Chapter 2
Tools for Preliminary Analysis of a Mechanical Failure

2.1 Methodologies for Field Investigation After a Failure

The aim of this chapter is to define guidelines for the preliminary analysis of a mechanical failure, in order to facilitate subsequent investigations and determine the causes of the failure. This chapter includes the definition of the investigation team, the removal and storage of failed parts and evidence, and the definition of guidelines for the failure analysis to be performed. The success of a post-failure investigation, especially in the case of mechanical breaks involving large energy (shocks, explosions, etc.) depends critically on the quality of the evidence collected at the site. The objectives of this section are:

- To list the main activities after an accident or explosion, and to indicate how to carry out a systematic investigation of causes.
- To discuss how the damage can be evaluated, and to understand the chain of events.

After a major accident, the task force, team, or investigation committee will be in charge of analyzing the accident. For smaller events, this activity is often done internally by the company responsible. Figure 2.1 shows the main objectives of this work. As shown in the figure, the coordination function is important since some of these activities will have different priorities or objectives. For example, repair of the failed equipment and damage documentation might be contradictory, if not coordinated. Evidence of failure mode may be lost during cleanup. After an accident, a common reaction is to start cleaning without documenting damage. It is necessary, therefore, that a person chairing the investigation committee coordinates all activities.

Investigating the cause of the accident is usually time- and resource-consuming. The purpose of the site assessment is to obtain the information necessary to reconstruct the events backwards, from observed damage and eyewitness recounts. Qualified personnel are required to perform these analyses. Baker et al. [3] recommend the participation of experts immediately after the accident. Otherwise we might miss most useful damage indicators. Damage documentation must begin

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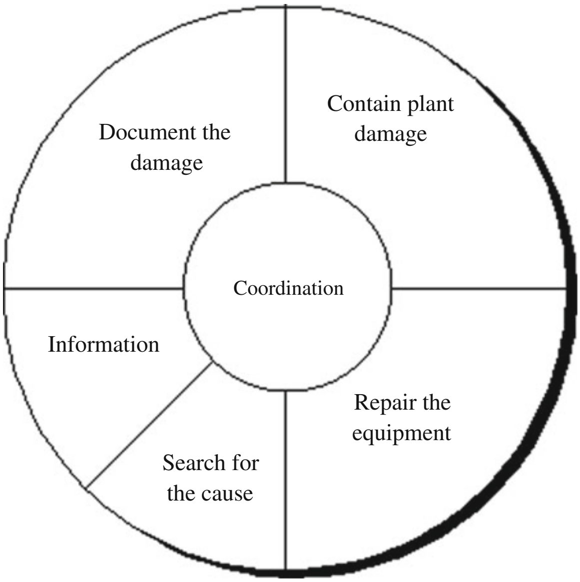


Fig. 2.1 Main objectives of investigation

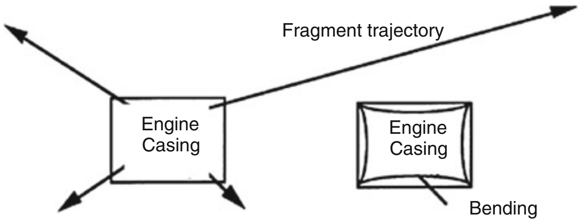


Fig. 2.2 Fragments and structural deformations provide valuable information

immediately and should be done by a specific expert in failure analysis (structural response, combustion turbines, etc.).

In many cases, the methods are based on a posteriori analysis of photographs taken at the site, of the general area and of specific damage, so a professional photographer should be used. Making systematic records of locations and directions of all pictures taken is required. A map of fragments, with original and final positions, should also be organized. Fragments are usually a good indicator of where the initial failure occurred and its magnitude. Figure 2.2 shows the trajectories of four parts of motor covers of a real case. A motor housing flew 15 m from its original position. The fragments of the motor housing "a" support the hypothesis that fuel gas entered the engine housing and the failure began as an explosion inside that housing.

The deformations and deflections of structures are also indicators of damage. Inward deflections in the motor housing "b" indicate loading from the outside. Typically, the deflection of pipes, panels, and other elements as well as the direction of broken glass can be used to estimate origin and load intensities during an explosion [3].

2.2 Collecting Data and History

The field representative must collect all the evidence of previous failures in the same area, failures of the same type, on-site inspections of the failure, etc. He should collect additional information if the case so requires, such as weather reports, flooding, or earthquake reports, etc. The field representative shall collect the historical operating data of the component or equipment, specifically at the time of the failure occurrence. He is in charge of interviewing operators, nearby residents, and any person who can provide information on the failure, and collect information on the extraction of samples and features of the failure zone, depending on the type of failure. The representative needs to know the environment at the initiation of a fire or explosion and/or what features of the environment helped it spread. It is important to make a sketch of the terrain and failure zone.

The field representative tentatively determines what type of failure caused the event and associated damage mechanisms identified in the preliminary integrity report. He should search databases for the same type of failures, with the aim of finding a correlation. The responsible for field inspections will develop a preliminary report detailing what he relieved, location plans, and operating conditions at the time of the failure, survey of external failure conditions, and other data of interest to define a preliminary overview of the event.

Usually it is a senior representative, e.g., a plant integrity chief, who will define the need and determine what types of failure analyses are undertaken. The field representative must then assume the responsibility to interact with the company performing this failure analysis, coordinating, and providing the necessary information, as well as with the various departments within the company.

2.3 Visual Inspection Techniques and Field Photography

Visual inspection is a test method based on the detection of specific elements using basically the human eye and the experience of the inspector. Usually help tools such as magnifying glasses, cameras, meters, borescopes, camcorders, etc., are required. To carry out a visual inspection, good lighting must be ensured; at least 1,000 lux can be taken as a reference value. Light sources may be needed in addition to those existing at the site. Also, the area and the components where the test is performed should be properly cleaned. All instruments used to enhance appreciation must be in good condition.

Visual inspection is usually the first test and one of the most useful ones, as it is a low-cost test it does not require sophisticated equipment and is complemented by all other test methods. Findings must be documented to avoid losing validity. Within the limitations of the method, it can be mentioned that only surface defects can be detected and that their detection requires a "trained eye."

Examination of fractured surfaces allows for a lot of information regarding the origin and causes of a broken component when subjected to mechanical loads. During the preliminary analysis, usually at the site or somewhere protected within the same premises where the failure occurred, visual assessments are made with the eventual help of a magnifying glass; magnification varies between **X**1 and **X**10. With this evaluation, it is possible to analyze damage, possible deformations, cracks, and other defects, and most importantly the failure initiation site. Qualitative visual descriptions are to be performed of the various areas of the fracture surface and other sites with signs of damage of any kind (corrosion, wear, fatigue, manufacturing defects, etc.). In some cases, it is necessary to resort to other methods of nondestructive evaluation, which are briefly discussed at the end of this chapter.

The field investigator must have knowledge and experience in photographic techniques. The core variables of a camera are diaphragm aperture and exposure time; their combination gets the right balance of light in each exposure. The diaphragm is a part of the objective that limits the amount of light entering the camera. It works like the iris of the human eye, opening and closing to allow more or less light. If the diaphragm aperture is increased (more light), the exposure time (time that the film or sensor is exposed to light) has to be reduced, otherwise the picture gets too bright (overexposed). If aperture is reduced (less light), the exposure must be extended, otherwise the picture gets dark (underexposed). The aperture is measured in f-numbers. The basic f number scale is f1, f1.4, f2, f2.8, f4, f5.6, f8, f11 and f16. The smaller the number indicates larger aperture. In each f-step, the brightness is reduced by half. F11, for example, has twice the brightness than f16 and half than f8.

The shutter limits the time that the beam of light entering the camera exposes the film or sensor. Usually, exposure times range from seconds (for very poor lighting conditions) to milliseconds (for very fast pictures). Most usual time, in seconds, are: … 4, 2, 1, 1/2, 1/4, 1/8, 1/15, 1/30, 1/60, 1/125, 1/250, 1/500, 1/1,000 and 1/2,000. Both automatic and manual cameras can pick a particular opening and get an exposure time estimate, and vice versa (Fig. 2.3).

In failure analysis, gently shooting and camera support are very important. Many times it is necessary to provide another source of light. If exposure times are greater than 1/15, a tripod must be used. When a photograph is completely blurred, it means that the shutter speed was too slow for the way the camera was held. When a portion of the image is blurred and another is not, no proper focus was achieved (Fig. 2.4a).

