TFYA21 Physical Metallurgy

Laboration Compendium

Fractography

A broken bicycle pedal crank

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Updates: Torun Berlind 1997
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Yes, things break – unfortunately. Sometimes the broken part can simply be thrown away and we buy a new instead, sometimes the failure consequences are much more severe, - as in the two examples below.

1. The de Havilland Comet was the first commercial air jet liner that reached production (first flight with fare-paying passengers in 1952). The beginning was, however, very unsuccessful: five crash accidents during the first two years. Investigations revealed that three of the crashes were caused by metal fatigue near one of the escape hatches. These early jet liner models were designed with square windows; analysis showed that stress concentration around window corners was much higher than expected. Increased stress supported fatigue crack growth around the rivet. For the upcoming jet liner models the shape of the windows was redesigned and the way of rivering improved.

2. Germany fastest train was travelling at 200 km/h from Munich to Hamburg when it derailed and crashed into a bridge. The accident occurred in 1998 and became the worst rail accident in Germany for 50 years. The reason for the disaster was a broken wheel, due to metal fatigue.

Obviously, a serious investigation must always be carried out to determine what caused the accident – human mistake? weather conditions? terrorism? *mechanical failure?*

The examples are here not to scare, but rather to convince that *fractography* – the study of fractured surfaces – takes an important part in investigation of materials and structures which failed or did not function as intended. Fractography provides information about crack initiation sites, crack sizes, their propagation characteristics, speed and direction, etc., i.e., *where* and *why* material started to break. Good understanding of failure mechanisms is crucial in order to design materials and constructions in such a way, that they do *not* break easily, i.e., fractography is also a method to *prevent* an accident. Inspection of fracture surfaces is part of mechanical tests, when materials and constructions are broken on purpose – subjected to static and cyclic loads of various strengths and directions. Influence of ageing, corrosive environment, surface wear, etc., on materials ability to sustain loads is also often investigated.

3. An example could be testing of climbing/mountaineering equipment, such as carabiners, ice-axes, various protection devices which are placed as anchor points on a rock to stop a fall, etc. A climber entrust his life to the equipment, and, clearly, each tiny piece of it must be extremely reliable.

4. *What examples of fractography applications could you give?*

Contents

1 Introduction

Metallic materials, especially structural engineering alloys, are highly complex: almost always polycrystalline and contain defects. Most common microstructural features are illustrated in Figure 1.

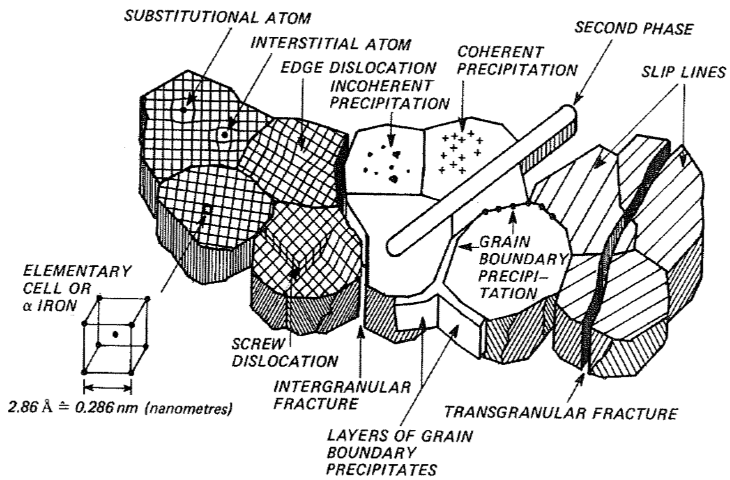

Figure 1 *Schematic of microstructural features in metallic materials [1].*

Materials microstructure together with crystal structure and the nature of bonding have a determining effect on the way material responds to loading and eventually fails (i.e., fractures). Fracture is defined as a breakage of materials continuity.

Fractography is a discipline within materials science that deals with studies of fracture surfaces and the determination of fracture propagation mechanisms. A careful examination of a fracture surface can give information about crack initiation site, triggering mechanisms, crack propagation direction and velocity, type and magnitude of experienced stress, etc. Knowledge of these factors enables reconstruction of the flow of events that ultimately ended up in a failure.

