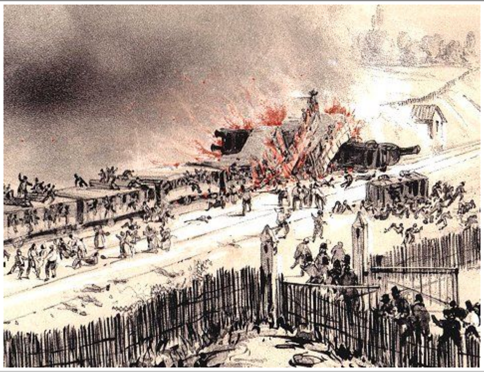
Fatigue

Advanced

Fatigue leads to Disasters

Major disasters involving catastrophical failure of steel (or other metals) are customarily explained by invoking **metal fatigue**. Here are a few examples:

- In May 1842, a train to Paris crashed in Meudon because the leading locomotive broke an axle. The picture tells it all; at least 55 passengers were killed.
  A first explanation of what might have happened came from **William John Macquorn Rankine** (* 1820 in Edinburgh; † 1872 in Glasgow), one of the many famous Scottish physicists. He had investigated broken axles, highlighting the importance of stress concentration, and the mechanism of crack growth with repeated loading or "vibrations". This means that he was the first to suggest that the basic mechanisms of fatigue is tied to vibrations.
  His papers, suggesting a crack growth mechanism through repeated stressing, were ignored (as a matter of course), and fatigue failures occurred at an ever increasing rate on the expanding railway system. The Meudon disaster was just one of many.
  Other spurious theories seemed to be more acceptable, such as the idea that the metal had somehow "crystallized". The notion was based on the crystalline appearance of the fast fracture region of the crack surface. It ignored the by then unknown fact that *any* metal is a crystal.



Meudon crash 1824; "discovery" of fatigue?

Source: Wikipedia

- Two de Havilland Comet passenger jets (the first commercial jet planes!) broke up in mid-air and crashed within a few months of each other in 1954. The crashes were a result of metal fatigue, caused by the repeated pressurization and de-pressurization of the aircraft cabin, subjecting the metal to an oscillating stress

A de Havilland Comet; the first commercially used jet

- On April 28, 1988, a Boeing 737-297 was on a scheduled Aloha Airlines flight between Hilo and Honolulu in Hawaii. Metal fatigue caused parts of the fuselage to a rip-off, turning the airplane into a kind of cabriolet. In one of the most spectacular feats of aviation, the pilots managed to get the plane down in one piece but sans roof. The picture tells it all

The happy ending of nightmare flight

- In 1998 a German high-speed ICE train derailed near the village of Eschede, killing 101 people. The disaster was caused by a single fatigue crack in one wheel. When that wheel finally failed, it caused the train to derail at a switch. The train hit a bridge, tore it down, and jack-knifed as shown below.

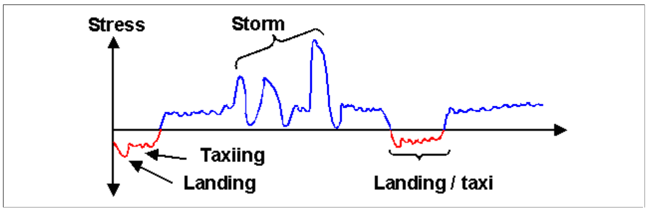
The 1998 train disaster in Eschede, Germany

The list could go on but you got the message by now: Metal fatigue is serious, indeed! The name, by the way, is ill-chosen. It was introduced in 1839 by one Jean Victor Poncelet. It's not a continuous process but disaster comes suddenly and without any warning. Periods of rest (no stress) will not restore the material to being "awake" again. Fatigue is cumulative!

What is And What Causes Fatigue?

Fatigue is the word for processes that lead to a very slow plastic deformation and eventually fracture of materials under a *oscillating* load that is far to small to cause plastic deformation right away in some tensile test. That's a definition that holds for all materials, not just crystals.
Apart from the "oscillating load" that's not much different from the definition of creep - but the mechanisms behind these two effects are are very different.

