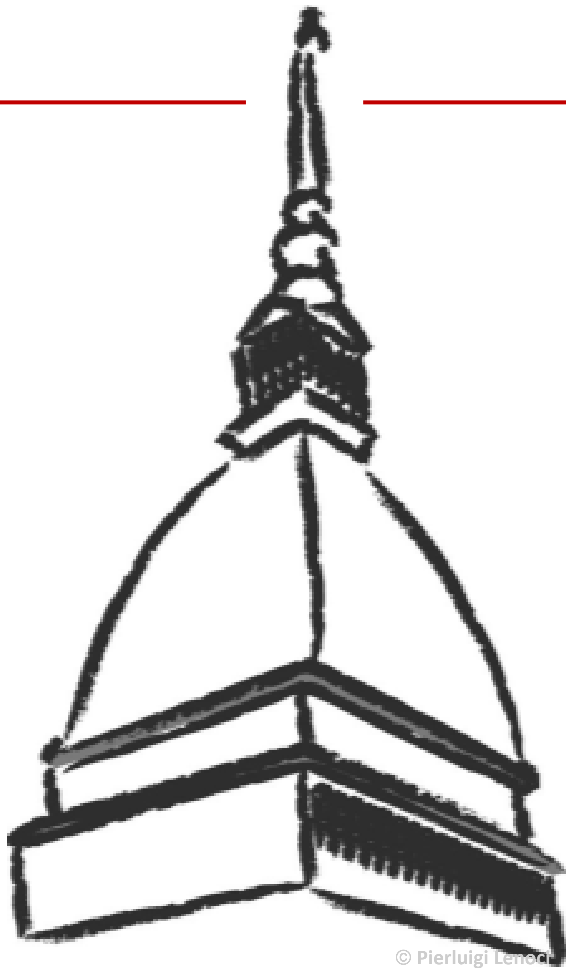
Daniele Botto

Costruzione di Motori per Aeromobili - Machine Design

Fatigue - Chapter 1



Chapters

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An ample knowledge on how materials and structures fail, and on how a component is loaded is necessary to understand the potential failure modes that must be considered in the design analysis;

e.g., overloads may cause yielding or brittle fracture or buckling … ...

Fatigue is just one of the many ways in which a structure or a mechanical component can fail: cyclic loads can eventually lead either to the initiation of fatigue cracks or to their propagation.

2. An overview of fatigue types

Controlling all factor relevant to fatigue, either with predictive models or with full scale tests is no joke.

Just from the phenomenological point of view, the following cases are possible:

- ✓ high cycle fatigue (HCF), stress controlled, > 10^4 cycles
- ✓ low cycle fatigue (LCF), strain controlled, < 10^4 cycles
- ✓ thermal fatigue (thermal gradients variable in time)
- ✓ surface fatigue (rolling contact, pitting, spalling, wear cracking)
- ✓ impact fatigue
- ✓ corrosion fatigue
- ✓ fretting fatigue

which are even more complex if they occur concomitantly and interact.

Sections 3, 4, 5 - Discovery of fatigue an first ideas

The purpose of Sections 3, 4, 5 is to introduce the reader to the basic ideas of stress-controlled fatigue with an eye to their historical formation.

Section 3 is a sketch of discovery of fatigue through one of the infamous accidents which showed that the design criteria of the time were not in full control of all aspects of strength of materials. And a sketch of how ideas and design criteria were developed by engineers; among them, stand August Wöhler and his experimental achievements.

Section 4 shows how Wöhler produced his data and organised them in a way later to become known as “Wöhler diagram”; and how contributed to the ideas of his times.

Section 5 gives symbols and definitions, relevant to stress controlled fatigue, to be remembered.

3. Discovery of fatigue (1/13)

Early 1800s, when investigators in Europe observed that bridge and railroad components cracked when subjected to loads variable with time.

With increasing use of machines, more and more failures of metal components were recorded.

One particular railway accident is frequently mentioned in the literature, because it was among the first major rail disasters causing multiple deaths. :

the “Versailles accident”

May 8, 1842

chemin de fer
Paris Montparnasse – Versailles
par la rive gauche

from “Notes on Railroad Accidents “ by Charles Francis Adams Jr

It was the birthday of the king, Louis Philippe, and, in accordance with the usual practice, the occasion had been celebrated at Versailles by a great display of the fountains.

At half past five o'clock these had stopped playing, and a general rush ensued for the trains then about to leave for Paris.

That which went by the road along the left bank of the Seine was densely crowded, and so long that two locomotives were required to draw it.

As it was moving at a high rate of speed between Bellevue and Meudon, the axle of the foremost of these two locomotives broke, letting the body of the engine drop to the ground.

It instantly stopped, and the second locomotive was then driven by its impetus on top of the first, crushing its engineer and fireman, while the contents of both the fire-boxes were scattered over the roadway and among the debris.

3. Discovery of fatigue (3 / 13)

Three carriages crowded with passengers were then piled on top of this burning mass and there crushed together into each other. ... ... They blazed up like pine kindlings.

Some of the carriages were so shattered that a portion of those in them were enabled to extricate themselves, but the very much larger number were held fast; and of these such as were not so fortunate as to be crushed to death in the first shock perished hopelessly in the flames before the eyes of a throng of lookers-on impotent to aid.

Fifty-two or fifty-three persons were supposed to have lost their lives in this disaster, and more than forty others were injured; the exact number of the killed, however, could never be ascertained, as the piling-up of the cars on top of the two locomotives had made of the destroyed portion of the train a veritable holocaust of the most hideous description.

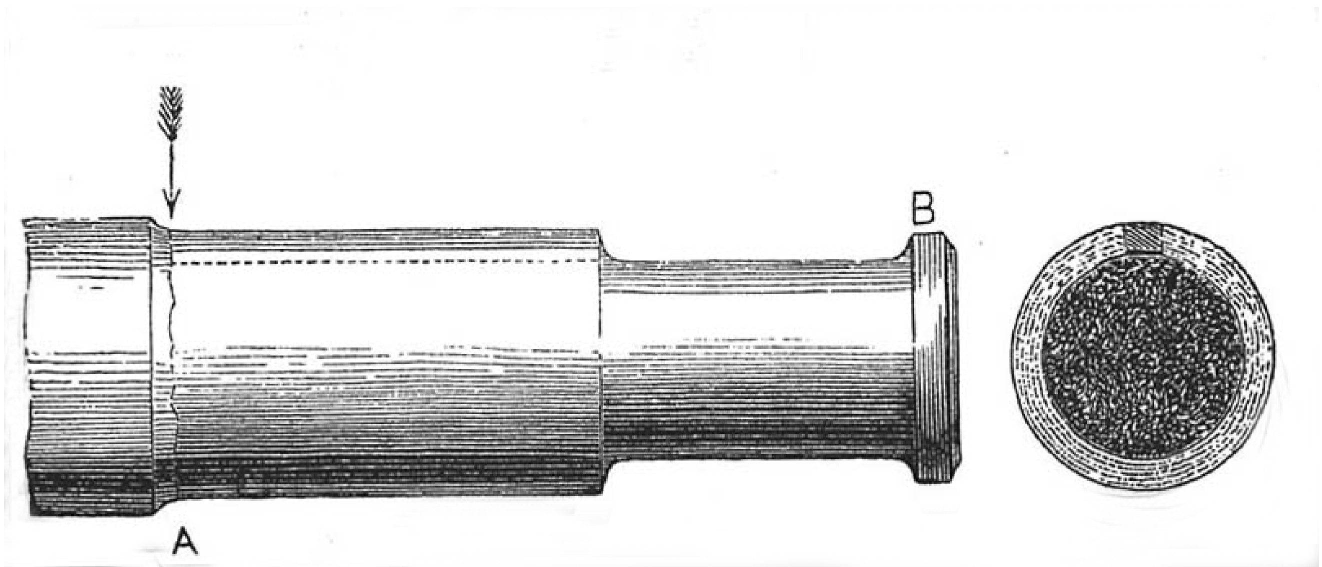
Not only did whole families perish together ... but the remains of such as were destroyed could neither be identified nor separated.

William John
Macquorn Rankine

Edinburgh 1820

Glasgow 1872

Rankine was one of the first engineers to recognise that fatigue failures of railway axles was caused by the initiation and growth of brittle cracks. In the early 1840s he examined several broken axles, and showed that the axles had failed by progressive growth of a brittle crack from a shoulder or stress concentration on the shaft.

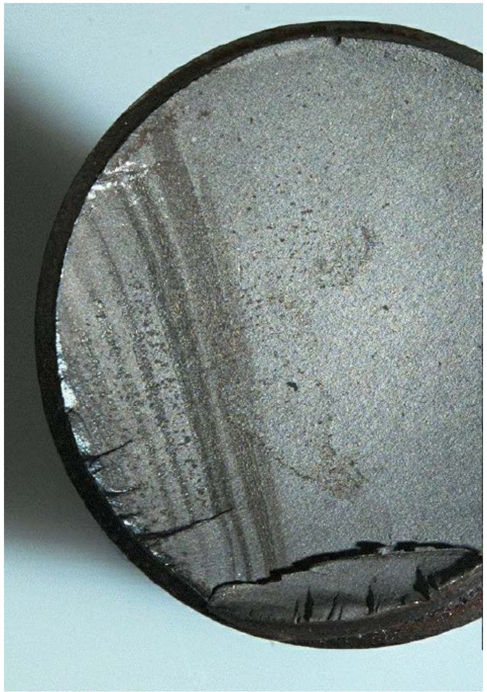


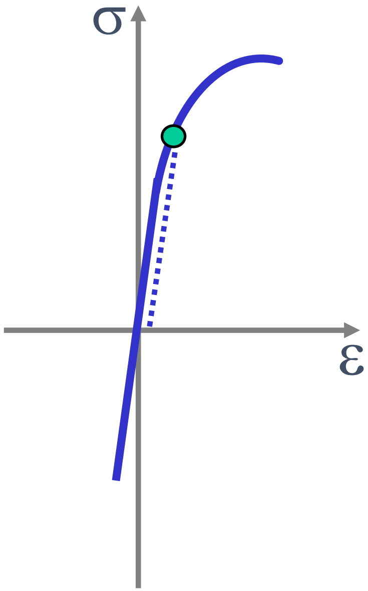
Rankine presented his conclusions in a paper delivered to the Institution of Civil Engineers. His work was ignored however, by many engineers who persisted in believing that stress could cause "re-crystallisation" of the metal.

The theory of recrystallisation was quite wrong in that context, and inhibited worthwhile research until the work of William Fairbairn a few years later.

This theory assumed that material properties changed, and was perhaps due to a “by that time” puzzling evidence:

fracture appeared brittle in parts made of materials which were ductile in monotonic tension tests.



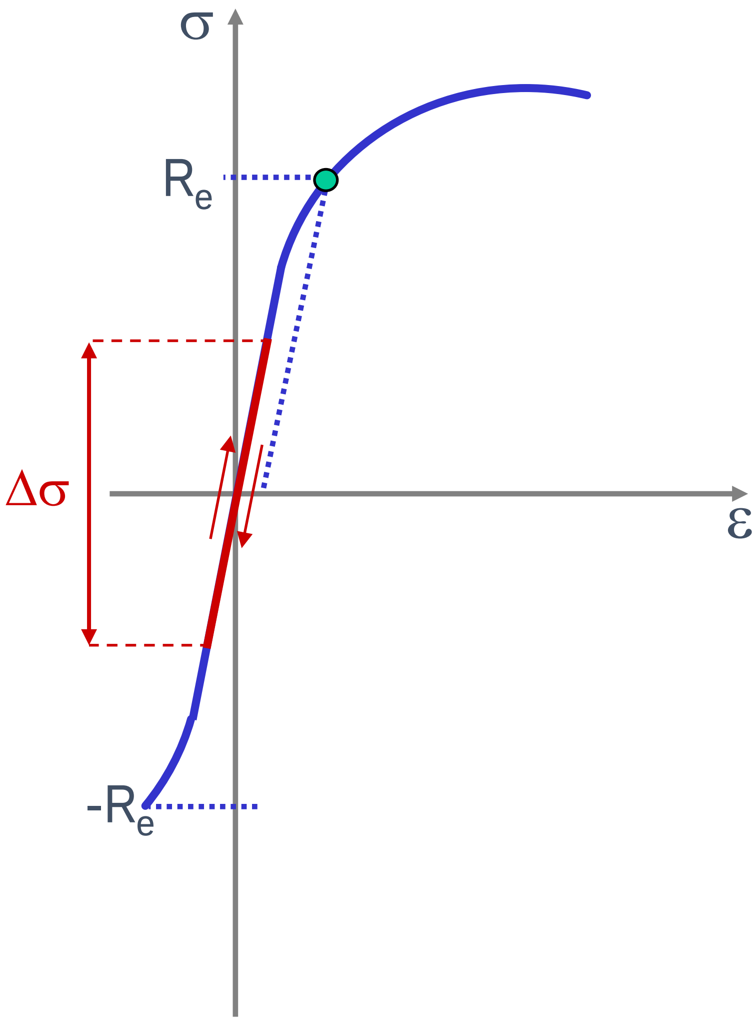


3. Discovery of fatigue (6 / 13)

Stress calculations showed that the stress oscillation at the crack initiation point was fully within the elastic range, as marked by a red line on the figure on the right.

$\Delta\sigma$ is the stress excursion experienced by metal during the fatigue cycles, and the highest and lowest stresses were well away from the onset on plasticity.

This a typical feature of “high cycle” fatigue (HCF), i.e., fatigue requiring a number of stress cycles to failure over (at least) 10^4, up to millions.



At that time fatigue was explained by changes in the structure of the metal: gradual crystallization of its “fiber structure” under cyclic stresses. Rankine did not observe anything similar.

Fairly soon, it was discovered that the concept of different “crystalline” and “fiber” structures is erroneous because both these structures are crystalline. This was demonstrated in 1850 by Stephenson who used a microscope with quite high magnification for that time.

In addition, we may suppose that a tension test made on a test coupon taken from a “fatigued” - but not yet failed - mechanical component, showed that monotonic tensile parameters of “fatigued” material had not changed from the original ones.

However ... behind this “wrong” theory there was a “sound” idea, i.e., to attribute the behaviour of metals under variable loads to some permanent material modification.

3. Discovery of fatigue (8/13)

Il est évident encore que pareille chose doit arriver quand, cette action étant seulement intermittente, les alternatives d'extension ou de compression sont suffisamment répétées; et c'est ce qui fait dire quelquefois aux ouvriers que *les ressorts les plus parfaits sont, à la longue, susceptibles de se fatiguer*. Mais ce fait s'explique de lui-même, si l'on admet que l'altération de l'élasticité, c'est-à-dire le dérangement intime et permanent des molécules, quoique insensible pour une seule compression suivie d'une détente, n'en existe pas moins en réalité, et fait des progrès de plus en plus marqués, à mesure qu'elle s'ajoute à elle-même, à chaque oscillation du ressort. D'ailleurs cette altération de l'élasticité peut fort bien provenir de ce que les alternatives ou oscillations, dont il s'agit, se succèdent dans des intervalles trop courts pour que les molécules aient, à chaque fois, le temps de revenir exactement à leurs positions primitives d'équilibre qu'elles atteindraient au bout d'un repos convenable, de sorte qu'elles s'en écartent, de plus en plus, à la fin de chaque oscillation.

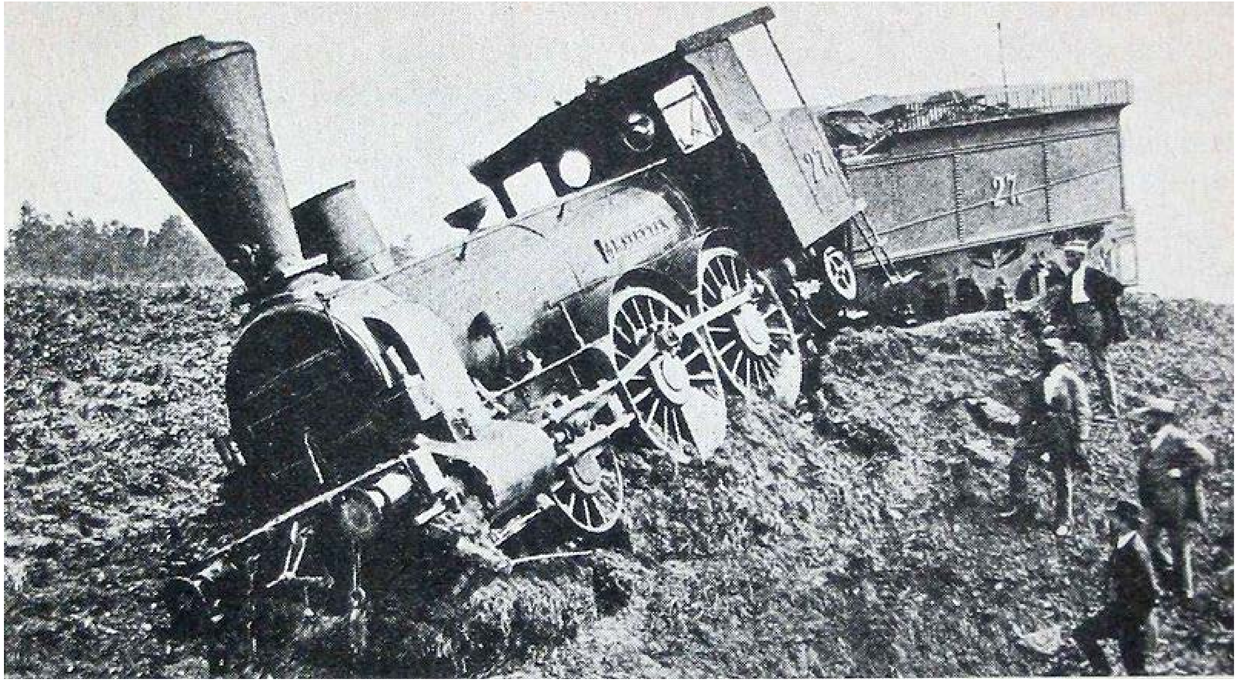
J.V. Poncelet, Introduction à la Mècanique Industrielle, III ed. Paris 1870

Jean-Victor Poncelet
Metz 1788 - Paris 1867

The term “fatigue” first appears in his lectures around 1837-1839

Until the early ‘900 not a great deal was known about the physical basis of fatigue, i.e. that repeated loading produced a new failure mechanism, different from that from monotonic tensile test.

However, as the fracture events continued to occur without any visible symptom of plastic deformation or defect, it was more



more urgent to put the phenomenon under control

than to find a physical explanation

3. Discovery of fatigue (10/13)

In other words, only after the turn of the century, it was possible to gradually introduce the:

microscopic approach, which investigates the reasons of phenomena in connection with the metallurgical and structural features of the material

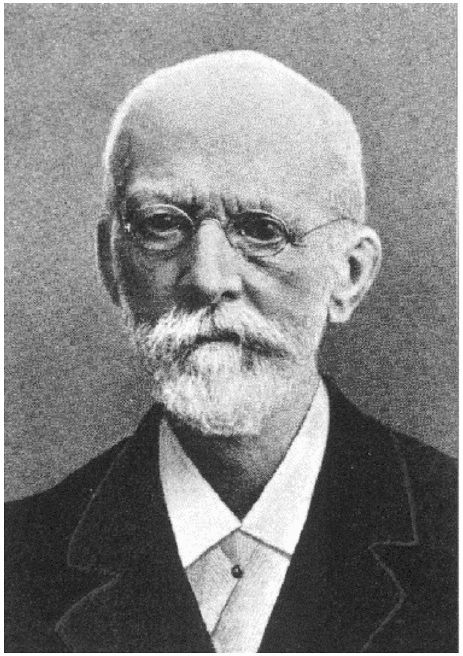
while at the mid ‘800s it was urgent to have in hand a:

phenomenological* or empirical **approach**, which aims at providing the designer with tools

- to prevent fatigue failure
- to predict life which the component can safely reach before any failure occurs

* The goal of a phenomenological approach is not to describe a theory or develop a model but to describe accurately experience in relation to what is being studied.

This was done in the 1860s, when special laboratories for testing materials under repeated or cyclic loading, appeared in UK and in Germany.



August Wöhler
Soltau 1819
Hannover 1914

Thanks to August Wöhler, Germany became a worldwide centre of fatigue research playing the leading role in the industrial revolution.

By the mid 1800s A. Wöhler proposed a method by which the failure of components from repeated loads could be mitigated and in some cases eliminated.

This method resulted in the stress-life response diagram approach and the component test model approach to fatigue design.

3. Discovery of fatigue (12/13)

An *extensive* account of Wöhler's contributions can be found in:

A History of Fatigue, W. Schütz, Eng. Fract. Mech., Vol. 54 n. 2, pp. 263-300, 1996

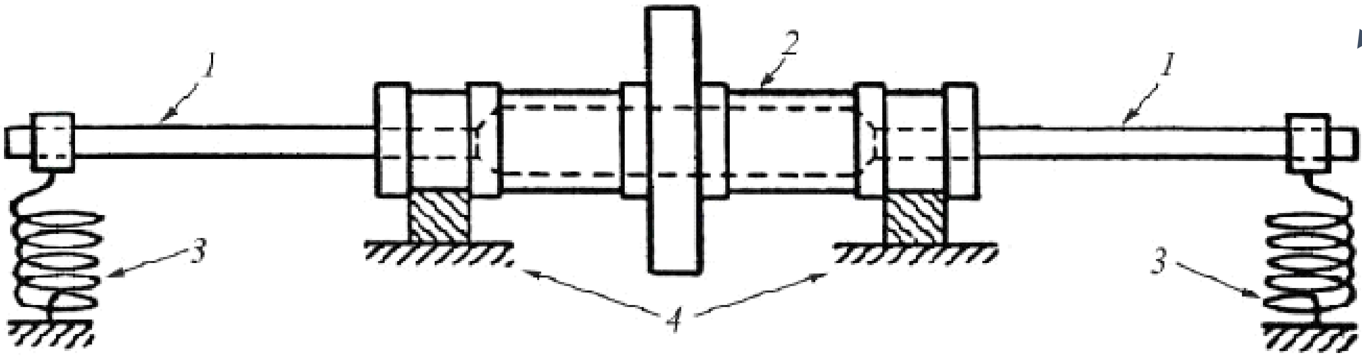
and in*:*

Formation of the Science of Fatigue of Metals, Part 1. 1825-1870, L. Tóth, S. Ya. Yarema, Materials Science, Vol. 42 n. 5, pp. 673-680, 2006

Wöhler created the methods of fatigue investigations and technical means for their realization. He designed new machines for the testing under cyclic loading, which were absolutely the best at that time (now exhibited in the Deutsches Museum in Munich).

