Chapter 2
Classification of Fracture Processes

Fracture processes are classified based on quite different individual aspects. The reason for that is the tremendous variety in which fracture processes appear and the diverse reasons leading to failure. First and foremost, a fracture depends on the properties of the considered material because the damage processes happening on a micro-structural level in the material determine its characteristic behavior. These microscopic structures and failure mechanisms vary diversely in the lineup of engineering materials. Just as important for fracture behavior is the type of external loading of the component. In this category one can differentiate between e.g. fractures due to static, dynamic or cyclic loading. Further important factors are the temperature, the multiaxiality of the loading, the rate of deformation and the chemical or environmental conditions.

2.1 Macroscopic Manifestations of Fracture

The macroscopic classification of fracture processes corresponds to the view of the designer and computation engineer. Fracture of a structure is inevitably connected to the propagation of one or more cracks which can eventually lead to entire rupture and loss of its load carrying capacity.

That is why particular emphasis is placed on the temporal and spatial progress of crack propagation. In fracture mechanics it is assumed that a macroscopic crack exists. This crack may be present from the very beginning due to a material defect or due to the component manufacturing. Often cracks originate in consequence of operational loading and material fatigue, which is the subject matter of the field of service strength of materials. After all, hypothetical cracks, which have to be assumed for purpose of safety assessment, are part of it as well. The macroscopic mechanical aspects of fracture can be categorized with respect to the load and fracture progression as follows:

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(a) Type of loading

According to their temporal progress, mechanical loads are divided into *static*, *dynamic* and (periodically-cyclic or random) *variable* loads, the respective types of fracture to which they can be assigned. Fracture processes under static load are typical for load-bearing constructions e.g. in civil engineering. Impact, drop or crash processes are associated with highly dynamically accelerated deformations and inertia forces. In mechanical engineering and vehicle construction, much attention needs to be paid to variable loads which can, in contrast to static loading, lead to cracks and crack propagation at considerably lower amplitudes. About 60 % of all technical failures happen because of material fatigue or propagation of fatigue cracks.

(b) Orientation of a crack in relation to its principal stresses

As it is known from the classical theory of strength of materials, failure is in most cases controlled by the local stress which is clearly determined by the principal stresses σ_{I}, σ_{II} and σ_{III} and their axes. Depending on the material, either hypotheses of the maximum principal stress (Rankine),the maximum shear stress (Coulomb) or extended mixed criteria (Mohr) are used. The macroscopic image of fracture is therefore often affected by the principle stress trajectories. A distinction is being made between:

- The normal-planar crack or *cleavage fracture* exists, when the fracture faces are located perpendicularly to the direction of the highest principal stress $\sigma_{\max} = \sigma_{\mathrm{I}}$.
- The shear-planar crack or *shear fracture* exists, when the fracture faces coincide with the intersection planes of the maximum shear stress $\tau_{\max} = (\sigma_{\mathrm{I}} - \sigma_{\mathrm{III}})/2$.

The situation is outlined for a simple tension rod in Fig. 2.1. However, it can be assigned to the local stress state at any point of the body. On a torsion rod (shaft) the fracture faces would run either vertically or inclined by 45° to the axis, depending on whether a shear or a cleavage fracture is assumed.

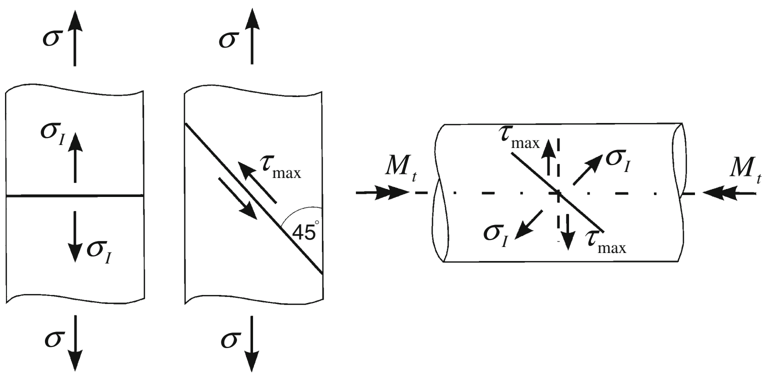

Fig. 2.1 Orientation of crack surfaces with respect to principal stress directions

(c) Stability of crack propagation

In the initial situation, a crack has a specific size and shape. As long as it does not change, the crack is regarded as a static or *stationary* crack. The moment in which the crack propagation starts due to critical loading, is called *crack initiation*. The crack size now increases and the crack is called *unsteady*.