The "macro" function is essential to get good details of a failed piece. It allows focusing very close to the target; in some cameras as close as 1 cm. Focal lengths under 30 cm are highly recommended. When seeking to obtain photographs of fracture surfaces, it must be understood that not necessarily all the fracture is in a same plane. Therefore, good depth of field must be obtained, whenever possible (Fig. 2.4b). Another important aspect is the variation in the direction of the light source. Figure 2.5 shows the same fracture surface illuminated from different

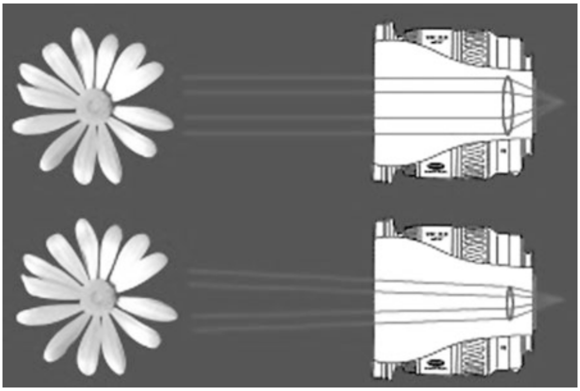


Fig. 2.3 Shutter opening and focus depth

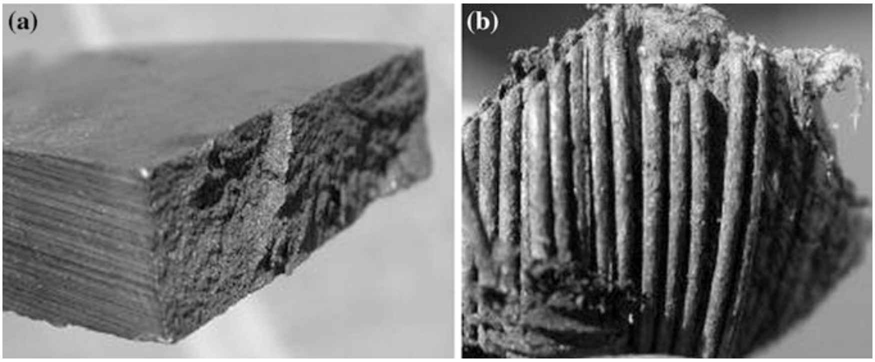


Fig. 2.4 **a** Bad depth of field **b** Good depth of field

angles; note how each picture shows different things. Believe it or not, some may be relevant in the future, even though at this time it would not seem so.

To photograph fractures, flash is not our friend since it "flattens" the image. Shoot under the sun or against a strong light source. Contradicting the usual rules for artistic or landscape photography, it is better to point against the light (angle of incidence).

Flat surfaces, such as metallographic samples, go well with both artificial and natural light. The depth of field is no longer a problem, just concentrate on the frame. If shooting with artificial light, whites should be compensated. Very shiny surfaces do not usually give much information on the photos; it is always easier if the surface is opaque, as in the case of a metallography revealed with a chemical etch, such as Nital, because there are fewer glares. If photographing a shiny surface is required, place the light source so as to eliminate glare into the lens (Fig. 2.6).

In summary, one can say that modern digital cameras have simplified the failure expert's activity, but they do make no miracles. Before taking the pictures, one

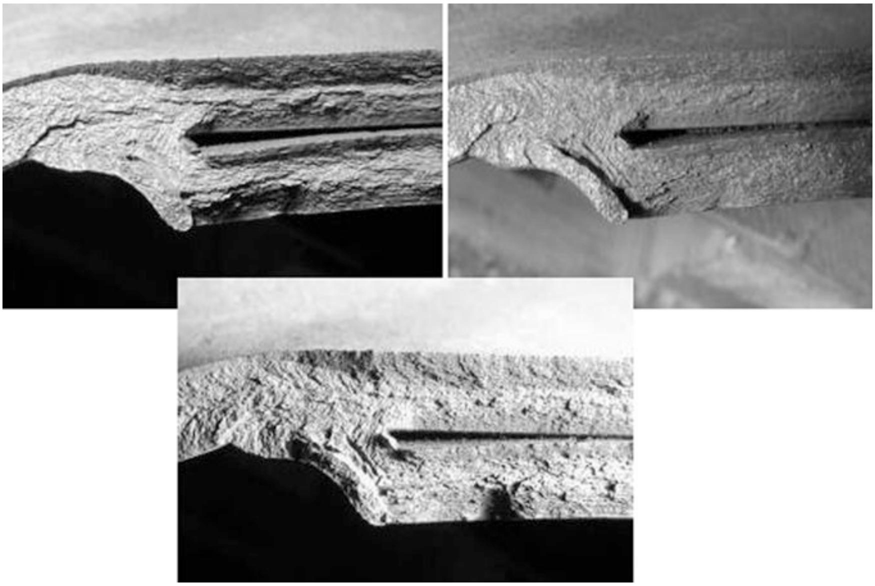
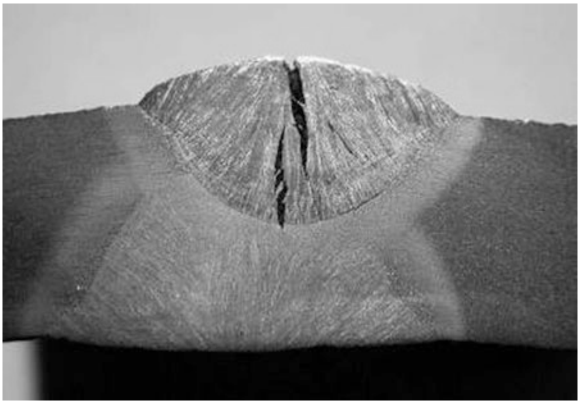


Fig. 2.5 Crack illuminated from different angles

Fig. 2.6 Macrophotograph of a metallographic section



must know what to display and search the position of the light source and the eye to see what is wanted to see. Then the camera will see the same as the operator. The appeal of the new high-resolution cameras (5 MP or more) is that in a well-taken photo more details can be later appreciated than those seen with the naked eye, through electronic zoom and a computer program. As with any photographic activity, it is always recommended to take lots of pictures with slight variations, and then choose the most suitable.

2.4 How to Detect the Site of Initiation of Mechanical Failure

2.4.1 Fractographic

By fractographic analysis or characterization, we mean the inspection of the surfaces of fractures and failures. In the preliminary in field stage, this can only be done to a low magnification (up to approx. **X**20). In laboratory, with optical techniques and scanning electron microscopy, it is possible to reach much higher magnifications. Preliminary fractographic analysis helps to define:

- Size of critical defect at failure
- Mode of flaw propagation
- Failure initiation site and pre-existing defects
- Mode of in-service propagation of pre-existing defects.

Let us see some examples of typical cases of fracture of components subjected to mechanical loads. We can define three types of fracture surface, which can be differentiated at this stage of preliminary inspection:

- Brittle fracture: instantaneous event at final failure (hundredths of a second).
- Ductile fracture: although its propagation can take from a few hundredths to a few seconds, it is also defined as an instantaneous failure event.
- Previous propagation: also called stable or subcritical propagation or growth, it occurs for some time during service life of the component, due to specific conditions of operation (cyclic loading, temperature, aggressive environments, etc.).

Table 2.1 summarizes the characteristics of ductile and brittle fracture, and their manifestations in a visual inspection of the fracture surface. Figure 2.7 shows typical ductile fractures in laboratory samples. Figure 2.7a shows a slant fracture at 45° to the surface of the component; this is typical in structural steel plates. In modern high strength steel pipes and pressure vessels, discontinuities are frequently produced by controlled thermal–mechanical treatment, which is discussed in some detail later. In these cases it may occur that the ductile fracture surface shows a series of flakes, as shown in Fig. 2.7b.

Another feature of ductile fracture is that it occurs after the section suffers a significant amount of plastic deformation. Plasticity usually results in a reduction of section, as shown in Fig. 2.8.

Brittle fracture of metals at the macroscopic level is characterized by a generally flat surface, perpendicular to the direction of maximum stress, with no signs of previous plastic deformation. If the fracture surface is clean enough to allow inspection with a magnifying glass, often a faceted surface with small bright planes can be defined, Fig. 2.9.

Table 2.1 Characteristics of ductile and brittle fracture

Ductile	Brittle
Metal surfaces are usually opaque with fibrous appearance	Metal surfaces are normally bright with granular appearance
Characterized by metal tear accompanied by plastic deformation	Characterized by rapid propagation and no plastic deformation

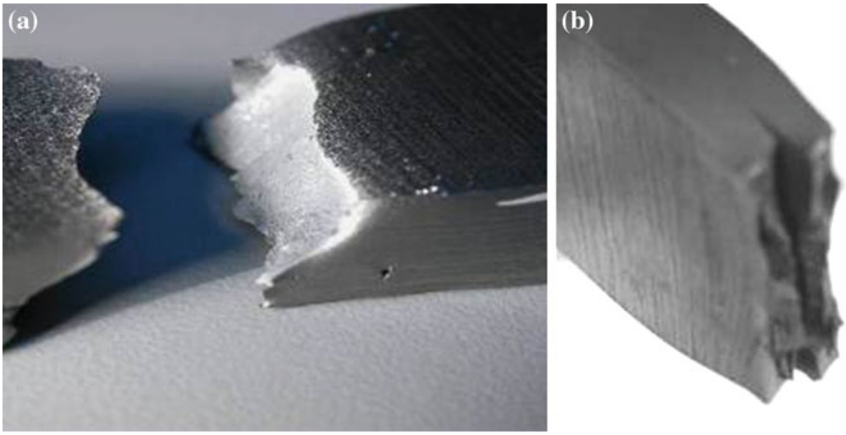
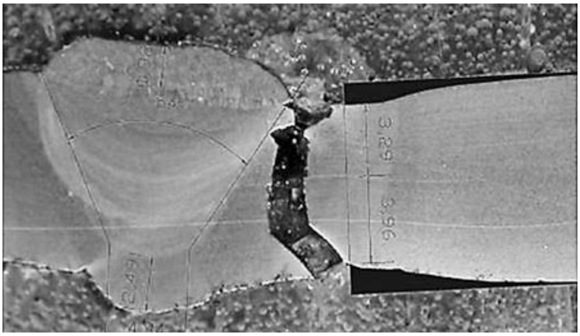


Fig. 2.7 **a** Fracture at 45° from the surface **b** Series of flakes at 45°

Fig. 2.8 Reduction of section previous to break in a welded joint (*shaded*)



At the macro level, a characteristic of brittle fracture is the formation of chevron marks. Figure 2.9 shows an example of such "chevrons"; these are arrow or V-shaped marks in the fracture surface. In brittle fractures these arrows point to the initiation site.