The list of these machines includes:

✓a machine for testing two half axles, Ø ≈100 mm, cantilever rotation bending, cyclic frequency 0,25 Hz, spring loading (below)

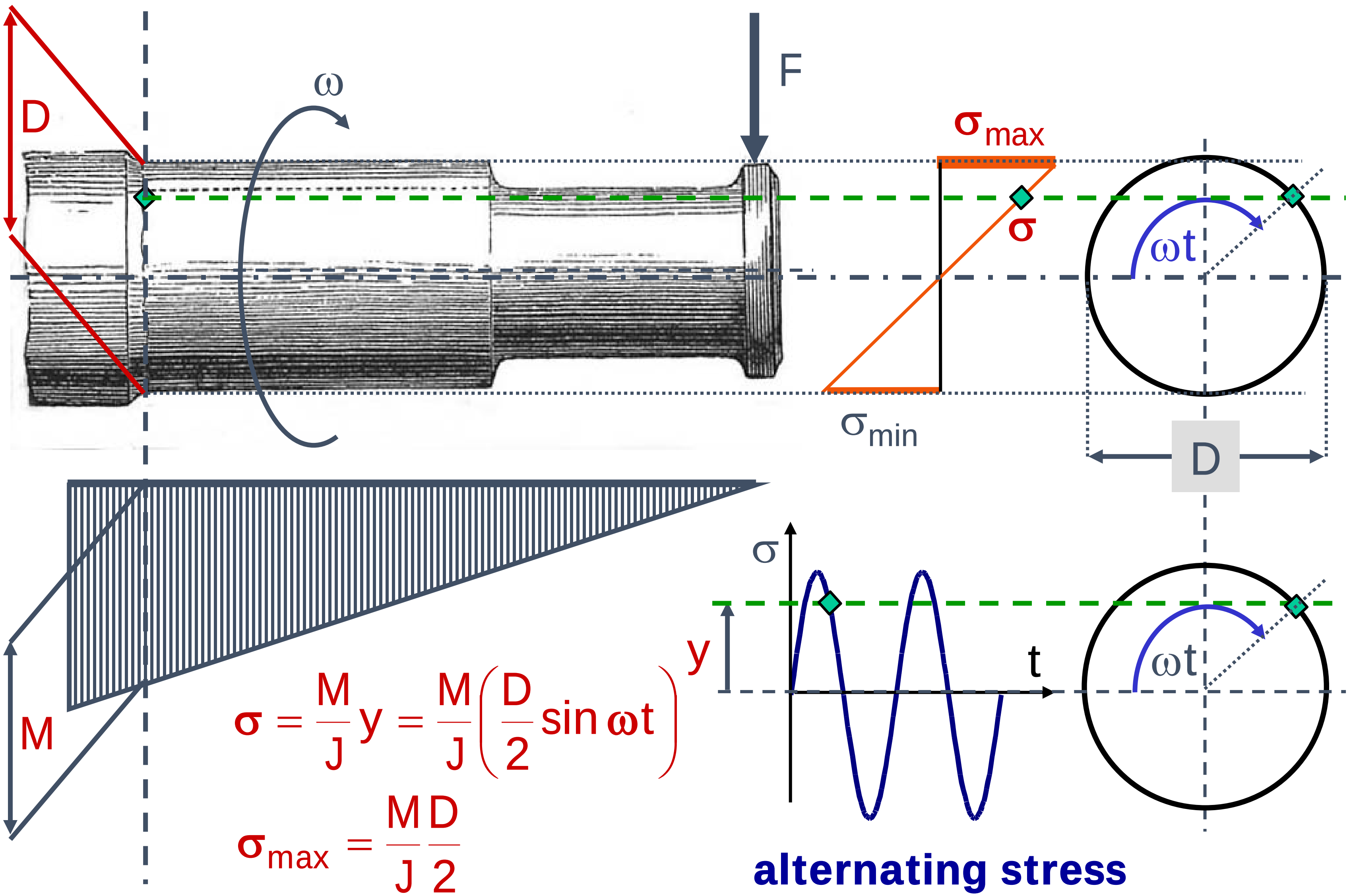


Wöhler's machine for testing two half axles for cyclic bending: (1) half axles, (2) rotor, (3) loading springs, (4) supports.

✓a rotating machine for specimens of smaller diameters (up to 37 mm) with higher frequency, hence for up to millions of cycles

✓a machine for cantilever prismatic specimens loaded in bending with an eccentric (*in order to be able to change the stress ratio*)

✓a machine for testing cylindrical specimens for symmetric cyclic torsion.



$$\sigma = \frac{M}{J} y = \frac{M}{J}\left(\frac{D}{2}\sin\omega t\right)$$

$$\sigma_{max} = \frac{M}{J}\frac{D}{2}$$

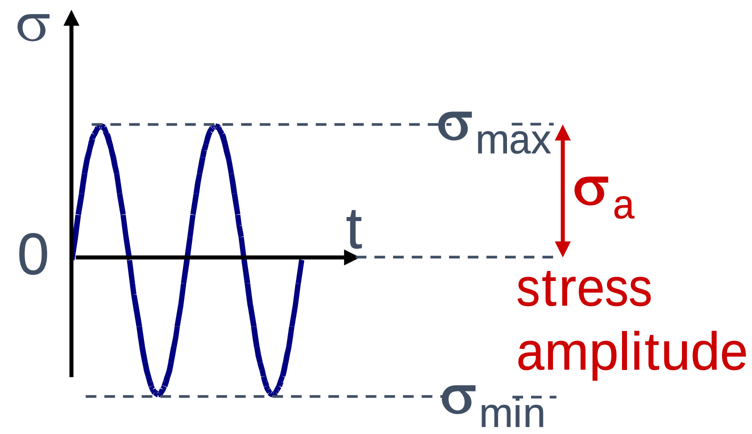
alternating stress

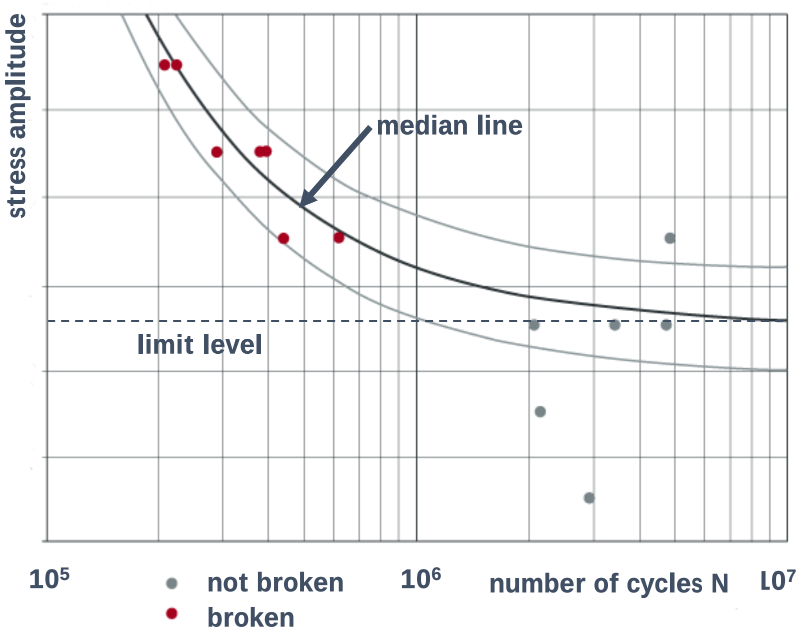
By these means Wöhler produced a stress amplitude σ_a and found the number N of cycles (rotations of the shaft) to failure.

To the right, we can see a modern "Wöhler diagram", where stress-life response data are plotted

Wöhler used tables, not diagrams!

The median line (bold) is the best fit of red points, showing the life of failed specimens; of course, one must adopt a failure criterion: complete rupture of the test specimen or the onset of a first visible crack?

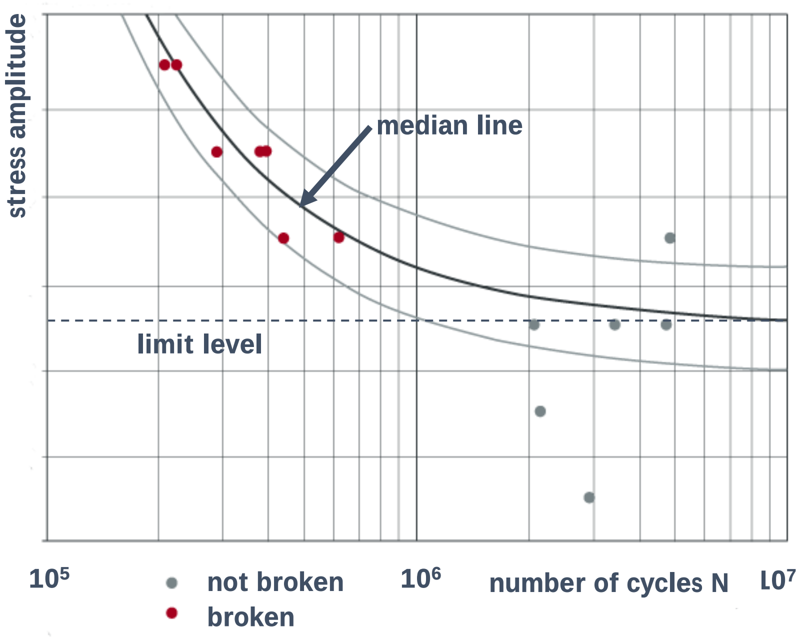




4. Wöhler stress-life diagram (3 / 5)

Main features of the Wöhler diagram to observe:

- ✓ measurements are taken in the elastic field: $\sigma_{max} < R_e$
- ✓ N, the dependent variable, is spread over a very wide range, then the logarithm is the scale of choice.
- ✓ for a given level of stress amplitude life span is large, up to 2 10^5
- ✓ under a certain level of stress no failure occurs (no broken or “runout” specimens); the curve tends to become horizontal to represent this “limit” level.
- ✓ the median line is a best fit of the 50% failure probability
- ✓ the other lines are 10% and 90% failure probability
- ✓ the limit level too requires a statistical estimate at some probability level



4. Wöhler stress-life diagram (4/5)

If component design is such to produce, under service loads, stresses “safely”below the limit (which implies a decision on a safety margin) then it can have infinite life.

However, after Wöhler it was possible to design also at finite life. In his own words: *It must be taken into consideration whether unlimited or limited life is required for the component. It follows that different components need different safety factors. In any case two such factors are necessary, one for the relation between the maximum stress in service and static strength, and the other for the allowable stress amplitude.*

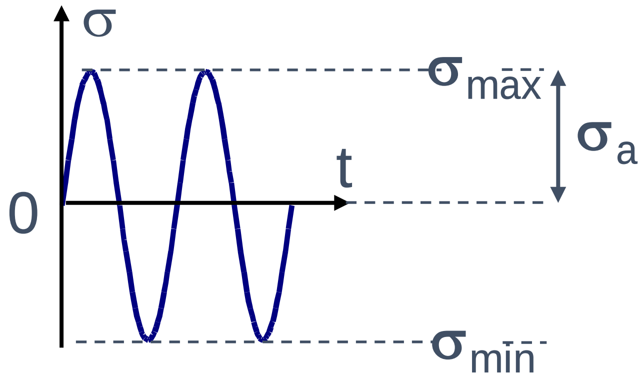
Wöhler realizes that the fatigue failure is not a type of static failure due to the fact that the material has changed, for some reason, its characteristics on the whole volume and therefore its static strength properties. The new facts are due to a new response of material to variable loads, to be treated separately and in addition to the first one. High cycle fatigue was born.

4. Wöhler stress-life diagram (5/5)

Again in his own words, with good sense of humor: *... the axles were sized so that they should never fail in service according to experience. It was therefore all the more embarrassing when they failed in large numbers. The cause of these failures was not immediately apparent nor were means of preventing them available. Crystallization due to vibrations, by earth's magnetism and other dark notions were resorted to before finally it was decided to believe that the axles had failed because they were too weak. When this was finally realized, the loads due to which the axles broke were soon found.*

By experiment, Wöhler became also aware of facts which would be the object of many later fruitful developments:

- notch effect (e.g., rounding radii at diameter variations)
- metallurgical size effect (smaller axles have higher allowable stresses than thicker ones)
- crack propagation (fine, hardly visible cracks in cast steel axles, after several years in service grew up to 20 mm)

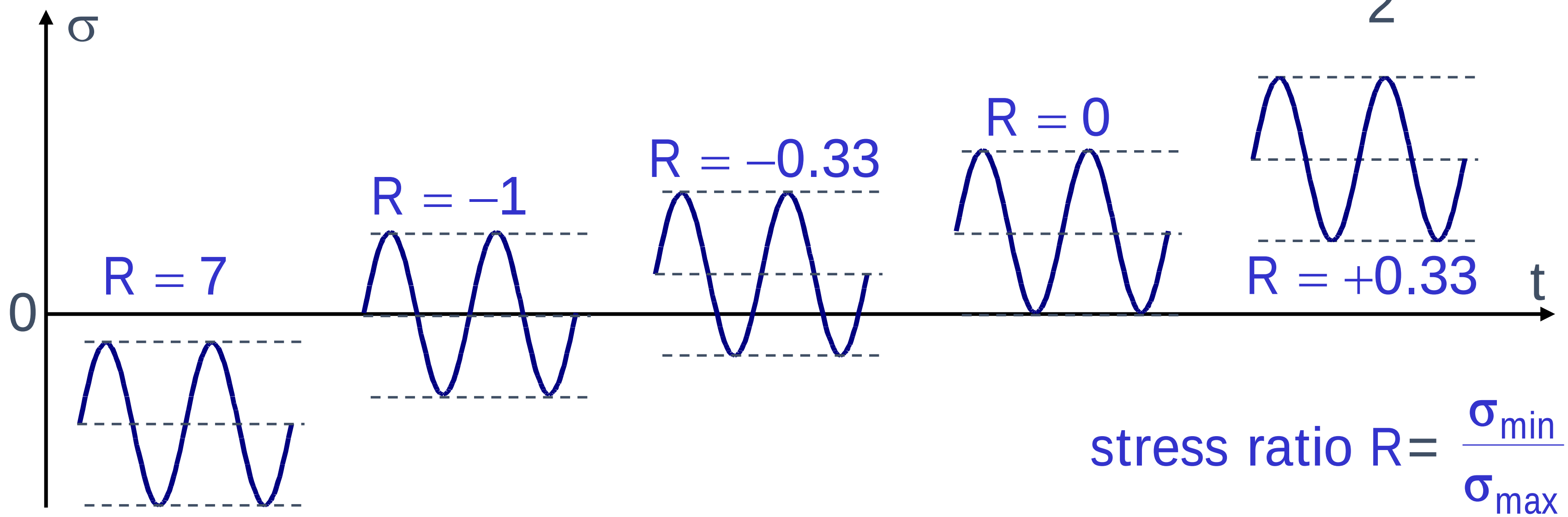


With a rotating bending test a stress amplitude:

$$\sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2}$$

is produced on surface points.

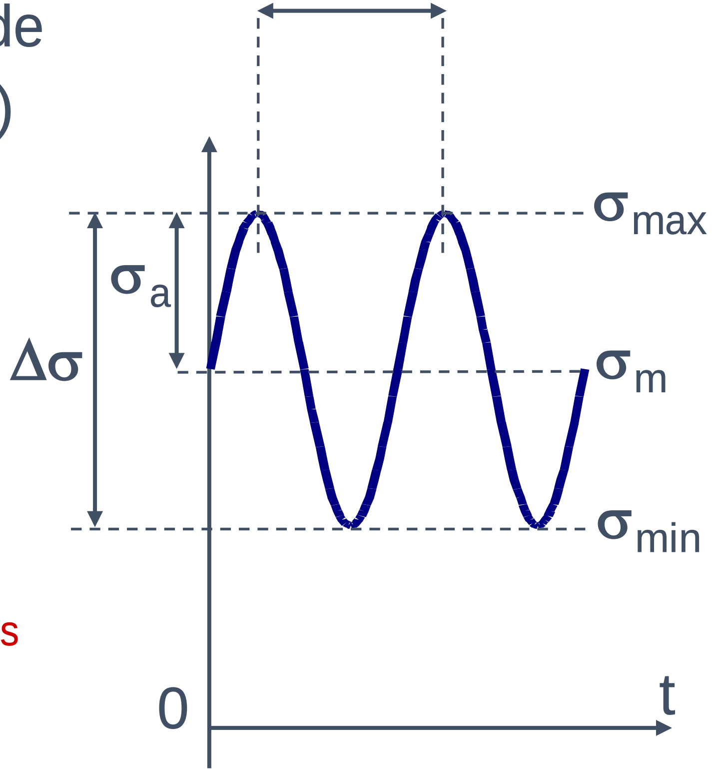
Other machines produce also a mean stress: $\sigma_m = \dfrac{\sigma_{max} + \sigma_{min}}{2}$



stress ratio $R = \dfrac{\sigma_{min}}{\sigma_{max}}$

σ_{max}	maximum stress
σ_{min}	minimum stress
$\sigma_m = \dfrac{\sigma_{max} + \sigma_{min}}{2}$	mean stress
$\sigma_a = \dfrac{\sigma_{max} - \sigma_{min}}{2}$	stress amplitude (always positive)
$\Delta\sigma = \sigma_{max} - \sigma_{min} = 2\sigma_a$	stress range
$R = \dfrac{\sigma_{min}}{\sigma_{max}}$	stress ratio

1 cycle or
2 reversals*



- Counting reversals (half cycles) instead of cycles is preferred in the Rainflow cycle counting method for variable amplitude fatigue (see later)

Sections 6, 7, 8 - Material behaviour, models and facts

The purpose of Sections 6, 7, 8 illustrate the models and mechanisms, at the crystal and dislocation level, which are used to explain crack incubation, in case a crack is not already present, and crack propagation (growth).

Section 7 presents crack nucleation at the surface and in the presence of sub-surface discontinuities.

Section 8 presents crack propagation with increasing dimensions.

In all cases a very limited, although very representative, experimental evidence is presented: this helps the reader to understand how models and mechanisms have been validated through direct observation.

6. Crack nucleation and propagation to failure (1/2)

The ASTM* definition of fatigue is:

“*The process of progressive, localized, permanent structural change occurring in a material, subjected to conditions that produce fluctuating stresses and strains at some point or points and that may culminate in cracks or complete fracture after a sufficient number of fluctuations”.*

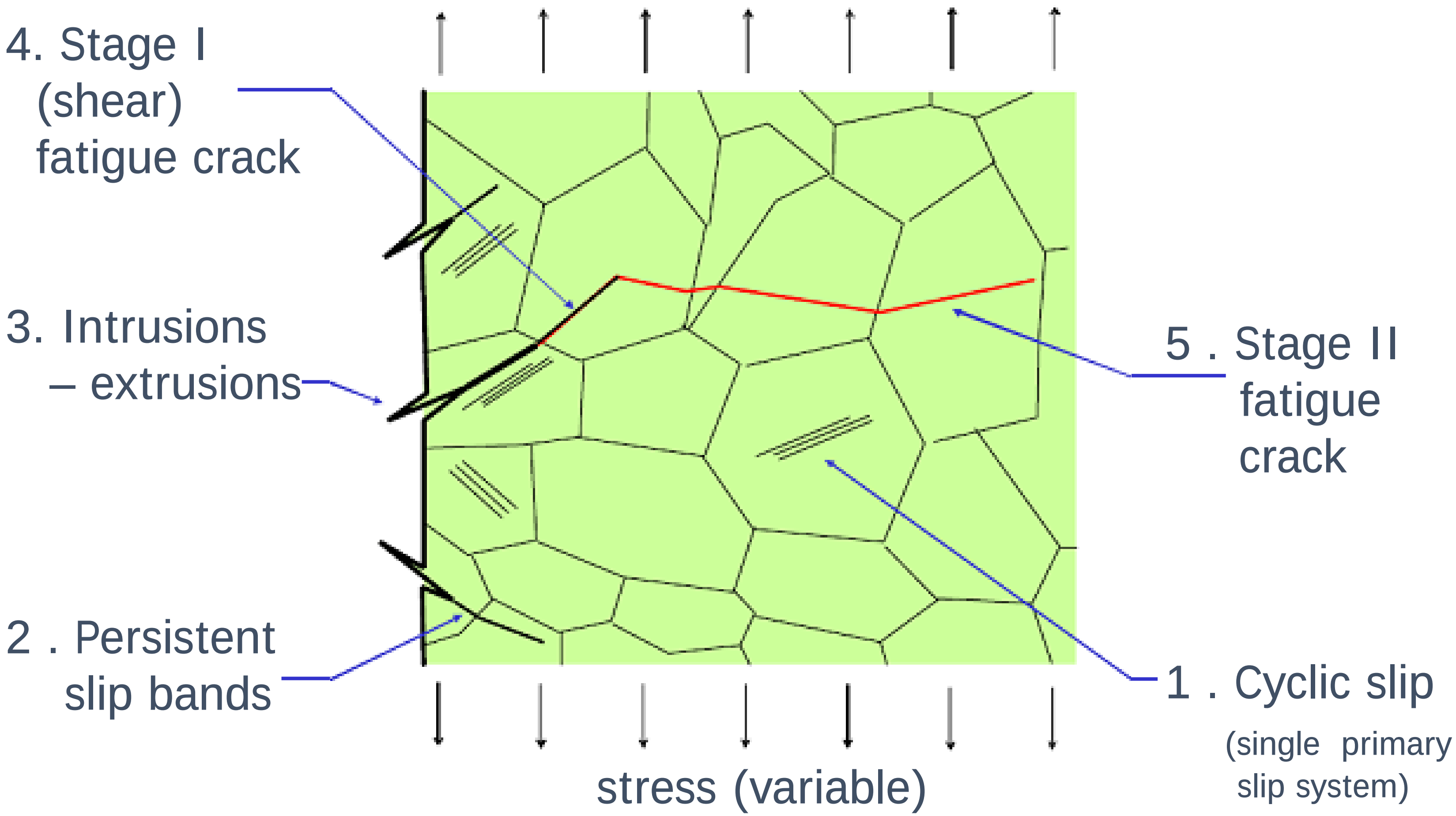
* ASTM (2000), Standard Terminology Relating to Fatigue and Fracture, vol.03.01 edition Testing ASTM designation E1823

