1 FUNDAMENTALS OF FRACTURE MECHANICS.

As it is known an aircraft service life in many cases limited by the fatigue cracks. Maintenance and design errors, as well as unpredictable operational factors can lead to the accidents caused by fatigue cracks (figs.1 – 3.).

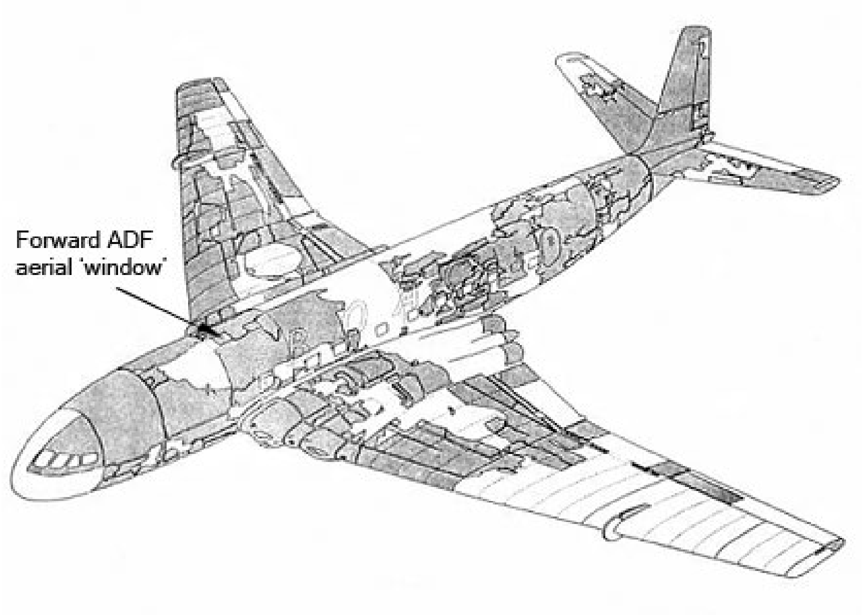


Fig.1. The recovered (shaded) parts of the wreckage of *G-ALYP* (Comet) and the site (arrowed) of the failure (1954).

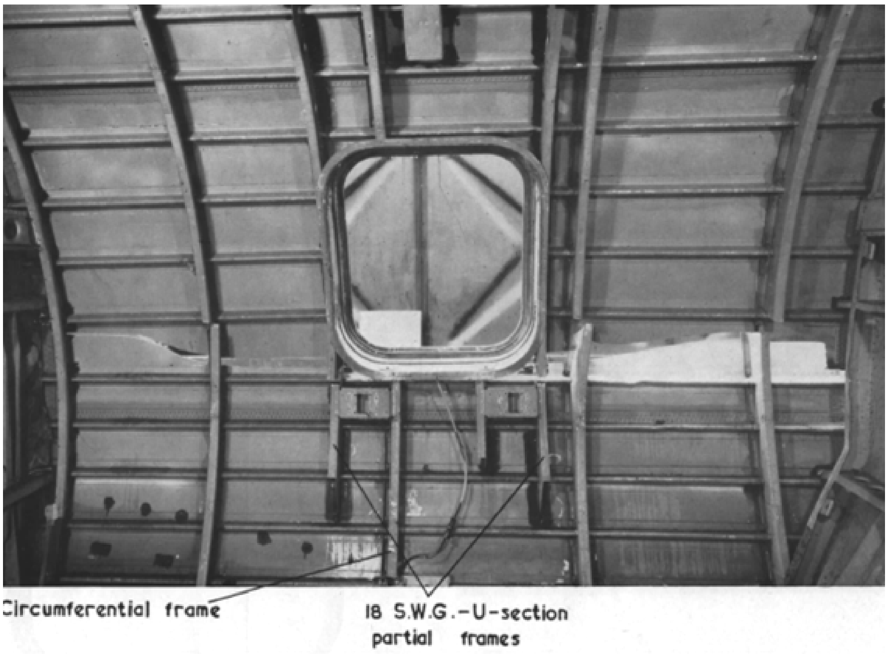
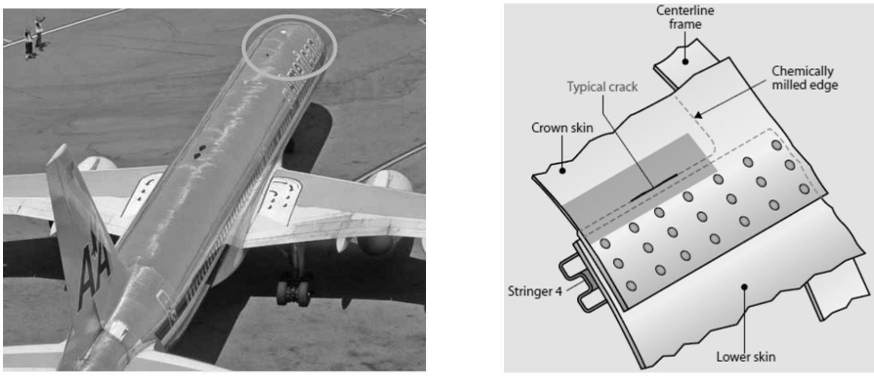


