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Fatigue
in
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Presented by:

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1 Introduction

When preparations for this paper started, it soon became apparent that a clear definition of the different forms of „similar appearances“ of failures had to be done. Obviously such definitions could deliver sufficient material to allow the creation of a paper in it self. Hence we tried to narrow down the description of the main causes for failures due to cracks and fractures by arranging them in a chart, as we will see on the next overhead folio.

Fatigue failure is probably the most common cause of mechanical failure in numerous sectors of engineering. It occurs under conditions of cyclic mechanical load exposing components to a constant change. After an incubation period of varying length, depending on the properties of the material used and a great number of other factors, a fatigue crack, or sometimes several cracks, propagate steadily into the component. If the remaining loadbearing section of the component cannot withstand the steadily increasing stress any longer, a forced rupture will occur. This fracture due to overload is normally referred to as the residual fracture. Following the reduction in the residual loadbearing section of the component, it is obvious that an external peak load, exceeding the design load, is not necessary to cause the final fracture. Fatigue failure can usually be identified by the characteristic appearance of the fractured surface.

The insidious hazard of fatigue failure is its spontaneous and unexpected appearance. Extremely small surface defects can be an initial point for cracks (e.g. turning marks and ignition marks from welding electrodes), which with time causes a fracture, which in turn in most cases result in a remarkably substantial damage. Initial fatigue failure cracks cannot reasonably be expected to be recognised by visual tests. The wide range of non destructive tests, offers various procedures for detection of cracks, but in practice these examinations are carried out only for critical sections of essential components. Many components are not or only with prohibitively expensive additional efforts accessible for in depth examinations. As a result and for economical reasons, „uncritical“ sections are not normally subject to a complete NDT during maintenance overhauls..

There are two other types of failure very closely related to the classical fatigue failure and its mechanism, being: a) the corrosion fatigue and b) the phenomenon of pitting.
Especially the boundary between classical fatigue and corrosion fatigue is not clearly defined, leaving a large ‘grey area’. Due to their importance, two separate sections of this paper are devoted to these issues.

Traditionally only metallic materials have been related with the expression fatigue. However the phenomenon of fatigue is also existent for plastics. Due to their very different microstructure compared with metals the fatigue in plastics is dealt with in a special chapter.

2 Fatigue

2.1 Classification

Generally the type of load is accepted as a main criteria for the classification for the emergence of cracks and fractures. The three typical categories are (see folio 2):

a) cracks due to mechanical load,
b) due to thermal load and

c) due to corrosion.

In most cases these loads occur in combination.

We will beginn with the classical fatigue failure due to mechanical load, leading to a fracture and the dreaded forced rupture.

2.2 Characteristics

The classical fatigue fracture is defined by the following characteristics:

- Cyclic mechanical load (tension, bending, torsion in amount and/or direction, see folio 3) and,
- gradual / slow development.

The crack starts after an incubation period with a delicately structured, transgranular surface without plastic deformation. The crack surface is perpendicular to the main principal stress. The propagation of crack continues undetected and slowly into the exposed component until the remaining section is no longer capable to withstand the stress. What follows is a sudden residual fracture with a roughly structured surface, commonly related with plastic deformation.

A fatigue failure is usually initiated at surfaces with stress concentrations (e.g. cross section steps in shafts, any type of notches , surface defects etc.), but can also start at inside flaws (e.g. non-metallic inclusions, porosities and the like).

The formation of a fatigue crack is mainly influenced by:

- the load (amount, type, frequency, surrounding temperature) and
- the material.

During the design stage of a new component it is essential for the engineer to know the specific properties of the material i.e. admissible stresses with static and cyclic loads. The behaviour of most materials under static loads is well known (i.e. ample availability of experimentally achieved tensile stress diagrams). The amount of cyclic load necessary to induce a fatigue crack, is in most cases considerably below the stress sustainable for static load (yield strength). To evaluate the material behaviour under a cyclic load, ample time and cost consuming tests have to be carried out. The results of every test run with a predetermined load and frequency is entered into a specific diagramm, the so-called Wöhler Diagram (see folio 4).

This diagram shows how many cycles a specimen can withstand until fracture. The accuracy of the results has of course a certain spread within the shown band width. The curve is typical for <u>body centered cubic</u> metals (bcc) i.e. most materials commonly used in mechanical engineering (e.g. ferritic pearlitic and heat treated steel). The two relevant load factors are the Mean Stress and the Amplitude of the Cyclic Stress acting on the component. With either of these reduced, a specimen can withstand more cycles. If a bcc component is able to withstand a certain number of cycles, mostly at 1x10E6 cycles, it is concidered fatigue resistant and no subsequent failure will occur. Hence it is possible to obtain the amount of fatigue strength with a certain accuracy from this diagram.

amount of fatigue strength with a certain accuracy from this diagram.
Face centered cubic (fcc) metals such as aluminium and austenitic steels do not show an asymptotic fatigue behaviour which means that no fatigue strength exists . If the designer for any reason wants to use a fcc material, the permissable stress design should take 1 E 7 load cycles into consideration. In this case it is obvious that the design life of the component becomes an integral part of the fatigue stress design.

The test results of numerous Wöhler Diagrams are summarised in the Smith Diagram (see folio 5). This diagram indicates the possible stress amplitudes for different component mean stresses. For every material and type of load (i.e. tension, compression, bending and torsion) there is a specific Smith Diagram.

It is important to bear in mind that the experimental results of various test runs are only valid for one specific specimen under well defined circumstances. Slight changes, for example in the quality of the specimen surface, can change the result considerably. Other factors such as design (e.g. abrupt steps in cross sections), notches (e.g. keyways, perforations), the size of the component and the surrounding temperature and atmosphere can influence the results far beyond acceptable limits and render the test useless.

In the design stage different parameters are considered with help of the empirically obtained fatigue resistance for the intended material in combination with the relevant security factor. However there are plenty of limiting factors for an exact design calculation, due to the often very complex shapes of the components and limited knowledge about the loads.

In addition there are of course further nearly unpredictable influences, which are difficult to consider during calculations, being the imperfections during production and manufacturing (e.g. inhomogenities in the material, surface defects, etc.) as well as not sufficiently known operational conditions.