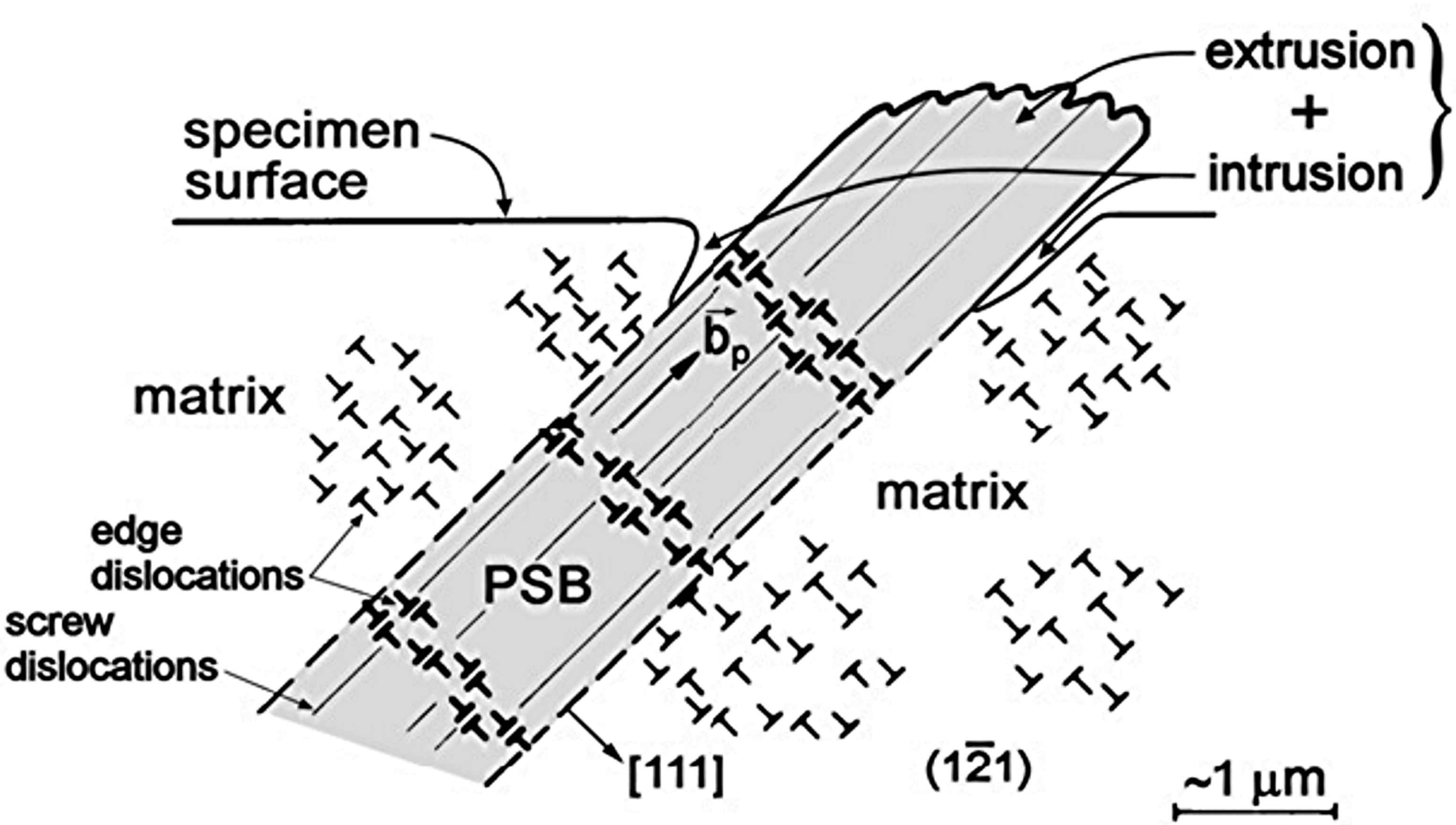
... and to modern fatigue: it is today generally understood that three main distinct phases may occur in the fatigue process:

- nucleation of a crack
- crack growth (first “small crack” then conventional “large crack” governed by linear elastic or plastic fracture mechanics)
- final instability (complete fracture)

6. Crack nucleation and propagation to failure (2/2)

If a defect, or a crack is not already present, its nucleation and propagation are described as follows (at a free surface):

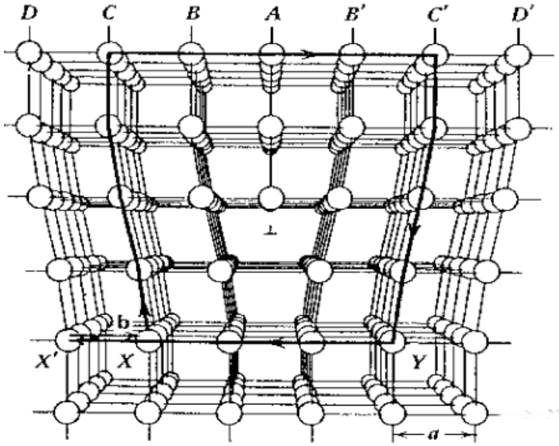


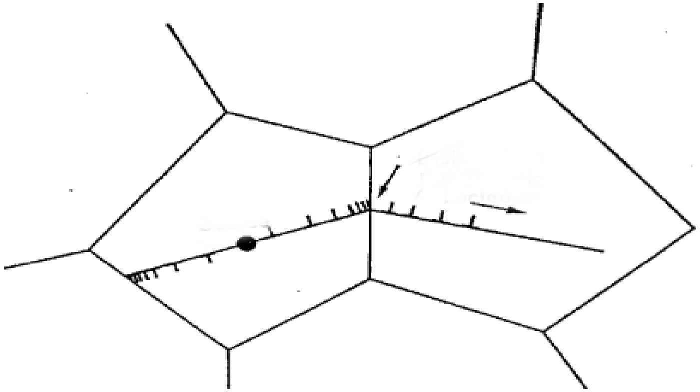


(Source: J. Man et al., *Extrusions and intrusions in fatigued metals Part 1*, Philosophical Magazine, Vol. 89, No. 16, 1295–1336, 2009 Taylor and Francis)

Surface roughening through cyclic plastic strains leads to the development of fatigue cracks. Time sequence: 1-dislocation distributions in Persistent Slip Bands (PSB), 2-mature Persistent Slip Markings (PSM) formed where the PSBs intersect the free surface

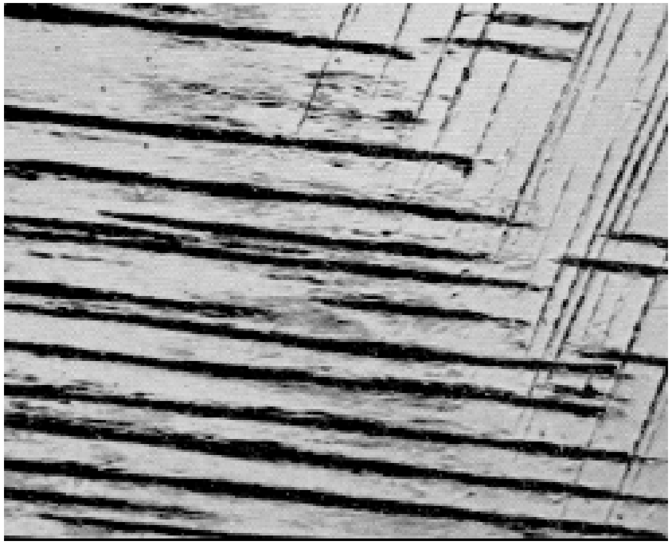
Dislocations under cyclic strain align and produce slips of weaker crystal planes



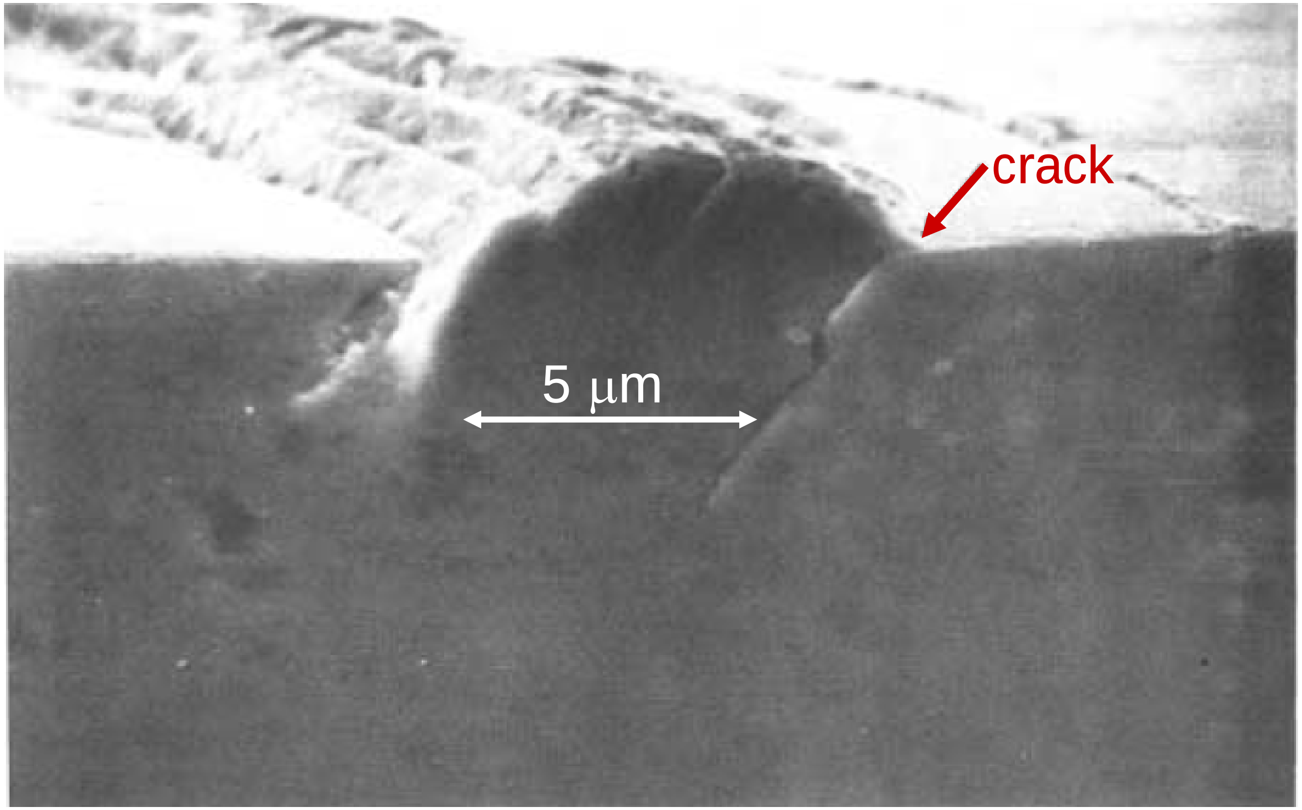


Cyclic slip occurs within a grain and therefore operates on an atomic scale.

It is controlled by features seen at that scale



Surface roughening through cyclic plastic strains leads to the development of fatigue cracks (fatigue crack initiation)



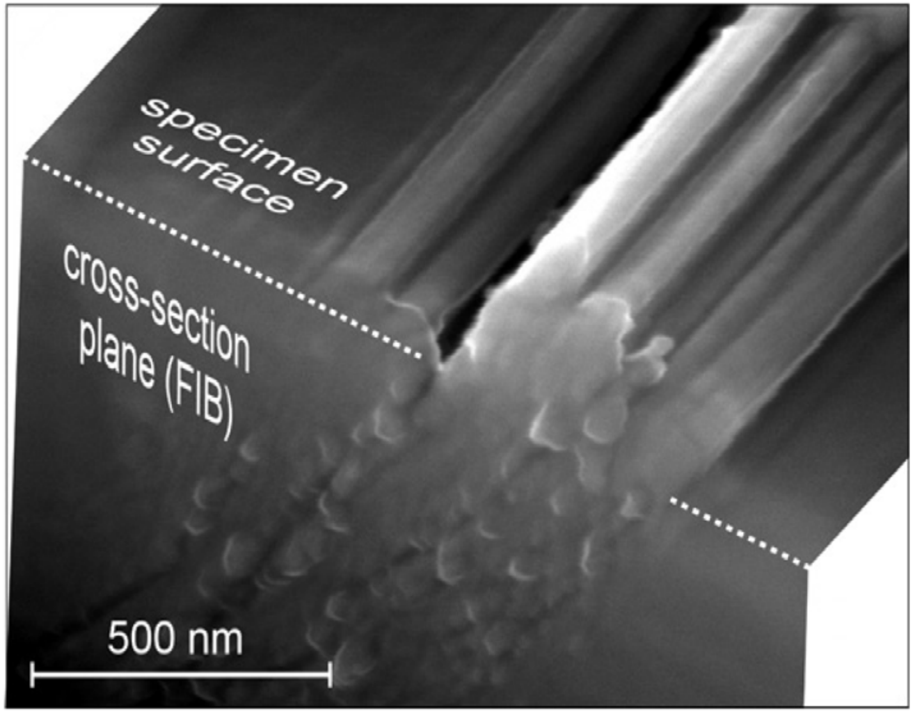
Experimental evidence

Source: Suresh, S., *Fatigue of Materials*, Cambridge University Press, Cambridge, UK , 1991

7. Crack nucleation (4/7) : intrusions-extrusions

PSM – Persistent Slip Markings on the surface due to the intersection of Persistent Slip Bands, PSB.

Intrusions and extrusions on the surface of a Ni specimen



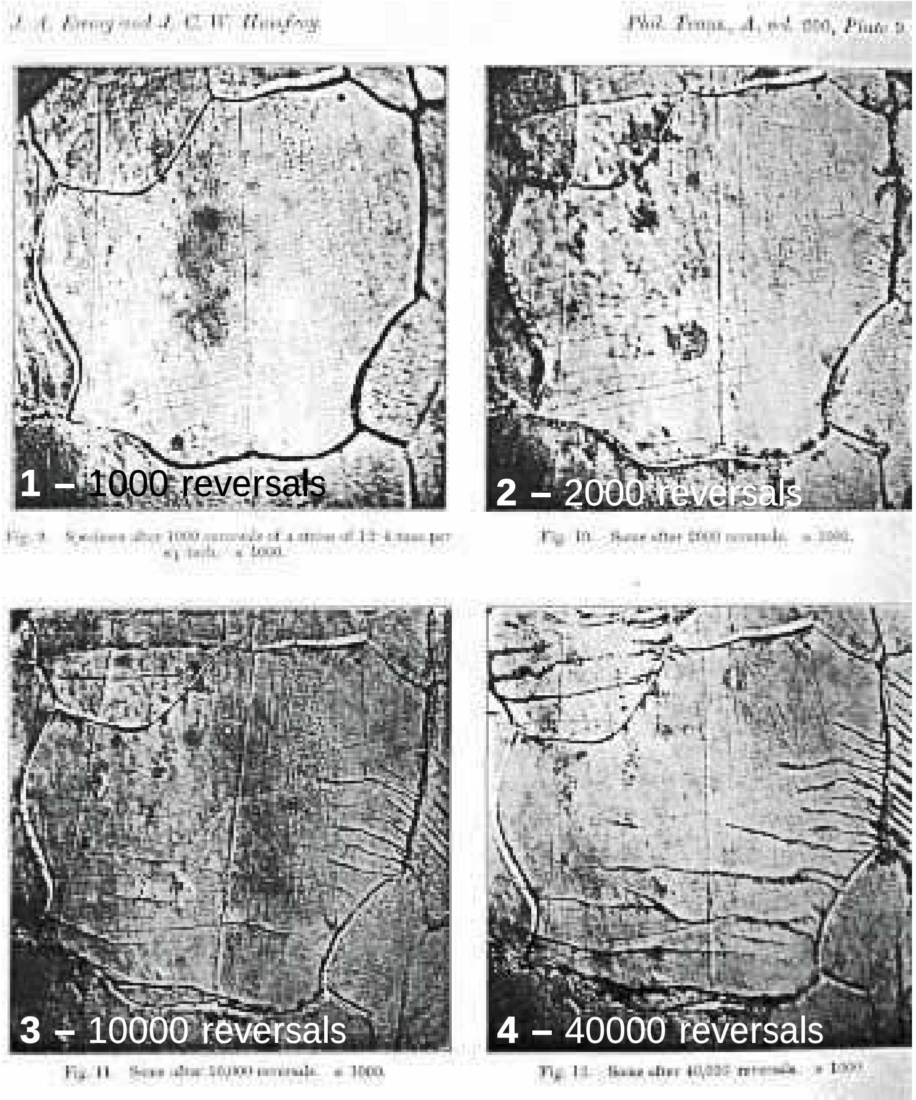
SEM–FEG micrograph of a cross-sectioned individual PSM in 316L cycled with $\varepsilon=1x10^{-3}$

(Source: J. Man et al., *Extrusions and intrusions in fatigued metals Part 2*, Philosophical Magazine, Vol. 89, No. 16, 1337–1372, 2009 Taylor and Francis)

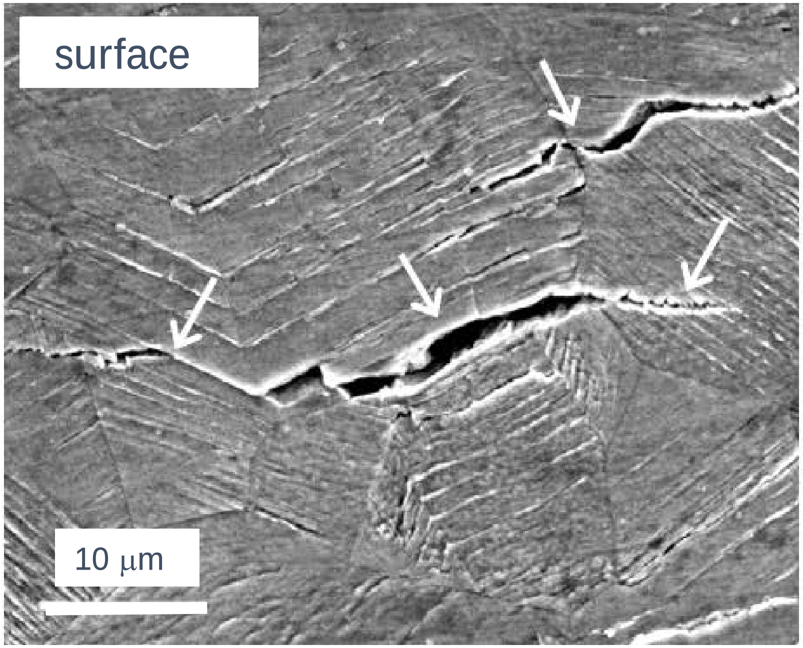
Seen on the surface, these early micrographs showed how surface fatigue cracks grow as material is further cycled.

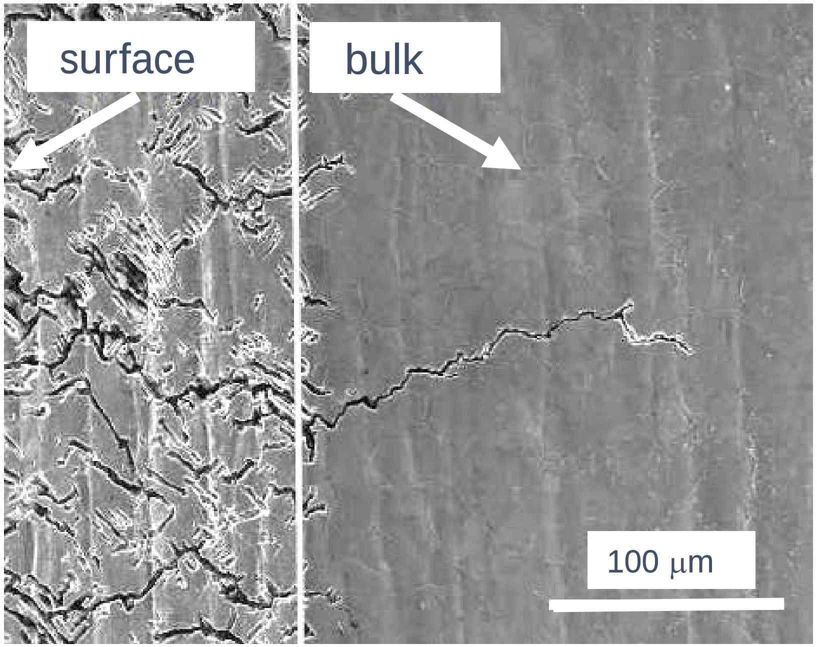
This historical photo from Ewing & Humfrey (1903) shows the apperance of slip bands and then cracks as they develop within a crystal grain and across its boundaries with grains around.

Ewing, J.A. and Humfrey, J.C.W. (1903) Philosophical Transactions Royal Society of London *Series A, Containing Papers of a Mathematical or Physical Character*, Volume 200, pp. 241-250



Formation of Surface Cracks in 20-25 Austenitic Steel, large strain cycles, low cycle fatigue





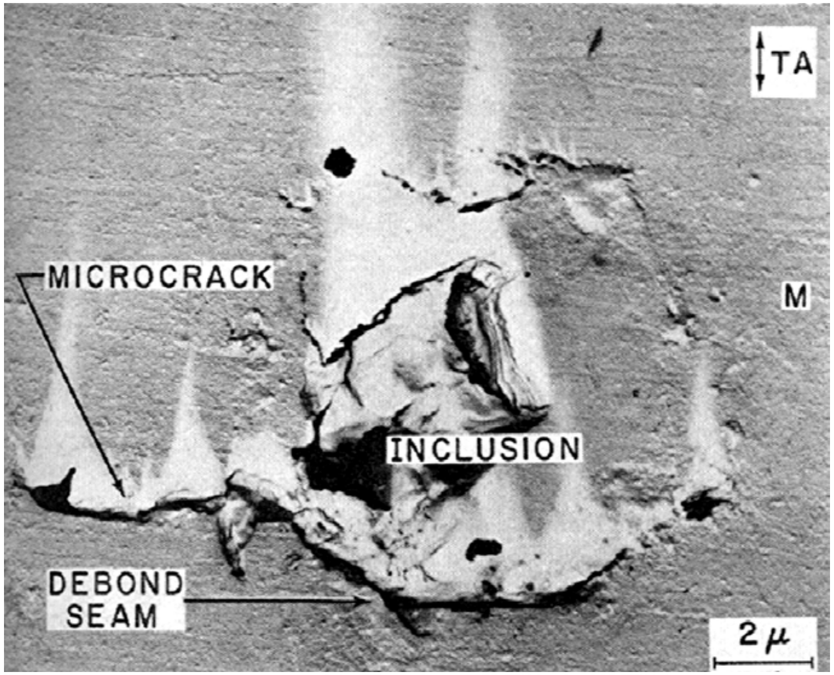
Stolarz J., 5th International Conference on Low Cycle Fatigue, Berlin, Sept. 2003
the left side shows the surface, the right side shows a cross section view; many microcracks nucleate on the surface, only a few of them are able to penetrate into the bulk of the material.