Fig.2. Fatigue crack in the Comet fuselage after 11246 cycles at the testing.



a) b)

Fig.3. Indicated area of the Boeing 757 fuselage did not meet specification thickness: a) indicated area of the crack; b) cracks above the left passenger door (2010).

Fracture Mechanics solve next main problems: a) prediction of the remaining life as a function of crack size; b) determination of the crack size that can be tolerated (critical crack size); determination of the time for a crack to grow from an initial size to the critical size (inspection interval).

Fracture Mechanics considers **three modes of cracking** (fig.4): a) Mode I - opening mode; b) Mode II - in-plane shearing/sliding mode; c) Mode III - out-of-plane shearing/tearing mode. Deal with Mode I most frequently.

It is believed that more than 95 percent of all mechanical failures can be attributed to fatigue. There are normally three distinct stages in the fatigue failure of a component, namely: **Crack Initiation, Incremental Crack Growth, and Final Fracture.**

Fatigue crack initiation usually occurs at free surfaces because of the higher stresses and the higher probability of the existence of defects at these locations (existence of corroded or eroded areas, scratches, etc.). Nevertheless, even at highly-polished defect-free surfaces, fatigue cracks can initiate through repeated microplastic deformations which result in the formation of “intrusions” and “extrusions” on the surface. The former can act as local stress concentration sites which may eventually lead to the formation of micro cracks.

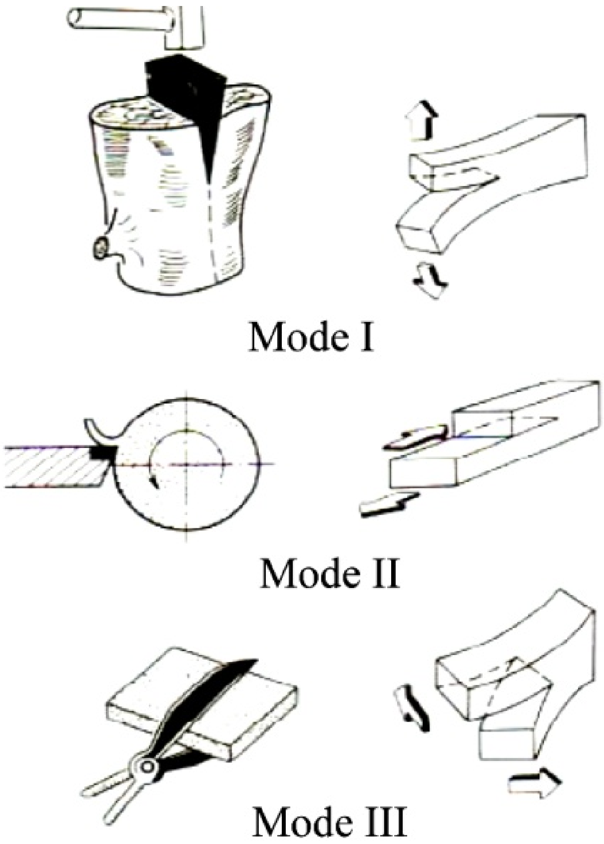


Fig. 4. Three Modes of Cracking.

Fatigue crack propagation occurs through repeated crack tip blunting and sharpening effects which are in turn caused by microplastic deformation mechanisms operating at the crack tip (fig.5).