Inspection of a fracture surface with a naked eye is called macrofractography. The term "*micro*fractography" is used when examination is performed using optical or electron microscope.

2 Scanning Electron Microscope

Scanning electron microscopes (SEMs) are primarily used for studies of surface topography. The major advantages of SEM, compared to an optical microscope, are broad magnification range (x10-100 000) and large depth of field (depth of field – distance along optical axis throughout which an image is sufficiently sharp). A large depth of field is particularly useful when studying fracture surfaces, which typically are quite uneven.

SEM consists of an electron gun, a column with a number of magnetic lenses, a specimen chamber, several detectors, and an image presentation system (Figure 2).

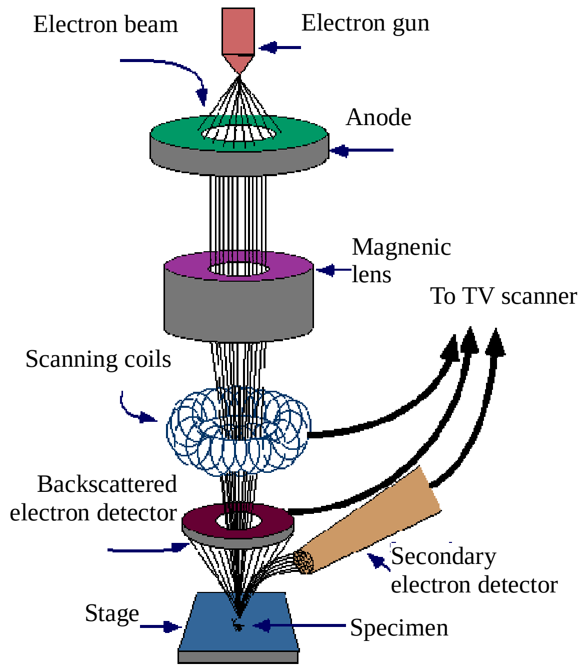

Figure 2 *Schematic illustration of a scanning electron microscope (SEM).*

In an electron gun, electrons are thermally emitted from a heated filament. The filament may be, e.g., a tungsten cathode or a lanthanum hexa-boride cathode (LaB_6). The emitted electrons are focused by magnetic lenses and swept over the sample surface using scanning coils.

A number of different processes are initiated when electron beam hits the sample surface: secondary and Auger electrons are ejected, primary electrons backscattered, X-rays emitted, etc. (Figure 3).

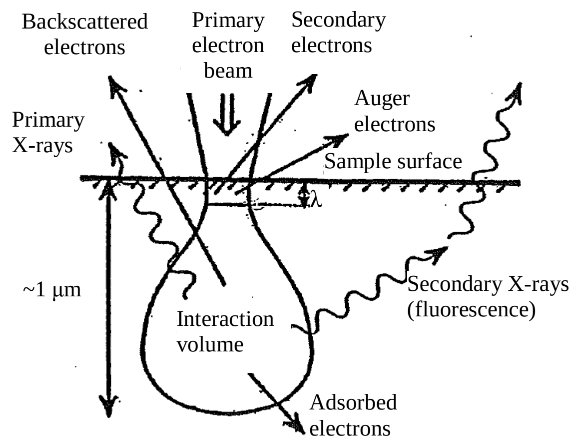

Figure 3 *Electron beam – sample interaction (λ – electron mean free path).*

Topographical information is gained as a result of different electron yields from different surface features (Figure 4). Secondary electrons are most often used for imaging. Information about composition can be obtained by analyzing the emitted X-rays (EDX – Energy Dispersive X-ray Spectroscopy) or Auger electrons (AES – Auger Electron Spectroscopy).