An important feature of fracture is the stability of the crack propagation. The fracture process is then marked as *unstable* if the crack grows abruptly without the need to increase external loading. The critical condition is exceeded for the first time and persists without any additional energy supply. A typical example is the crack in the American Liberty Bell (Fig. 2.2), which developed spontaneously (allegedly on G. Washington's birthday), supposedly due to a casting defect. In contrast to this, if an additional increase of the external load is necessary in order to let the crack grow further, it is called *stable crack growth*. This means the critical condition needs to be induced by supplying additional energy again and again. Decisive for the stability of crack growth is the issue of how the stress situation changes in the body and at the crack itself due to the growth of the crack. Stable crack growth is often connected with plastic, energy consuming deformations in the component, which the failure case of a tube (Fig. 2.5) shows. Yet, this connection is by no means sufficient, which the example of a slowly growing crack in a car's windshield made of brittle glass teaches us.

If the crack propagation in the body comes to a standstill, it is called *crack arrest*.

(d) Magnitude of inelastic deformations

Depending on the amount of inelastic deformations or accumulated plastic work in the body that precede or accompany crack growth, distinctions are made between:

- **deformation-poor, or macroscopically brittle fracture** The nominal stresses are far below the plastic yield limit, the plastic or viscoplastic zones are very small and the load-deformation diagram runs linearly until crack initiation.
- **deformation-rich, or macroscopically ductile fracture** appears when the fracture process is connected with large inelastic deformations. The load-deformation diagram displays a distinctive non-linearity and the inelastic domains spread out over the entire cross-section (plastic limit load exceeded).

(e) Subcritical crack growth

In contrast to the above-mentioned types of crack propagation, there are fracture processes that happen far below the critical load and develop in a stable manner with a very low rate of growth . To describe them, the term *subcritical crack growth* was introduced. The most important form of appearance is *fatigue crack growth*, whereby the crack gradually grows under alternating loads. A characteristic failure case on a shaft loaded cyclically by rotation-bending is shown in Fig. 2.4. Subcritical constant loading in connection with viscoplastic deformations can lead to the so-called *creep fracture*. If a corrosive medium acts on the crack slit, a crack growth due to *stress corrosion cracking* is observed in spite of subcritical loading.

