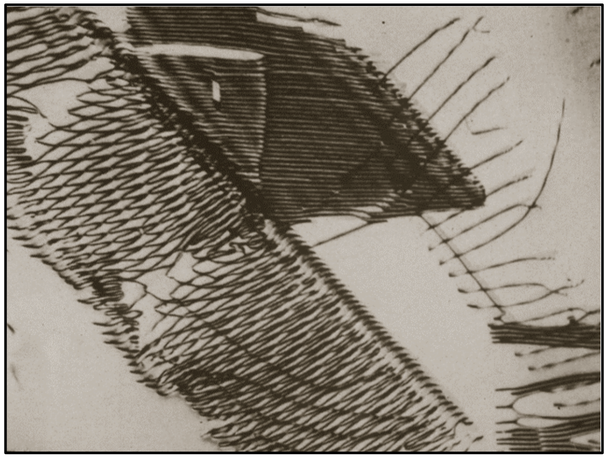
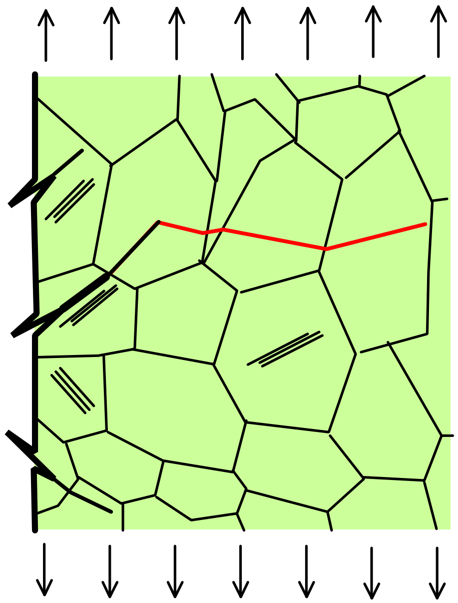
Materials Issues in Fatigue and Fracture



- 5.1 **Fundamental Concepts**
- 5.2 Ensuring Infinite Life
- 5.3 Finite Life
- 5.4 Summary

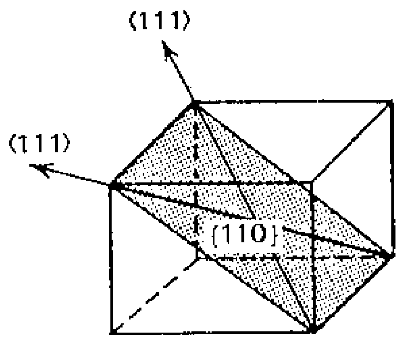
5.1 Fundamental Concepts

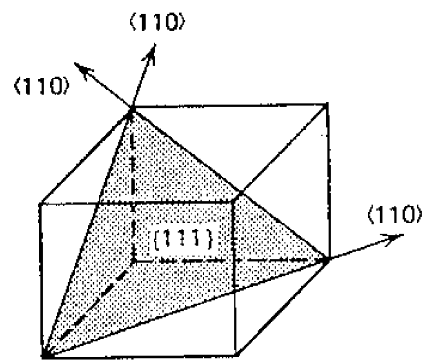


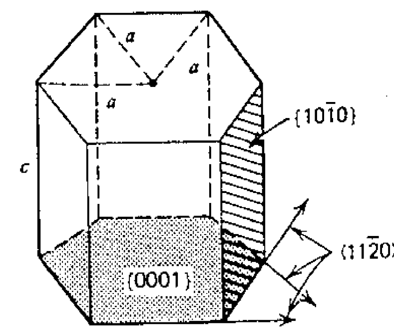
- **Structural metals**
- Process of fatigue
- A simple view of fatigue

Three common structural metals

FCC	BCC	HCP
Face-centered Cubic	**Body-centered Cubic**	**Hexagonal close-packed**
Aluminum	Iron	Titanium
12 Slip systems	48 Slip systems	3 Slip systems







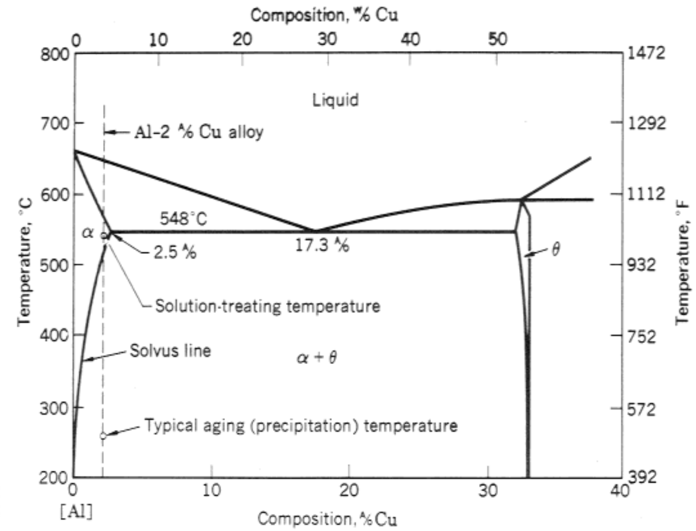
The three structural metals have entirely different crystal structures and slip systems, which leads one to imagine that they would have differing responses to cyclic loading.

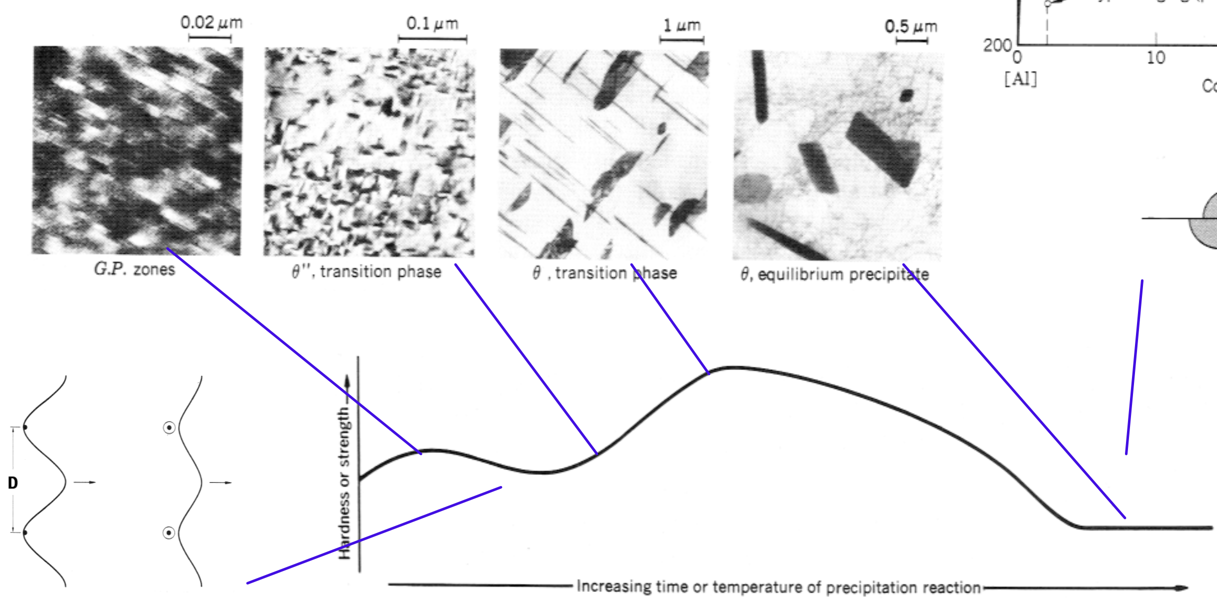
Aluminum Alloys

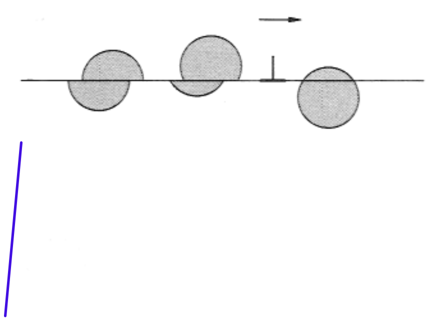
Property	Value	Consequences
Crystal Structure	FCC	Polycrystals ductile, low yield strength, strain-rate and temperature insensitive
Modulus (GPa)	70	Low bond strength
RT Homologous T	0.29	Close to creep temperature
Yield Strength (MPa)	25-600	
Basic Microstructure	Single or two phase	
Strengthening Strategy	Solid solution	
Strengthening Strategy	Precipitation	

Precipitation hardening of Al

Extended solubility permits creation of dispersoids or precipitates which impede dislocation motion.