Image from Fatigue and Fracture (basic course), Darrell F. Socie, University of Illinois at Urbana-Champaign
See also: https://www.efatigue.com/hightemp/background/tmf.html

Subsurface cracks can also be nucleated; examples are those initiated at particles or inclusions.

Initiation occurring at the interface

S. Pearson, “Initiation of Fatigue Cracks in Commercial Aluminum Alloys and the Subsequent Propagation of Very Short Cracks,” Engineering Fracture Mechanics, 1975, Vol. 7, pp. 235-247



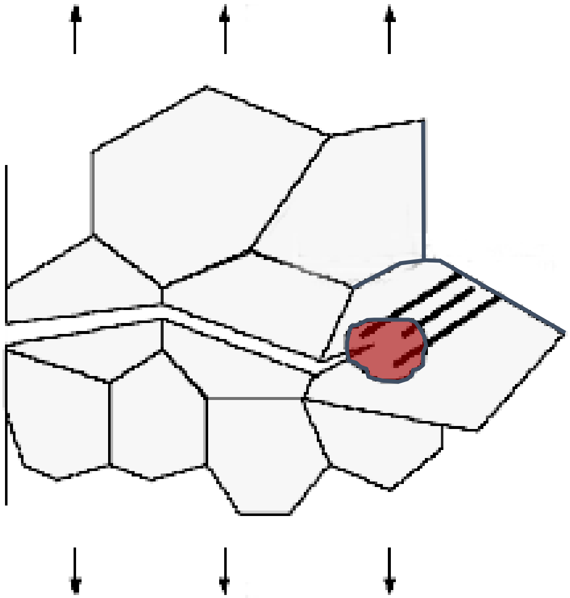
Langford and Kusenberger, “Initiation of Fatigue Cracks in 4340 Steel”, *Metallurgical Transactions*, Vol 4, 1977, 553-559

8. Crack propagation : stage I - small cracks (1/2)

Stage I: fatigue cracks are "small", the size of the grains, and are thus controlled by features seen at that scale:

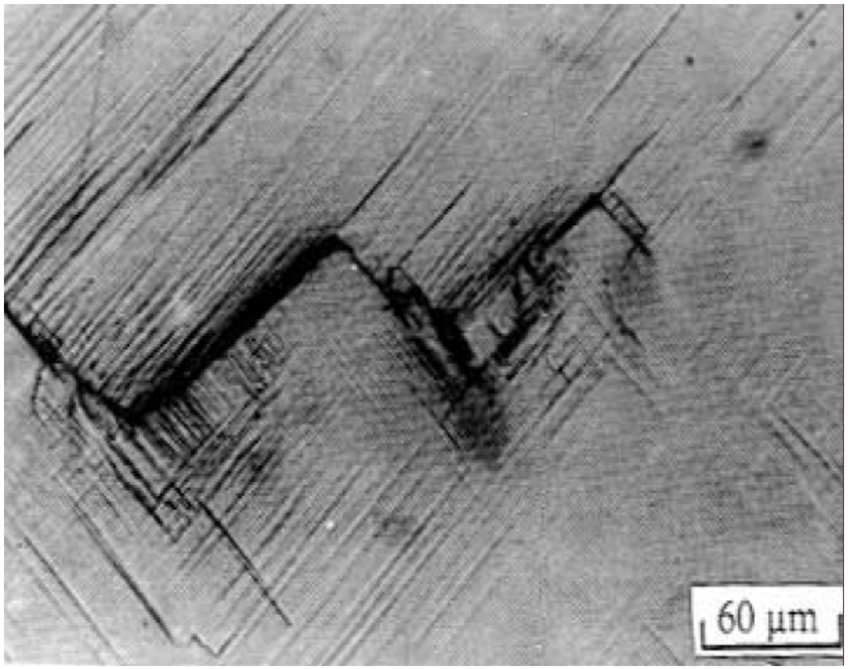
✓ grain boundaries

✓ grain strains

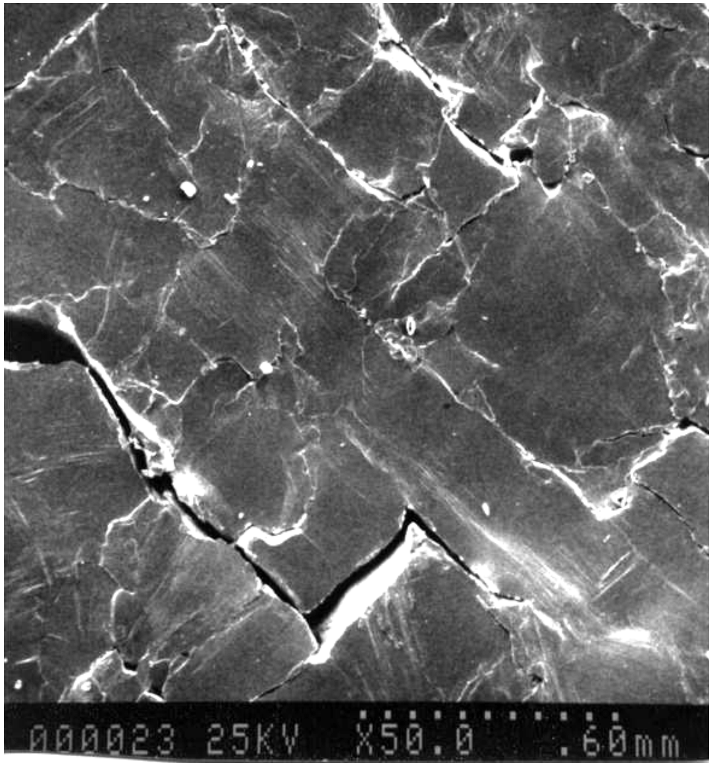


Pearson 1975

Small cracks behave differently from "large" cracks which are the object of fracture mechanics.



Fatigue cracks prefer to form along specific weak crystallographic planes or along the interfaces between crystals in the metal.

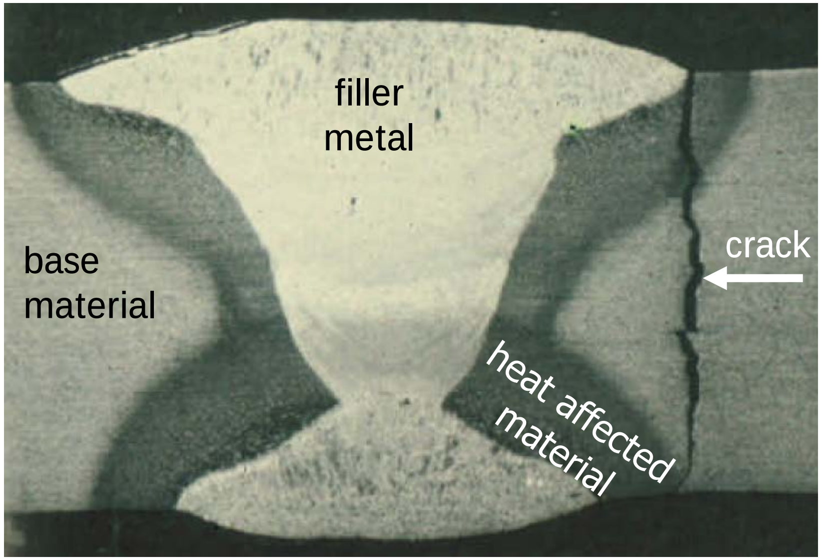


Eventually microcracks encounter other microcracks and join together. This coalescence is usually the way a large-enough-to-be-seen crack or engineering crack forms.

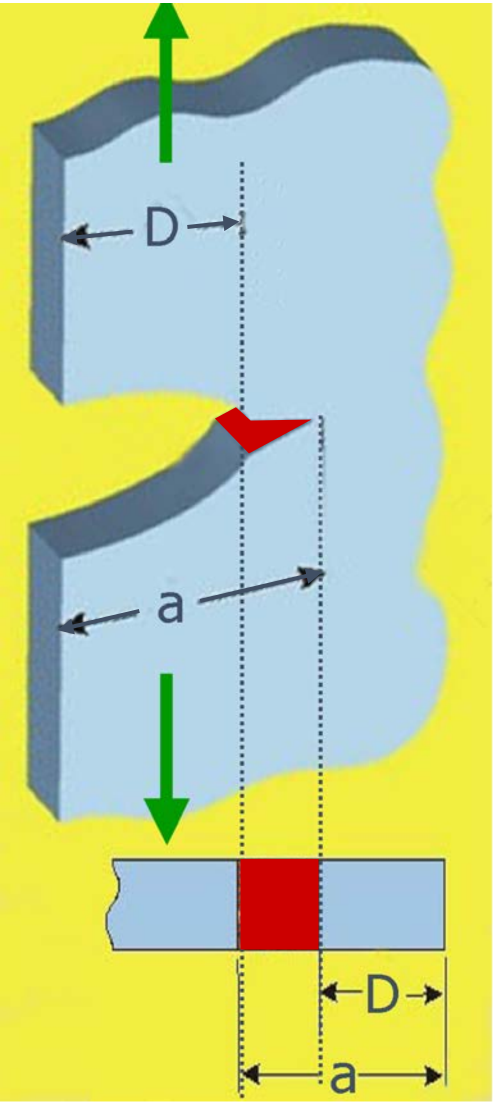
This discontinuity tends to grow into a microcrack, a crack with a size measured in microns. In areas of stress concentration, microcracks may be abundant.

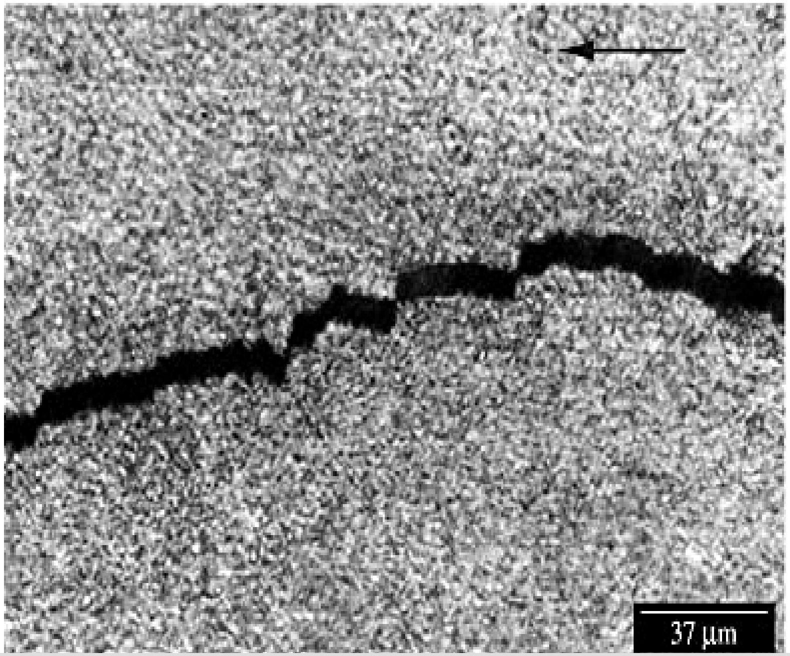
Since they generally cannot be seen without an electron microscope, they are often regarded as non-present.

Stage II: fatigue cracks are “large” (it means, much larger than the grain size); they are thus sensitive only to large scale microstructural features, like texture, “continuum mechanics” global residual stresses

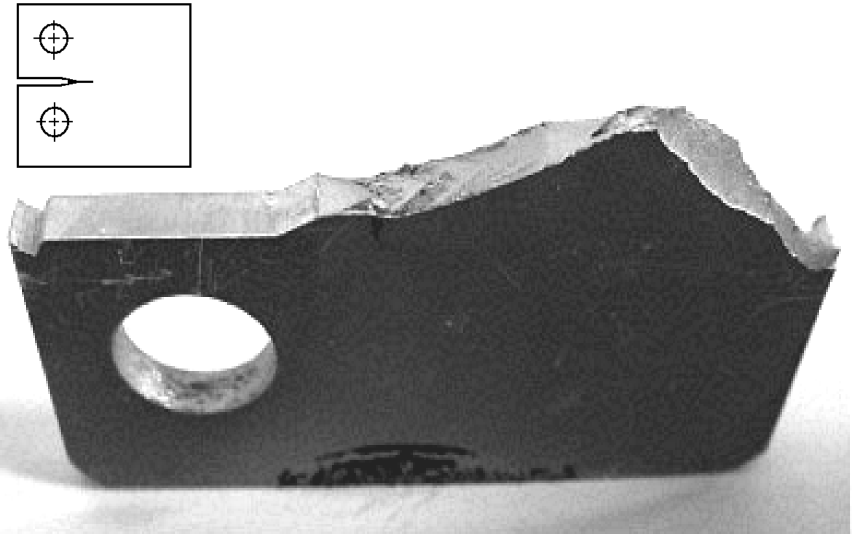


A through crack seen in the cross section of a welding





Crack propagated in a Al 8090 (an aluminum-lithium alloy developed primarily to reduce the weight of aircraft and aerospace structures)



Final fracture on a Compact Tension (CT) specimen (4 mm thick, 50 mm wide) from AL 8090 rolled plate, solution-treated and naturally aged.

From: E.M. Rodrigues et. al, *Fatigue crack growth resistance and crack closure behavior in two aluminum alloys for aeronautical applications*, Materials Research - Print ISSN 1516-1439 (on web)

In summary ...up to Section 9

- Already in the 19th century fatigue was recognized as a fracture phenomenon occurring after a large numbers of load cycles where a single load of the same magnitude would not do any harm.
- At that time it was considered mysterious that a fatigue fracture did not show visible plastic deformation.
- The problem was handled through a phenomenological approach, without an understanding of inner mechanisms
- A fundamental step regarding fatigue as a material problem was made in the beginning of the 20th century by Ewing and Humfrey in 1903: they carried out a microscopic investigation which showed that fatigue crack nuclei start as microcracks in slip bands.

In summary ...up to Section 9

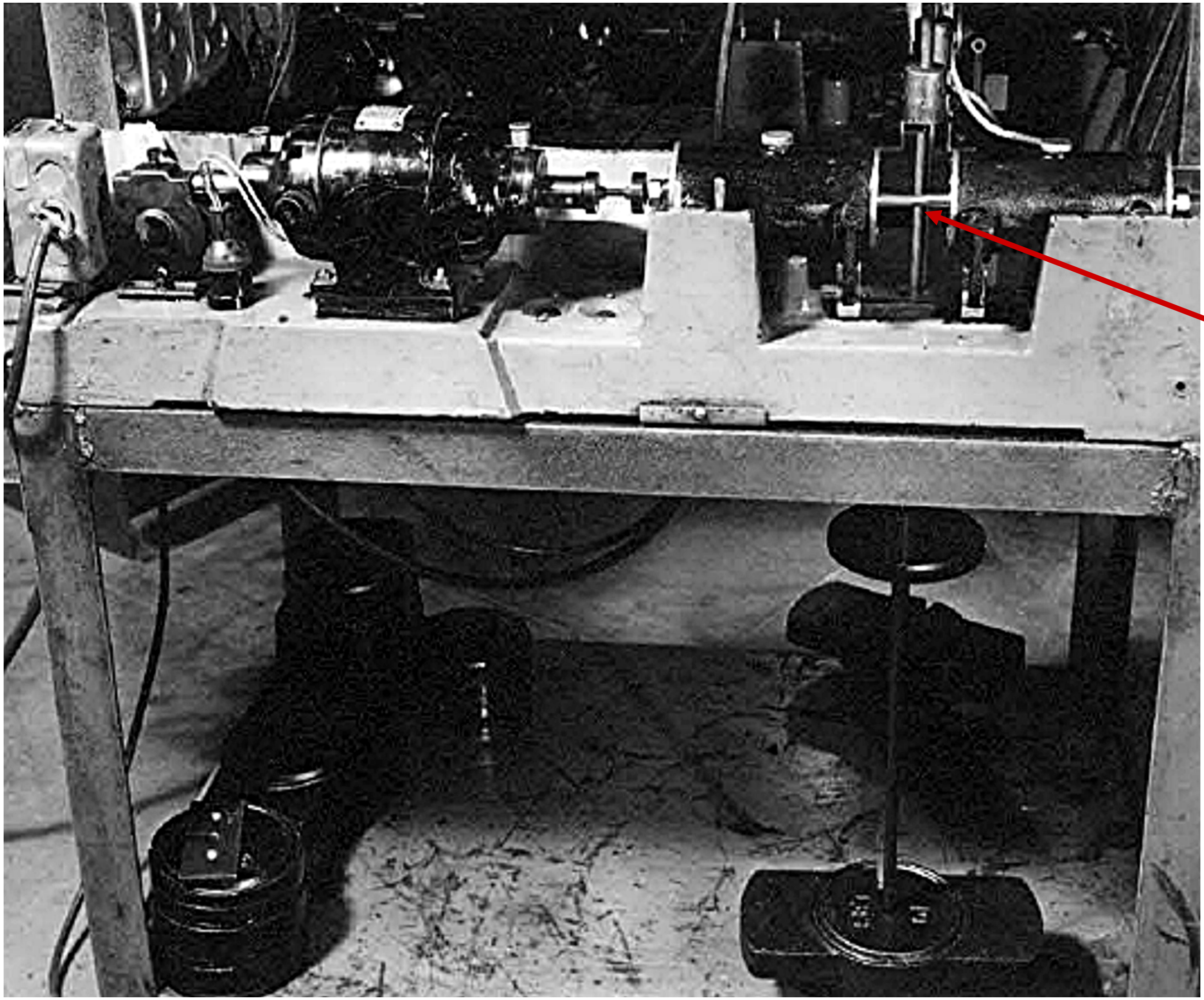
- Now we know that dislocations play a major role in the fatigue crack initiation phase.
- Large number of loading cycles dislocations pile up and form structures called persistent slip bands (PSB).
- 1st stage: PSBs are areas that rise above (extrusion) or fall below (intrusion) the surface of the component due to movement of material along slip planes.
- 2nd stage: tiny microcracks join together and begin to propagate through the material in a direction that is perpendicular to the maximum tensile stress.
- Eventually, the growth of one or a few crack of the larger cracks will dominate over the rest of the cracks, until failure.

Sections 10, 11 - Test machines, design to fatigue

Section 10 illustrates the test machines that have been or are currently in use to produce the experimental data on stress-controlled fatigue.

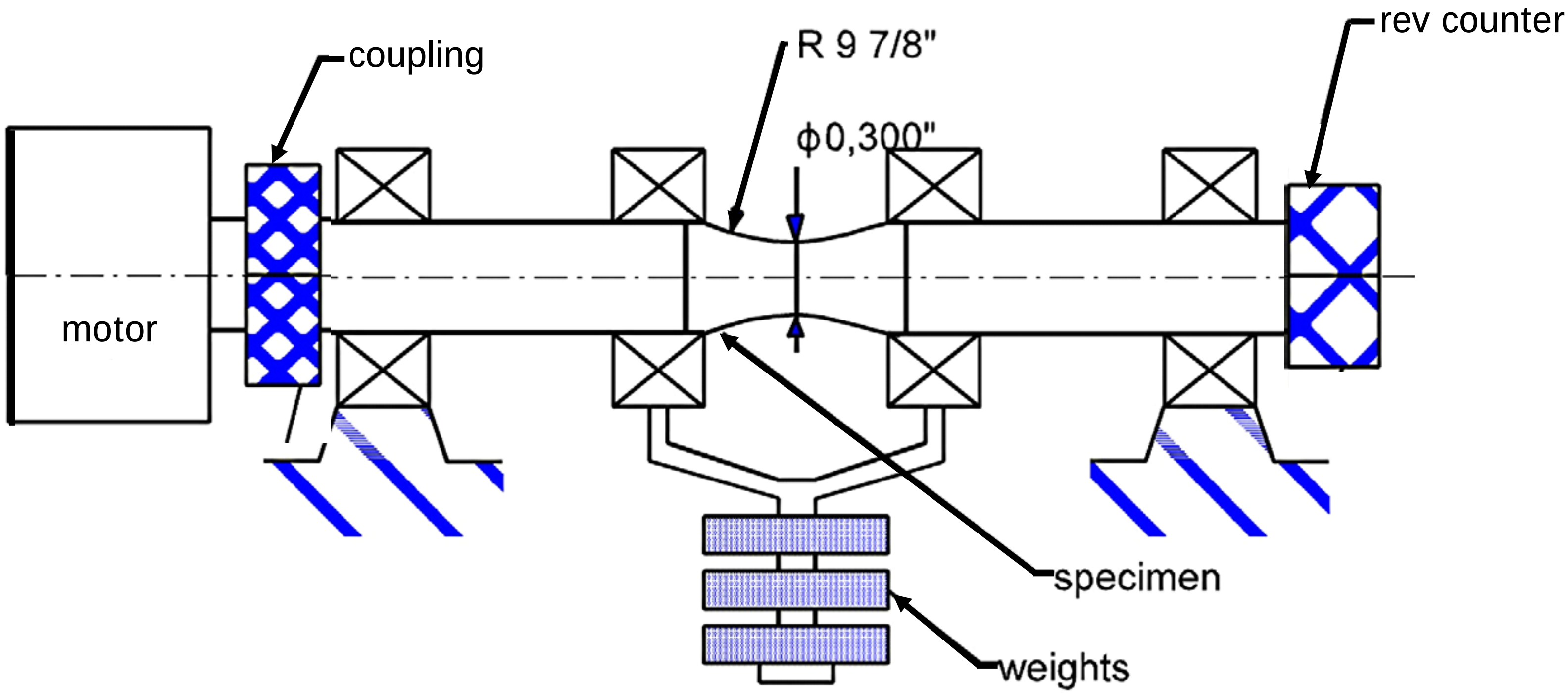
Section 11 is an overview on how data on crack incubation, crack growth/propagation and critical length are used by the designer to the purpose of determining when a failure will occur, and take appropriate safety margins against that.

