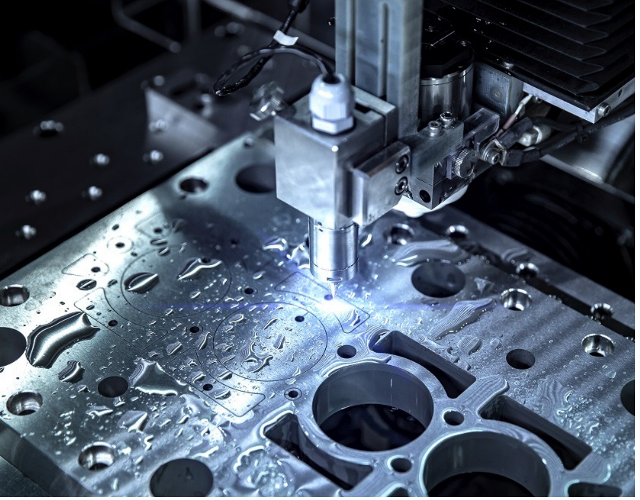
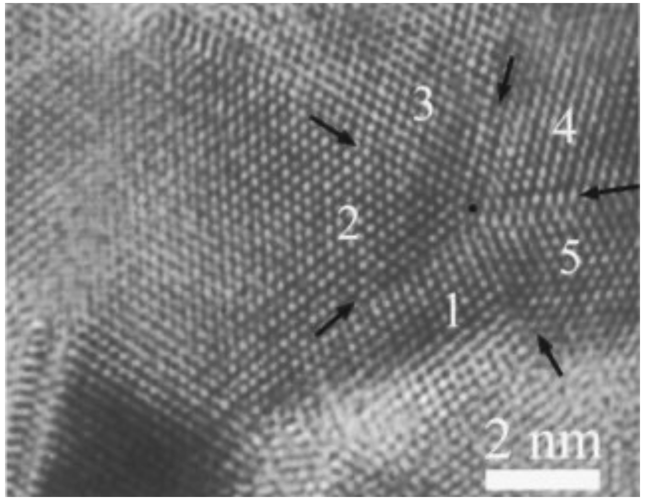


Materials Engineering I (MSE 214)

Lecture 10: Metals – Mechanical Properties

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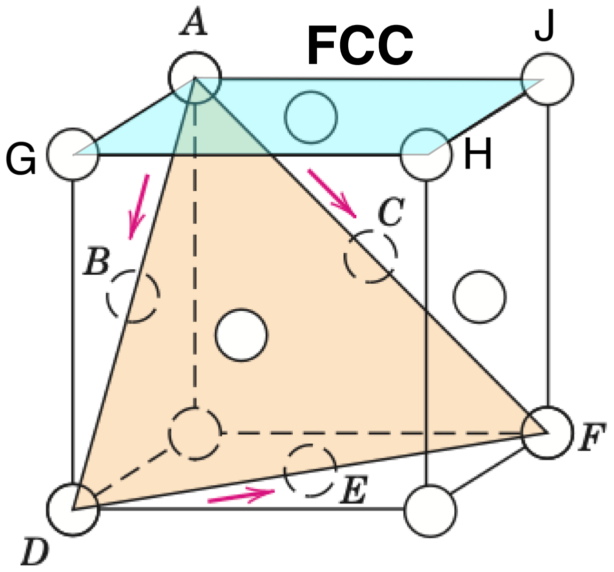
EPFL

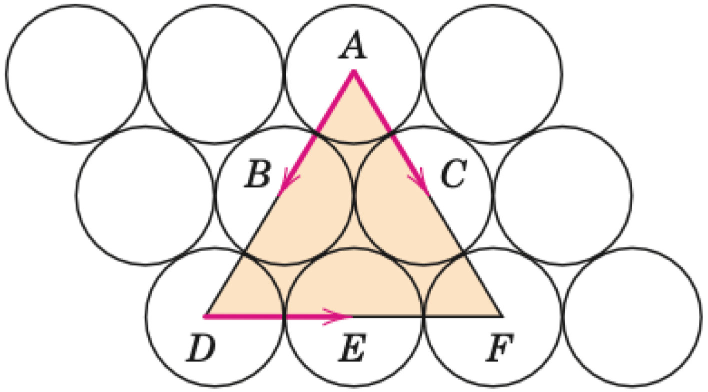
Recap: Slip systems

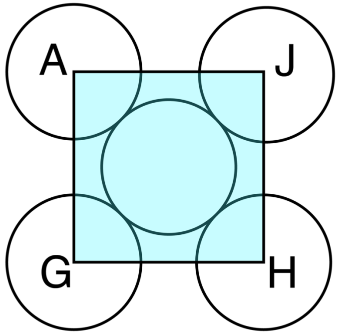
Dislocations do not move with the same ease in all directions

Preferred plane of dislocation movement → Slip plane
Preferred direction of movement → Slip direction

→ Slip system → The system that allows dislocations to move with lowest applied energy



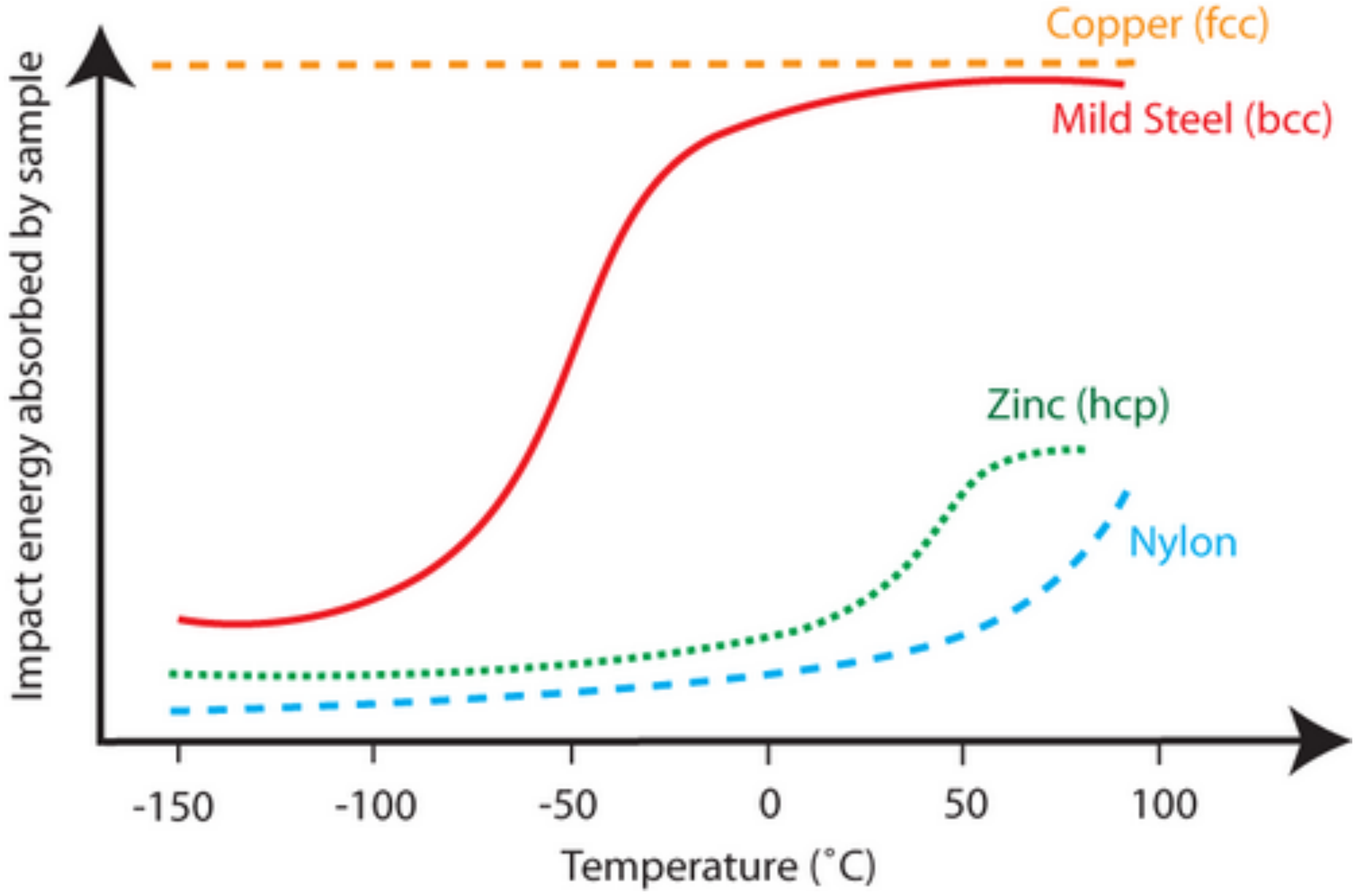




→ Which is easier?

Not all slip systems are created equal: Some need thermal energy to activate

Recap: Ductile–to-Brittle Transition Temperature (DBTT)



Can think of energy absorbed as area under the stress-strain plot

↓

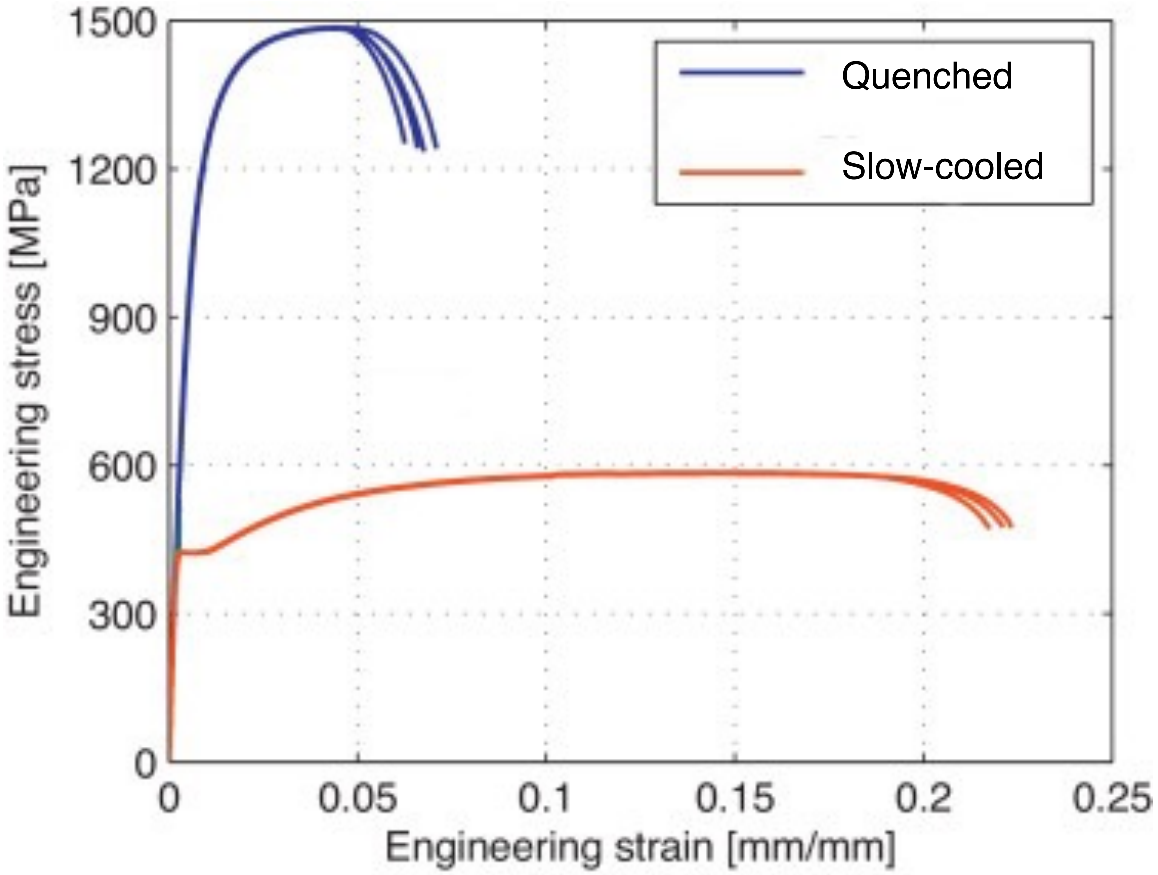
More energy absorbed = more ductile

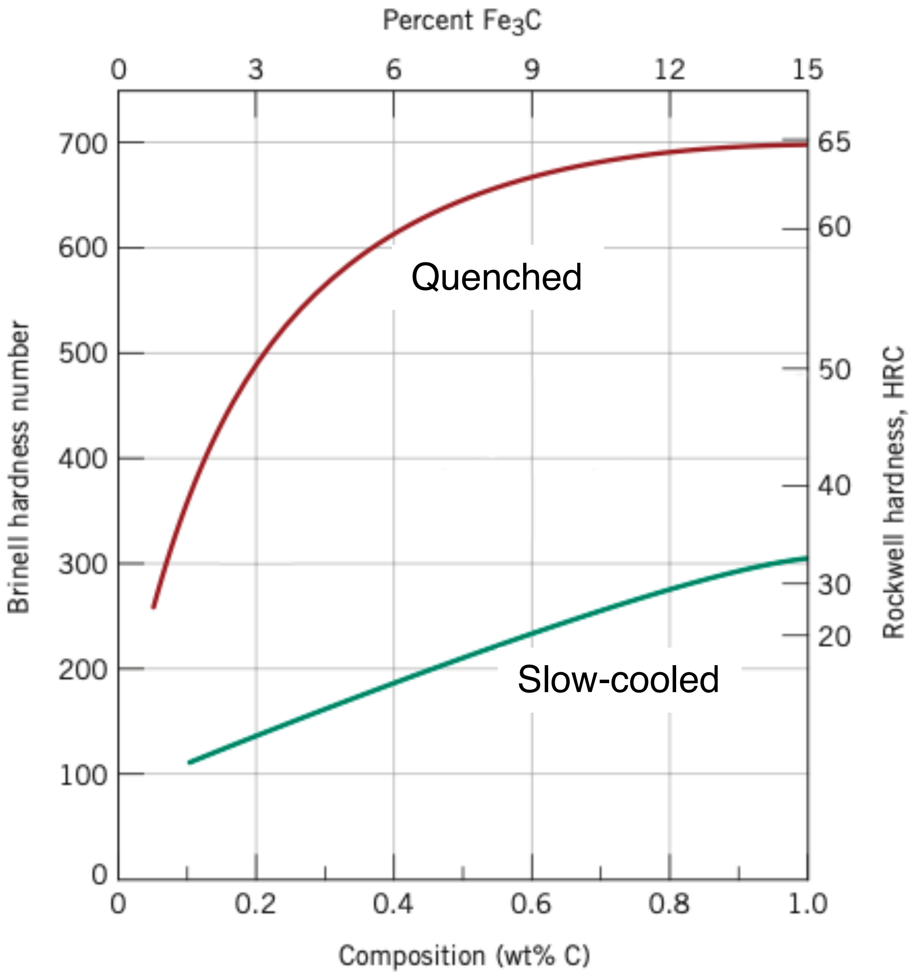
Temperature does not affect FCC metals much

BCC and HCP have temperature-dependent behavior!

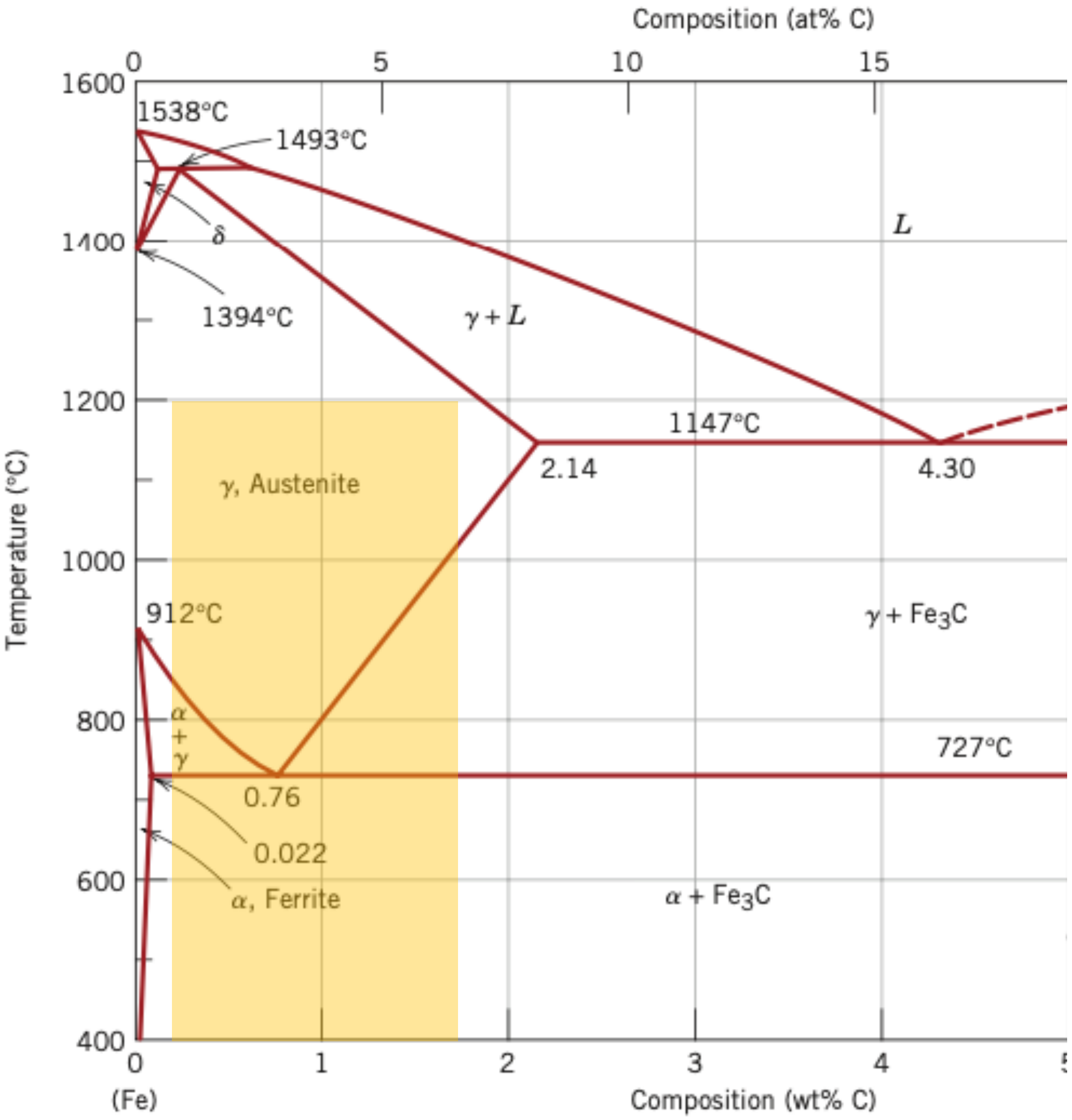
Nylon does as well. Why? (Recap polymers)

Recap: Rapid cooling of steel makes it stronger





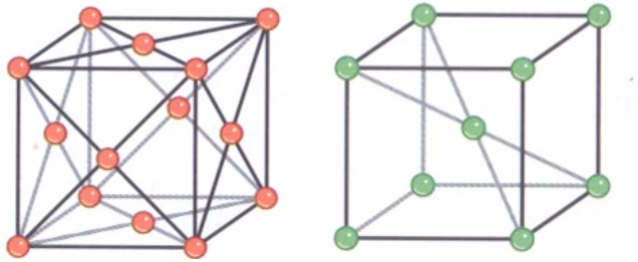
Recap: Rapid cooling makes martensite



<u>Rapid cooling → Quench</u>

Austenite (γ) is FCC

Ferrite (α) is BCC

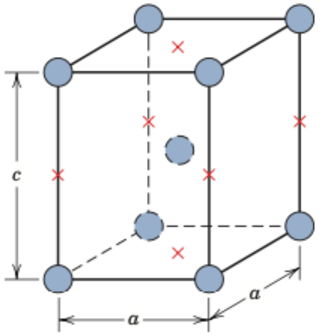


How do we rapidly transform from FCC to BCC?

You kinda can't…not enough time to rearrange the atoms!

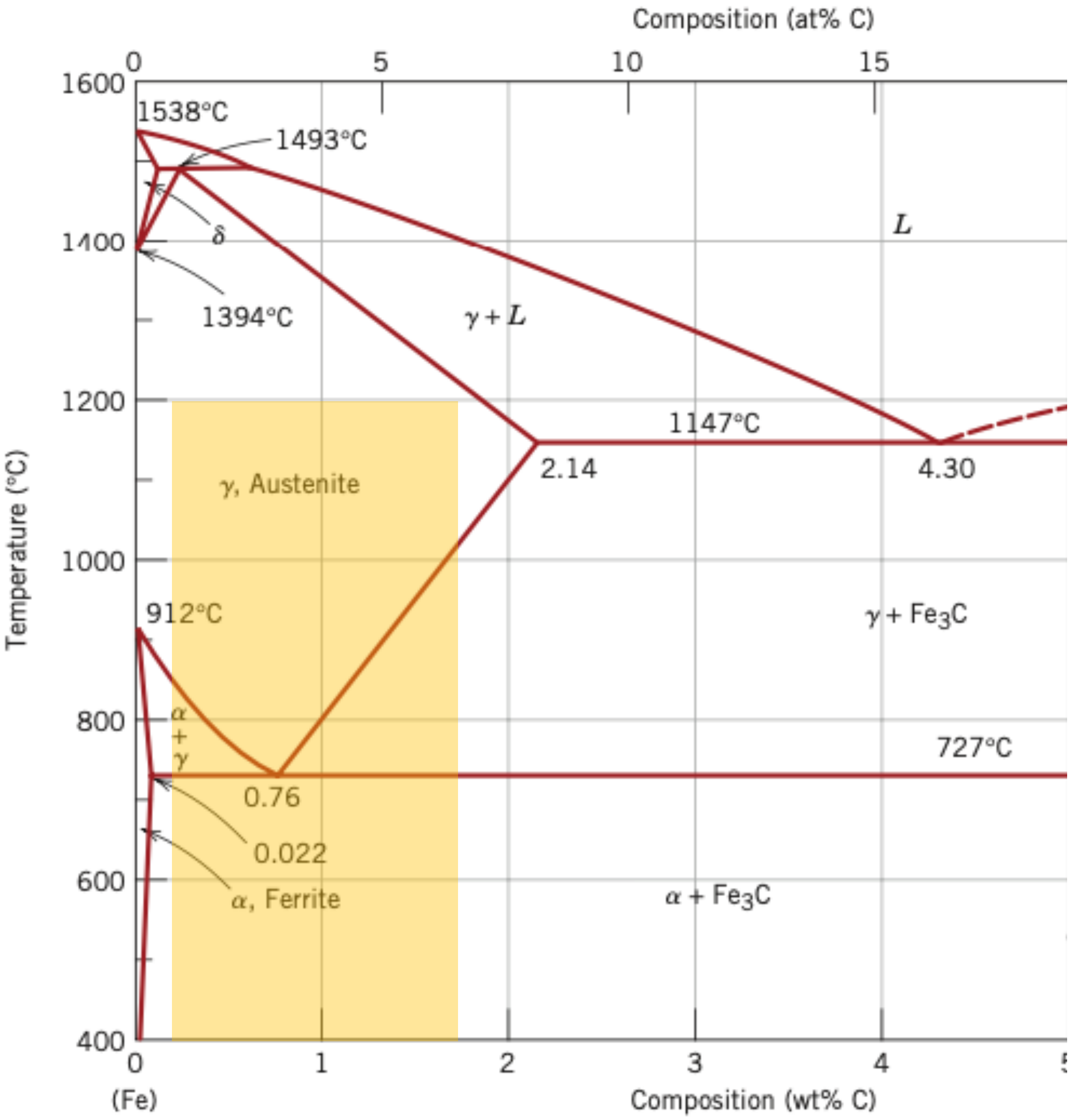
Induce the formation of a new phase → Martensite

(Body Centered Tetragonal, BCT)



Can think of it as an elongated BCC

Recap: Why is martensite so hard?



Supersaturated with carbon since carbon cannot diffuse away in time. Lattice is strained / distorted due to excess carbon

Martensite formation causes volume expansion (different densities) and shape change → Internal stresses

BCT structure has fewer active slip systems than FCC and BCC

Impede dislocation movement!

