

Chapter 2

Damages Caused by Crack Growth

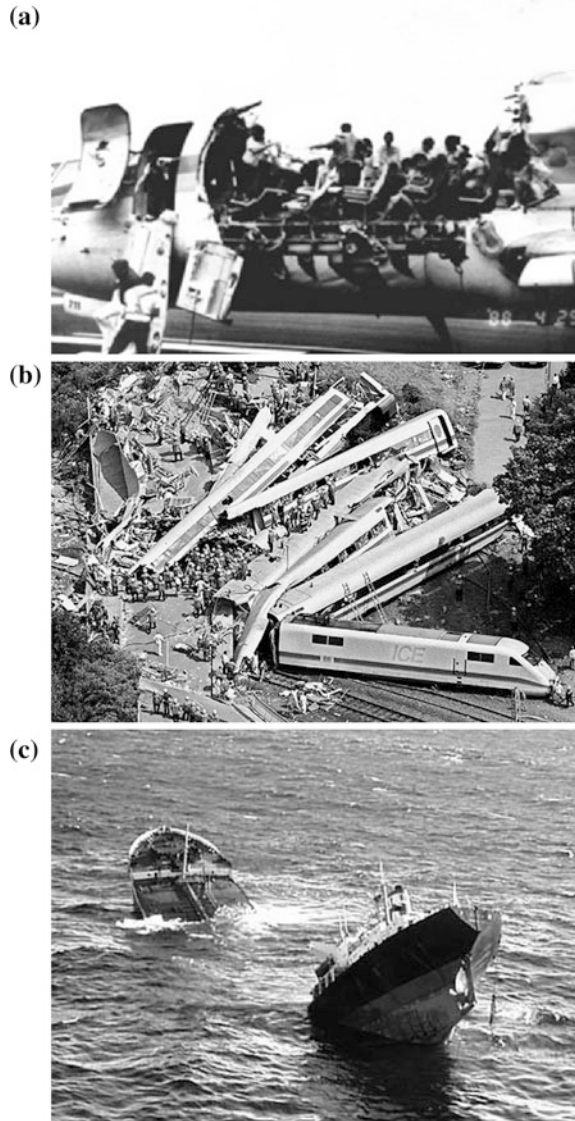
Until a few decades ago, components, machines and equipment were designed solely with classical methods of strength calculation, i.e., using the strength criteria described in Chap. 1. Despite careful calculation, damage occurred again and again in bridges, ships, aircraft, pressure vessels, reactor components, pipelines as well as road and rail vehicles, sometimes with catastrophic consequences. Concrete examples of such damage include a traverse fracture in a hydraulic press [1], torsion fracture in a drive shaft [2], crank pin fracture [3] and a burst pressurized gas cylinder [4]. Early, sensational events like the explosion of steam boilers in the 19th century, the collapse of welded bridges in the first half of the 20th century, extensive cases of damage to American ships between 1942 and 1948 (several Liberty ships collapsed completely), the crashes of Comet aircraft in 1953 and 1954 [5–8] such events led to intensified research into their causes. Yet much more recent cases—the 1988 Aloha Airlines accident (Fig. 2.1a), the catastrophic ICE accident of 1998 in Eschede, Germany (Fig. 2.1b) and the tanker accidents of Erika 1999 and Prestige 2002 (Fig. 2.1c), for example—have shown that considerably more research is needed with respect to the safe design of machines, components and structures.

The cause of such damage and fracture are generally small defects or cracks that are either already in the component (discontinuities in the material or manufacture-related faults, for example) or arise later due to the loading of components and structures. As a result of service loads (particularly time-varying mechanical or thermal loads), these cracks can grow in size. If they reach a critical size, they begin to propagate unstably, usually at high crack speed, and thus lead to the fracture of a component or even to the collapse of the entire structure.

Crack initiation on a smooth surface is generally a local event in the microstructure, caused for example by crystal defects or cyclic loading processes. Crack propagation, on the other hand, is a macroscopic process controlled by service loading.

For processes of crack propagation that can lead to sudden residual fracture, the circumstances directly at the crack tip are essential. Fracture mechanics [5, 9–14], an interdisciplinary subject, has developed approaches, on the basis of stress and

Fig. 2.1 Serious cases of damage in the recent past. **a** Destruction of the canopy due to material fatigue during an Aloha Airlines passenger flight in 1988. **b** ICE high-speed train disaster in 1998 resulting from the fatigue fracture of a wheel tire. **c** Collapse of the oil tanker Prestige on the Spanish Atlantic coast in 2002 as a result of stable and unstable crack growth



displacement fields, for predicting fatigue crack growth and for avoiding brittle and ductile fractures. These approaches will be explored in detail in Chaps. 3–6. Damage events caused by crack growth can only be prevented if fracture-mechanical concepts are taken into account when designing components and structures.

This first part of this book will concern itself initially with basic questions of crack initiation and crack growth, the foundations of damage and fracture surface analysis, crack paths and crack shapes, with selected damage cases and with crack detection.

2.1 Crack Initiation and Crack Growth

Cracks are local material separations in a machine part or structure. Cracks can already exist as material and/or manufacturing defects prior to bringing a component into operation or develop later in the course of service loading. Material defects might include cavities or inclusions. Manufacturing defects can be the result of machining or heat treatment (e.g. hardening). Time-varying loads can trigger the initiation and/or growth of fatigue cracks (Fig. 2.2).

Crack initiation on a smooth surface results primarily from microstructural processes (see e.g. [5, 6, 10, 15]). Sliding processes controlled by the principal shear stress (see Sect. 1.2.3 or [16]) lead, usually among tensile-loaded components, to an incipient crack of under 45° to the loading direction. After a certain amount of crack growth (of up to an incipient crack length of about 200–250 μm [17]), the crack then begins to grow under the control of normal stress, i.e., perpendicular to the active normal stress. In the situation depicted in Fig. 2.2a, this would be perpendicular to the cyclic force.

If the component has a notch, Fig. 2.2b, this favors the initiation of fatigue cracks. The crack initiates in the area of the highest notch stress and, because of the cyclic load, develops under the control of the normal stress, i.e. perpendicular to the largest normal stress (principal normal stress, see Sect. 1.2.3 or [16]).

If there is already a defect (material defect, manufacturing defect, etc.), it can in many cases already be considered to be an incipient crack. The fatigue crack grows perpendicular to the principal normal stress, Fig. 2.2c.

The total service life of a component can be subdivided into a crack initiation phase and a crack propagation phase (Fig. 2.3). The term “crack formation” refers to the actual initiation of the crack and the beginning of microcrack growth. Crack propagation under time-varying loading includes stable macrocrack growth and residual fracture, which is generally unstable.

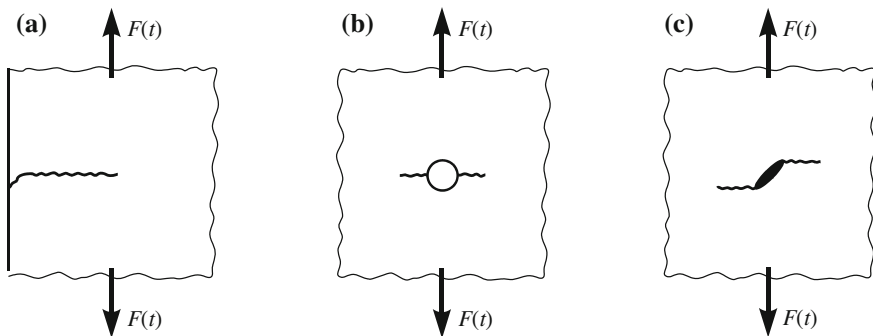


Fig. 2.2 Different types of crack initiation and crack growth. **a** Crack initiation on a smooth surface. **b** Crack initiation at a notch. **c** Crack initiation at a defect

Lifetime			
Crack formation		Crack propagation	
<i>Crack initiation</i>	<i>Microcrack growth</i>	<i>Macrocrack growth</i>	<i>Residual fracture</i>

Fig. 2.3 Phases of component service life

A component’s total service life N_f can be determined by adding up the two service life values N_i and N_p :

$$N_f = N_i + N_p. \tag{2.1}$$

Here, N_i is the initiation service life until the appearance of the first incipient crack of length a_i . N_p designates the remaining life for crack propagation until component fracture. The phases of crack initiation and crack propagation differ very significantly in duration depending on the situation and type of crack initiation (Fig. 2.4).