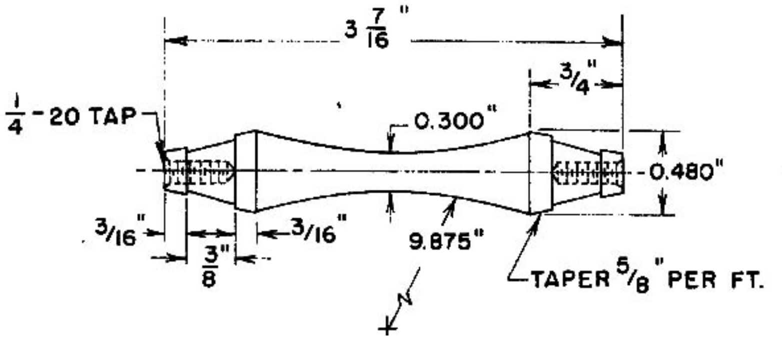
10. To-day's fatigue tests (1/5) : rotating bending



specimen

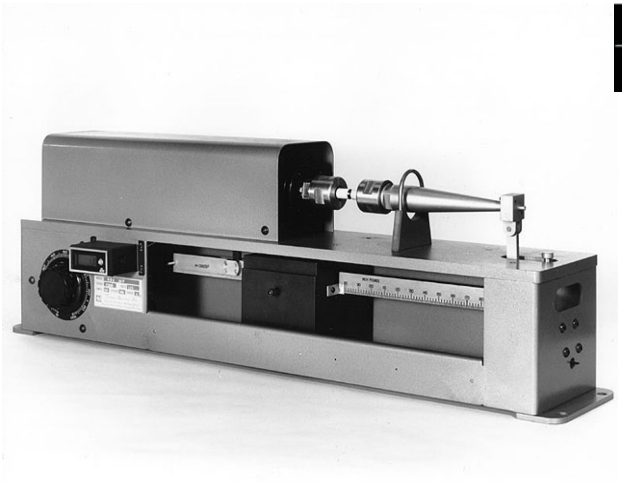
Early techniques: the H.F.Moore machine (around 1920)





Source: Dirk Pons, Mechanical Failure, New Zealand, 518 Hurunui Bluff Rd, Hawarden

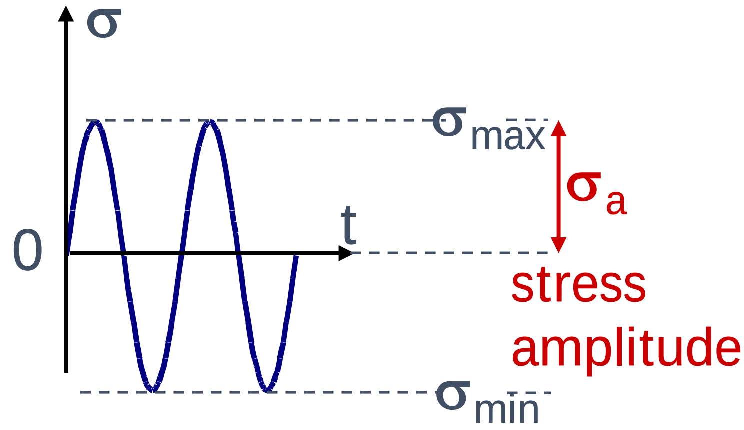
The Moore machine principle (four point bending) and its specimen according to ASTM Standard

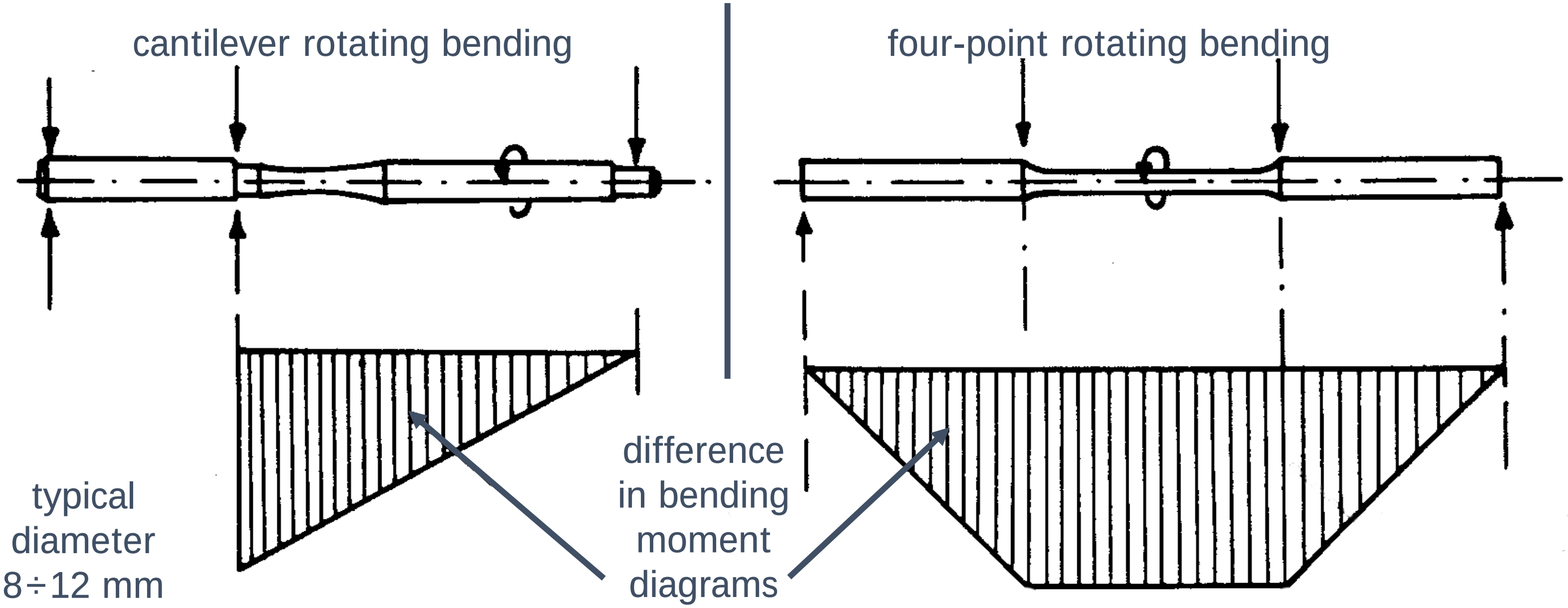


Model RBF-200

200 in-lb max bending moment

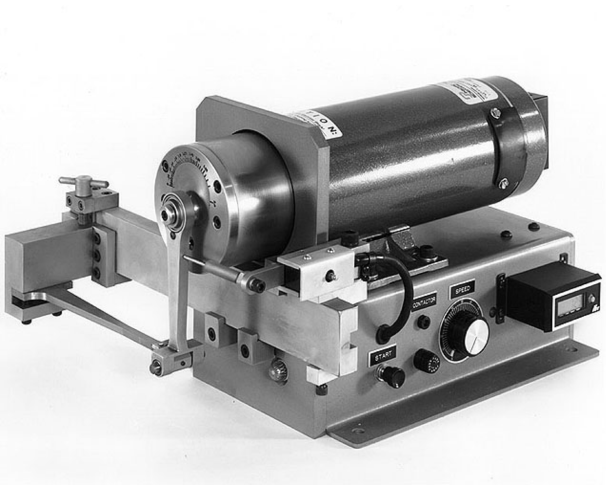
test speed 500÷10000 cycles/min





typical diameter 8÷12 mm

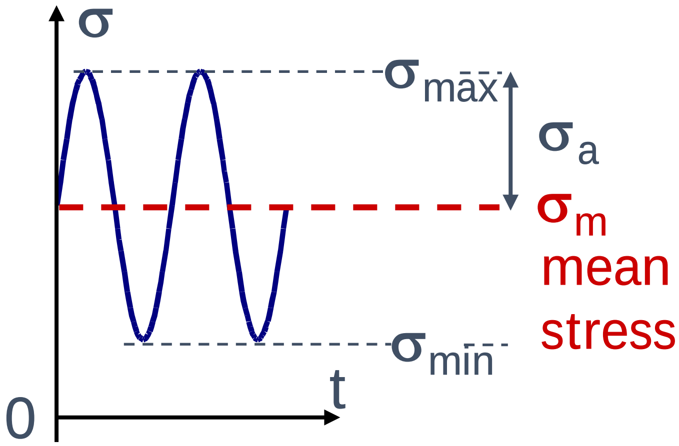
difference in bending moment diagrams



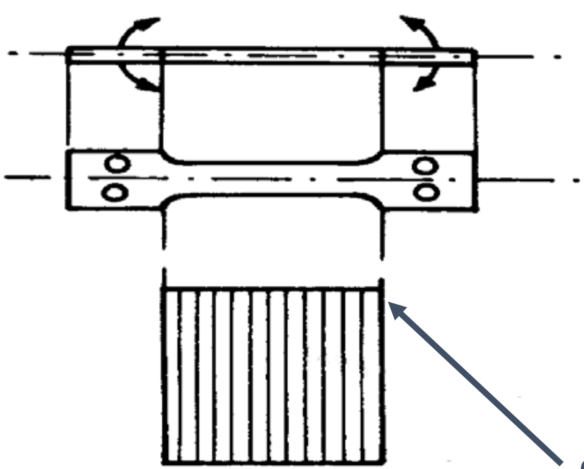
Model VSS-40H

max force 40 lb
max stroke 2"

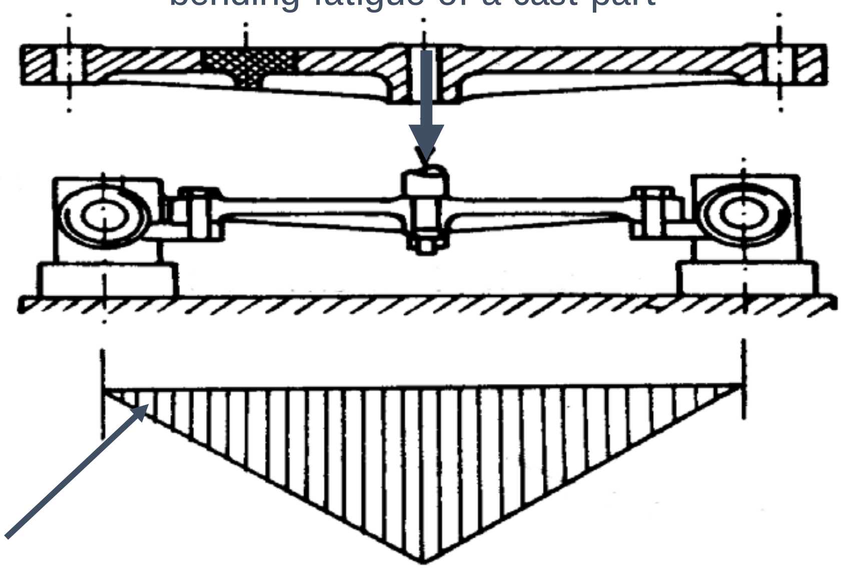
test speed
200÷2400
cycles/min



plane bending

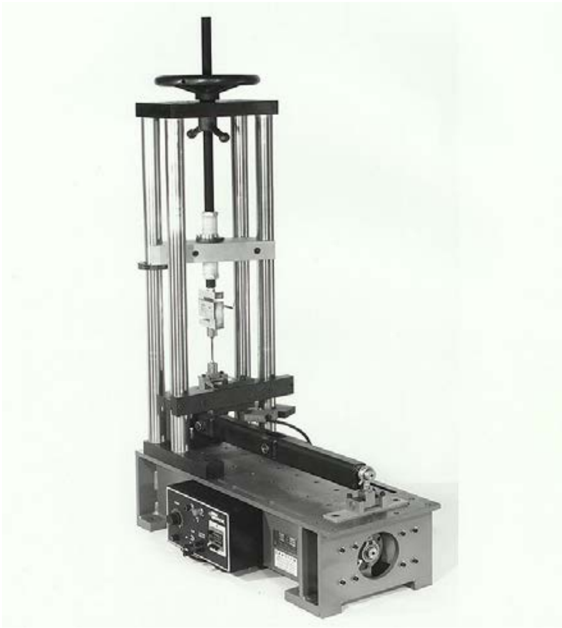


bending fatigue of a cast part



bending
moment
diagrams

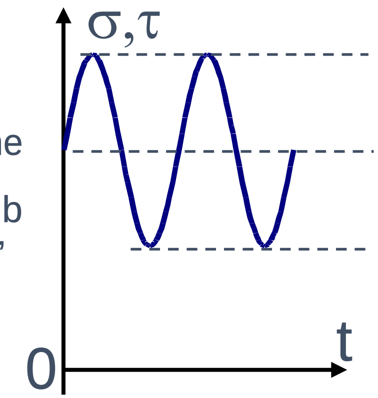
10. To-day’s fatigue tests (5/5) : axial and torsional



Model DS-6000
servo-hydraulic
axial test machine

max force 6000 lb
max stroke 0.12”

speed range
200÷2000
cycles/min



specimen on a 100 kN
AMSLER HFP 422
axial test

tension, threaded heads

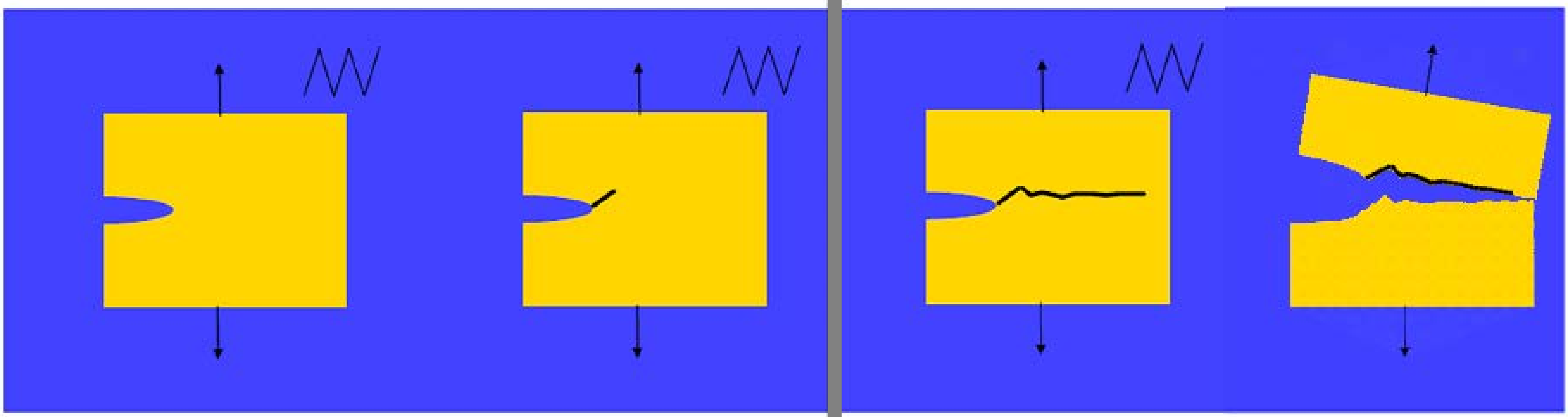
tension, shoulder heads

torsion

typical diameter
8÷12 mm

11. The Design point of view (1/5)

1. Will a crack nucleate? 2. Will it grow? 3. How fast will it grow ... to critical length?



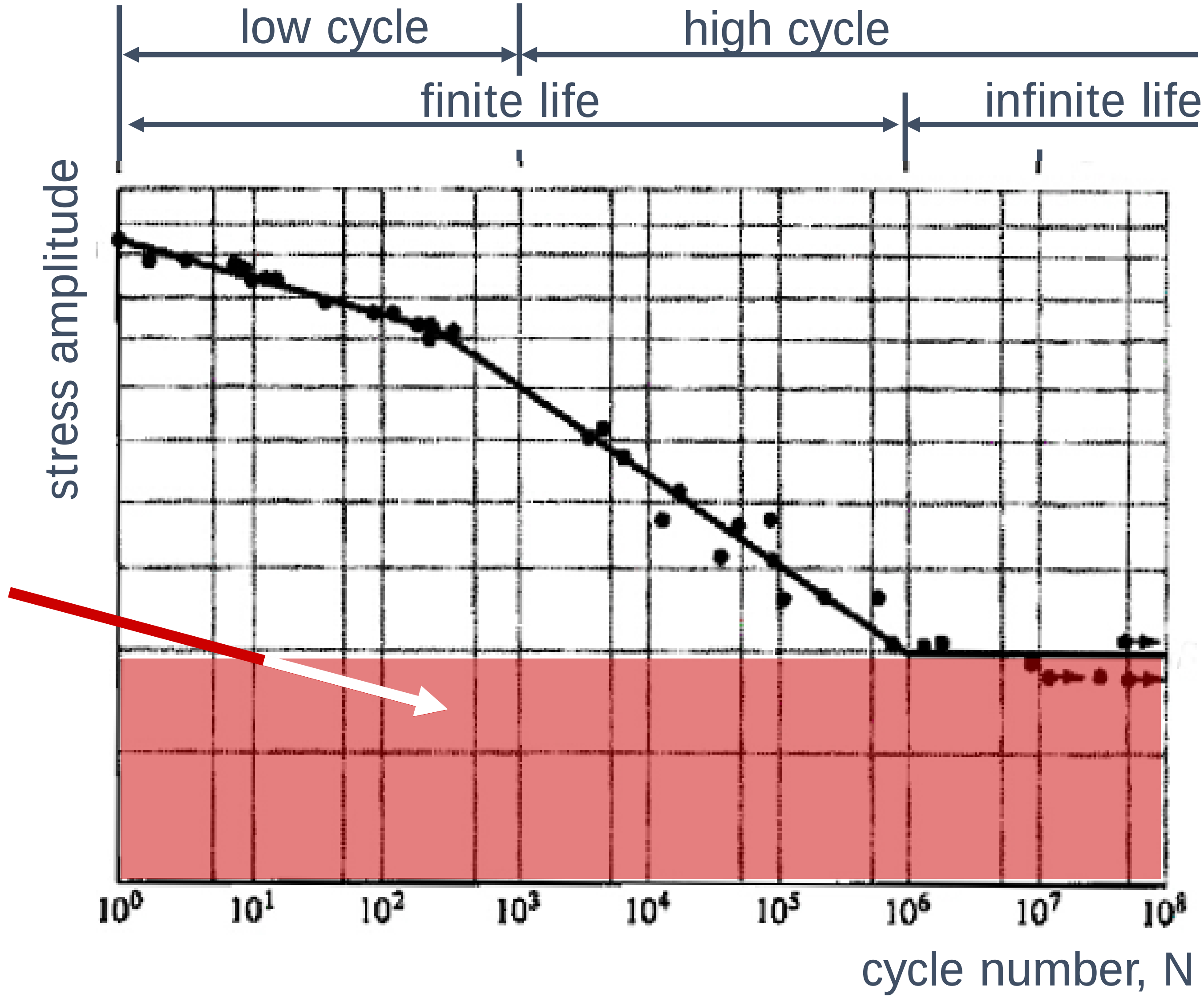
Cyclic nucleation and arrested growth — Crack growth — Final rupture

Infinite life — Finite life — Instability

A designer needs a theory and supporting experimental evidence to be able to answer the three main questions above.

Infinite life, avoiding crack nucleation:

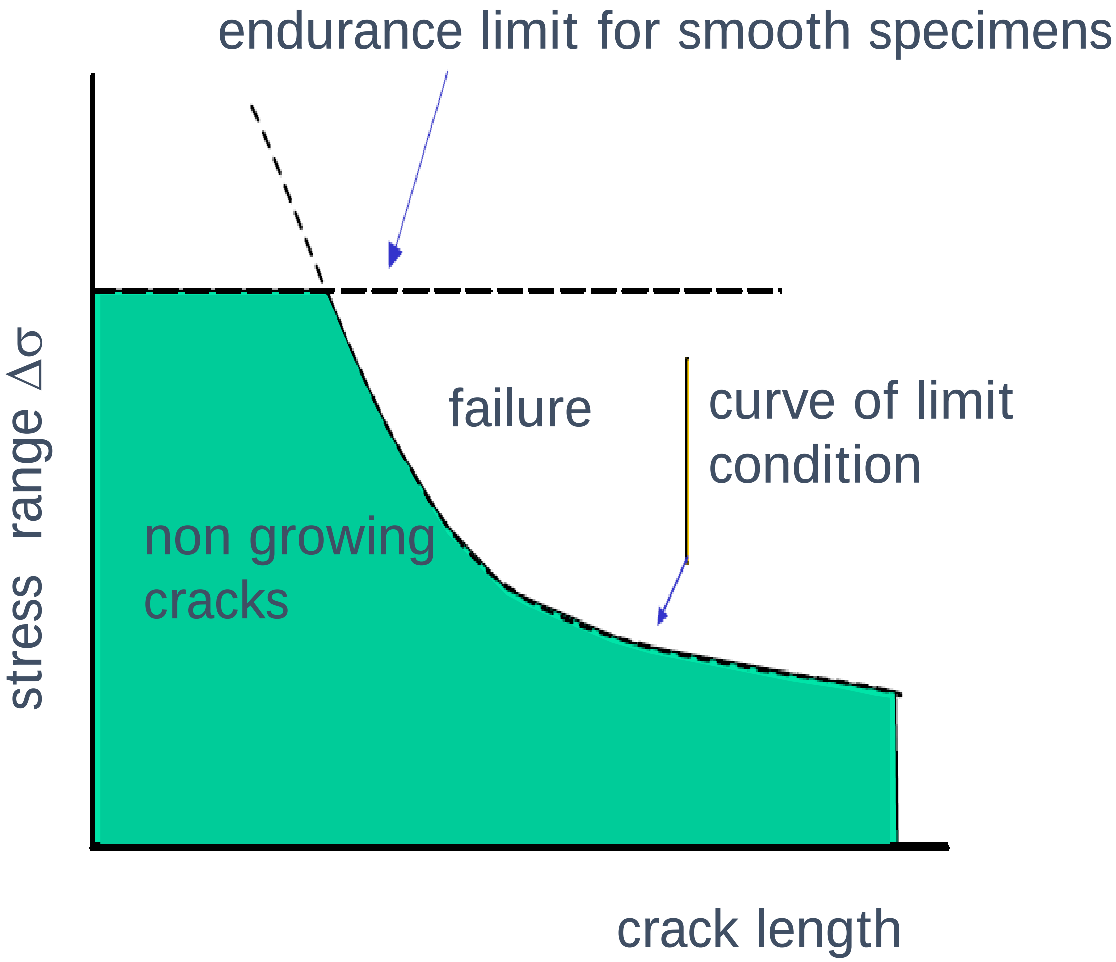
at a sufficiently low alternating stress no fatigue cracks will form.