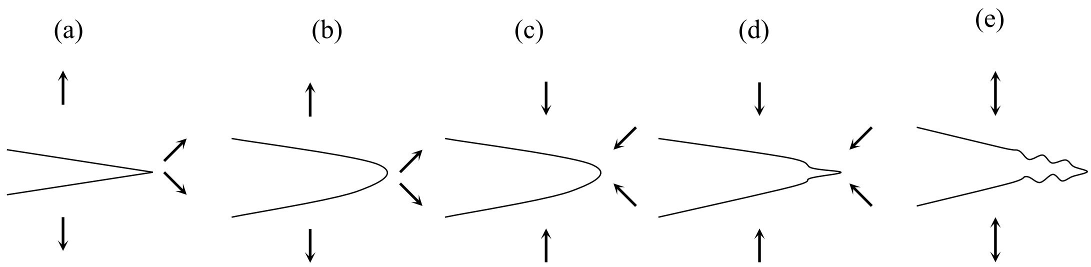


Fig.5. Schematics of fatigue crack propagation

The rate of crack propagation, measured in terms of incremental crack growth per cycle of loading, depends primarily on the range of crack tip stress intensity, as follows:

$$\frac{da}{dN} = f(\Delta K)$$

The most widely used expression, proposed by Paris, is:

$$\frac{da}{dN} = C(\Delta K)^m$$

where ***K*** - stress intensity factor.

Stress intensity factor. The stress intensity factor, K is used in fracture mechanics to predict the stress state ("stress intensity") near the tip of a crack caused by a remote load or residual stresses. It is a theoretical construct usually applied to a homogeneous, linear elastic material and is useful for providing a failure criterion for brittle materials. The concept can also be applied to materials that exhibit small-scale yielding at a crack tip.

The magnitude of K depends on sample geometry, the size and location of the crack, and the magnitude and the modal distribution of loads on the material.

Three linearly independent cracking modes are used in fracture mechanics. These load types are categorized as Mode I, II, or III.

The stress intensity factor for a through crack of length $2a$, at right angles, in an infinite plane, to a uniform stress field σ is

$$K_1 = \sigma\sqrt{\pi a}$$

If the crack is located centrally in a finite plate of width $2b$ and height $2h$, an approximate relation for the stress intensity factor is

$$K_1 = \sigma\sqrt{\pi a}\left[\frac{1 - \frac{a}{2b} + 0.326\left(\frac{a}{b}\right)^2}{\sqrt{1 - \frac{a}{b}}}\right].$$

The typical **crack-growth-rate versus stress-intensity-range diagram** is shown on fig.6**.** Three regions of different behavior can normally be identified on such data presentations:

1. The **threshold** region is attributed to very low levels of ΔKs, where the crack does not propagate. The ‘threshold’ region is strongly influenced by the mean stress.

2. The **stable propagation** region where the crack grows incrementally according to the Paris law.

3. The final **unstable** region, where the crack propagates more rapidly, often in a less uniformly incremental manner. In the unstable region, various mechanisms are responsible for the increased growth rate.

