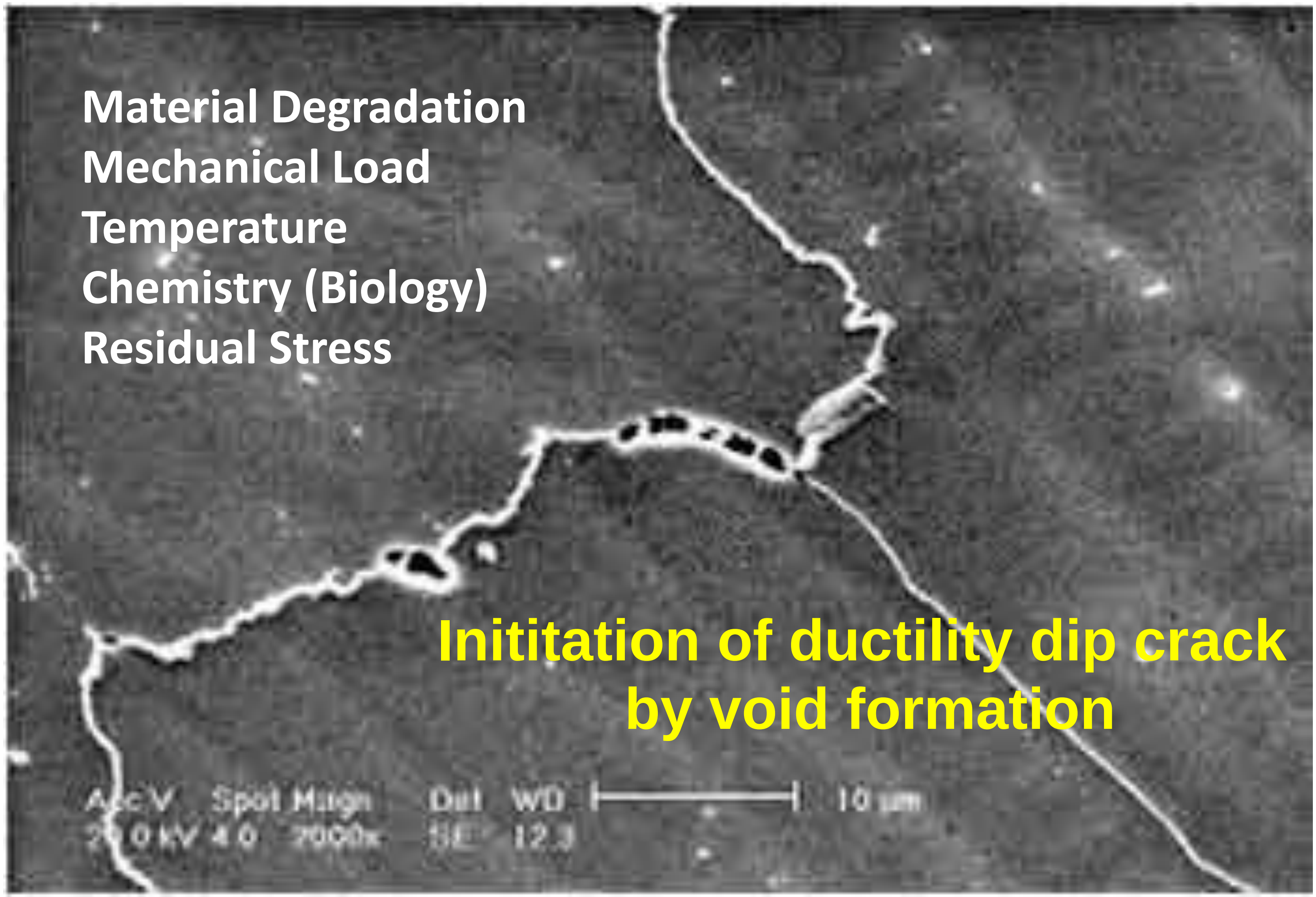
Degradation of nuclear structures during operation

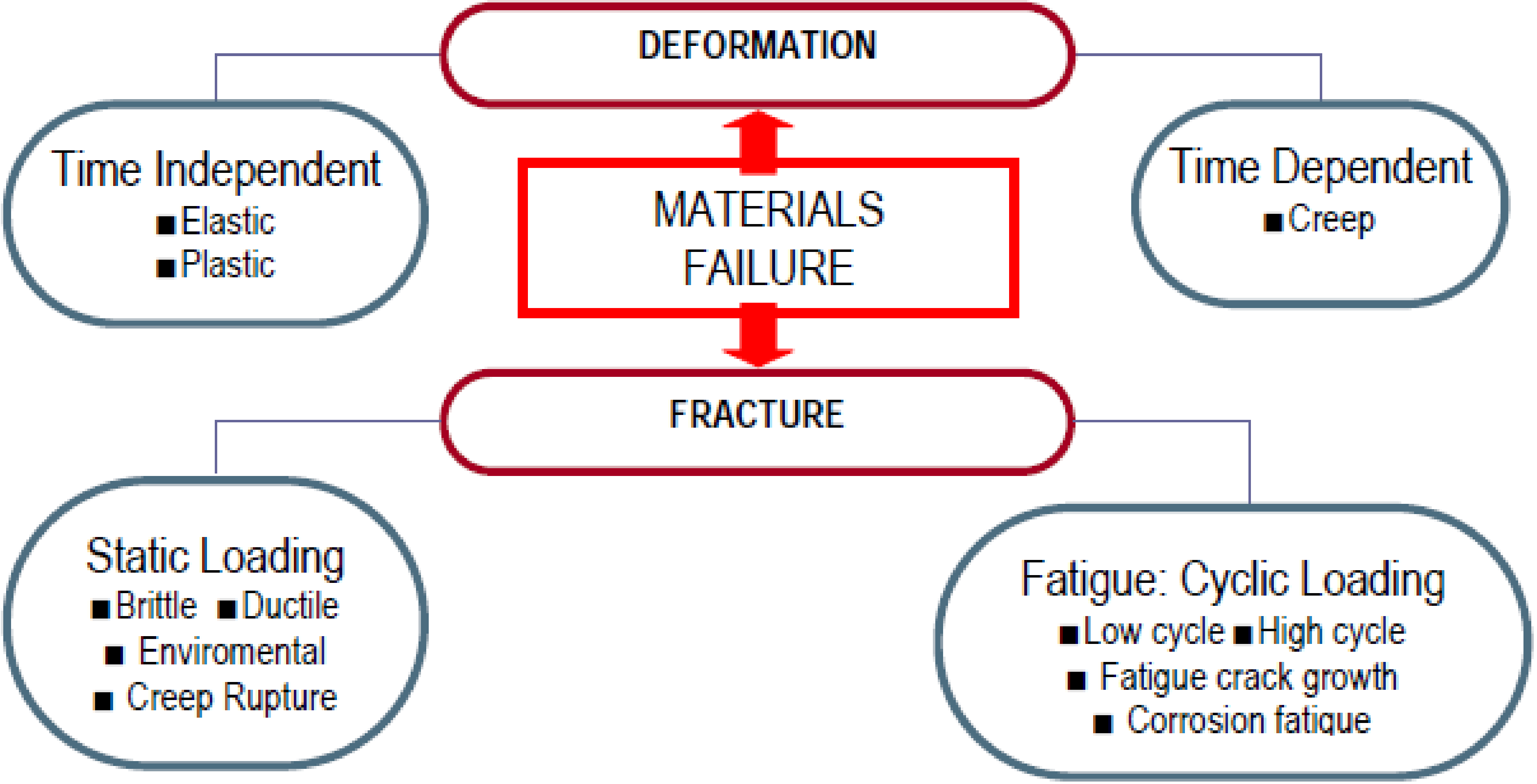


Material Degradation
Mechanical Load
Temperature
Chemistry (Biology)
Residual Stress

Initiation of ductility dip crack by void formation

Degradation of nuclear structures during operation

2.	Degradation of nuclear structures during operation
2.1.	Aging, Neutron Embrittlement, Structural Material Parameters
2.2.	Stress Corrosion Cracking
2.3.	**Fatigue**
2.4.	(Unexpected events)



DEFORMATION

Time Independent
- Elastic
- Plastic

MATERIALS FAILURE

Time Dependent
- Creep

FRACTURE

Static Loading
- Brittle
- Ductile
- Enviromental
- Creep Rupture

Fatigue: Cyclic Loading
- Low cycle
- High cycle
- Fatigue crack growth
- Corrosion fatique

Basic Types of Material Failure

Fatigue

a failure phenomenon
associated with work-hardening of materials
caused by fluctuating or repeated loads
that result in increased brittleness and reduced service life.

Fatigue is characteristic of ductile materials;
***the final failure is rapid and characteristic of brittle fracture*.**

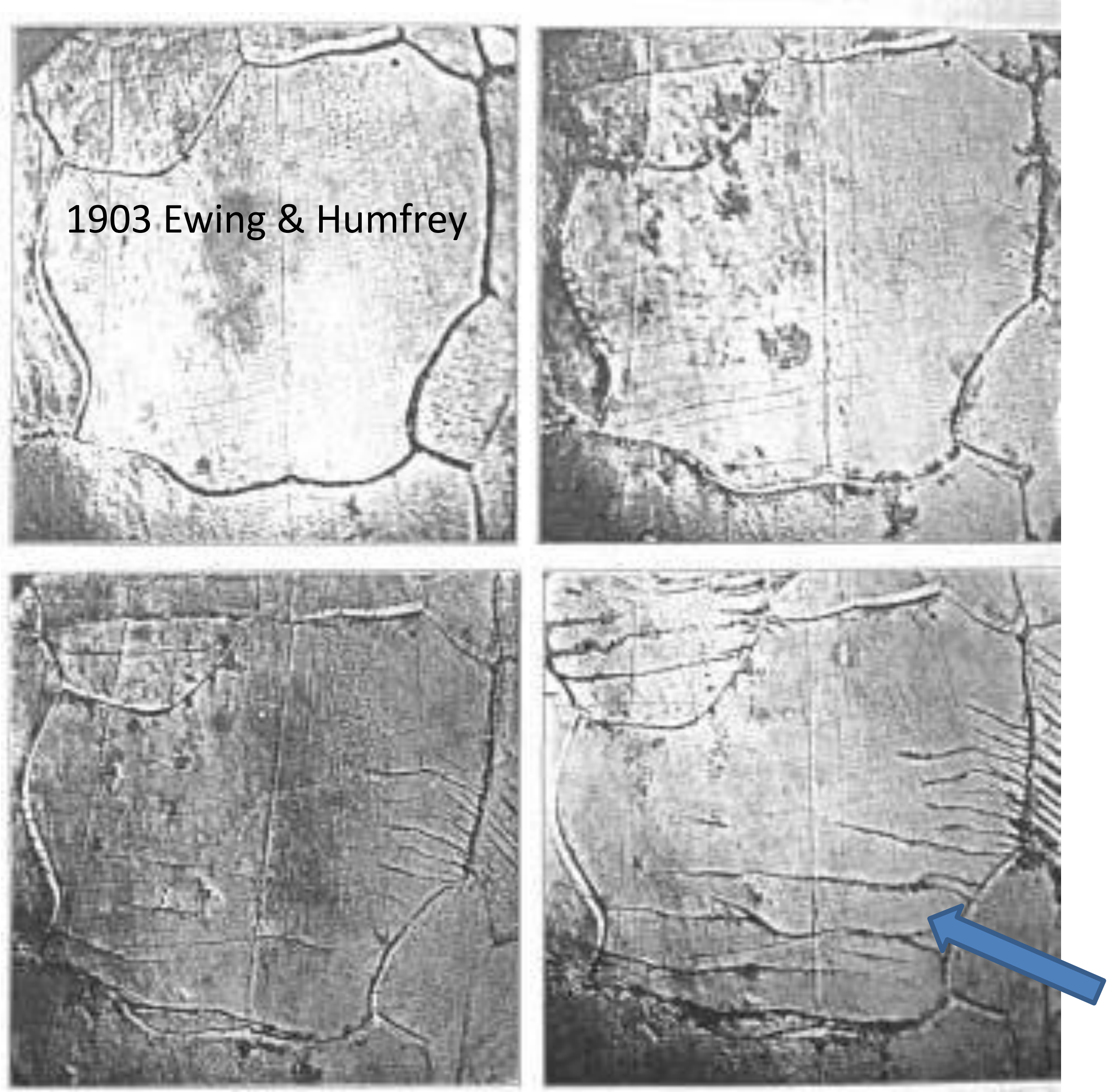
Fatigue

The following conditions result in work- hardening, leading to fatigue:

- a relatively large, fluctuating applied stress
- a sufficiently large number of stress cycles

Fracture failure due to fatigue often occurs at relatively low applied stress and well within specified design loads. The stress can be mechanical, thermal or both and can alternate between compression and tension, or simply alternate between high and low values.