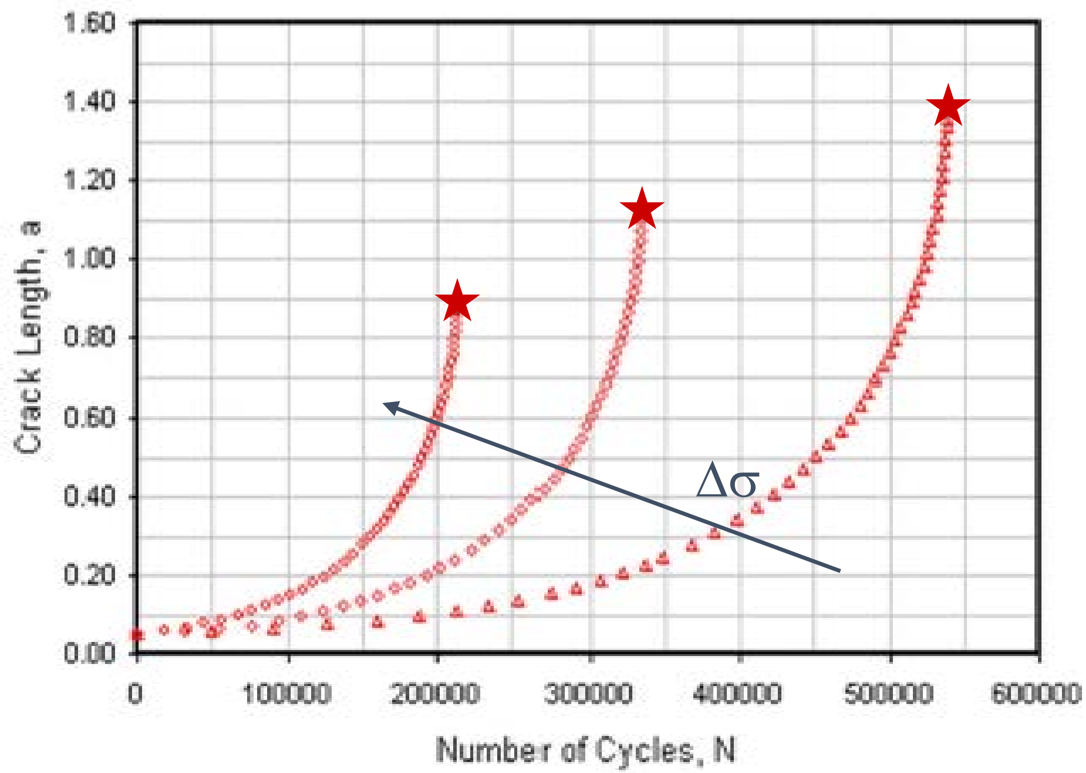
Infinite life, avoiding crack growth:

sharp notches may nucleate cracks but the remote, alternating stress may not be large enough to cause the crack to leave the notch

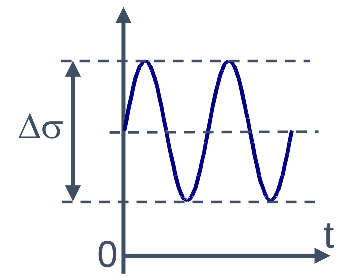
(where stresses are highest, then they decrease)



If we know the curves on the right, we may predict how long it will take before a crack will reach the unstable condition, marked ★ , where the crack length becomes "critical" , i.e., propagates under static load in zero time



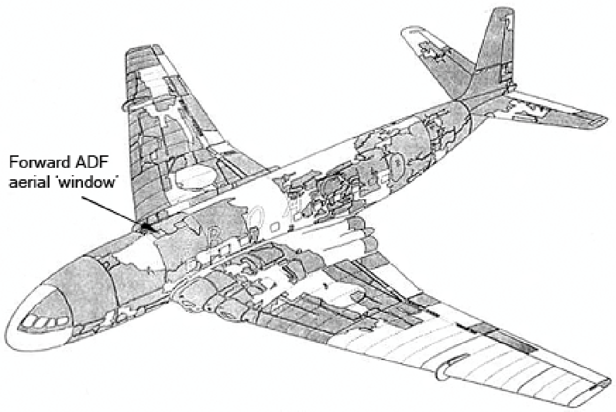
Curves of crack length with increasing number of cycles, at three values of stress range $\Delta\sigma$



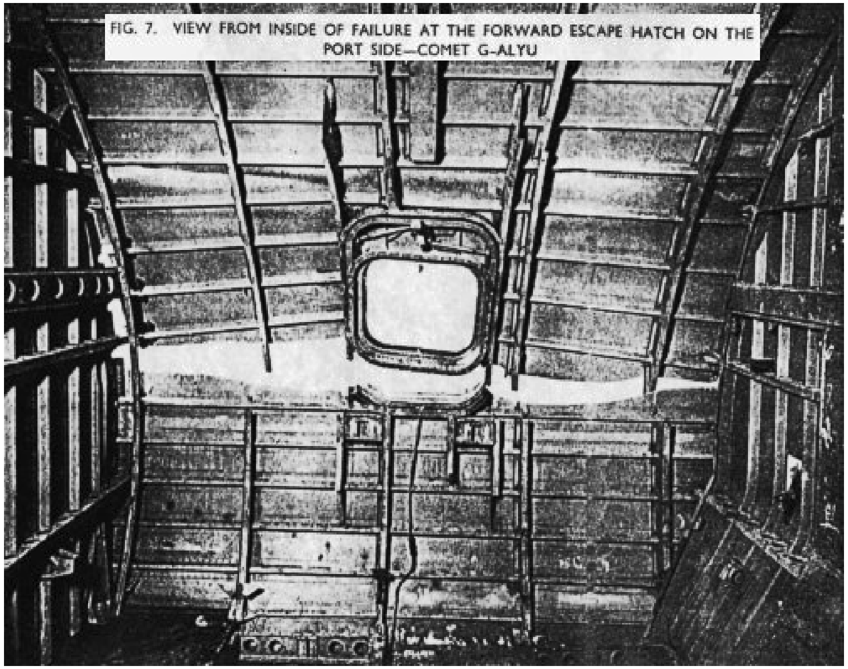
Structural failure of the De Havilland COMET airliner (1954)

After two planes were lost in 54, 10 Juanuary and 8 April - they broke in mid air and crashed in the sea - pressurisation cycles were simulated in in a dedicated water tank that was built specifically at Farnborough to accommodate the full length of G-ALYU aircraft .

Engineers subjected G-ALYU to repeated re-pressurisation and over-pressurisation, and on 24 June 1954, after 3,057 flight cycles (1,221 actual and 1,836 simulated) G-ALYU burst open. The picture shows the ruptured section of the cabin wall.



The recovered (shaded) parts of the wreckage of *G-ALYP* (lost 10 January) and the site (arrow) of the failure



Sections 12, 13 - Diagnosing fatigue failures

Sections 12, 13 introduce the reader to the appearance of a small number of fatigue fracture cases, limited to visual observation.

Surfaces display patterns which can be related to crack initiation areas, crack propagation and final rupture of the reduced cross section. Section 13 gives elements to diagnose shaft failures.

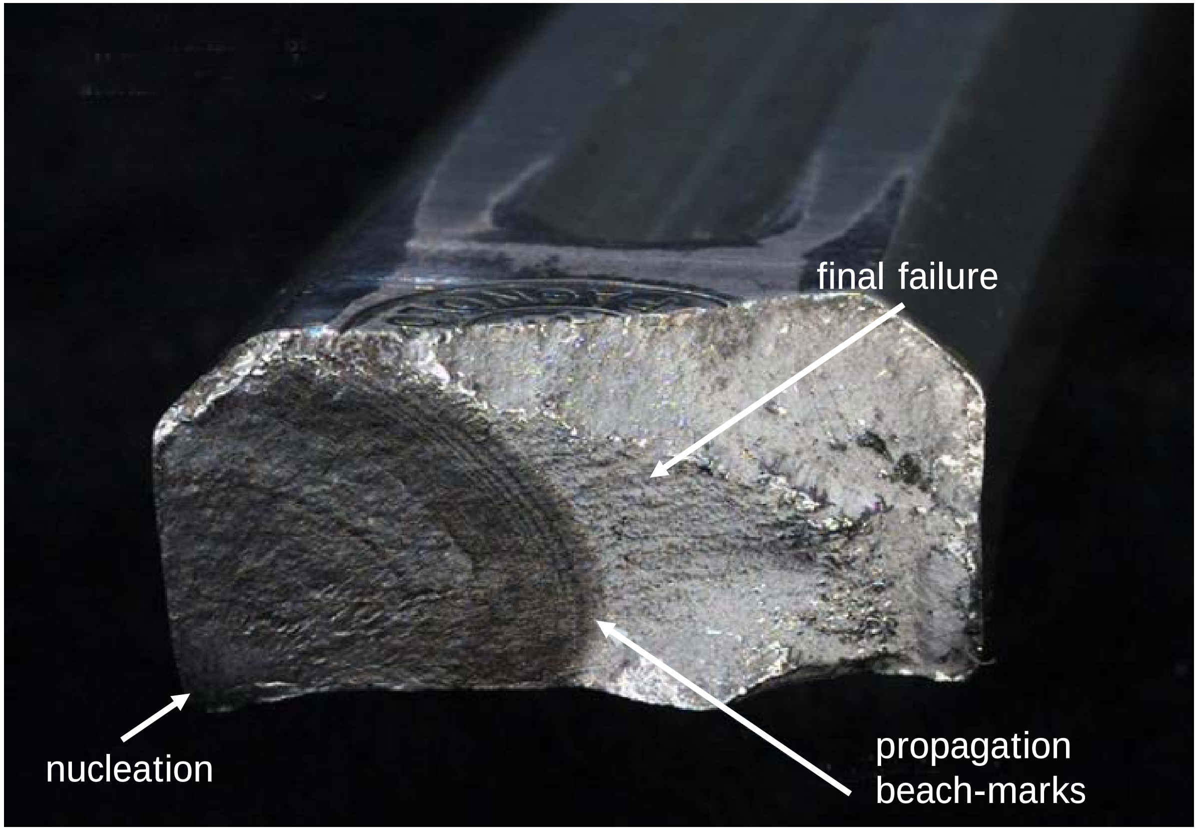
The reader is warned that the treatment of the subject is here just a first approach, and that it does not examine all the techniques which are necessary to decide whether fatigue failure was the effect of a deficient design, or poor material, or mistakes in manufacturing. Was the part abused or defective? Much should be known to answer this question.

Many defects are visible only with microscopes, which require expert use and expert interpretation. The advent of scanning electron microscopes has helped to provide a more fact based foundation to judgment. Talking to a material engineer is a good idea, in these cases.

The inquisitive reader is urged to deepen the knowledge with a book such as:
ASM Handbook, Vol. 11, Failure Analysis and Prevention, ASM International, 2002, pages 1164, ISBN: 978-0-87170-704-8 www.asminternational.org

Bicycle crank failure (bending)

The fatigue crack initiated exactly at the location of the maximum tensile bending moment, close to the crank axle on the tensile side of the crank

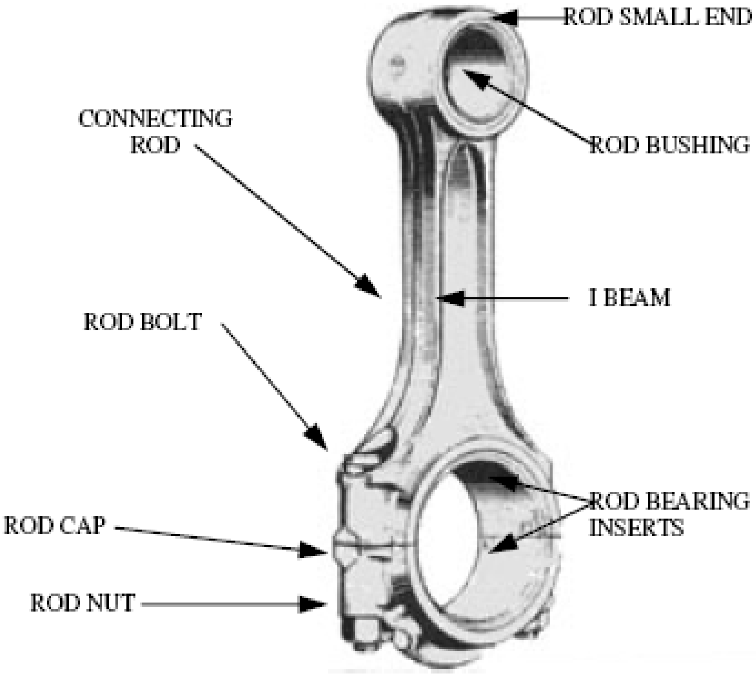


The crack progressed slowly through the crank arm (dark area) until the remaining fragment was incapable of supporting the bending moment generated by the force on the pedal and the crank arm fractured rapidly.

12. Fatigue failure diagnosis - examples (2/9)

Failure on a reciprocating piston engine connecting rod (conrod). Rupture in the rod cap. Crack is initiated at the low-left corner, then propagates with evident beach-marks.

Courtesy RTM BREDA



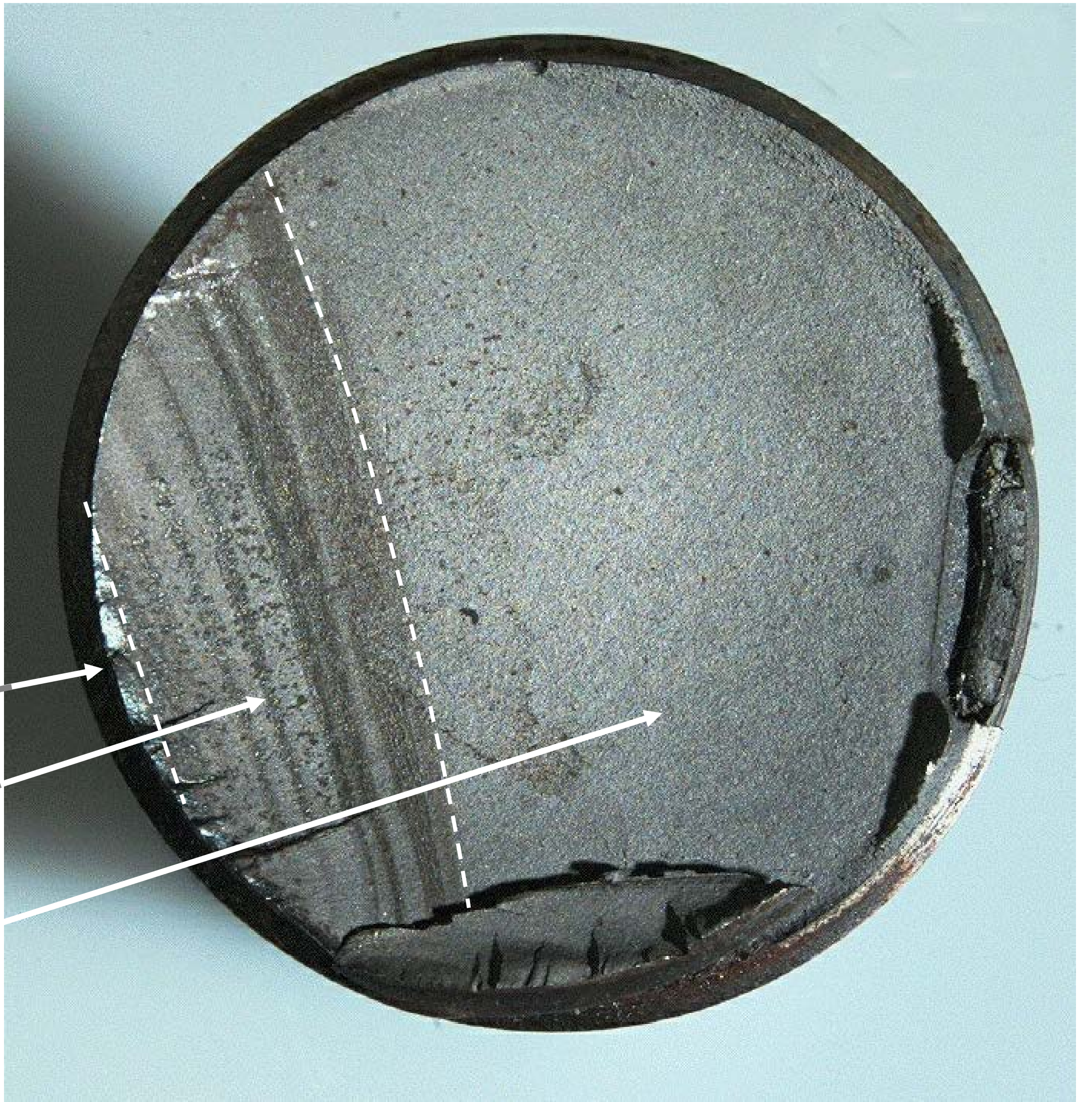
Bolt Failure

This high tensile steel bolt failed under low stress amplitude, high mean stress, high number of cycles (tension).
Nucleation started at the thread root.

Crack nucleation

Beach-marks

Final fracture



12. Fatigue failure diagnosis - examples (4/9)

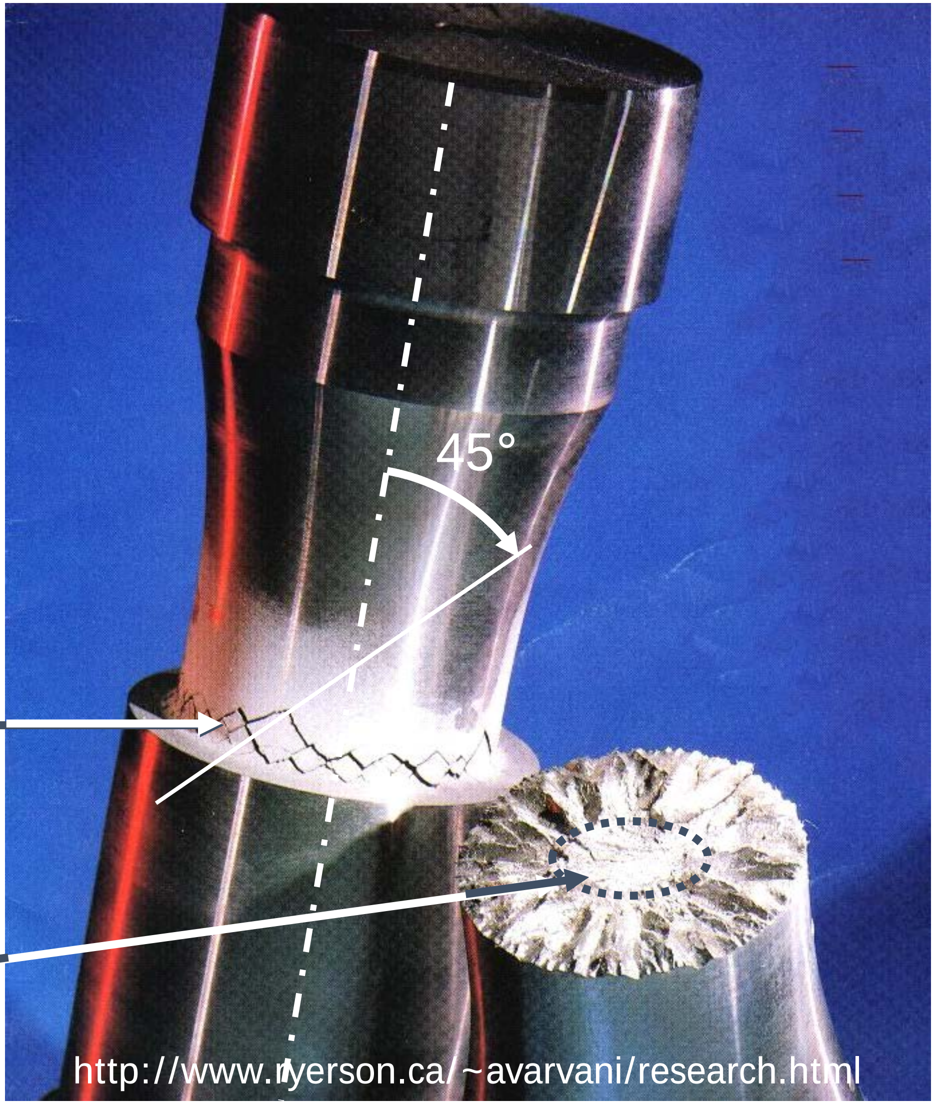
Shaft under torsional load

Nucleation started somewhere at the outer diameter near at the fillet radius of the shoulder.

Torsional moment was alternating.

Stresses propagated multiple cracks on the principal stress (when in tension) planes at 45° to the axis (star pattern).

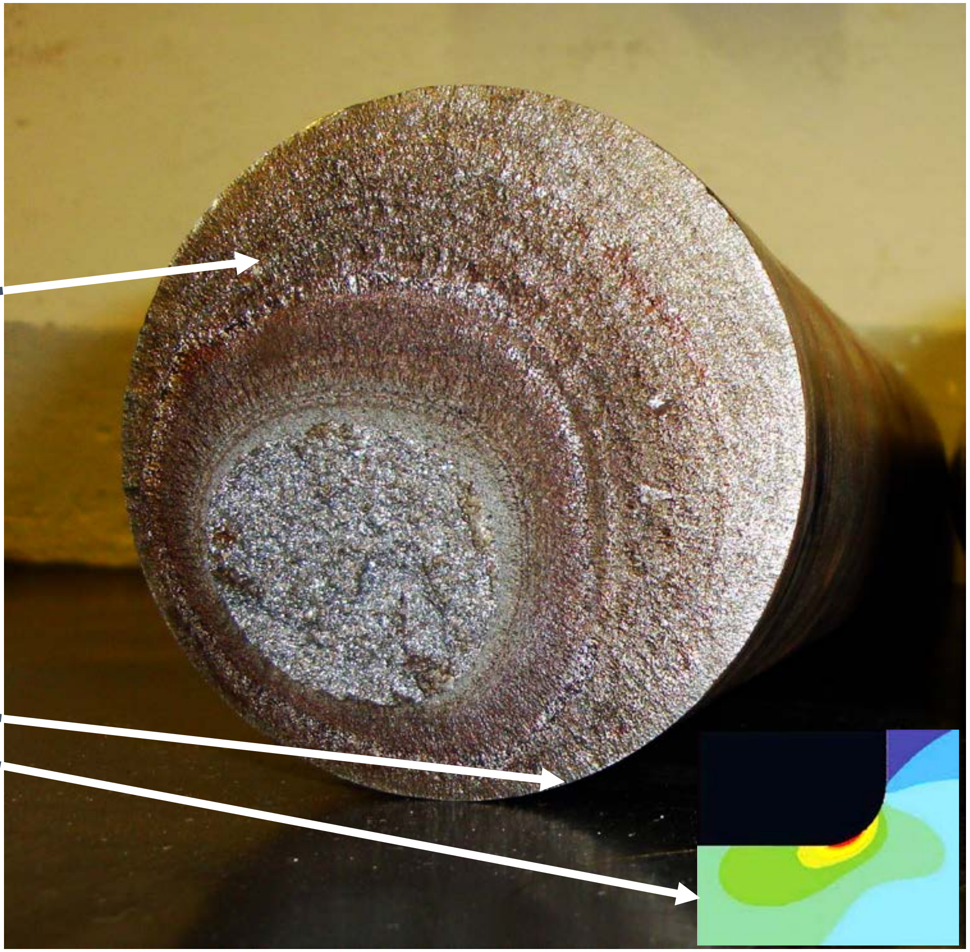
Cracks propagated to the interior gradually reducing net section and shaft static strength, until final static failure.