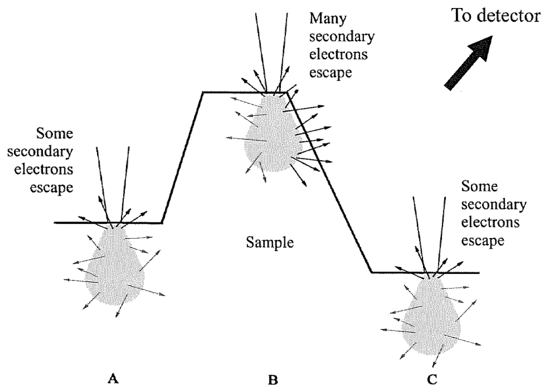

Figure 4 *Contrast principle: highest electron yield is gained from protrusions (B), i.e., protrusions appear as bright areas in SEM images.*

3 Fracture Mechanisms and Fracture Surfaces

Fractures can be classified on the basis of the following criteria:

Deformation experienced prior to fracture:
- Ductile – material is able to accommodate a substantial amount of deformation
- Brittle – material fails without being deformed

Fracture path:
- Transcrystalline – crack propagates through grains
- Intercrystalline – crack propagates along grain boundaries

Fracture energy:
- Low energy fracture
- High energy fracture

In this laboration four different failure modes are analyzed: ductile, transcrystalline (cleavage), intercrystalline, and fatigue. Each of them is briefly described in the following sub-sections.

3.1 Ductile Fracture

Manufactured crystalline materials normally contain unwanted particles, both in grain boundaries and in grain interiors. If the material is subjected to load, the interface between particles and matrix ruptures, and cavities, or voids, are formed (Figure 5).

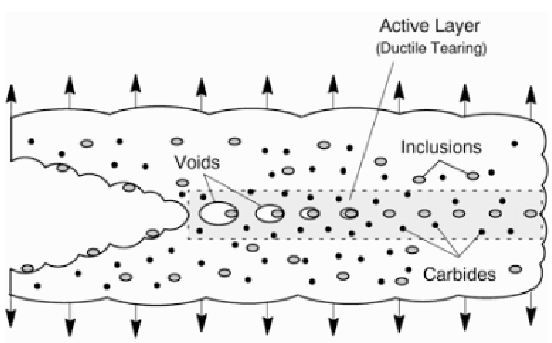

Figure 5 *Void nucleation and growth in a ductile material under tensile stress [2].*

Characteristic feature of a ductile fracture is the "cup-like" pattern on both fracture surfaces (Figure 6). The resultant indents are termed dimples. The form of the dimples indicates the type of the breaking force (Figure 7).

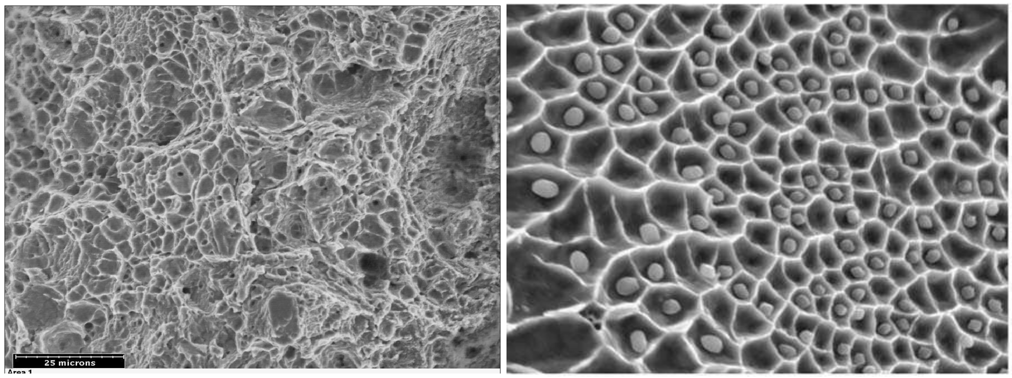

Figure 6 *SEM images of a ductile fracture surfaces. Note foreign particles inside the dimples in the right image.*

