anodes and cathodes which are connected by water - a good electrolyte. Protect metal surfaces that are very clean from corrosion during storage or handling.

Illustration 148 g01203556

Black corrosion deposits - "Black Acid Etching"

Corrosion does not always produce red or orange discoloration. Here, another form of corrosion known as "black acid etching" has produced black corrosion deposits on the surface of a bearing race indicating an electrolyte has contaminated the oil.

Illustration 149 g01203561

Valve stem showing pitting from corrosion

General corrosion may remove material evenly from a metal surface or may produce pitting on the surface as seen in illustration 149.

Illustration 150 g01203564

Oil cooler tube showing galvanic corrosion at the arrow and general corrosion on the left

Galvanic corrosion requires two different metals and an electrolyte. The oil cooler tube in illustration 150 has experienced two types of corrosion. General corrosion has occurred on the left side. There is also galvanic corrosion at the arrow where the copper tube and steel baffle reacted.

High Temperature Oxidation

The broad definition of corrosion (chemical change, deterioration, and removal of material from the surface of a part) allows high temperature oxidation damage to be included under the heading of corrosion. High temperature oxidation occurs when a heated metal surface is exposed to an atmosphere containing oxygen. At high temperatures, oxygen combines more readily with many metals forming an oxide layer than can be lost during operation thus removing material from the surface of a part through a chemical reaction.

Illustration 151 g01203552

Surface of a turbocharger heat shield that is scaled and missing material due to high temperature oxidation

High temperature oxidation wear damage can be identified by the following characteristics:

1. The surface of the parts is scaling or missing material.
2. The surface of the part may be discolored.

3. The surface of the part has been exposed to high temperatures and an atmosphere containing oxygen.

Significance of Corrosion Wear

Corrosion wear found on the surface of parts indicates that either the part has been exposed to an electrolyte or high temperatures during operation.

Look for the following things:

1. Has the corrosion occurred over the whole surface of the part or is the corrosion more localized pitting?
2. Is the corrosion limited to one part?
3. Is there a possibility of galvanic corrosion – two dissimilar metals?
4. What is the electrolyte causing the corrosion? Obtain a sample if possible.
5. What are the general environmental conditions surrounding the corroded part?
    - What liquids are in the environment?
    - What is the temperature of the environment?
    - Is the environment moving or stagnant?
    - Is the environment aerated?
    - Are there any unusual odors present?
    - What is the pH of the environment?
6. Has the part been exposed to elevated temperatures for an extended time?

Erosion Wear

Erosion wear occurs when particles impacting a surface remove tiny bits of material from the surface.

The particles doing the damage can be large or small. The energy moving the particles can simply be momentum as in a large part being "thrown" against the surface of another part. Or, if the particles are small, the energy moving the particles often comes from a moving gas (for example, sand blasting) or fluid (for example, particles in a cooling system) stream. The eroded surface will often have a sand blasted or matte finish appearance.

Note: Erosive wear and abrasive wear are similar in that both involve damage due to particles. The difference between abrasive and erosive wear is the "angle of attack" of the particles. In abrasive wear, the particles move parallel to the surface and "machine" bits of material from the surface. With erosive wear, the particles impact at a steeper angle and chip bits of material from the surface.

The following road signs may be observed when surfaces are damaged by erosive wear:

1. Material has been removed from the surface of the part.
2. Surfaces are dented or pitted from impacting particles.

3. Self-generated, secondary debris particles.
4. Surface has a sand blasted or matte finish appearance.

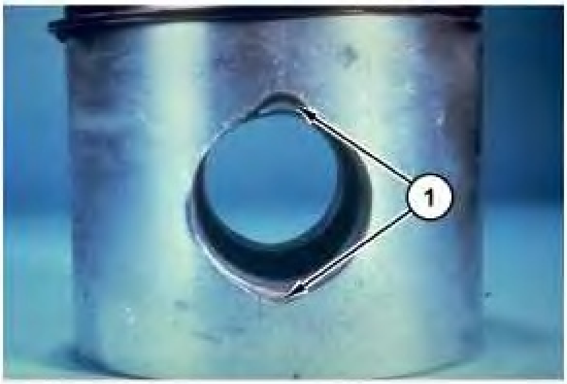

Illustration 152 g01203591

(1) Material has been removed from the surface of the part

A piston pin retainer broke and the loose pieces have severely eroded the piston pin bore. Note the missing material at the top and bottom of the bore.