2.3 Appearance

2.3.1 Macroscopic

Fatigue cracks start at one or more surface spots and later converge to a common crack line. The surface of the crack is usually a smooth, even plain and perpendicular to the principal stress. The structure is fine. If the residual cross section is to small to withstand the stress the so called residual fracture or forced fracture occurs. Depending on the properties of the material (ductile or brittle) and the type of load, individually typical forced fracture features can be observed (shear or cleavage fracture). In rare cases there is no residual fracture zone. This behavour is given if for example another component takes over the bulk of the load so that the fatigue crack can propagate through the complete cross section.

Typical for fatigue failures are the beach marks lines on the softly structured fatigue crack surface. These lines result from major changes in the operation of the machine, e.g. significant load changes or standstills. The macroscopically observable beach marks should not be confused with the fatigue lines, which are only visible by scanning with an electronic beam microscope. By studying the appearance of the beach marks it is possible to determine the direction of the propagation of the crack (starting point and end point) and the type of load that caused the fatigue crack. The size of the residual fracture surface allows determination of the forces which acted on the component at the time of sudden failure : High stresses lead to a large, low stresses to a small residual fracture areas. In case of a very small residual fracture area it could be assumed that a peak load was responsible for the residual fracture.

In some cases the plain crack surface of the fatigue failure can be destroyed due to compression or bending stresses occuring before or at the time of the residual fracture. In many cases the surface is also changed by corrosion and its products. Especially if the period of fatigue crack development is long and there are corrosive agents in the vicinity.

2.3.2 Microscopic

By using a scanning electron microscope the typical characteristics of fatigue failure are often easily detectable (see folio 6): fatigue lines or striations, numerous fatigue fracture paths and adjacent cracks. At the starting point of the fracture it is not unusual to find individual cracks in different stages of propagation which later will combine to form a single crack. With increasing strength of the material the features are less cleary identifiable.

In materials with a high ductility the cracks run transgranular. In contrast low ductility materials can represent intergranular fatigue fracture (e.g. heat treated steel casting, spherodial graphite iron casting, high silicon electric sheets, nickel, cobalt and titanium cast alloys).

2.4 Theory of mechanism

The growth of the fatigue failure is divided into three characteristic stages: the crack initiation, the crack propagation and the residual fracture.

The fatigue failure is caused by local plastic deformation at some sites of the material, for example at grain boundaries, inclusions or material inhomogeneities. The combined mean stress and cyclic stress for the overall cross section is below the yield point and thus shows only elastic deformation. The explanations of the physical mechanisms for fatigue are all based on the idea of plastification effects and thus on the behaviour of the carrier of plastic deformation the dislocations and their movement in the metal grid.

Fatigue cracks starts with preference on free surfaces at following locations (see folio 7): slip bands, grain boundaries, twin boundaries and inclusions. Slip bands are produced during the fatigue process and are thus a pre-stage in the formation of cracks. The other three possible sites are inhomogenities, which are present before the process starts. In components, fatigue cracks are initiated in regions of local stress concentration such as notches or abrupt changes in cross sections.

Slip bands are formed on the surface due to cyclic plastifications. The plastic deformation occurs in crystallographic planes. These slip bands or extrusions and intrusions can only be observed on the surface of well polished test specimens.

During the first Stage of the fatigue process various cracks and notches are formed. The cracks will propagate with an angle of 45 degrees to the orientation of the principal stress and thus to the surface. These first initiation cracks normally affect only a small region, i.e. one or two grains. In high temperature resistant alloys based on nickel and cobalt these region of the initiating process can be well observed. Although inhomogeneities will faciliate the formation of fatigue cracks, failures can also be observed on components with a polished surface.

This crack initiating stage is followed by the Second Stage with the crack propagation perpendicular to the orientation of the principal stress. During this stage the crack propagates a certain distance with each load cycle. At the crack front high local stresses occur, leading to plastic deformations. This mechanism causes a pattern of fatigue lines on the crack surface.

The third Stage is the sudden residual forced fracture.

2.5 Preventive measures

The measures for prevention of fatigue focus on the design, manufacturing, erection and operation, summerized in the sentence: **„Avoid stress concentrations and surface defects“.** The measures are (see folio 8 and 9):

Design : (prevention or at least abatement/ reduction)

- Choose adequate material
- Avoid abrupt changes in stiffness e.g. section steps in shafts
- Avoid drill holes, screw threads, keyways, perforations,
- Avoid punch marks

Manufacturing / erection / operation:

- Avoid turning and grinding marks
- Avoid embedded foreign particles
- Avoid rolling and forging folds
- Avoid defects in welded joints, ignition marks from the electrodes
- Avoid cast defects (inclusions, slags, coarse precipitates, porosity)
- Avoid press fits of other components, pressure or abrasion marks from seats
- Avoid cracks caused by incorrect sand blasting or shot peening
- Avoid corrosion marks, fretting corrosion (no corrodents)

3 Corrosion Fatigue

In case of corrosion fatigue the cyclic load is accompanied by a corrosion mechanism. According to DIN 50 900, corrosion fatigue is defined as (see folio 10) ‘the formation of transgranular, low-ductility cracks in metals due to simultaneous effects of alternating mechanical loads and corrosion’. The distiction line between the classical fatigue and corrosion fatigue is not clearly marked. The fractures are classified depending on the magnitude of the cyclic load and/or the contribution of corrosive agents. Every environment, including the surrounding air, containes some kind of corrosive agents, thus one can observe pure classical fatigue only under vacuum conditions. With high frequency alternating loads and large amplitudes the crack features look similar to those of classical fatigue. With low amounts they look more like the ones of stress corrosion cracking.

In contrast to stress corrosion cracking, fatigue corrosion does not require any specific conditions regarding the the magnitude of the load and corrosion system (materials / corrosive agents).

Corrosion fatigue can occur in the active and passive condition of the material. The cracks propagates perpendicular to the principal stress. In case of active material the crack surface present a scarred surface with numerous preinduced cracks. The surface in the passive condition is usually smooth.

With active corrosion of the material cracks originate at sites of stress concentration (e.g. notches, corrosion pits, abrupt steps in cross section). In passive materials corrosion fatigue cracks are mainly caused on smooth surfaces by stimulation of local metal dissolution (e.g. emerging slip bands or repeatedly destroyed protection layers).

The microscopic distinction between the typical features of pure fatigue and fatigue corrosion is difficult. In both cases the (corrosion-) fatigue cracks are transgranular. On the surface sometimes corrosion products are detectable, which could serve as a hint for the classification. In case of predominat mechanical load, fatigue lines can be observed. In case of predominat corrosive load the crack features are similar to those of the fine structured stress corrosion cracking with its share of intergranular cracks.