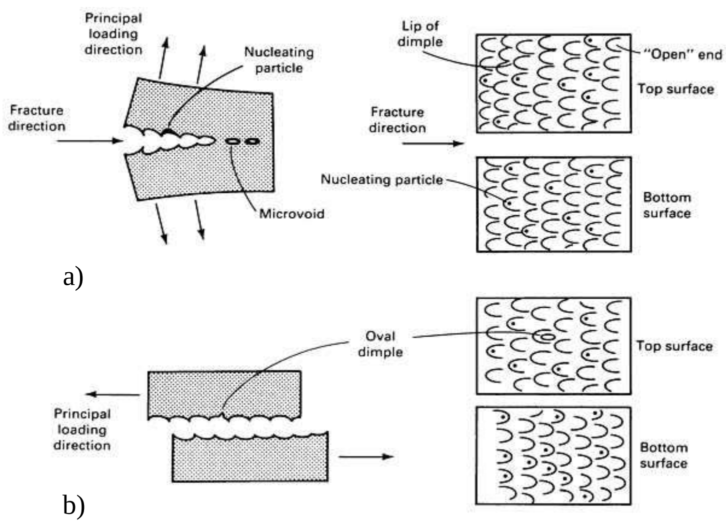

Figure 7 *Examples of ductile fractures with varying dimple shapes. a) Tearing produces elongated dimples on both fracture surfaces that point back to the crack origin; b) shear stresses generate dimples elongated in the shearing direction [3].*

Ductile materials undergo macroscopic deformation prior to failure (Figure 8).

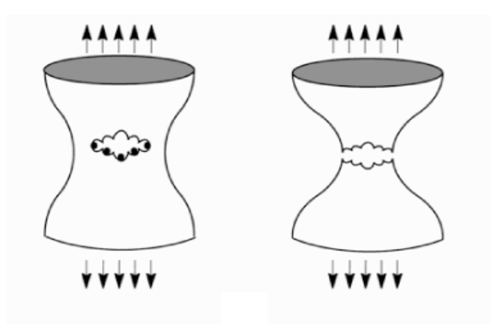

Figure 8 *Ductile failure of a metal rod under tensile stress.*

3.2 Transcrystalline Fracture (Cleavage)

Cleavage is a low energy fracture which propagates along well-defined low-index planes called “cleavage planes” (i.e., a crack propagates *inside grains*). In a perfect crystal cleavage would result in two totally smooth, featureless and perfectly matching surfaces. However, most engineering materials are polycrystalline and contain various defects such as grain boundaries, inclusions, dislocations, etc., which seldom make fracture surfaces appear without contours.

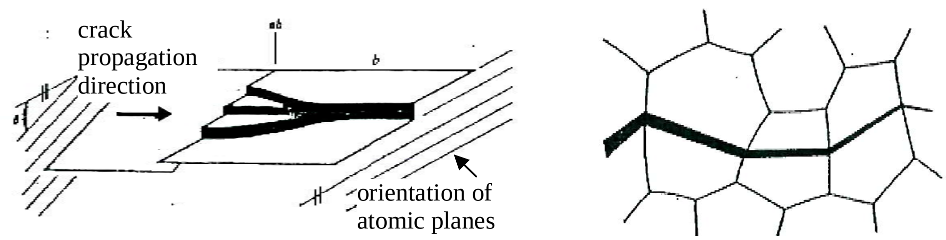

Figure 9 *a) Height of the cleavage step increases along crack propagation direction; b) a crack propagates through a polycrystalline material (transcrystalline fracture), from left to right. The crack changes direction locally as it passes each grain boundary [3].*

Cleavage fractures are often initiated on several parallel cleavage planes. When a crack propagates through a material, the number of cleavage planes decreases, which in turn increases the height of the cleavage steps (Figure 9a). The network of cleavage steps is termed "river pattern" and is characteristic for a cleavage fracture (Figure 10). The branches in a river pattern converge in the same direction as the crack propagates, which makes it possible to determine the crack propagation direction (Figure 9a and Figure 11).