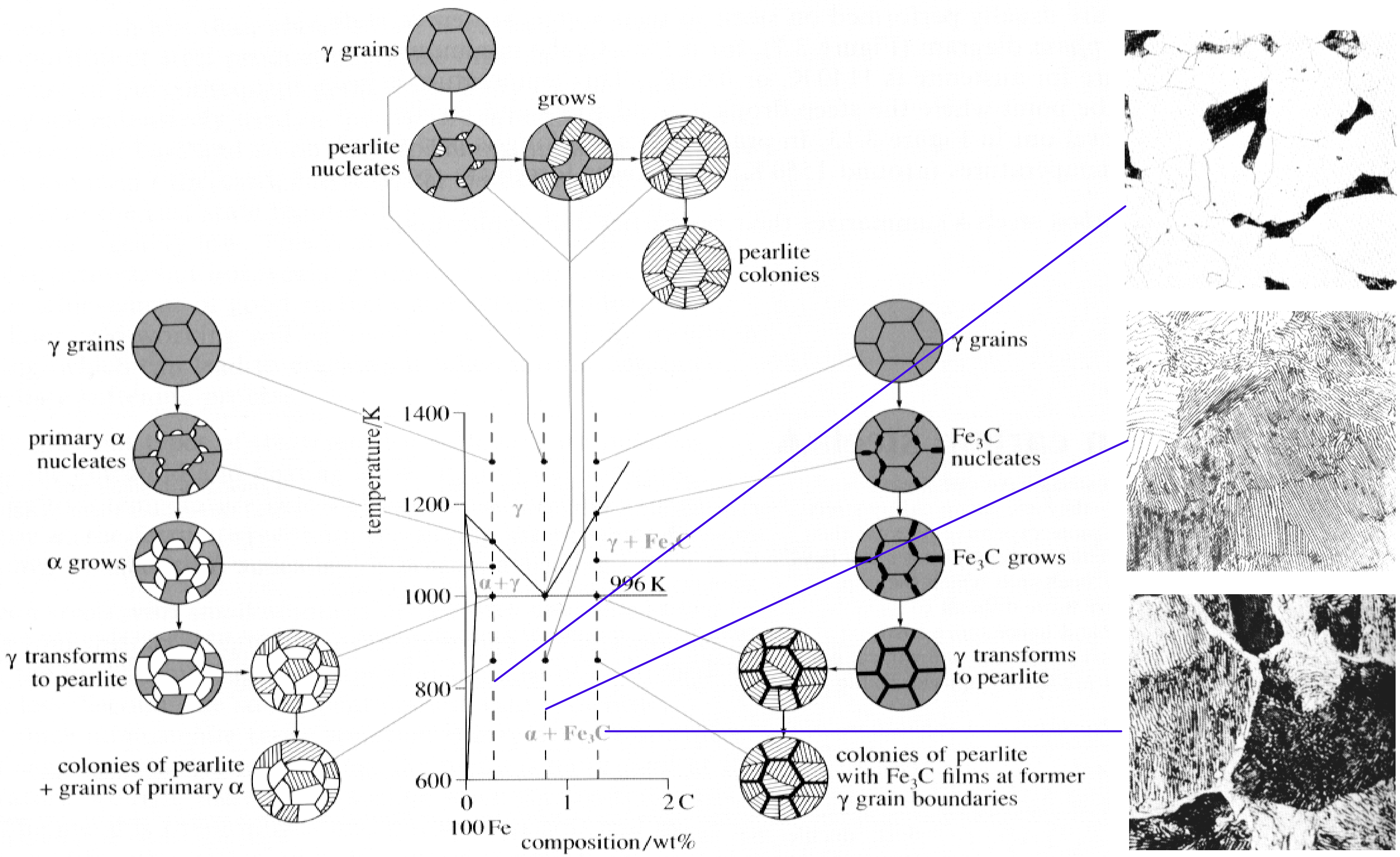


Structural steel

Property	Value	Consequences
Crystal Structure	BCC (FCC)	Polycrystals ductile, high yield strength, strain-rate and temperature sensitive
Modulus (GPa)	189	Reflects high bond strength
RT Homologous T	0.15	High melting point
Yield Strength (MPa)	220-1600	
Basic Microstructure	Two phase	Ferrite-pearlite
Strengthening Strategy	Microstructure size control	Wide range of strengths possible through heat treatment
Strengthening Strategy	Transformation products	Martensitic transformation