When cracks develop on smooth surfaces, the period of crack initiation is longer than that of propagation. That is to say, 80–90 % of a component’s total service life elapses before an incipient crack develops. Crack growth until component fracture than requires a relatively short amount of time in relation to the total service life. Components with smooth, polished surfaces without notches (design-based or manufacturing-caused stress concentration areas) or without defects are, however, rather rare in practice.

When a crack initiates at a notch, the crack initiation phase is significantly shorter depending on the sharpness of the notch or stress concentration. The total

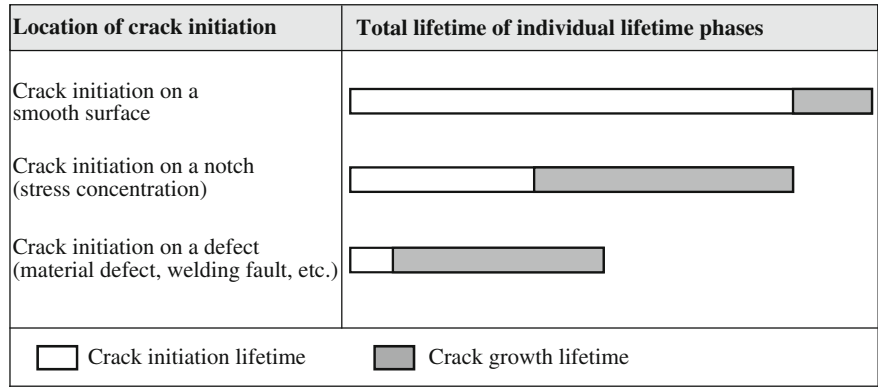


Fig. 2.4 Total service life and phases of service life as functions of the crack initiation position

service life then also tends to be shorter than that of ideal components with smooth, polished surfaces (Fig. 2.4). Components with defects have a very short crack initiation phase compared to the crack growth phase as well as a much shorter total service life.

2.2 Stable and Unstable Crack Growth

Crack growth is the cause of many cases of damage (see Fig. 2.1). The conditions for sudden fracture or serious damage-related failure usually do not exist from the start. Rather, they are often created later by the gradual growth of fine incipient cracks within a relatively long duration of time as a result of service loading. As a rule, a period of stable, controlled crack growth precedes sudden, uncontrolled and unstable crack growth and resultant component and structure fracture. Stable crack growth arises when components are subjected to time-varying loads, among other ways. Under certain conditions, a crack will grow by a small amount during each load cycle. The crack becomes larger with more load cycles. When a critical crack size is reached, or in cases of considerable increase in load, crack growth can become unstable, leading to sudden fracture in the component or structure.

While stable crack growth can take place for a very long period of time (e.g. several hundred thousand or even millions of load cycles), unstable crack growth transpires very quickly. Crack speed of up to 2000 m/s can be reached.

However, stable crack growth need not necessarily lead to unstable crack growth and thus to fracture of components and structures. For example, fatigue crack growth can also lead to the partial failure of vessel walls without the vessel itself exploding. But, this may lead to the leakage of liquid or gaseous substances, which can damage the environment under some conditions.

We can generally recognize the phases of stable and unstable crack growth very clearly on the fracture surfaces of broken machine parts and structures (see Figs. 2.5 and 2.9). For this reason, damage analysis and fracture surface analysis in particular is exceedingly important.

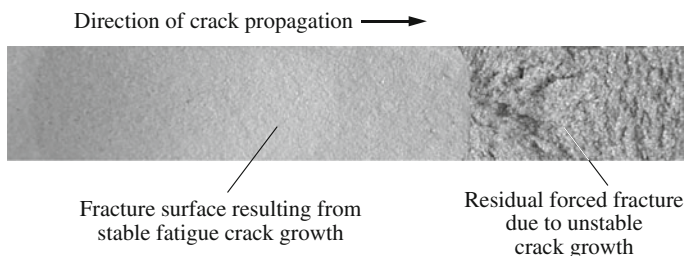


Fig. 2.5 Fracture surface of a steel with areas of fatigue fracture and unstable crack growth

2.3 Damage Analysis/Fracture Surface Analysis

If damage occurs, a damage analysis (see [18–20]) can provide with information about the cause of damage, the damage process, the size and direction of the load and ways to prevent damage. In addition to the damage symptoms and the crack path, an examination of the fracture surface is especially informative about damage that has arisen. This may be done both macroscopically by visual inspection and microscopically, using an optical or scanning electron microscope.

In many cases, a macroscopic analysis of the fracture surface is perfectly adequate. With such an analysis, it can be recognized, for example, whether it is a cleavage fracture or a ductile fracture, what loads the component was exposed to and their directions, and whether it is a fatigue fracture or a forced fracture.

For a *cleavage fracture*, the maximum normal stress (principal normal stress, see Sects. 1.2.3 and 1.3 or [16]) in the component is decisive. Component separation runs perpendicular to the principal normal stress (see Fig. 2.6a); fracture takes place with little deformation.

A *ductile fracture* is caused by the maximum shear stress (principal shear stress, see Sects. 1.2.3 and 1.3 or [16]) in the component and, given a tensile-loaded plate, occurs under 45° to the plate plane, Fig. 2.6b. Ductile fracture is usually preceded by large component deformations. Cleavage and ductile fracture surfaces usually differ very markedly.

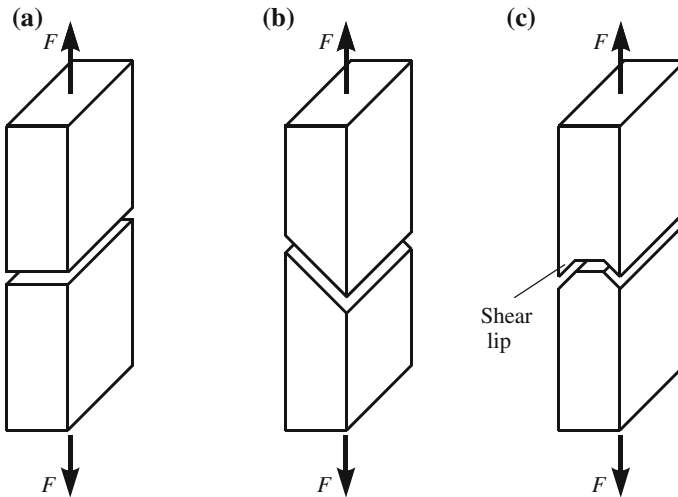


Fig. 2.6 Distinguishing between cleavage and ductile fracture. **a** Cleavage fracture (runs perpendicular to the principal normal stress σ_1). **b** Ductile fracture (runs in the direction of the principal shear stress τ_H). **c** Mixed fracture (cleavage fracture with shear lips)

While pure cleavage fracture occurs in brittle materials, ductile fractures can arise in tough materials as well as “mixed fractures”, which are cleavage fractures with shear lips (Fig. 2.6c). Shear lips are ductile zones near the surface, which are more or less pronounced depending on the stress state (see e.g. Sect. 1.2 and especially Sect. 1.2.4) and material toughness.

Fatigue fractures are caused by time-varying loads with a large number of load changes. Beginning with an incipient crack (see Fig. 2.2), a fatigue crack grows in a component under the influence of normal stress until unstable crack growth occurs (i.e., residual forced fracture).

Fatigue cracks grow with little deformation, even in ductile materials. The orientation of fatigue crack surfaces is thus comparable to that of cleavage fracture surfaces. Like the cleavage fracture surface, it runs perpendicular to the principal normal stress in the component. Because the damage involves a minimum amount of deformation, a fatigue crack on the surface of a component or structure can often only be recognized as a hairline crack (see e.g. Fig. 2.15a). Only given a large crack length does the crack open perceptibly under loading.