Recap: Tempering martensite makes it softer

Temper = Reheat the quenched steel to change mechanical properties

Effect 1: Allows carbon supersaturated martensite to transform to equilibrium phases

Martensite (BCT, single phase)

↓

Tempered martensite (α + Fe_3C phase)

This generates a new microstructure that is tougher than pure martensite

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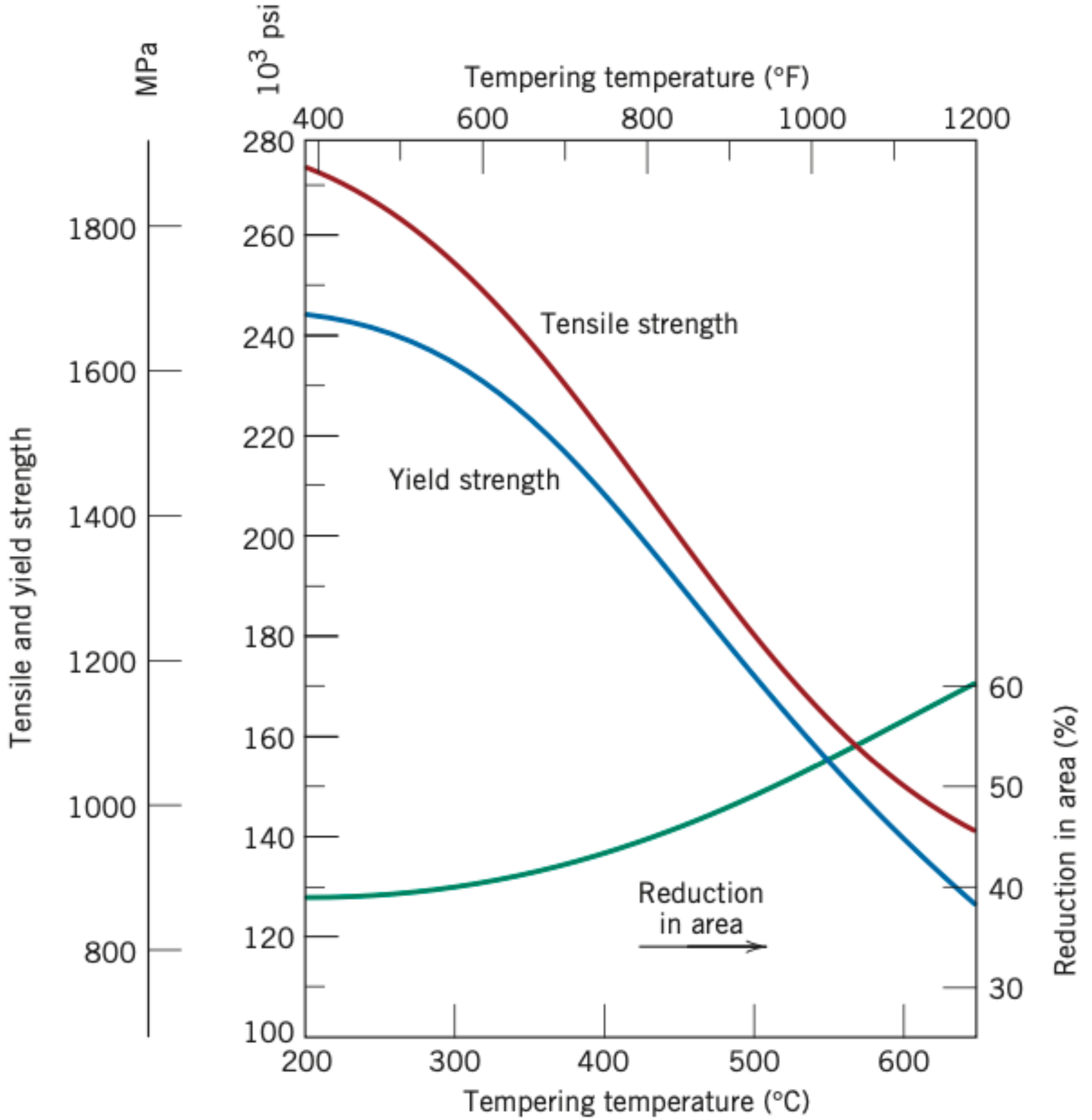
Effect 2: Reduce dislocation density due to increased atom mobility



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Recap: Solid-state transformations

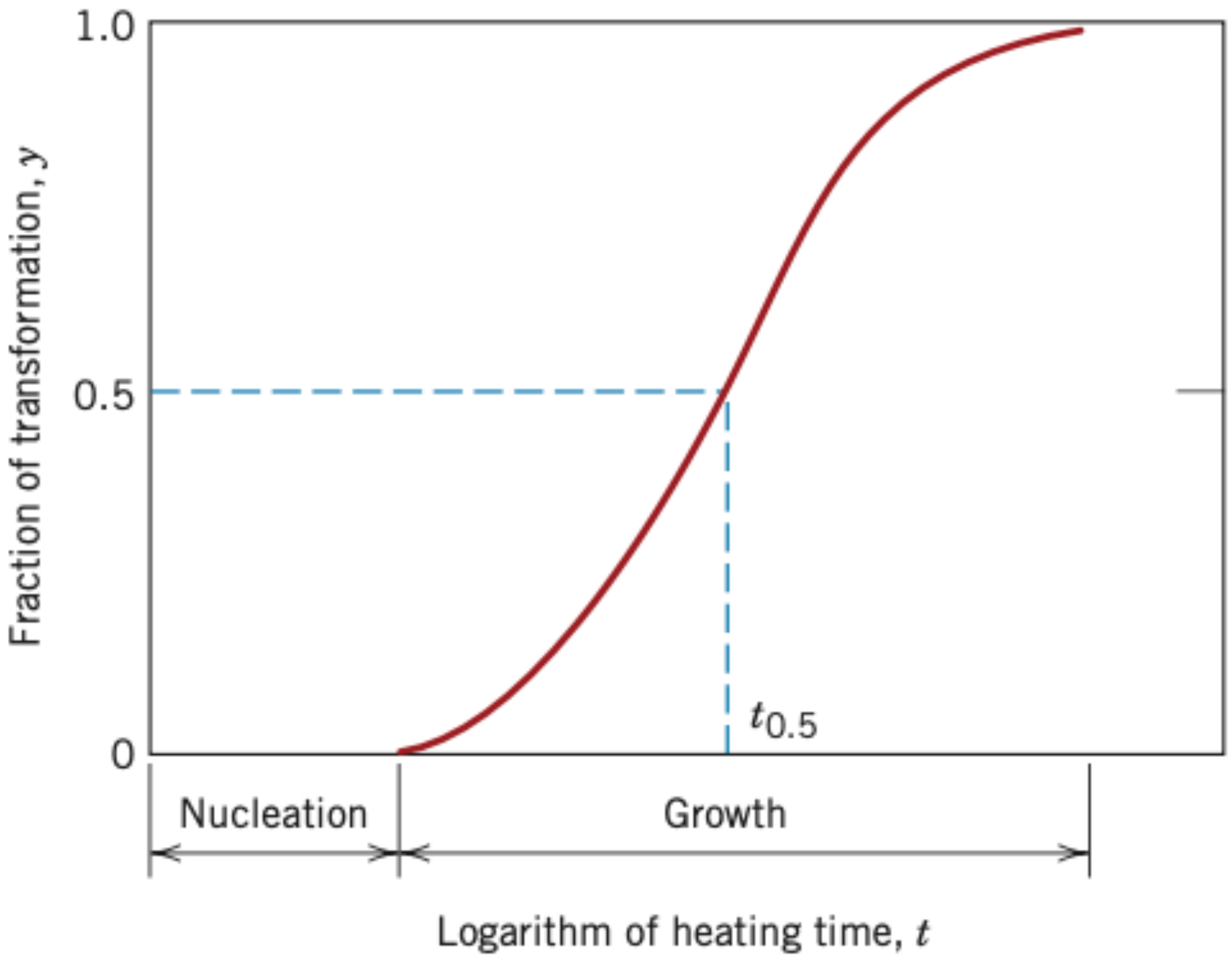
Solid-state transformation can be described by the Avrami equation:

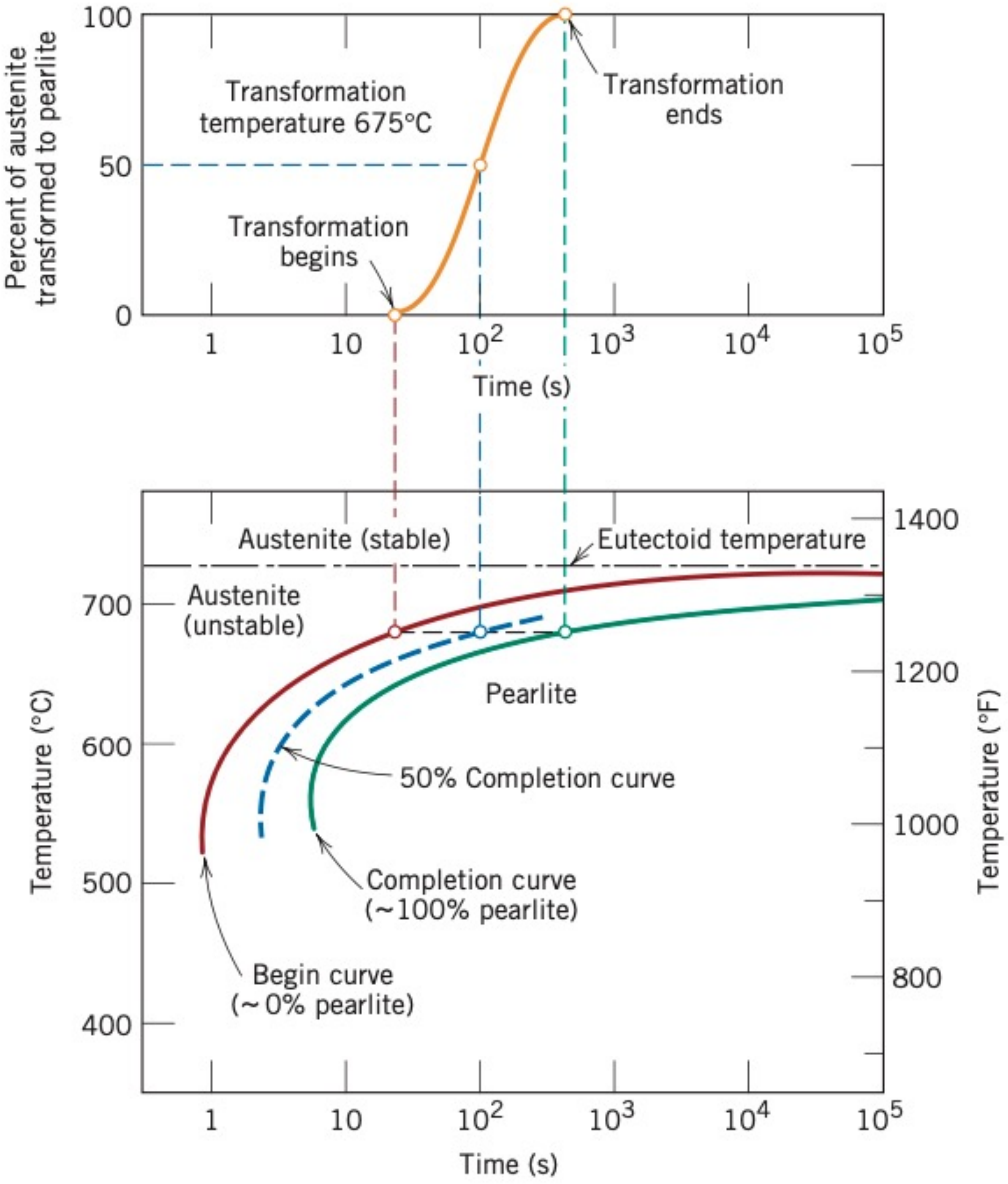
$$y = 1 - e^{-kt^n}$$

y = fraction of transformation
k, n = time independent constants for the transformation

By convention, the rate of a transformation is taken as the reciprocal of time requires for 50% transformation

$$Rate = \frac{1}{t_{0.5}}$$





Recap: Time-Temperature-Transformation (TTT) diagrams*

<u>Let's walk through this diagram:</u>

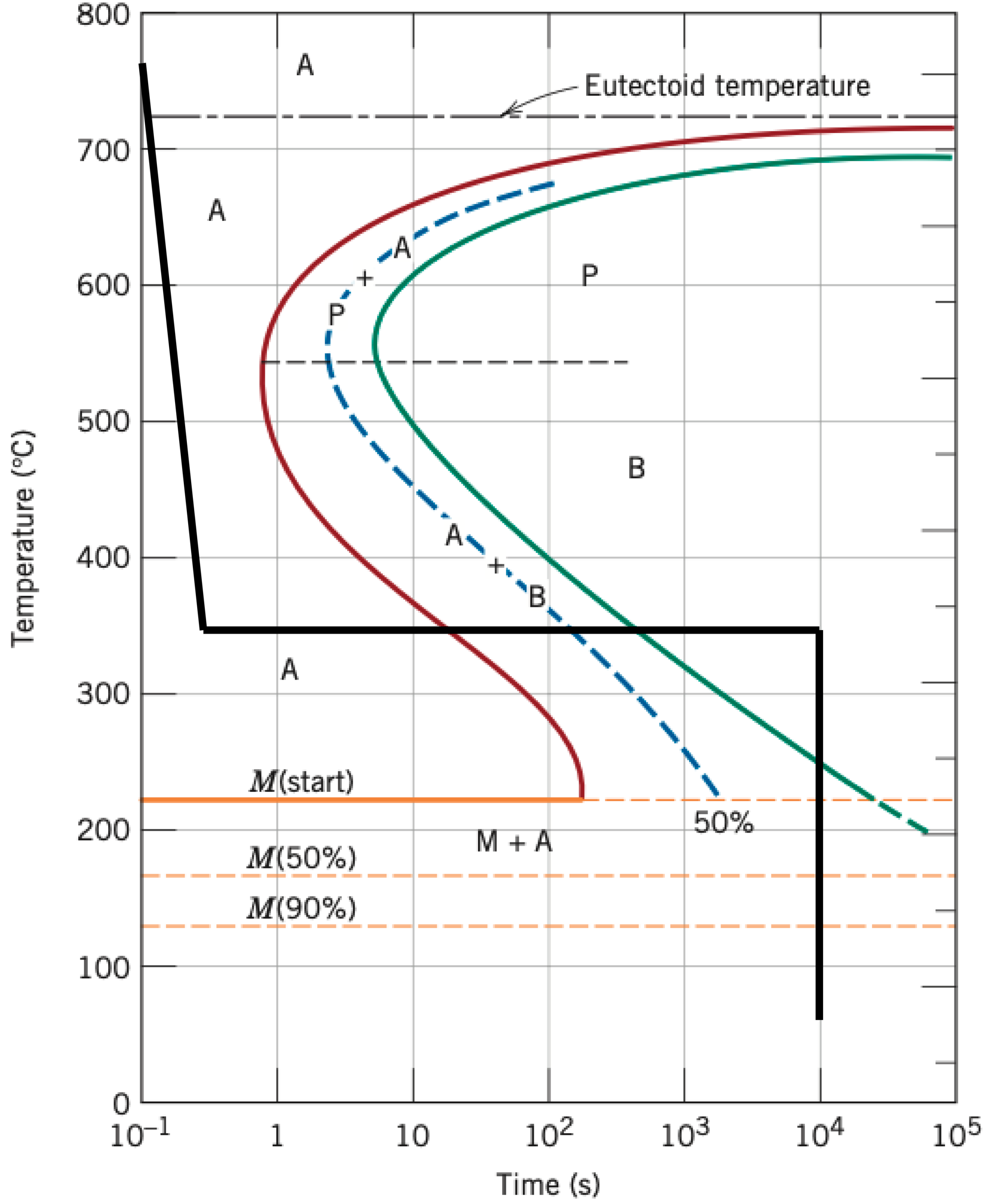
Above the eutectoid temperature (727˚C), only stable austenite → No change over any timeframe

The time needed for the austentite to pearlite transformation depends on the degree of supercooling

On the left is of the red line is 100% unstable austenite. It will transform to pearlite given enough time

On the right of the green line is 100% pearlite

*Sometimes called isothermal transformation diagrams



Recap: Let's use a TTT diagram to predict metastable microstructure

Starting from 760˚C:

<u>**a)** Rapidly cool to 350˚C, hold for 10^4 s, quench to RT</u>

Assume initial cooling is rapid enough to prevent any transformations from happening

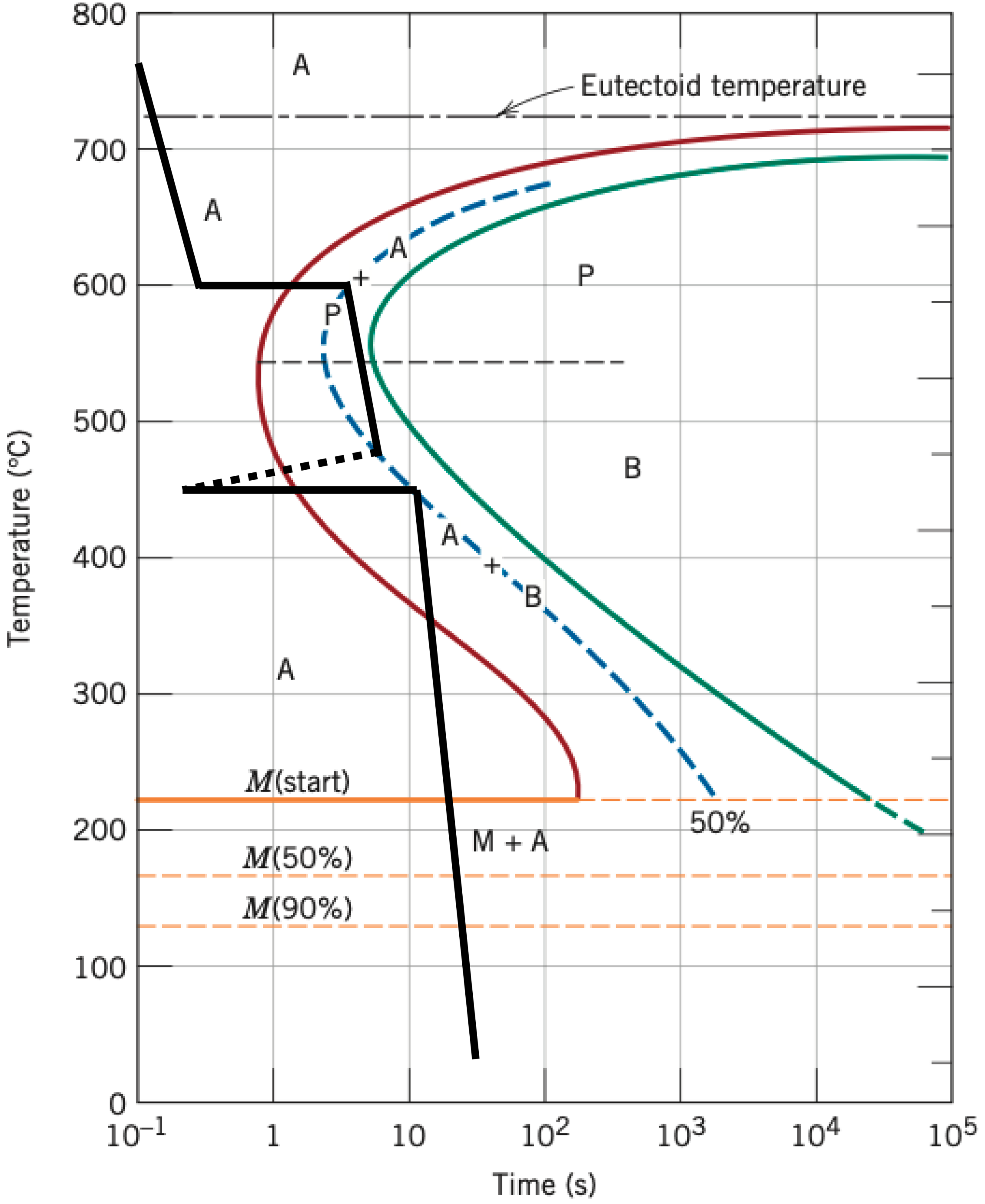
Austenite (A) → Bainite (B) starts ~10s and is completed after ~600 s. After 10^4s, it's 100% B

Quenching to RT does not produce any martensite even though it passes through the martensite region.

No austenite left to transform! Only austenite can transform to martensite

Week 10 Learning Objectives

- Understand what a CCT diagram is and how it differs from a TTT diagram
- Understand how to qualitatively use a CCT diagram to predict the microconstituents of a cooling alloy
- Understand the difference between brittle and ductile fracture
- Understand what the fracture toughness of a material is
- Use the fracture toughness of a material to predict of a material will fracture
- Understand what fatigue is
- Be able to use Miner’s rule to predict fatigue failure
- Be able to use Paris’ Law to predict fatigue failure
- Understand the factors that affect fatigue fracture



Let's try to use a TTT diagram to predict metastable microstructure

Starting from 760˚C:

<u>**c)** Rapidly cool to 600˚C, hold for 4s, rapidly cool to 450˚C, hold for 10s, then quench to RT</u>