Structural steel

Development of hypoeutectoid, eutectoid, and hypereutectoid microstructures

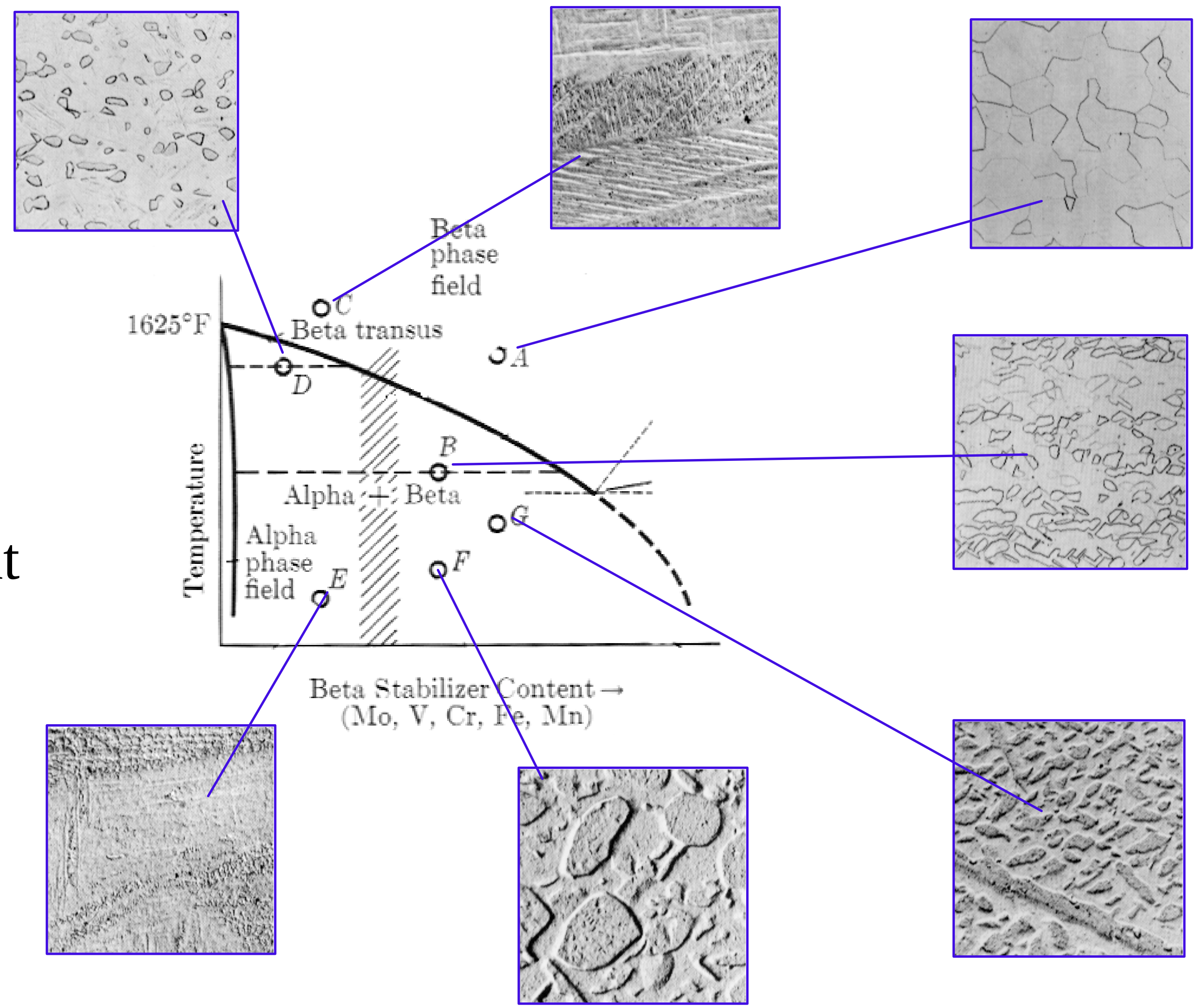


Titanium alloys

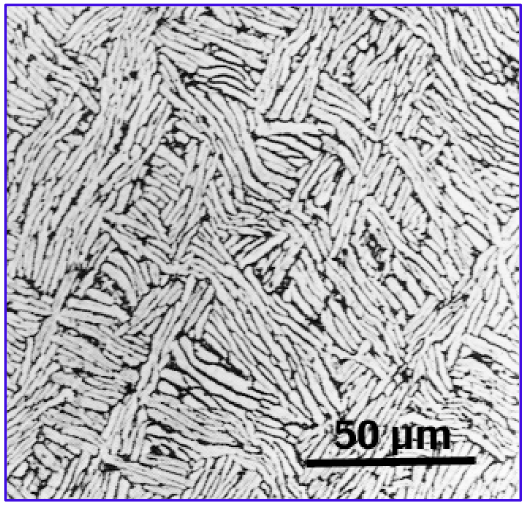
Property	Value	Consequences
Crystal Structure	HCP (BCC)	β Titanium is BCC and hence very ductile; whereas, HCP α is less so.
Modulus (GPa)	120	Reflects high bond strength
RT Homologous T	0.15	High melting point
Yield Strength (MPa)	170-1280	
Basic Microstructure	Two phase	Alpha and Beta phases
Strengthening Strategy	Microstructure size control	Wide range of strengths possible through heat treatment and control of microstructure
Strengthening Strategy	Transformation products	Martensitic transformation

Titanium microstructures

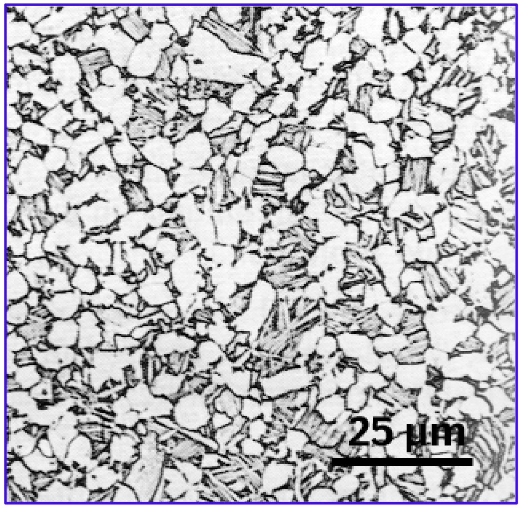
Effects of composition and heat treatment



Titanium heat treatment

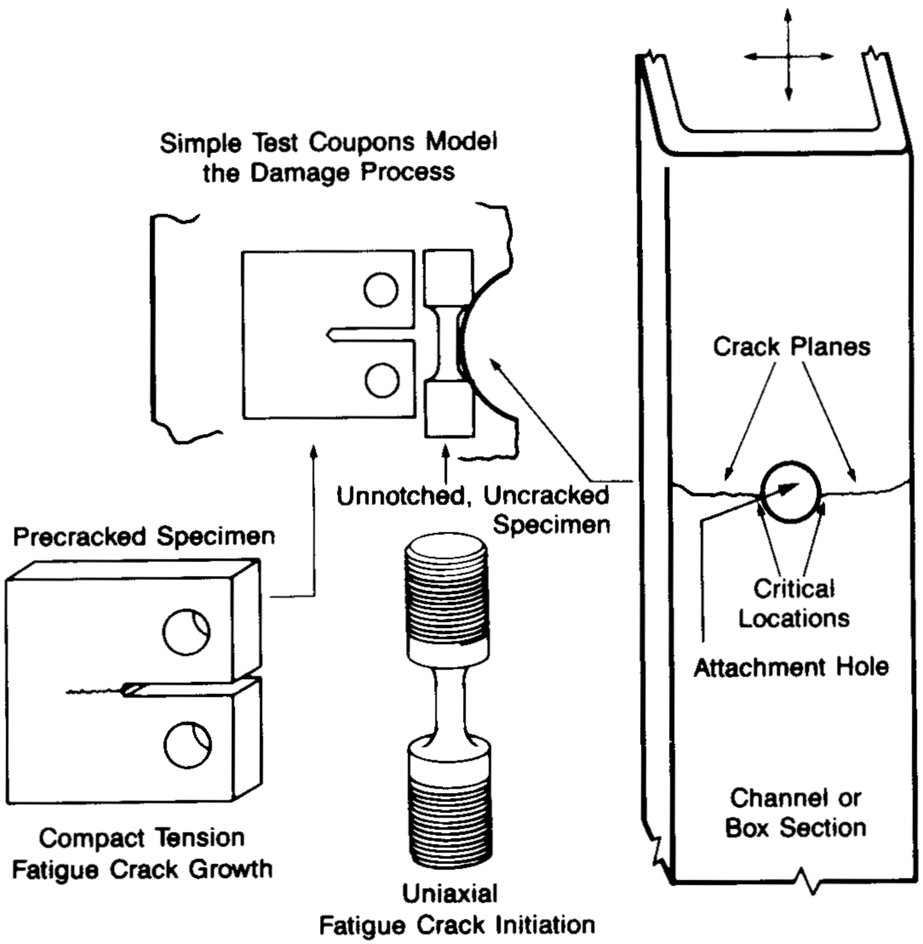


Ti6Al4V annealed at T>1278 ? °K in the ß field. Upon cooling, get Widmanstatten or basket weave as β -> α by diffusion.



Ti6Al4V annealed at 973 °K in a region having both α and β equi-axed grains. Upon slow cooling get ? plus Widmanstatten α.

Fatigue of a component



The fatigue life of an engineering component consists of two main life periods:

Initiation or nucleation of a fatigue crack (N_I)

And

Its growth to failure (N_P)

Simple questions:

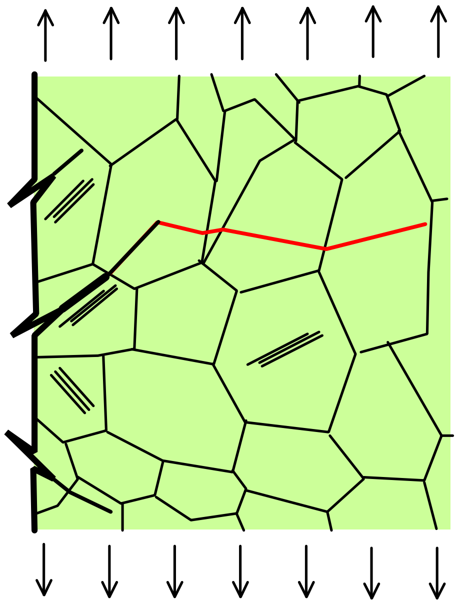
- How do basic material properties influence a component's fatigue life?
- Which materials are most fatigue resistant?

Complex answers

- The answer depends upon the situation.
  - Life regime - short or long?
  - Presence of residual stresses?
    - Compressive residuals
    - Tensile residuals?