- A few things became clear rather early while studying fatigue:
  - In contrast to creep, where we have a *constant* (small) stress, fatigue is caused by (small) *oscillating* stress. That means we need to consider loads that change in magnitude in a more or less periodic way, including changes of the sign, i.e. from tensile to compressive and back. Fatigue eventually leads to fracture without much visible deformation (as in creep) before the catastrophe happens.
  - The stress encountered during those oscillating movements is well below the yield stress of the bulk material, so nothing *should* happen since the strain should be purely elastic. Amplitudes (amount of stress) and frequency (how many changes per time unit) are important. That makes testing very difficult because in real situations amplitude and frequency change all the time (see below).
  - Nothing *will* happen on a short time scale. Fracturing by fatigue takes time, typically far more than 100.000 load cycles.

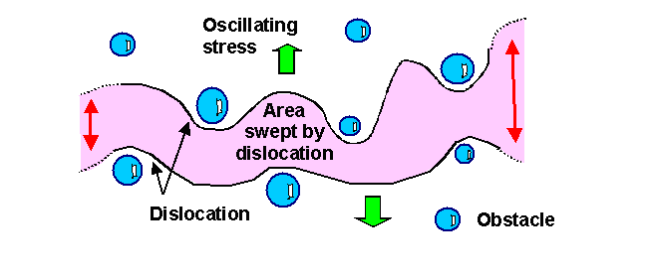


Loads on an aircraft part

Source. Adopted from: N.E. Dowling, Mechanical behavior of materials, 3rd edition, (Pearson / Prentice hall)

Let's not dawdle anymore! What happens? I wish I would know. Details are very complex and not understood as well as we would wish.
In order to get some insight, I first need to discuss that the good old mantra "*Plastic deformation of all crystals is done by moving dislocations through the crystal*" is still correct - but only because I cunningly inserted the "*through*" in the sentence above. Just moving dislocations some distance*in* the crystal will not produce noticeable macroscopic plastic deformation. This only happens if they move completely *through* the crystal; see that old but to-the-point figure.

What that means is simple. Stresses that are not large enough to move dislocations all the way through a crystal, i.e. stresses below the global yield stress, might still be large enough to move dislocations a bit *locally* in the crystal. We have seen that already in the creep module, where it became clear that dislocations move for stresses well below the yield stress until they get caught at obstacles. If we modify the figure used there for *oscillating* stress, i.e. for fatigue, we get:



Dislocation movement during oscillating stress.

So a dislocation will bow out a little more or a little less, or even move back and force between obstacles, if the stress oscillates. That by itself will not produce anything new or remarkable. What causes fatigue is that every once in a while, the dislocation does something different. For example, portions of it might move back on a different glide plane than the regular one (i.e. on a plane inclined to the screen plane in the figure above). Then something *new* has happened.
"Cross-slip" is geometrically possible for some dislocations on some planes, and it is easier or more likely to happen in bcc crystals than in fcc ones. Of course, what is going to happen is more pronounced in regions with large shear stress as seen from the viewpoint of a dislocation. That means that fatigue-related stuff happens more likely on:

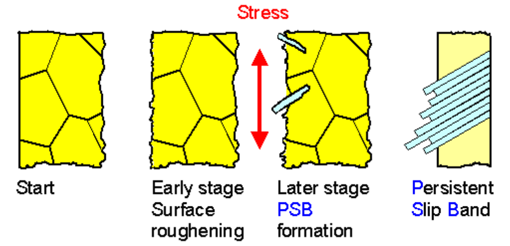
- Planes inclined at 45^0 to the (uniaxial) stress direction, where we always have the largest shear stress.
- Around defects like notches, microcracks and pores that act as local stress concentrators.

What happens during oscillating stress is that the dislocation structure slowly changes in some "high local stress" regions of the metal in such a way that these regions are more susceptible to fracture. This may take millions or more back-and forth events. Fracture by fatigue after only about 100.000 cycles is considered to be "short-time" fatigue. You see that there is a problem with doing fatigue testing. It is rather boring to watch your machine going back-and-forth a million times or so. The solution to this problem, once more, is called grad student.

In essence, and for reasons I won't go into (since I'm not so sure myself), dislocations in affected areas produce rather special structures in the end:

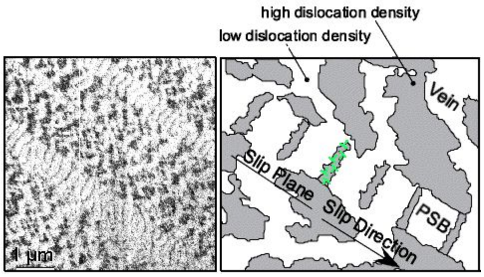
- Tangles of dislocations in a bundle structure called 'vein' that surround almost dislocation-free areas. That is understandable because the end is reached when dislocations can't move anymore at all under any circumstances because they are bunched up and completely entangled. This sort of roughens a formerly polished surface and means that the material is now rather brittle in the affected areas.
- In later stages, something well visible on the surface (with a microscope) develops, called "**persistent slip band**" or ***PSB***.