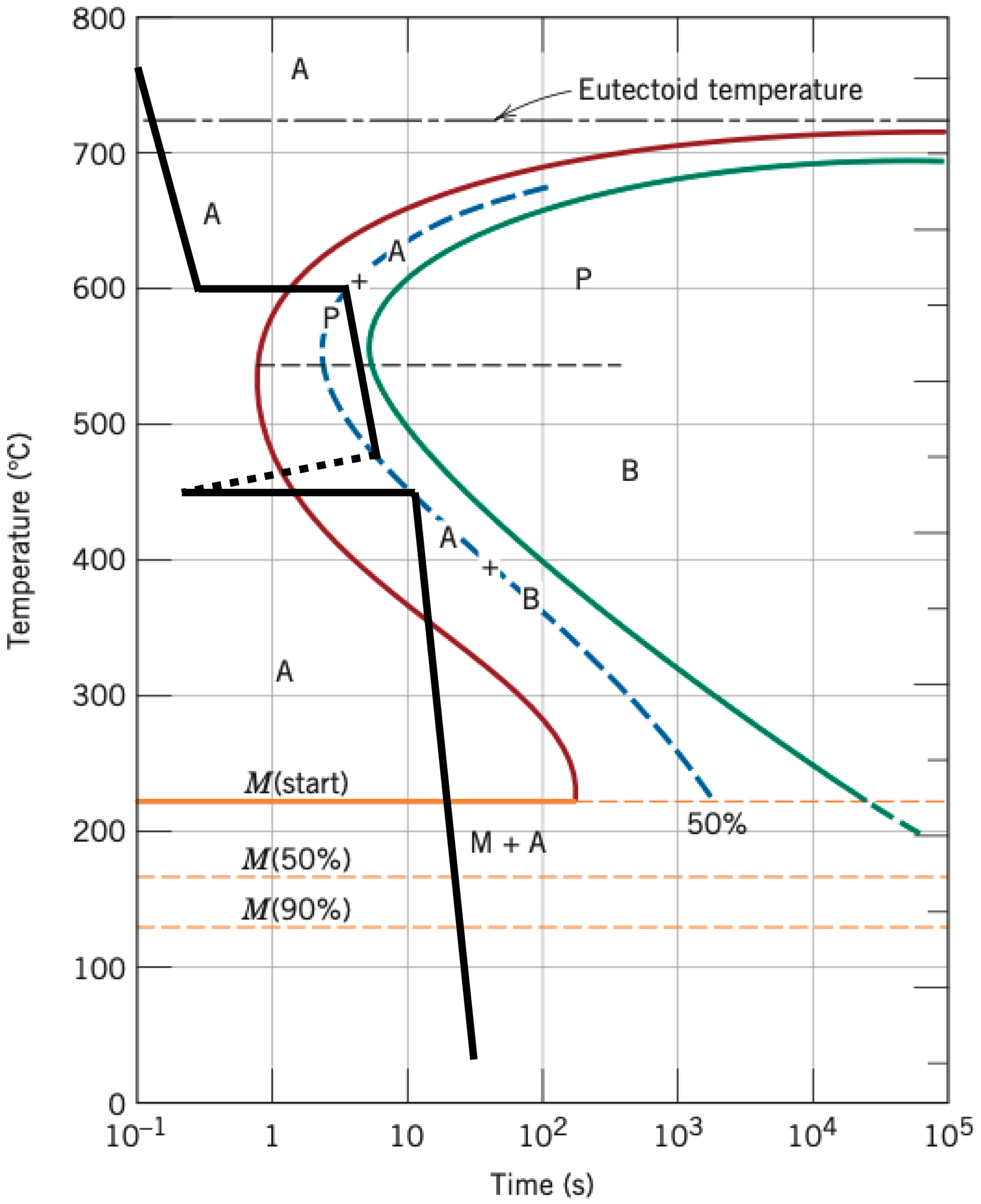
Holding at 600˚C for 4s → ~50% A + P

Assume during rapid cooling to 450˚C, nothing happens

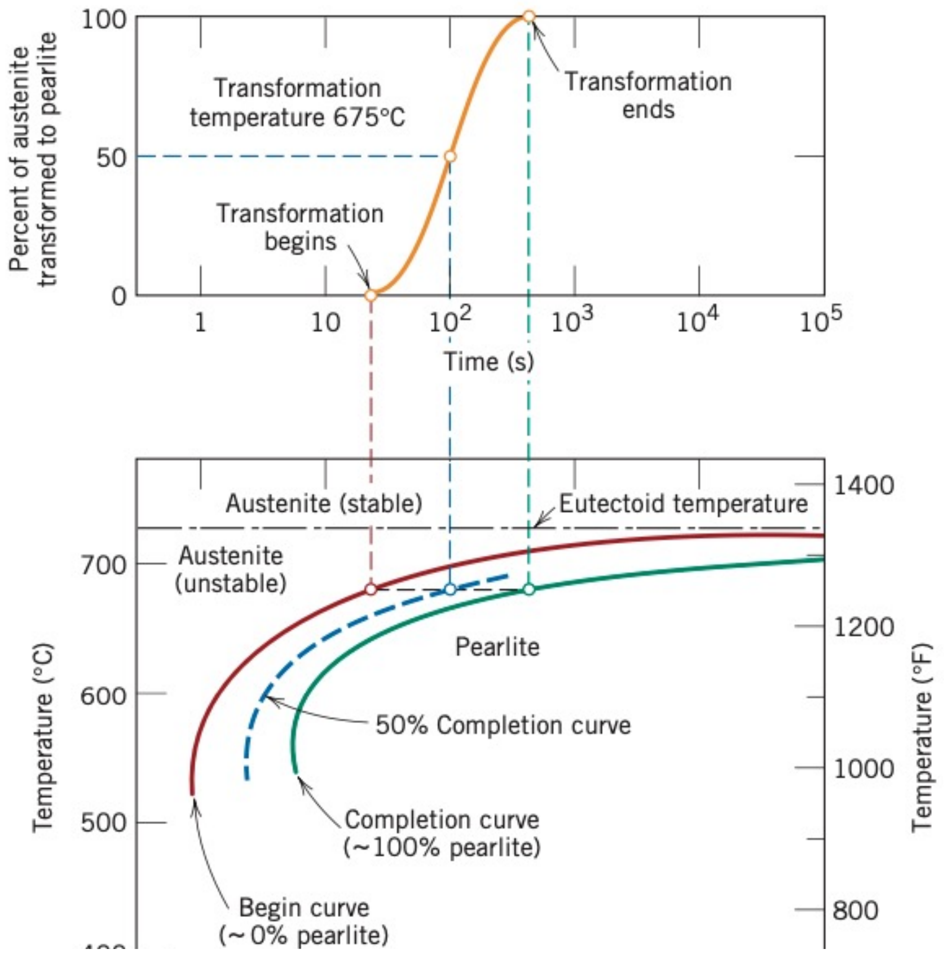
At 450˚C, we start timing from 0 again to see what happens to the unstable austenite.

Holding at 450˚C for 10s → 50% of remaining A till transform into B (25% of original sample is B)

Quenching to RT transforms the remaining A to M.

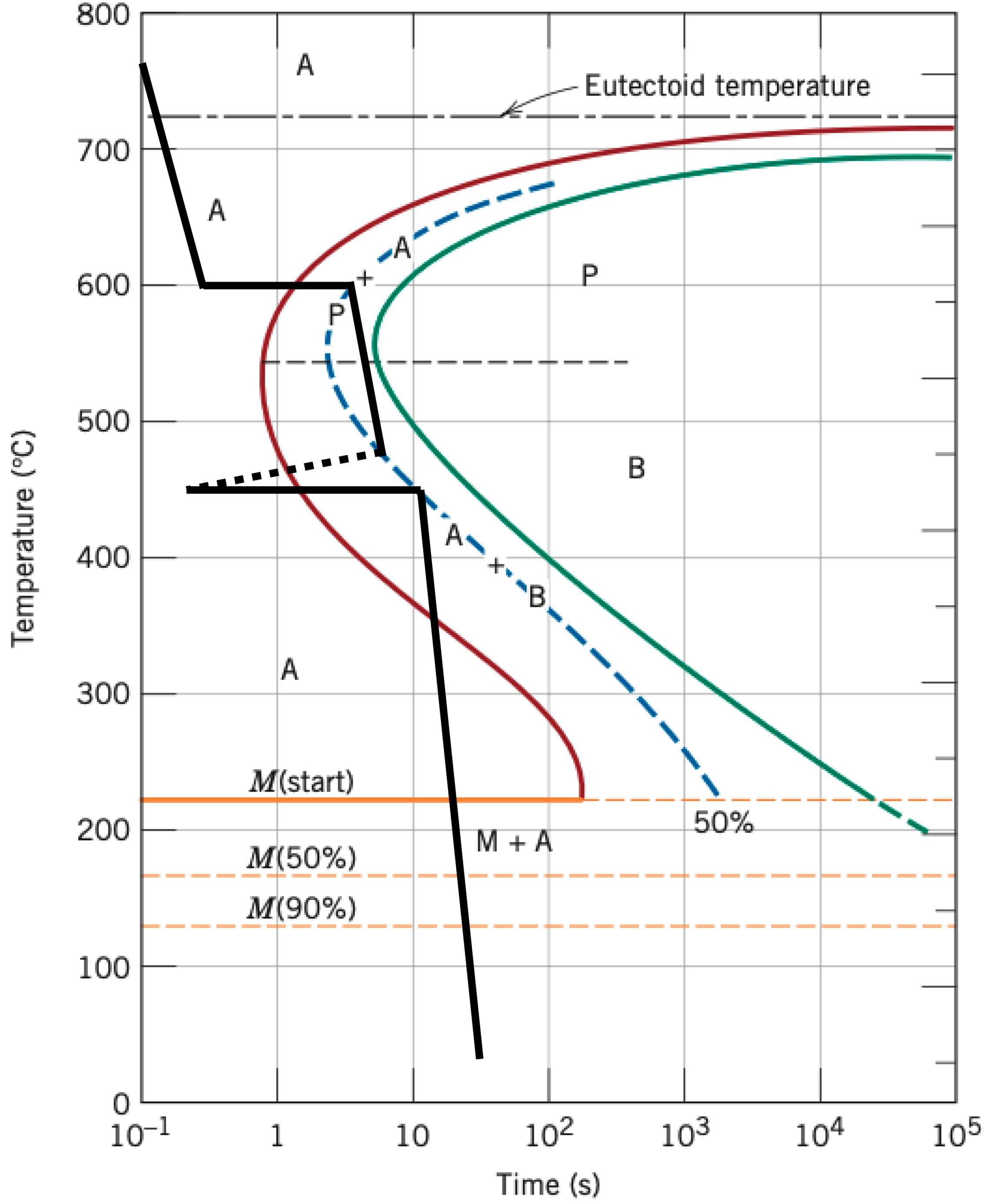


Why do we go back in time?



Different transformations!

Reactions rate change with % transformation



Limitations of TTT diagrams

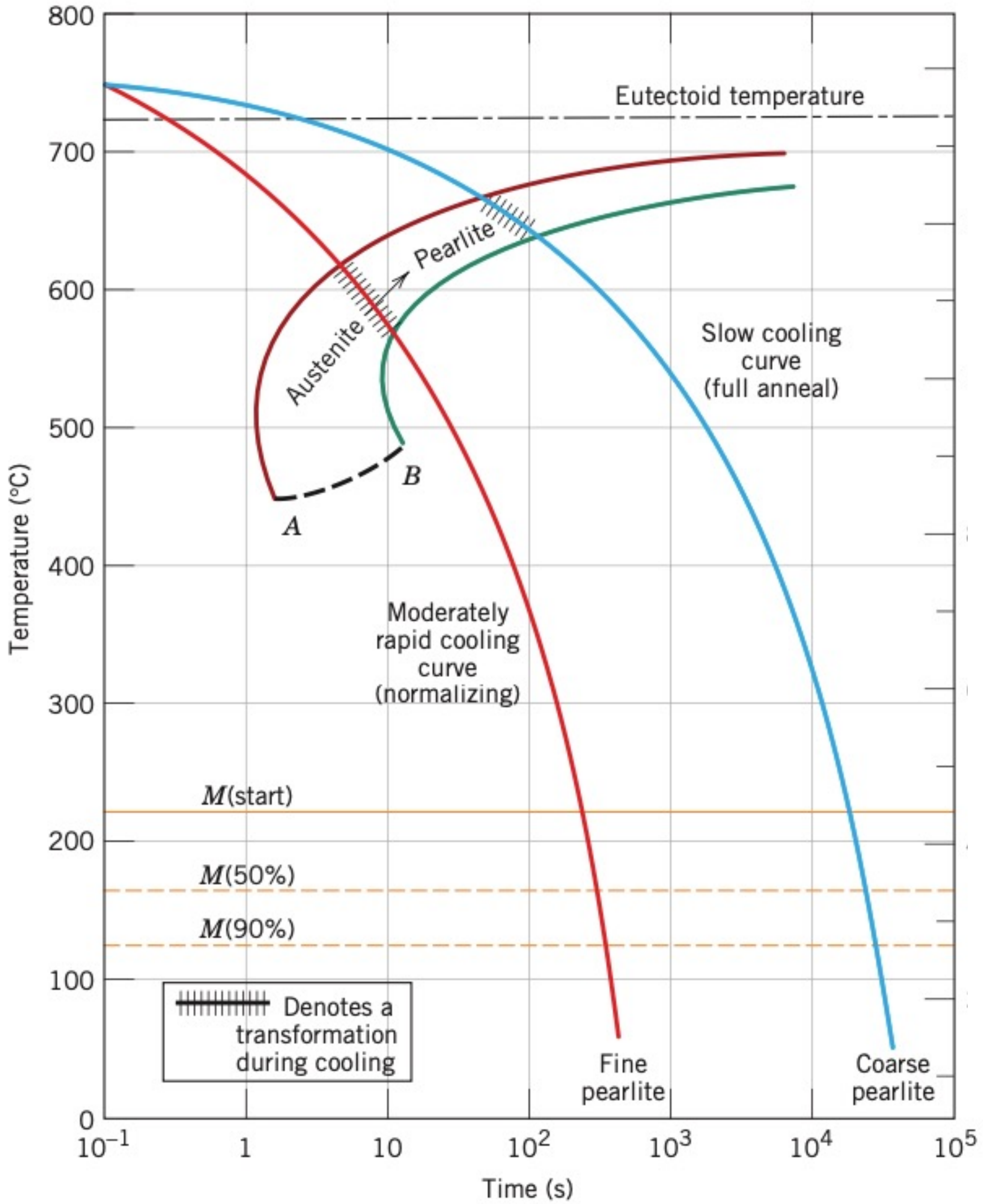
TTT diagrams: Only valid for conditions of constant temperature

In real life, not practical to rapidly cool a metal to a set temperature and then hold it there for time.

Instead, we cool the metal continuously over time

TTT
(Time-Temperature-Transformation)

CCT
(Continuous cooling transformation)



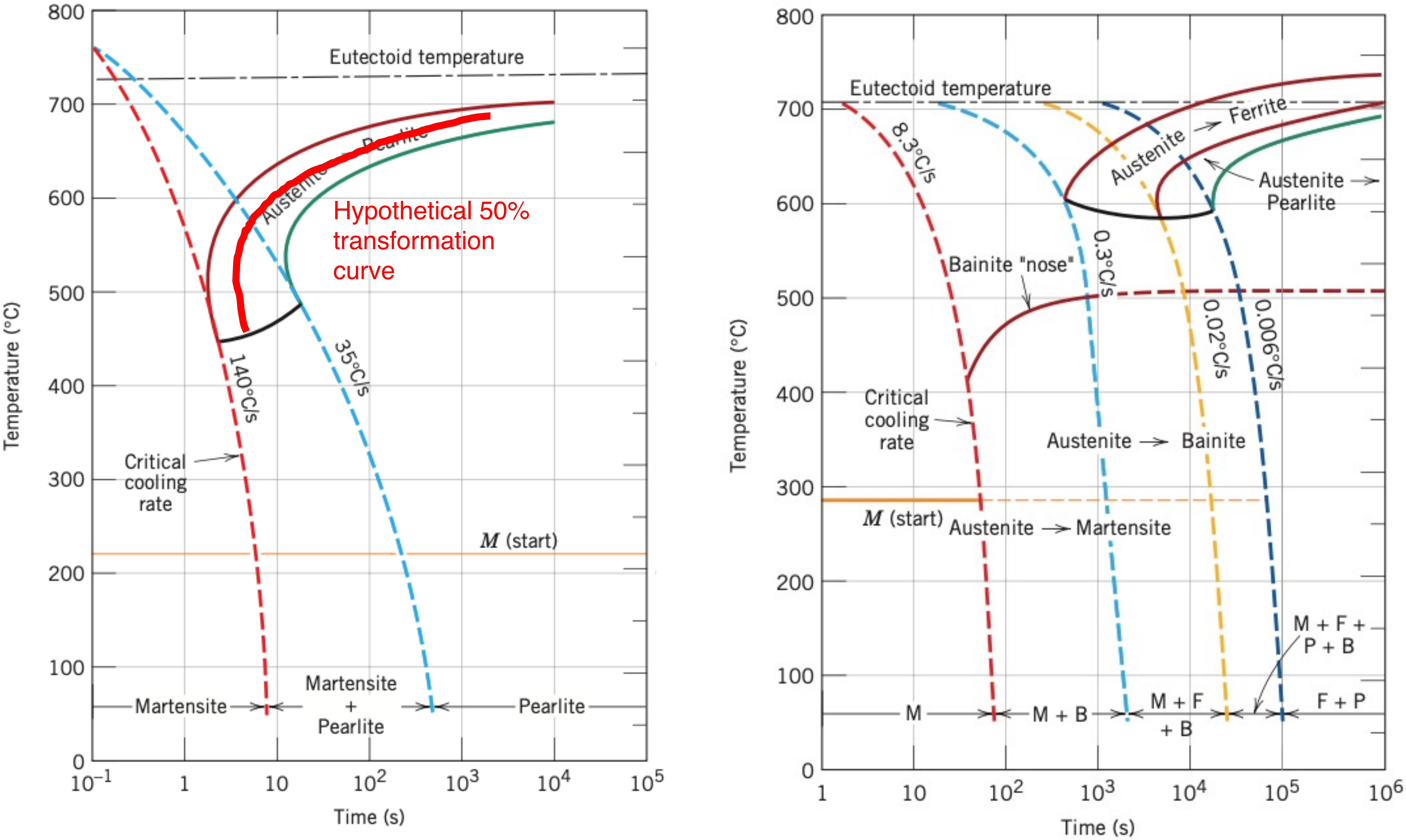
← CCT diagram

CCT diagrams can look similar to TTT diagrams!

Cooling curves (cooling at different rates) superimposed onto CCT diagrams

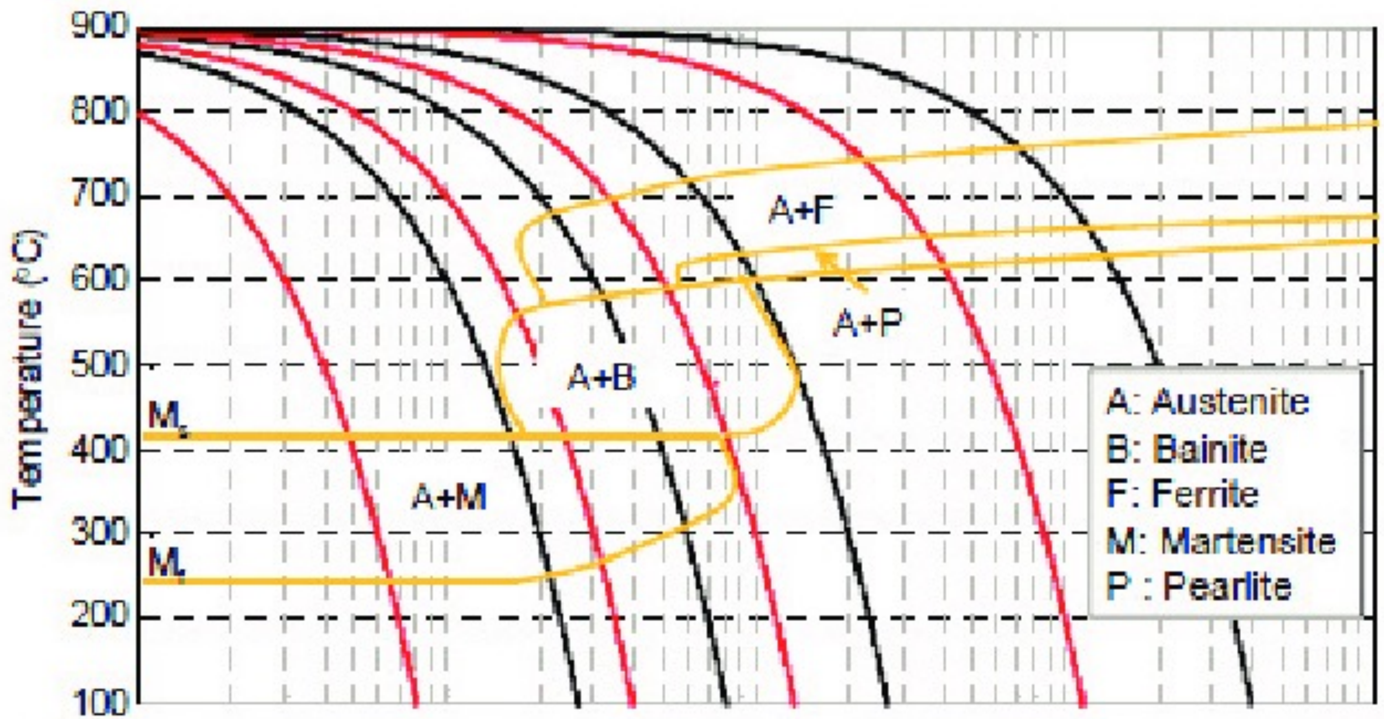
Transformation starts when the cooling curve intersects the beginning reaction curve and is completed when it crosses the completion curve.

If the cooling curve exits the region before crossing the completion curve, only some fraction of the metal transformed

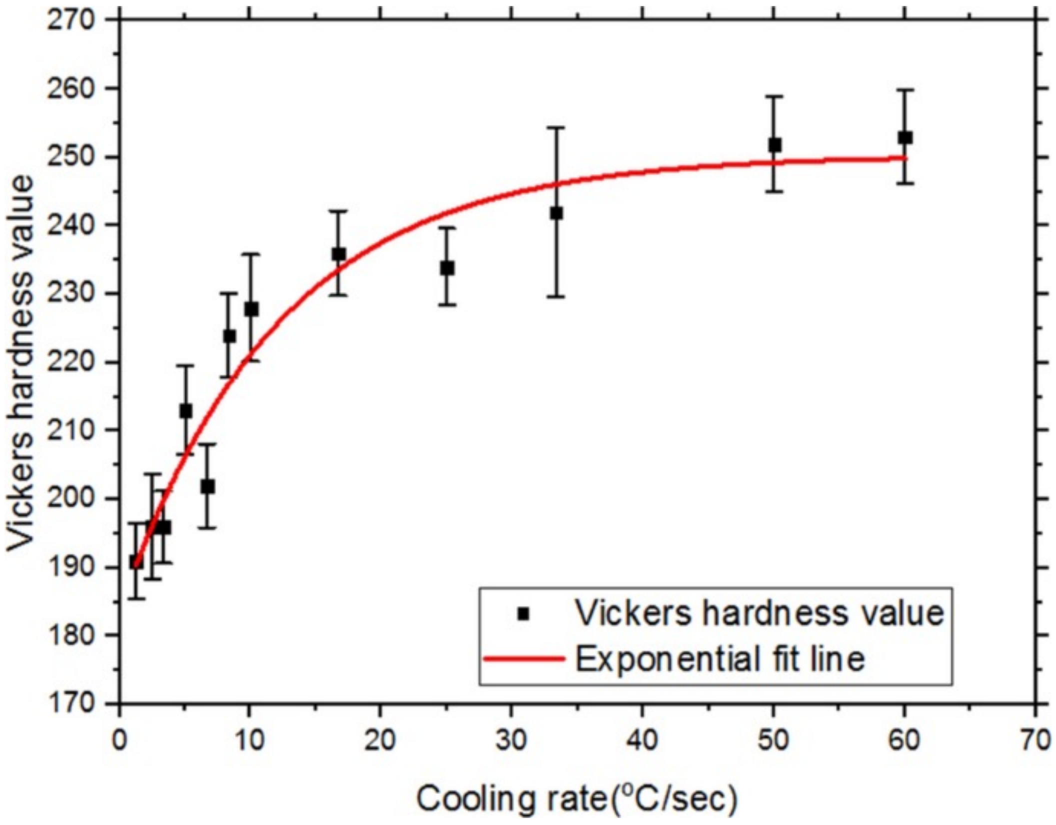


Eutectoid temperature
Pearlite
Austenite
Hypothetical 50% transformation curve
140°C/s
35°C/s
Critical cooling rate
M (start)
Martensite
Martensite + Pearlite
Pearlite
Temperature (°C)
Time (s)
Eutectoid temperature
8.3°C/s
0.3°C/s
0.02°C/s
0.006°C/s
Austenite → Ferrite
Austenite → Pearlite
Bainite "nose"
Critical cooling rate
Austenite → Bainite
M (start)
Austenite → Martensite
M + F + P + B
M
M + B
M + F + B
F + P
Temperature (°C)
Time (s)

Cooling Rate → Microstructure → Mechanical Properties



Time to cool (s)	8	27	40	80	133	266	1143	4000
Cooling Rate (°C/s)	100	30	20	10	6	3	0.7	0.2
Hardness (HV)	475	474	417	278	232	182	163	150



Key takeaway: When dealing with metals/materials, it is important to know that cooling rate plays a large role in material properties