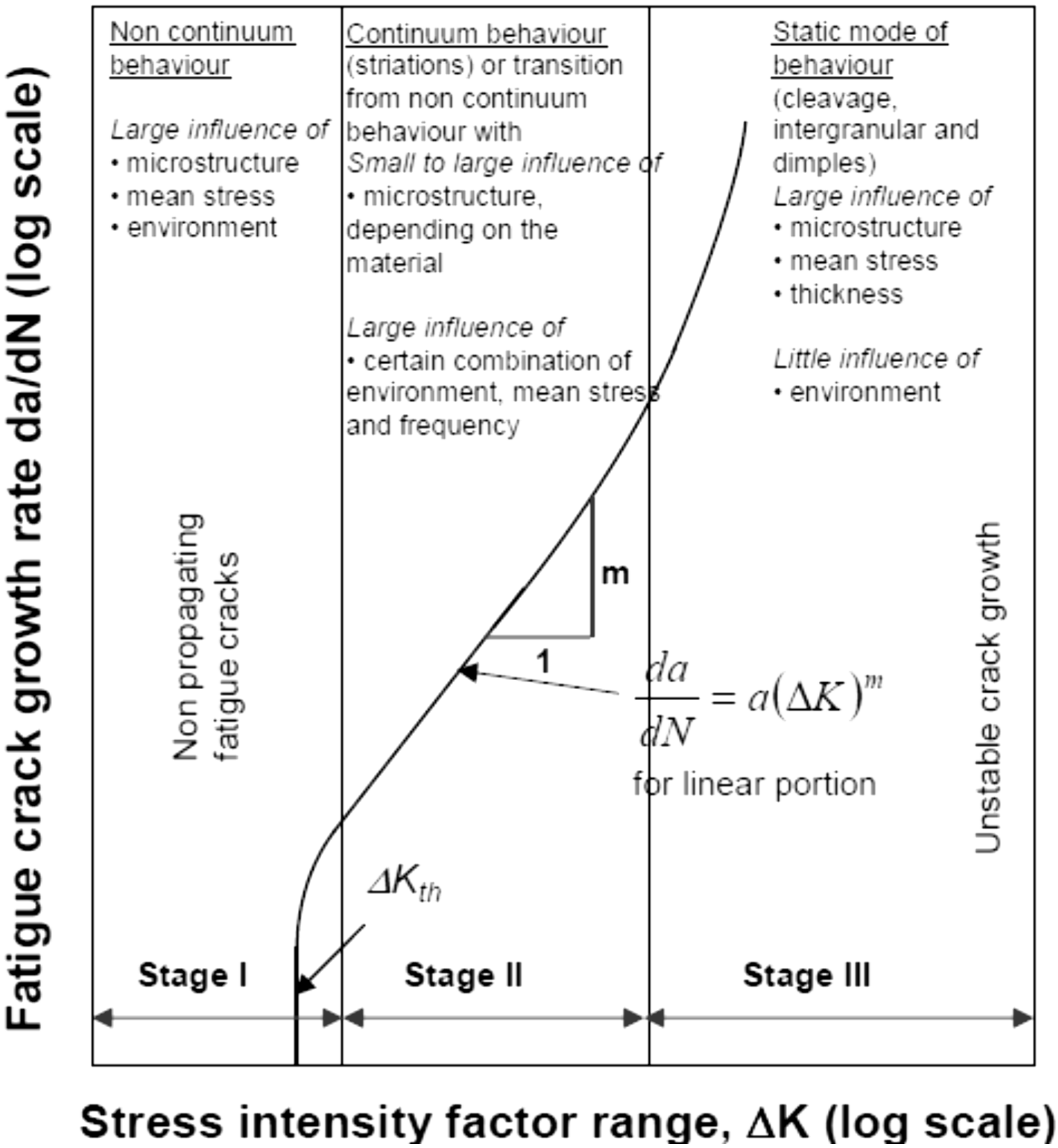


Fig.6. Crack-growth-rate versus stress-intensity-range diagram.

The useful aspect of fatigue crack growth laws is that they can be used to calculate the number of cycles required to propagate a crack from a given initial size to some final size which is critical for failure. Thus if the initial size is *ai* and the final size *af* we may write:

$$\frac{da}{dN} = C(\Delta K)^m \Rightarrow dN \frac{1}{C(\Delta K)^m} da$$

$$\int_0^N dN = \frac{1}{C} \int_{a_i}^{af} \frac{1}{\left[\beta\Delta\sigma(\pi a^{1/2}\right]^m} da$$

$$N = \frac{1}{C\beta^m(\Delta\sigma)^m \pi^{m/2}} \frac{\left[a_f^{(1-m/2)} - a_i^{1-m/2}\right]}{1 - m/2}$$

In the above equations, the geometric factor *β* is assumed to be constant because the inclusion of a function of *a*/*W* within the integral sign will usually lead to a formulation which cannot be integrated analytically. In practice, it is more straightforward and very often sufficiently accurate to solve the fatigue life equation by splitting the crack growth history into a series of crack increments.

An average value within each step may then be used to calculate *β* and hence an average *K* is considered during the step. The average propagation rate within the step can then be calculated from the Paris Law. In the case of a pressure vessel, a_f may simply be defined in terms of a crack big enough to cause leakage, or one which results in the limiting fracture toughness being reached.

Characteristics of fatigue fracture surfaces. Typical fracture surfaces in mechanical components that were subjected to fatigue loads are shown in fig.8.