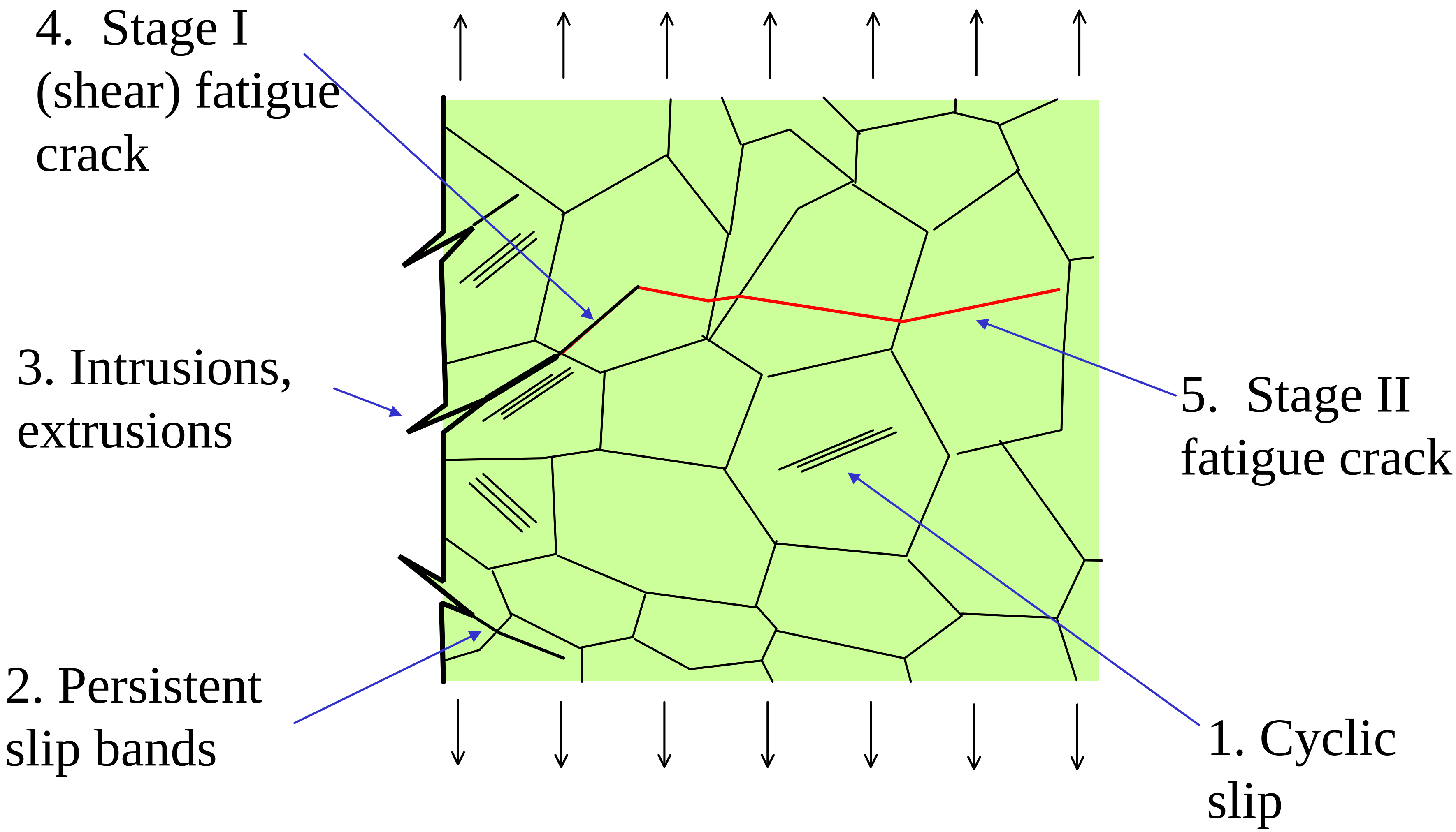
  - Presence of stress-strain concentrators?
    - Due to component shape.
    - Due to mistakes during material processing.
    - Due to inherent flaws in the material.

5.1 Fundamental Concepts

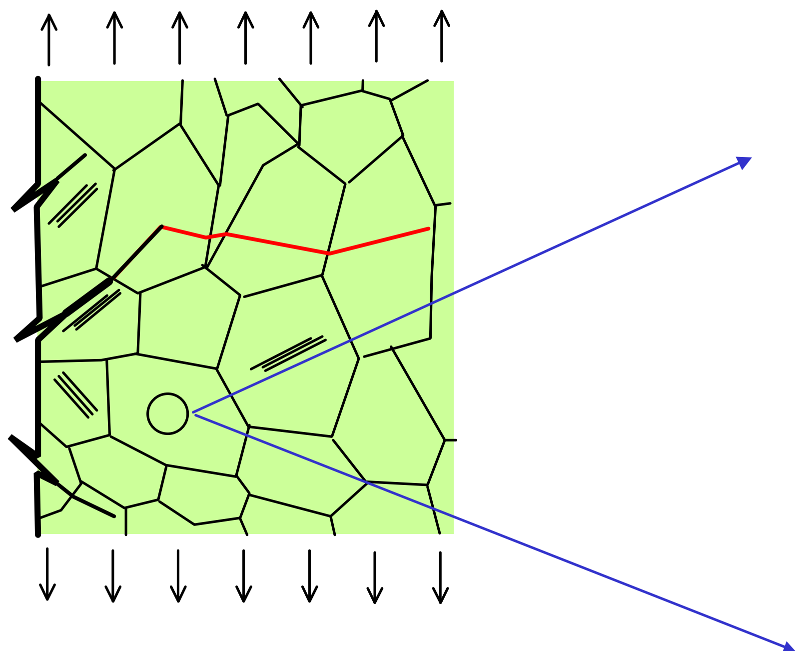


- Structural metals
- **Process of fatigue**
- A simple view of fatigue

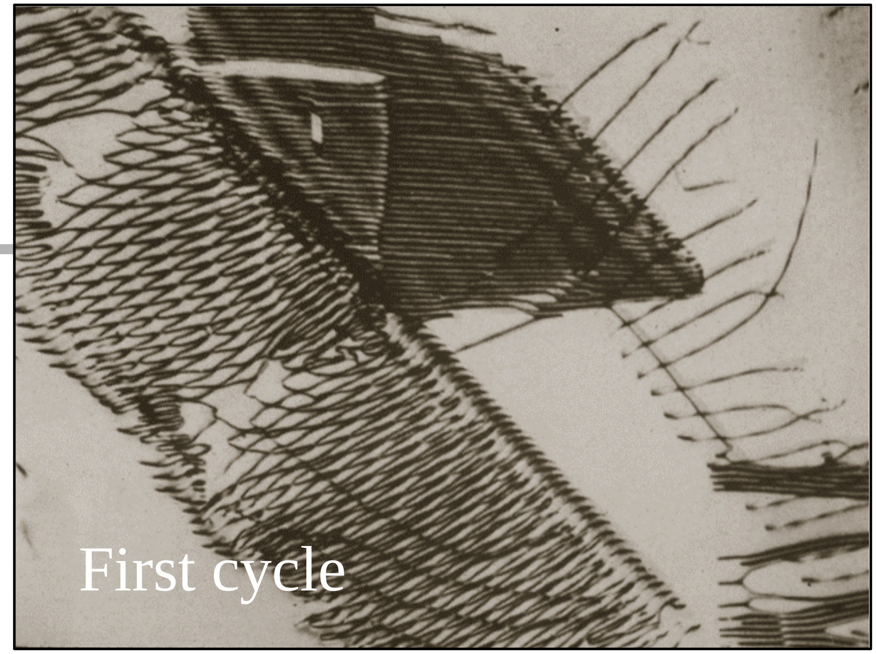
Process of fatigue

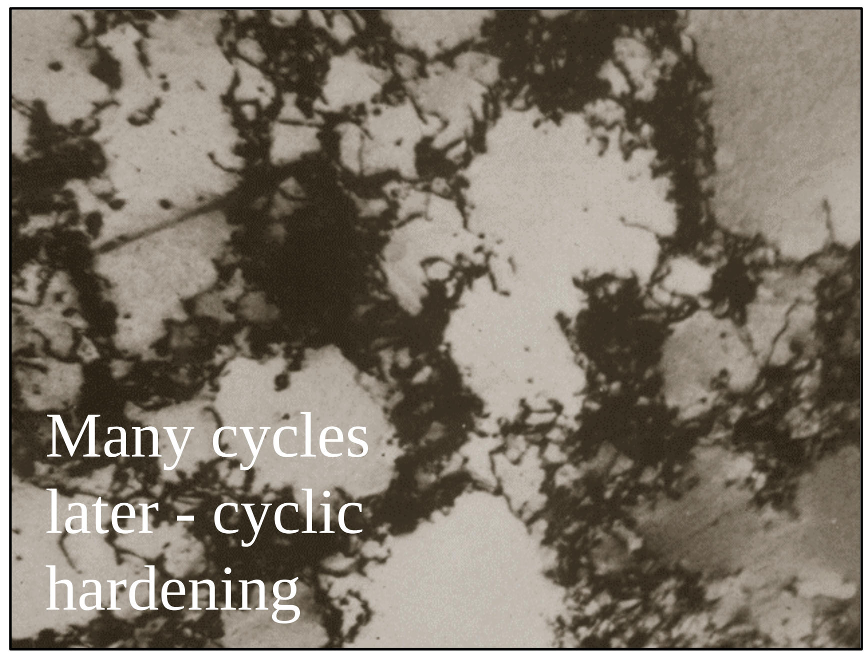


1. Cyclic slip



Cyclic slip occurs within a grain and therefore operates on an atomic scale and are thus is controlled by features seen at that scale.