4 Pitting

A special type of fatigue is the phenomenon of pitting (see folio 11). In this case a material damage originates in the region near the surface of machine components, e.g. gear wheels or roller bearings.

The surfaces are exposed to alternating rolling and sliding loads. Hertzian stress in the contact zone with force transmission leads to shear stresses below the surface (e.g. at a depth of 0,1 to 0,7 mm). When these stresses reach a level sufficiently high to cause a local plastic deformation, e.g. in case of lubrication problems or overload, micro-cracks develop in this zone. Microstructural changes, so-called butterflies can be noticed in the micro section. The micro cracks start predominantly at non-metal inclusions. A relation between the pureness of the material and the susceptibility for pitting is established. The fully developped crack propagation leads to the breakout of material, i.e. pitting. The main direction of the propagation is the same as the direction of the load. The cracks on the surface form flat-, crater- or shell shaped breakouts. Several small breakouts can combine to a large area of damage.

With the help of a scanning electron microscope, shear traces, dimple structures and sometimes fatigue fracture zones in the crack surface can be observed.

5 Fatigue in plastics

Due to the fact that the molecular structures of plastics (thermo plastics, thermo setting plastics, elastomere plastics, etc.) and their individual behaviour and characteristics are so basically different <u>and</u> in addition can be significantly further influenced by a wide range of fillers, this chapter only makes some general remarks about fatigue failure of plastics.

Plastics do not differ from other materials in so much that they can take less stresses under cyclic loads than under static loads. With decreasing alternating stresses the admissable number of cycles increases.

With plastics a distinction is made between the pure fatigue cracks and the vibration induced creep cracks. The vibration induced creep cracks have a similar mechanism as the wellknown continious creep cracks under static load.

Materials with low elasticity will under cyclic loads form a real crack tip. Due to the three-dimensional stiffness of the molecular cluster the molecular chains are cut after a short elongation. A crack front with a sharp V notch is formed and can propagate through the plastic under cyclic load.

Pure brittle fatigue failures results in fatigue lines with flat profiles and steeply edged steps among the fracture paths. Also adjacent cracks can be observed. This type of fatigue propagation is quite similar to the one observed in metals. Pure ductile fatigue failure result in folded and rounded, tongue shaped residual fractures. The parallel fatigue lines are tongue shaped and rounded and in the crack stage inclusions are exposed.

Pure fatigue cracks have been discovered in PC, PVC, PE, PA and PP. With higher operating temperatures and higher loads the typical features are not so distinct anymore. Sometimes only features of forced fractures can be observed.

Vibration induced creep/cracks occur at inhomogenities inside the material or on the surface characterised by irreversible elongation processes of macro molecules. The simultaniously developing heat stimulates the movement of the molecules chaines. This effect is similar to the continuing creep/crack process of plastics. The result is that a lot of cavities are formed, which due to the elongation process will be spherically shaped. After the separation funnels or hemispheres with beaded edge remain on the crack surface. Due to the limited heat transmission performance inherent in the material, the vibration induced creep crack is heavily dependent on the amount of load and the frequency. High frequencies and high loads can lead to local softening or melting in the center of a cross section.

6 Literature

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/4/ Systematic Analysis of technical failures
G. Lange
Deutsche Gesellschaft für Metallkunde 1986

/5/ Korrosion der Metalle, Begriffe
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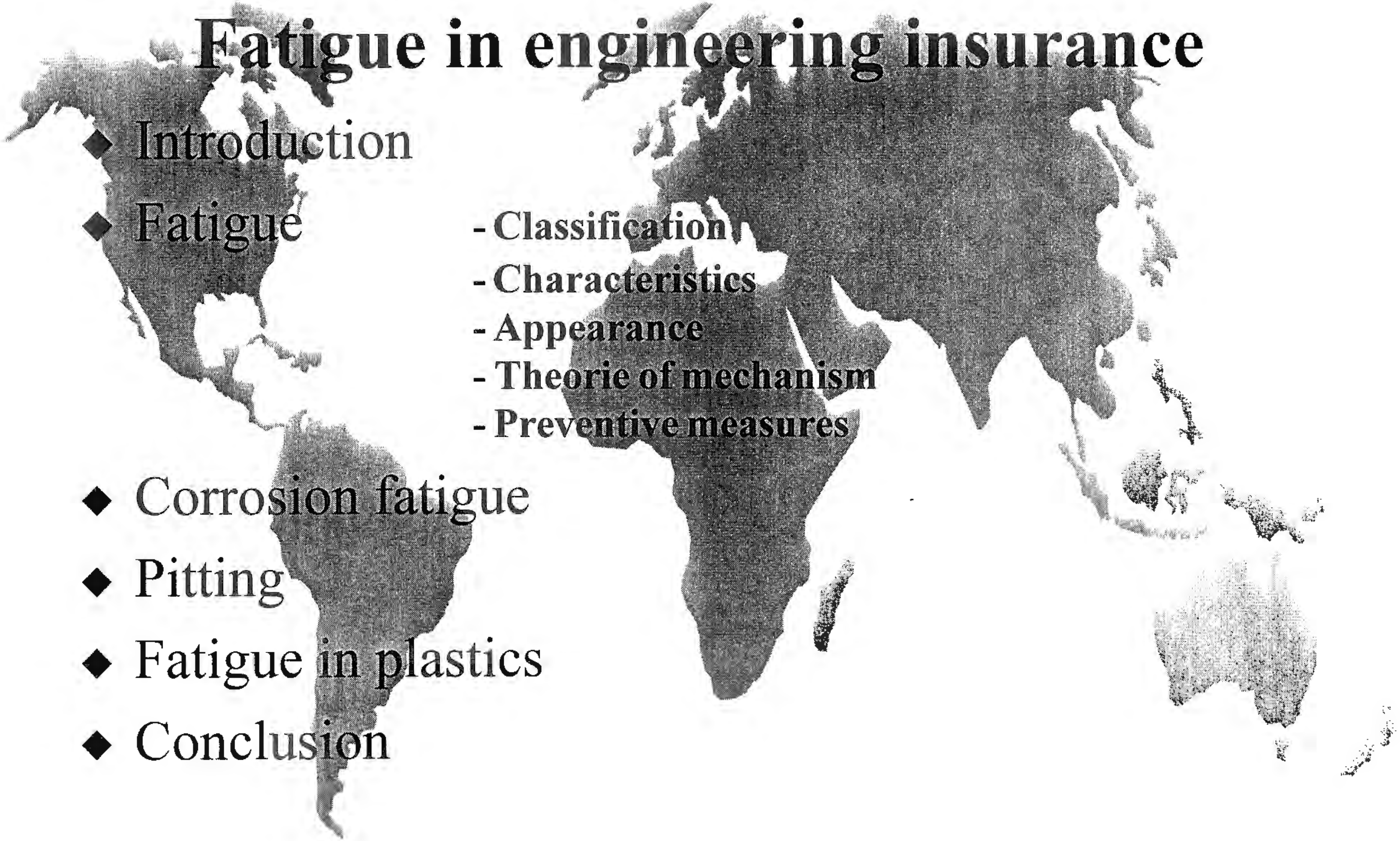