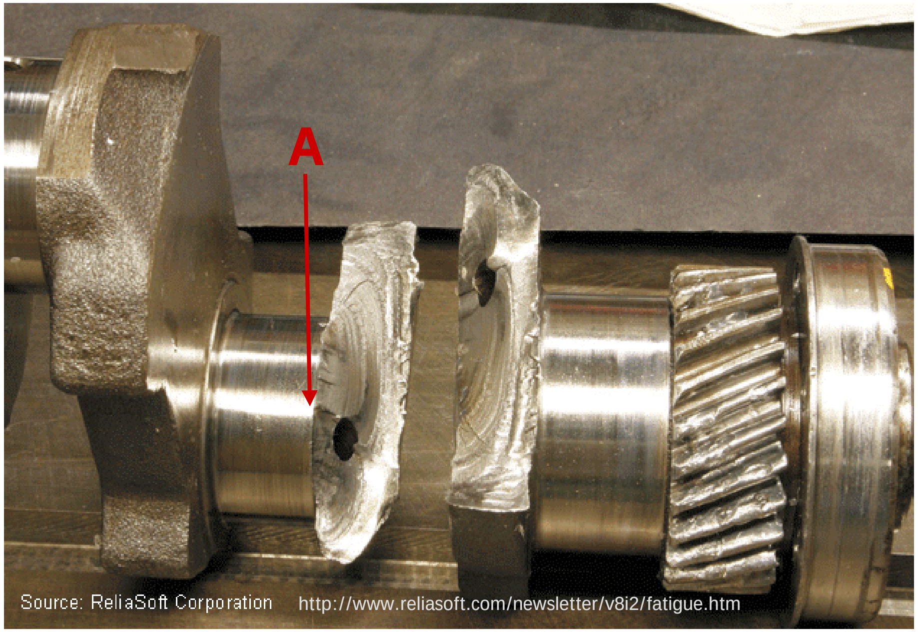
Combined bending and torsion produces this final static failure area which, unlike the case of pure torsion (see one slide back) is not central but eccentric.

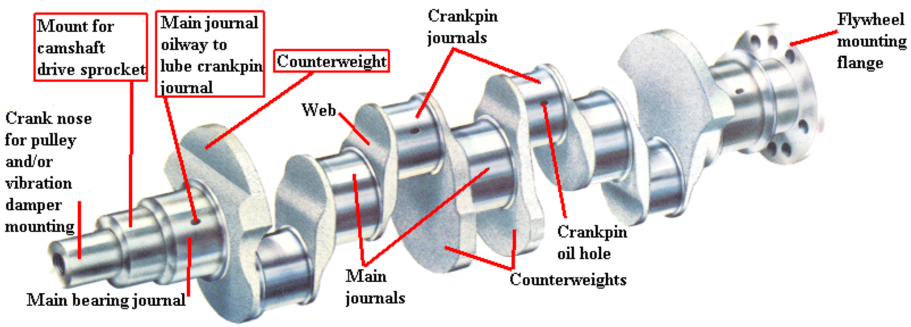
Beach-marks are visible; crack nucleation is not evident in this picture; however, it occurred at the root of a shaft shoulder.

Shaft in rotating bending and torsion



Crank-shaft fatigue failure





http://www.ustudy.in/node/4970

A crack was originated at the fillet between the crankpin journal and the web not far from the crankpin oil hole (point A).

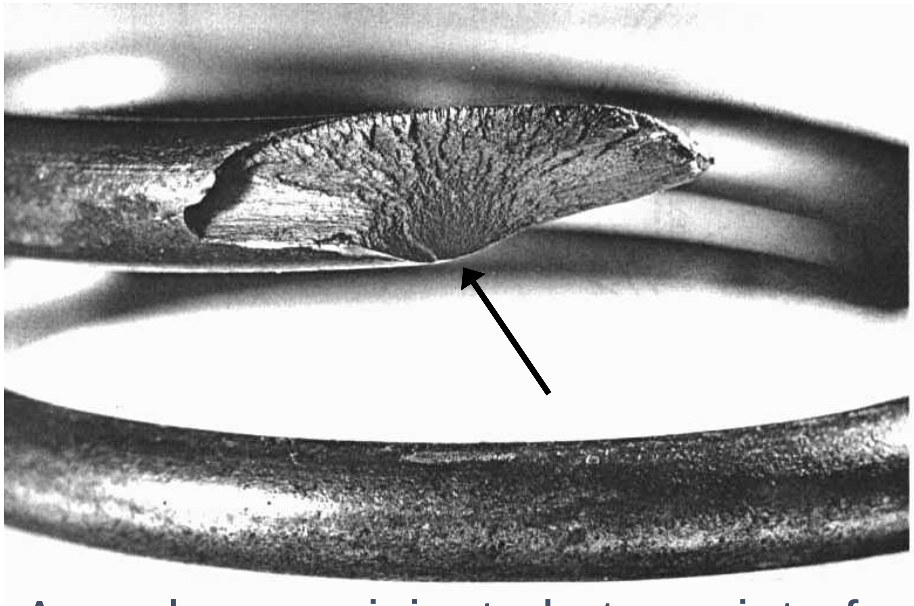
Note that the separated crank-shaft on the right is upside down.

The crack was produced by bending.

It then propagated into the web (darker zone) until the web section was reduced, the propagation speed increased, with more visile beach-marks, to final failure with plastic lips.

At separation, the right section rotated enough to damage the teeth of the helical gear placed near the main journal.

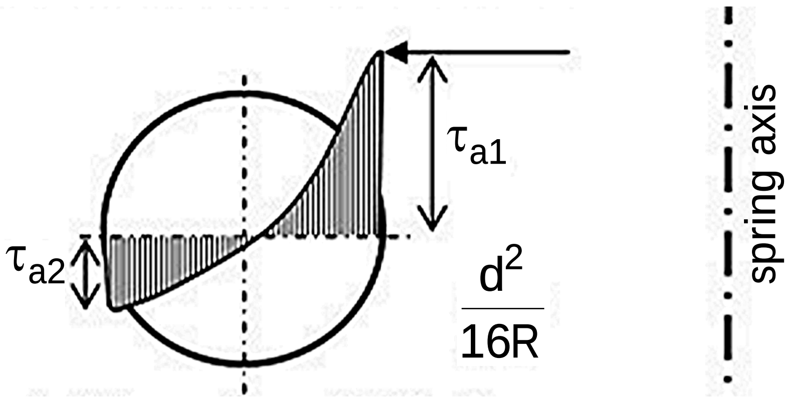
Helical spring fatigue failure



A crack was originated at a point of the spring surface, due to a local material or surface imperfection.

Failure is attributed to fatigue since - in this case - the loads applied to the spring are under control, and produce stresses below yield stress with certainty.

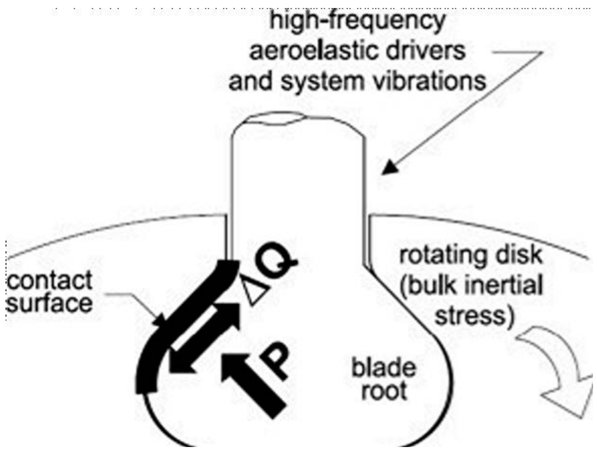
The crack source at the inner surface of the wire may be a combination of the fact that here the stresses are higher:



and that stress raisers may occur due to poor manufacture or to corrosion (investigation here not discussed).

The crack then propagates at 45° on the plane of maximum tensile stress.

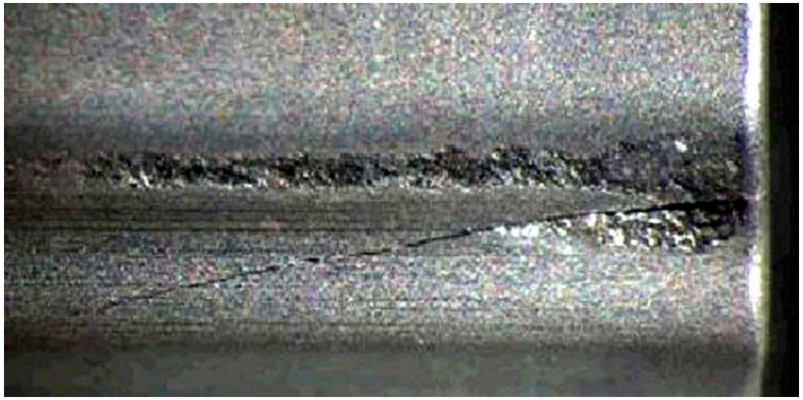
A typical fretting fatigue contact case present at the dovetail notch of blade disk components in rotating aircraft engines.



Example on a dovetail: fretting is due to sliding under high contact forces, when the disk expands due to thermal and centrifugal factors from idle to full speed.

Left: a crack is generated from the location of fretting.

Below: detail of a fretted blade root contact.

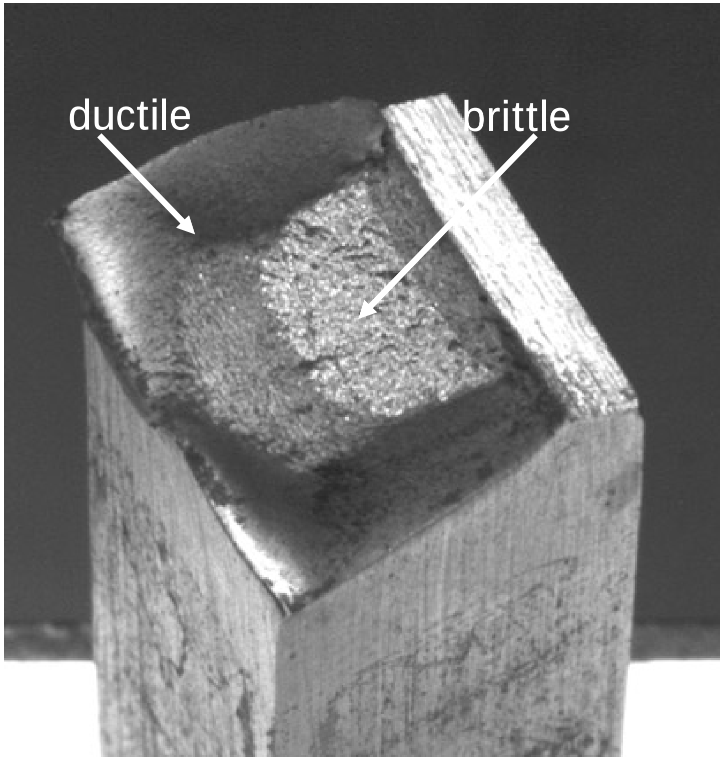


How does a cracked cross section finally fail?

The - difficult - answer is given by Fracture Mechanics: according to material and part geometry, the type of failure will be somewhere between two extreme situations:

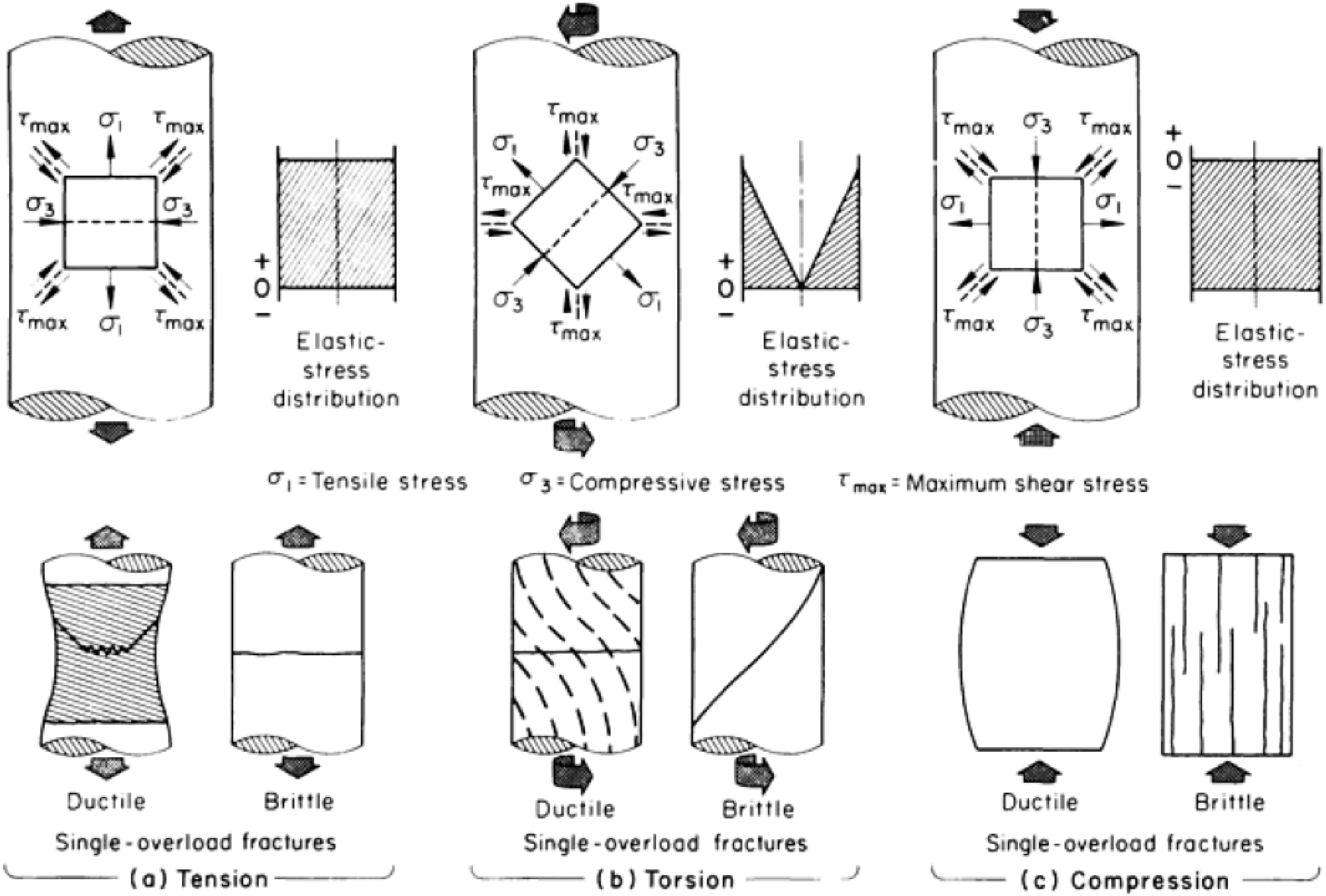
1 – fully ductile: the reduced cross section fails at yield, exactly as it would happen in a smooth specimen under tension with the same cross section area

2 – fully brittle: the reduced cross section fails in a brittle manner because the crack becomes unstable, i.e. it propagates all of a sudden



mixed brittle-ductile failure

However, pat attention to the fact that this figure DOES NOT refer to a cracked specimen under fatigue, but to a Charpy impact test on a notched specimen.



Stress system and single overload failure on unnotched shafts (reminder)

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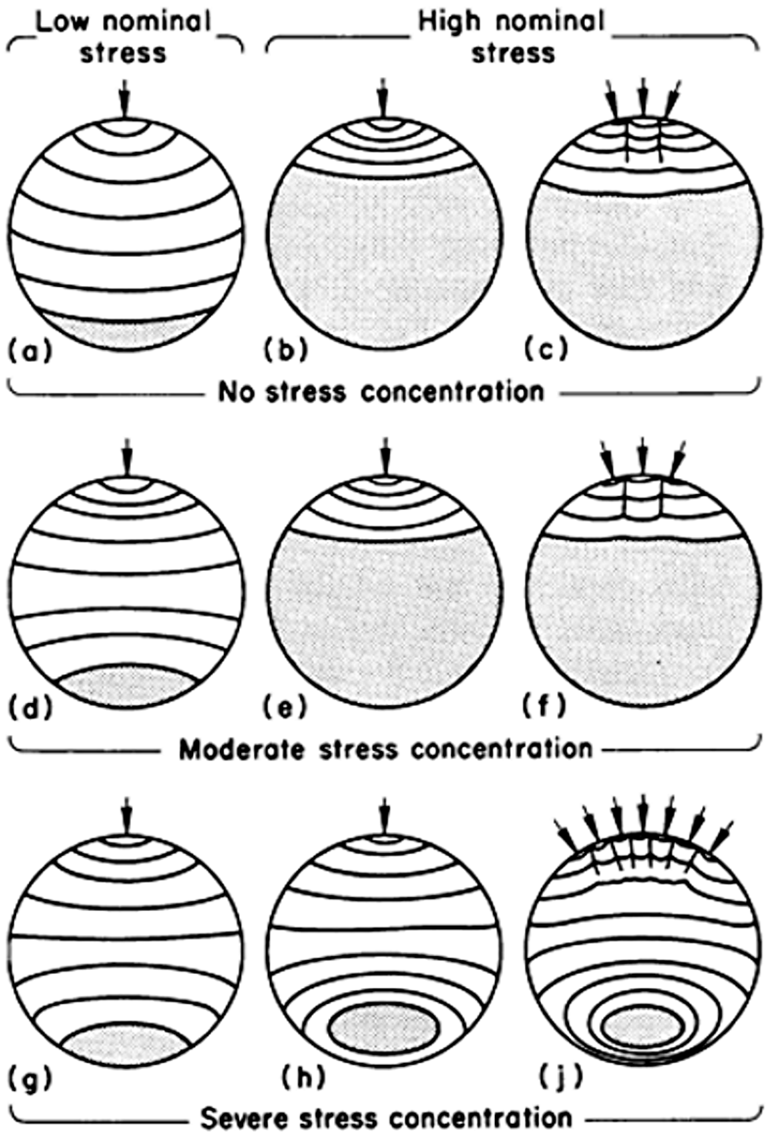

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Beach-marks (lines) and final fracture zones (shaded areas) on the cross section of non-rotating shafts subjected to uni-directional bending.

Arrows indicate crack origins. Nominal stresses (i.e. bending stresses without the local effect of stress concentration, when present, typically a fillet radius on shoulder) can be either low or high: this determines the dimension of the final fracture zone.

Presence of the fillet radius makes the crack front concave due to higher propagation speed at the fillet surface where stresses are at their highest.

These figures have a less than obvious explanation. Keep in mind that fatigue crack incubation depend on local stresses vs. fatigue strength, while final failure depends mostly on nominal bending stresses (specially with ductile materials) vs. tensile strength. In cases (h) and (j) nominal stresses cannot be really high, because of the severe stress concentration.

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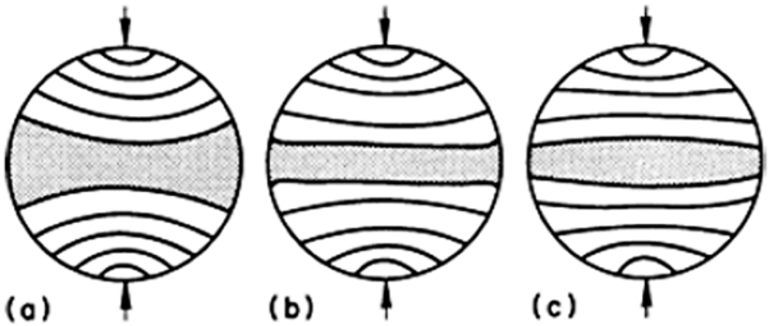
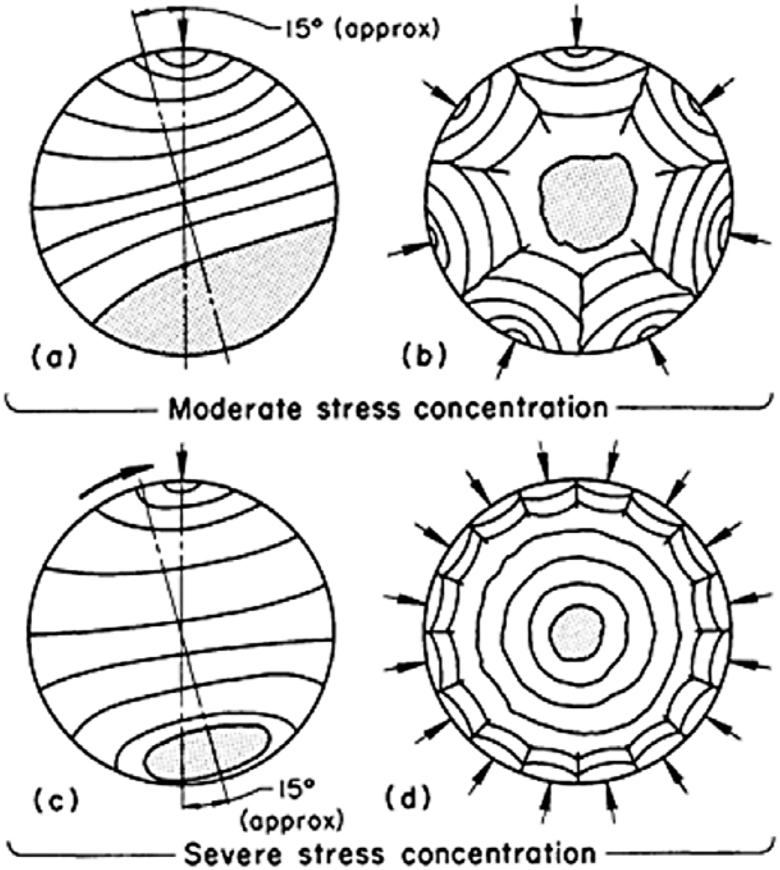


Beach-marks (lines) and final fracture zones (shaded areas) on the cross section of non-rotating shafts subjected to reversed bending.
a) no stress concentration
b) moderate stress concentration
c) severe stress concentration

Arrows indicate crack origins. Pattern in (c) is different from (a) and (b) because the fatifue crack propagates faster in the severe stress concentration peripheral zone - typically a small fillet at a shoulder - than in the interior.