Fig. 2.2 Macroscopic brittle fracture of the Liberty Bell, Philadelphia 1752

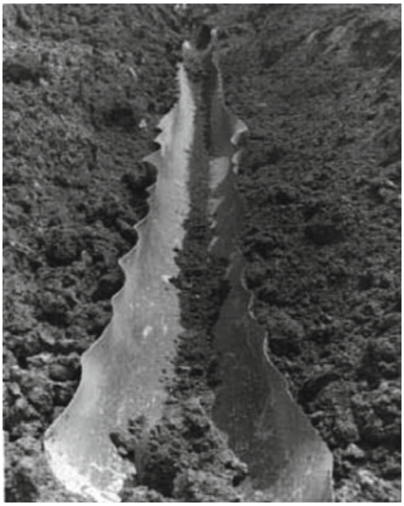

Fig. 2.3 Failure case of a gas pipeline with dynamic crack growth

Fig. 2.4 Failure case due to fatigue crack growth on a shaft

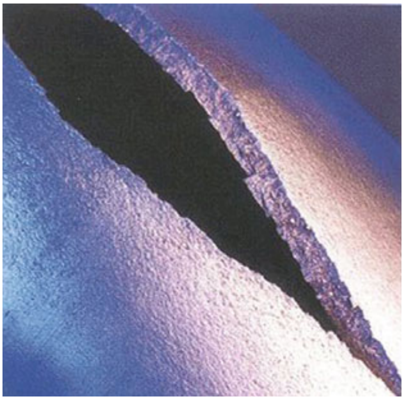

Fig. 2.5 Macroscopic ductile fracture of a tube made of steel

(f) Crack growth rate

In contrast to the dynamic, impulsive load of a stationary crack, the dynamics of the fracture process itself will be considered. In most cases the crack propagation happens so slowly, that all dynamic effects in the structure may be neglected. In that case a *quasi-static analysis* is sufficient. If the crack growth rate reaches the level of acoustic wave speeds in the solid, velocity terms, inertia forces as well as interactions between the crack and the sound waves need to be taken into account. Additionally to that, failure mechanisms in the material depend on the deformation rate, which mostly leads to an embrittlement on fast running cracks. In this way, dynamic crack growth processes have already caused catastrophic failures, as the example of a gas pipeline in Fig. 2.3 shows.

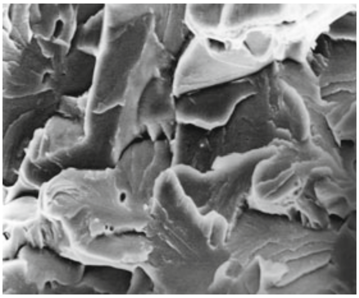

Fig. 2.6 Transcrystalline brittle fracture of steel at room temperature

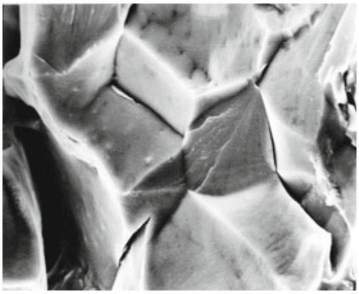

Fig. 2.7 Intercrystalline cleavage fracture of steel St52 at −196 °C

2.2 Microscopic Appearances of Fracture

For a better understanding of the material-specific failure mechanisms during fracture, it is necessary and especially useful to visit the »scene of the crime«—the fracture surface. To do that, the best choice is to use a scanning electron microscope, because of its depth of sharpness, chemical element analysis and material contrast. It is also possible to infer the reasons of damage from the characteristic patterns of the fracture surface (fractography). The different failure mechanisms lead to characteristic patterns of the fracture faces. These typical »faces« of all the various fracture types are catalogued in fractographic atlases, see e.g. [1]. Hereby, the view point of material scientists and failure case studies is put into focus. The most important microscopic appearances of a crack are:

- The *cleavage fracture* is characterized by plane fracture faces and minor deformations. The reason for this is brittle cracking along preferred crystallographic orientations due to high normal stresses. Body-centered cubic metals at low temperatures (Fig. 2.7) and ceramic materials (Fig. 2.8) tend towards cleavage fracture.
- In polycrystalline ceramic and metallic materials, characteristic differences of the fracture surfaces can be observed. Depending on whether cracking occurs along the boundaries between the individual grains or separates the grains by cleavage, it is called *intercrystalline* or *transcrystalline*, respectively. The difference can be seen very clearly by comparing Figs. 2.6 and 2.7.
- During a *dimple fracture*, the failure mechanism is associated with large plastic deformations in the process zone. Due to this, microscopic voids form, grow and eventually coalesce, which leads to a distinctive dimple structure of the fracture surface. Figure 2.9 shows the typical fracture pattern of high-alloyed steel.

- The *fatigue fracture* is quite smooth and mixed with fatigue striations due to very minor plastic deformations as the overall picture in Fig. 2.4 shows. It usually proceeds in a transcrystalline manner. Distinctive traces of cyclic plastic straining can be identified in the detailed microscopic view of Fig. 2.10.
- *Creep fracture* occurs often in metals due to damage of the grain boundaries, where creep pores are forming due to diffusion processes. This eventually leads to intercrystalline failure. Figure 2.11 shows a fracture surface of an aluminium alloy at high temperatures.