Fatigue in engineering insurance

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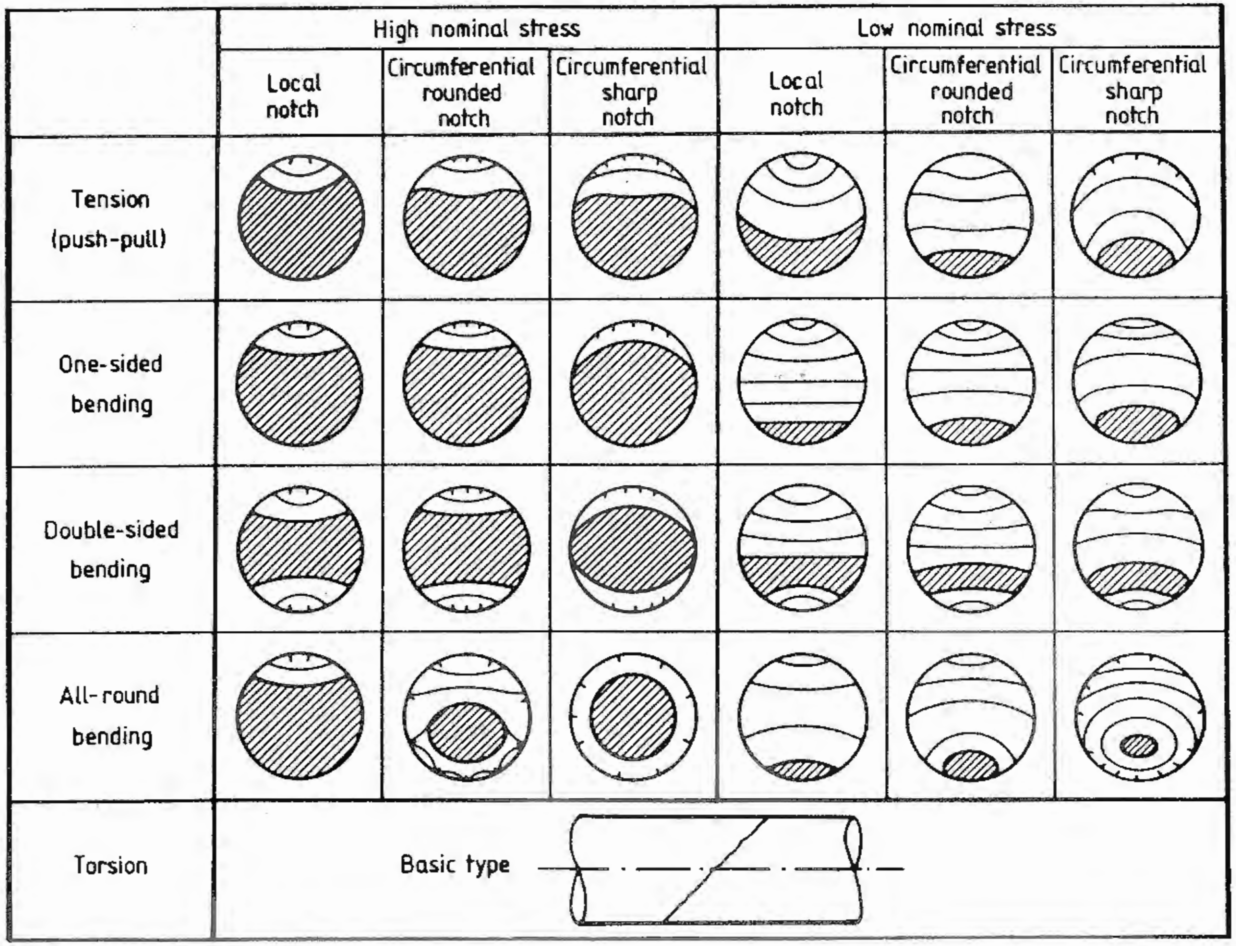
- Fatigue in plastics
- Conclusion

Classification of cracks and fractures

- **Mechanical induced**
  - **Forced fracture**
  - **Fatigue**
- **Caused by heat**
  - **Manufacturing induced**
    - Quench crack
    - Relaxation crack
    - Shrinkage crack
    - Welding crack
  - **Service induced**
    - Creep crack
    - Thermal shock crack
- **Caused by corrosion**
  - **Mechanical load**
    - **without**
      - Intergranular corrosion
    - **with**
      - Stress Corrosion Cracking
      - Corrosion Fatigue
      - Strain induced CC
      - Hydrogen induced SCC
  - **Hydrogen induced**