A residual forced fracture can occur as a cleavage fracture, ductile fracture or mixed fracture depending on the material's toughness. A cleavage fracture will appear in a brittle material, a ductile fracture in tough material and a cleavage fracture with shear lips in medium-strength material. In ductile material, forced fracture is usually preceded by a large plastic deformation. This is the more pronounced the smaller the fatigue fracture surface and the larger the forced fracture surface. Ductile failure and the formation of shear lips depends among other things on the existing stress state (see e.g. Sect. 1.2.4). Thick-walled components with a plane strain state tend more towards cleavage fracture or mixed fracture with small shear lips on the surface.

If a fatigue fracture has occurred, the starting point of the fatigue crack and its path are generally easy to recognize on the fracture surface (see e.g. Figs. 2.13b and 2.14a–c). The transition from stable to unstable crack growth can also be seen. This means that the fatigue crack surface is clearly distinguishable from the residual forced fracture surface (see e.g. Figs. 2.5 and 2.13b).

Under time-varying loading, rest marks (Fig. 2.7) are visible on the fatigue fracture surface. With certain materials, significant color differences can also be seen, Fig. 2.8.

The rest marks in Fig. 2.7 result from individual overloads interspersed in a cyclic baseline level loading. The color effects in the fracture surface of a steel, Fig. 2.8, are the result of block loads with different block load ratios.

The darker hue indicates slow fatigue crack growth at a low load level, the brighter colors indicate higher crack growth rates with blocks of higher load.

Significant differences can be recognized between the fatigue fracture and residual forced fracture surfaces of aluminum alloys as well. Figure 2.9 also shows rest marks caused by individual overloads. Here, the fatigue fracture surface differs clearly from the residual forced fracture surface. The transition from stable to unstable crack growth is thus definitely recognizable.

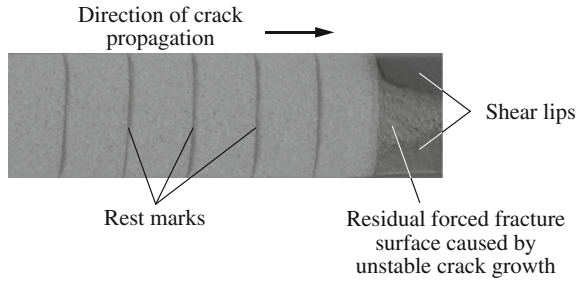


Fig. 2.7 Fatigue fracture surface of a steel with rest marks resulting from overloads interspersed in a cyclic baseline level loading and a residual forced fracture surface with shear lips

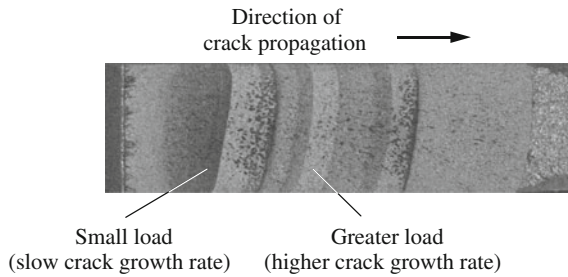


Fig. 2.8 Fatigue fracture surface of a steel with distinct color effects resulting from time-varying block loading

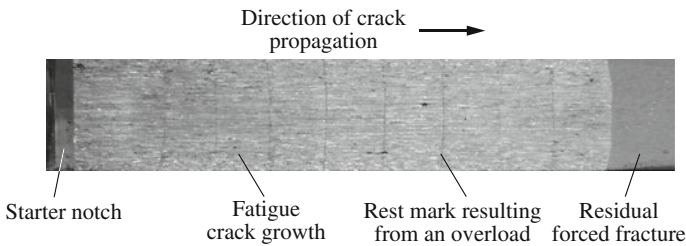


Fig. 2.9 Fatigue fracture surface with rest marks due to single overloads and the residual forced fracture surface of an aluminum alloy

It is also possible to see block-wise alterations of the block load level on the fracture surface, Fig. 2.10. An arbitrarily time-varying loading, e.g. from an service load sequence, leads on the other hand to a completely different fracture surface pattern, Fig. 2.11.

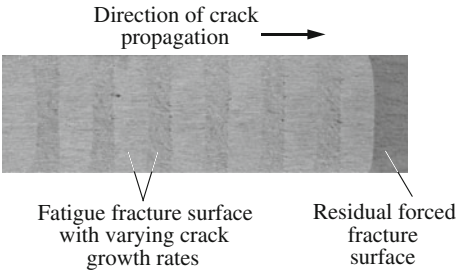


Fig. 2.10 Fatigue fracture surface of an aluminum alloy with a block-wise alteration of the block load level

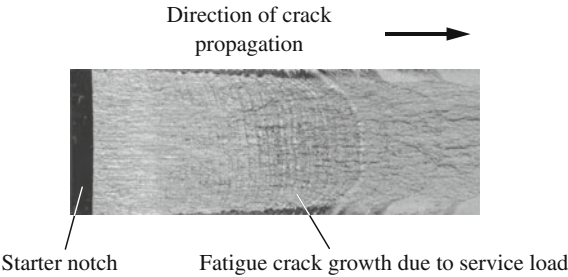


Fig. 2.11 Fatigue fracture surface of an aluminum alloy resulting from a service load spectrum

Fatigue cracks will commonly grow under the influence of loadings far below the static strength limits. Thus, extensive fatigue crack growth is a sign of relatively low component loading, Fig. 2.12a. However, if residual forced fracture already occurs after a short period of fatigue crack growth, it can be assumed a relatively high amount of component loading, Fig. 2.12b.

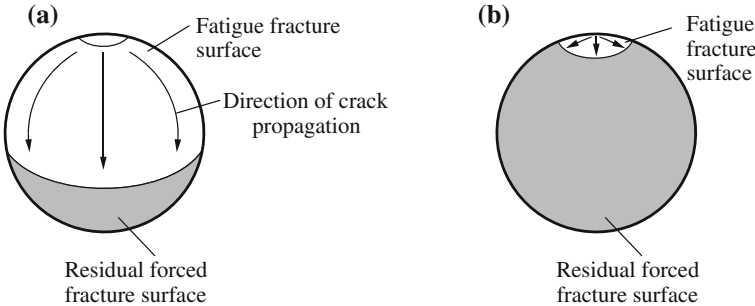


Fig. 2.12 Comparison of the fatigue crack and residual forced crack surfaces of a shaft under tensile loading or bending. **a** Extensive fatigue crack growth under relatively low loading far below the static strength limit. **b** Limited expansion of the fatigue crack surface and large expansion of the residual forced fracture surface due to high component loading

These examples show that the damage process can be tracked very well with the help of fracture surfaces. The following damage cases, stemming from actual technical practice, will serve to clarify these observations in more detail.

2.4 Fatigue Crack Growth in an ICE Wheel Tire

On June 3, 1998, the high-speed ICE train “Wilhelm Conrad Röntgen” derailed and crashed near the village of Eschede on route from Munich to Hamburg with well-known, disastrous consequences. Several cars of the train were equipped with rubber-sprung wheels. One of these wheels broke at a switch. Afterwards the train careened into a bridge, Fig. 2.1. The cause of the accident was determined to be the fractured wheel tire of a rubber-sprung train wheel, Fig. 2.13a. Extensive fatigue crack growth led to tire fracture, Fig. 2.13b. Crack growth in the ICE wheel initiated in the inner edge of the tire. Initially, the crack was growing more in the