The diversity of failure mechanisms is further illustrated by the fractographic views of a crack resulting from stress corrosion cracking (Fig. 2.12) and a modern fiber-reinforced glass composite (Fig. 2.13).

Understanding of micro-structural failure mechanisms during fracture is not only important for material scientists and failure analysts. It also provides continuum mechanics engineers with useful information about which stress or deformation states control these mechanisms in order to describe them properly by means of macroscopic parameters and criteria.

2.3 Classification of Fracture Processes

In summary a classification of the fracture processes shall be given in the way it is used today. The overview in Fig. 2.14 is geared to the deformation properties of the materials, which are explained in detail in Appendix A. The following chapters on fracture mechanics are structured according to this classification.

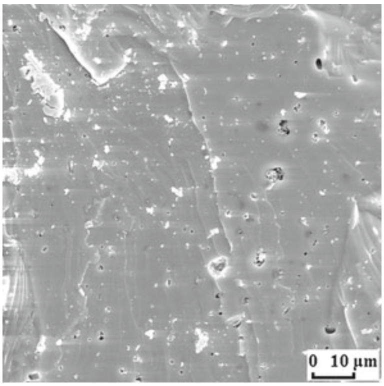

Fig. 2.8 Fracture surface of a brittle sinter ceramic (transcrystalline)

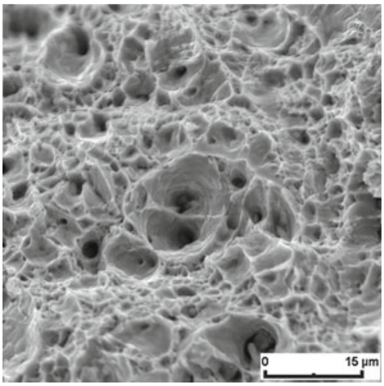

Fig. 2.9 Ductile dimple fracture of the high-alloyed steel 27MnSiVS6

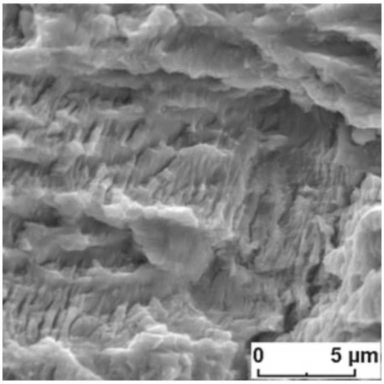

Fig. 2.10 Fractographic view of a fatigue fracture of steel C15

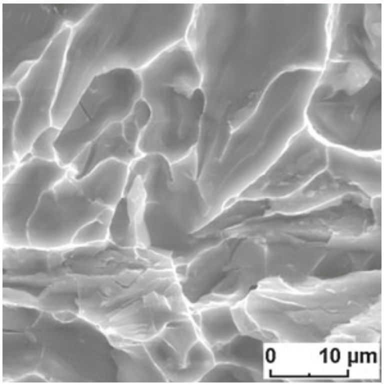

Fig. 2.11 Fracture surface of a creep fracture in aluminum AlSi10Mg at 300 °C

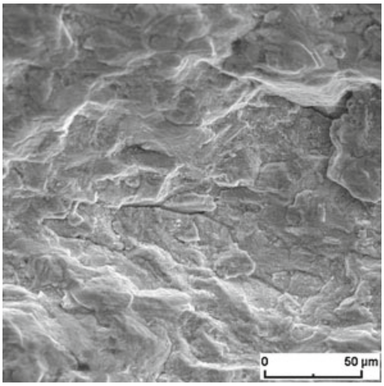

Fig. 2.12 Fracture surface of a stress corrosion crack in a CuZn37 alloy

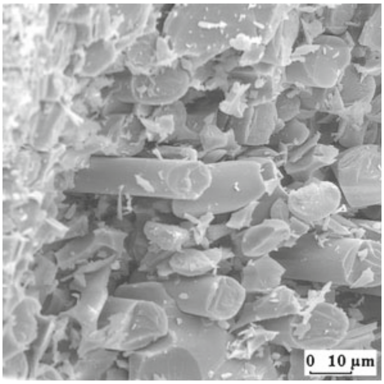

Fig. 2.13 Fracture surface of the fiber composite Fortadur (SiC fibers in Duran glass)