based on /3/

Basic types of fatigue fracture



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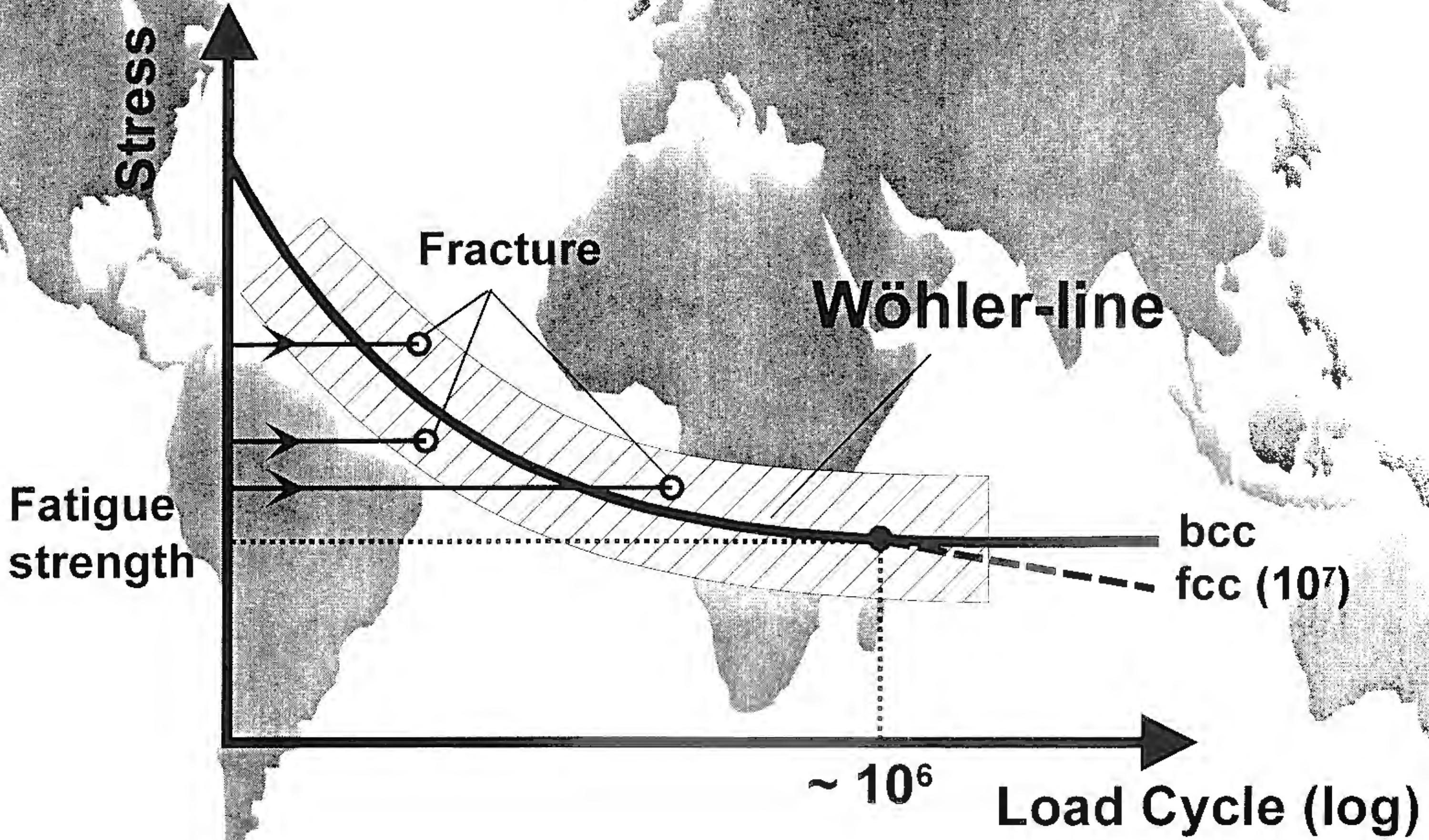
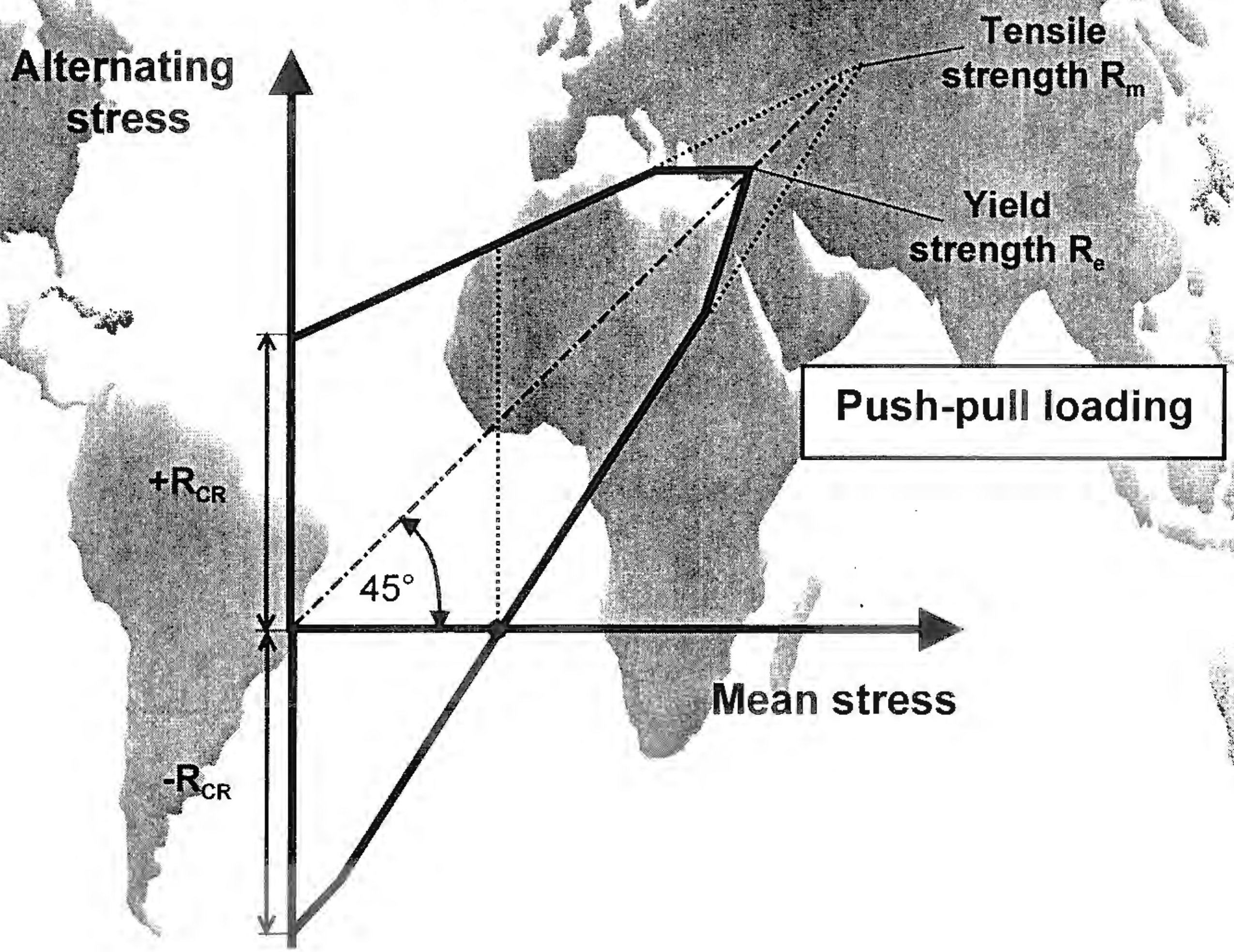
Wöhler-Diagram