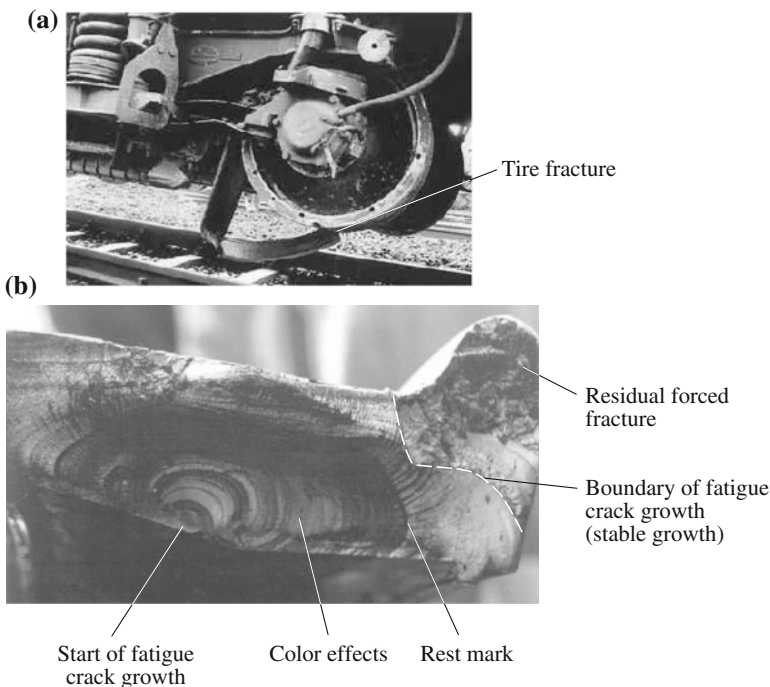


Fig. 2.13 ICE tire fracture. **a** Broken tire. **b** Fracture surface of the broken tire with extensive fatigue crack growth and a relatively small residual forced fracture surface

depth, propagating later in semi-elliptical shape. Only when about 80 % of the cross-section of the tire was damaged by fatigue crack growth did the residual forced fracture of the tire take place. The fracture surface exhibited color effects and fracture surface structures indicating a highly discontinuous process of crack growth. That is to say, fast and slow phases of crack growth alternated with phases of stagnation (see also Fig. 2.8). Further details on the tire fracture can be found in [21–24] and Sect. 9.2.

2.5 Crack Growth in a Press Frame

During the operation of a hydraulic press, a crack appeared in the press body, which led to fracture of the press components after about 860,000 press cycles (load changes), Fig. 2.14a. The crack initiated in a design-based notch. After prolonged

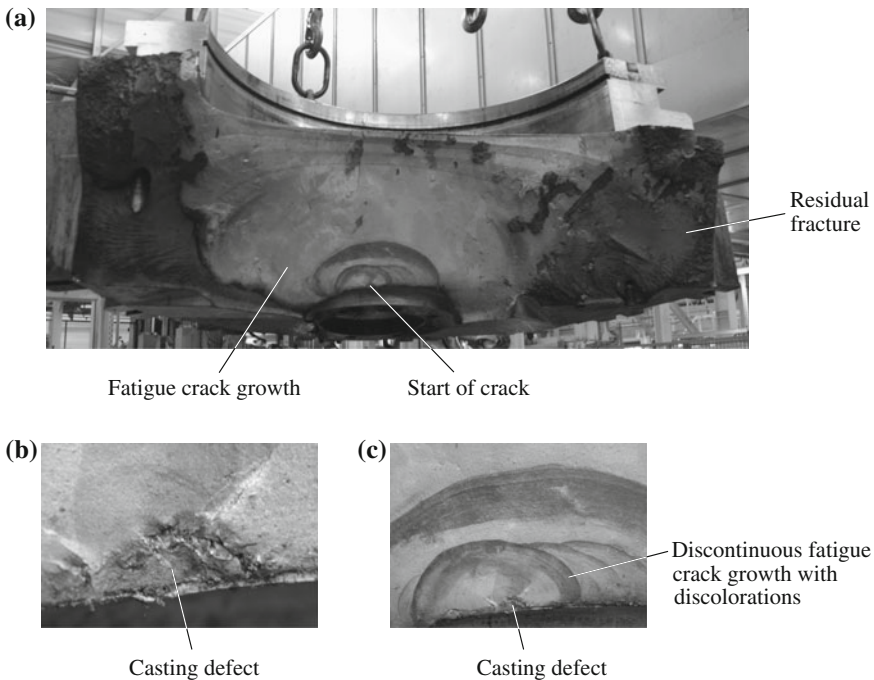


Fig. 2.14 Crack growth in the press frame of a hydraulic press. **a** Global view of the fractured components. **b** Material defect as starting point for the fatigue crack. **c** First phase of fatigue crack growth with rest marks and discolorations on the fracture surface

fatigue crack growth, extending over the entire middle area of the press frame, the press frame has been broken. Only the lateral edges of the fracture surface exhibit the high level of roughness typical of forced fractures. The nearly semi-elliptical casting defect in the base of the notch, Fig. 2.14b, with a width of about 28 mm and depth of 10 mm, was the starting point of fatigue crack growth. This proceeded highly discontinuously at first, as rest marks and discolorations on the fracture surface show, Fig. 2.14c.

For further details on this damage case, see [25]. The combined influence of the notch effect and the material defect in the notch was the cause for the fatigue fracture (spatial notch crack problem: surface crack initiating at a notch, see Fig. 2.21b). Fracture-mechanical investigations of fatigue crack growth are also described extensively in Sect. 9.3.

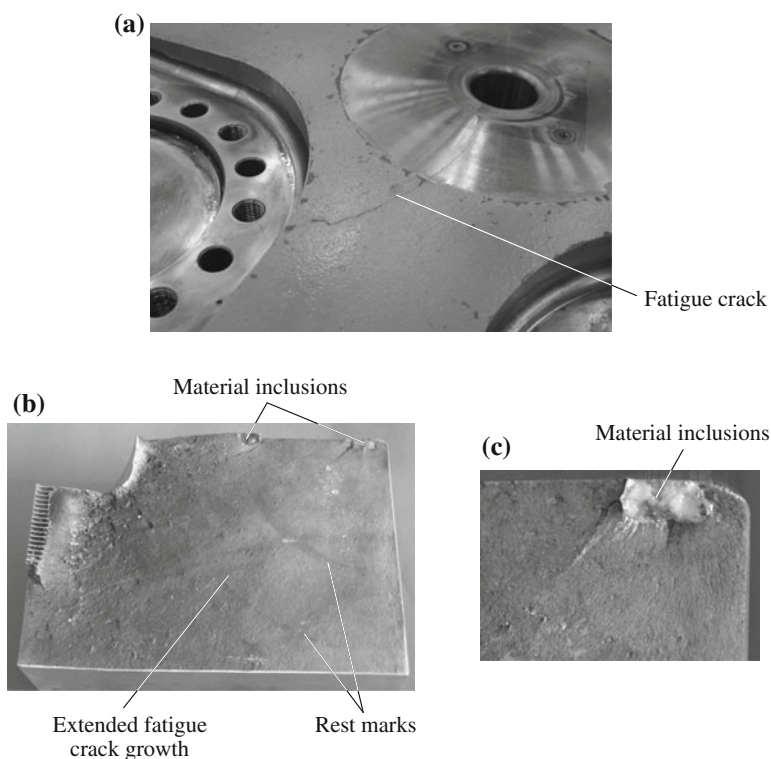


Fig. 2.15 Fatigue crack growth in the fastener body of an internal high-pressure metal forming machine. **a** Fatigue crack visible on the casting surface. **b** Fracture surface resulting from fatigue crack growth with clearly recognizable material inclusions and rest marks. **c** Material inclusion as the starting point of fatigue crack growth

2.6 Fatigue Crack Growth in the Fastener Body of an Internal High-Pressure Metal Forming Machine

In the head region of the fastener body of an internal high-pressure metal forming machine, a fatigue crack developed, which was visible on the surface, Fig. 2.15a. The crack was discovered after about 165,000 press cycles. The fastener body was not in use up to the final fracture. Since the crack on the component's surface did not provide enough information about the cause of damage, the press frame was dismantled, exposing the fracture surface. On the quite smooth fracture surface, Fig. 2.15b, it can be seen an extended fatigue crack growth proceeding from two material inclusions (casting defects). The faintly visible rest marks on the fracture surface show that the fatigue crack propagated in a quarter-elliptical shape. Figure 2.15c provides a detailed view of a material inclusion. A more extensive discussion of the entire damage case and further details concerning the damage analysis can be found in [25, 26].