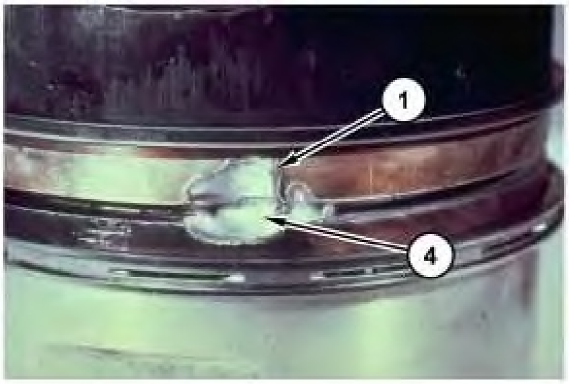

Illustration 153 g01203597

(1) Material has been removed from the surface of the part

(4) Surface has a sand blasted or matte finish appearance.

Pieces of a broken piston ring have eroded the area around the ring groove. Note the missing material and the blasted, or matte, appearance in the area of the erosion damage.

Significance of Erosion Wear

Erosion wear found on parts indicates that impacting particles have damaged the surface of the part. So, as with abrasive wear, identify the particles doing the damage and the source of the particles.

Look for the following things:

1. What are the particles doing the erosion wear damage?
2. What is the source of the particles doing the erosion wear damage?
3. What is energizing the particles to do the damage?

The answer to the first two questions usually involves finding an example of the particles doing the damage.

1. Look for particles adhering to the worn surface.
2. Check filters for particles
3. In fluid systems look for "dead areas" where particles may drop out.
4. Look for particles embedded in the worn surface.
5. Look for broken parts in the vicinity of the erosion damage area.

Cavitation Erosion Wear

Cavitation erosion wear is pitting damage that results when bubbles collapse and the fluid stream that had been supported by the bubble impacts the part surface. Two things are required for cavitation erosion wear to take place: bubbles and an area of increasing pressure capable of collapsing (imploding) the bubbles. Bubbles can form in a fluid as a result of an air leak or as a result of a low-pressure area that releases dissolved gasses or vaporizes (boils) the fluid. High-pressure areas generally result from the design or operation of a system.

If the material being damaged by cavitation erosion is susceptible to corrosion by the fluid, then the processes of cavitation erosion and corrosion may work together to accelerate damage. Cavitation erosion produces a clean surface that is more likely to corrode. So, in operation the surface corrodes, cavitation cleans off the corroded material, the surface corrodes again, and the process repeats itself.

When cavitation erosion occurs, the following road signs may be observed:

1. Irregular shaped surface pits and holes in the damaged area, possible narrowing toward one end.
2. Pitted surfaces with a rough and crystalline appearance (brittle fractures from fluid impact.)
3. Self-generated, secondary debris particles – may also produce abrasive wear damage.
4. In some systems, such as pumps, there may be a noticeable change in sound during operation.

Illustration 154 g01203621

Bubbles in the cooling system of an engine have collapsed in a high-pressure area in the fluid near the surface of a cylinder liner. The result is cavitation erosion and a rough, pitted surface.

Illustration 155 g01203625

Pressure changes in the oil film between an engine bearing and the crankshaft journal can collapse bubbles in the oil and produce cavitation erosion damage. Here the lead tin overlay has been removed exposing the aluminum below.

Illustration 156 g01203631

Bubbles in the engine coolant can collapse in the high-pressure areas of the water pump producing cavitation erosion damage.

Illustration 157 g01203634

This illustration is a higher magnification view of the cavitation erosion damage shown on the water pump cover in illustration 156. Note the bright, crystalline appearance of the pitted area.

Significance of Cavitation Erosion Wear

Cavitation erosion wear found on the surface of parts indicates that bubbles have been collapsing in a high-pressure area near that surface. Look for the following things:

1. What was the source of the bubbles in the fluid?
    a. Is there an air leak in the system?
    b. Are all seals and gaskets working properly?
    c. Was there any recent repairs or maintenance that might have resulted in air in the system.
    d. Is the fluid contaminated with anything that could cause bubbles?
    e. Is the viscosity of the fluid correct for the operating temperature?
    f. What was the ambient temperature during startup and operation?
    g. Are the coolers in the system clean and working properly?
    h. If the damage is in a cooling system, does the coolant contain the specified amount of conditioner?
2. What was the source of the high-pressure area in the fluid?
    a. Was there severe loading during operation?
    b. Was there a severe pressure change during operation?
    c. Does the design of the system result in high-pressure areas?
3. Are there any restrictions to fluid flow in the system?

a. Are all filters and screens capable of passing the required volume of fluid?

b. Are all of the lines clean and unrestricted?

c. Are any of the lines bent or kinked?

d. Are there any restrictions in the tank?

e. Does the fluid being used meet Caterpillar specifications?

Contact Stress Fatigue (CSF) Wear

Contact stress fatigue (CSF) wear occurs when surfaces that roll or slide against each other are overloaded. Overloading may occur also because of misalignment or because that lubricant film has weakened due to lower viscosity or higher temperature. CSF also may occur because parts have been used beyond their expected service life. Engine bearings and rolling-element (anti-friction) bearings have a finite life and should be changed before they show evidence of CSF wear.