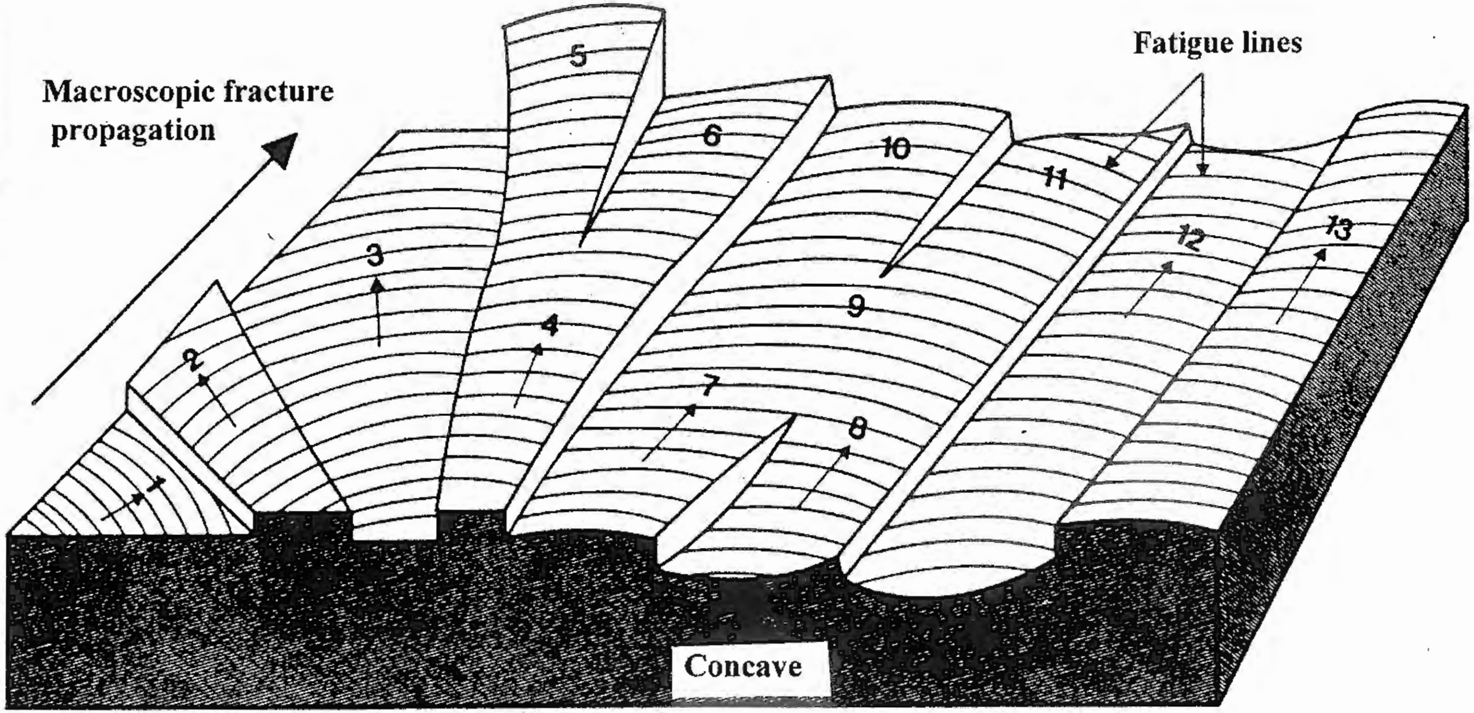


Smith-Diagram



Push-pull loading

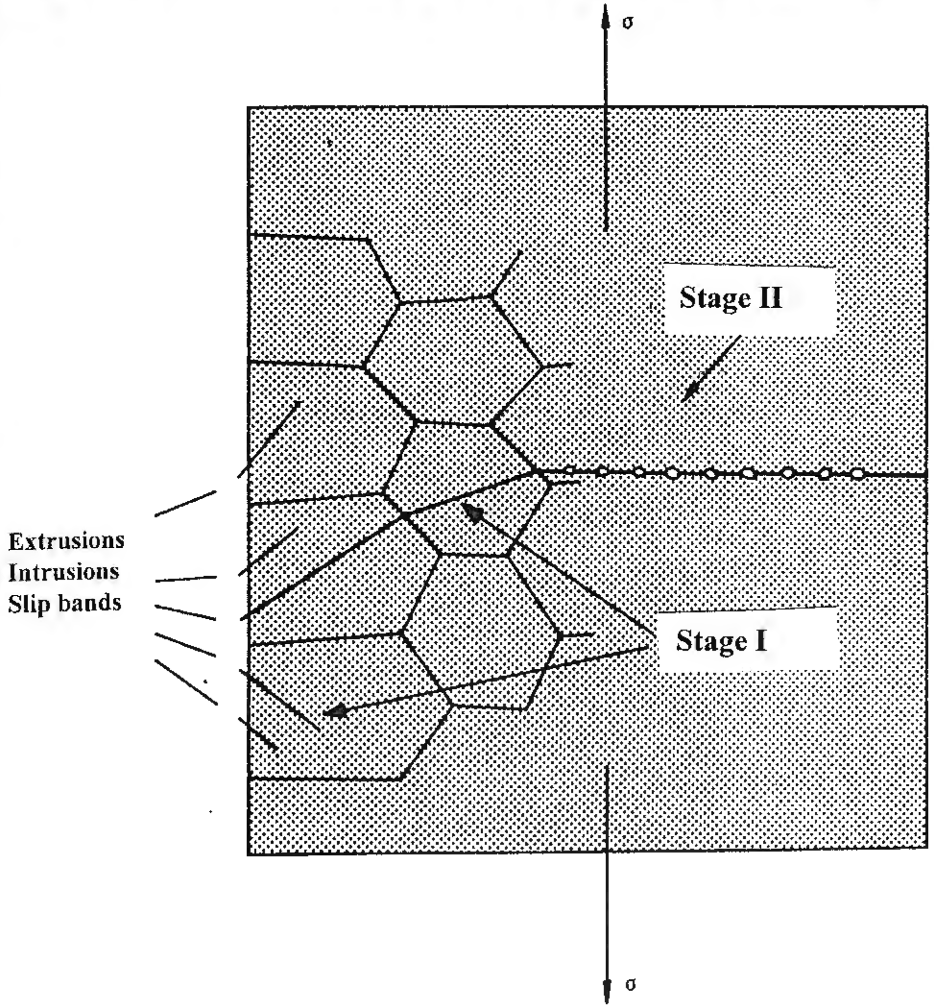
Features of fatigue fracture



Fracture pathes (1-13)