2.7 Fracture of the Drive Shaft of a Vintage Car

The drive shaft of a vintage car completely collapsed after a large number of operating hours, Fig. 2.16a. Crack growth initiated at a cross-sectional variation (change in stiffness) of the shaft. Fatigue fractures formed at several gear locations. As a result of rotating bending, these fractures enlarged and joined to create a cumulative crack, Fig. 2.16b. After extensive fatigue crack growth, residual forced fracture finally occurred. The residual forced fracture surface is relatively small in comparison to that of the fatigue fracture. This indicates a loading well below the static strength limit.

2.8 Other Damage Events

The examples of damage described above were selected with the objective of providing basic information about damage and fracture surface analysis and to show what crack shapes (crack geometries) appear in real structures as a consequence of service loading. Other interesting damage cases and information on the basic procedure of damage analysis can be found in [6, 18–20, 27–30]. Further examples of cracks in train structures are described in [31–34].

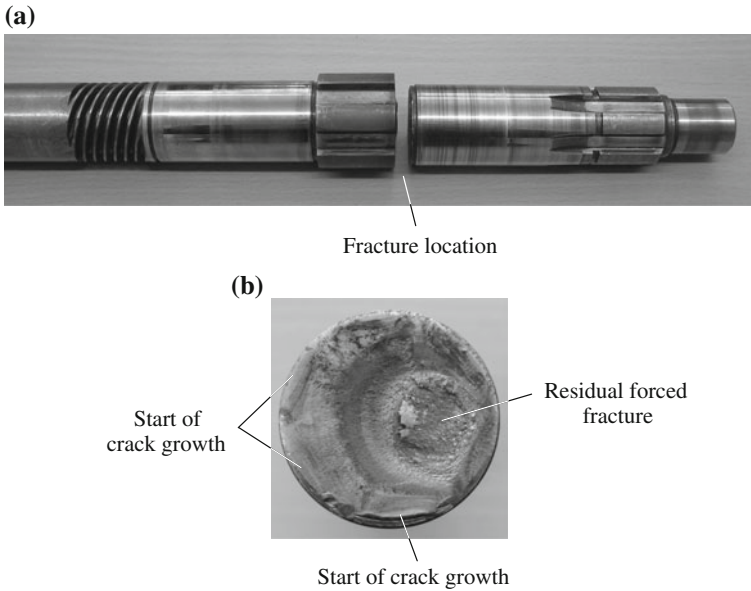


Fig. 2.16 Fracture of a drive shaft. **a** Broken drive shaft with fracture on a cross-sectional variation (change in stiffness). **b** Fracture surface with several incipient cracks, extensive fatigue crack growth and a small residual forced fracture surface

Example 2.1



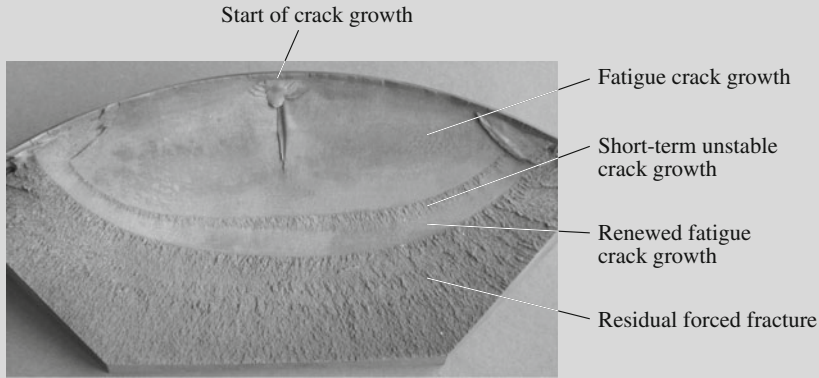
The adjacent figure shows a detail of the fracture surface of a tensile rod.

Determine the location of crack initiation and the different phases of crack growth on the fracture surface.

Solution

The fatigue crack starts on the surface of the tensile rod and propagates in semi-elliptical shape (see figure below). After a short period of unstable crack growth, there is a phase of stable fatigue crack growth before residual forced

fracture occurs. In comparison to the entire fracture surface (circular cross-section of the solid shaft), the area of fatigue crack growth is very small, from which we can deduce a high static loading of the tensile bar.



2.9 Basic Crack Paths and Crack Shapes in Components and Structures

In order to examine and calculate/estimate

- what local loads are responsible for growth at the crack,
- to what extent the crack is capable of growth,
- with what crack growth rate it propagates,
- what the remaining service life of a component is or
- what dangers are inherent in a case of unstable crack growth,

it is essential to recognize basic crack paths and crack shapes in components and structures.

From practical experience (see also Sects. 2.1–2.8), typical crack paths and shapes (crack geometries) can be defined that result from the loading and component geometry. These will be explored in the following.

A “crack path” is defined as the visible course a crack makes in plate structures or on the surface of components or any three-dimensional structures.

The term “crack shape” (crack type, crack geometry) generally refers to crack growth inside the structure. That is, the crack shape is not recognizable from the outside, assuming the component is intact. As a rule, it only becomes visible when the component breaks apart due to service loading, or the component’s fracture surface becomes exposed via component separation.

2.9.1 Crack Paths of Basic Stress States

Figure 2.17 shows crack paths resulting from basic loadings and stress states.

Fatigue cracks always run, from a global standpoint, perpendicular to the largest normal stress (principal normal stress, see Sect. 1.2.3) in the component. This results in clearly distinguishable crack paths for different stress states in plate-like structures or on the surface of three-dimensional structures.

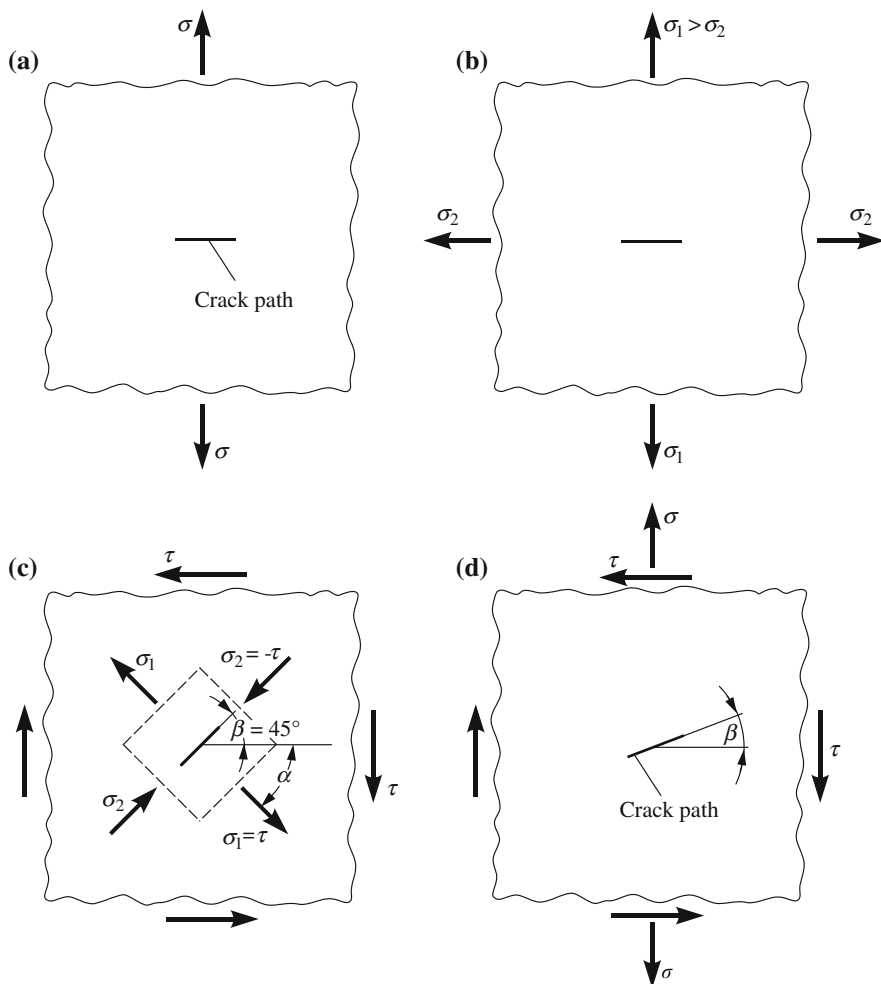


Fig. 2.17 Basic crack paths in plate-like structures or on surfaces of real components as functions of basic stress states. **a** Uniaxial loading (normal stress σ). **b** Biaxial loading (with the principal normal stresses σ_1 and σ_2) with $\sigma_1 > \sigma_2$. **c** Pure shear loading (shear stress τ). **d** Superimposed normal and shear loading. For the definitions of stress states, normal stress σ , shear stress τ , principal normal stresses σ_1 and σ_2 and the principal stress angle $\alpha = \alpha_H$ see Sect. 1.2 and [16]

Under uniaxial loading (Sect. 1.2, [16]) by a normal stress σ , Fig. 2.17a, the fatigue crack grows perpendicular to this normal force.