The reason for the formation of these chevrons is as follows. In areas close to the surfaces of the piece, the front of the crack propagates in a plane stress field, while in the middle of the thickness the crack front grows in an area of high tensile

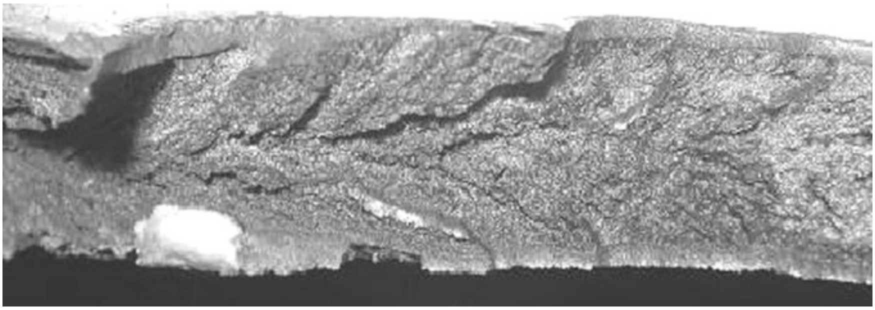


Fig. 2.9 "Chevrons" in a brittle fracture, and shear lips near plate surfaces

stress triaxiality. As will be seen in Chap. 6, a triaxial stress field hinders plastic deformation, so that crack growth tends to occur in a more brittle condition. Therefore, crack propagation tends to be delayed near the component surfaces, which leads to a V-shaped crack front, instead of a flat front. Small variations in the successive planes of the crack path through different microstructures in the material produce steps in the crack surface which are normal to the crack front. These form the characteristic chevron marks, the tips of the arrows located near the middle of the thickness. When the stress field is not fully tensile but has a bending component, stresses near one surface are larger than in the other. This makes the two branches of the chevron marks not to be of the same length.

Frequently, in the vicinity of the component surfaces a change in the restriction to plastic flow reduces the degree of stress triaxiality. This change in conditions (from plane deformation to plane strain, which will also be discussed in more detail in Chap. 6), in many cases causes a change in propagation mode. Although the fracture is brittle in most of the thickness, two thin layers of ductile fracture are formed adjacent to the component surfaces. These layers are characterized by forming 45° slanted lips, called shear lips. These are also related to ductile growth, which is controlled by maximum shear stresses.

Such shear lips can be clearly seen in Fig. 2.9, as two opaque narrow bands at the top and bottom of the figure. The width of the shear lips indicates the ductility or brittleness of the material. The shear lips in Fig. 2.5, for example, cover 75 % of the fracture surface, and are much larger than those in Fig. 2.9. The use of this information is discussed in greater detail in other sections.

A common feature is that a fracture begins in a brittle mode in areas with previous defects and/or stress concentrations. When the fracture reaches a certain size, the driving force is enough to keep it growing, even if the material is ductile. The mechanical conditions for his phenomenon will be seen in some detail in Chap. 6. Thus, the transition between brittle fracture and ductile fracture is a first indication of the zone where the failure began. For example, Fig. 2.10 shows a circumferential fracture occurred in a girth weld of a pipe, under the effect of axial loads. Most of the fracture is ductile (Fig. 2.10a), with steps at 45° and lateral shrinkage. But at initiation (Fig. 2.10b), the fracture is through the thickness

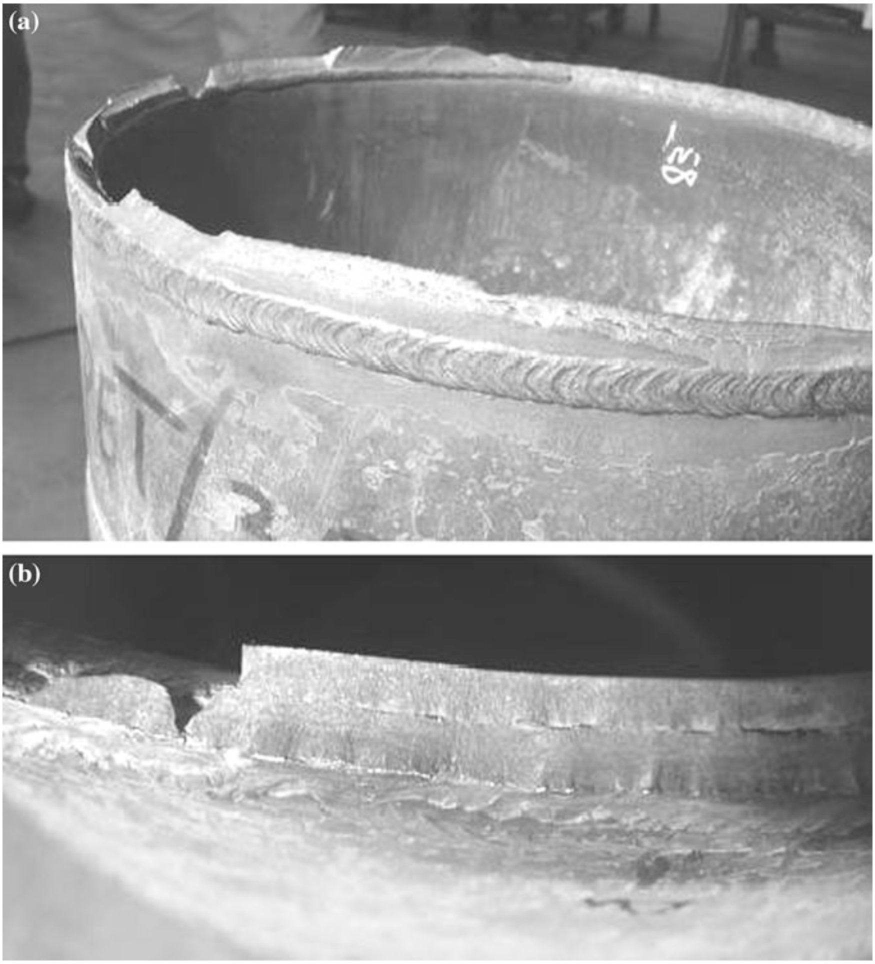


Fig. 2.10 **a** Ductile fracture of a pipeline **b** Close-up of the through-thickness fracture

(at 90° from the surface of the tube), without lateral contraction. Also seen here are parallel marks advancing from the outer surface of the tube, like sea marks on a sandy beach. We will later discuss in more detail about these "beach marks."

2.4.2 Example 2.A Identification of Failure Origin

Figure 2.A1 shows the casing of a centrifugal pump from a liquid hydrocarbon (oil) pumping station. Circumferential fracture was propagated by the stresses due to internal pressure. The arrows indicate how the crack propagated, as defined by the fractographic analysis. In this case, there has been an unusual situation: the

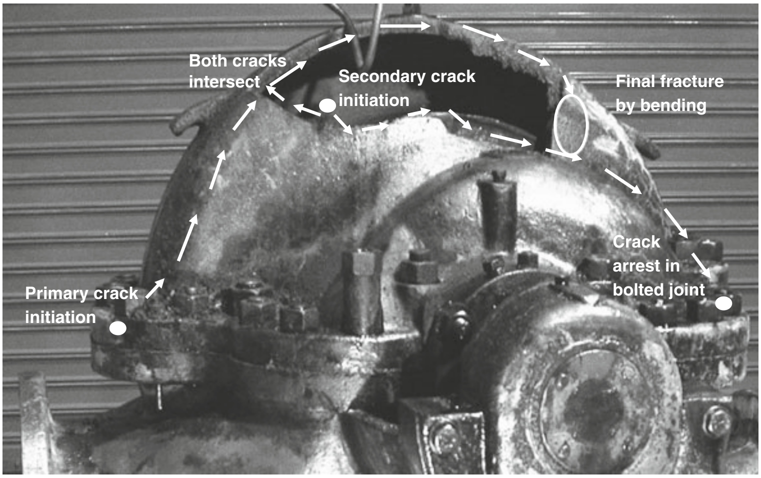


Fig. 2.A1 Cracked casing of a centrifugal pump

propagation of the fracture was such that a window opened. The right (final) part of the window broke due to bending; the area that became a "hinge" is highlighted by an ellipse in the figure.

Figure 2.A2 shows the chevron marks in the fracture zone shown at the top of Fig. 2.A1. From the analysis of the chevrons in Fig. 2.A1, it was possible to reconstruct the failure occurred in the pump casing, and the definition of its origin (central circle in the Figure). Note that the tips of the chevrons are not located in the middle of the thickness, but in the third closest to the inner surface. This asymmetry is associated with the bending stress field generated by the outward force produced by fluid pressure acting against the inner surface of the "window."