Fatigue



surface fatigue cracks grow as material is further cycled.

NDT

The only reasonably reliable methods of checking the progress of fatigue are by

- visual,
- x-ray or
- ultra-sound examination

for surface and other cracks of the parts likely to be subject to work- hardening

Characteristics of Fatigue in Metal Alloys Process

- **Dislocation Movements**
- **Persistant Slip Bands**
- **Short Cracks**
- **(Fatigue Cracks)**

Basics of Metal Fatigue

Macroscopic and microscopic discontinuities as well as component design features which cause stress concentrations (holes, keyways, sharp changes of direction etc.) are common locations at which the fatigue process begins

Fatigue is a process that has a degree of randomness, often showing considerable scatter even in well controlled environments.

The greater the applied stress range, the shorter the life.

Damage is cumulative. Materials do not recover when rested

***Fatigue life is influenced by a variety of factors, such as temperature, surface finish, metallurgical microstructure, presence of oxidizing or inert chemicals, residual stresses, etc*.**

HIGH-CYCLE/LOW-CYCLE FATIGUE

Low cycle fatigue:

loading that typically causes failure in less than 10^4 cycles
associated with localized plastic behavior in metals

High cycle fatigue:

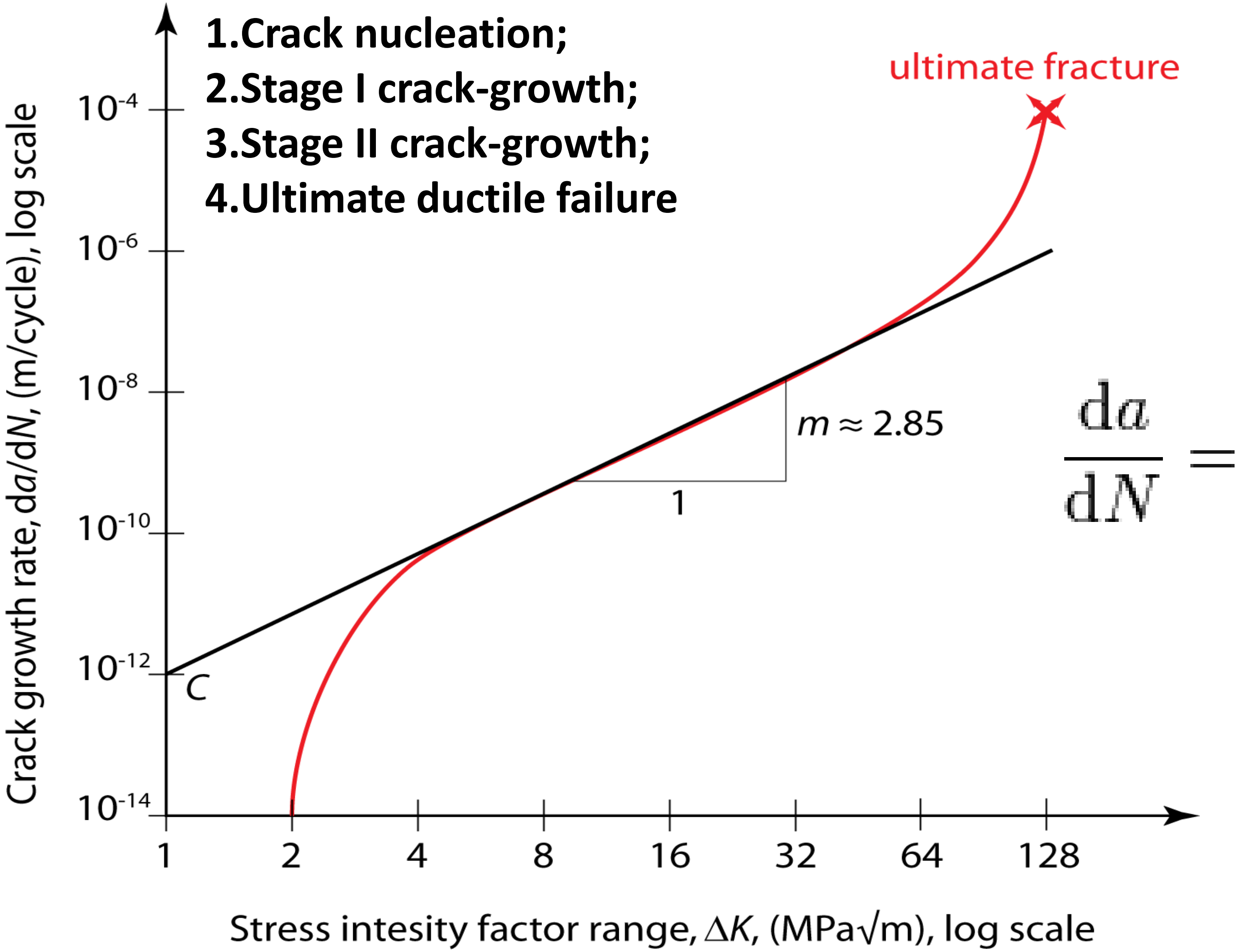
about 10^4 to 10^8 cycles
described by stress-based parameters

Some materials (e.g., some steel and titanium alloys)
exhibit a theoretical fatigue limit
below which continued loading does not lead to fatigue failure

S-N (Wöhler) curve

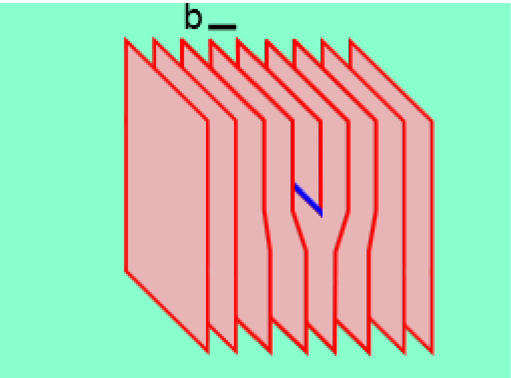
Fatigue Crack Growth to Fracture

1. **Crack nucleation;**
2. **Stage I crack-growth;**
3. **Stage II crack-growth;**
4. **Ultimate ductile failure**

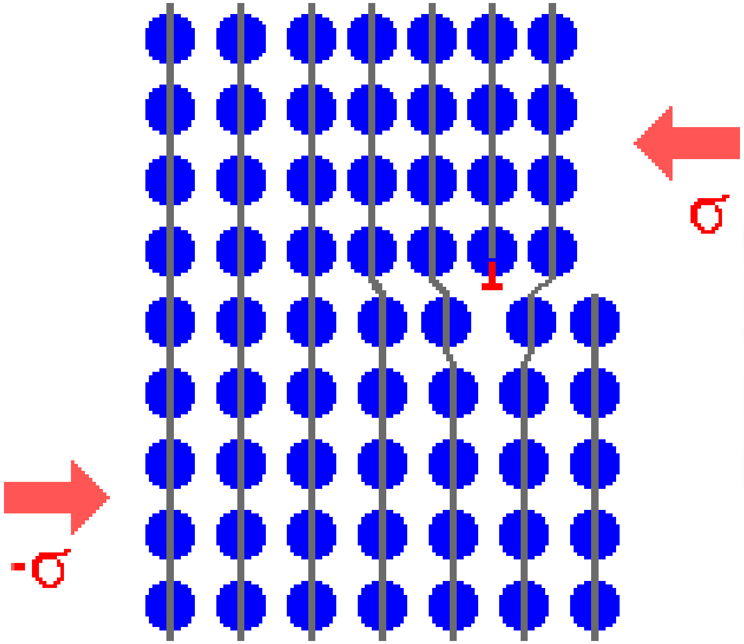


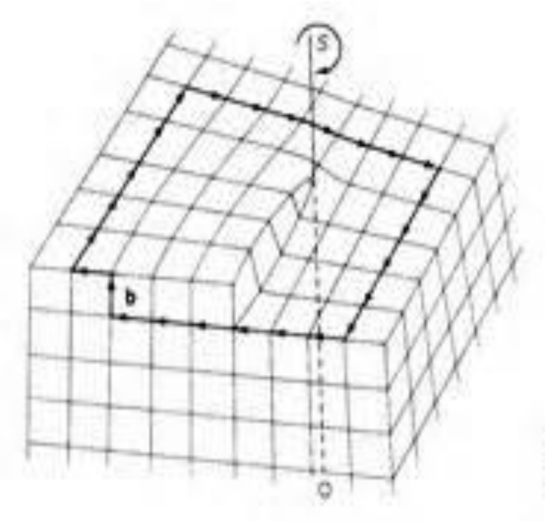
$$\frac{\mathrm{d}a}{\mathrm{d}N} = C(\Delta K)^m$$