One characteristic feature of the surface morphology which is evident in both macrographs is the flat, smooth region of the surface exhibiting **beach marks** (also called **clamshell marks**). This part represents the portion of the fracture surface over which the crack grew in a stable, slow mode. The rougher regions, showing evidence of large plastic deformation, is the final fracture area through which the crack progressed in an unstable mode. The beach marks may form concentric rings that point toward the areas of initiation. The origin of the fatigue crack may be more or less distinct. In some cases a defect may be identified as the origin of the crack, in other cases there is no apparent reason why the crack should start at a particular point in a fracture surface. If the critical section is at a high stress concentration fatigue initiation may occur at many points, in contrast to the case of unnotched parts where the crack usually grows from one point only. While the presence of any defects at the origin may indicate the cause of the fatigue failure, the crack propagation area may yield some information regarding the magnitude of the fatigue loads and also about the variation in the loading pattern. Firstly, the relative magnitude of the areas of slow-growth and final fracture regions give an indication of the maximum stresses and the fracture toughness of the material. Thus, a large final fracture area for a given material indicates a high maximum load, whereas a small area indicates that the load was lower at fracture. Similarly, for a fixed maximum stress, the relative area corresponding to slow crack growth increases with the fracture toughness of the material (or with the tensile strength if the final fracture is a fully ductile overload fracture).

Beach marks are formed when the crack grows intermittently and at different rates during random variations in the loading pattern under the influence of a changing corrosive environment. Beach marks are therefore not observed in the surfaces of fatigue specimens tested under constant amplitude loading conditions without any start-stop periods. The average crack growth is of the order of a few millimetres per million cycles in high cycle fatigue, and it is clear that the distance between bands in the beach marks are not a measure of the rate of crack advance per load cycle.

However, examination by electron microscope at magnifications between 1,000x and 30,000x may reveal characteristic surface ripples called **fatigue striations** (fig.9, 10).

Although somewhat similar in appearance, these lines are not the beach marks described above as one beach mark may contain thousands of striations. During constant amplitude fatigue loading at relatively high growth rates in ductile material such as stainless steels and aluminium alloys the striation spacing represents the crack advancement per load cycle. However, in low stress, high cycle fatigue where the striation spacing is less than one atomic spacing (- 2.5 x 10^{-8}m) per cycle. Under these conditions the crack does not advance simultaneously along the crack front, growth occurring instead only along some portions during a few cycles, then arrests while growth occurs along other segments. Striations are not seen if the crack grows by other mechanisms such as microvoid coalescence or, in brittle materials, microclevage. In structural steels the crack can propagate by all three mechanism, and striations may be difficult to observe.