In cases of biaxial loading [16], characterized by a biaxial tensile stress field with the principal normal stresses σ_1 and σ_2 , where $\sigma_1 > \sigma_2$, Fig. 2.17b, a fatigue crack will grow perpendicular to the largest principal normal stress σ_1 .

Under pure shear loading (Sect. 1.2, [16]) by shear stress τ , Fig. 2.17c, the crack also runs perpendicular to the largest principal normal stress σ_1 . Since the latter acts at an angle of $\alpha = 45^\circ$ to the horizontal, the fatigue crack lies at an angle of $\beta = 45^\circ$, i.e., also 45° to the directions of shear stress.

If there are superimposed normal and shear stresses (see also Sect. 1.2.1 and [16]), characterized by the normal stress σ and the shear stress τ , then, depending on the magnitude of σ and τ (i.e. depending on the direction of the principal normal stress σ_1), the crack path will lie at an angle β , Fig. 2.17d.

For $\sigma > 0$ and $\tau = 0$ (uniaxial loading), $\beta = 0^\circ$ and for $\sigma = 0$ and $\tau > 0$ (pure shear loading), $\beta = 45^\circ$.

2.9.2 Crack Paths and Crack Shapes in Shafts

Depending on the loading type, the global crack paths shown in Fig. 2.18 appear in shafts. If the shaft (prismatic structure) is under a cyclic tensile loading $F(t)$, then

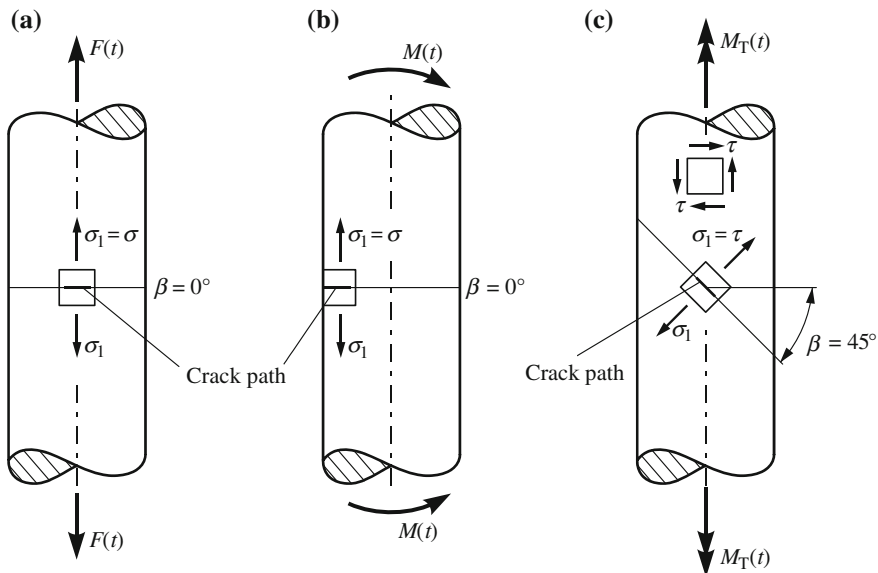


Fig. 2.18 Fatigue crack growth in shafts under different loading conditions. **a** Tensile loading with cyclic force $F(t)$. **b** Bending loading with bending moment $M(t)$. **c** Torsional loading with torque $M_T(t)$

the fatigue crack will grow perpendicular to the principal normal stress $\sigma_1 = \sigma$, i.e., perpendicular to the longitudinal axis of the shaft and the force $F(t)$, Fig. 2.18a. Growth thus takes place in the shaft cross-section at an angle of $\beta = 0^\circ$.

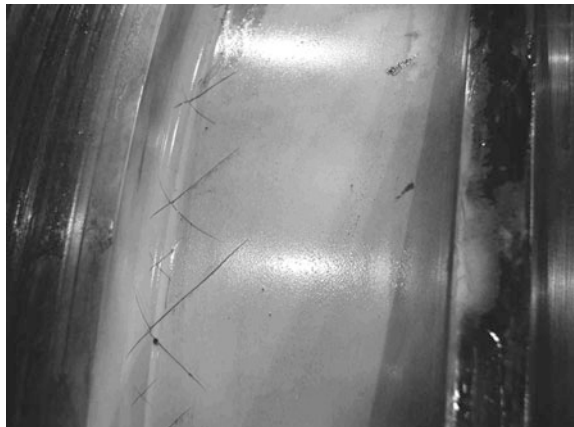
Bending loading with a time-varying moment $M(t)$, Fig. 2.18b, results in the maximum normal stress (principal normal stress) $\sigma_1 = \sigma = \sigma_{\max}$ [16] on the shaft surface with the maximum distance from the neutral layer. Fatigue crack growth begins in this highly stressed shaft area. The crack grows perpendicular to the principal normal stress $\sigma_1 = \sigma$, i.e., in the shaft cross-section (angle $\beta = 0^\circ$).

In the case of torsional loading by torque $M_T(t)$, on the other hand, a crack path at an angle of $\beta = 45^\circ$ to the shaft cross-section or the longitudinal axis of the shaft is obtained, Fig. 2.18c. The torque brings about a shear stress that is constant on the entire shaft surface τ , [16]. The principal normal stress $\sigma_1 = \tau$ then acts at an angle of 45° to the longitudinal axis. Since a fatigue crack will also grow perpendicular to the principal normal stress σ_1 in cases of pure shear loading, the crack path lies at an angle of $\beta = 45^\circ$.

The crack pattern shown in Fig. 2.19 arose in a drive shaft under alternating torsional loading. The cracks grew at an angle of 45° to the longitudinal axis (or the shaft cross-section). Since the torque changes its direction of rotation in the case of alternating torsion, the shear stress τ and the principal normal stress σ_1 also change direction, resulting in a crossed crack pattern due to alternating crack growth.

Figure 2.20 shows fatigue crack surfaces (fracture surfaces) such as develop in shafts under tensile and bending loading. A semi-elliptical surface crack, Fig. 2.20a, may be produced by tensile loading and bending loading (see also Fig. 2.12 and the fracture pattern in Example 2.1). The circumferential crack, Fig. 2.20b, forms e.g. in surface-hardened shafts under tensile loading, in rotating shafts under bending loading (see also Fig. 2.16) or in components with circumferential grooves. Double-sided surface cracks, Fig. 2.20c, are the product of alternating bending loading.

Fig. 2.19 Fatigue crack growth in a drive shaft under alternating torsional loading



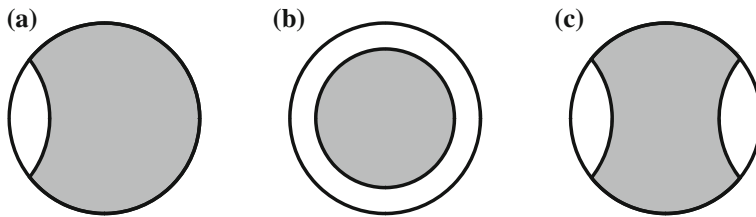


Fig. 2.20 Typical fatigue surfaces (fracture surfaces) resulting from tensile and bending loading of shafts. **a** Semi-elliptical surface crack due to tensile or bending loading. **b** Circumferential fatigue crack in surface-hardened shafts under tensile loading or in shafts under rotating bending loading. **c** Double-sided surface cracks resulting from alternating bending loading

2.9.3 *Systematizing Crack Types in Components and Structures*

Figure 2.21 shows typical crack types that appear frequently in components and structures. It can be essentially distinguished between the following crack types:

- Through cracks,
- Surface cracks,
- Internal cracks,
- Edge cracks.