Dislocations



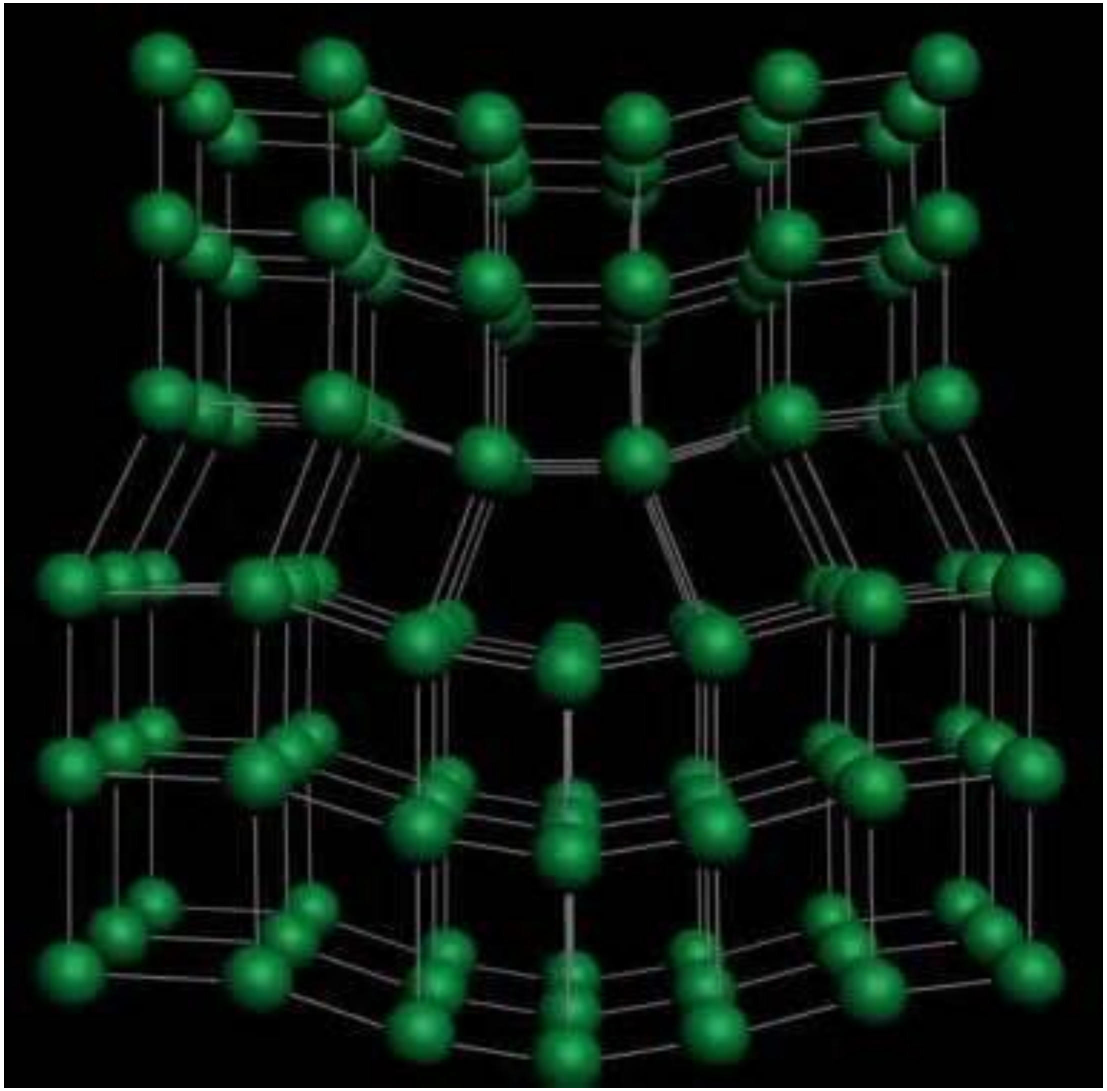
Edge Dislocation



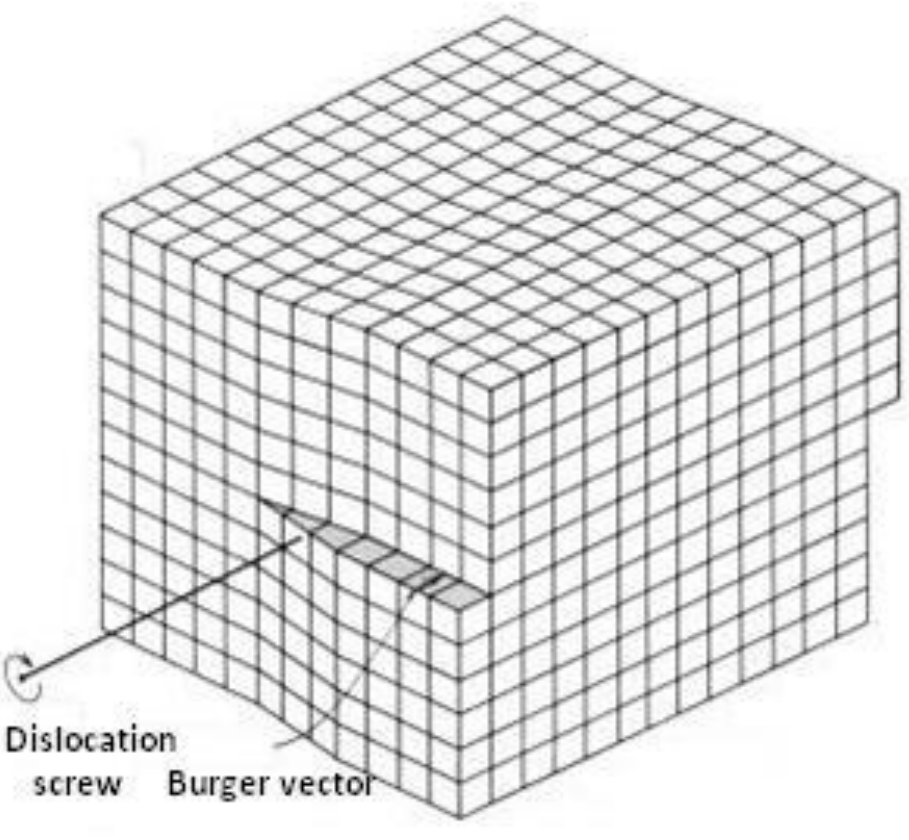


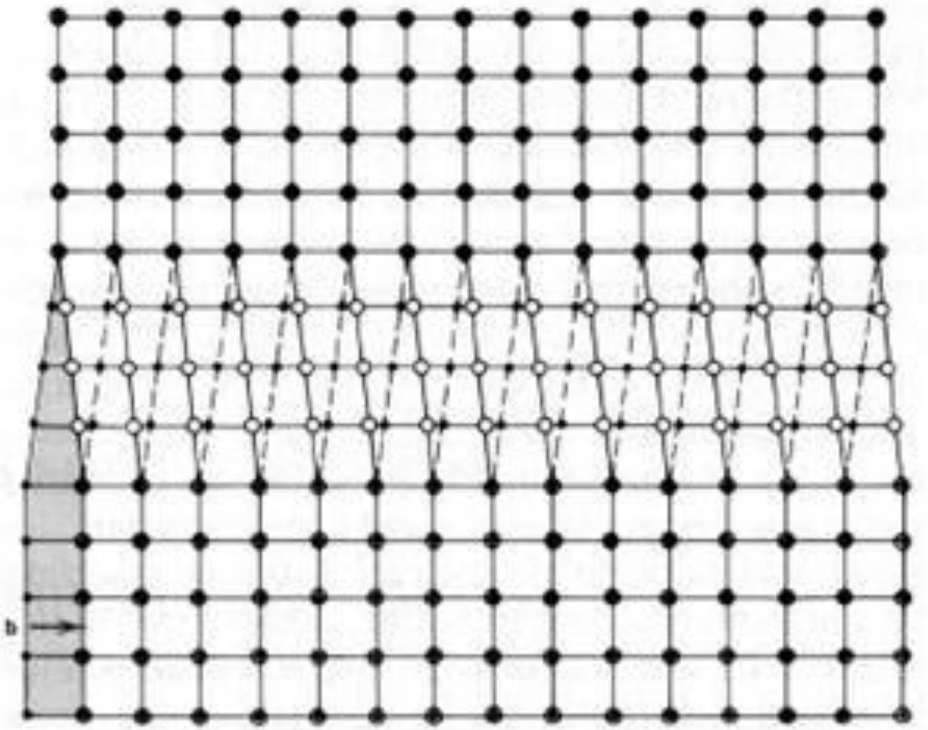
Screw Dislocation

Edge Dislocation

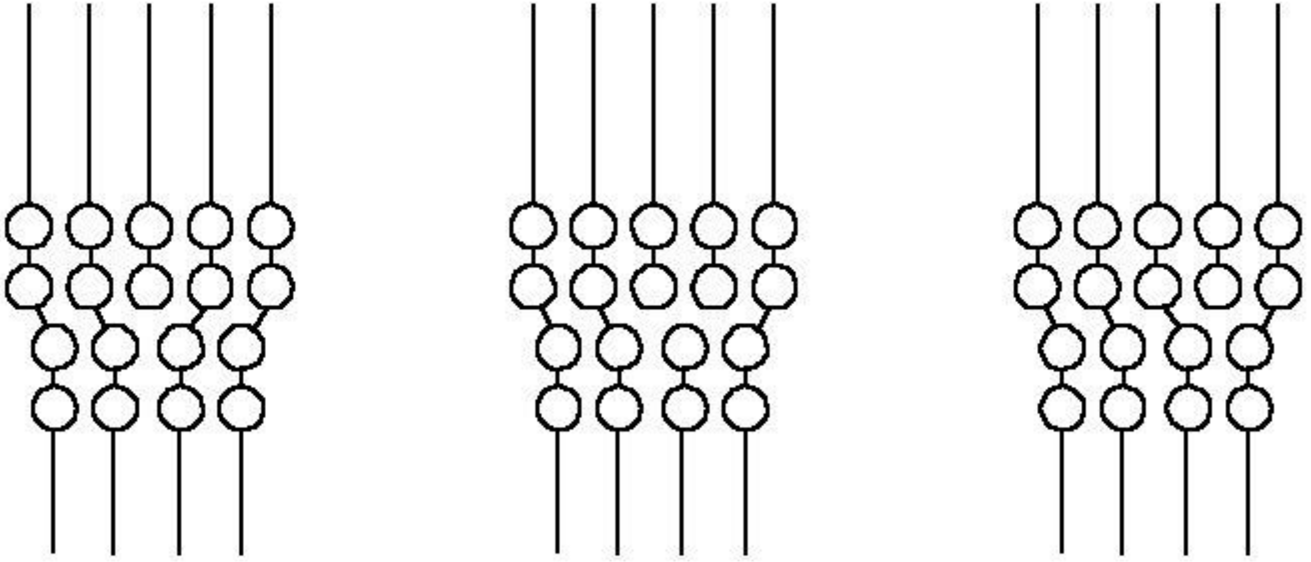


Screw Dislocation



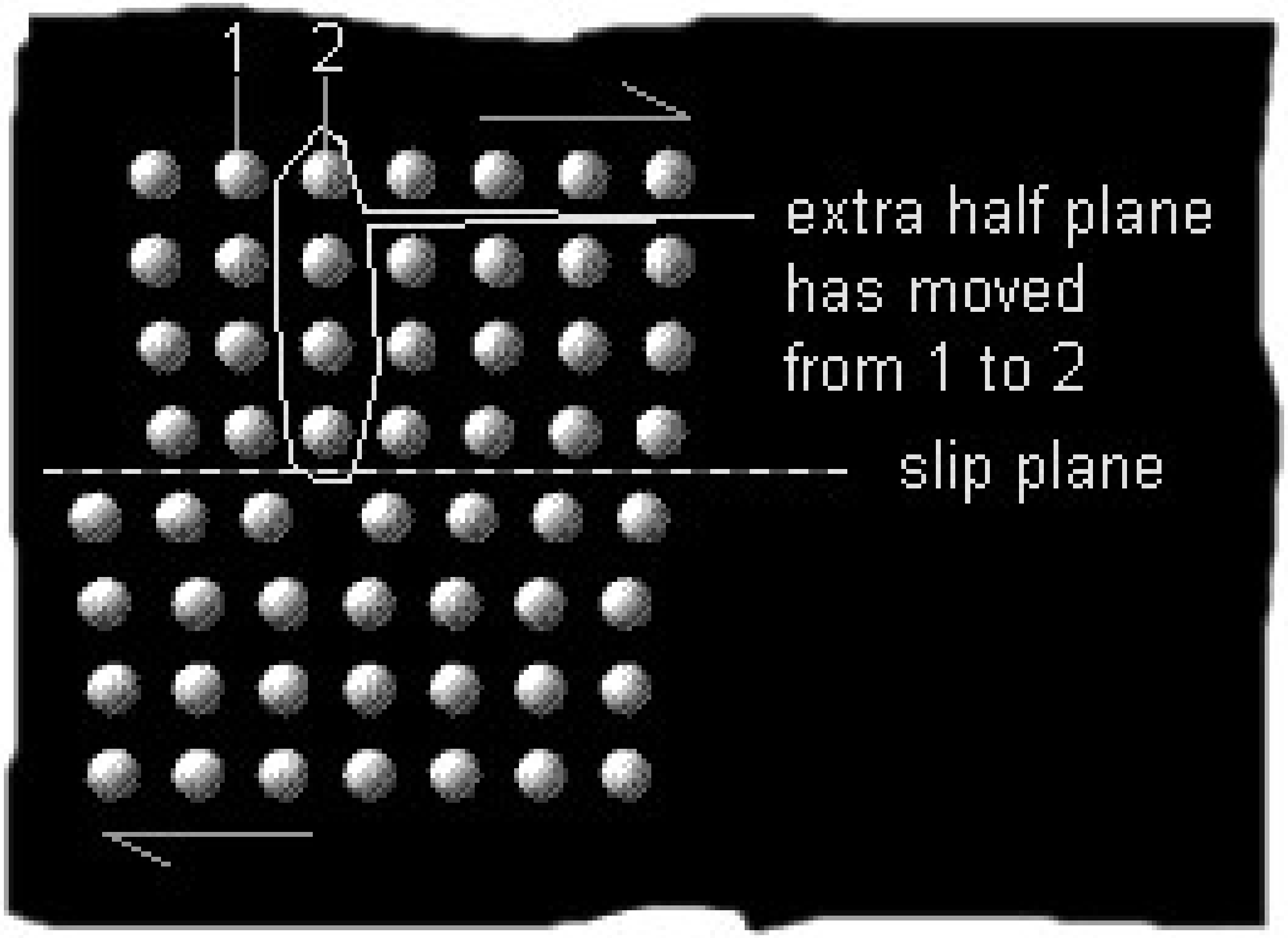


Intercrystalline Slip



Movement of a Dislocation through a Crystal Lattice

Intercrystalline Slip



Definitions

Slip Plane:

Particular set of crystallographic planes where slip occurs

Slip Direction:

Set of directions within these slip planes along which slip always takes place

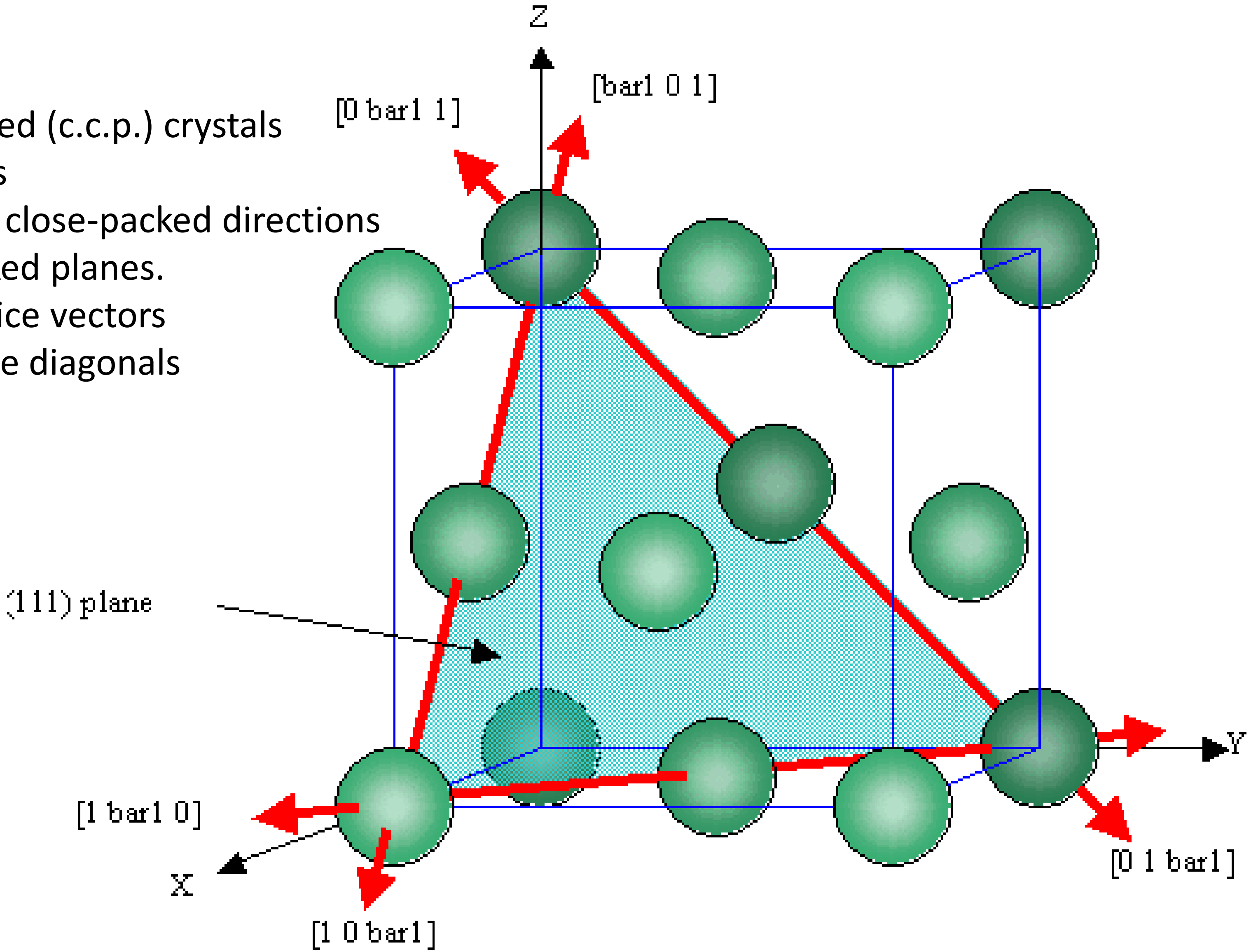
Slip System:

Combination of slip plane and slip direction;

Slip systems are specified by using Miller index notation

Slip Systems of Cubic close –packed Crystals

Cubic close-packed (c.c.p.) crystals have slip systems consisting of the close-packed directions in the close-packed planes.
The shortest lattice vectors are along the face diagonals of the unit cell



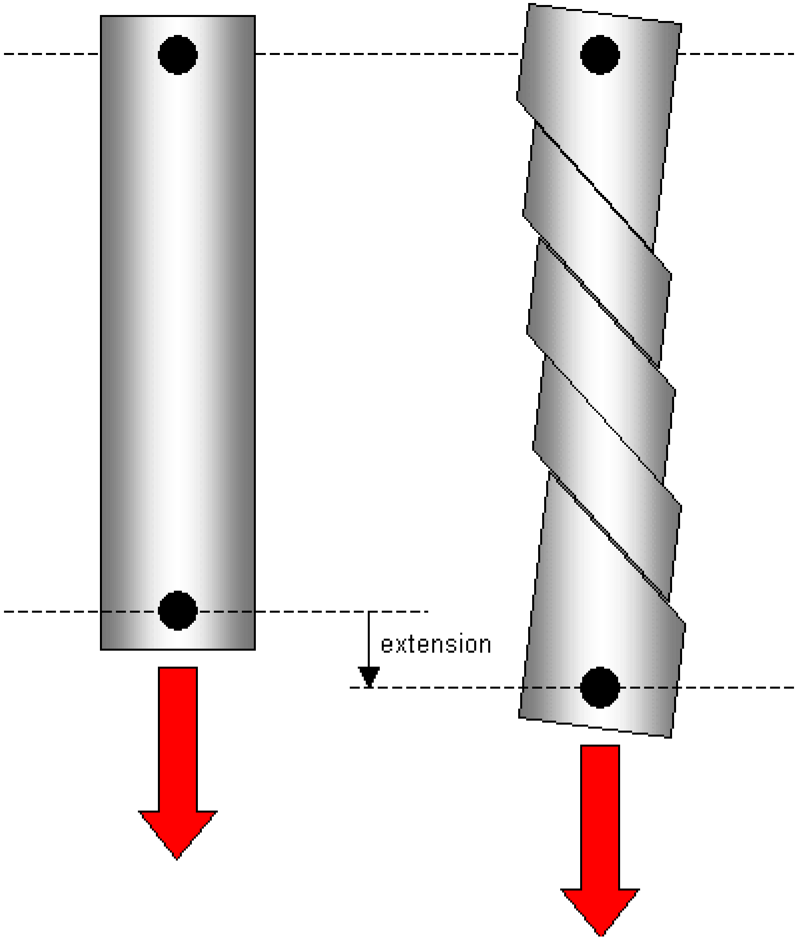
Slip Systems in C.C.P. Crystals

There are 3 distinct slip directions lying in the (111) plane
There are 3 other planes of the {111} type,
making 12 distinct slip systems of the <1 bar1 0>{111} type.

The cubic symmetry requires that there be many distinct slip systems,
using all <1 bar1 0> directions and {111} planes.
There are 12 such <1 bar1 0>{111} systems,
five of which are independent.

Note that on a given slip system,
slip may occur in either direction along the specified slip vector.

Plastic deformation of a single crystal occurs by slip on well-defined parallel crystal planes.

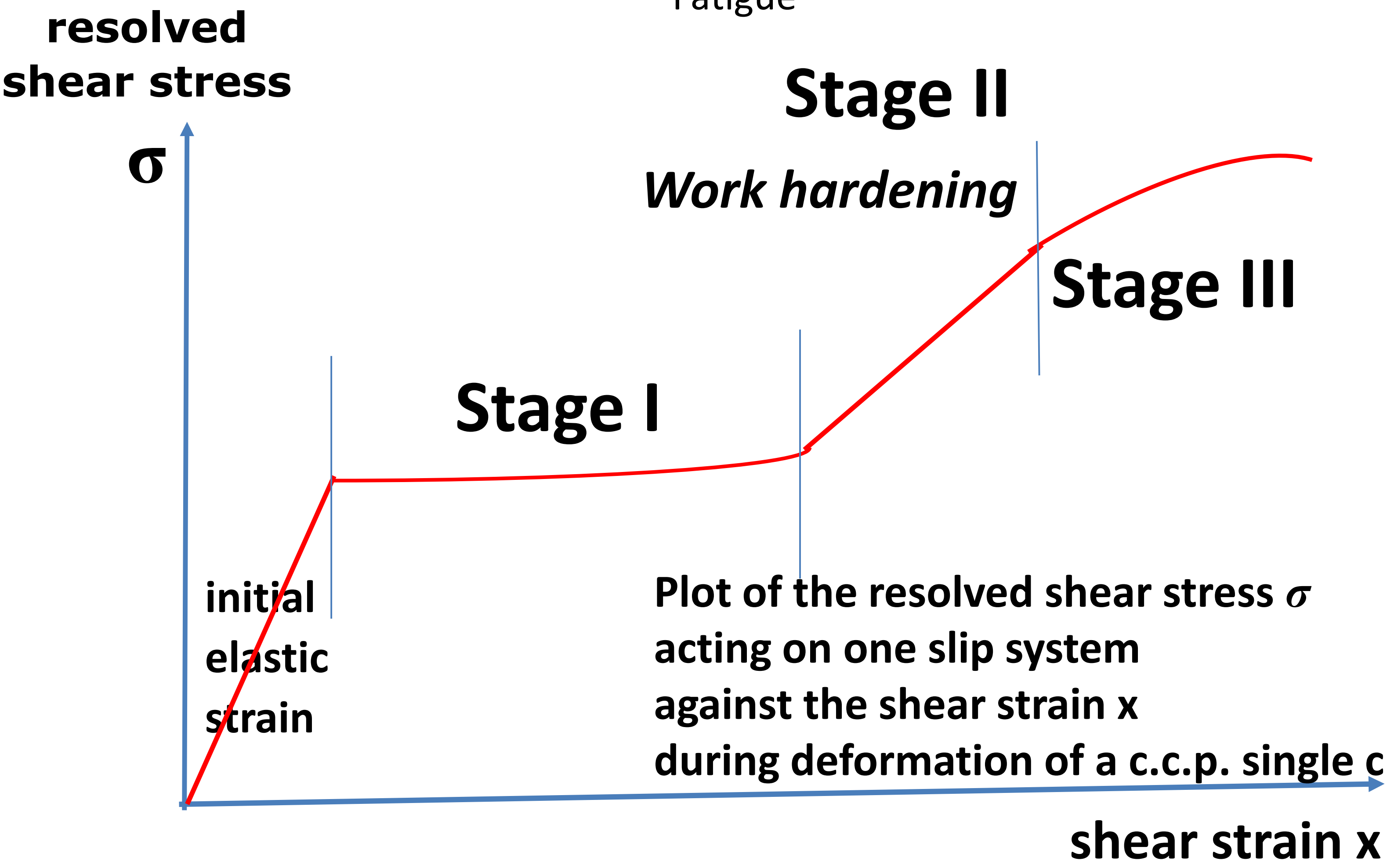


Unslipped single crystal
fixed at the top

Single crystal
after plastic deformation
by tensile stress

Many objects can impede dislocation motion:

- *Other dislocations*
- *Precipitates* → **PINNING**
- *Grain boundaries*



Plot of the resolved shear stress σ acting on one slip system against the shear strain x during deformation of a c.c.p. single crystal.

Stage 1: *easy glide*, caused by slip on one slip system (the *primary* slip system)
Stage II: dislocations are gliding on two slip systems;
they can interact in ways that *inhibit* further glide.
Stage III: corresponds to extension at high stresses; ends with the failure of the crystal

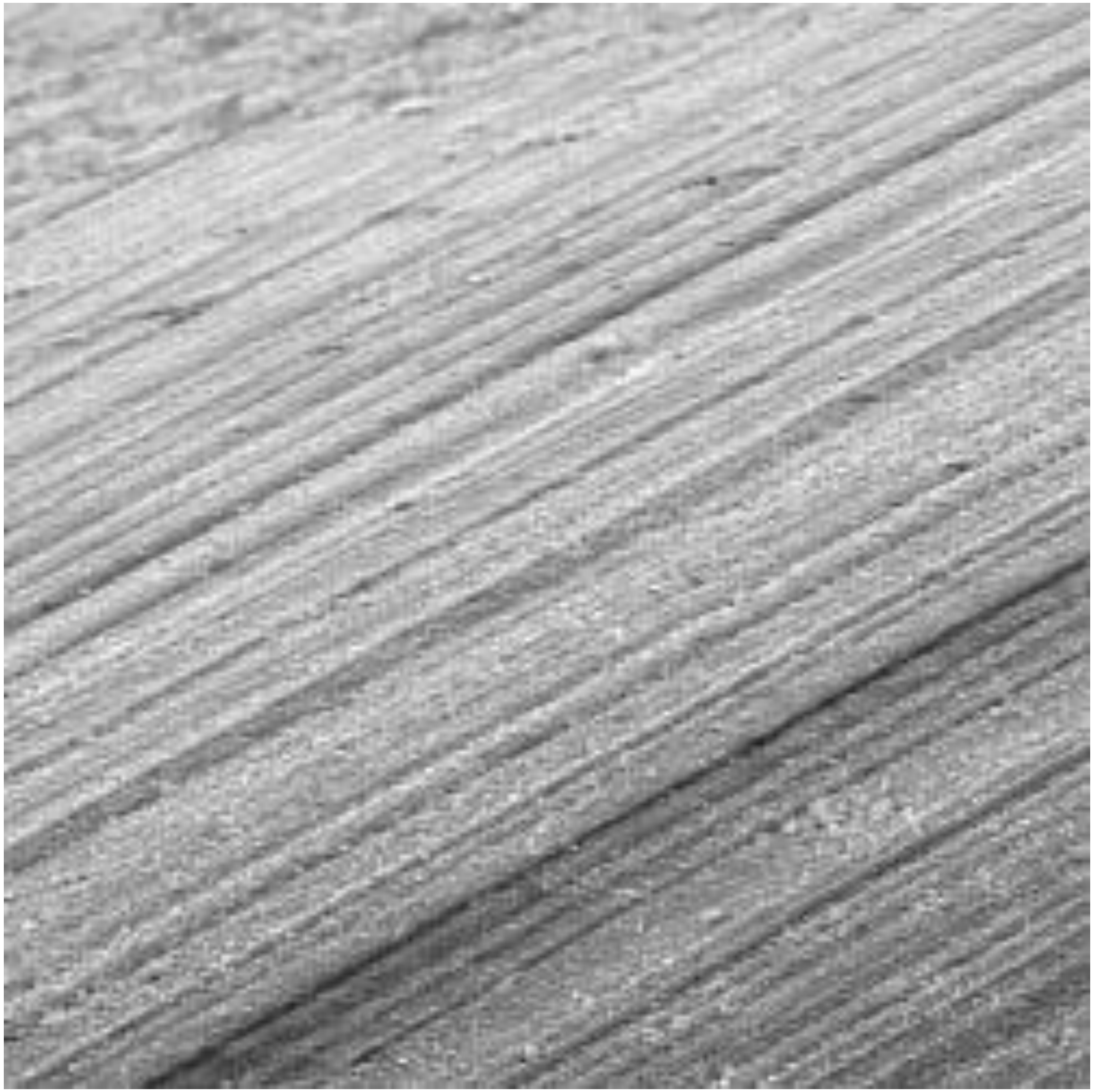
Fatigue

- **The *initial elastic strain* is caused by the simple stretching of bonds.**
  Hooke's Law applies to this region.