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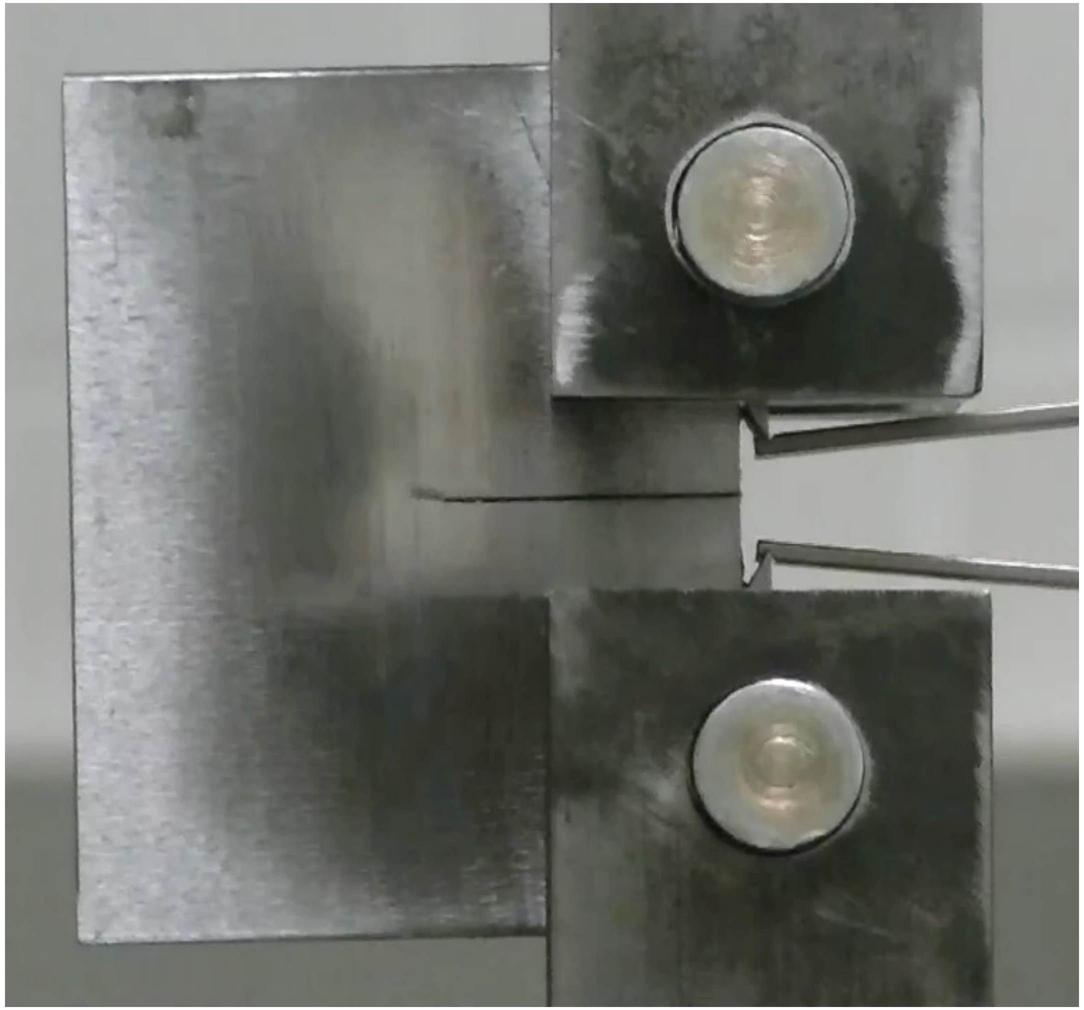
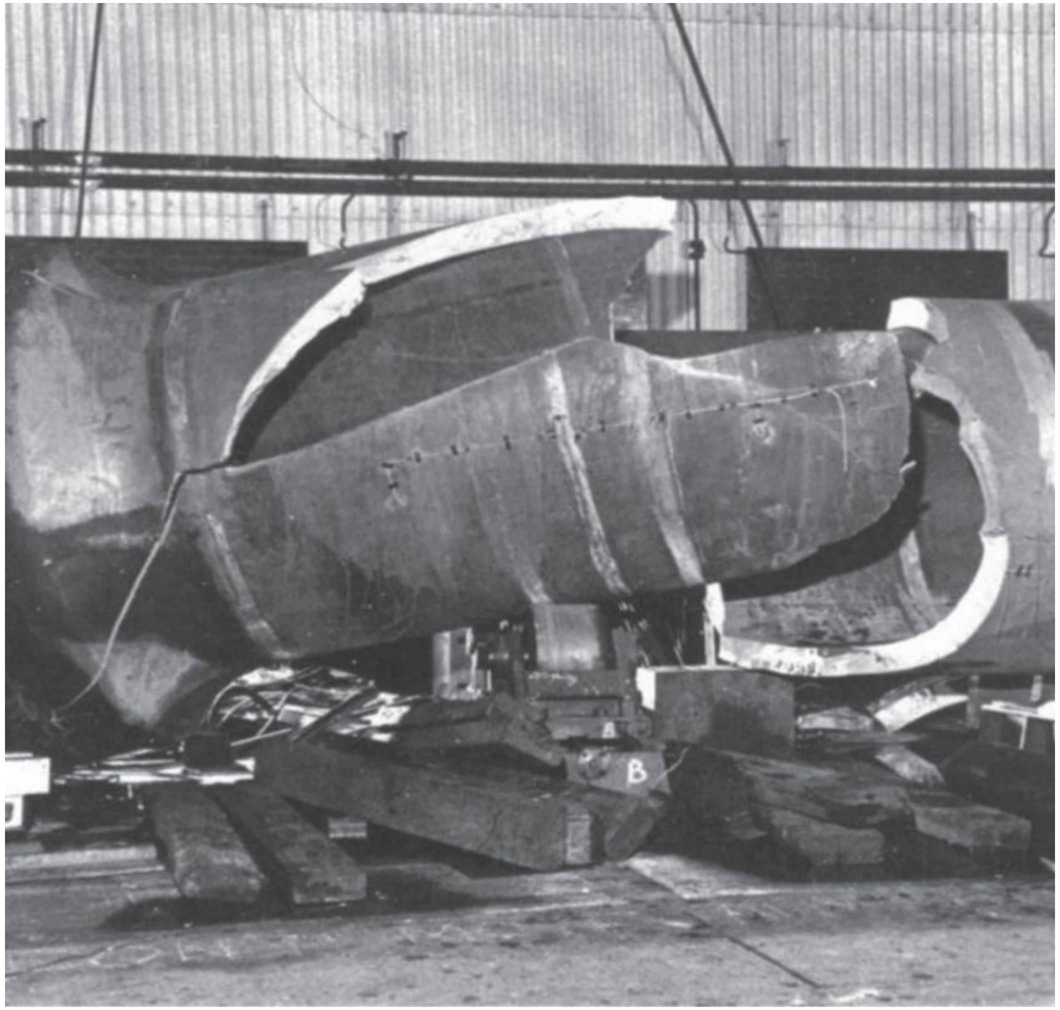
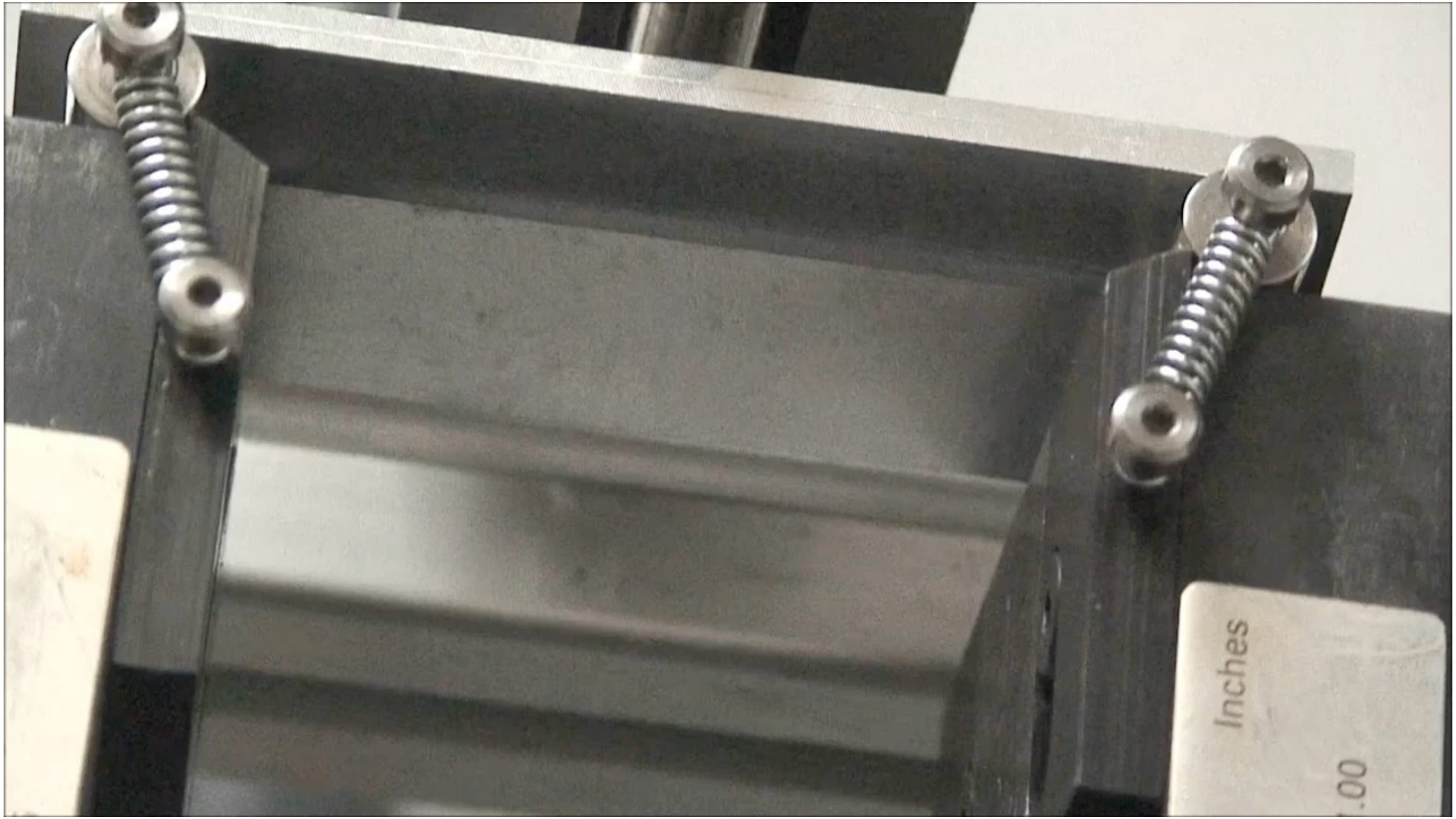
How do metals / materials fail? — Fracture





How do metals / materials fail? — Fatigue



EPFL

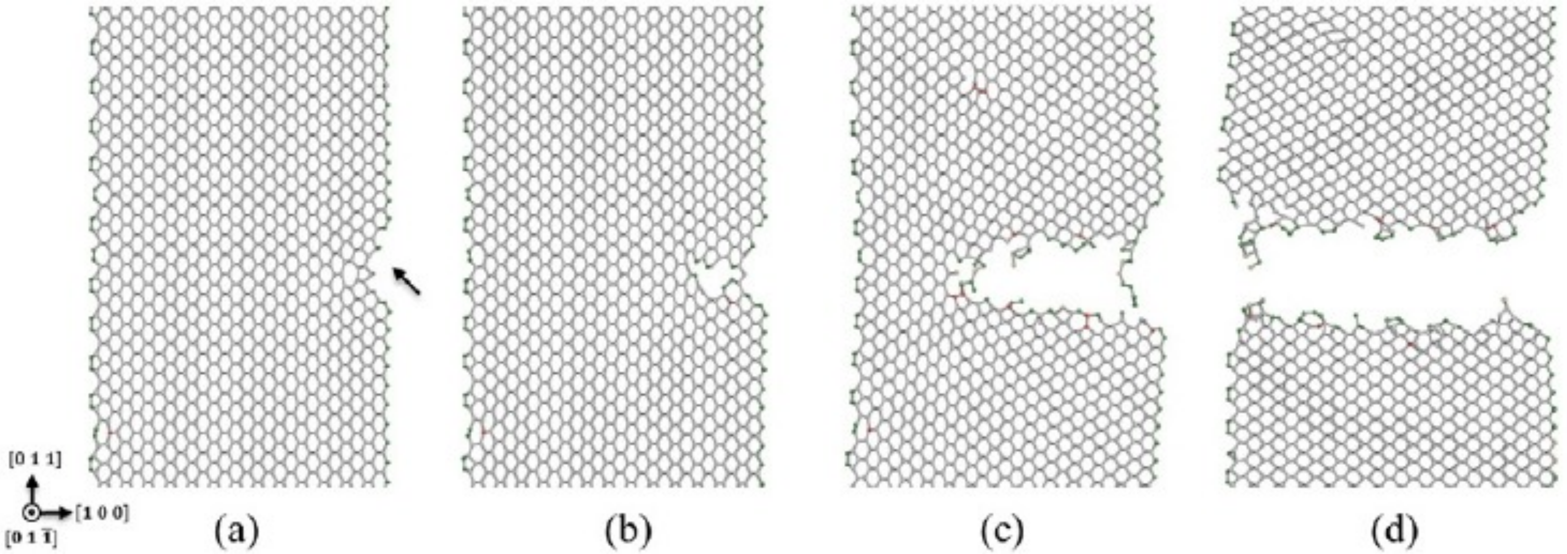
Fracture

Simple definition: Separation of a body into two or more pieces in response to an imposed stress → Stress can be tensile, compressive, shear, torsional, or combinations of them

Fracture involves two steps:

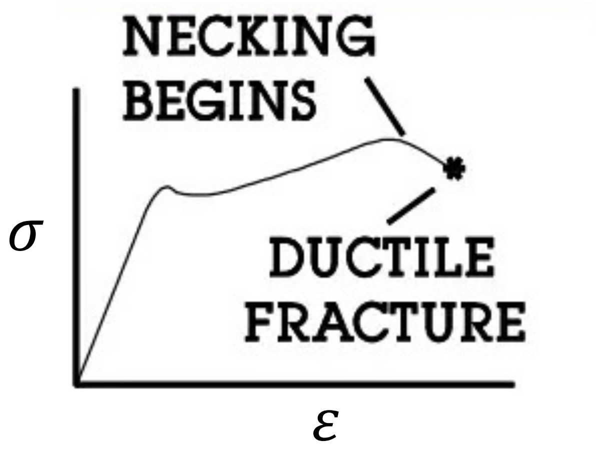
1. Crack formation

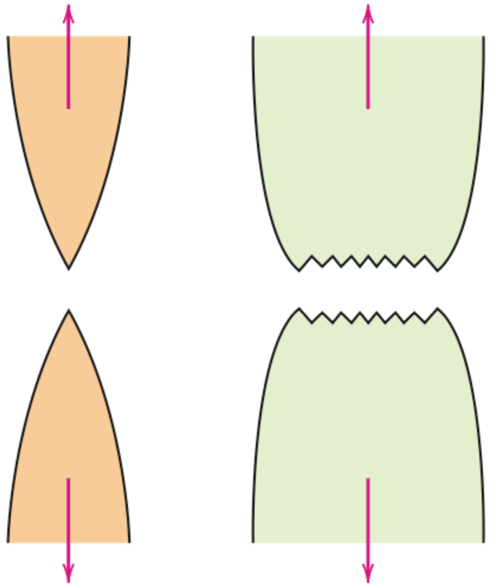
2. Crack propagation



Fracture can be either **ductile** or **brittle** → Depends on temperature, strain rate, and how the stress is being applied

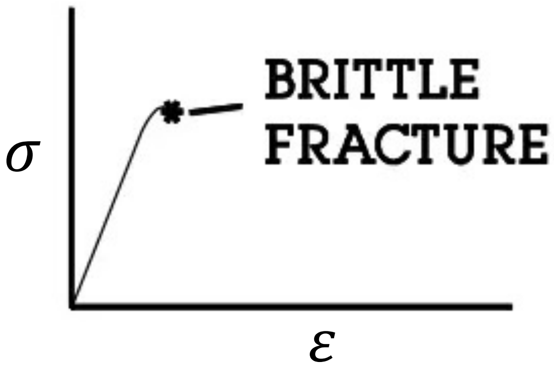
Ductile Fracture

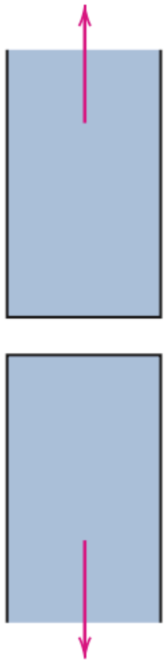




- High energy absorption before failure
- Substantial plastic deformation in the vicinity of the growing crack
- Crack grows relatively slowly.
  Often called stable crack growth
- Crack growth requires additional stress to be applied
- Can be identified by deformation at fracture surface (twisting/tearing/etc.)

Brittle Fracture



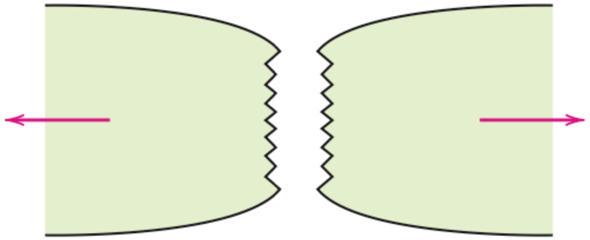


- Little energy absorption before failure
- Little to no plastic deformation in the vincinity of the growing crack
- Crack can grow rapidly. Often called unstable crack growth
- Crack growth, once started, can continue without additional stress
- Can be identified by relatively flat fracture surface

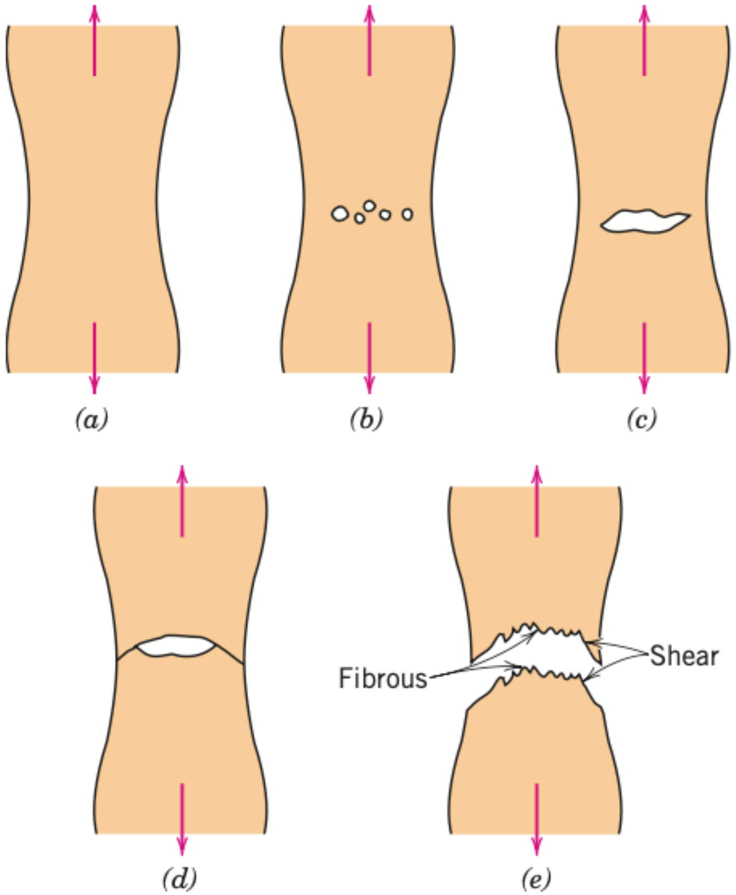
Fracture Surfaces

Ductile fracture

Highly ductile metals
(Neck down to a point fracture)



Moderately ductile metals
(Most common type of profile for ductile metals)



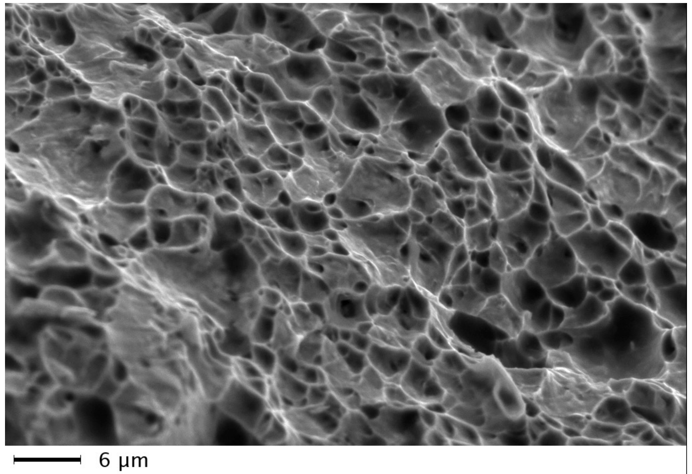
a) Initial necking

b) Microvoid formation

c) Microvoids enlarge and combine to form elliptical crack

d) Crack propagation via microvoid formation and combination

e) Final shear fracture

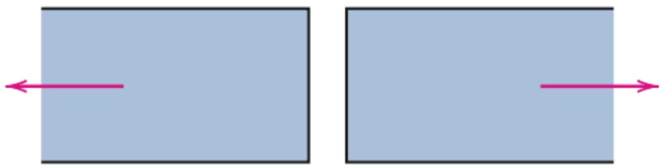


Ductile fracture surfaces often look fibrous.

Dimples come from the microvoids

Fracture Surfaces

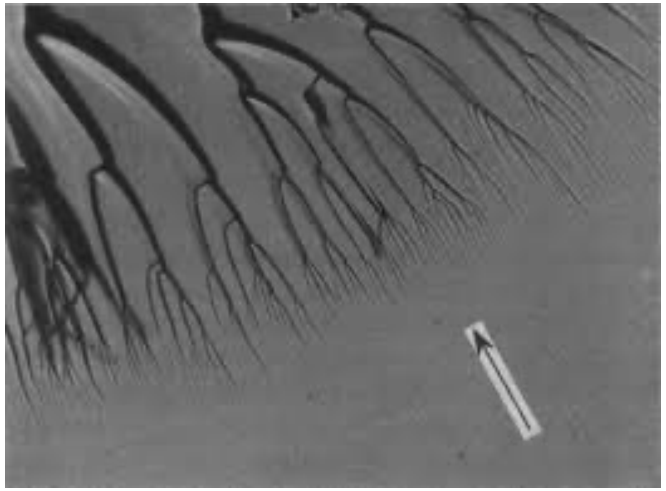
Brittle fracture



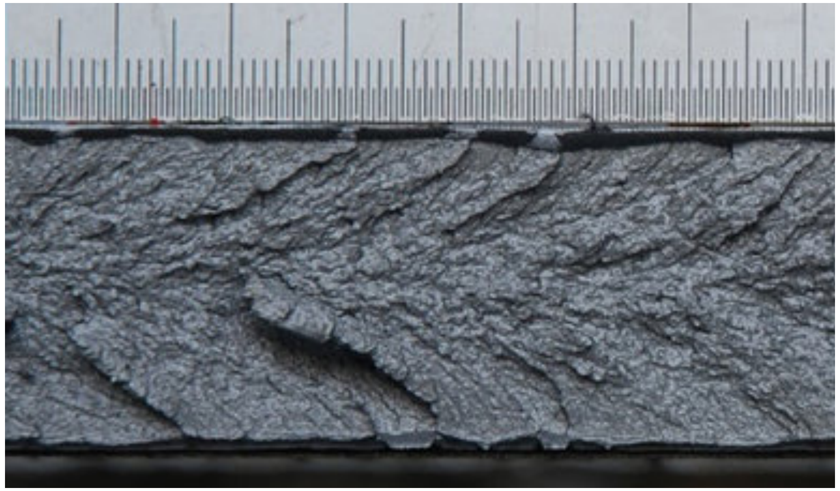
Brittle metals
(Fracture with minimal plastic deformation)