based on /1/

Fatigue fracture propagation



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Preventive measures I

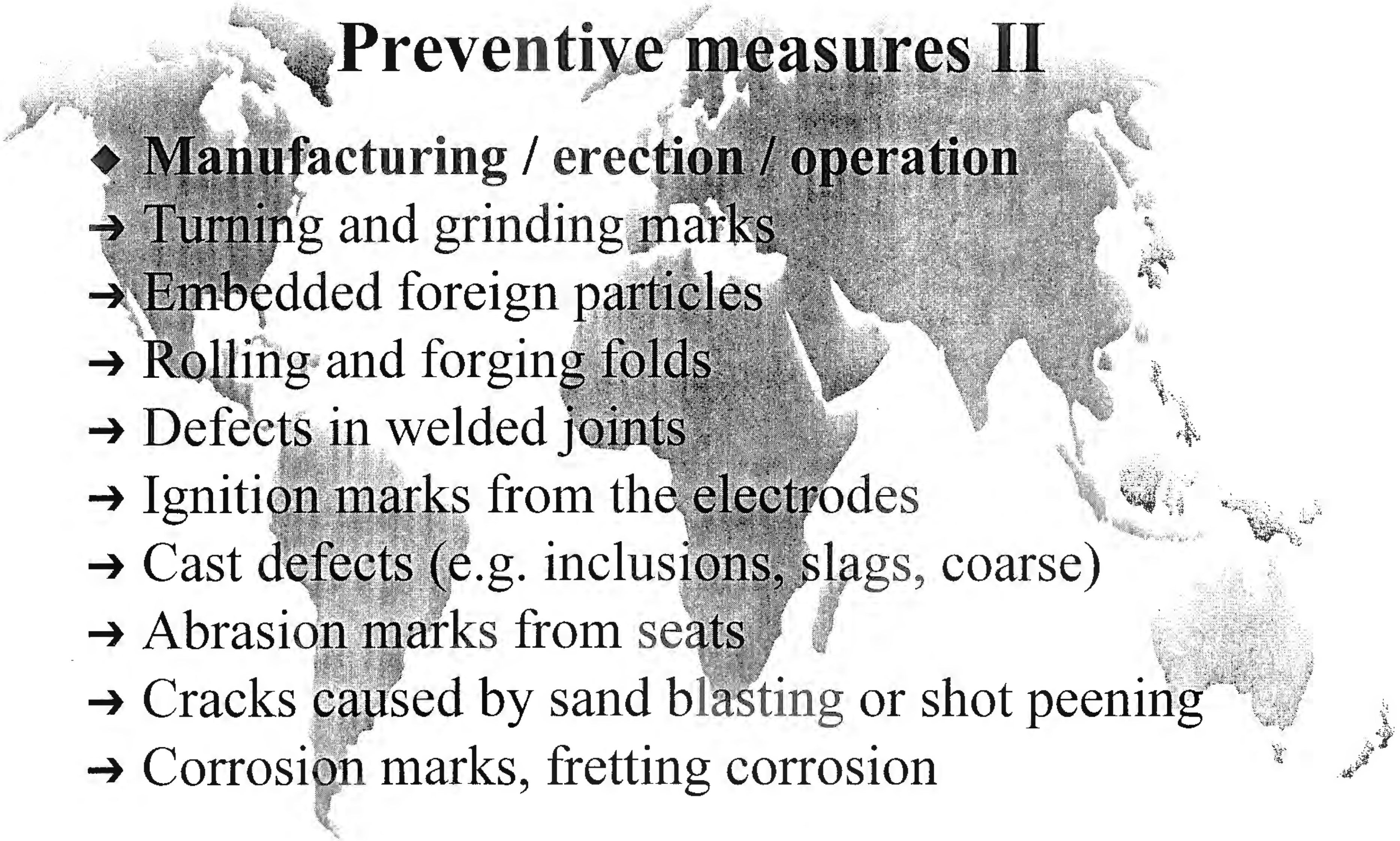
◆ **Design**

➔ Choose adequate material

➔ Avoid abrupt changes in stiffness e.g. section steps in shafts

➔ Avoid drill holes, screw threads, keyways, perforations

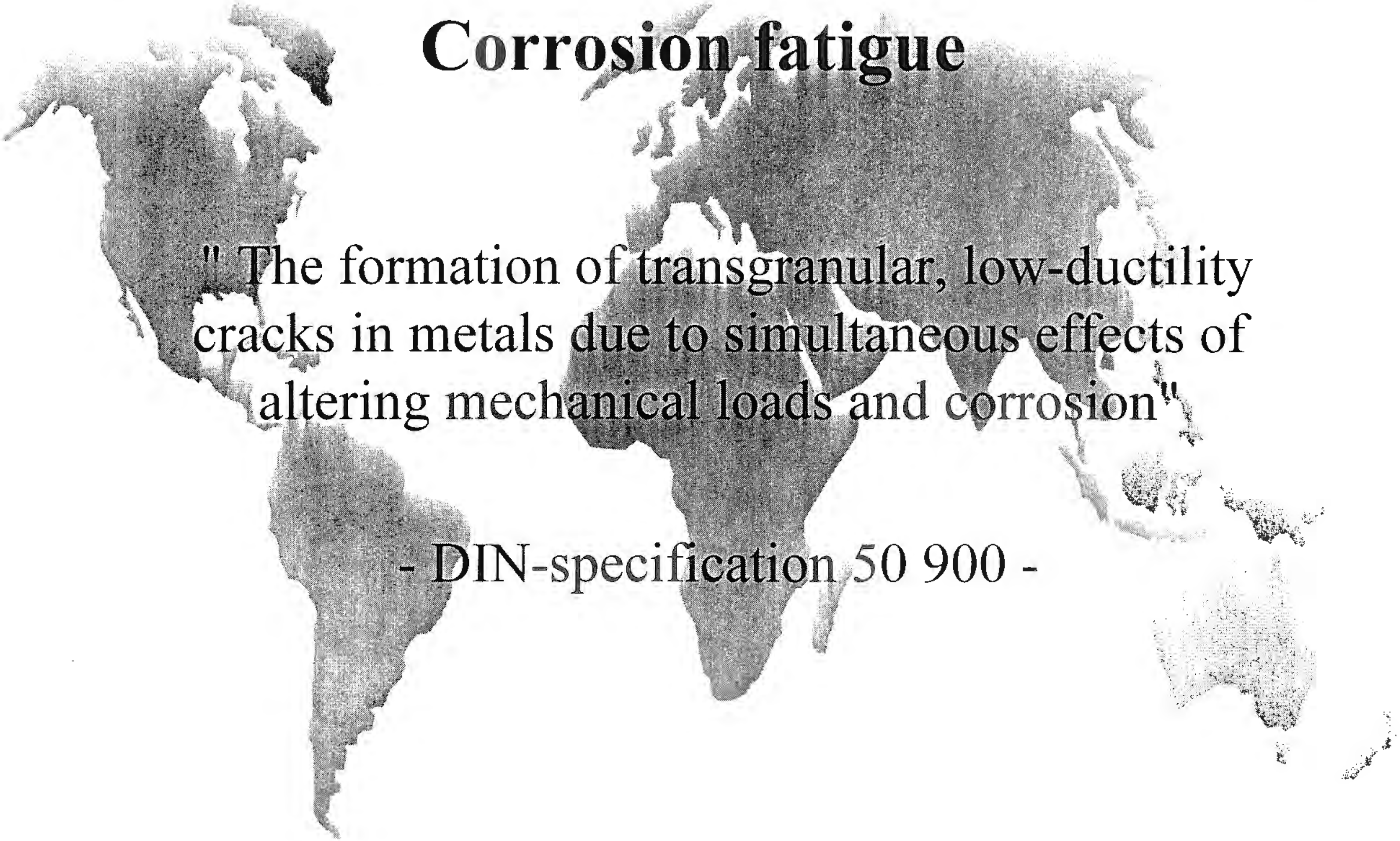
➔ Avoid punch marks



Preventive measures II

- ◆ **Manufacturing / erection / operation**
- → Turning and grinding marks
- → Embedded foreign particles
- → Rolling and forging folds
- → Defects in welded joints
- → Ignition marks from the electrodes
- → Cast defects (e.g. inclusions, slags, coarse)