- **At the yield point, *stage I* begins. The crystal will extend considerably at almost constant stress. This is called *easy glide*, and is caused by slip on one slip system (the *primary* slip system).**
  The geometry of the crystal changes as slip proceeds.

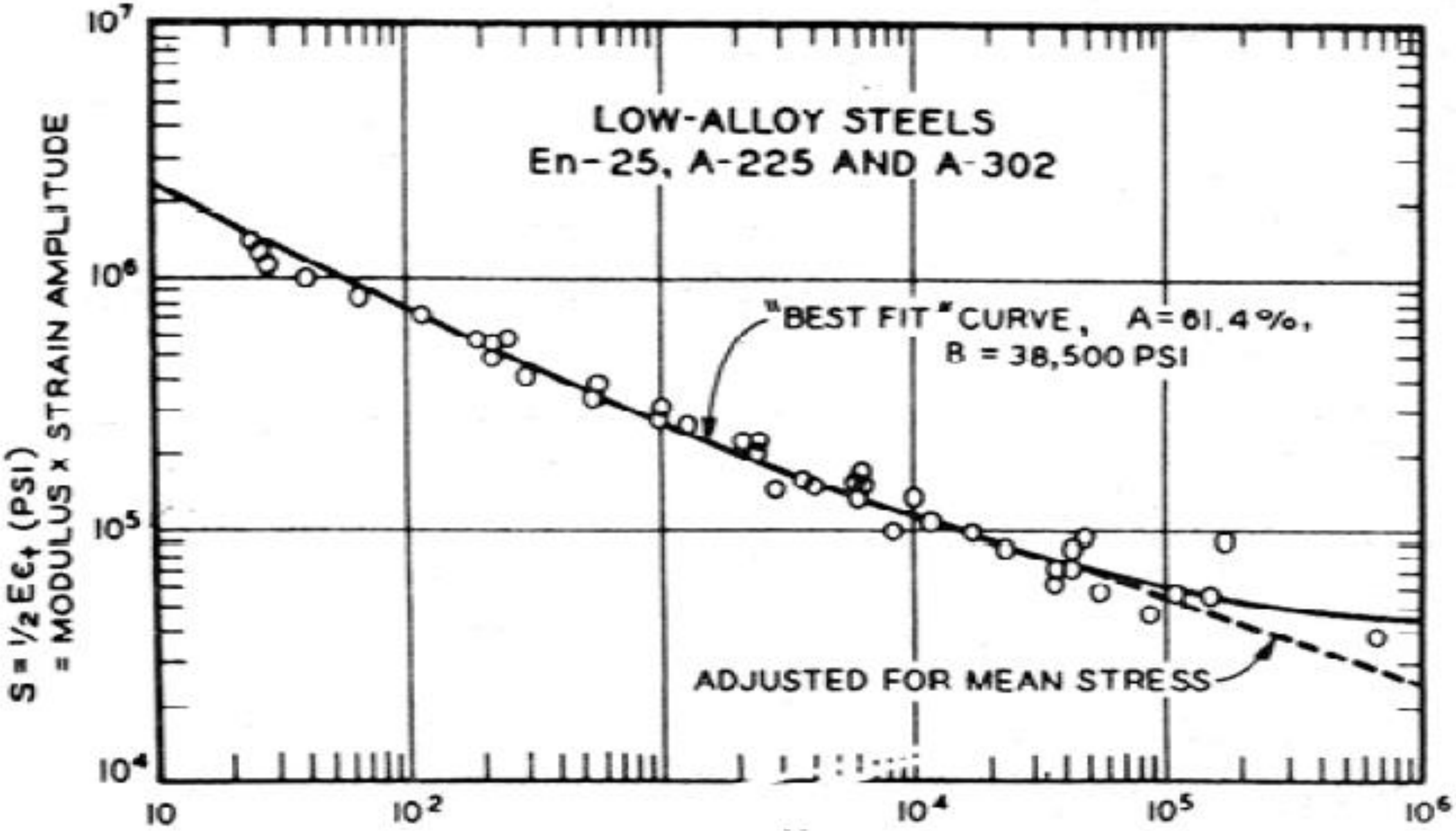
- **Slip may begin on a second slip system. In this stage of deformation, known as *stage II*, dislocations are gliding on two slip systems, and they can interact in ways that *inhibit* further glide. Consequently, the crystal becomes more difficult to extend. This phenomenon is called *work hardening*. The stress / strain ratio in stage II may be constant.**

- ***Stage III* corresponds to extension at high stresses, where the applied force becomes sufficient to overcome the obstacles, so the slope of the graph becomes progressively less steep. The work hardening *saturates*. Stage III ends with the failure of the crystal.**



Multiple Slip Bands

Design Fatigue Curves: best fit



N Cycles to Failure

Plot of S-N-sample fatigue data (Carbon Steels)

basis for design fatigue curves in the ASME code, section III

Fatigue Design Curve
Provision for Realistic Loads

Procedure:

- Analysis of all types of loads
- Specification of load spectrum

Concept:

- Additive accumulation of partial fatigue behavior

$$U = U_1 + U_2 + U_3 + ... + U_n$$

With $U < 1$ ($U = 1$: crack initiation)

Sample Fatigue versus Component Fatigue

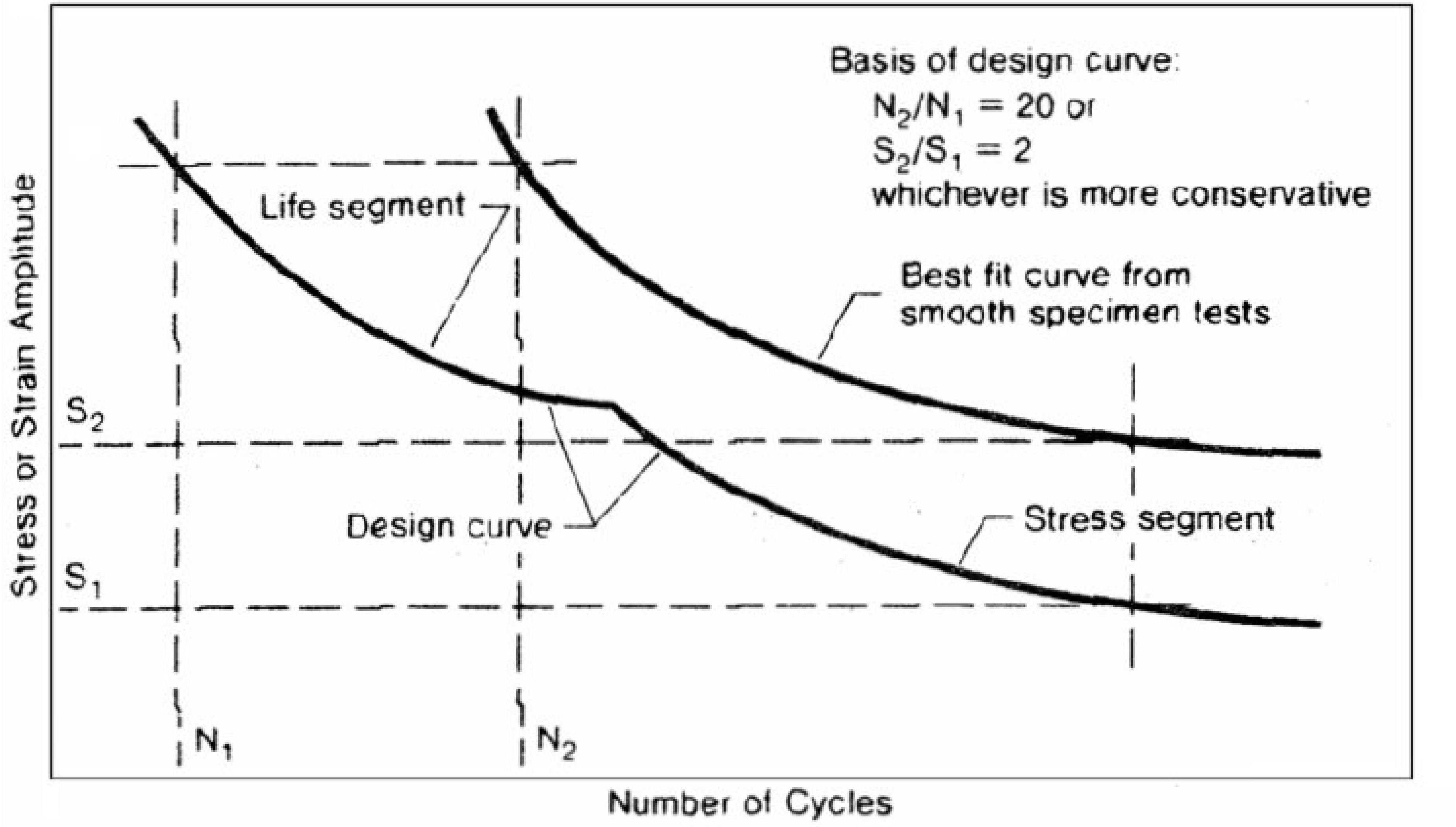
Design Curve

with Experienced based Reduction Factors

- ***Data Scattering:*** **2**
- ***Scale & Geometry Effects*** **2,5**
  (Sample size versus component size)
- ***Surface Quality & Atmosphere*** **4**

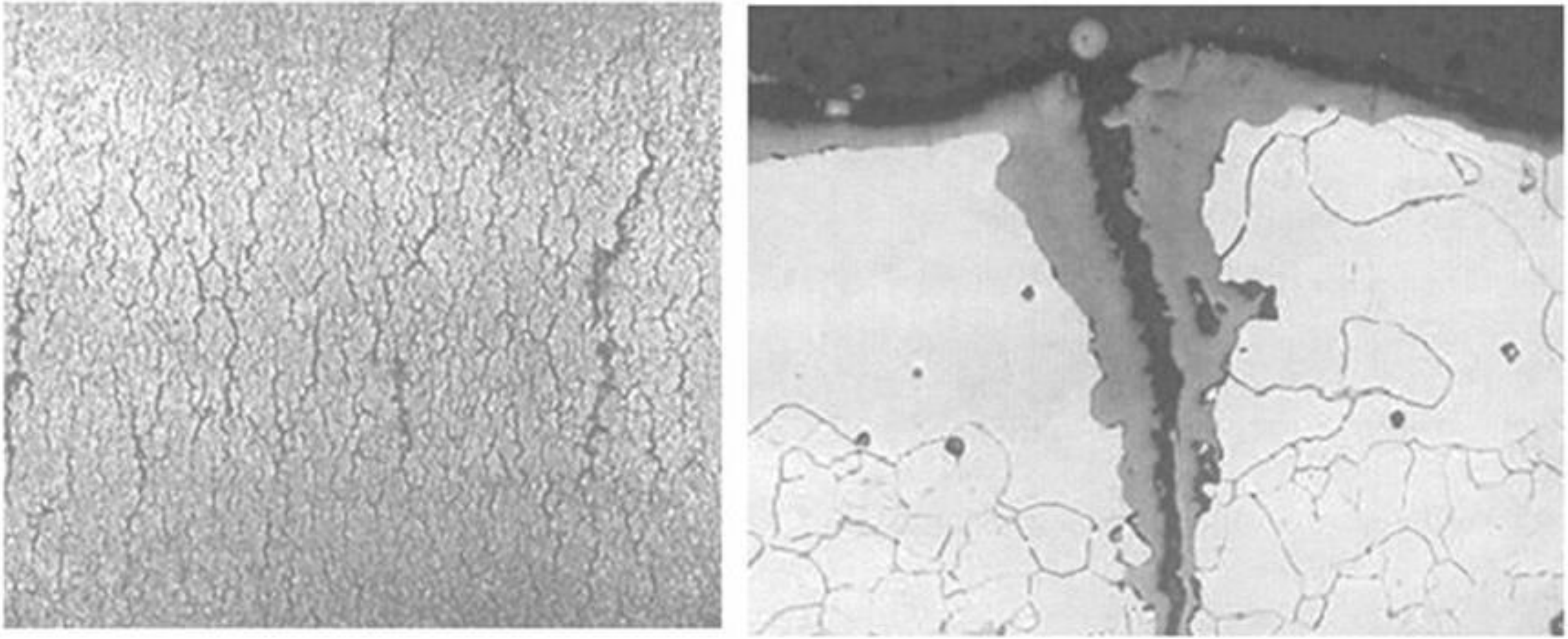
$\}$ **20**

Fatigue



Development of ASME B&PVC, Section III, fatigue design curves
From best fit curves of laboratory test results
by application of factor 20 on cycles and factor 2 on stress or strain amplitude