2.4.3 Initiation Site of a Fracture

Any fracture resulting in instant failure that starts at a given site can be called failure initiation. We have seen that the most important part of the effort during the preliminary analysis is referred to detecting failure initiation. This site is defined by one or more of the following factors, which will be discussed in detail in other sections of this book:

- Stress concentration.
- Material weakness.
- Previous defects (manufacturing or grown during the previous service).

Initiation of fast fracture is often the result of a damage mechanism developed during service. In this case, we speak of three stages in the fracture surface:

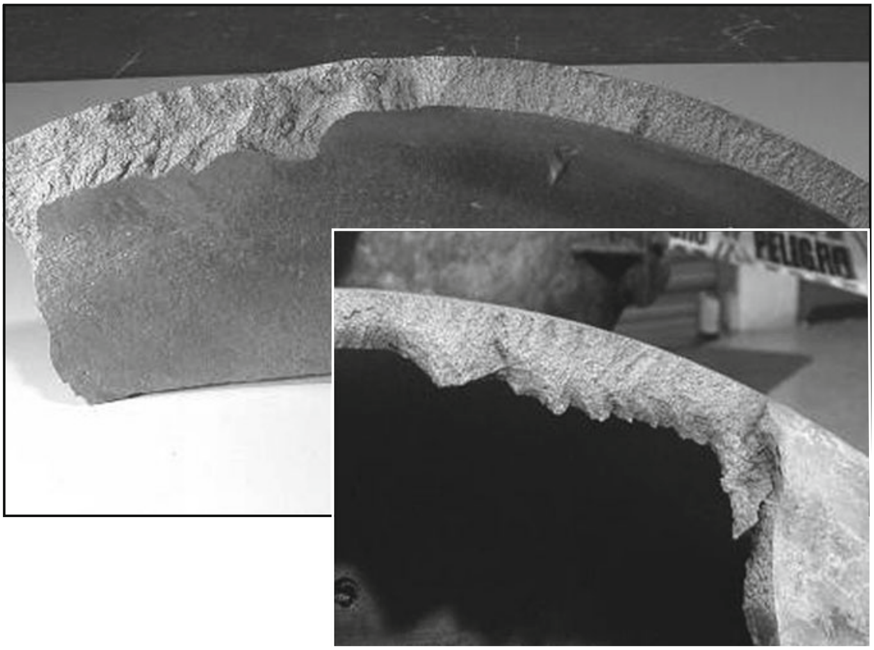


Fig. 2.A2 Chevrons in different parts of the fracture surface

- Initiation of previous damage.
- Propagation of previous damage.
- Final failure.

Figure 2.11 shows an example of the initiation of a crack from a stress concentration due to cyclic loading during service; which is called fatigue and is also discussed later in greater detail. It is a welded joint; weld reinforcement is at the bottom of the figure. Cracks propagated from defects in the material of the two welds, identified as A and B. Direction of crack growth is indicated by black arrows. When cracks reached a certain size, they joined (coalesced), and continued to propagate as a single crack. The dotted line indicates both crack fronts at the time of coalescing. The dashed line indicates the crack front when the component finally fractured; direction of fast fracture is indicated by white arrows.

What are the clues that indicate initiation and prior in-service propagation? Many are on the fracture surface. First, the slow (stable or subcritical) service propagation typically generates a rather smooth fracture surface, while fast propagation tends to form rough fracture surfaces. As stable propagation occurs during a certain time, operating conditions frequently change during crack growth, thus changing propagation rate. These different growth rates result in variations in the appearance of the fracture surface. The boundaries between different surfaces

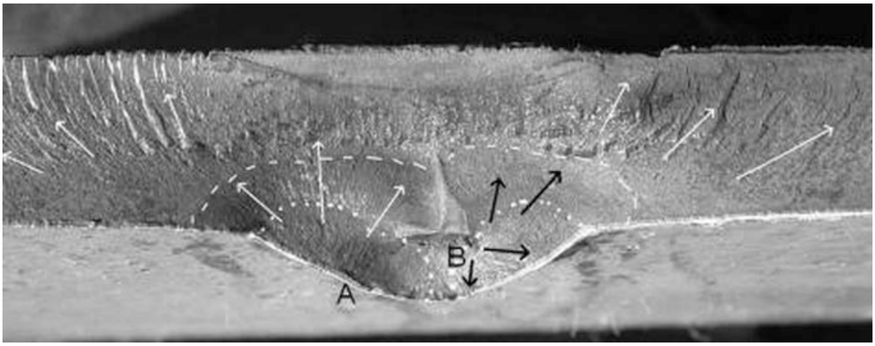


Fig. 2.11 Crack initiations from a stress concentrator

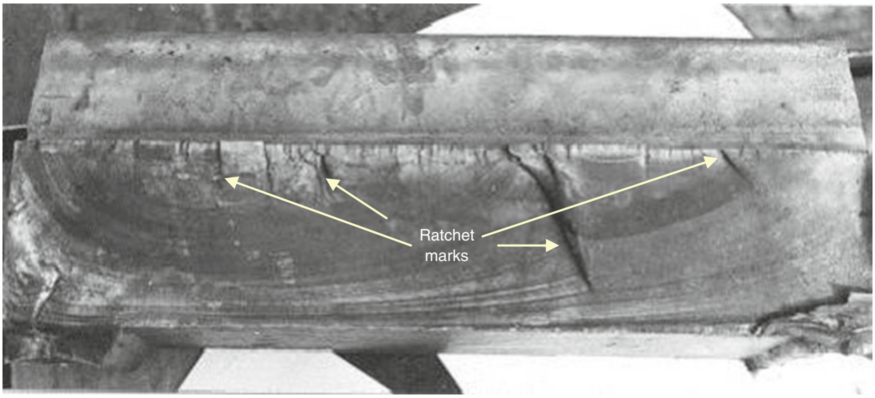


Fig. 2.12 Fatigue crack growth

indicate the shape of the crack front at each time. These limits are those already defined as beach marks, and are often detectable during visual inspection.

If the service propagation occurs from multiple initiation sites, cracks initiate in different planes, which eventually merge. This leaves between them wedge-shaped marks (ratchet marks). The analysis of beach marks and ratchet marks identify crack initiation sites.

As an example, Fig. 2.12 shows a fatigue crack grown from the surface of the component, in the upper part of the figure. Beach marks are clearly visible even when the cracks are very small. Ratchet marks in the vertical direction are indicated with white arrows.

Figure 2.13 shows another fatigue crack, also grown from the surface (upper part). Beach marks are visible in most of the fracture surface shown.

When the crack reached the dark mark there was an increase in growth rate, presumably due to an increase in operating load. Beach marks become less clear,

Fig. 2.13 Fatigue crack grown from the *upper* surface

and other marks which are mutually parallel are visible in the vertical direction. These are called river marks, and also frequent in fast fractures. These river marks indicate different planes of crack growth, which occur along certain crystallographic planes (also discussed in a later chapter), and indicate the direction of fracture.

2.4.4 Example 2.B Detection of Previous In-Service Damage

An instant fracture of a cylinder liner of a piston compressor at a petrochemical plant is depicted in Fig. 2.B1. Figure 2.B1a shows the characteristic chevron marks and shear lips of a brittle fast fracture. Chevron marks indicate initiation at the left of the Figure, and point to the location of a threaded hole. This hole hosts one of the bolts used in positioning of the cylinder during maintenance. Figure 2.B1b shows the smooth crack surface, typical of subcritical propagation, that is to say, it occurred during a service period. The analysis of beach marks and ratchet marks allow identifying the site of crack initiation at the bottom of the second thread in the hole, Fig. 2.B1c.

Higher magnification allowed observing signs of plastic deformation within the thread. Apparently, during maintenance activities at the last plant stop, a bolt was used that did not correspond exactly with the geometry of the thread. As a result, interference generated between the threads damaged the threaded hole. Many months later, the cyclic stresses from the compressor ended up propagating a fatigue crack, which grew as a quarter circle. When the size of this crack was of the order of the hole depth, a critical condition was reached: the crack became unstable and propagated instantaneously, causing the catastrophic failure of the component.

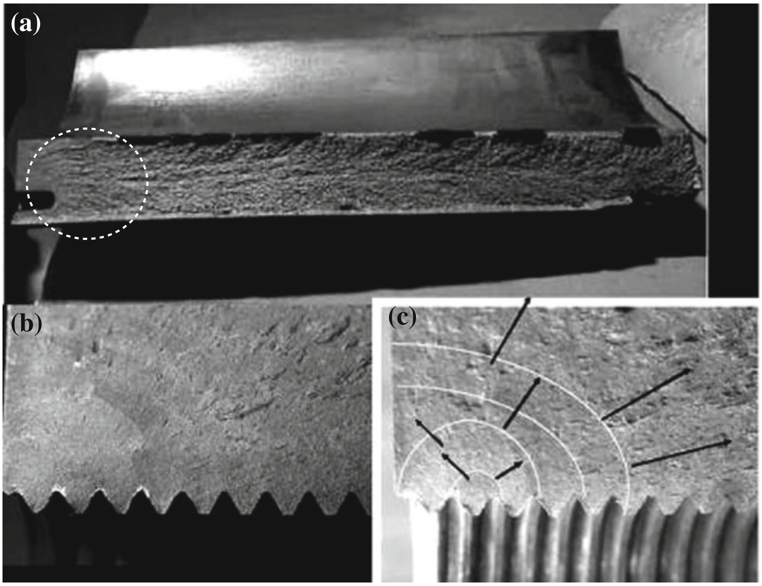


Fig. 2.B1 **a** Brittle propagation with chevron marks and shear lips **b** Smooth crack surface **c** Crack initiation site

2.5 Failure of Threaded and Rotating Elements

Due to their large share in the occurrence of failures in mechanical components, some attention will be paid to the visual analysis of threaded (screws, bolts, and nuts) and rotating (shafts and axles) elements.