- → Abrasion marks from seats
- → Cracks caused by sand blasting or shot peening
- → Corrosion marks, fretting corrosion

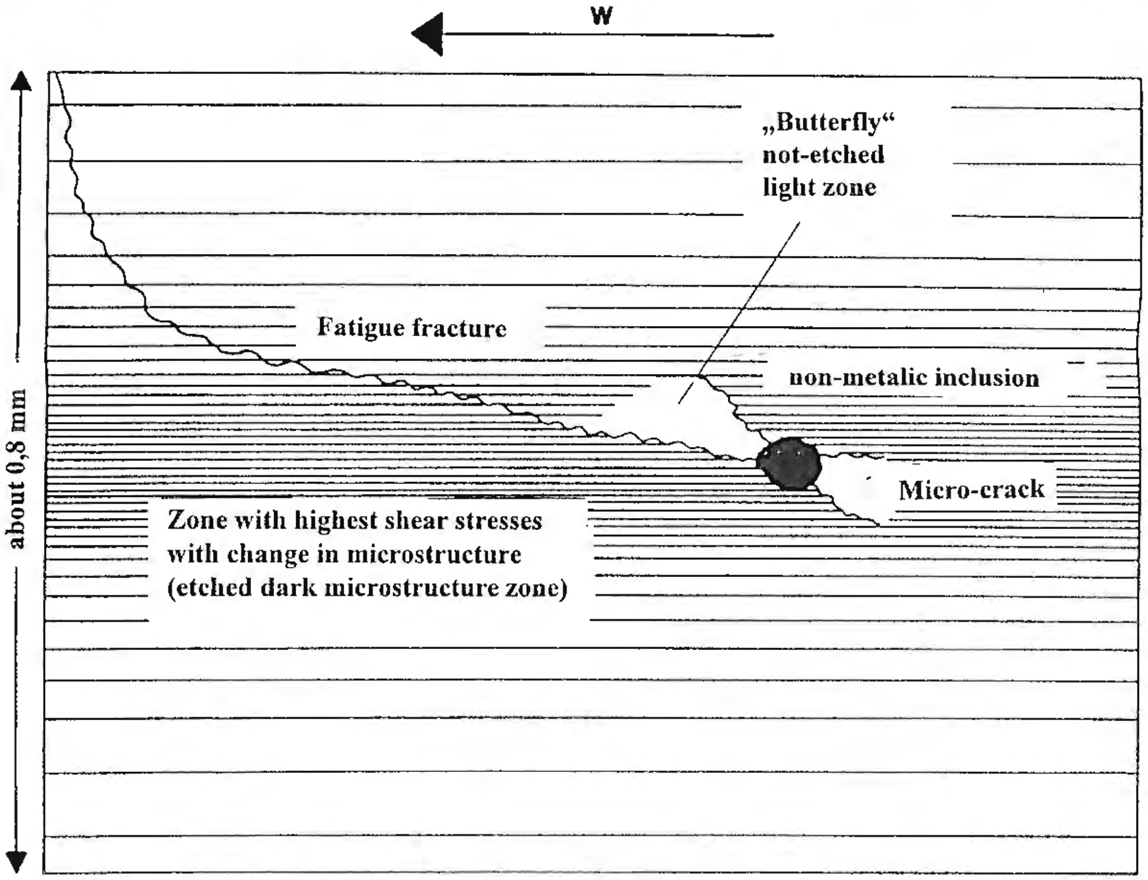
Corrosion fatigue



" The formation of transgranular, low-ductility cracks in metals due to simultaneous effects of altering mechanical loads and corrosion"

- DIN-specification 50 900 -

Pitting in roller bearing



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„Butterfly“
not-etched
light zone

Fatigue fracture

non-metalic inclusion

Micro-crack

Zone with highest shear stresses
with change in microstructure
(etched dark microstructure zone)

about 0,8 mm

based on /1/