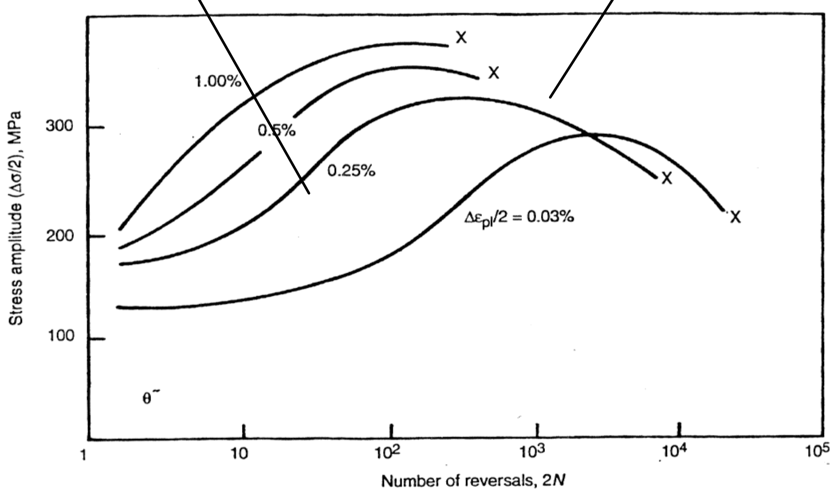


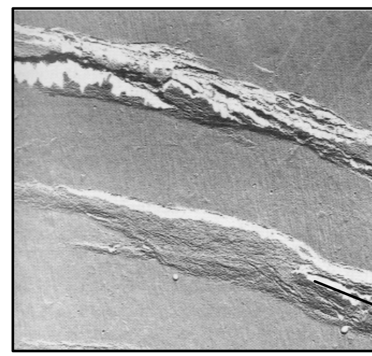


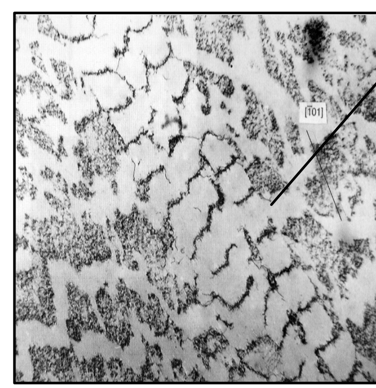
2. Persistent slip bands (PSB)

- •Development of cell structures (hardening)
- •Increase in stress amplitude (under strain control)
- •Break down of cell structure to form PSBs
- •Localization of slip in PSBs