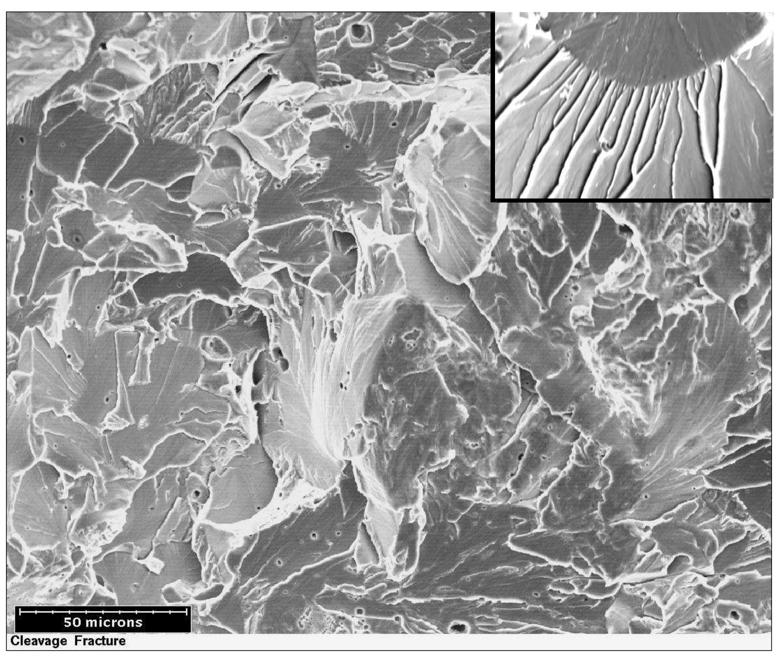

Figure 10 *SEM image of a cleavage fracture. The inset shows a twist boundary at higher magnification.*

In order to remain on low-index planes (which means least energy needed to advance a crack, and therefore preferred), a crack changes direction as it crosses tilt boundaries (Figure 9b and Figure 11a). Mismatch at twist boundaries is, however, quite large, therefore river patterns often *originate* at twist boundaries instead of crossing them (Figure 9a, inset in Figure 10, Figure 11b).

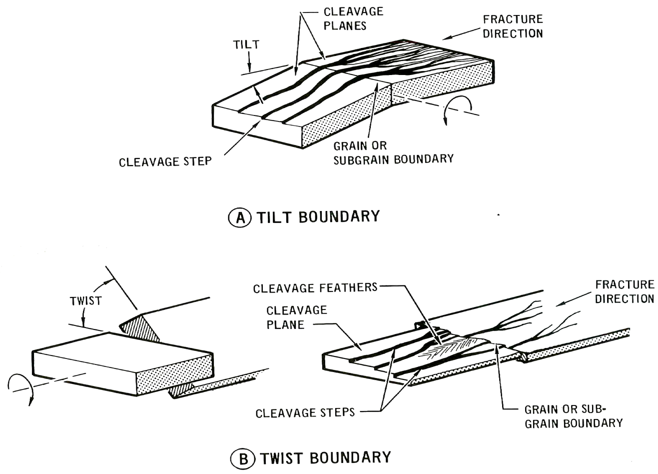

Figure 11 *Cleavage fracture: a) crack propagation direction changes at tilt boundary; b) branches of river pattern originate at twist boundary [3].*

3.3 Intercrystalline Fracture

Crack propagation *along grain boundaries* becomes preferred if grain boundaries are weakened by, e.g., diffusion of impurity atoms from grain interiors, formation of secondory phase, concentration of vacancies, etc. Since the fracture propagates along the grain boundaries, the grain borders are observed in SEM images. Intercrystalline fracture may occur with or without microvoid coalescence (Figure 12).

a)