Because CSF damage occurs by two different processes, there are two types of CSF. CSF damage on sliding surfaces is called sliding contact stress fatigue. CSF damage on rolling surfaces is called rolling contact stress fatigue.

When the surface of one part repeatedly slides against the surface of another part it produces a cyclic stretching action at the surfaces. If the surface stress that develops as a result of the stretching action exceeds the fatigue strength of the metal, tiny surface cracks will initiate and grow into the part. Surface pits form when the cracks join. Once pitting starts, more pits form until the surface is no longer usable. This action is sliding contact stress fatigue wear.

When the surface on one part rolls against the surface of another part, it produces a repeated (cyclic) stretching action below the surfaces of the parts. If the subsurface stress that develops as a result of the subsurface stretching action exceeds the fatigue strength of the metal, tiny subsurface cracks initiate and grow until chunks of the surface spall and break away. Once spalling starts, surfaces continue to deteriorate until the part is no longer usable. This action is rolling contact stress fatigue wear.

CSF wear can also result in secondary damage. As each type of CSF develops and progresses, small, hard particles are produced that can cause abrasive damage elsewhere in the system.

Contact stress fatigue wear produces the following road signs on parts:

1. Surface pitting (sliding CSF)
2. Subsurface fatigue and spalling (rolling CSF)
3. Self-generated, secondary particles

Sliding Contact Stress Fatigue Wear

Illustration 158 g01203645

Sliding CSF has produced pitting on the nose of this camshaft lobe due to excessive sliding loads.

Illustration 159 g01203646

Transverse cracks on the surface of this engine bearing are the result of sliding CSF. As the cracks grow, pits form and material is lost from the surface.

Rolling Contact Stress Fatigue Wear

Illustration 160 g01203649

When two surfaces roll against each other, excessive load can result in rolling CSF which initiates cracks below the surface and causes pieces to spall out of the surface.

Illustration 161 g01203651

Rolling CSF damage can start in a small area and then spread out over a larger area as damage progresses. Here, the entire surface area of a bearing race is damaged.

Gear Teeth

Illustration 162 g01203656

Gear tooth showing pitting and spalling

Gear teeth are a special case for contact stress fatigue wear. The sliding and rolling action of one gear tooth against another can produce both sliding and rolling CSF damage. As a result, gear teeth can show both pitting and spalling damage depending on the location of the damage on the gear tooth.

Significance of Contact Stress Fatigue Wear

Contact stress fatigue wear found on parts indicates that surfaces have been overloaded by excessive sliding or rolling loads. It may also indicate that the part has been in service too long because sliding or rolling contact stress fatigue is a normal wear out condition for many sliding or rolling bearings.

Look for the following things:

1. How long has the part been in service?
2. Have the parts received adequate lubrication in service?
    a. Was the specified lubricant used?
    b. Was there an adequate amount of lube available during operation?
    c. Does the lube used meet Cat specifications?
    d. Were operating temperatures excessive?
    e. Was the lube correct for the ambient operating temperature?
    f. Did the parts receive proper lubrication at all times?
    g. Is the surface finish on the parts acceptable?
    h. Is maintenance performed at the specified intervals?
3. Has the part been subjected to excessive sliding or rolling loads?
    a. Were loads from operation excessive?
    b. Are there any alignment problems?
    c. Do the parts conform to print requirements?
    d. Are any other parts damaged that would cause excessive sliding or rolling loads?
    e. Was alignment and preload set properly?
    f. Have there been any recent repairs or service?

Fretting (Corrosion) Wear

Fretting (corrosion) wear typically results from movement between two surfaces that are pressed tightly together. The type of movement that causes fretting is high frequency, low amplitude, that is, movement resulting from vibration of the parts.

Note: Moving surfaces not pressed tightly together tend to polish and become smoother rather than fretting and becoming rougher.

Fretting damage occurs when frictional heating causes high points (called asperities) on two surfaces to weld together and then movement rips the surfaces apart. This action roughens the surfaces, pits the surfaces, and produces fine debris particles. When the debris particles produced by the fretting action corrode and are smeared back on the moving surfaces, the damage is referred to as fretting corrosion.

Tight contact between two surfaces can result from several things:

1. Bolted joints
2. Press fit parts
3. The weight of one part pressing against another

Fretting wear damage can be identified by the following characteristics:

1. The wear damage is at a tight contact area between two parts.
2. The contact surface area between two parts is rough and pitted.
3. The contact surface area is discolored in or around the rough, pitted area.