Cyclic hardening Cyclic softening







PSB

3. Intrusions and extusions

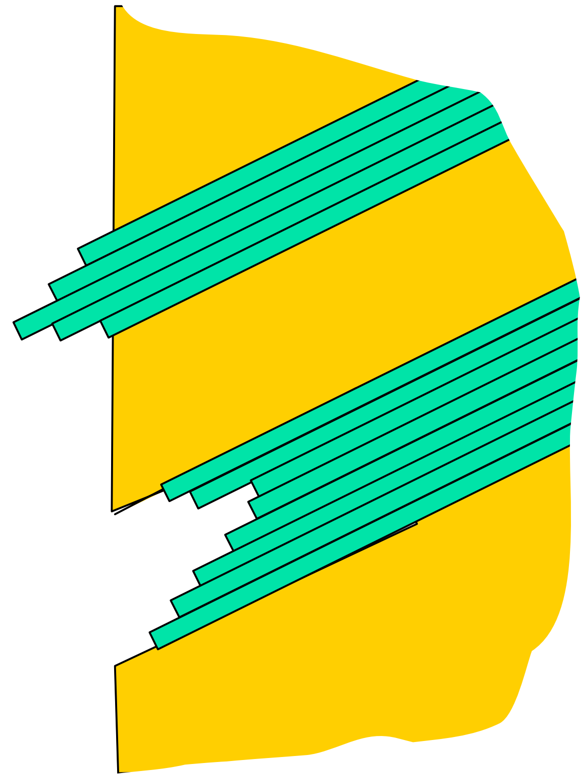
Cyclically hardened material

Extrusion

Cyclically hardened material

Intrusion

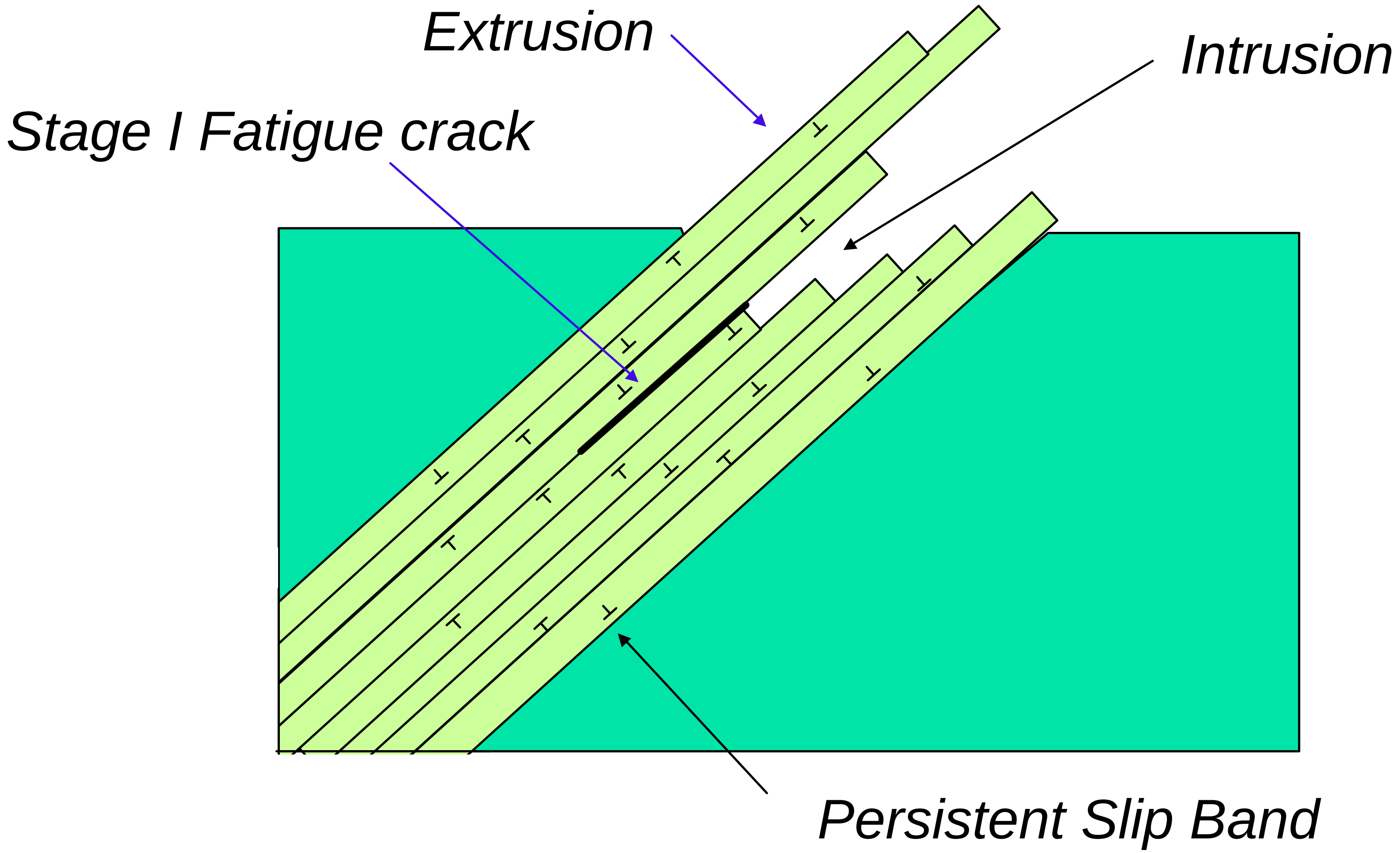
Cyclically hardened material



3. Intrusions and extrusions

Intrusions and extrusions on the surface of a Ni specimen

3. Intrusions and extrusions



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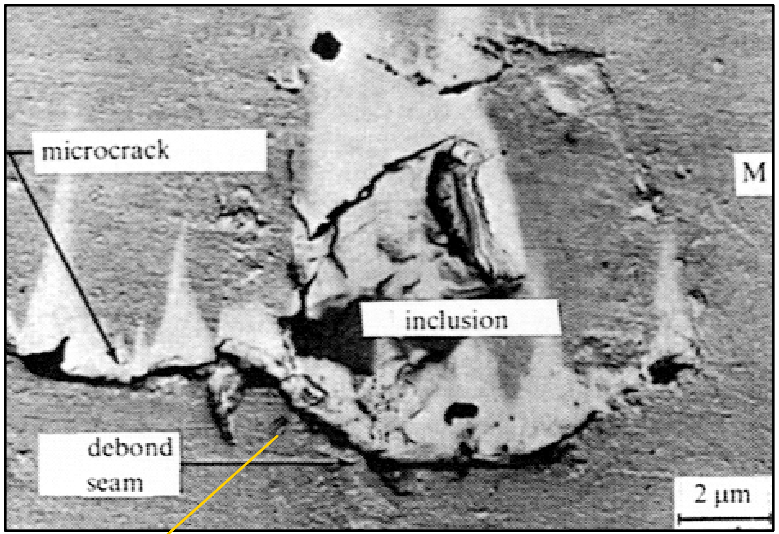
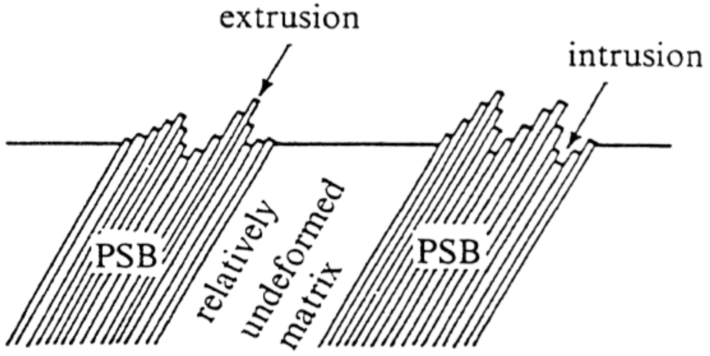
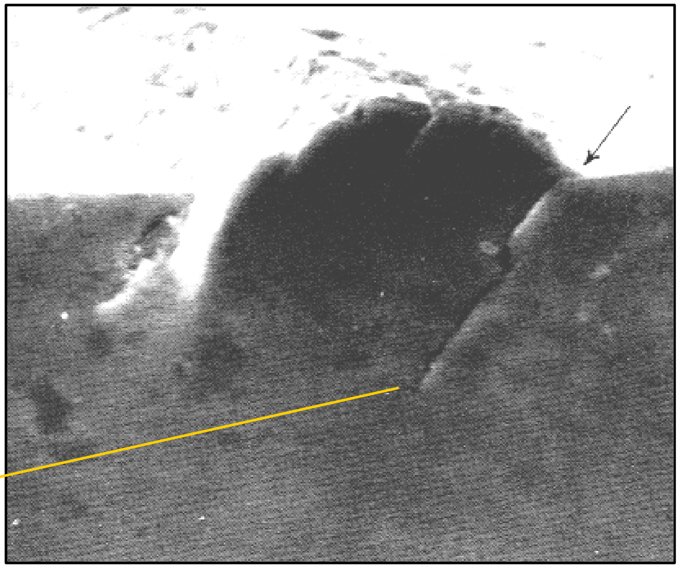
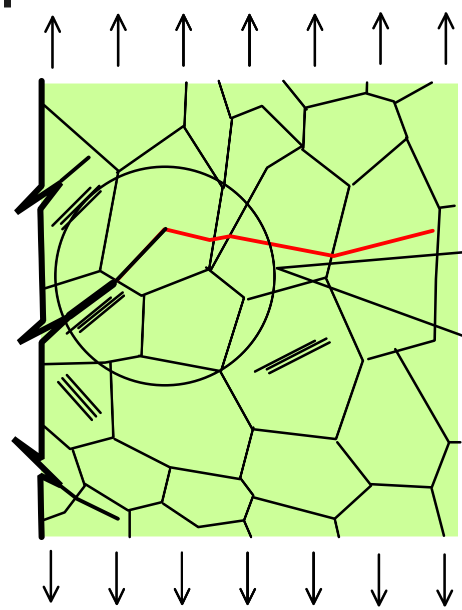


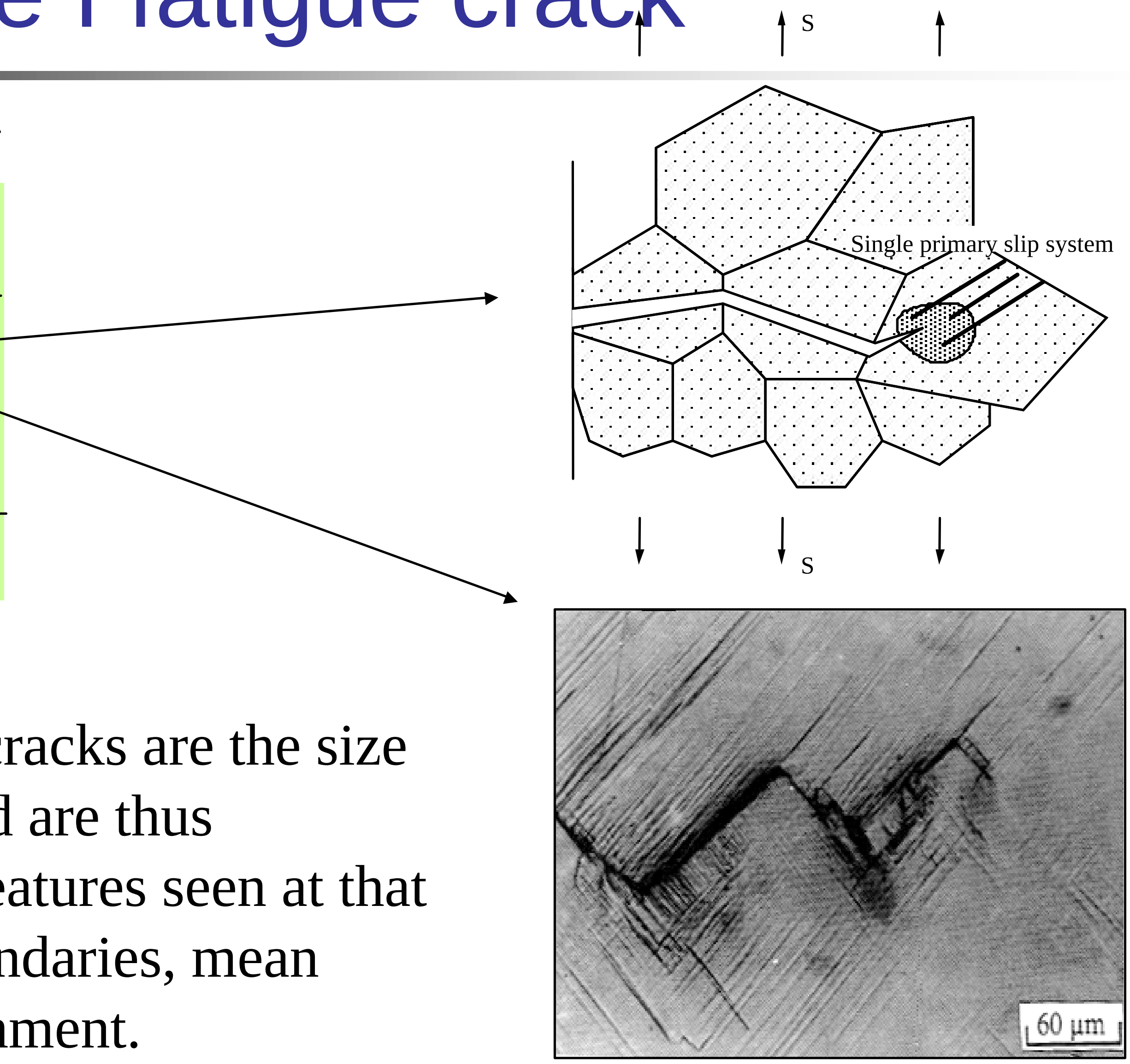




Fatigue crack initiation at an inclusion
Cyclic slip steps (PSB)
Fatigue crack initiation at a PSB