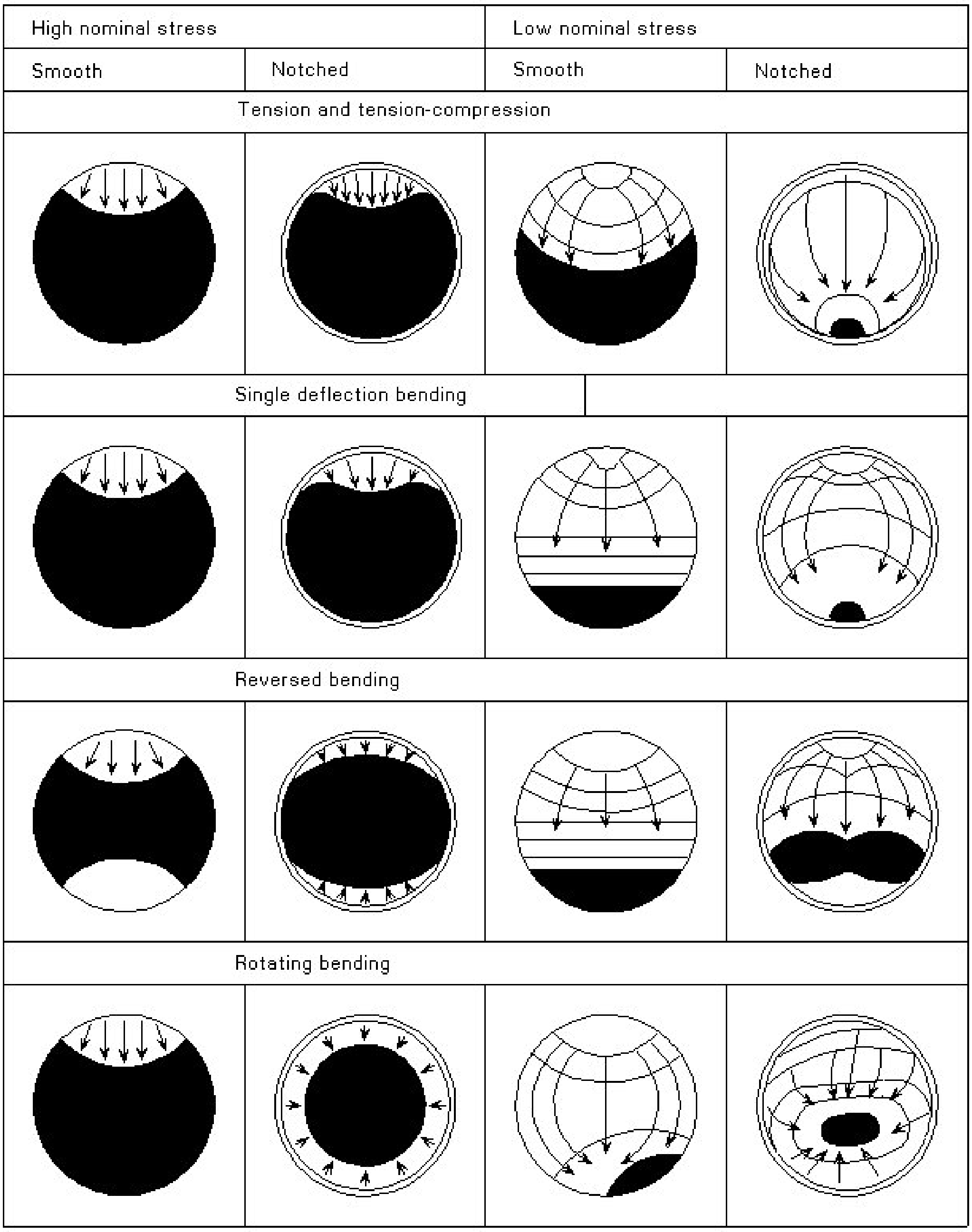


Fig.8. Fracture surfaces at high stress and low stress (schematic).

Fig.9. Striations in the stable fatigue crack growth propagation in aluminium alloy

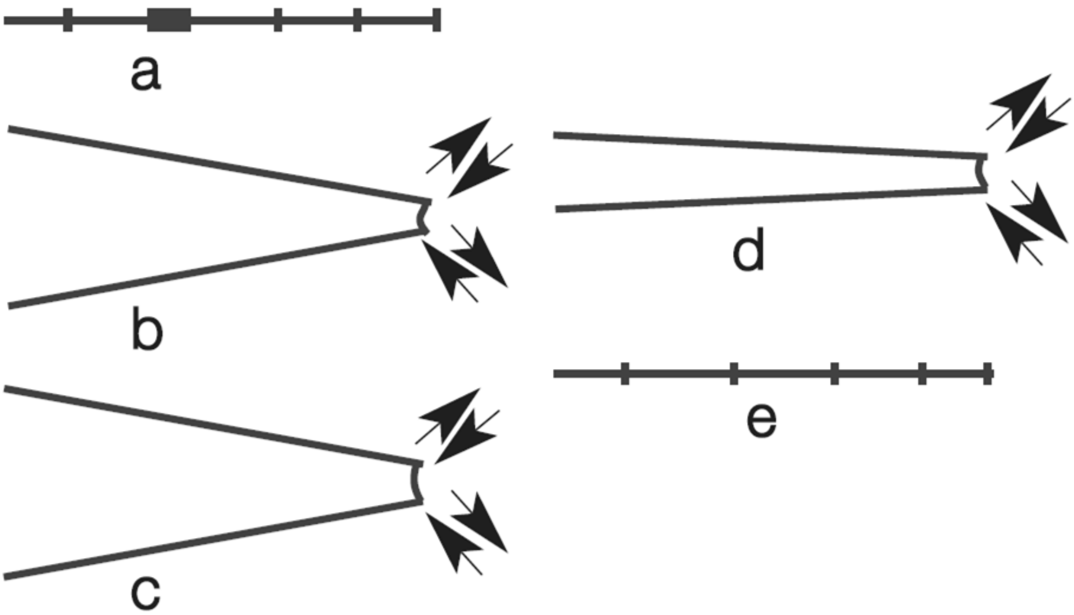


Fig.10. Fatigue striations formation due to plastic blunting process