Some features of brittle fracture surfaces

River Lines



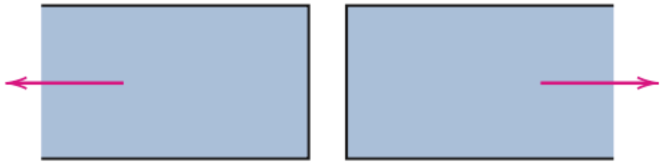
V-shaped lines



Fan-shaped ridges

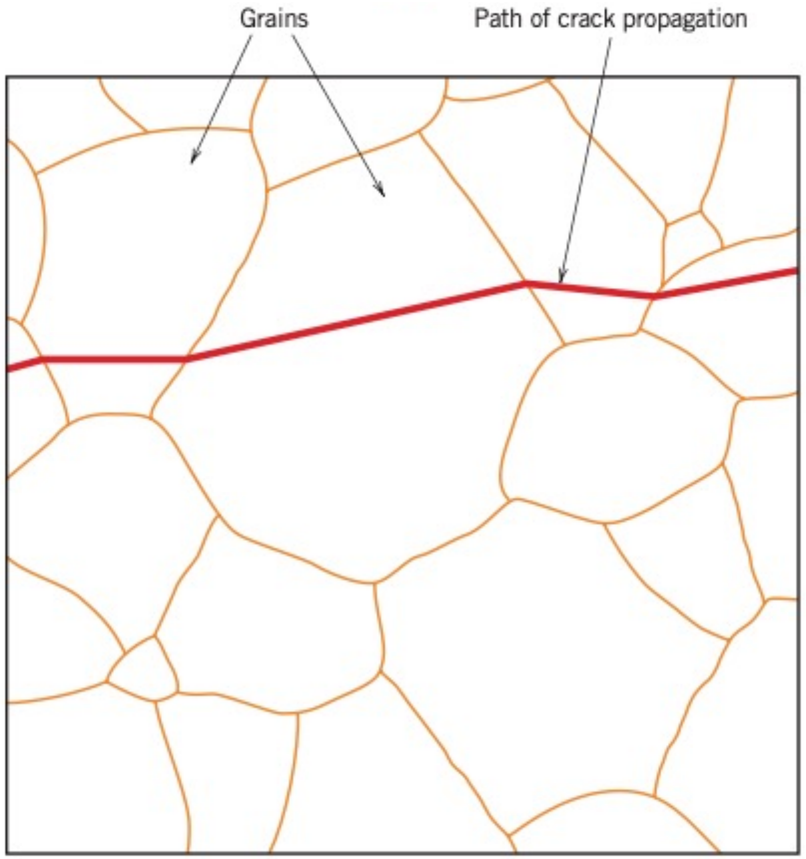
Fracture Surfaces

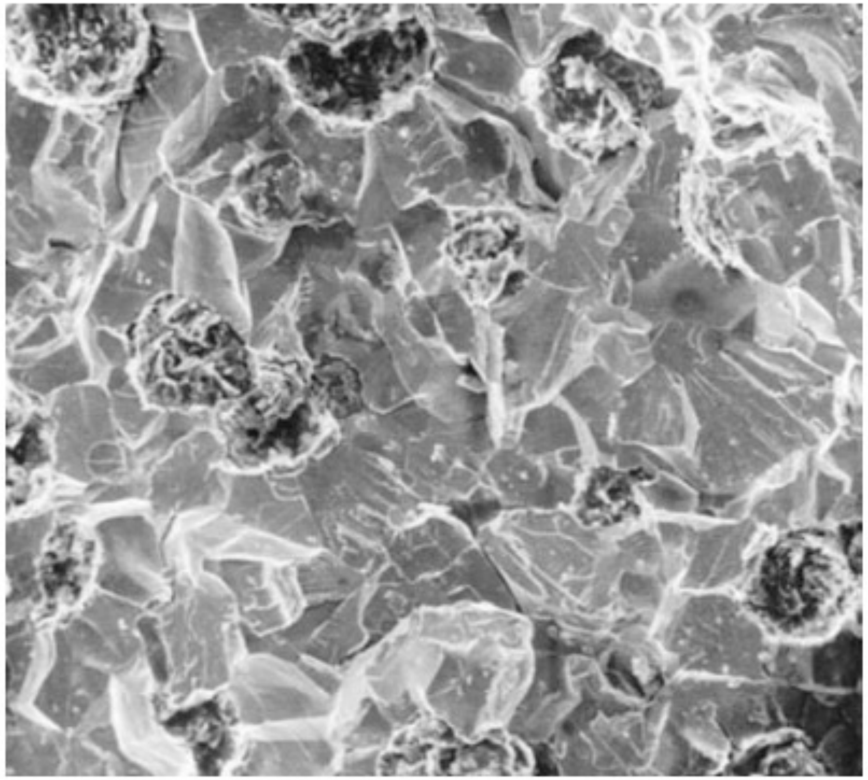
Brittle fracture



Brittle metals
(Fracture with minimal plastic deformation)

Transgranular fracture: Through the grains

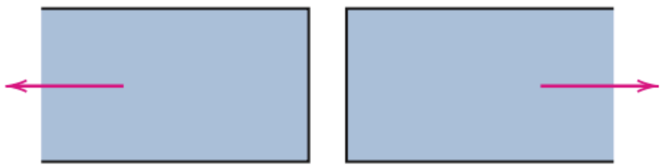




Crack propagates through specific planes in the crystal structure

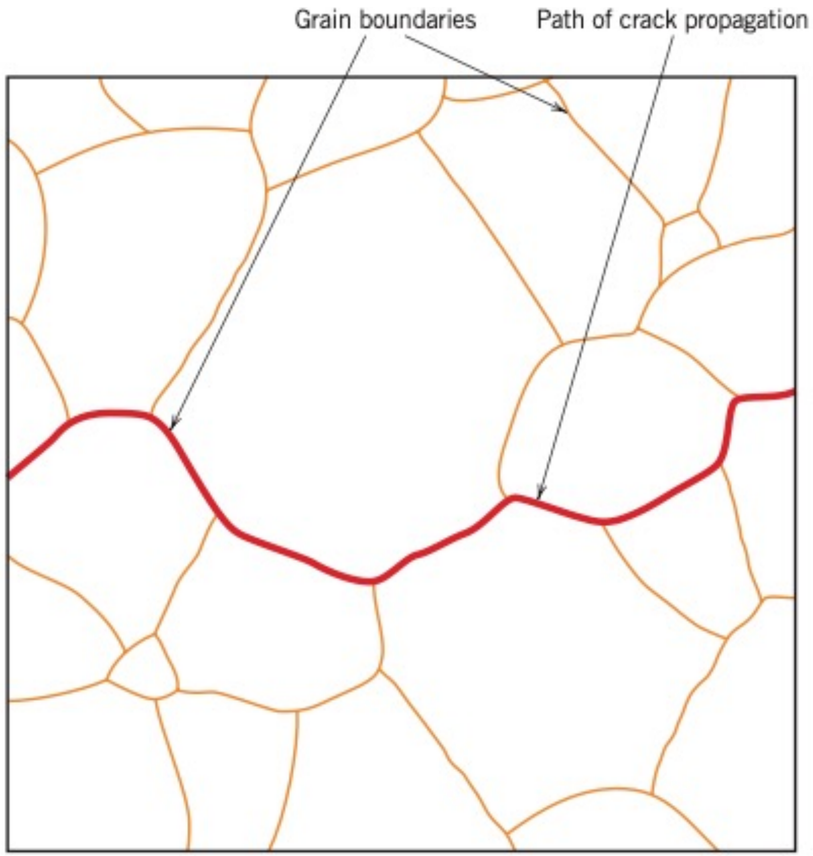
Fracture Surfaces

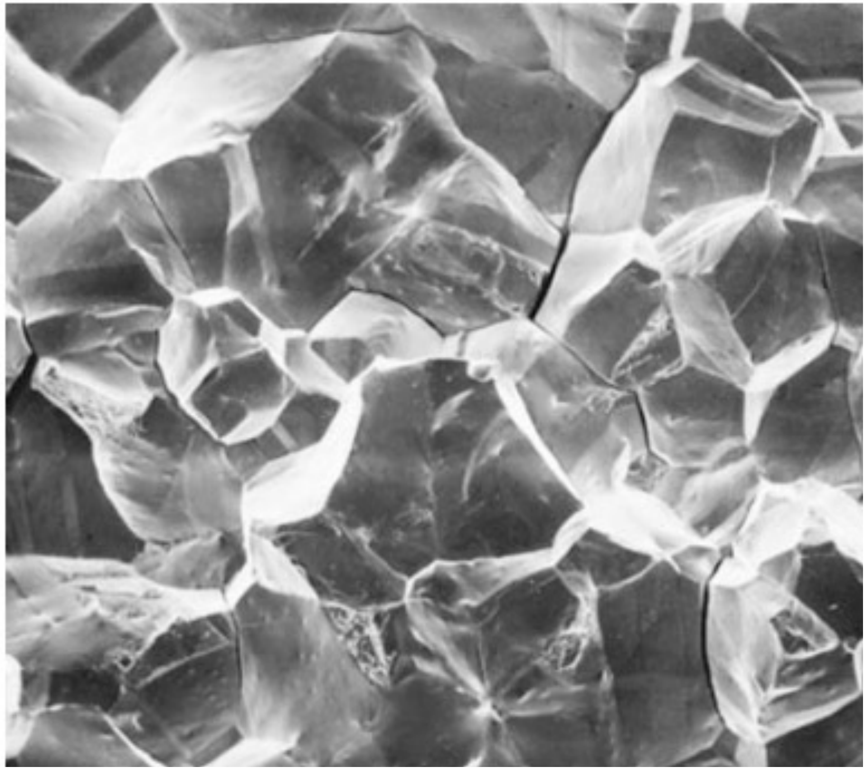
Brittle fracture



Brittle metals
(Fracture with minimal
plastic deformation)

Intergranular fracture: Along the grain boundaries



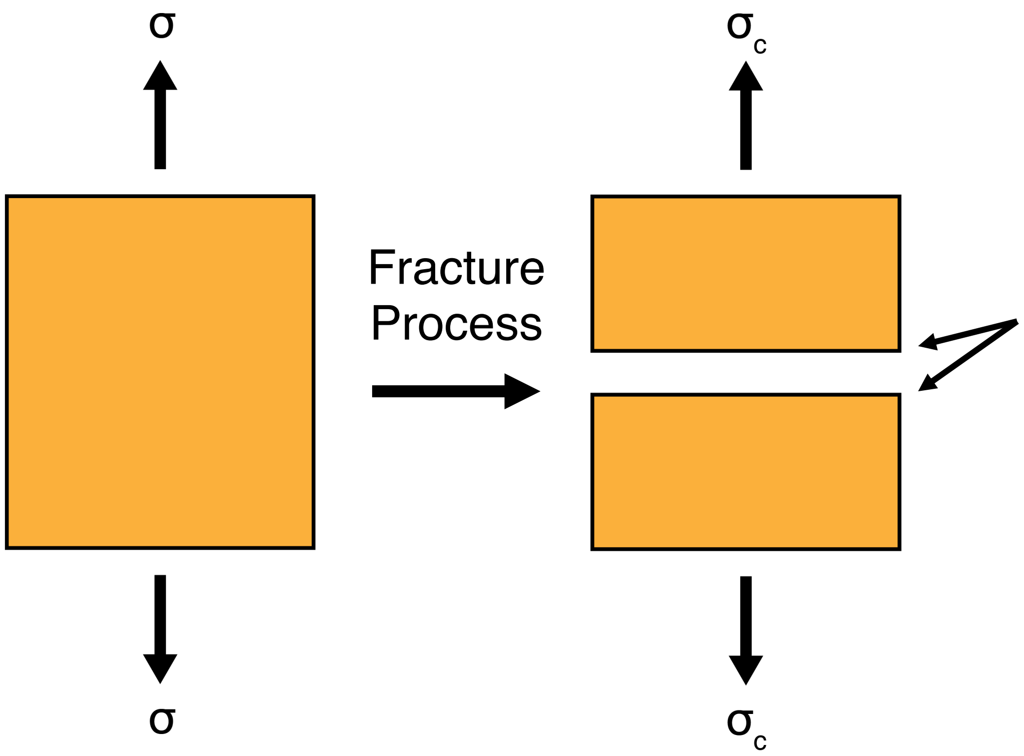


Crack propagates through weaker/brittle grain boundaries

Introduction to Fracture Mechanics

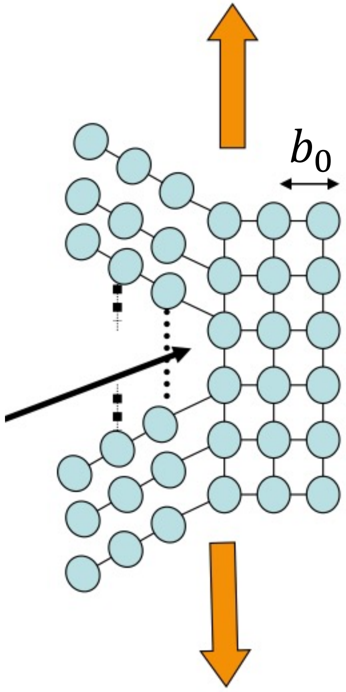
Fracture mechanics → Quantitative way to understand fracture in materials

What is the <u>theoretical</u> fracture strength* of a material?



Created 2 new surfaces:

A: Surface area
γ: Surface energy



<u>Energy balance</u>

Energy released when the crack propagated

vs

Energy created by new surface

A lot of math later… $\boldsymbol{\sigma_c} = \sqrt{\frac{\boldsymbol{E\gamma}}{\boldsymbol{b_0}}}$

*Different from when we looked at dislocations, that was in shear. This is in tension

Introduction to Fracture Mechanics

Fracture mechanics → Quantitative way to understand fracture in materials

What is the theoretical fracture strength* of a material?

Let's consider glass:

E ~ 100 GPa
b_0 ~ 5 x 10^{-10}m
γ ~ 1 J/m^2

$$\boldsymbol{\sigma_c} = \sqrt{\frac{\boldsymbol{E\gamma}}{\boldsymbol{b_0}}} = E\sqrt{\frac{\gamma}{Eb_0}} \approx \frac{E}{7}$$

The theoretical strength of glass is ~ 14 GPa

Experimental strength of glass is ~ 0.01 GPa

In general, the theoretical strength of most materials is ~ *E*/10

The experimental strength of most materials is ~ *E/10000* to *E/1000*

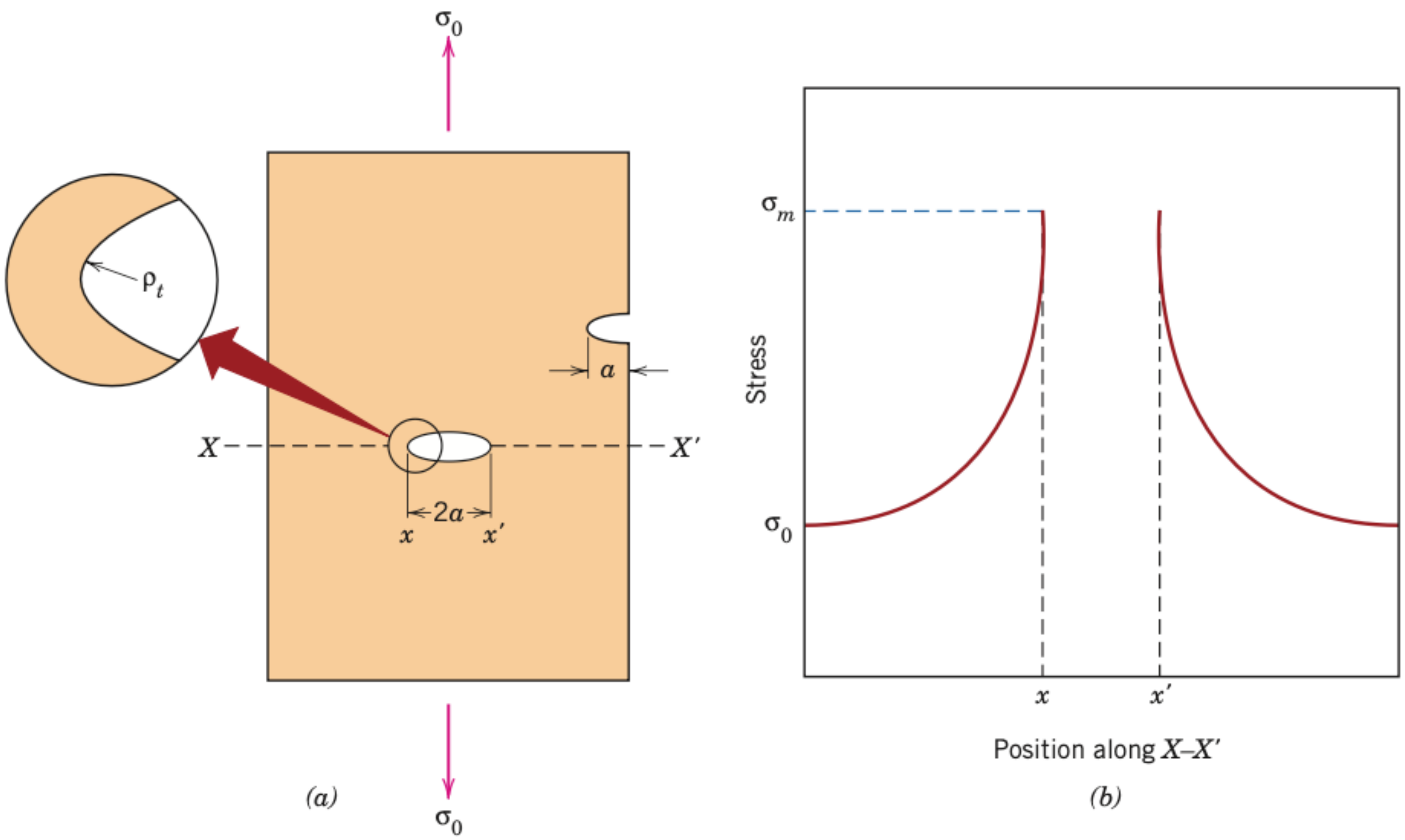
↓

Stress concentration at the crack tip is not accounted for!

*Different from when we looked at dislocations, that was in shear. This is in tension

Stress concentration

Consider an elliptical crack of width 2*a* in the center of a body subjected to an applied stress σ_0



Magnitude of localized stress decreases with distance away from the crack tip

Far from the crack tip, the stress is just the applied stress σ_0

Maximum stress at the crack tip

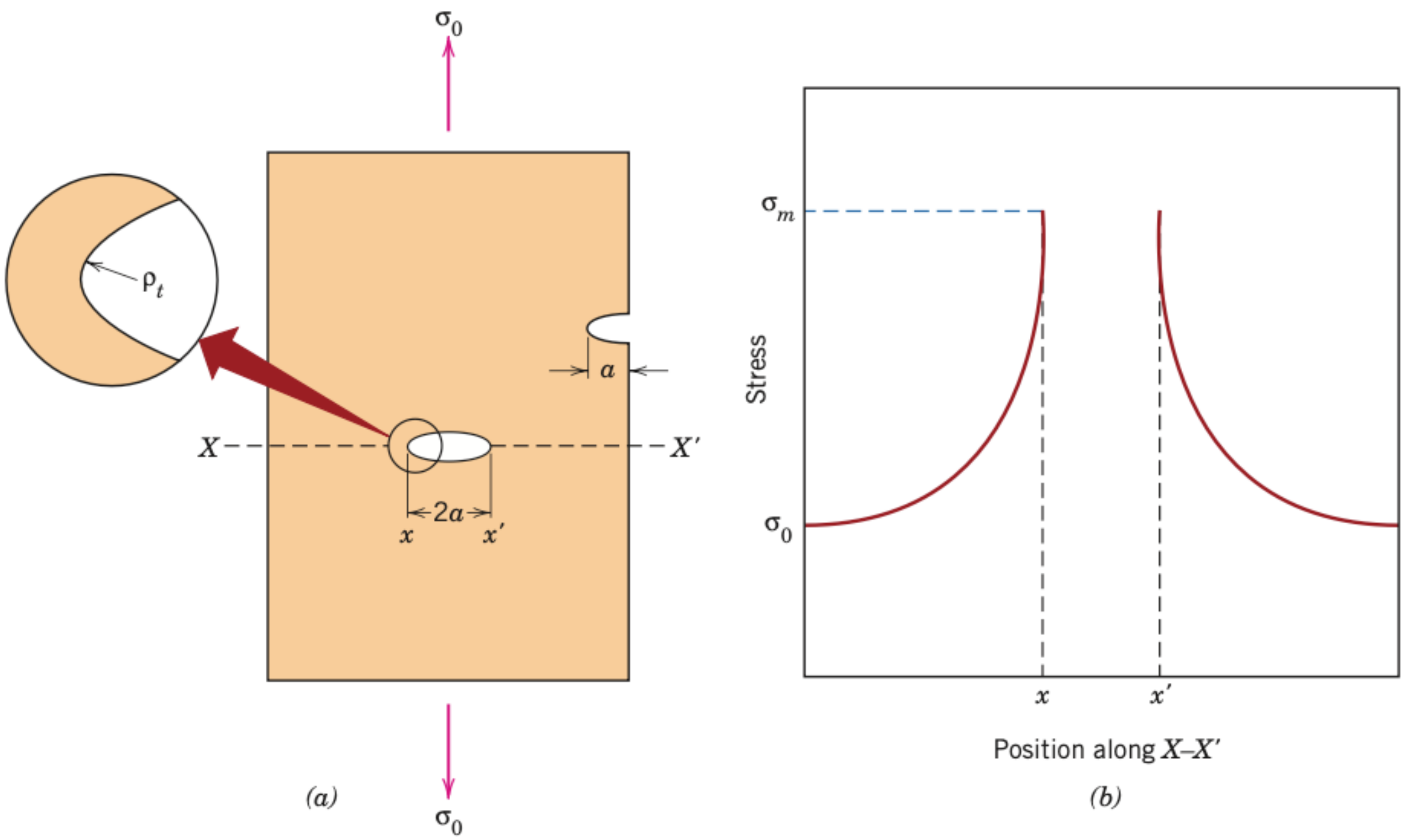
$$\boldsymbol{\sigma_m} = 2\sigma_0 \sqrt{\frac{a}{p_t}}$$

a: length of surface crack or half the length of an internal crack

p_t: the radius of curvature of the crack tip

Stress concentration

Consider an elliptical crack of width $2a$ in the center of a body subjected to an applied stress σ_0



Maximum stress at the crack tip

$$\boldsymbol{\sigma_m} = 2\sigma_0 \sqrt{\frac{a}{p_t}}$$

a: length of surface crack or half the length of an internal crack

p_t: the radius of curvature of the crack tip

Stress concentration factor K_t:

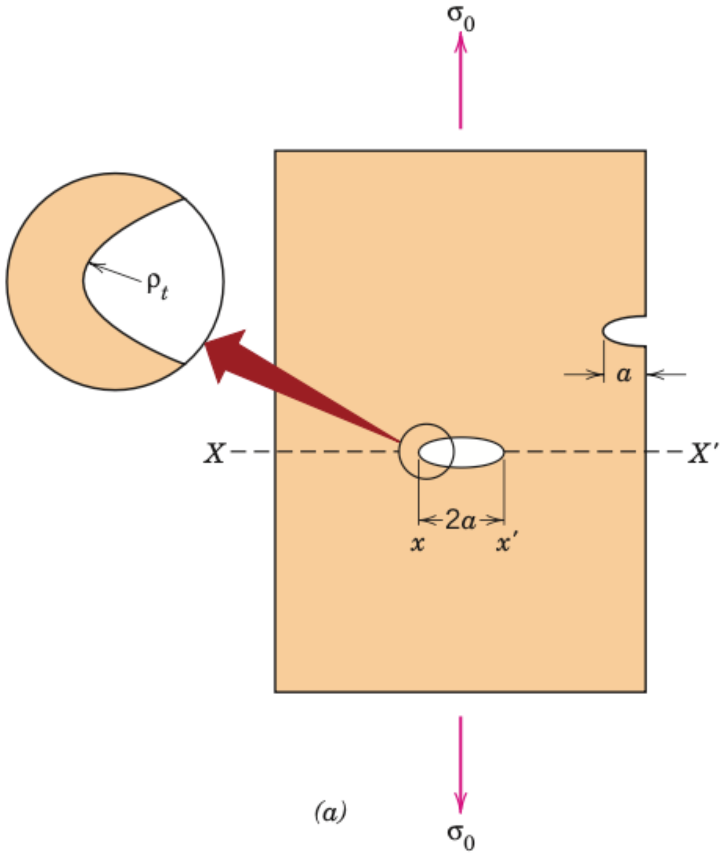
$$\boldsymbol{K_t} = \frac{\sigma_m}{\sigma_0} = 2\sqrt{\frac{a}{p_t}}$$

For a long crack with small crack tip radius, K_t can be a large value!

Griffith Theory of Brittle Fracture

When a crack propagates:

Release in elastic strain energy (decrease energy)
Create new surfaces (increase energy)



Griffith in 1921

Crack grows under a constant applied stress σ_c when the decrease in elastic strain energy **=** Energy required to form new surfaces

↓

No change in total energy of the system with crack growth

Surface energy (U_s)

$$\boldsymbol{U_s} = 4a\gamma$$

a: Crack length
γ: Surface energy
2 surfaces created!