Under these conditions, each crack is subjected alternatively to tensile and compresisve stresses, with the result that the crack surfaces are forced into contact with one another during the compression cycle. Rubbing then occurs, and is sufficient to “fret” the beach-marks: the crack surfaces may then become dull or polished.

In non-rotating shafts subjected to reverse bending, the origins of cracks are two and diametrically opposite, while in uni-directional bending the origin is in the location of the maximum tensile stress.



Beach-marks (lines) and final fracture zones (shaded areas) on the cross section of rotating shafts subjected to bending and torsion.

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The essential difference between a stationary shaft and a rotating shaft subjected to the same bending moment is that in a stationary shaft the highest tensile stress is confined to a portion of the periphery, while in a rotating shaft every point on the periphery cyclically sustains the same tensile stress followed by the same compressive stress once every revolution, and can then initiate the crack.

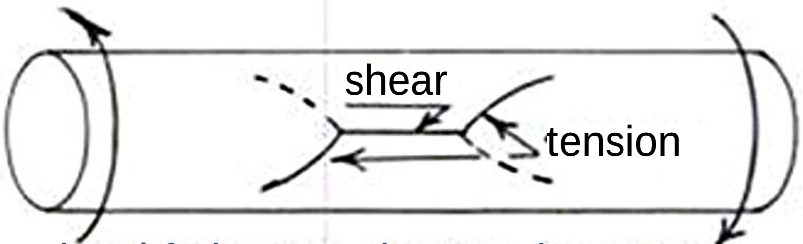
These stress values are changed from point to point only in case of imbalance of the shaft.

Another difference introduced by rotation is the asymmetrical development of the crack from a single origin: there is a marked tendency of the crack front to extend preferentially in a direction opposite to that of rotation (15° or more – shaft rotation in the figure is clockwise).

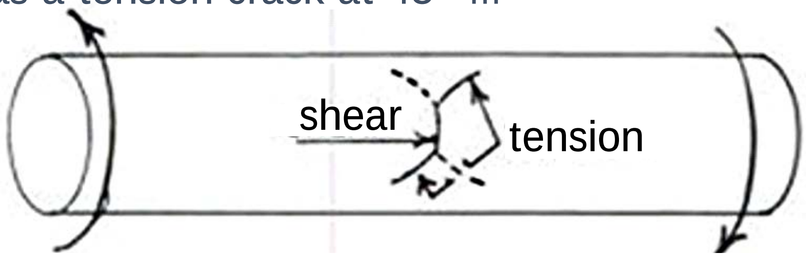
The third difference is the distribution of the initiation sites when the origin may be multiple, due to the high stress concentration.

Torsion on shafts is most often combined with rotating bending. It produces beach-marks and final fracture zones as in rotating bending. They however have different frequencies.

In the case of pure torsion:



Torsional fatigue crack started on a longitudinal shear plane, the propagated as a tension crack at 45° ...



... or started as a transverse shear crack and propagated as a tension crack at 45°

Cracks in pure torsion are originated at the surface, where stresses are highest. This is true also for torsion and bending combinations.

Longitudinal stress raisers, such as splines and keyways, which are comparatively harmless under bending stresses, are important under torsional loading.

The sensitivity of shafts loaded in torsion to longitudinal stress raisers is of considerable practical importance because inclusions in the shaft material are almost always parallel to axis of rotation.

It is usual to see a torsional fatigue crack to originate at a longitudinal inclusion, a surface mark, or a spline or keyway corner and then to branch at about 45°. A conical or a star-shaped fracture surface is then produced.

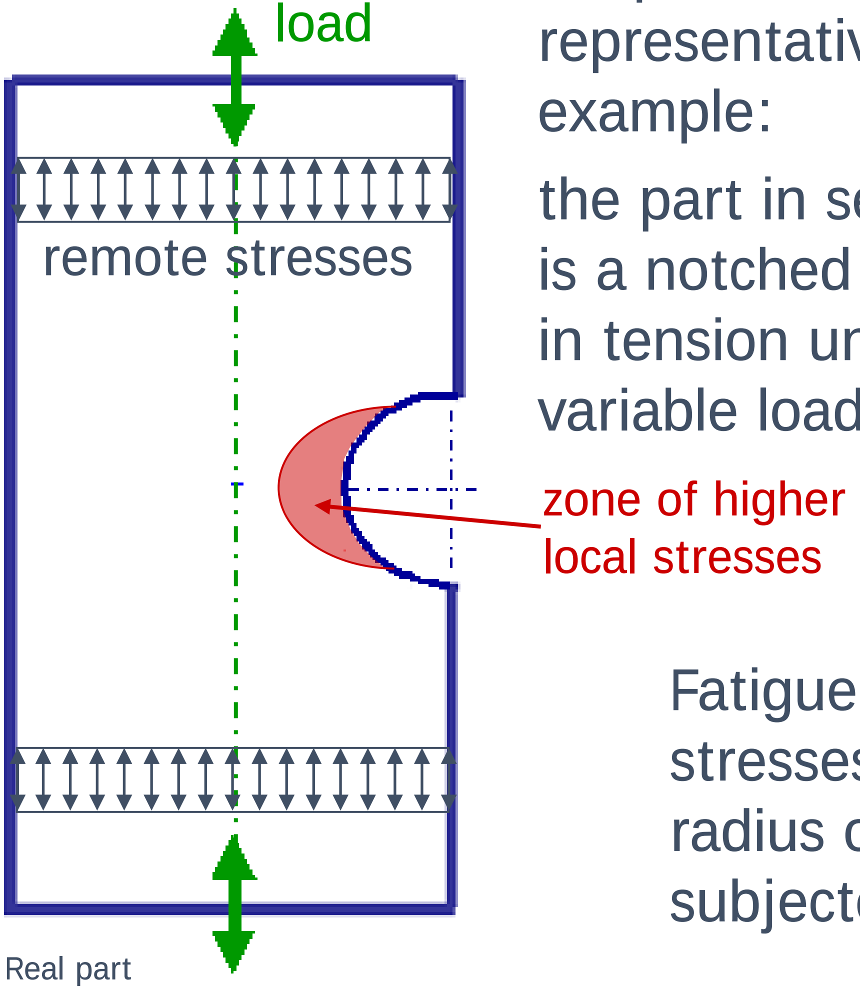
A one sided torsion, like in helical springs, produces a failure on a spiral at 45°. Reversed torsion produces a star shaped failure, as it involves both planes ±45° to the axis.

Section 14 - Tests for predictions or for validations

Section 14 treats the different roles that testing fatigue and fracture properties of materials takes in the context of engineering design.

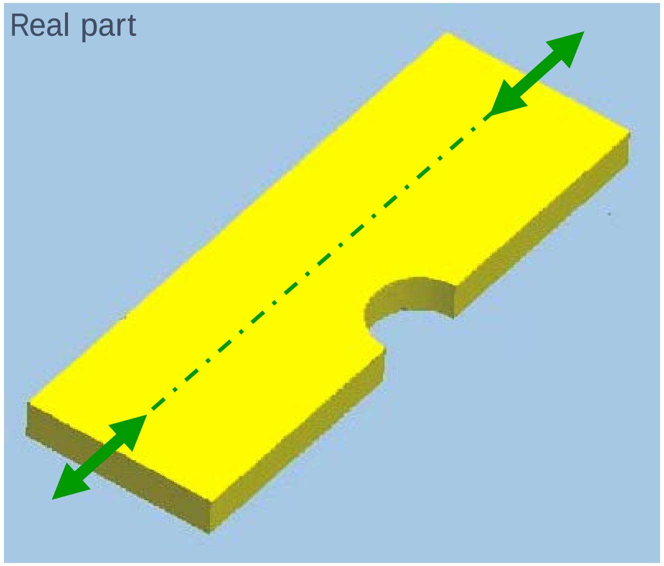
In a first approach, the component is tested at full scale and with the manufacturing technologies employed in production. This is expensive and lengthy. It does not eliminate all uncertainties as the testing loads are anyway different from real service loads.

In a second approach, data gathered in the laboratory on the same component material, but on reduced scale specimens. The relation between the component condition and the specimen behavior is established by means of a fatigue/fracture failure “model”, and conclusions are drawn about the real component on the basis that equal conditions shall produce equal effects. This of course requires certainty that the governing parameters are under control, i.e. that the “model” takes them all into account, and that experimental data from specimens have a statistical dispersion which is compatible with the required safety factor.



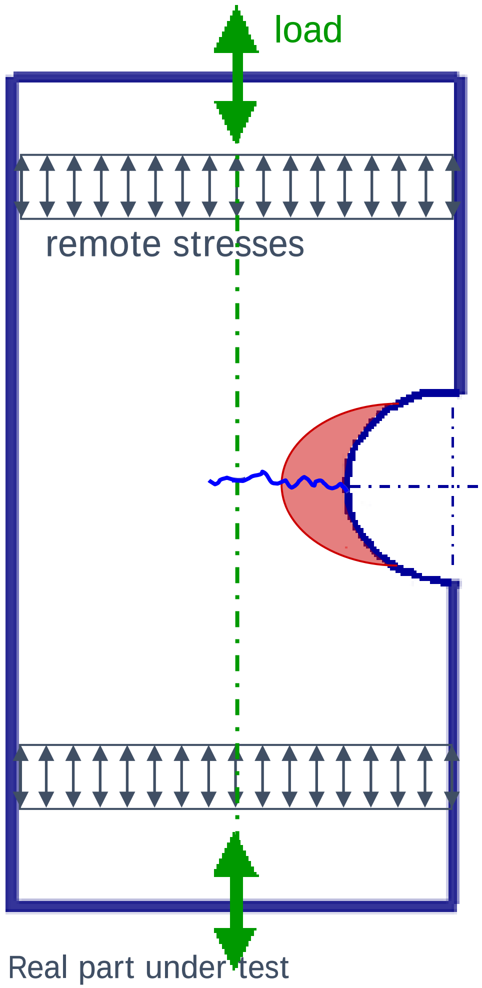
Simple but representative example:

the part in service is a notched plate in tension under variable loads

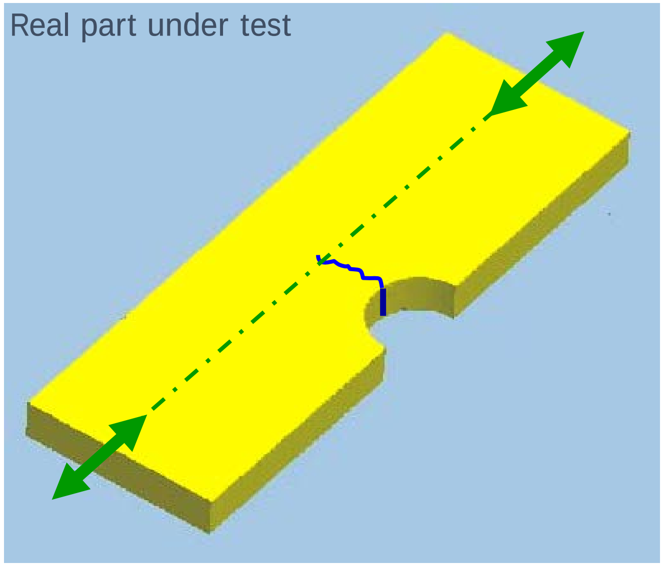


Fatigue is started at the location of higher stresses, in this example, at the inner radius of a circular “notch” on a flat plate subjected to a tensile stress.

Approach 1 - Test on the real full-size part



(problems:
how many tests are necessary to get a fair picture?
how expensive are they?)

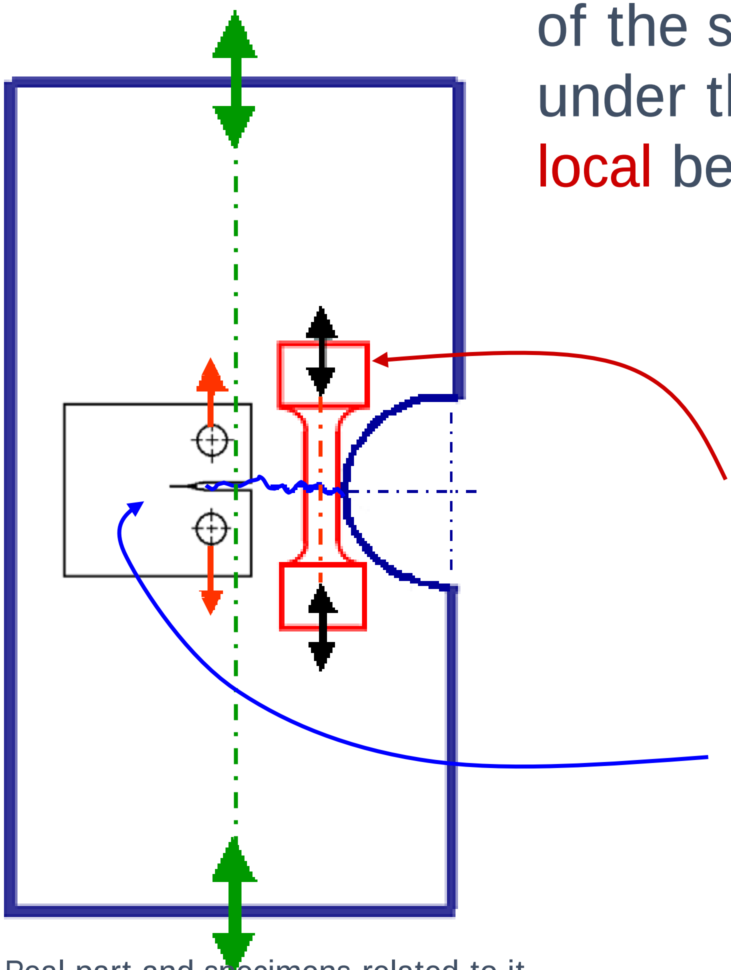


The full-size part or component is tested "as built" on a dedicated testing machine, service loads are reproduced, together with environmental conditions; a crack is nucleated and propagated.

This check on the real part (i.e. a design validation) is necessary when the failure model is not fully trusted, or the statistical dispersion of available data is higher then desired, or/and the safety factor is quite low.

Approach 2 - Lab tests on specimens

of the same material, different scale (lower), under the same stress conditions, to reproduce local behaviour.

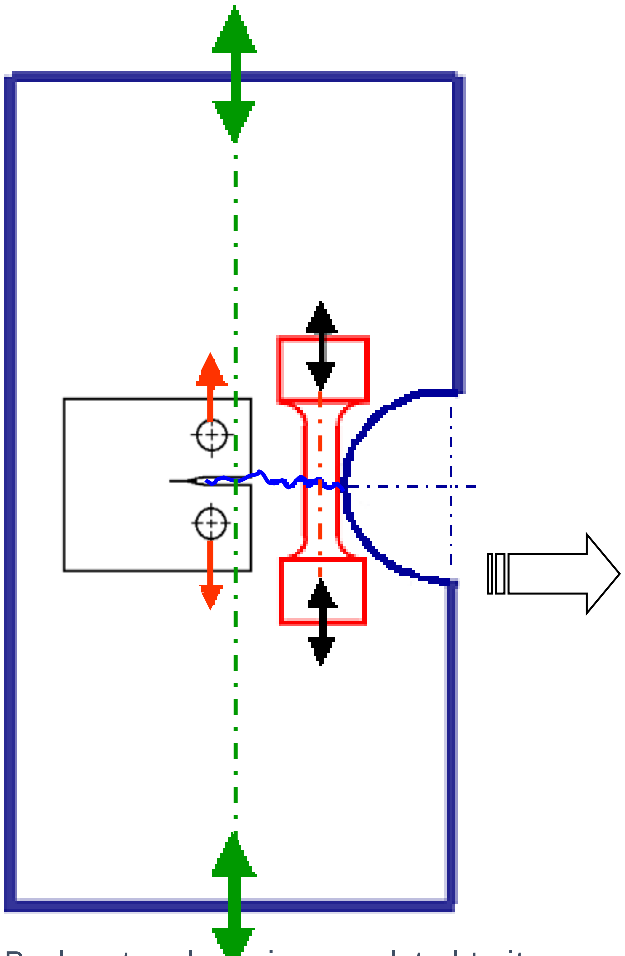


This “fatigue” specimen tests local crack nucleation characteristics of the material, up to the onset of a crack.

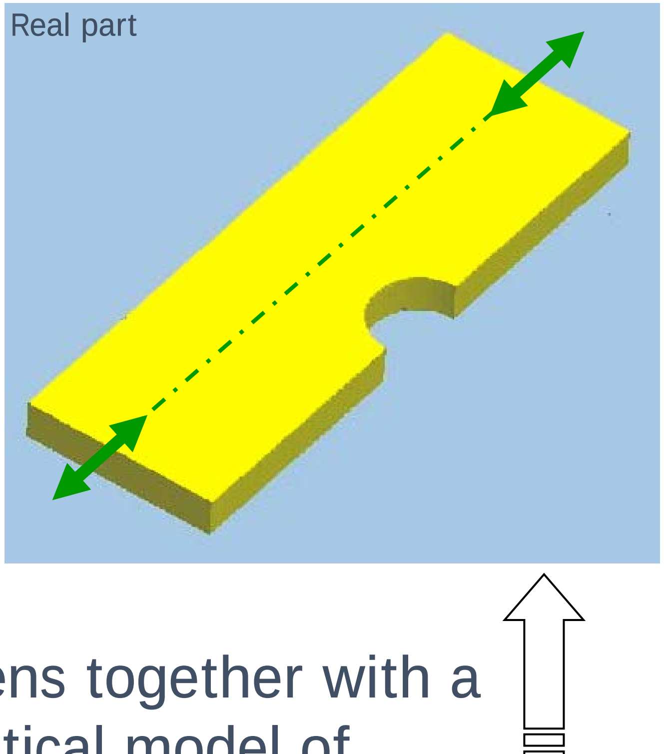
This “fracture mechanics” specimen tests gradual crack propagation up to final unstable crack growth.

Real part and specimens related to it

According to approach 2, predictions are based on the similarity of conditions:
similar conditions, applied to similar systems, should produce the same consequences.



Real part and specimens related to it



Data from specimens together with a "predictive" theoretical model of phenomena are used to estimate crack nucleation, crack propagation, crack length at final instability.

Failure theory or model is considered reliable, dispersion of data is compatible with the desired value of the safety factor.

Sections 15, 16 - Safe life, fail-safe and damage tolerance

Sections 15, 16 introduce the reader to the safety measures that engineers and designers have devised in order to guarantee an acceptable degree of reliability in presence of inevitable manufacturing or materials defects, imperfect models, parameter uncertainties, occasional or exceptional damage.

15. Design approaches to fatigue (1/3)

The fatigue failure mechanisms described so far are to be applied in the following alternative design contexts:

- ✓ **Infinite life design** - Based on fatigue limit.

  It assumes that the material is either an ideal continuum free of defects / flaws, or that they will not start a crack, or that the crack is one that will not propagate under the given stress conditions.

  Obviously, one should prove that the material is either crack free or with certain tolerable defects (ND testing*); design (theory/data) insures that no failure or damage will ever appear (appropriate in very high cycle cases, as in many parts of aircraft engines)

- ✓ **Finite life design** - described in the following slides

15. Design approaches to fatigue (2/3)

a: Safe life design

In Safe-Life design products are designed to survive a specific design life (retirement life) with a chosen reserve (expected life divided by a factor greater than one) to account for the many uncertainties (materials, manufacturing).

Factors in Safe Life Analysis:
- Stress Concentration Factor determination by means of FE models or experimental data.
- S-N curves
- Cumulative Damage Rule.

However, the original ASIP (Airframe Structural Integrity Program, 1958) relied on the results of the lab fatigue test of a full-scale aircraft, emulating the actual loads that aircraft would experience during its anticipated lifetime. The “safe life” was established by dividing the number of successful test-simulated flight hours by a factor of four.

b: Fail-safe design - Fail-safe is the attribute of the structure that permits it to retain its required residual strength for a period of unrepaired use after the failure or partial failure of a principal structural

It admits failure in design. A fail-safe design typically consists of the fail-safe component or primary structural element, and a redundant or backup structural element. A fail-safe design is, therefore, often said to be a redundant design or a multi-load path design.

Caveat: designers must be really confident that they are identifying and avoiding potential failures, i.e., avoid designs mistakenly thought to be fail-safe.

16. Damage tolerance (1/3)

Damage tolerance — Is the ability to withstand damage i.e., it comes from a fatigue design philosophy based on the assumption that a structure must be safe even if damaged.

Damage tolerance design requirements are generally satisfied by applying two concepts:

• first of all: slow crack growth design concept: where flaws or defects are not allowed to attain the size required for unstable crack propagation.

• however, include fail-safe design criteria: in case of unstable crack propagation, this will be locally contained through the use of multiple load paths or crack stoppers.

(It then takes into account flaws, accidental damages and manufacturing discrepancies)

16. Damage tolerance (2/3)

In more detail, damage tolerance:

- is a complement of the safe life approach; it started from the fact that, if cracks or defects beyond design assumptions escape detection in either the initial product release or during field inspection practices, consequences can be dramatic;
- it is necessary, in aerospace engineering, to ensure that an aircraft can be operated in the presence of these initial flaws;
- structure is designed to be tolerant of these defects for a selected period of service usage prior to the next inspection;
- a safety limit is defined as the time for the crack to grow from its assumed initial size up to failure, Non Destructive (ND) Inspection intervals are prescribed, e.g., half the safety limit.

16. Damage tolerance (3/3)

In aerospace engineering, structure is considered to be damage tolerant if a maintenance program has been implemented that will result in the detection and repair of damage (corrosion and fatigue cracking) before it degrades structural strength below an acceptable limit. The aircraft component into play has to be **inspectable**.

Damage tolerance design requires that fracture (or damage) mechanics models be available to assist in the evaluation of potential behaviour, as well as full knowledge of the required material properties.

Suggested readings on history of fatigue

J. Schijve, *Fatigue of structures and materials in the 20th century and the state of the art (Review article)*, International Journal of Fatigue 2003), pp. 679–702

W. Schütz, *A history of fatigue* 25 (Engineering Fracture Mechanics Vol. 54, No. 2 (1996), pp. 263-300