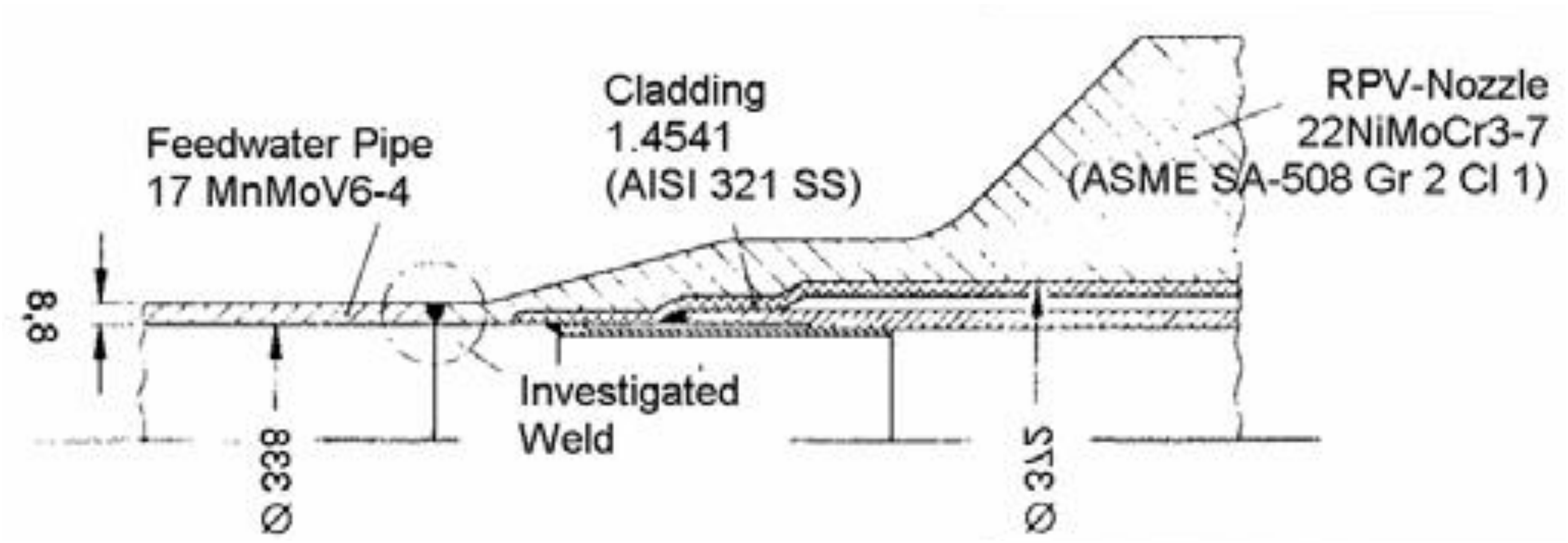
Thermo-Mechanical Fatigue



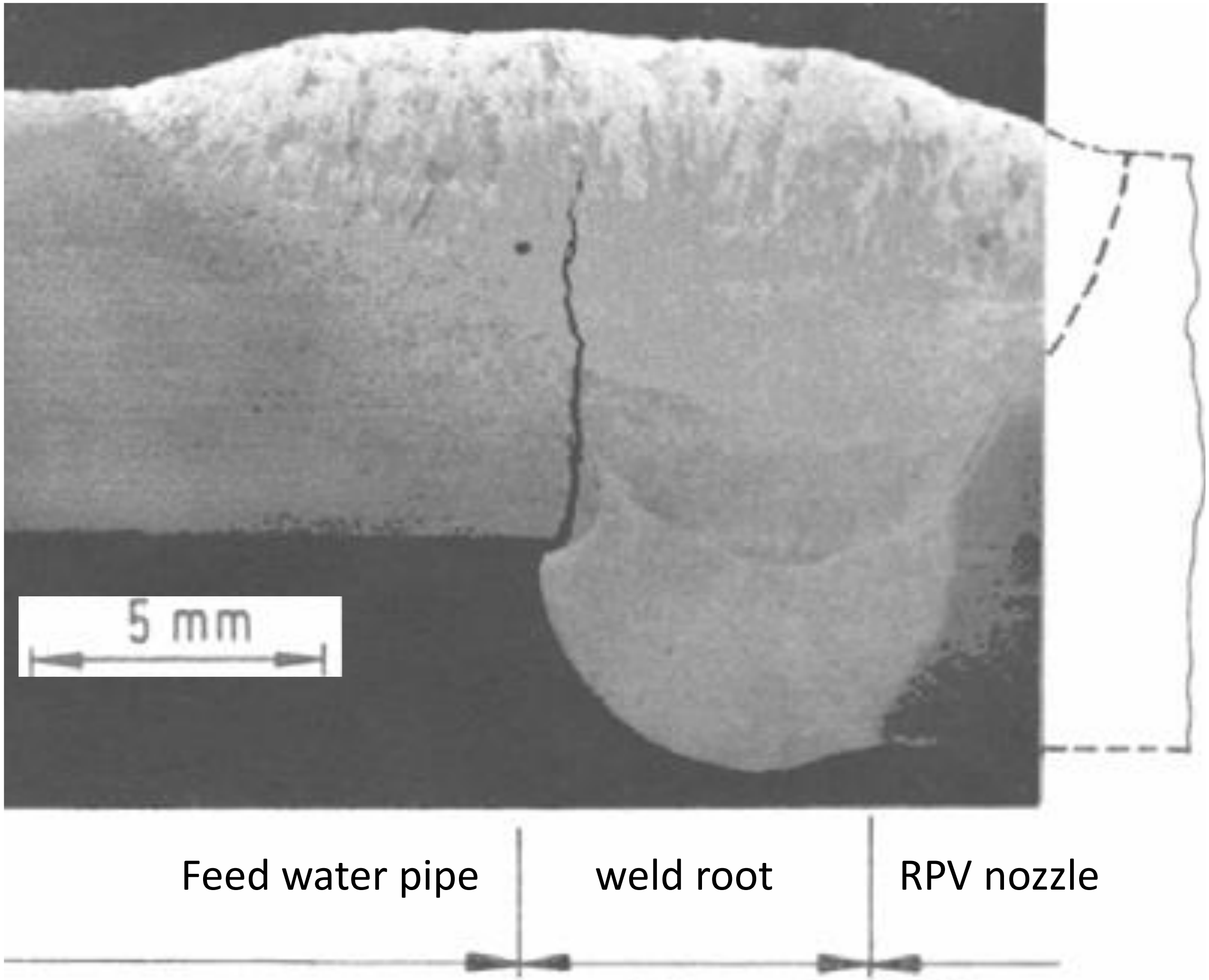
Thermal fatigue

Case Study:

development of thermal stratification at low cold feedwater injection rates to PWR SG's and BWR RPV's and consequential transient thermal stress