The main function of a screw is to transfer the load. Threaded components come in many types, dependent upon design requirements and environment in which the fastener is to be used. Threaded elements frequently fail due to high stresses at the root of the thread, which is a geometrical stress raiser. Small machining errors, surface defects caused by corrosion or mechanical damage (as we have already seen in our previous example) are sufficient to initiate cracks, often propagated by fatigue.

Surface damage by fretting may be the result of small movements between adjacent surfaces. Atmospheric corrosion, galvanic and crevice corrosion, stress corrosion, and hydrogen embrittlement are frequent contributors to the failure of these elements. Those will be discussed in other chapters.

One aspect that is not minor in the case of failures involving bolts and nuts is recovering failed parts. Many times the remains are scattered, and then it becomes difficult to define where each recovered piece was located before failure. It is common for a failed component to involve many threaded fasteners; it is important to identify those screws that caused the failure and separate them from those who

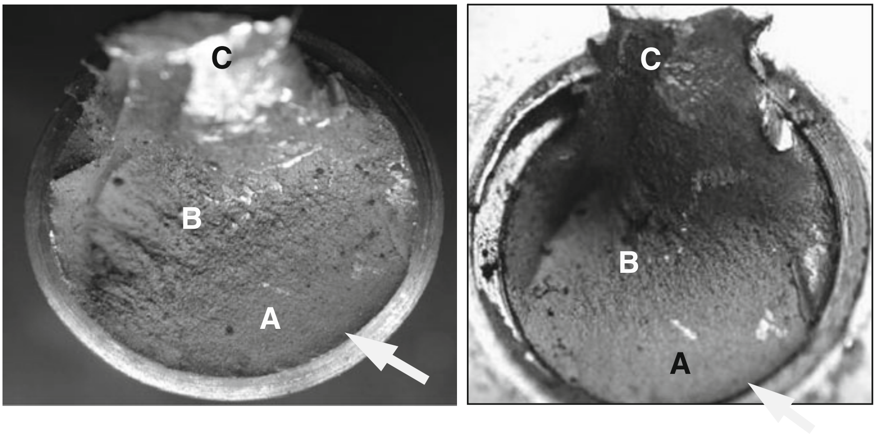


Fig. 2.14 Typical failure of a screw

may have failed due to overload after the failure of the others. That is, separate the elements causing the failure from the elements that failed as a result of it.

American Codes ASTM and SAE require that heads of threaded fasteners are identification marked with its grade (strength). These markings allow quick verification of proper selection by visual inspection. A visual confirmation of grade and verification of specification is the kickoff of any investigation. Then the areas in the fracture surface related to modes of initiation and propagation should be investigated, similarly to what has already been discussed. Figure 2.14 shows a typical failure of a screw, and we find:

a: initiation area, opaque and flat, without visible beach marks.
b: a fibrous area with river marks indicating direction of propagation of the fracture.
c: a narrow shear lip corresponding to the final fracture due to ductile overload.

An example of a threaded bolt which failed by fatigue is shown in Fig. 2.15. Here almost 100 % of the fracture surface is subcritical growth. The insert shows in some detail the initiation of cracks in the bottom of the thread. Conversely, the overload failure of a bolt is indicated by a 100 % fracture surface corresponding to ductile tearing. Also in these cases it is possible to distinguish some features related to the load that caused the failure, and identify signs of crack growth due to tension or to shear.

The relationship between the areas of cracking and ductile tearing is related to the relationship between the amplitude of cyclic loading and the maximum load achieved during service. Surfaces of final fracture in threaded elements of high strength, low ductility steel show brittle fracture, with indications such as river marks, as shown in the example of Fig. 2.16. Two initiation sites (A and B) are seen at the top of the figure, separated by a ratchet mark; the black line underscores

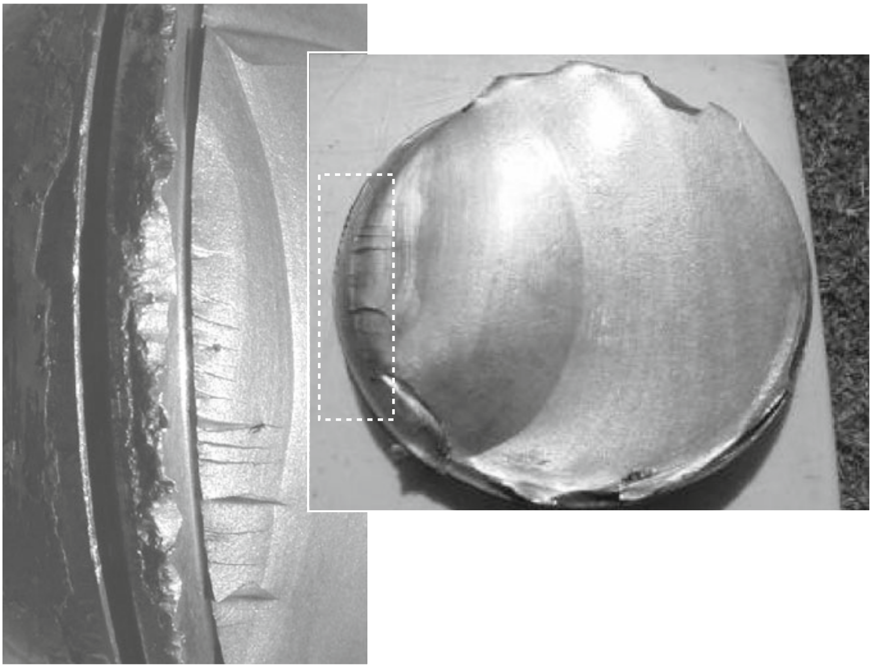


Fig. 2.15 Fatigue failure of threaded bolt

Fig. 2.16 Initiation sites separated by a ratchet mark

the beach mark at the time of final breakage. Note that this coincides with the ratchet mark. This indicates that the crack unstabilized at the time the two fatigue cracks coalesced, which is consistent with fracture mechanics concepts for criticality of cracks (see Chap. 6).

Shafts work in a wide range of conditions, including corrosive environments, at very high or very low temperatures, and may experience a range of loading conditions: tension, compression, bending, torsion, or a combination of these conditions. In addition, they may experience vibratory stress. The most common causes of failure are:

- Abrasive wear: material detaches from a solid surface due to hard particles or protuberances on the sliding surface. Examples of abrasive materials are sand, dirt, metal particles, and other debris in the lubricant.
- Fatigue: commonly begins at a stress concentration, as do also other cracking mechanisms. Typical features of these stress concentrators are corners, keyways, gutters, forged shapes, weld defects, nicks, cracks, pitting corrosion, clearances, and bends.
- Misalignment: may be made after a repair; resulting vibrations often cause fatigue failure of the shaft.

Each cause of failure is associated with certain characteristics of both the location of the failure and its fractographic surfaces. Figure 2.17 shows some characteristics associated with the shape of the beach marks and the relationship between the areas of subcritical propagation and final fracture.

2.5.1 Example 2.C Failure of a Bolted Structure

In this example we analyze the failure of a crane used in port activities, which failed by rupture of the anchor bolts to the base. The principal interest is aimed at determining the causes of the incident, if it is due to gradual wear or deterioration resulting from overload in operating conditions, if it is related to construction deficiencies or material, or installation deficiencies. Figure 2.C1 shows the jib crane, mounted on a base. Detachment occurred in the highlighted area at the bolted joint, which allows rotation of the structure along the base. The ring is composed of two rows of 44 pins each, Fig. 2.C2. In this case, the plume fell by the failure of the bolts that secure the inner bearing top. These bolts are the only connection between the rotating loader arm and the rest of the base.