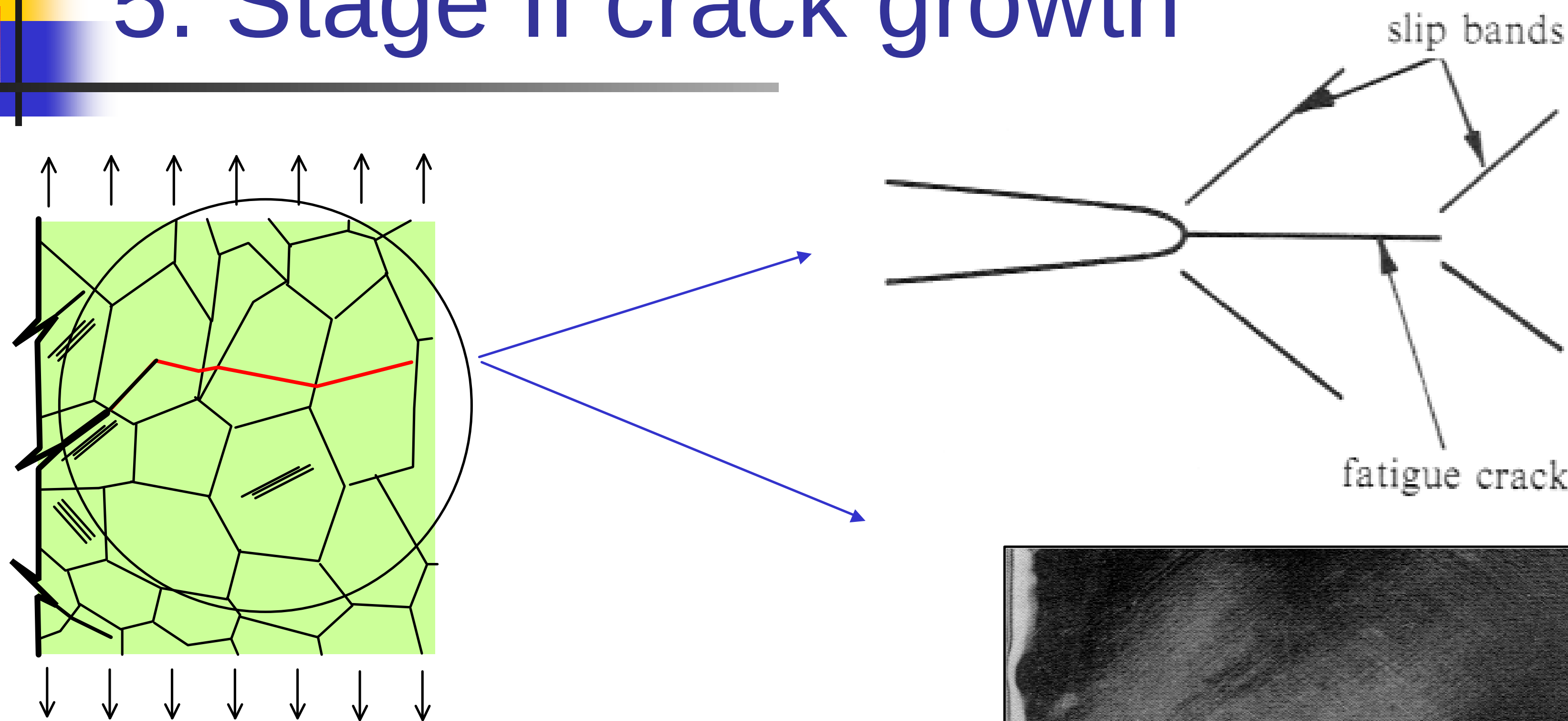
4. Stage I fatigue crack



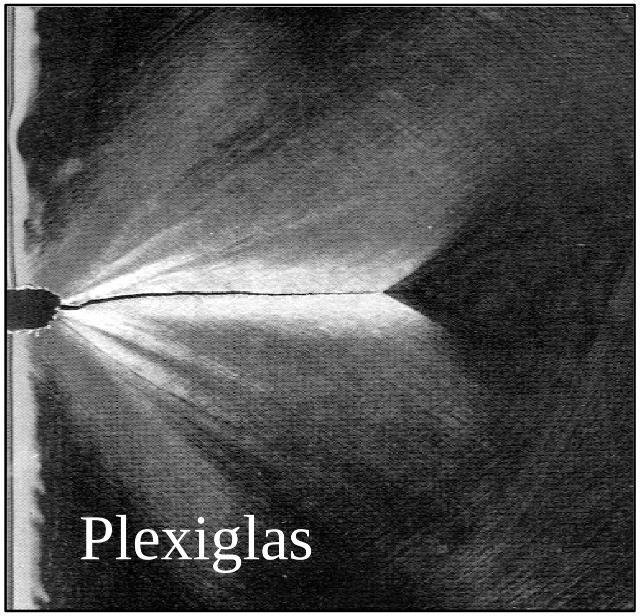


Stage I fatigue cracks are the size of the grains and are thus controlled by features seen at that scale: grain boundaries, mean stresses, environment.

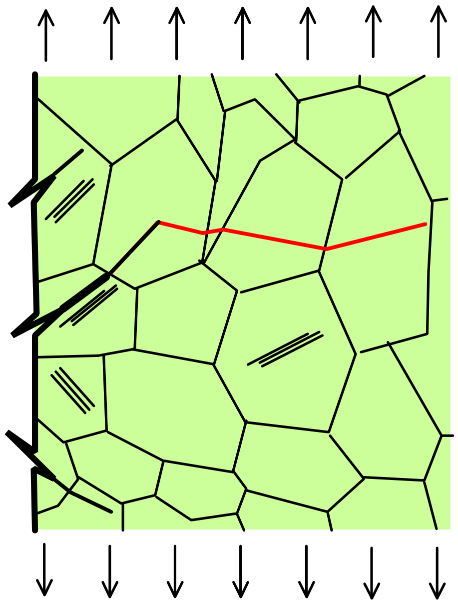
5. Stage II crack growth



Stage II fatigue cracks much larger than the grain size and are thus sensitive only to large scale microstructural features - texture, global residual stresses, etc.



5.1 Fundamental Concepts



- Structural metals
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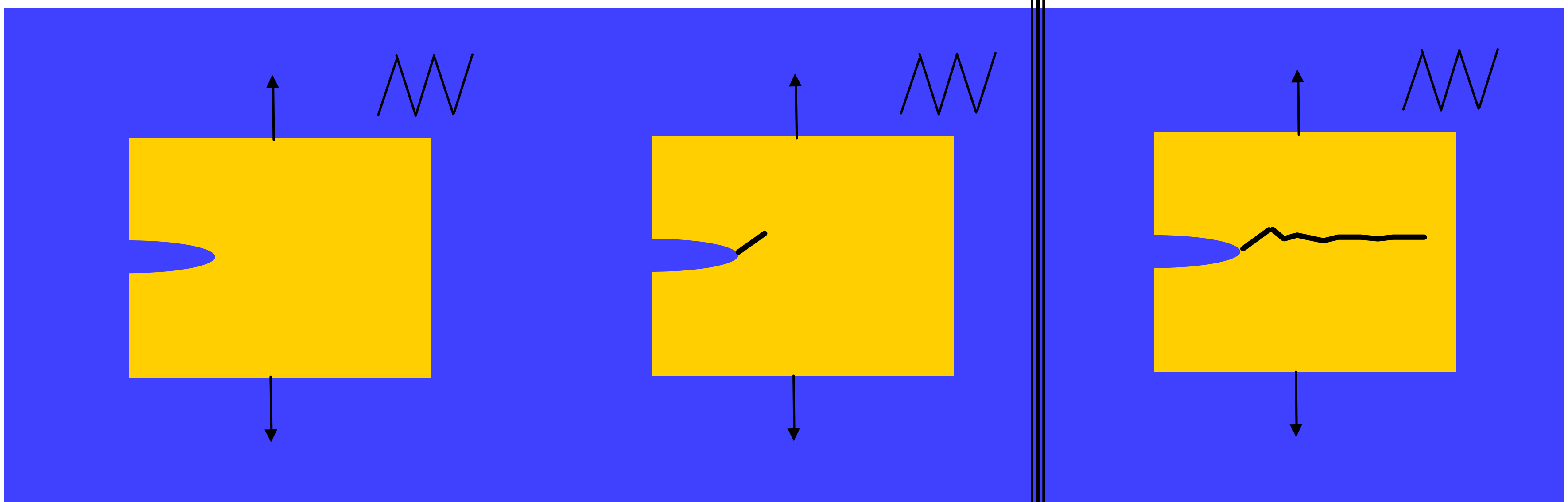
A simple view of fatigue