The simplest crack shapes are through cracks, Fig. 2.21a. These usually appear in thin, plate-shaped components or test samples (see also the crack growth in Figs. 2.5, 2.7, 2.8, 2.9, and 2.10). A through crack develops within the entire thickness of the material and grows, when considered from the side of the plate structure, as a hairline crack. Thus, if only the plate plane or the surface of a thin-walled structure is observed, through cracks can be considered as plane crack problems (see Fig. 2.22). These are much easier to describe mathematically than surface cracks, Fig. 2.21b, internal cracks, Fig. 2.21c, and edge cracks, Fig. 2.21d.

Surface cracks (also called “part-through cracks”) start on the component surface and grow in a semi-elliptical or semi-circular shape into the component, Fig. 2.21b. Such surface cracks often initiate in notches or bores. Practical examples of surface cracks can be found in Figs. 2.13 and 2.14 as well as Example 2.1.

Internal cracks, Fig. 2.21c, are cracks lying inside the component or structure that do not reach the surface. As a result, they also cannot be observed on the component surface. Internal cracks propagate as fatigue cracks in a circular or elliptical shape.

Edge cracks generally start at an edge or corner of a component, Fig. 2.21d. They grow as fatigue cracks both within the component and along the surface. Edge cracks often appear in bores as well. After extensive crack growth, edge cracks can develop into through cracks. A practical example of an edge crack is shown in Fig. 2.15b (recognizable by the resulting rest marks). In this case, the edge crack developed in the area of the inner bore of the fastener body, Fig. 2.15c.

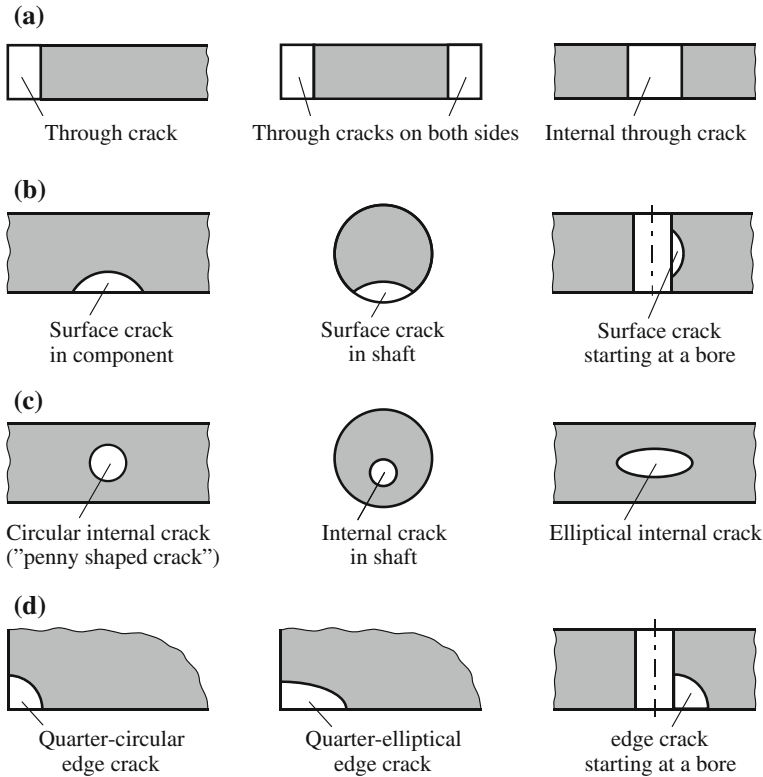


Fig. 2.21 Typical crack types (fracture surfaces) in components and structures. **a** Through cracks. **b** Surface cracks. **c** Enclosed internal cracks. **d** Edge cracks

The crack types shown in Figs. 2.21 and 2.22 will be the basis for further investigations in the following chapters of this book. While through cracks, Fig. 2.21a, can be treated as plane crack problems (see Fig. 2.22), surface cracks, Fig. 2.21b, internal cracks, Fig. 2.21c, and edge cracks, Fig. 2.21d, are spatial (three-dimensional) crack problems.

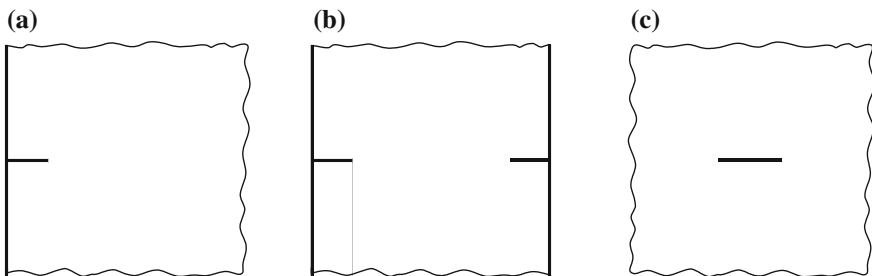
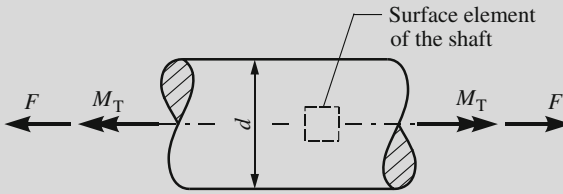


Fig. 2.22 Representation of the through crack in Fig. 2.21a as plane crack problems (lateral view). **a** External crack. **b** Double-sided external cracks. **c** Internal crack

Example 2.2

The component shown (shaft with diameter d) is simultaneously loaded by force F and torque M_T .

Determine

- the normal and shear stresses acting on one surface element of the shaft,
- the magnitude and direction of the largest principal normal stress and
- the direction, in which a fatigue crack will grow.

Given: $F = 140 \text{ kN}$, $M_T = 400 \text{ Nm}$, $d = 30 \text{ mm}$

Solution

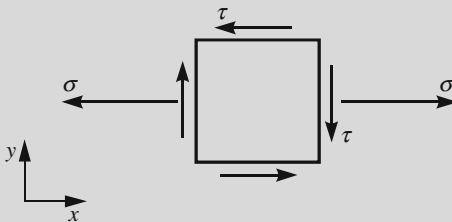
- The normal and shear stresses acting on a surface element of the shaft
The force F induces a normal stress σ [16]:

$$\sigma = \frac{F}{A} = \frac{F}{\frac{\pi \cdot d^2}{4}} = \frac{140,000 \text{ N}}{\frac{\pi \cdot 30^2 \text{ mm}^2}{4}} = 198.1 \frac{\text{N}}{\text{mm}^2}$$

The torque induces a shear stress τ [16]:

$$\tau = \frac{M_T}{W_T} = \frac{M_T}{\frac{\pi \cdot d^3}{16}} = \frac{400,000 \text{ Nmm}}{\frac{\pi \cdot 30^3 \text{ mm}^3}{16}} = 75.5 \frac{\text{N}}{\text{mm}^2}$$

Thus, the normal stress σ and the shear stress τ act on one surface element:



- Magnitude and direction of the principal normal stress
The principal normal stress σ_1 is obtained from the normal stress σ and the shear stress τ via the relation (see e.g. [16])

$$\sigma_1 = \frac{\sigma}{2} + \frac{1}{2} \sqrt{\sigma^2 + 4\tau^2} \quad (\text{see also Eq. (1.3) in Sect. 1.2})$$

The direction of the principal normal stress σ is yielded by the angle $\alpha = \alpha_H$, which can be calculated with the relation (see e.g. [16])

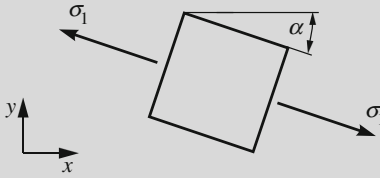
$$\tan 2\alpha_H = -\frac{2\tau}{\sigma}.$$