Elastic strain energy* U_{SE}

$$\boldsymbol{U_{SE}} = -\frac{\pi\sigma^2 a^2}{E}$$

σ: Applied stress

Change in potential energy from crack growth (ΔU)

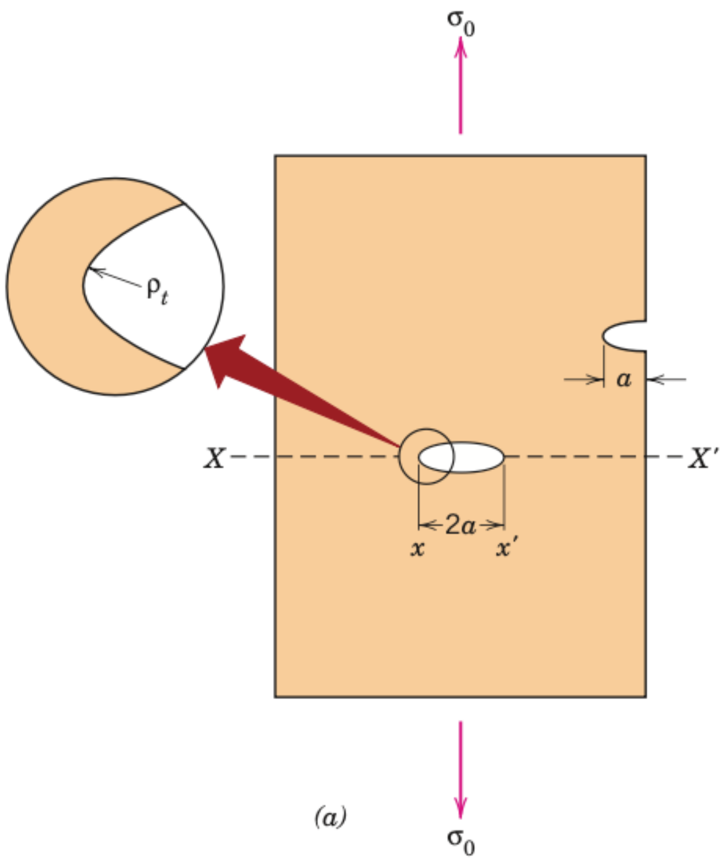
$$\Delta \boldsymbol{U} = U_S + U_{SE}$$
$$= 4a\gamma - \frac{\pi\sigma^2 a^2}{E}$$

*We won't derive it so just believe me

Griffith Theory of Brittle Fracture

When a crack propagates:

Release in elastic strain energy (decrease energy)
Create new surfaces (increase energy)



<u>Griffith in 1921</u>

Crack grows under a constant applied stress σ_c when the decrease in elastic strain energy **=** Energy required to form new surfaces

↓

No change in total energy of the system with crack growth

Griffith's criterion for crack growth

$$\frac{d\Delta U}{da} = \frac{d}{da}\left(4a\gamma - \frac{\pi\sigma_c^2 a^2}{E}\right) = 0$$

$$4\gamma - \frac{2\pi{\sigma_c}^2 a}{E} = 0$$

$$\sigma_c = \sqrt{\frac{2E\gamma}{\pi a}}$$

For a crack of length *a*, σ_c is the stress required for crack propagation

Griffith Theory of Brittle Fracture

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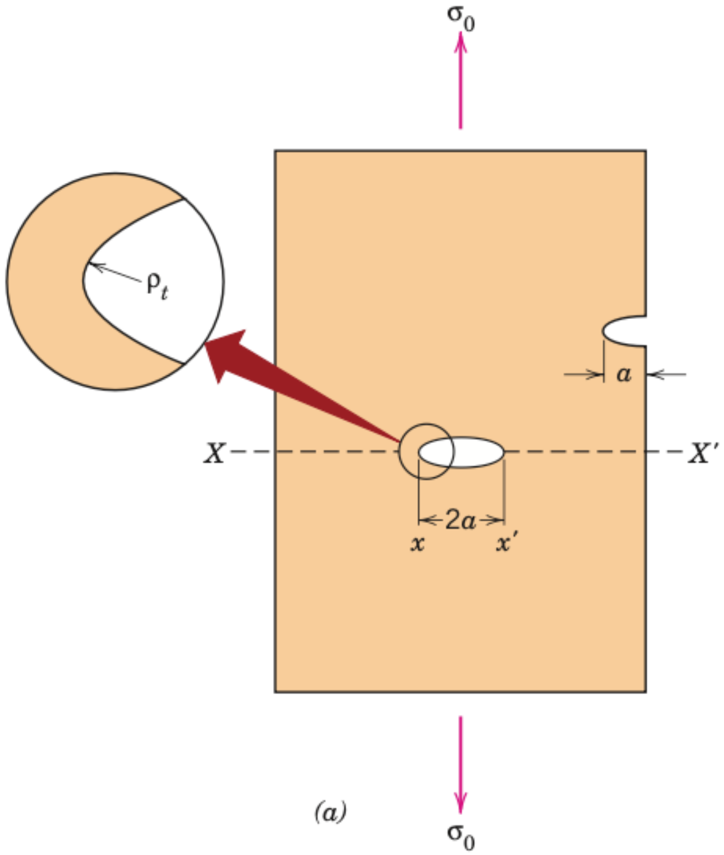
Release in elastic strain energy (decrease energy)
Create new surfaces (increase energy)



<u>Griffith in 1921</u>

Crack grows under a constant applied stress σ_c when the decrease in elastic strain energy = Energy required to form new surfaces

↓

No change in total energy of the system with crack growth

Let's look at glass again

$$\sigma_c = \sqrt{\frac{2E\gamma}{\pi a}}$$

E ~ 100 GPa (100E9 J/m^3)
γ ~ 1 J/m^2
σ_c ~ 0.01 GPa

If you do the math, a ~ 600 μm

For a crack of length ~ 600 μm only 0.01 GPa of stress is needed for brittle fracture!

Fracture Toughness

$$\sigma_c = \sqrt{\frac{2E\gamma}{\pi a}}$$

$$\sigma_c\sqrt{\pi a} = \boxed{\sqrt{2E\gamma}}$$ → Material properties

$$\sigma_c\sqrt{\pi a} = \boxed{K_c}$$ → Critical stress intensity factor or Fracture Toughness

More generally:

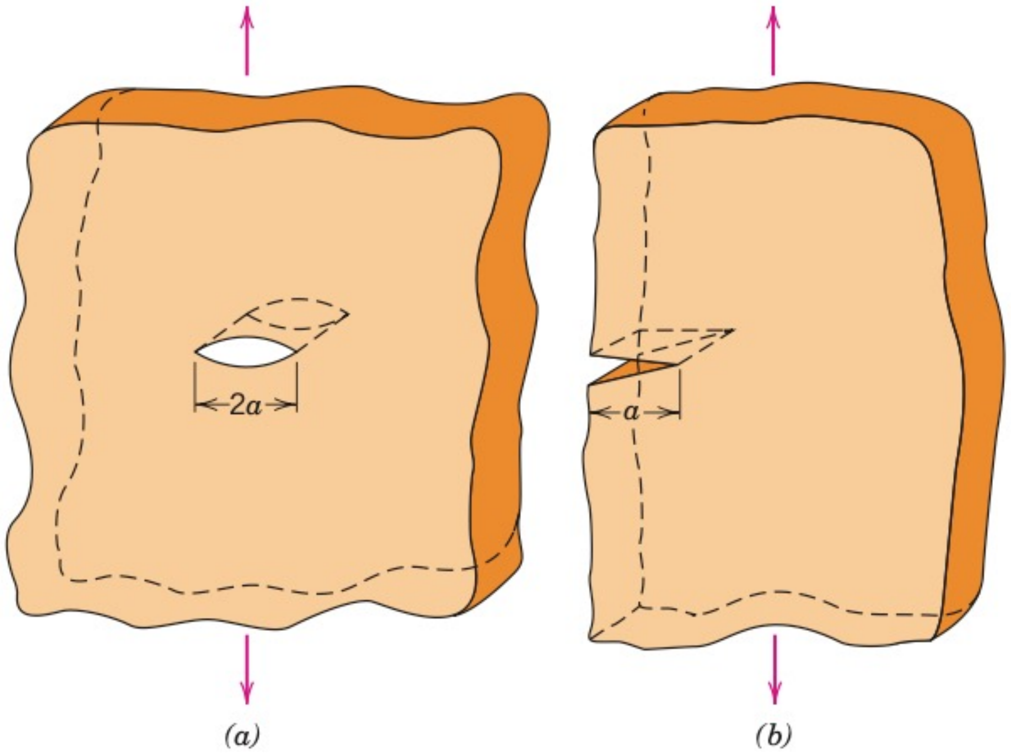
$$\boldsymbol{K_c = Y\sigma_c\sqrt{\pi a}}$$

Y: Dimensionless geometric constant

K_c has units of MPa $\sqrt{m}$

Y depends on the crack, specimen, and loading conditions

For cracks that are much shorter than the sample width, Y is ~ 1



$Y = 1$ $Y \approx 1.1$

Y can be very complex!

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Fracture Toughness

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Why is K_c important?

If you know K_c and a, you can solve for stress needed to cause fracture (σ_c)

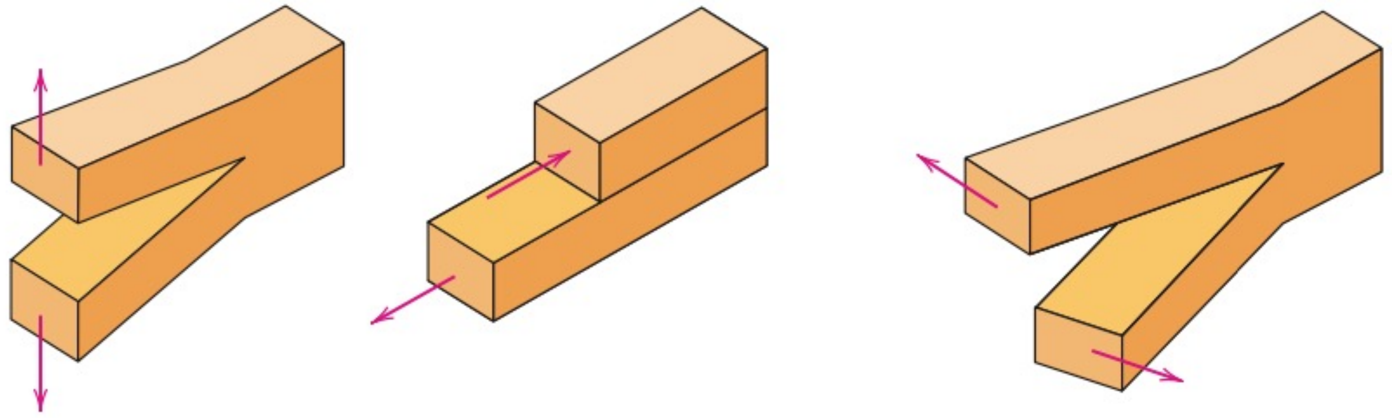
If you know K_c and the stress in the system (σ_c), you can solve for the maximum crack size that can be tolerated before fracture (*a*)

Note 1: K_c is independent of sample thickness only when sample thickness is much greater than crack dimensions

Note 2: The constant value K_c is the one that is most often reported. It is called the *plane strain fracture toughness*

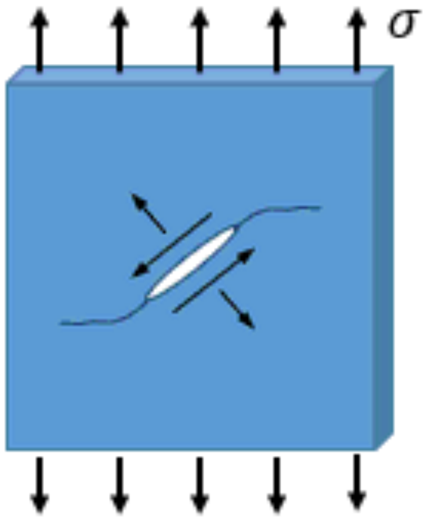
There are different kinds of Fracture Toughness

Mode I (Opening) | **Mode II** (In-plane shear) | **Mode III** (Out-of-plane shear)



Each loading mode has its own associated fracture toughness value!

$$K_{Ic}\, , K_{IIc}\, , K_{IIIc}$$



Engineering analysis almost always considers **Mode I** since it is:

a) Worse-case situation
b) Most common
c) Cracks that don't start in Mode I often become Mode I

Material	K_{Ic} $MPa\sqrt{m}$
Aluminum alloy[a] (7075-T651)	24
Aluminum alloy[a] (2024-T3)	44
Titanium alloy[a] (Ti-6Al-4V)	55
Alloy steel[a] (4340 tempered @ 260°C)	50.0
Alloy steel[a] (4340 tempered @ 425°C)	87.4
Polystyrene (PS)	0.7–1.1
Poly(methyl methacrylate) (PMMA)	0.7–1.6
Polycarbonate (PC)	2.2

Let's look at an example of how to use K_{IC}

An aircraft component is made from an aluminum alloy with a K_{IC} of 40 MPa$\sqrt{m}$

Fracture results at a stress of 300 MPa when the critical internal crack length is 4.0 mm

For this component and alloy, will fracture occur at a stress of 260 MPa with an internal crack length of 6.0 mm?

Why or why not?

Initial information:

K_{IC} = 40 MPa$\sqrt{m}$
σ = 300 MPa
$2a$ = 4.0 mm

$$\boldsymbol{K_{Ic} = Y\sigma_c\sqrt{\pi a}}$$

Normally assume Y = 1,but in this case, we have to solve for Y

$$Y = \frac{40\ MPa\sqrt{m}}{300\ MPa\ \sqrt{\pi\ .\ 0.002}}$$

$$= 1.682$$

Scenario:

K_{IC} = 40 MPa$\sqrt{m}$
σ = 260 MPa
Y = 1.682

$$\boldsymbol{K_{Ic} = Y\sigma\sqrt{\pi a_c}}$$

a_c = 2.3 mm < 3.0 mm

At these conditions, the component will fail at a crack length of 2.3 mm. Since the crack length is 3.0 mm, **fracture will occur**.

Let's look at an example of how to use K_{IC}

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→ Normally assume Y = 1,but in this case, we have to solve for Y

$$Y = \frac{40\ MPa\sqrt{m}}{300\ MPa\ \sqrt{\pi\ .\ 0.002}}$$

$$= 1.682$$

Scenario:

$2a$ = 6.0 mm
σ = 260 MPa
Y = 1.682

→ $$\boldsymbol{K = Y\sigma\sqrt{\pi a}}$$

K = 42.44 MPa$\sqrt{m}$

As the stress intensity factor (K) is larger than the fracture toughness of the material (K_{IC}), **fracture will occur**.

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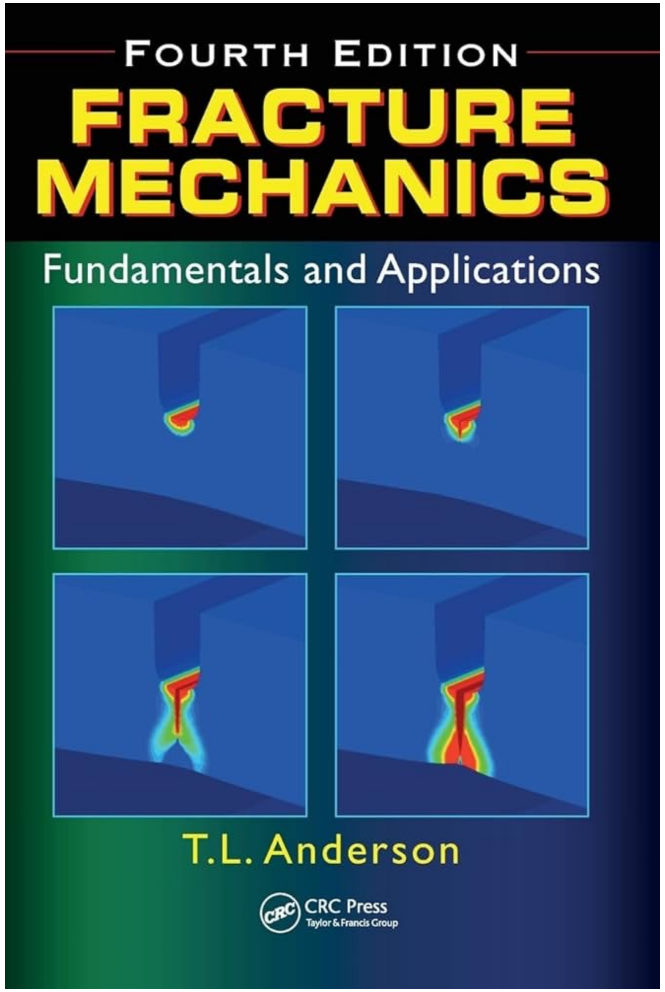
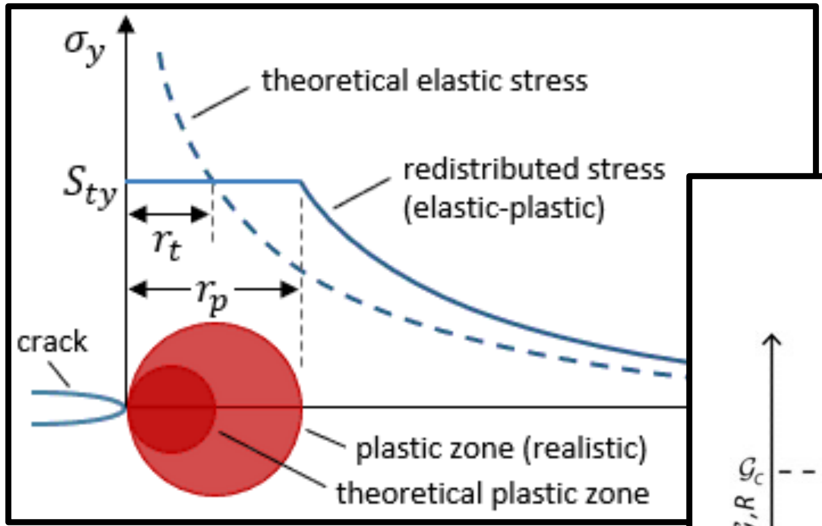
We have only just scratched the surface of fracture mechanics

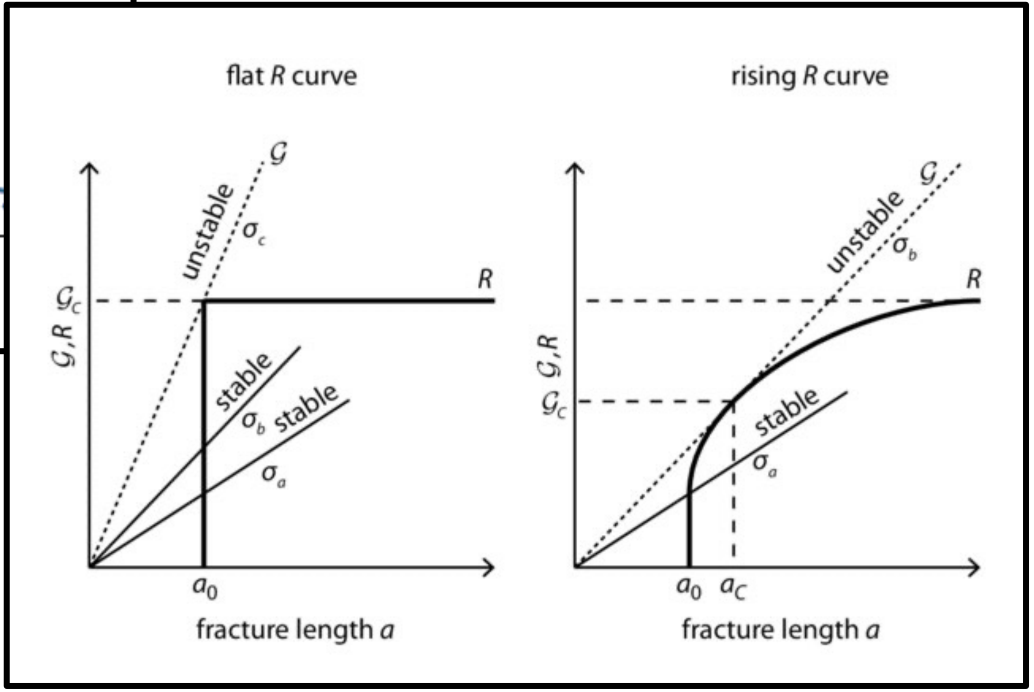


Whole field by itself!

Plasticity at crack tip



Crack growth resistance



Highly complex topic, but necessary for any material application

Typically a graduate level course

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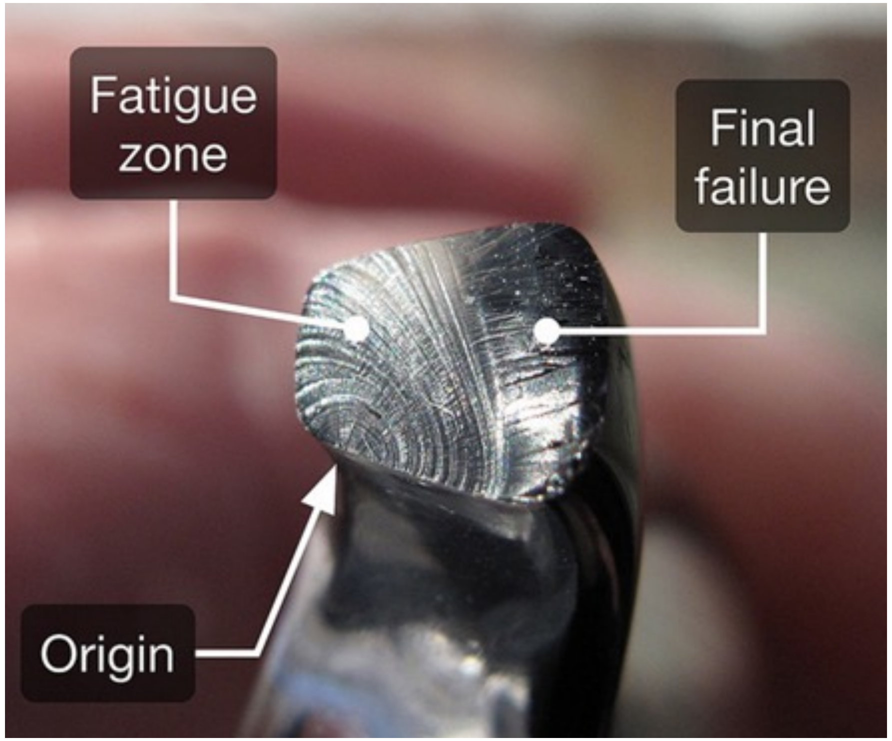
Fatigue

Form of fracture in structures subjected to dynamic and fluctuating stresses → Here, fracture can occur at a stress level **much lower** than the tensile or yield strength

Fatigue fracture is often sudden and without warning

Fatigue fracture is brittle-like even in normally ductile metals

Little to no plastic deformation associated with fracture

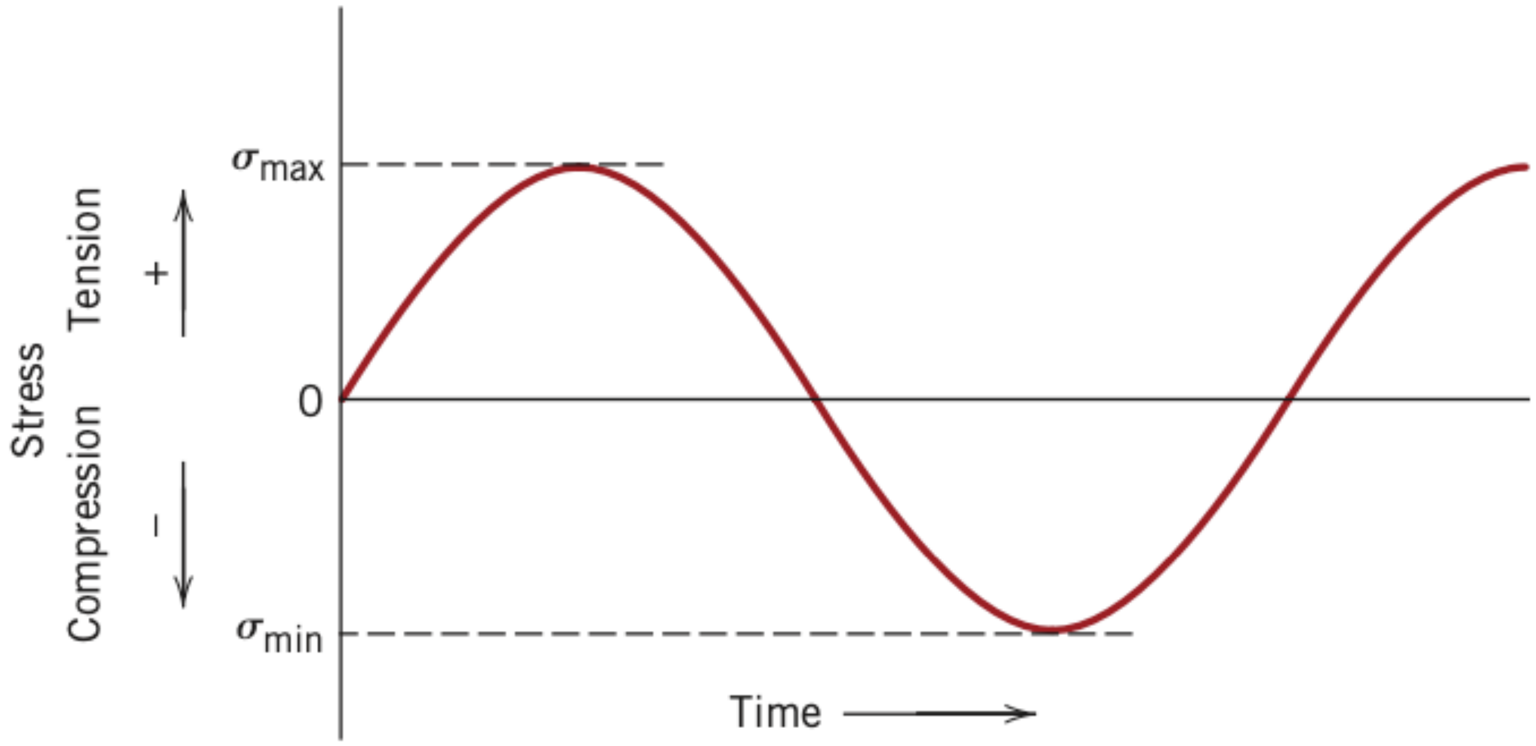


Fatigue fracture looks like brittle failure!