The figure below gives some idea of what I'm talking about.



Structural changes during cyclic loads

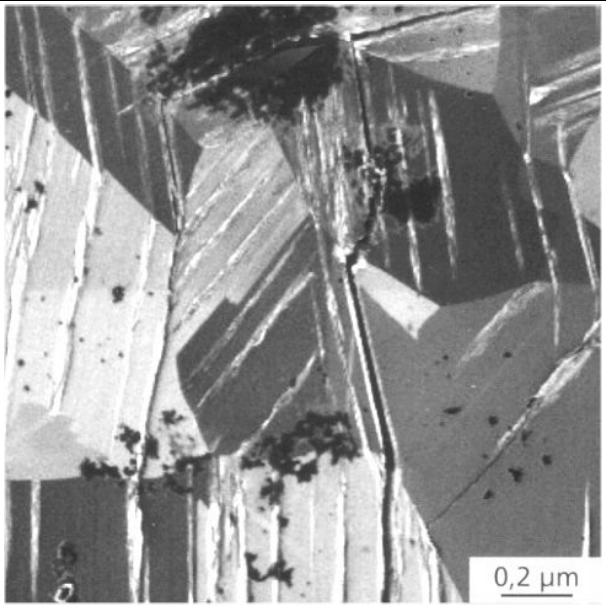
- A PSB's is what you need to watch out for. It consists of a highly organized bunch of dislocations. It develops in a kind of self-organization process from the dislocations tangles in the "vein" and enables dislocations to move again, producing massive and strongly localized deformation. In effect a lot of glide takes place on closely spaced parallel glide planes, producing largish extrusions (or intrusions) as shown schematically on the upper right.
  With some rather tricky SEM technique you can distinguish areas with a large density of dislocations from those with low densities. What you see is shown below



Dislocation density below the surface of a "fatigued" sample.

Source: From the Internet part of the diploma thesis of Markus Welsch (Application of ECCI and OIM to the interaction of dislocations grain boundaries in polycrystals), Universität des Saarlandes; Germany

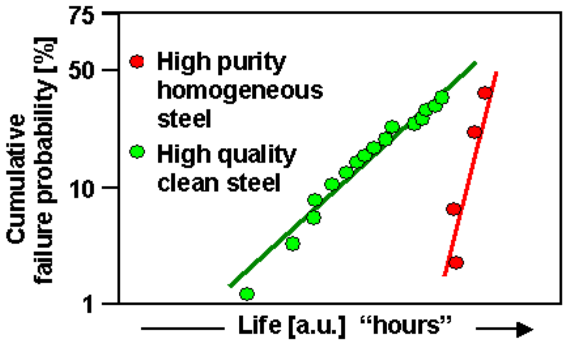
- The light green symbols give some idea on how the dislocations are distributed in a PSB. As soon as PSB's get massive enough, the game is about over. They essentially provide for nanocracks in a by now rather brittle environment (dislocation movement is almost impossible), and that triggers fracture.
  In reality things are far more complicated. But one fact remains: Fatigue is always tied to what dislocations do during cyclic loading, however complex that might be!
  Here is a picture showing persistent slip bands protruding from the surface of a fatigued nickel (Ni) sample and a crack that runs up on the right-hand side of the picture.



Persistent slip bands protruding from the grains of a fatigued nickel (Ni) sample and a crack

Source: From the team of Prof. D. C. Eberl; Yearly report 2014, Fraunhofer Institut für Werkstoffmechanik, Halle, Germany. With permission

Of course, all of that does not only happen around susceptible areas at the surface but also inside the materials at stress raising defects like nanocracks, pores, precipitates, whatever. It's just not easily seen. That fatigue relates very much to the finer details of the internal structure is shown in the next figure.



Fatigue in good and excellent steel.
The life "hours" scale has no number and only serves to show the relative differences

- The figure shows how many percent of samples fails due to fatigue after the "life" time. The high purity steel lives much longer then mere high quality steel - but then fails very quickly!