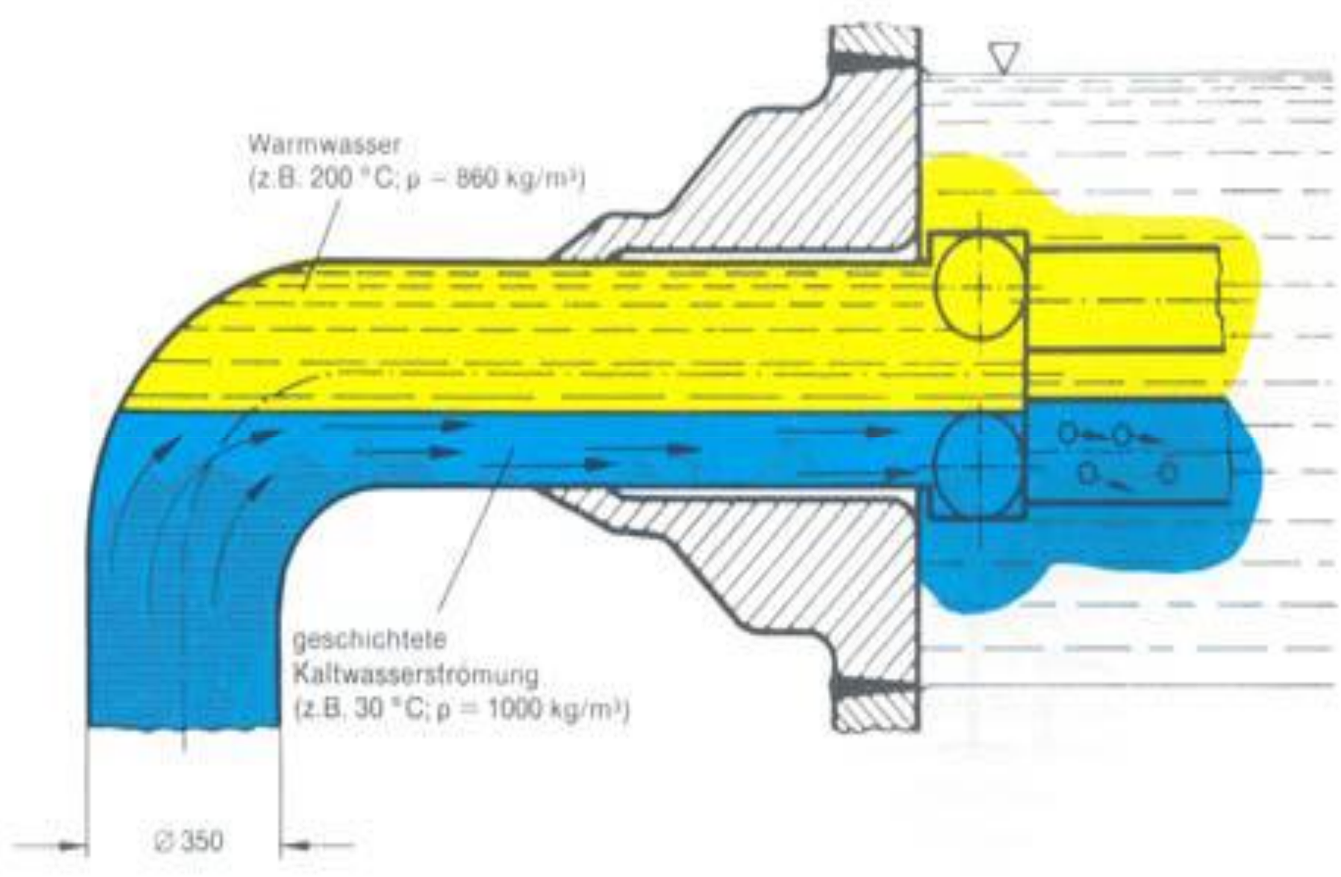


Fatigue



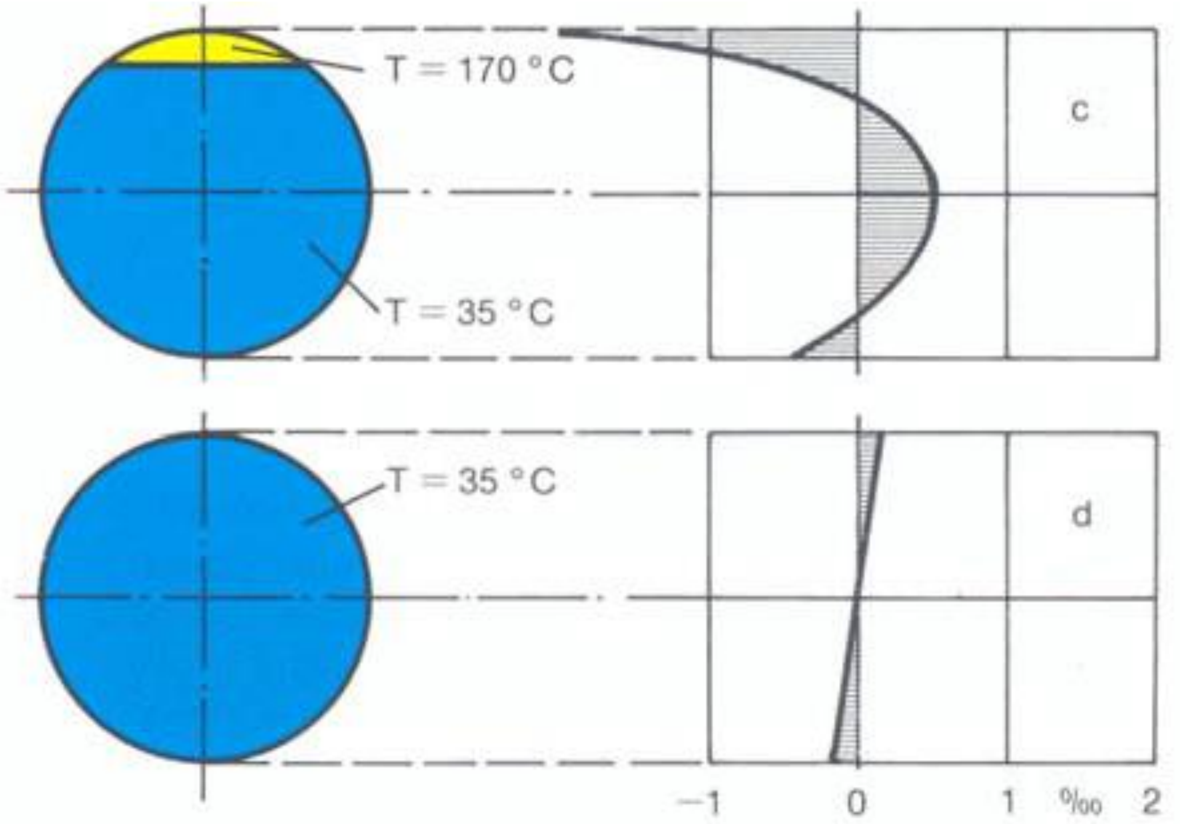
Fatigue Crack

Thermal Fatigue

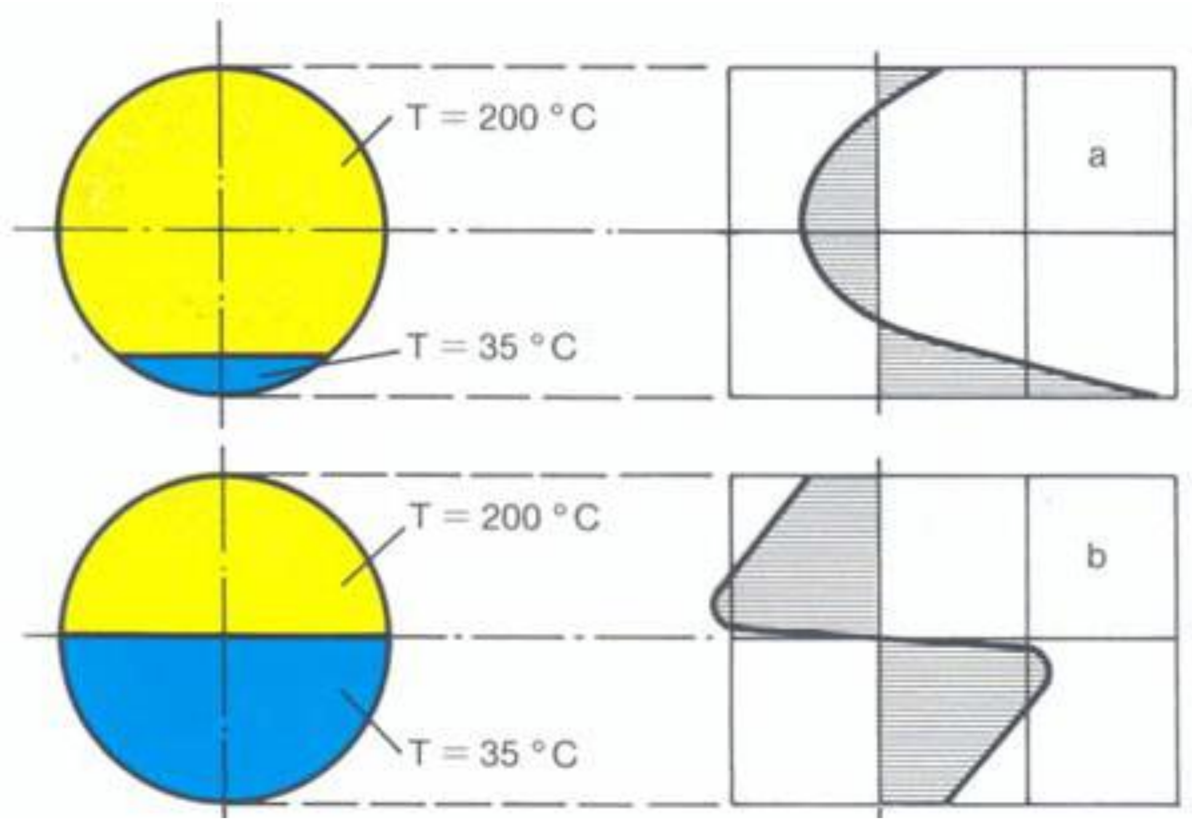


Longitudinal cross section of nozzle/pipe during thermal stratification

Fatigue

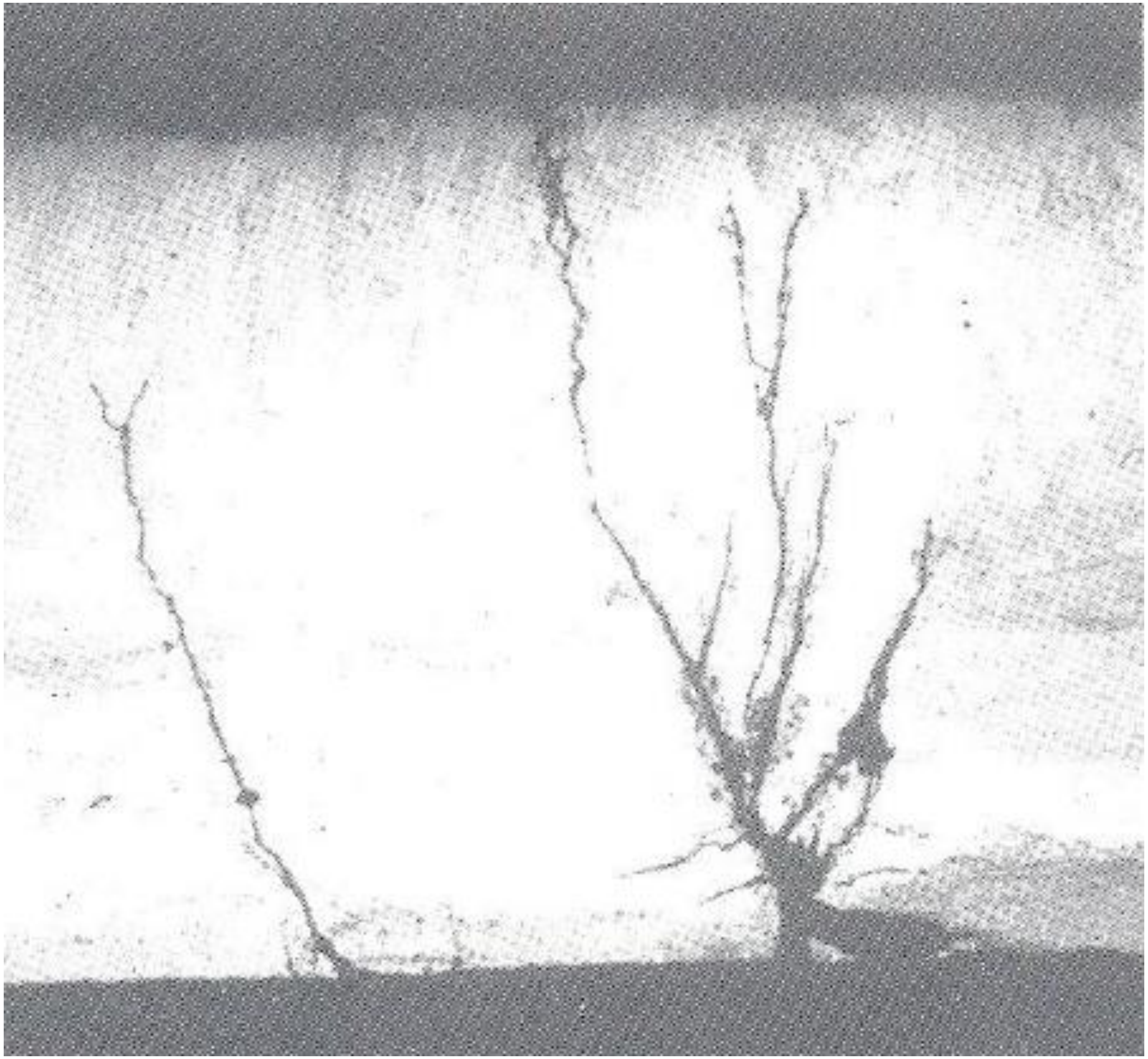


Transverse cross section of nozzle/pipe and derivation of transient thermal stress along the circumference (1)

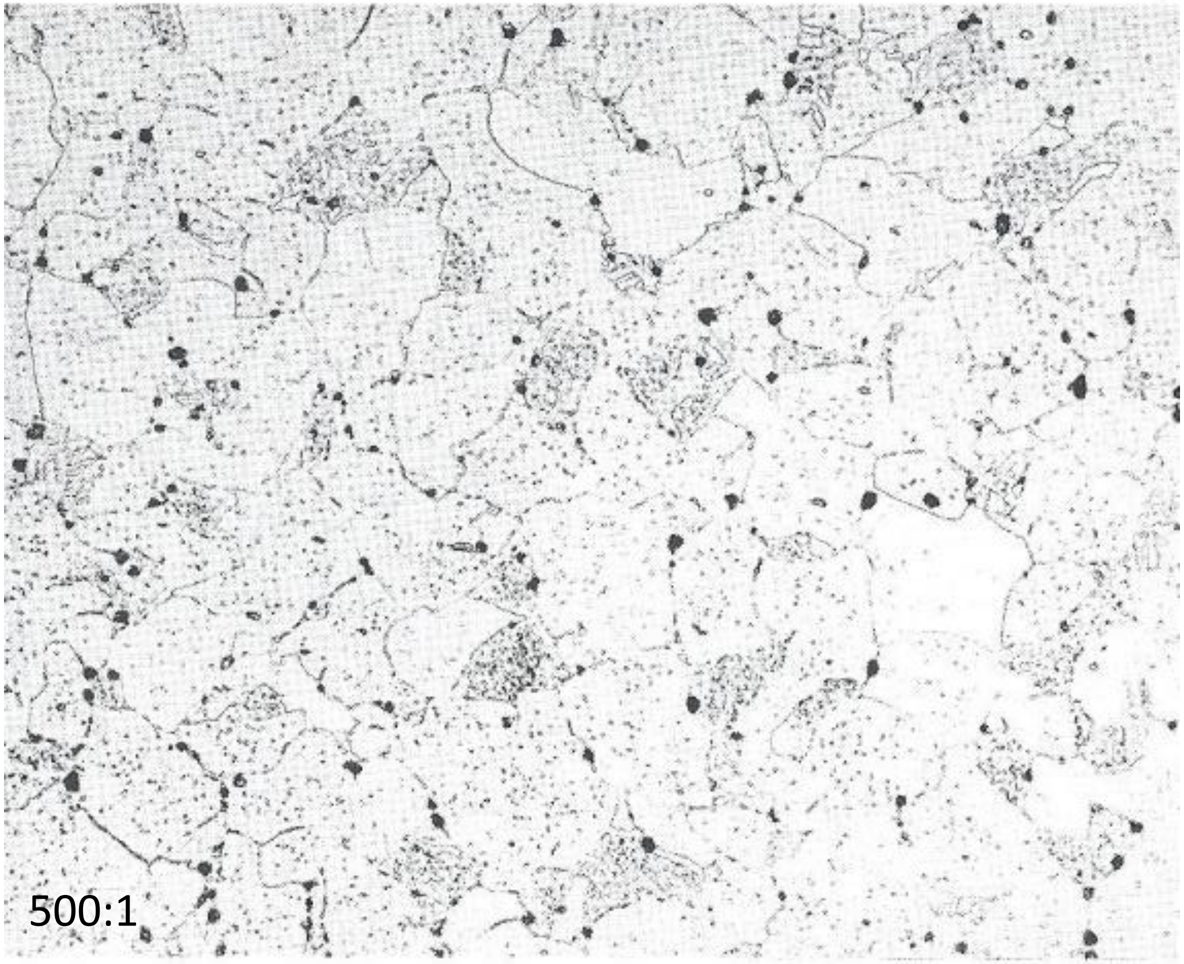


Transverse cross section of nozzle/pipe and derivation of transient thermal stress along the circumference (2)