Fatigue involves cyclic stresses

The applied stress may be axial, flexural, torsional, or combinations of them

In general, three different varying stress-time modes are possible:



Reversed stress cycle

Regular and sinusoidal

Amplitude is symmetrical about a mean zero stress level

Alternative from maximum tensile to minium compression stress of equal magnitude

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Fatigue involves cyclic stresses

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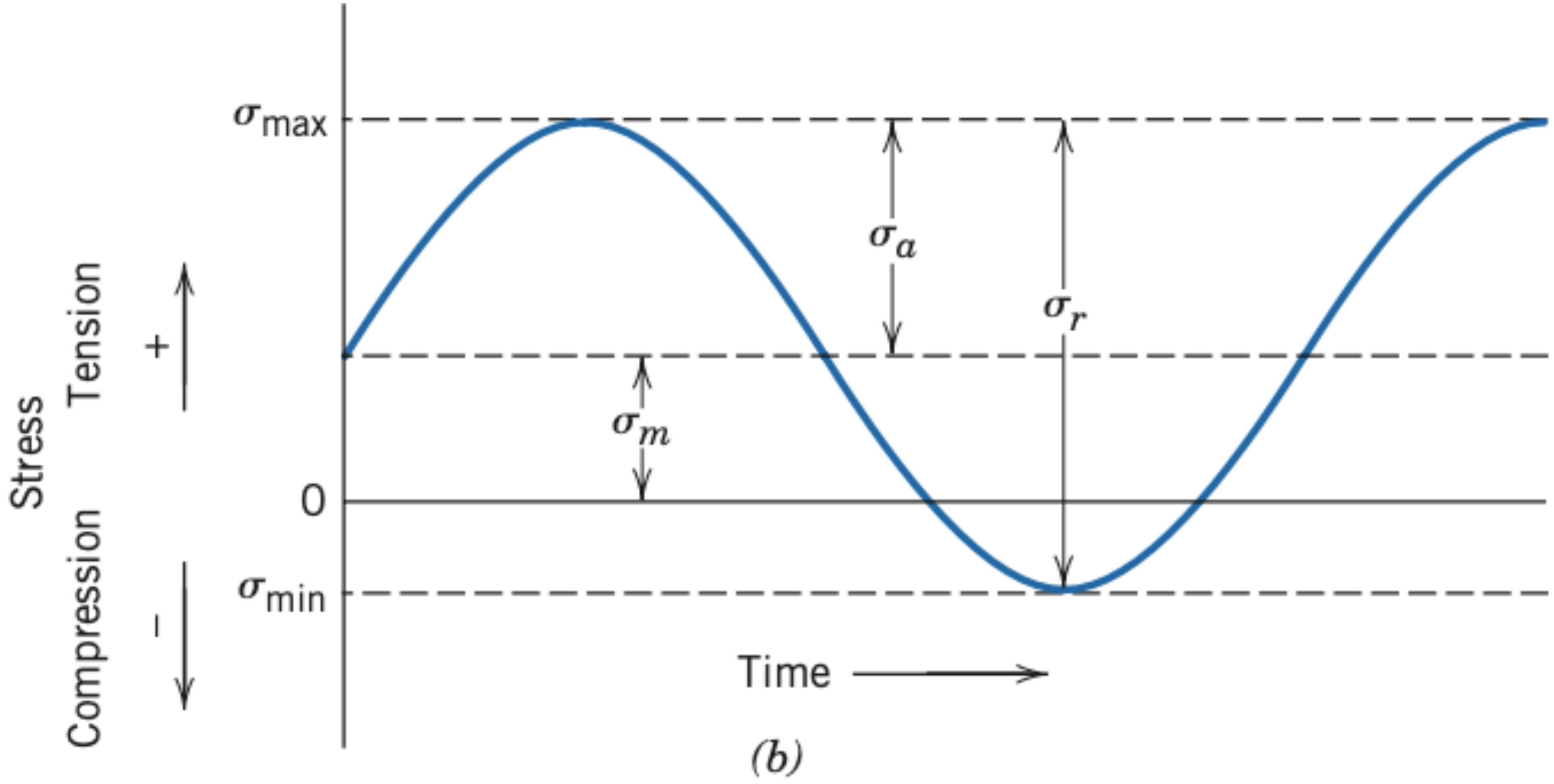
In general, three different varying stress-time modes are possible:



σ_m = mean stress

σ_r = range of stress

σ_a = stress amplitude

<ins>Repeated stress cycle</ins>

Regular and sinusoidal

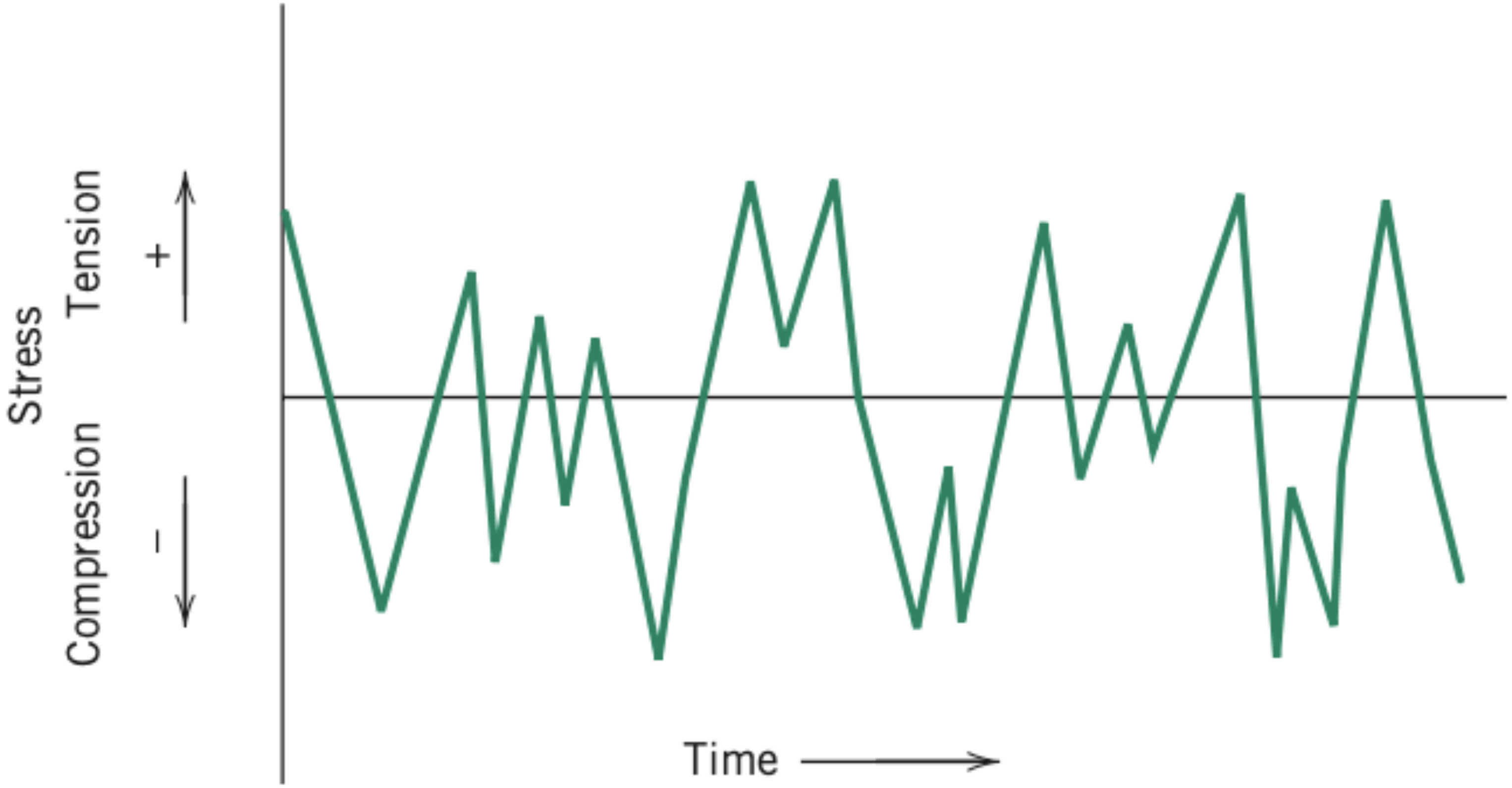
Maxima and minima are asymmetrical relative to the zero stress level

Symmetrical about the mean stress σ_m

Fatigue involves cyclic stresses

The applied stress may be axial, flexural, torsional, or combinations of them

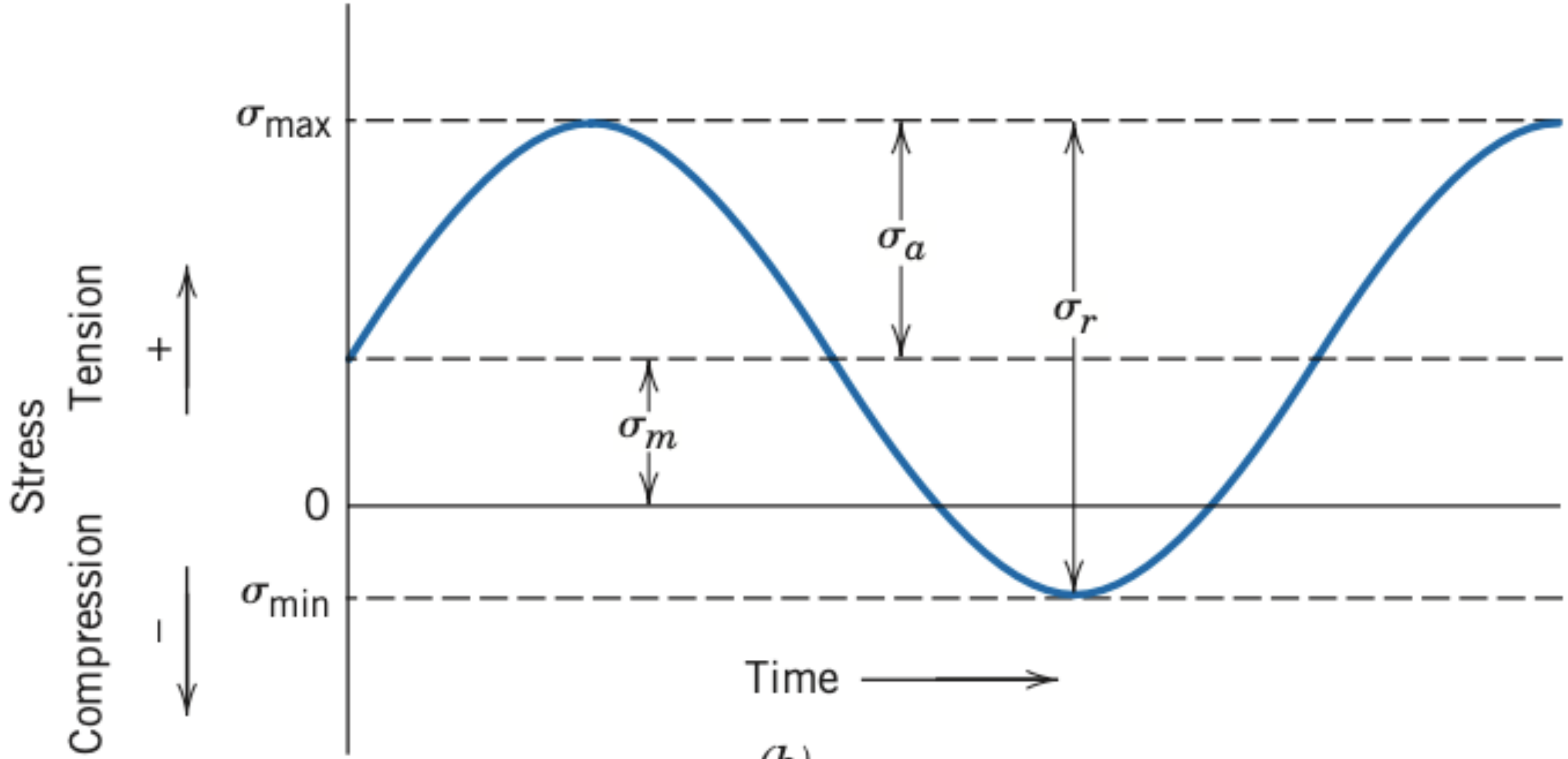
In general, three different varying stress-time modes are possible:



Random stress cycle

Stress level varies in amplitude and frequency

Parameters to characterize a stress cycle



(b)

σ_m = mean stress
σ_r = range of stress
σ_a = stress amplitude

Mean stress

$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2}$$

Range of stress

$$\sigma_r = \sigma_{max} - \sigma_{min}$$

Stress amplitude

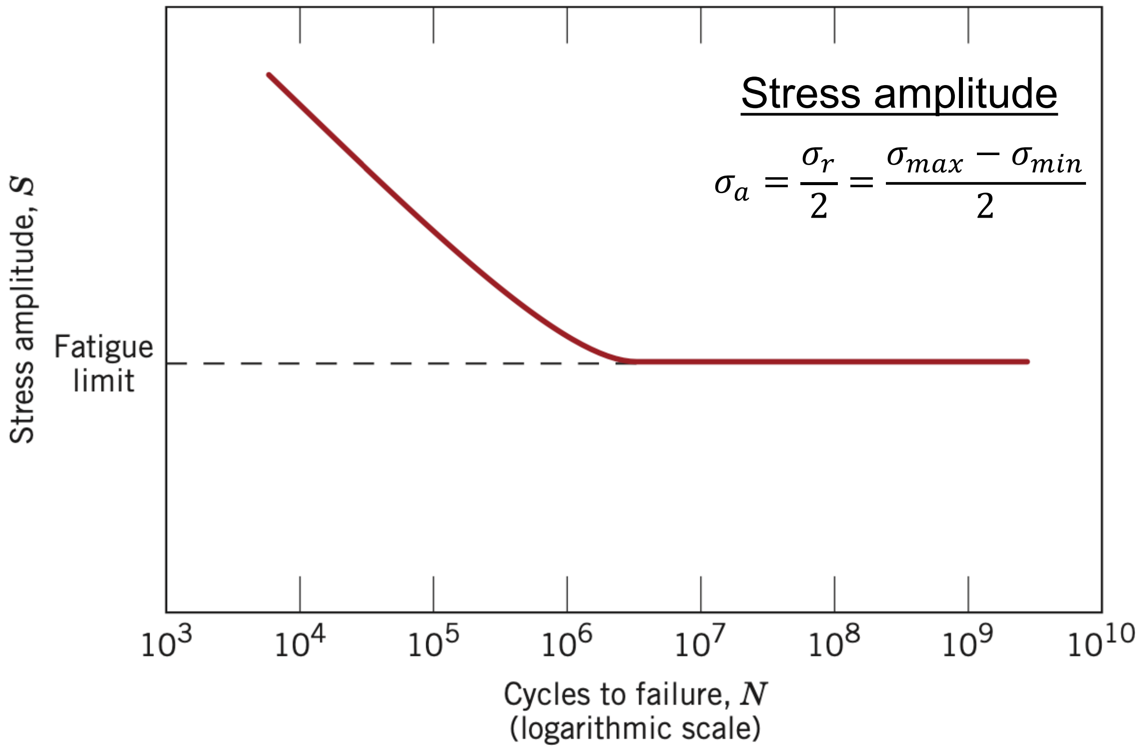
$$\sigma_a = \frac{\sigma_r}{2} = \frac{\sigma_{max} - \sigma_{min}}{2}$$

Stress ratio

$$R = \frac{\sigma_{min}}{\sigma_{max}}$$

S-N Curve (Applied Stress vs. Number of cycles to failure)

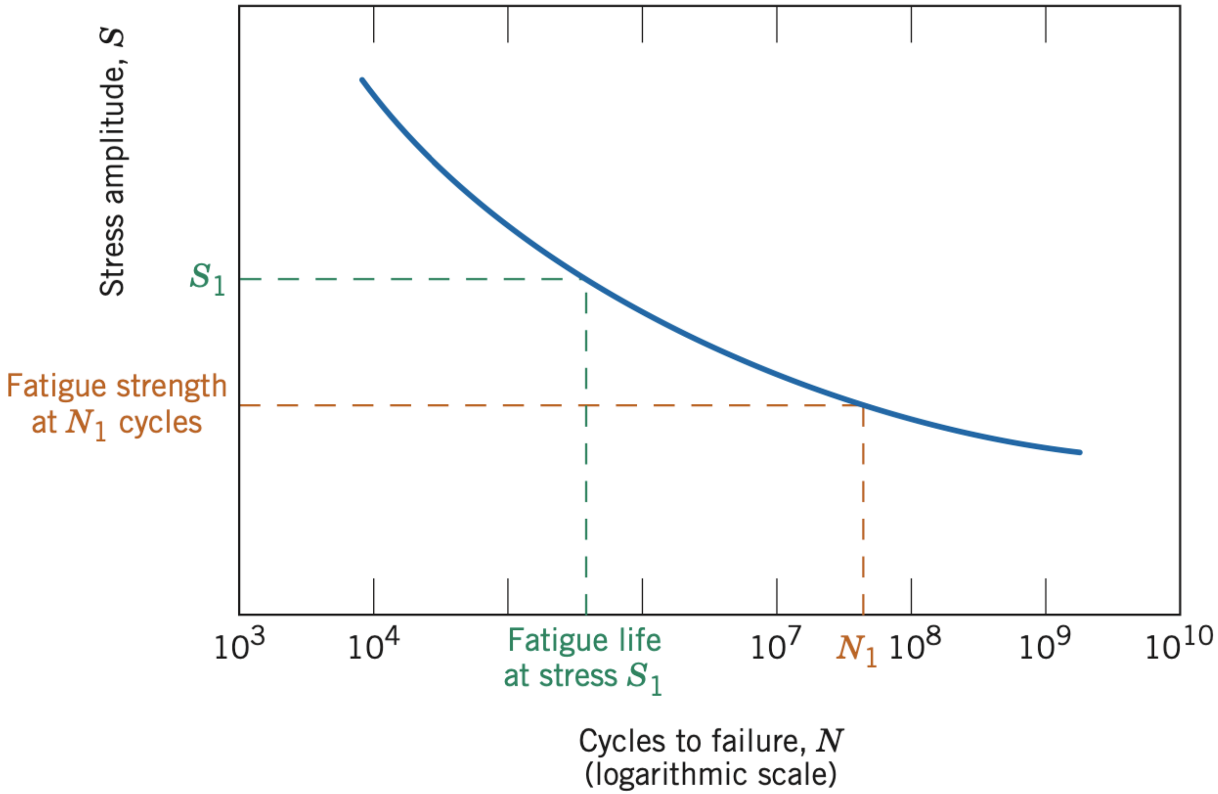
Possesses a fatigue limit



No fatigue fracture below the fatigue limit

(Seen in some ferrous and titanium alloys)

Does not possess a fatigue limit



Fatigue fracture will occur eventually

Fatigue strength is defined with respect to a specified number to failure

(Often seen in non-ferrous alloys)