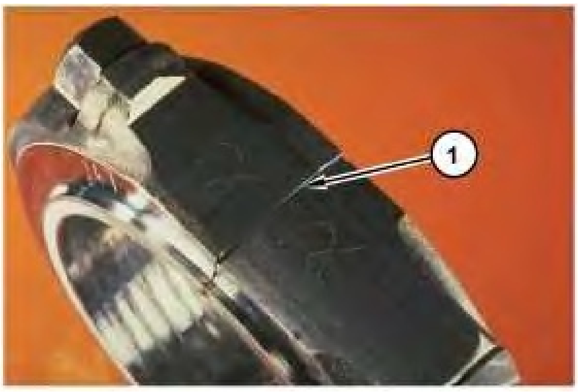

Illustration 163 g01203657

(1) The wear damage is at a tight contact area between two parts.

When the load on a part exceeds the clamping force between two surfaces (such as this connecting rod and cap joint), movement can produce fretting damage.

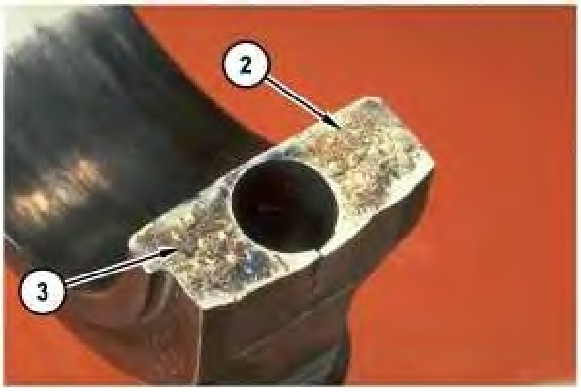

Illustration 164 g01203663

(2) The contact surface area between two parts is rough and pitted.

(3) The contact surface area is discolored in or around the rough, pitted area.

Fretted surfaces are rough because tiny areas have welded and pulled pieces of metal out of the surface. Fretting debris sometimes corrodes and discolors fretted surfaces.

Illustration 165 g01203667

Sometimes fretted surfaces appear roughened by microwelding and metal pull out as on this bolt head surface.

Illustration 166 g01203668

With iron-based materials, fretting often produces a red to reddish brown surface discoloration in the damaged area as on this bolt shank.

Illustration 167 g01203672

Black colored deposits produced by fretting

Fretting can produce black colored deposits, too. The color of the deposits, if present, depends on the metal that is fretting and the conditions under which the fretting damage occurred. The left side of this figure shows fretting damage with a black deposit on a connecting rod bore. The right side of the figure shows bearing damage resulting from running a bearing over area built up from fretting.

Significance of Fretting (Corrosion) Wear

Fretting (corrosion) wear found on parts indicates that two surfaces that were held tightly together have been forced to move, vibrate or oscillate slightly against each other at high frequency. Look for the following things:

1. What was the load that caused the surfaces to move?
2. If fretting has occurred at a bolted joint:
    a. Were the joint surfaces clean prior to tightening?
    b. Was the correct hardware used?
    c. Were any of the clamped surfaces excessively rough?
    d. Were the fasteners properly tightened?
    e. Were instructions regarding lubrication followed?
    f. What might have overloaded the joint in service?
    g. Is there any evidence of overheating at the joint?
    h. In multi-fastener joints, were the other fasteners tightened properly?

Failure Analysis Training and Consulting Services

The information in this tool has dealt primarily with collecting wear and fracture facts that can be used in analyzing failures. Additional training and experience are required to use wear and fracture facts to perform failure analysis. There are several sources for failure analysis training within the Caterpillar enterprise.

Sources for Applied Failure Analysis Training

Caterpillar Product Support Center

The Peoria Applied Failure Analysis Team offers two different failure analysis training courses at the Customer Service Support Center in Building LC in Peoria, IL. Details and availability of failure analysis training classes can be found at the Dealer Performance Center (formerly DLMS) on line or by contacting the class Registrar at 309-578-6377.

Caterpillar Marketing Profit Center Training Centers

Failure analysis training is available at the following MPC training centers:

- Asia Pacific Learning Center, Melbourne, Australia (Certified for AFA 1, 2, 3)
- Asia Pacific Learning Center, Singapore
- Malaga Demonstration and Learning Center, Malaga, Spain (Certified for AFA 1 & 2)
- Miami Skills Acquisition Center, Miami Lakes, FL, USA (Certified for AFA 1 & 2)

Caterpillar Regional Training Centers

Several Cat dealers provide failure analysis training at Regional Training Centers:

- Empire Machinery (Certified for AFA 1 & 2/3)
- Finning Ca. (Certified for AFA 1 & 2/3)
- Holt TX.
- Carolina Tractor & Eq.

Cat Dealers

Several Cat dealers provide failure analysis training for their staff. Contact the training department at your dealership to see what is available.