In loaders and cranes which are mounted on a rolling base, the most common failure modes are failure of the bolts and bearing track wear failures. With this preliminary information and failed items collected in the field, previous to calculations and analysis of the material, it was possible to obtain some important conclusions regarding the cause of the fall of the crane. Broken bolts were found at the level of threads due to tensile overload (Fig. 2.C3). The position of these bolts

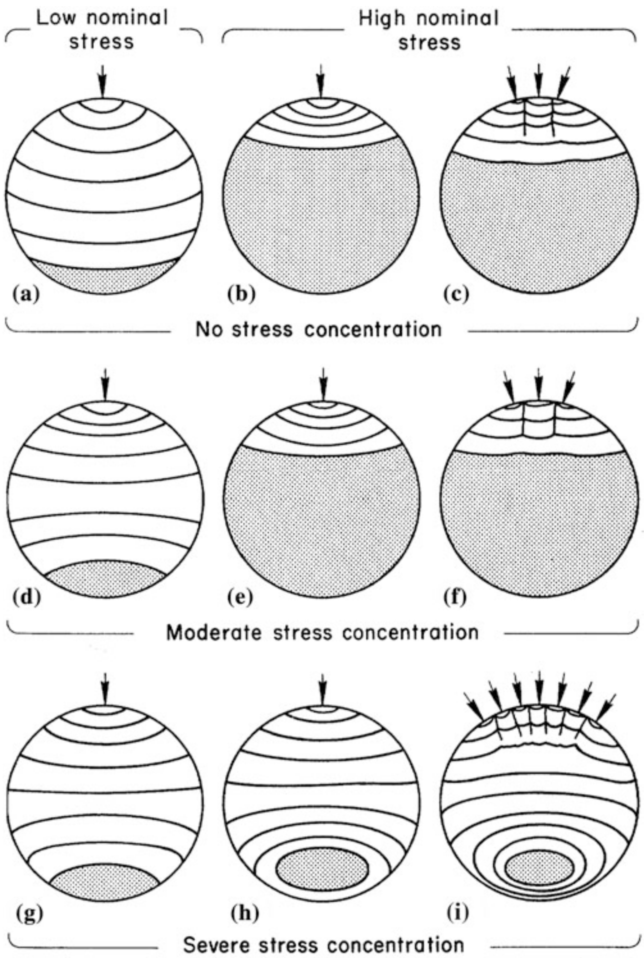


Fig. 2.17 Fatigue crack growth of rods (from ASM materials handbook)

confirmed that the ultimate catastrophic event occurred when the arm dropped, first forward, and after a few minutes later laterally, to its final position.

Other bolts presented worn out threads, both in rod and nuts, Fig. 2.C4. This failure can be progressive in nature and no obvious cumulative damage be detected until final failure. Nut threads were sliced at their roots, as the bolt material is stronger than the nut. This is normal, intended to redistribute the stresses in the fillets.

Some bolts were also found with obvious signs of fatigue; this is normally associated with a deficiency in preloading (Fig. 2.C5). Black arrows indicate microcracks at initiation sites at the bottom of the thread, white arrows indicate fatigue propagation until final failure.

Fig. 2.C1 Jib crane

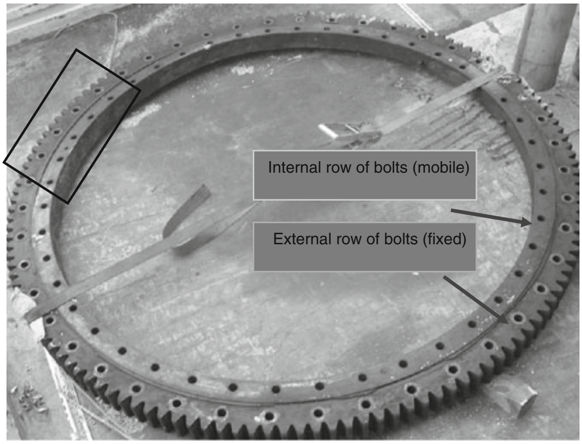


Fig. 2.C2 Ring composition

Fig. 2.C3 Cut bolts at the level of threads

Fig. 2.C4 Worn out threads

These bolts were located in the crown area diametrically opposite to the direction of the loading arm and were the first to fail, thus increasing the load on the rest of the fastening system. Due to lack of proper tool access, verification of torque applied to the bolts of the inner row was performed using an impact wrench, making it impossible to apply the torque accurately (Fig. 2.C6).

Figure 2.C7 shows an outline of the damage to the bolts around the crown, viewed from below. The distribution of damage clearly identifies what were the bolts whose rupture was the cause of the failure, and what were broken during the collapse of the structure.

The requirement to control tightness in the crown was in the maintenance documentation, but through two indirect references and without the importance that such control has. Currently, this check is required on a biannual basis for certification of offshore equipment and, in the future, this criterion should be applied to this equipment.

2.6 Extraction and Storage of Samples

The collection of evidence must be carried out independently while repairs are being made to restore service without affecting these repairs. Ideally, there should be a protocol for hurried working conditions, which are never the same as the previous ones. A protocol would avoid methodological errors that might prejudice the outcome of the analysis. Here are some things to keep in mind:

Prior to removing the pieces

- Collect the evidence in the area that may have contributed to the failure: state of coatings, component identification, welds, foreign bodies, etc.
- Evidence of the position of the failure and the different components with respect to physical references, using graphic recordings (drawings, video, and/or photos).

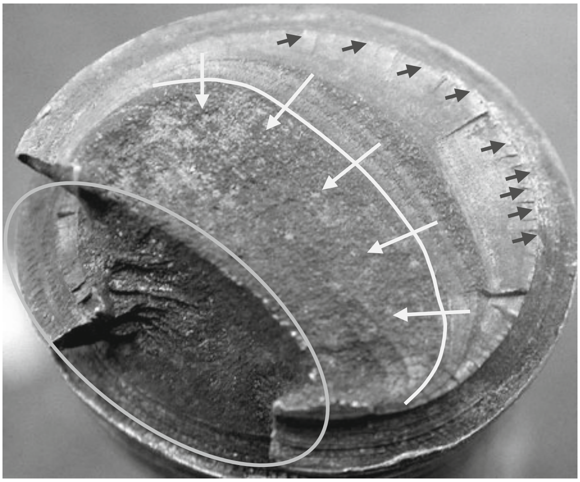


Fig. 2.C5 Bolts with clear evidence of fatigue

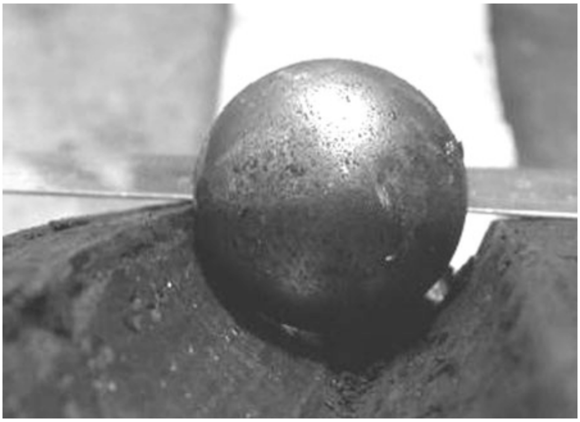


Fig. 2.C6 Excessive wear increased clearance between balls and bearing track

- Perform the appropriate markings to identify the location where each piece was removed.
- Photographically record all marks made.

Removal of pieces

- Prevent degradation of the sample during cutting, for example by overheating of the fracture zone when grinding or cutting with thermal processes (plasma, oxy-acetylene, etc.). Make cuts at an adequate distance zone and remove samples of both the failure zone and in non-failed areas.
- Perform cold cutting. If the distance available for the cut is not enough or would be dangerous to make flame cutting, grinding and coolant should be used to keep the area at low temperature.

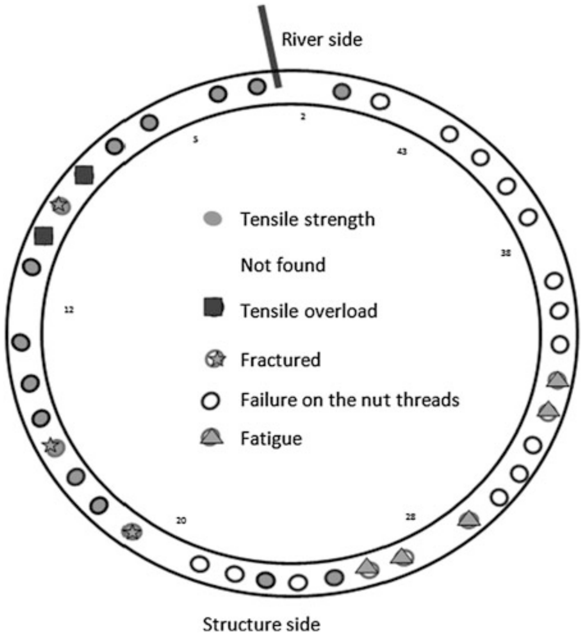


Fig. 2.C7 Scheme of damage in the bolted ring

- Transport samples so that fracture surfaces are not subjected to the components' own weight.
- While moving large pieces, use preferably nylon slings at all times avoiding the use of steel cables that may accidentally lean on the fracture surface and deform evidence.

Conservation of samples

- Do not clean the samples by any mechanical or manual means; avoid erasing important evidence such as corrosion and surface cracks, among others.
- If the part is wet or with a certain level of humidity, spray a jet of alcohol or kerosene to the fracture surface to displace the water and then air-dry.
- Waterproof the fracture area with transparent lacquer or varnish spray, cover with kitchen plastic film, or apply lubricating grease if no lacquer or varnish is available. Cover the fracture surface with corrugated cardboard, expanded polystyrene, or paper in order to avoid damaging the piece at the time of transportation.
- Store samples in a suitable location, which does not change the characteristics of the failure.
- If the failure surfaces are separated, DO NOT reassemble them together. This will generate mechanical damage by crushing at a microstructural level, and valuable information might be lost.