Fatigue



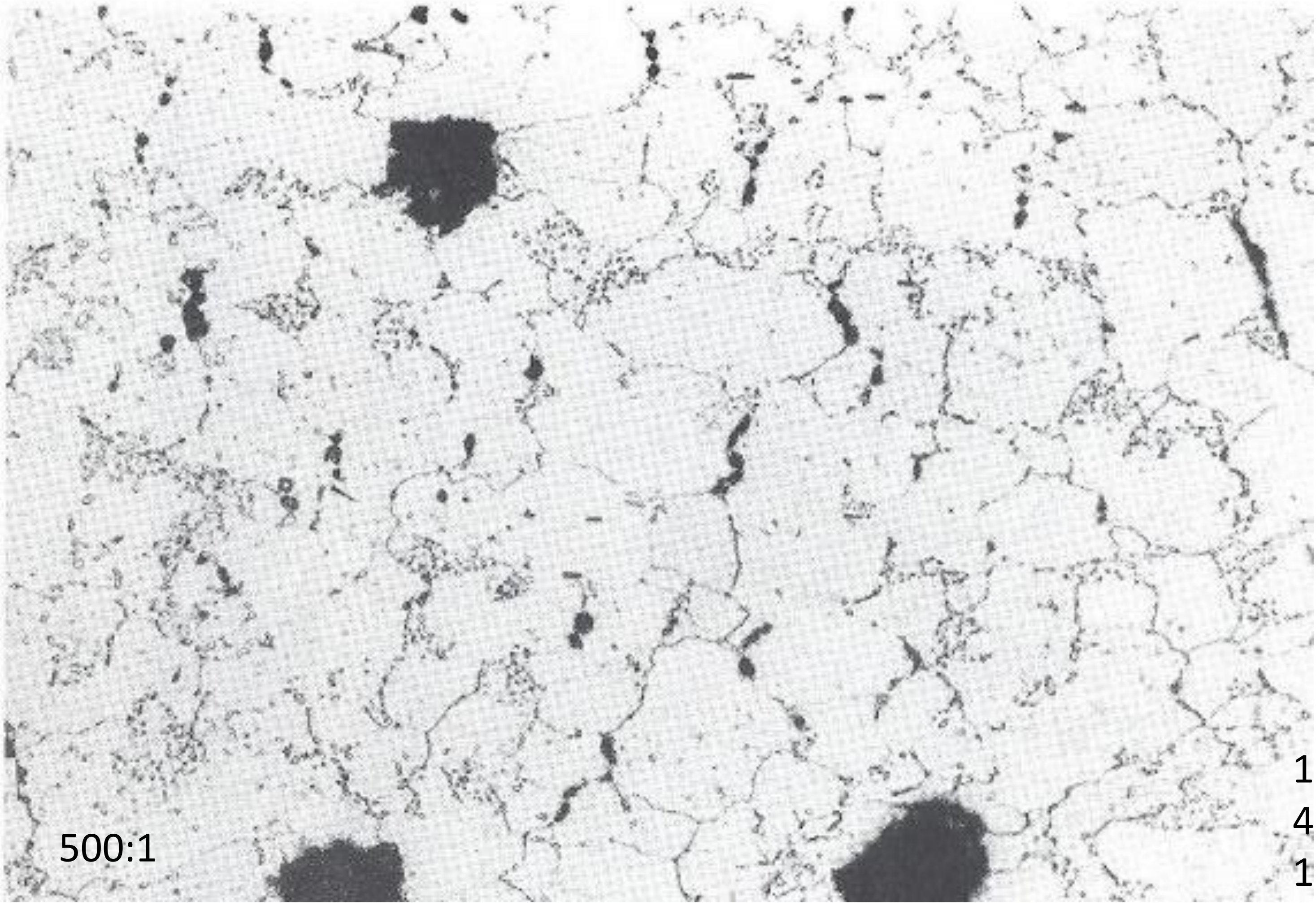
Transgranular Stress Corrosion Cracks (Chloric Water)



13 CrMo 44

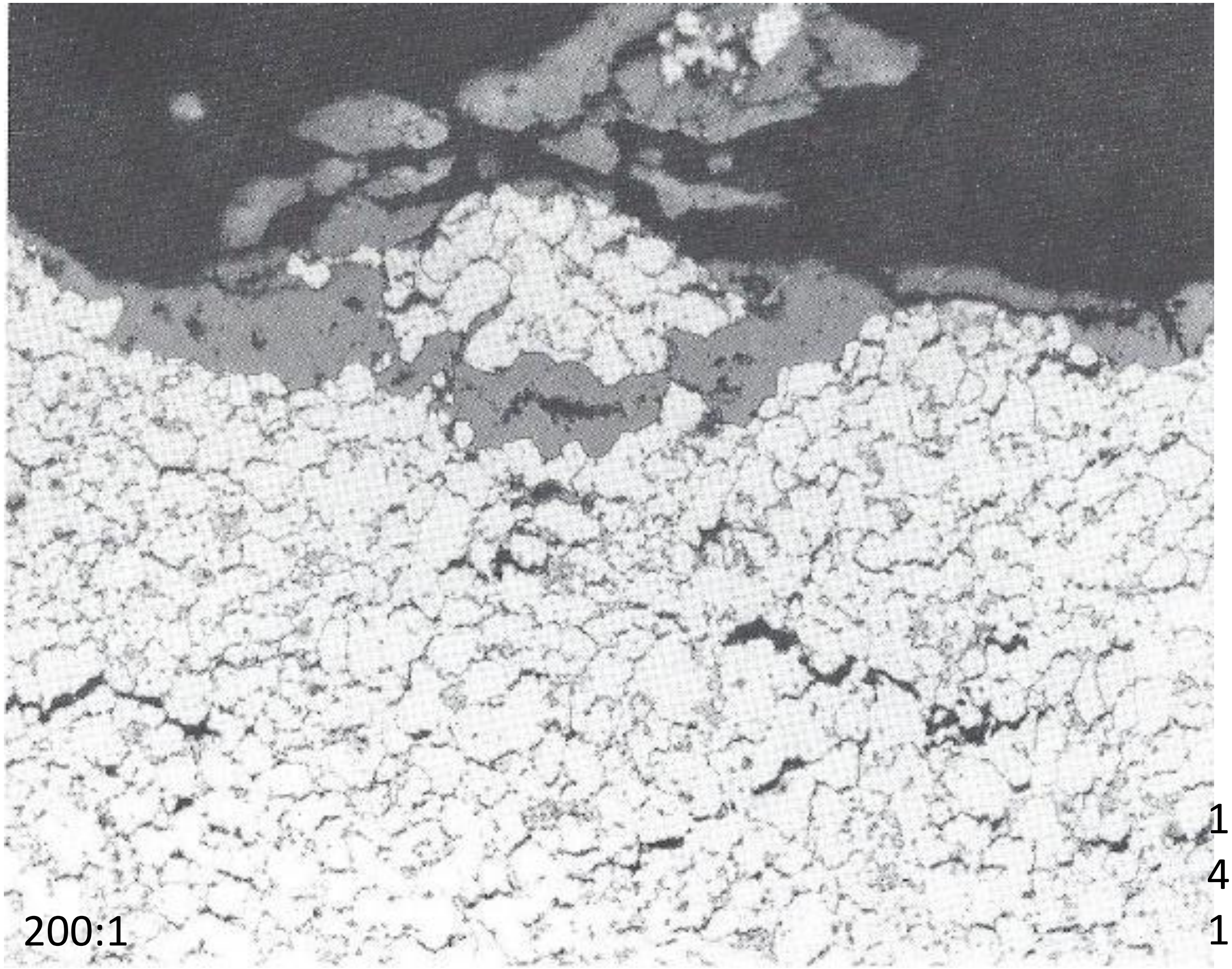
Creep Damage: Voids

Fatigue



15Mo3
480°
165bar

Creep Damage



Creep Damage close to the Crack Face
Intergranular Short Cracks

A Continuing Challenge:

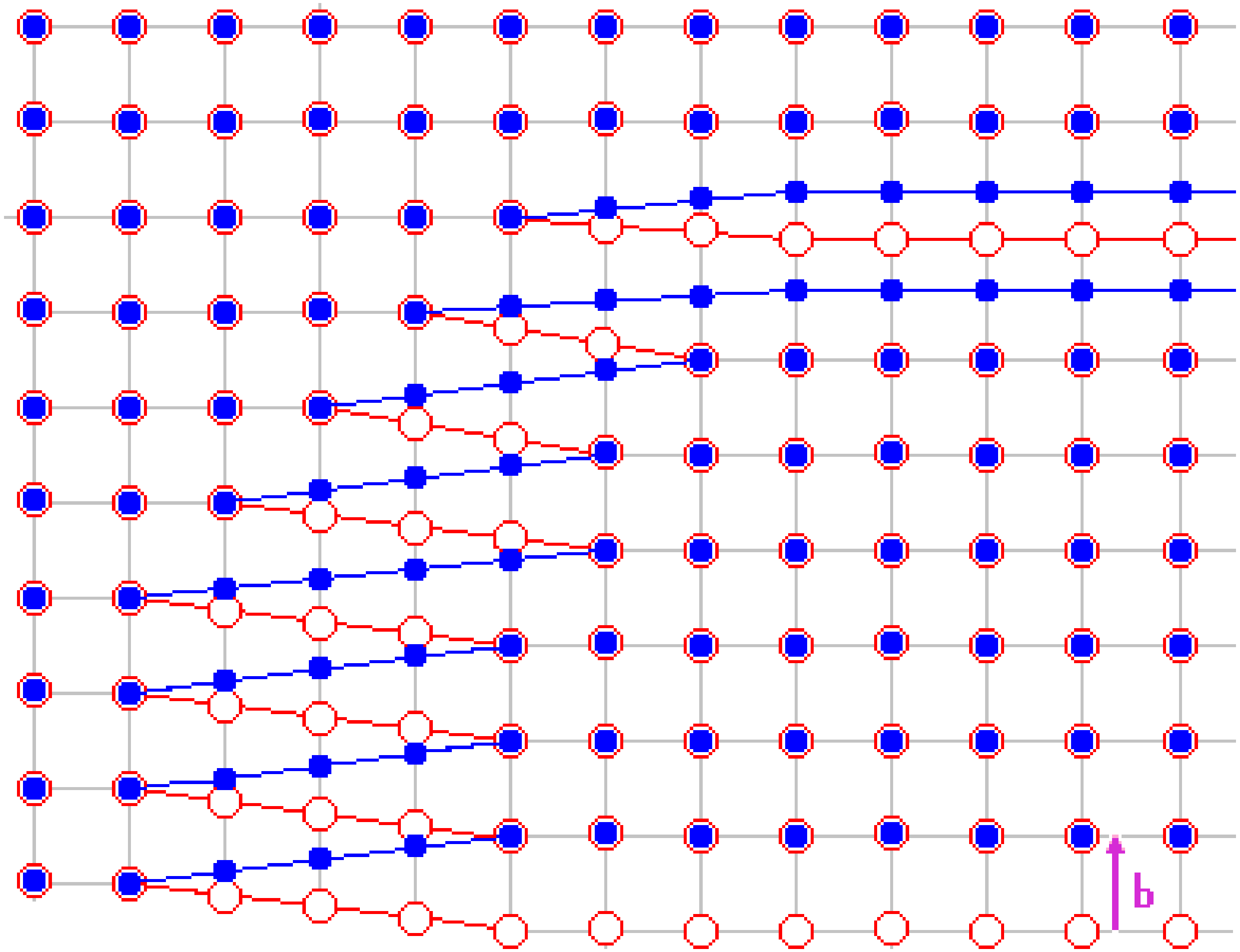
Can we identify contrast mechanisms for characterization of early material degradation

A challenge for the next generation

Literature

1. Ralph I. Stephens; Henry O. Fuchs: *Metal Fatigue in Engineering* (Second edition ed.), John Wiley & Sons, Inc. p. 69. ISBN 0-471-51059-9, (2001).
2. *Benjamin M. Ma: Thermal, irradiation and cyclic loading analysis for stress fatigue crack in reactor vessels,* International Journal of Pressure Vessels and Piping, Vol. 31, Issue 2, Elsevier, (1988).

Fatigue



Fatigue