Thus it is obtained for

$$\begin{aligned} \sigma_1 &= \frac{198.1 \text{ N/mm}^2}{2} + \frac{1}{2} \sqrt{\left(198.1 \frac{\text{N}}{\text{mm}^2}\right)^2 + 4\left(75.5 \frac{\text{N}}{\text{mm}^2}\right)^2} \\ &= 223.6 \frac{\text{N}}{\text{mm}^2} \end{aligned}$$

and

$$\alpha = |\alpha_H| = \frac{1}{2} \arctan \frac{2 \cdot 75.5 \text{ N/mm}^2}{198.1 \text{ N/mm}^2} = \frac{37.3^\circ}{2} = 18.6^\circ$$

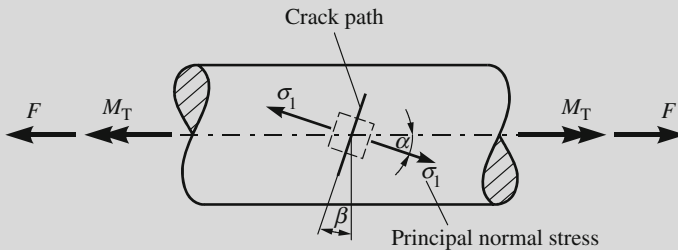


- (c) The direction, in which a fatigue crack will grow

The fatigue crack grows perpendicular to the principal normal stress σ_1 , i.e., at an angle β to the cross-sectional surface of the shaft.

As a result, $\beta = \alpha = 18.6^\circ$.

Basic crack growth is shown in the following sketch:



2.10 Crack Detection Using Non-destructive Testing Methods

Non-destructive testing methods are used to detect defects, discontinuities or cracks (as a quality assurance measure immediately after manufacture, for instance) since they permit investigation without permanent changes. With them, absence of defects can be ensured with a 100 % testing, particularly in the case of safety-related components. Moreover, non-destructive testing methods are also utilized for the inspection of components and structures during operation in order to detect cracks. Aside from basic fault detection, non-destructive testing methods are also responsible for locating and sizing [35].

Non-destructive testing methods are generally classified by:

- Basic physical principle,
- Material application,
- Detectable defect type or
- Application area [36].

Basic principles include:

- Optical methods, e.g. visual inspection (DIN EN 13018), penetrant testing (DIN EN 571) or laser extensometry,
- Acoustic methods, e.g. ring testing or ultrasound testing (DIN EN 583),
- Electric and magnetic methods, e.g. eddy current testing (DIN EN 12084) or magnetic particle testing (DIN 54130) or
- Radiography (DIN EN 444) and computed tomography.

In a visual inspection, a human being examines a component for external defects or cracks using means such as light sources, mirrors, magnifying lenses or endoscopes [37].

Surface cracks that are not visible to the eye are very often detected by means of penetrant testing. After the test piece is carefully cleaned and dried, a suitable penetrant is added to its surface. By capillary action, the liquid penetrates into the defect that has been opened to the surface. After a certain waiting period, extra penetrant is removed from the surface and a developer is applied. The developer absorbs the liquid that remains in the crack, resulting in a clearly visible view of the defect. The penetrant is partially fluorescent, so the test piece has to be observed with ultraviolet light [35, 38].

The ring test is a very simple acoustic test method in which the component is tapped with a hammer. The existence of a defect or crack can be detected by the component's altered sound, but not its position [39].

The most common non-destructive testing method is ultrasound testing. A transducer transmits ultrasound impulses with defined frequencies into the component. In addition to the component's geometry, the signal is also reflected by defects or cracks. The signal is received by the same or another transducer, converted into an electrical signal and graphically depicted on a screen [39].

Electric and magnetic testing methods are used to detect defects and cracks in surface areas [39]. Eddy current testing is based on the induction of electric current in conductive material [40]. In it, eddy currents are induced in the component to be tested by means of a coil. Defects (e.g. cracks, pores, cavities, or changes in the microstructure) affect the distribution of the eddy currents. With high-resolution coil systems and computer-based signal processing, even complex defects are capable of visual depiction [39].

The magnetic particle test can detect defects by magnetizing the test piece from the outside. According to DIN EN ISO 9934-1 [41], current flow (e.g. axial current flow or induction flow) and field flow methods (e.g. inner and outer conductors, fixed coils or manual magnets) are available for this purpose. A component defect induces a magnetic leakage flux that can be detected with a suspension of fine magnetic powder particles. The magnetic powder contained in the suspension is attracted by the leakage flux, yielding a clearly visible display. If a fluorescent test medium is used, the defect display should be carried out using UV-A radiation in a darkened test room [35, 39, 41]. Figure 2.23a shows a view of two cracks detected using the magnetic particle method. For comparison, Fig. 2.23b illustrates detection by breaking open the component in the vicinity of the cracks. Following the test, the component should be demagnetized.

Like in medicine, radiographic methods are also used for material testing. The component to be tested is transilluminated, for example, with X-rays after radiation intensity, wavelength, test object thickness and transmission time have been adjusted. The result is an X-ray image that shows thickness and density distribution. With such an image, defects of varying thickness (e.g. cavities or pores) or material inhomogeneities (e.g. foreign inclusions or alloys) can be detected [39].

With computer tomography, it is possible to examine the component for defects with a large number of cross-section images [39].

Non-destructive testing methods exhibit varying basic sensitivities that depend on the component geometry, surface condition, accessibility of the test surface and the selected test technology in addition to the physical principles of the testing method [33, 42]. Defect detection also depends on the size of the defect.

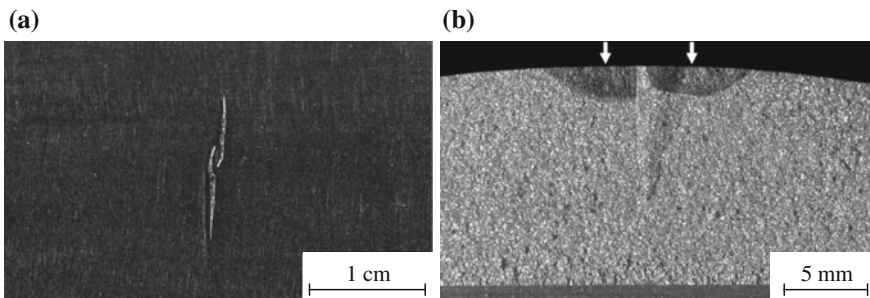


Fig. 2.23 Crack detection with the magnetic particle test [43]. **a** Magnetic particle test display. **b** Visible cracks in the broken component

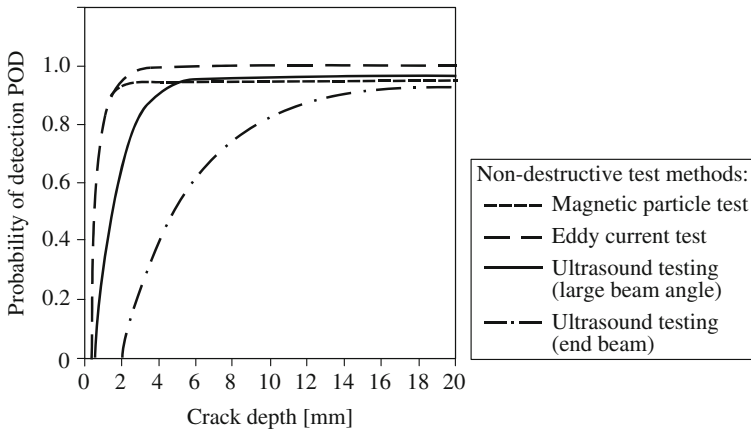


Fig. 2.24 Probability of detection (POD) as a function of crack depth and various methods of non-destructive testing [44]

Figure 2.24 shows that a crack's probability of detection POD goes up with increasing crack depth. However, the decision of which method is to be used plays an essential role, especially if the defect is small in size.

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2016, XIX, 292 p. 226 illus., Hardcover

ISBN: 978-3-319-32532-3