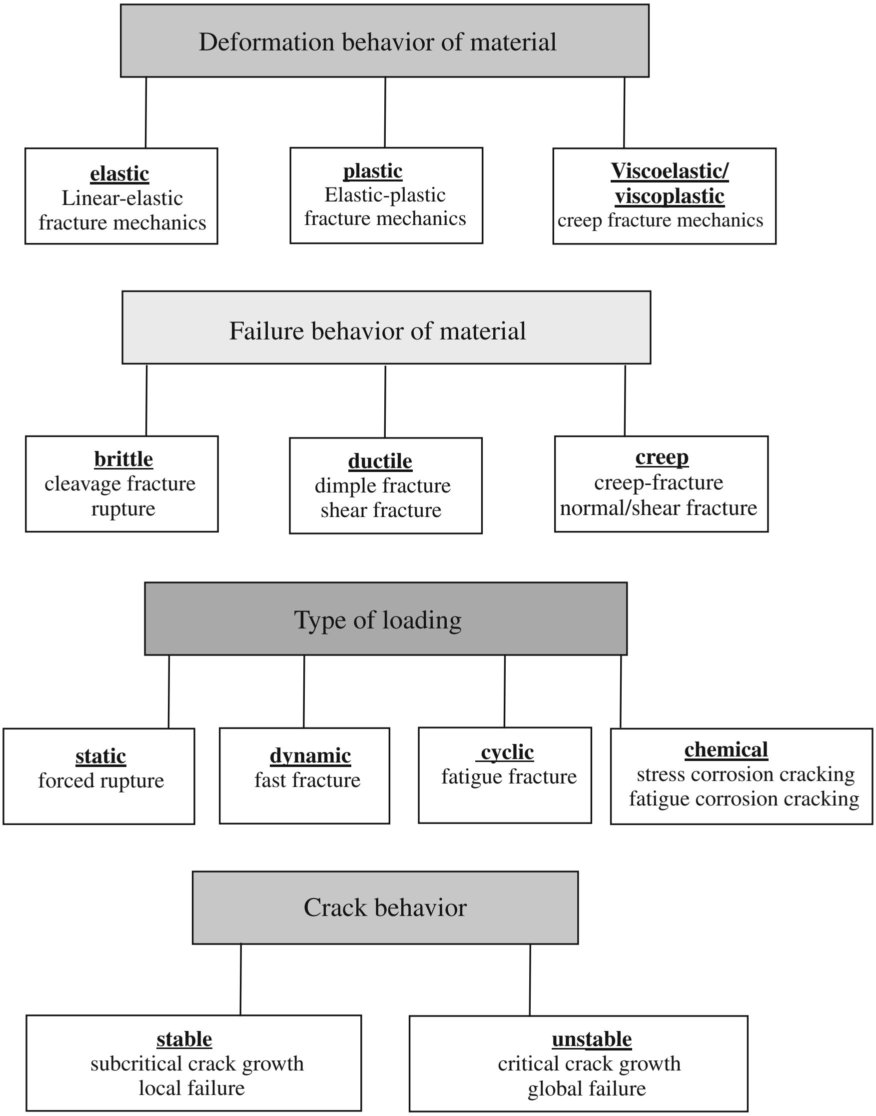

Fig. 2.14 Classification of fracture processes

Reference

1. Engel L, Klingele H (1982) Rasterelektronenmikroskopische Untersuchungen von Metallschäden. Gerling-Institut für Schadensforschung und Schadensverhütung, Köln

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