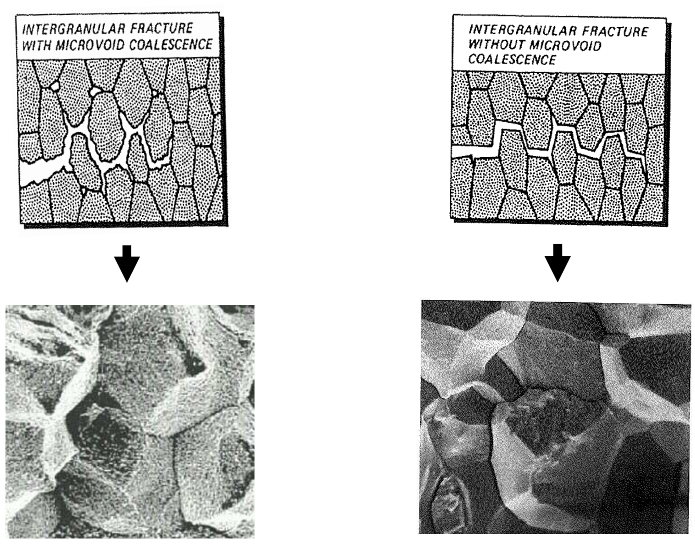

Figure 12 *SEM image of intercrystalline fracture a) with microvoid coalescence b) without microvoid coalescence [1].*

Special external conditions, e.g., aggressive environment or high temperature, promote intercrystalline fracture as grain boundaries are relatively easily affected by the surrounding atmosphere and high temperature enhances diffusion rate.

3.4 Fatigue Fracture

Fatigue fracture is a failure mode observed as a consequence of a repetitive load. Much lower magnitude of this repetitive load causes materials failure than would be required for static loading conditions.

In SEM images characteristic fatigue striations are often observed (Figure 13). Each striation forms during one load cycle and defines the position of the crack front at that time (Figure 14). Increase in magnitude of the alternating stress increases the striation spacing, while it is not much affected by the cycling frequency.

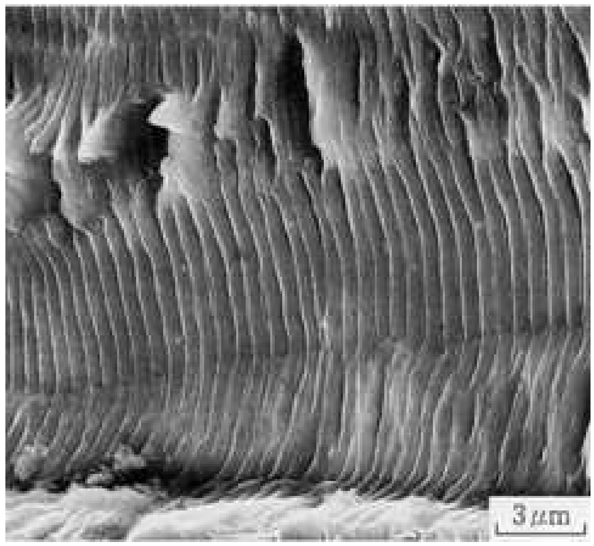

Figure 13 *SEM image of fatigue striations. (Can you guess the crack propagation direction?).*

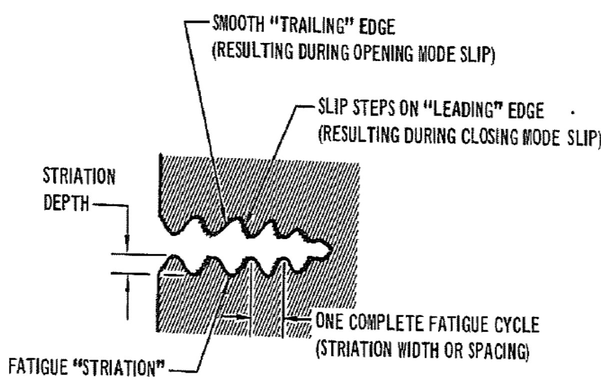

Figure 14 *Schematic presentation of formation of fatigue striations.*

Sudden rupture occurs when part of the material, not affected by fatigue, becomes too weak to sustain the load. The area of final fracture gives indication of the load magnitude.

What type of discussed failure mechanisms was a reason for the failure of a bicycle pedal shown on the cover?

4 References

1. M. Janssen, J. Zuidema and R. Wanhill, *Fracture Mechanics*, Spon Press, 2004.

2. C. Ruggieri, *Numerical investigation of constraint effects on ductile fracture in tensile specimens*, J. Braz. Soc. Mech. Sci. & Eng. vol.26 no.2, 2004**.**

3. *SEM/TEM Fractography Handbook*, Metals and Ceramics Information Center, 1975.