2.7 Inspection by NDT Techniques

Nondestructive Tests (NDT) are those that allow an assessment of the equipment or component without compromising its integrity. This means that the tests do not damage or interfere with the future use of the parts inspected. NDT are based on the application of physical phenomena such as electromagnetic, ultrasonic, acoustic, and elastic waves, subatomic particle emission, capillarity, absorption, etc. There are a variety of NDT, each with its advantages and disadvantages; they differ in the principles of operation and the type of application.

The wide application of NDT methods in materials is summarized in the following three groups:

- Defectology: this allows the detection of discontinuities, evaluation of corrosion and deterioration caused by environmental agents, determination of stress, and leak detection.
- Characterization: evaluation of chemical, structural, and mechanical properties of materials, physical properties (elastic, electrical, and electromagnetic), and isotherms in heat transfer path.
- Metrology: control of thickness, local dimensional measurements, coating thickness, filling levels.

An indication is produced by a disturbance in a signal, detected through a nondestructive testing method. In this sense, the information may be false, relevant, or not relevant. A discontinuity can be defined as the lack of homogeneity or interruption in the normal physical structure of a material, or a deficiency in the normal configuration of a piece, part, or component. The discontinuities can be classified according to:

- location: surface, subsurface, and internal (or embedded),
- origin: inherent to manufacture, process, service, etc.,
- morphology: planar and volumetric.

The generation of corresponding records is as important as testing. These should include test conditions, data on geometry, and properties of the components under study, and an appropriate record of the characteristics of the discontinuities detected.

When using such NDT techniques for integrity assurance in the manufacturing steps or in-service inspection, discontinuities may be relevant or nonrelevant. A defect is considered when the size, shape, or location of the indication exceeds acceptable limits established by the Code, Standard, or applicable specification.

The use of NDT techniques for the preliminary evaluation of a failure becomes important when looking for evidence of damage to other parts of the components, apart from the fracture zones. The detection of these secondary defects is often very useful; rarely a failure due to a defect has only one initiation site. Often what ends up causing the failure is the most critical of a number of previous defects or discontinuities of similar origin. But nonpropagated defects are rarely detectable by visual inspection. In case of suspicion of their existence, it is required to apply evaluation techniques sensitive enough to find and evaluate them, or to rule out their existence.

The method of magnetic particles (MP) detects surface and occasionally subsurface (near surface) discontinuities in ferromagnetic materials. When placing the poles of a magnet on the surface to evaluate, flow lines are formed by the magnetic field generated between the north and south poles. These power lines are altered by the presence of discontinuities, causing leakage of the magnetic field. The magnetic particles will be directed according to the flow lines and will give an indication of the discontinuity. Typical defects found are fatigue cracks and stress corrosion cracking (SCC).

Magnetic particle testing can be dry or wet. In the latter case, the particles are applied in suspension in a liquid (water or kerosene). The test requires white light with a minimum intensity of 500 lux to ensure adequate sensitivity for the evaluation of indications. Also, the wet test can be performed with fluorescent particles with ultraviolet light from mercury arc lamps. In this case, it is necessary to obscure the working area and light will be at a maximum of 1,000 mW.

To determine whether a defect at a failure origin is repeated elsewhere, it is common to test the rest of the component. This is particularly common in welds. Figure 2.18 shows the position of the magnetizing yoke for cracks parallel to the weld joint.

Figure 2.19 shows an example of application of the magnetic particle technique to the verification of an SCC failure of a buried pipeline. SCC is characterized by the initiation of colonies of microcracks on the outer surface of a buried pipeline (as shown in the middle part of the figure). Propagation and coalescence of some of these cracks may cause longitudinal fracture (burst) of the tube (upper Figure), or in rare cases a leak (bottom of Figure). It is unlikely to obtain sufficient field magnification to detect crack colonies visually, especially when they cover large areas of the surface of the component. Figure 2.20 shows a colony of this type, as revealed by the black over white MP technique (a thin white coating and black particles).

The liquid penetrant testing reveals surface discontinuities by absorbing contrasting dye in ferrous and nonferrous metals, and other nonporous materials. It is standardized by ASTM E-165, which classifies fluorescent (ultraviolet visible) and colored dyes, which are also classified by the method of removal. The principle is very simple. First a liquid is dispersed on the clean surface of the material and allowed to penetrate the discontinuities. The liquid is then removed leaving the surface dry; part of the liquid will be retained within cracks or other defects. Finally a developer is applied, which absorbs the liquid housed in the cracks, indicating their presence.

Figure 2.21 shows an example of the technique applied to detect the cause of a failure in a threaded rod. The figure shows the threaded housing in the steel body of a reciprocating compressor. Cracks become apparent, showing a process of

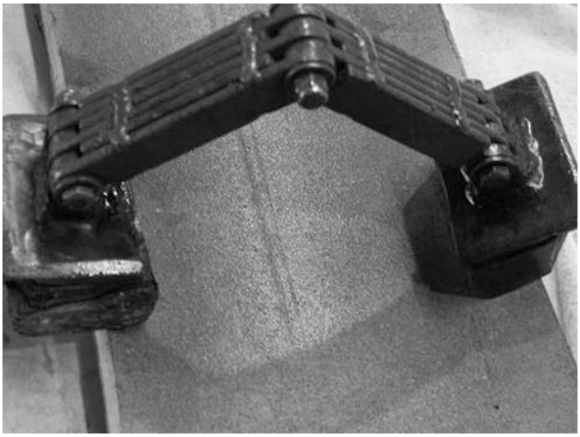


Fig. 2.18 Magnetizing yoke

tearing in layers parallel to the seat surface, indicative of high tensile loads in the connection. Note that in this case, even when the material is ferromagnetic, there is no way to magnetize the piece in the thickness direction. Although the method is fast and inexpensive, it only detects surface defects, has a lower resolution than magnetic particles, and can lead to misinterpretations if not applied correctly.

The ultrasonic test (US) can be classified into two types: Thickness Measurement and Failure Detection. The ultrasonic inspection method involves sending ultrasonic waves through the material with the aid of a coupling material. Sound travels through the material losing some of its energy when reflected at each interface. The reflected waves are picked up by a transducer (receiver) and then analyzed. In the case of Thickness Measurement, sound velocity in the piece is known, so that the time taken for the signal to be released back from the component is measured, when reflected by the other wall surface.

In the case of failure detection, the method uses the same principle to detect the presence of discontinuities within the material. The big difference is that the equipment measures intensity of emitted and received sound. With these data, a reflected wave can be analyzed, indicating position and size of the defect. Normal defects that can be identified and measured include laminations, cracks, pores, inclusions, lack of penetration, lack of fusion, etc.

Some of the advantages of the method:

- The high sensitivity of the method makes it possible to detect small discontinuities.
- US only requires access to one surface of the material.
- Excellent resolution to determine size and location of the defect.
- US does not require special personal safety items.

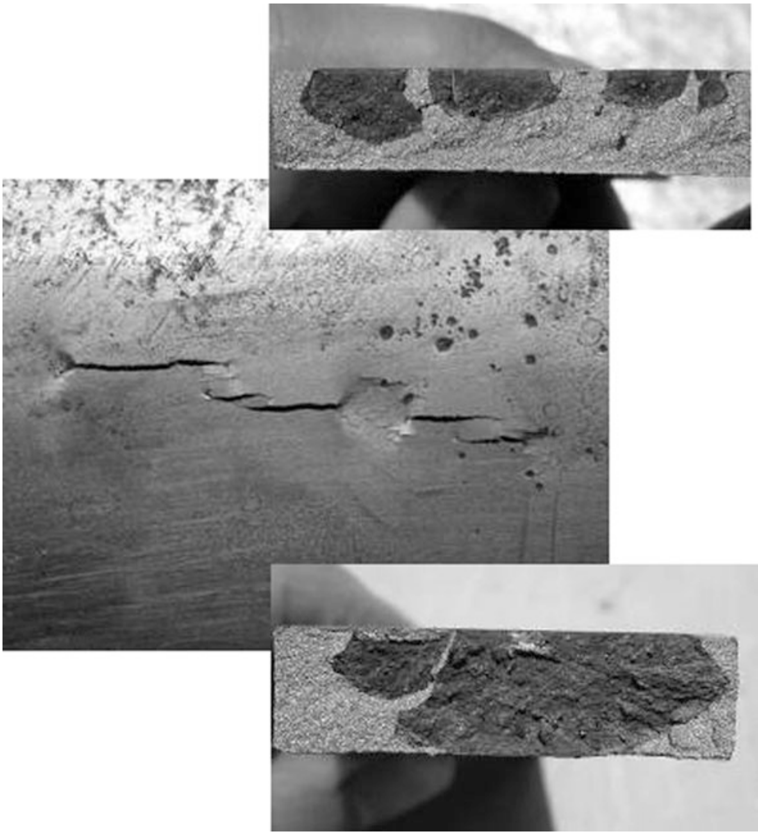


Fig. 2.19 Magnetic particles reveal surface cracks (Center)

In contrast, high training is required for planning and operation, and application of a coupling medium. Rough parts or parts with complicated, small, very thin, or inhomogeneous shapes are very difficult to inspect. In addition, records are interpreted only by competent personnel.