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



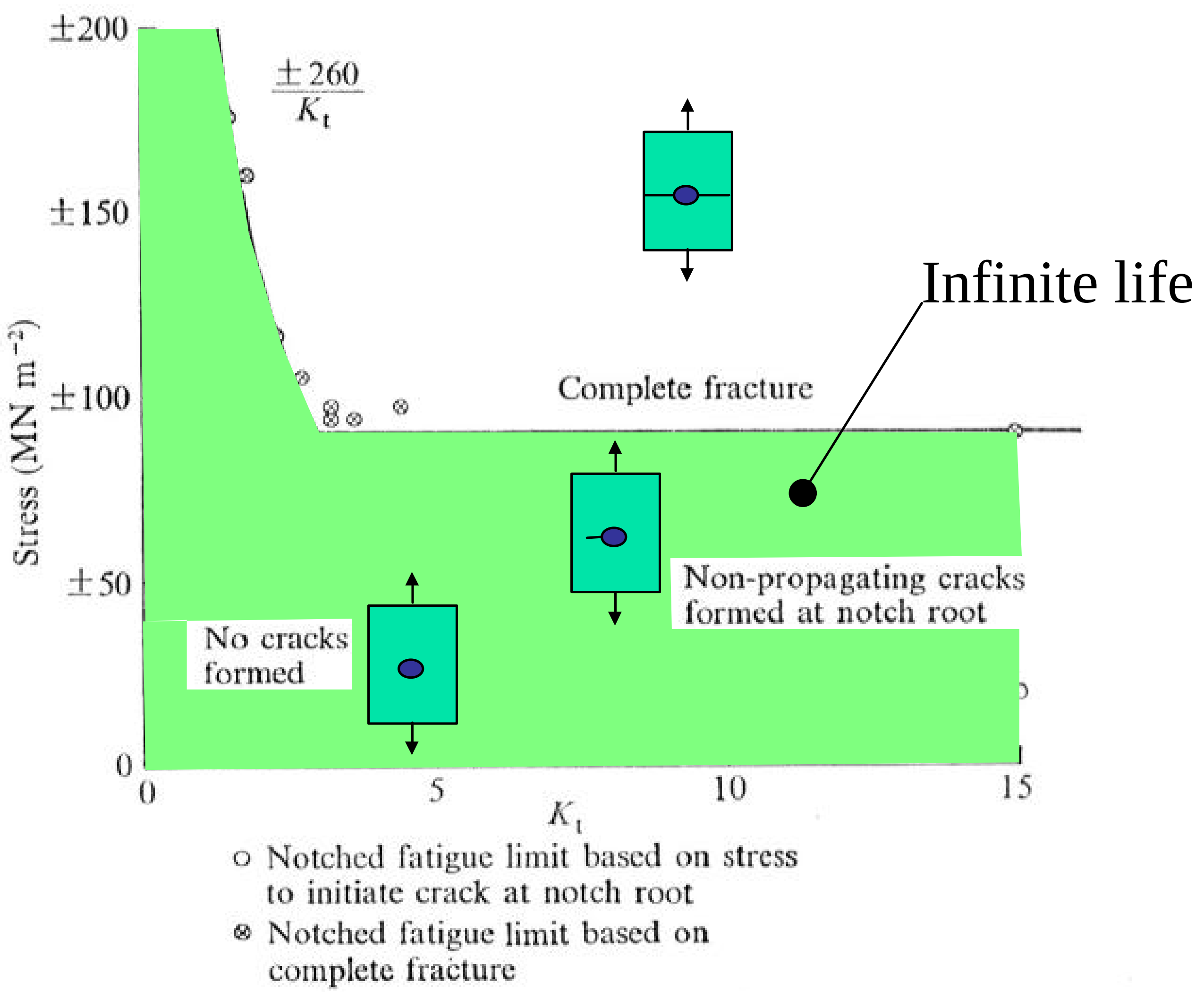
Cyclic nucleation and arrested growth

Infinite Life

Crack growth

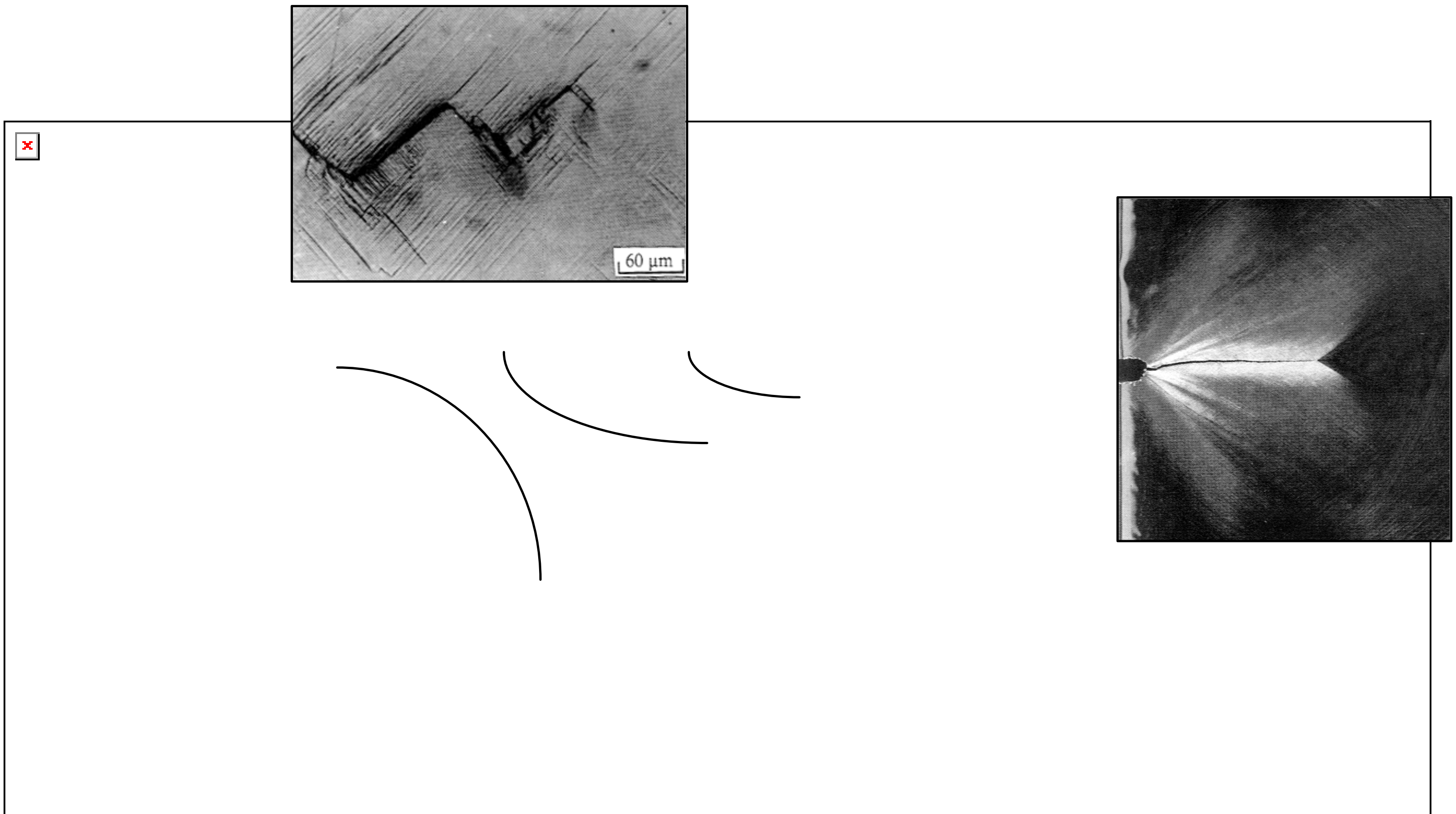
Finite Life

Infinite life - no crack growth



Sharp notches may nucleate cracks but the remote stress may not be large enough to allow the crack to leave the notch stress field.

Finite Life - growth of cracks



Small cracks behave differently than long cracks.

Summary

- The Fatigue process consists of: Cyclic slip, Crack initiation, Stage I crack growth, Stage II crack growth, Failure.

- In the simplest terms, there are two problems:
  - Ensuring infinite fatigue life
  - Prolonging a finite fatigue life