US testing must be in accordance with a written procedure. Each procedure must include at least the information referred to welding and/or material being tested, thickness, surface preparation, and final cleaning. It must also incorporate data of the equipment and coupling used, type of probe (straight or angled) and size of the transducer, angles and modes of wave propagation in the material, frequency, instrument type, calibration description, directions and magnitude of waves, test data to be recorded, and recording method (manual or automatic).

Figure 2.22 shows an example of the use of US for detecting angular secondary defects in a circumferential weld of a large diameter pipe. A fundamental aspect of the test is equipment checking and calibration. To verify proper operation of the

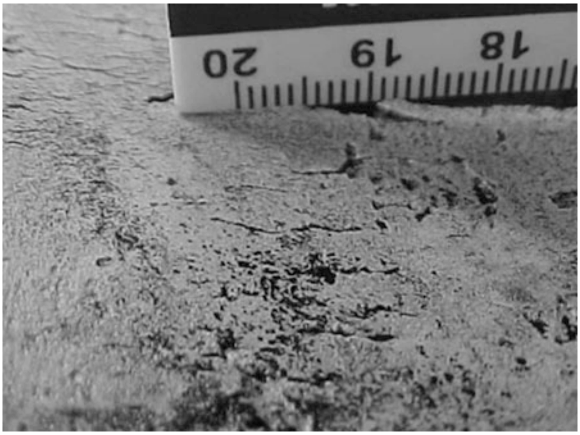


Fig. 2.20 Colony of microcracks

Fig. 2.21 Application of liquid penetrant to threaded bore

test, the equipment must be calibrated at the beginning and end of each test, when examiners change and at any time a malfunction is suspected.

Eddy Current (EC) is an electromagnetic leak testing in which small currents are induced in the material and any changes in the flow of these currents are recorded. These changes are due to inhomogeneities in the material. The basic principle of operation is to pass an alternating current through a coil located in the vicinity of the part to be analyzed. The so-created alternating magnetic field generates a small circulation of eddy currents in the piece. This current in turn generates its own magnetic field, which interacts with the detection coil. The coil then captures disorders caused by discontinuities through an electrical circuit.

The interpretation is based primarily on the analysis of the amplitude and phase of voltage changes in the detection coil by the influence of variations in the parameters of interest of the tested part. The evaluation of the indications is based on comparisons with calibration samples, specially prepared for each test case,

Fig. 2.22 Ultrasonic test with angular probe

according to established rules and procedures. The test is very versatile and very useful in pipelines. It also quickly identifies the defects location and generates a lot of information, but sometimes what is important is difficult to distinguish; it requires highly specialized interpretation of results. EC creates a magnetic field in ferromagnetic materials that can mask some of the results.

Other NDT methods widely used in manufacturing and inspection are not applicable to the preliminary inspection of failures. Such is the case of industrial radiography, which uses radiation to penetrate the material and reveal information. In acoustic emission (AE) testing, transient elastic waves are generated by the rapid release of energy from localized sources, such as plastic deformation or crack propagation. Elastic waves move through the solid to the surface, where they are detected by sensors. This method gets information about the existence and location of possible sources. But the test requires that the component is loaded and therefore in-service, with varying operating conditions. After a failure, the equipment or component is normally out of service.

Field metallography and replica testing involve copying the metallographic microstructure of a material (metals, ceramics, etc.) without destroying the part to be examined. Then the "copy" can be seen under a microscope. It is very useful when it is not possible to extract a sample to examine in the laboratory. The main instrument for the realization of a metallographic analysis is the metallographic microscope, with which a sample can be inspected with magnifications between X50 and X200. For this test, mirror polishing of the piece is required; and various methods and elements are used to etch the microstructure. The information that a metallographic examination can provide is varied: microstructural degradation, quality of material, different phases, determination of alloy types, etc.

Hardness is a measure of the resistance to indentation and friction wear. There are several ways to measure hardness. Most tests use a small indenter device that penetrates the material; indenters can be in the shape of a small ball or a needle. Depending on the type of tip used and the range of loads applied, different scales are defined, suitable for different ranges of hardness: Brinell hardness (HB), Rockwell (HRC–HRB), surface Rockwell, Webster, and Vickers (HV). The interest in the determination of hardness in carbon steels lies in the correlation between hardness and mechanical strength. In cases where getting the equipment out of service for Destructive Testing is not practical, hardness testing is very convenient. An improved variant is the instrumented indentation method, which will be discussed in a later chapter.

2.8 Organization of Work Teams

The areas of the company involved in a failure are the same three areas sharing technical responsibilities: engineering, maintenance, and operations. They may have other names, but the roles are well defined. Operations (production, for example) is the heart of the company, the area that gives meaning to the organization, it is the "client" of the other areas. The engineering area is responsible for the design and construction of infrastructure. The maintenance area (also called Integrity, etc.) is responsible for the normal function of this infrastructure. It is also common that external companies are contracted for short or long periods or for specific events or components, and therefore also become involved in these three fields.

In many cases, Integrity Management is included within the Engineering Department; sometimes, Integrity Management is independent or is included within the Maintenance Department. External consultants ("experts") and contractors are also usually involved in the process of surveying information and failure analysis.

During normal operation of a plant, the three mentioned areas (those that built the equipment, those that use it and those that keep it working properly) often have complex relationships. In the case of a failure, the relationship between these groups becomes even more complex. The staffs of these "subcompanies" that coexist within the company tend to make common cause against those responsible for the other areas. To put it simply:

- For "engineering," the most likely cause of failure is an operational error (it is common to hear that components are ran over 100 %, to increase profitability, or to overcome production losses from other causes).
- For operation and maintenance, the most likely cause is an error in the design or construction of the defective component.

- For engineering and operations, the most likely cause is an error in maintenance; perhaps an oversight or a wrongly reassembled component after a routine inspection, etc.

To complete, we find insurance companies and adjusters. Adjusters have a stake in the outcome of a failure analysis, since in some cases the result defines who will be responsible for the costs arising from the failure, and to what amount.

These emotional attitudes must be dismantled and be replaced by a professional and proactive attitude toward failure analysis. As responsibilities and roles to emergencies such as fires are defined, it is also advisable to set (before the occurrence of a failure) the responsibilities for each of the managements. Here, as an example, the responsibilities defined by a natural gas transport company for leak events and other failures in their pipelines and associated components:

Integrity Management

- Communicate to operations and maintenance managers to take actions based on the preliminary failure analysis.
- Provide the necessary resources or outsource for further analysis.

Head of Integrity

- Coordinate as necessary with maintenance and gas transport areas for the activities needed to obtain the required information to avoid occurrence of the incident.
- Define the type of analysis and tests to be performed, as well as the vendor for the services according to the need.

Integrity Supervisor

- Collect information from mechanical, operational, gas control, inspections, and other relevant sources to determine the possible(s) mechanism(s) of damage.
- Develop a detailed drawing with the location of the failure.
- Prepare a preliminary integrity analysis.
- Inform those responsible for field maintenance of criteria for proper identification, extraction, preservation, and transfer of the sample(s).
- Perform coordination and monitoring of the transfer of the samples from the area of the event to warehouses or maintenance base.
- Perform a preliminary integrity analysis report for closing the event.

Operations Management

- Coordinate with maintenance all integrity activities and samples removal.
- Maintain a continuous fluid communication with maintenance personnel involved in these tasks.

Maintenance Head

- Coordinate with the integrity area and transport management all activities for sample removal.
- Set the required implementation of surveys, collection, and transfer of samples, following Integrity recommendations.

Responsible for Site Maintenance

- Provide the necessary elements for taking samples, photographic survey, and other instruments for the analysis.
- Ensure the preservation, identification, and transfer of the samples to the maintenance base.
- Draw up records for data mining activities and preservation of samples (including all necessary field tests), ensuring delivery on time.

In this scheme, the Integrity Supervisor has the central role in organizing the failure analysis. Elsewhere in this section, this person is defined as responsible in the field. Once preliminary expert activity is finished, he is to develop a preliminary report detailing what was relieved, location plans, and operating conditions at the time of the failure, survey of external conditions, and other data of interest. This report is delivered to management with an overview of the event.

In this gas transport company, the responsibilities of the Integrity Supervisor are defined in a protocol or internal procedure, applicable to the entire company:

- Collect the whole failure data in the area, failures of the same type, on-site inspections.
- Collect additional reports if the case so requires, such as weather reports, reports of floods, earthquakes, etc.
- Collect historical information from operation of the line and specifically the moment of failure.
- Interviewing or request that the interview is made to operators, nearby residents, and any person who can provide information on the failure.
- Collect information, samples, and characteristics of the failure zone, depending on the failure occurred. He needs to know environmental characteristics that helped failure.
- Make a sketch of the terrain and failure zone.
- Determine what type of previous defects caused the event, and identify associated damage mechanisms in a preliminary integrity report.
- Search in databases for the same type of failures, if any, with the aim of finding a correlation.
- Interact with the company performing the failure analysis and the other departments of the company, to coordinate and provide the necessary information.

The Head of Integrity, the supervisor's immediate superior, defines the needs and determines what types of failure analysis should be performed. It is also responsible for defining the scope of the analysis, depending on the type of failure and its consequences for the organization. There is a range of possibilities, some were already mentioned in Chap. 1, and others are discussed in greater detail in later chapters.

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