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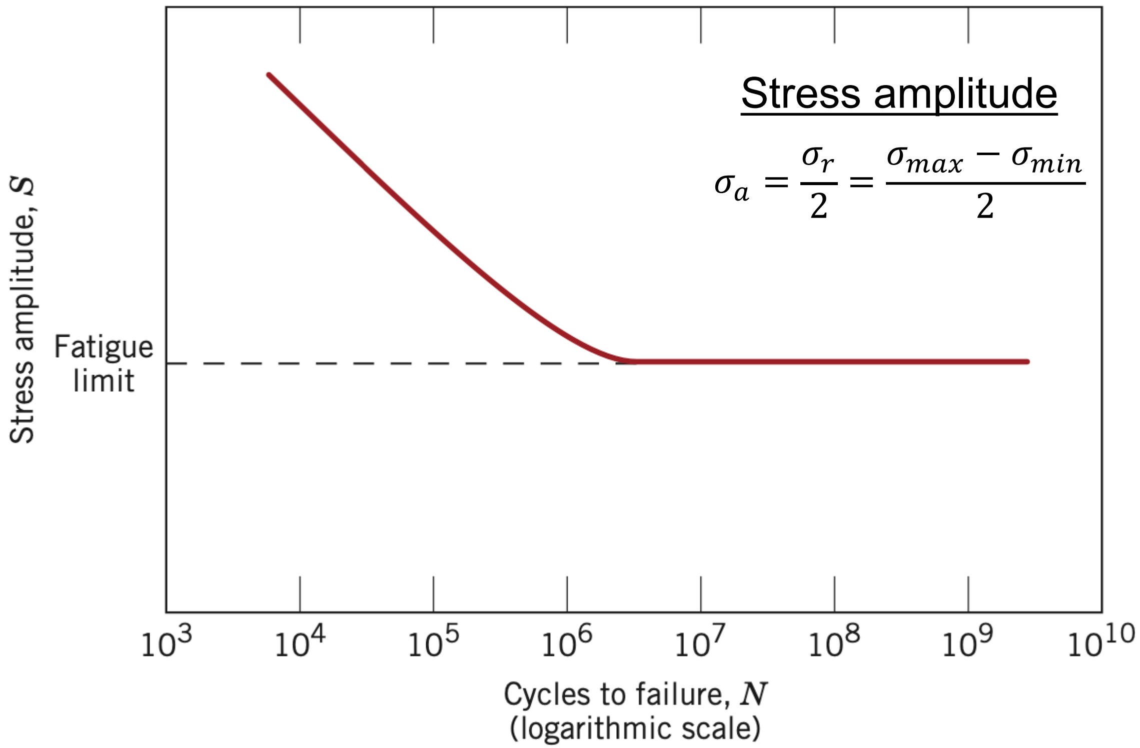
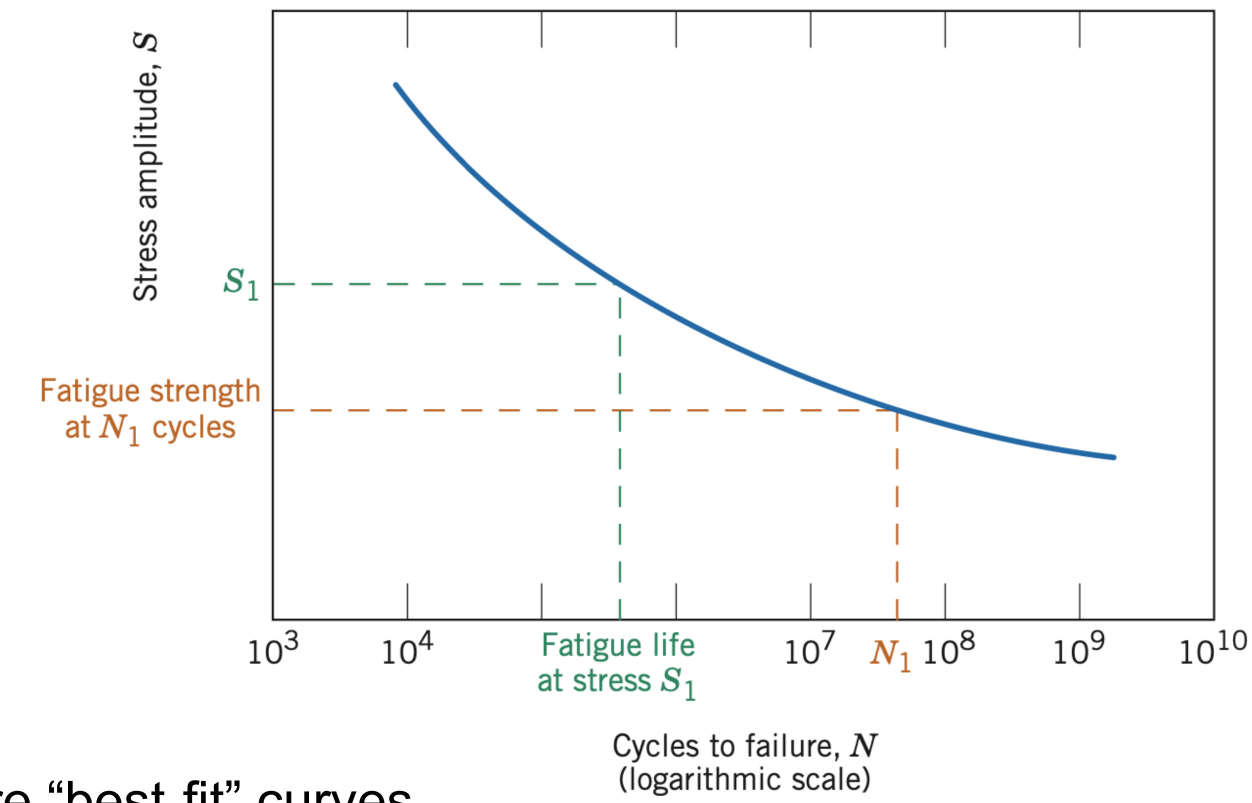
S-N Curve (Applied Stress vs. Number of cycles to failure)

Possesses a fatigue limit



Does not possess a fatigue limit



These curves are "best-fit" curves

Represents the average stress amplitude values to fatigue fracture

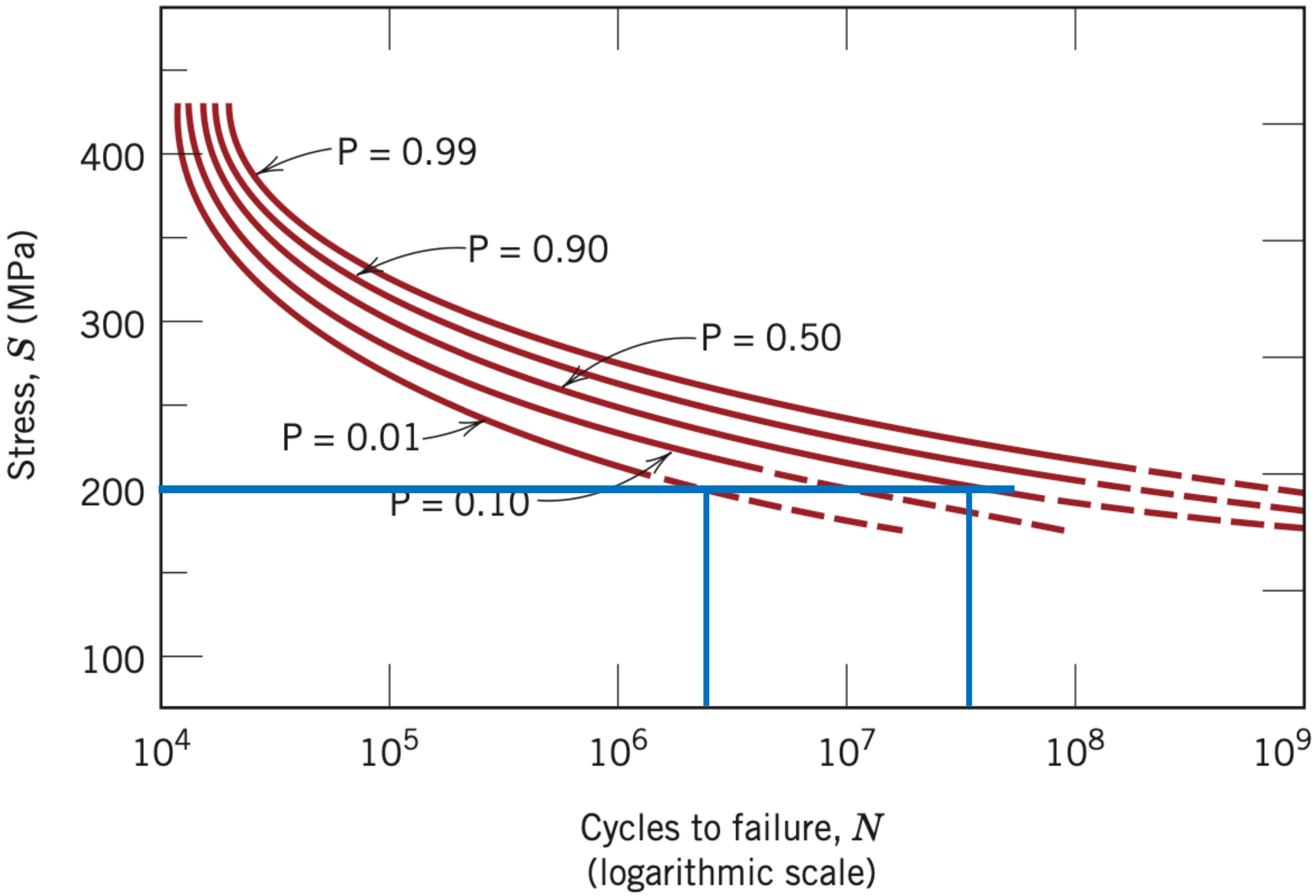
High stresses → Elastic and plastic strain → Low cycle fatigue (<10^5 cycles)

Low stresses → Only elastic strain → High cycle fatigue (>10^5 cycles)

Constant probability S-N curves

Fatigue is sensitive to many variables that are hard to control precisely → Significant scatter in fatigue data

Constant probability S-N curves



How to read a constant probability S-N curve

P values represent the probability of failure

For a certain stress level, draw a horizontal line and observe where it intersects the probability curves

At 200 MPa, we can see that ~ 1% of samples will fail at ~ 4 x 10^6 cycles

At 200 MPa, we can see that ~ 50% of samples will fail at ~ 6 x 10^7 cycles

Miner's Rule

$$\sum_{i=1}^{k} \frac{n_i}{N_i} = C$$

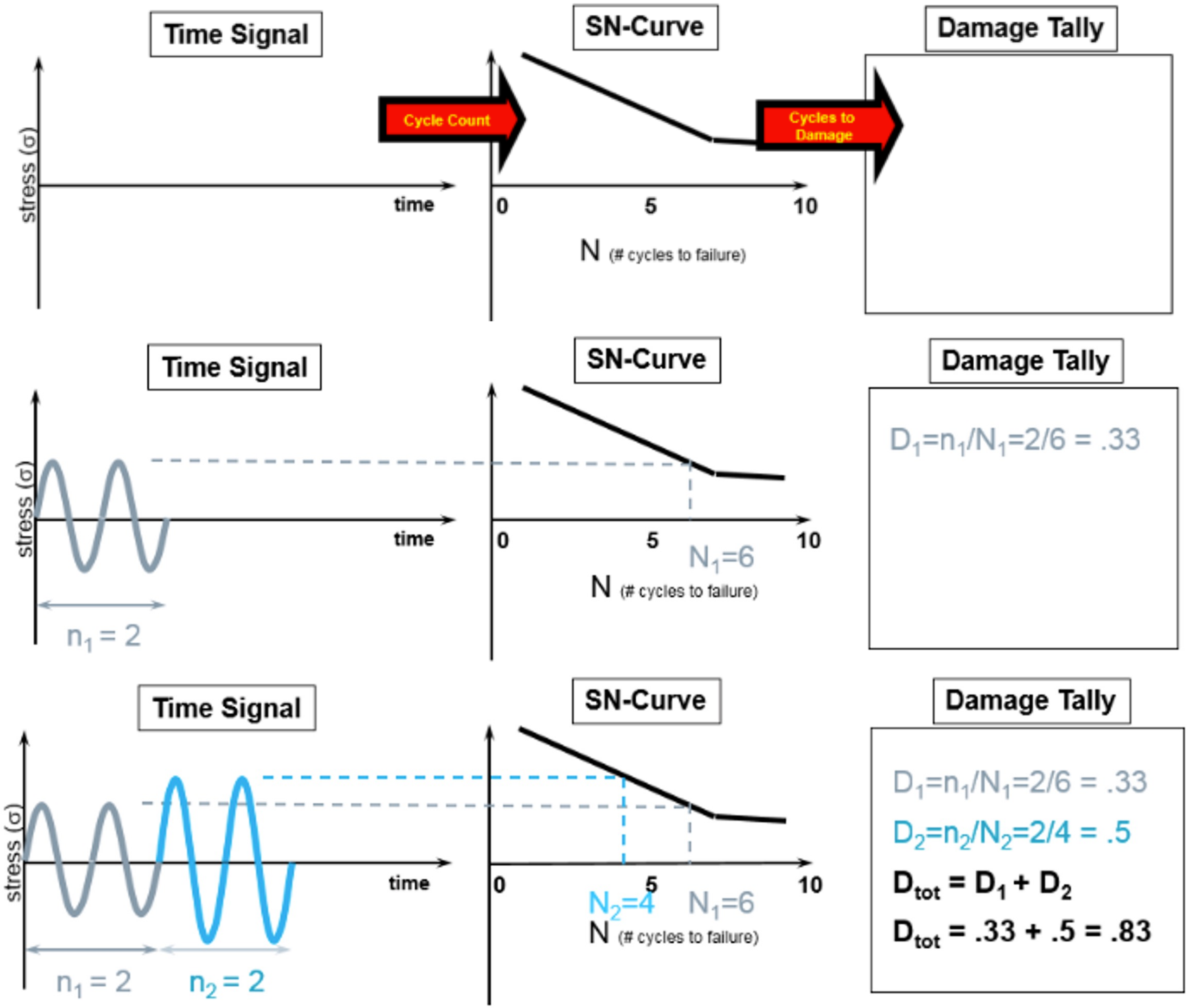
n_i is the number of cycles accumulated at stress S_i

N_i is the average number of cycles to failure at stress S_i

C is the fraction of life consumed
Sometimes denoted as D

Can think of Miner's rule as determining the fraction of life consumed at each stress level and then summing them to predict how much "life" is left

Miner's rule: Simple predictions of fatigue failure



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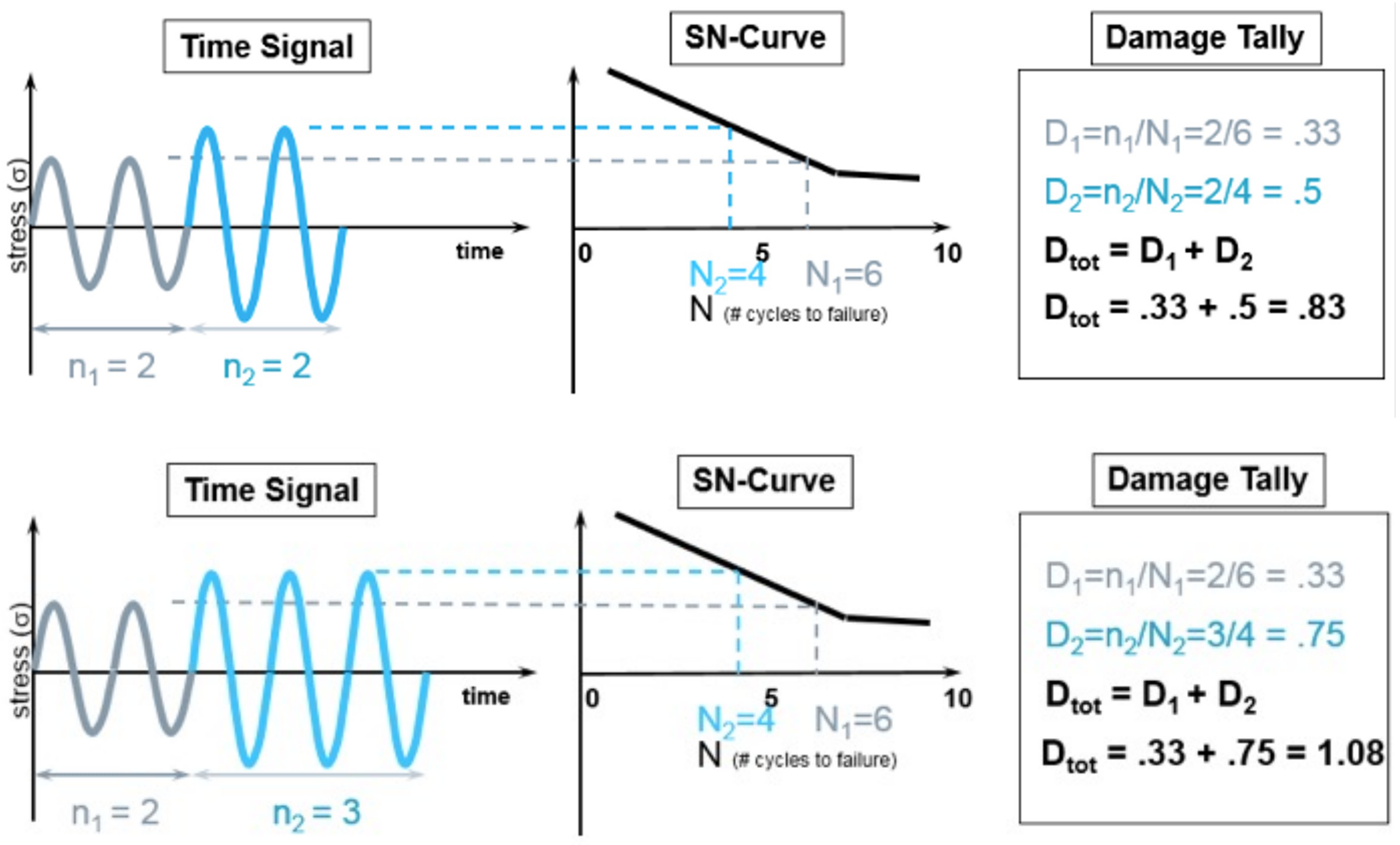

Since $D_{tot} > 1$, Miner's rule predicts that the application of one more stress cycle will result in failure

Miner's Rule

$$\sum_{i=1}^{k} \frac{n_i}{N_i} = C$$

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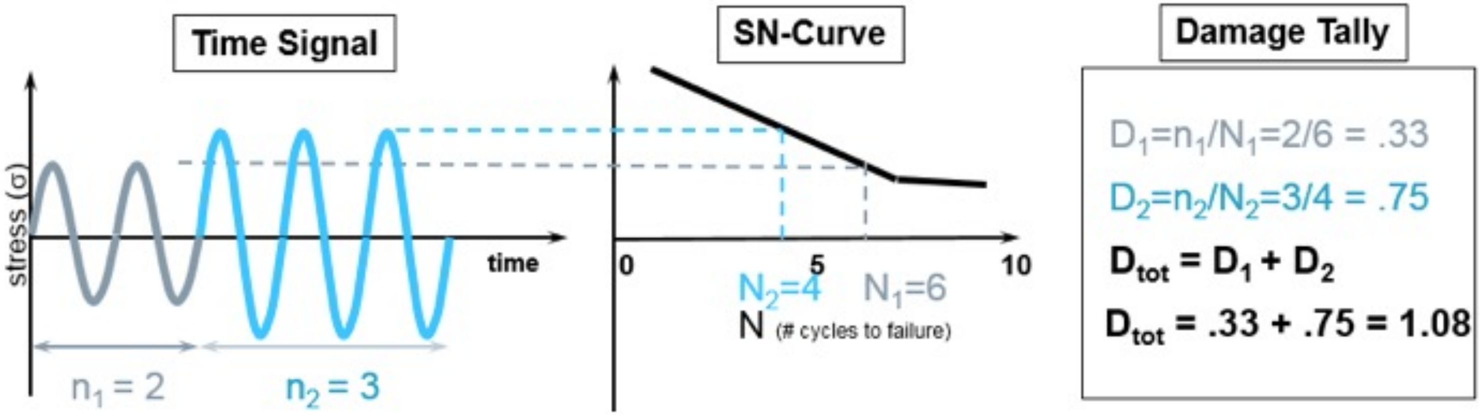
Limitations of Miner's Rule



Independent damage: Damage from each stress cycle is independent of the previous stress cycles

No effect of load sequence: The order of applied stress does not matter. High stress → Low stress = Low stress → High stres

Linear accumulation of damage: Damage from each stress level is additive. Ignores possibility of higher-order effects

Does not include probability: Only uses average values, ignores probabilistic component of fatigue fracture

Fatigue crack initiation and propagation

Fatigue failure is characterized by:

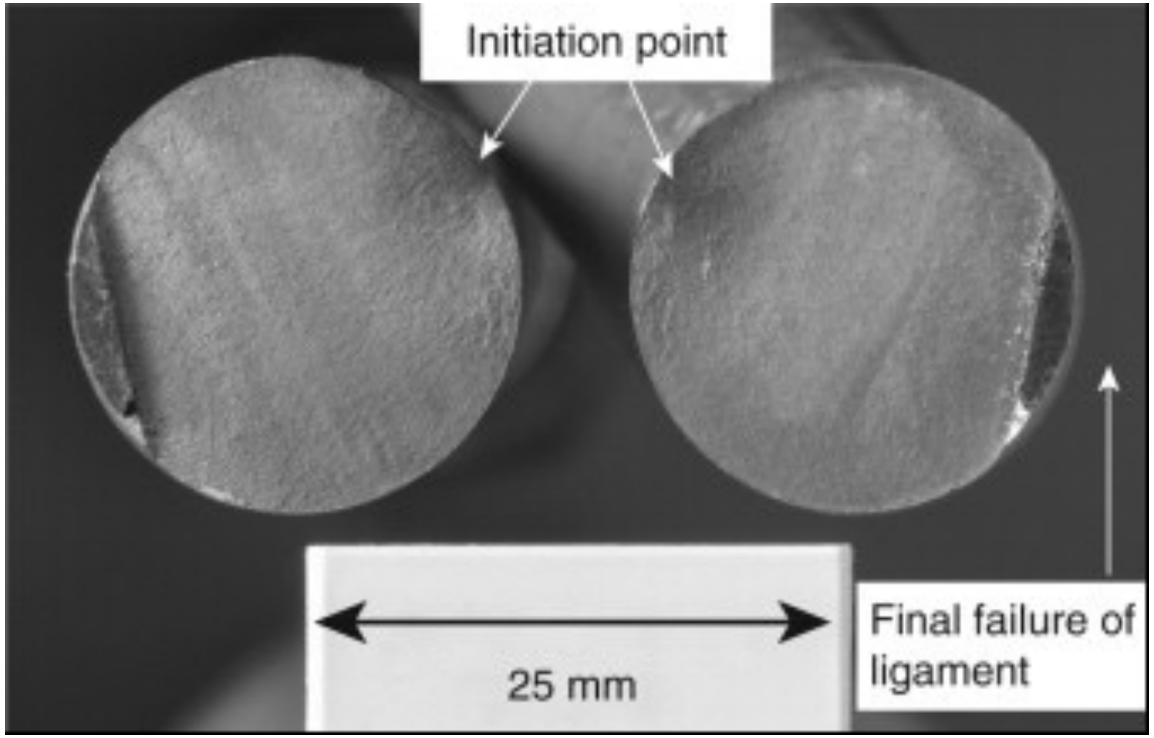
1. **Crack initiation** where a small crack forms at some point of high stress concentration

2. **Crack propagation** where the crack advances incrementally with each stress cycle

3. **Failure** once the crack reaches a critical size

Initiation almost always starts from the surface → Could be from a scratch, threads, dents, etc.

Could even be from dislocation slip!



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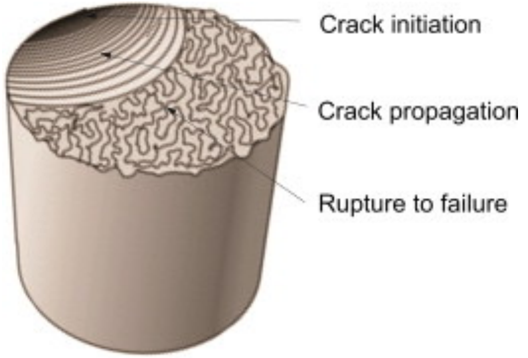
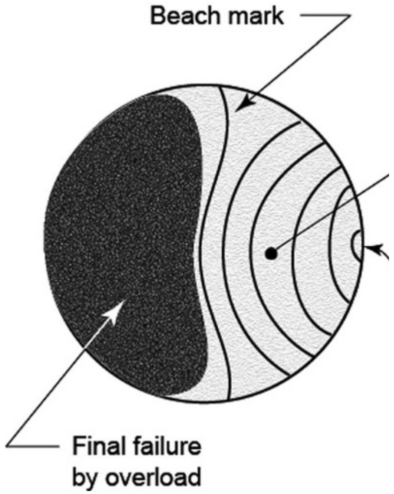
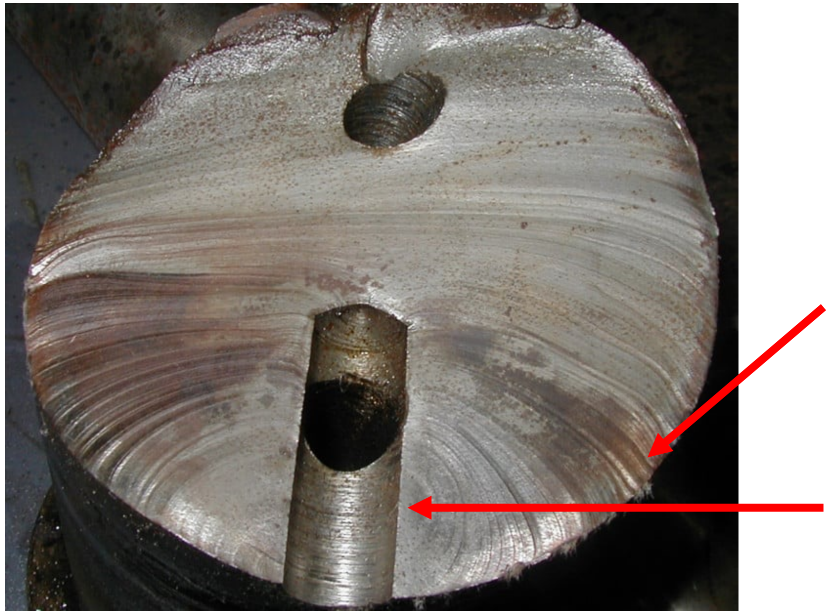


Fatigue crack propagation has distinct features



Beachmarks are macroscopic features and can be seen by eye

Each beachmark band represents a period of time where crack growth occured



Beachmark bands

Crack initiation (concentric rings coming out of it)

Fatigue crack initiation and propagation

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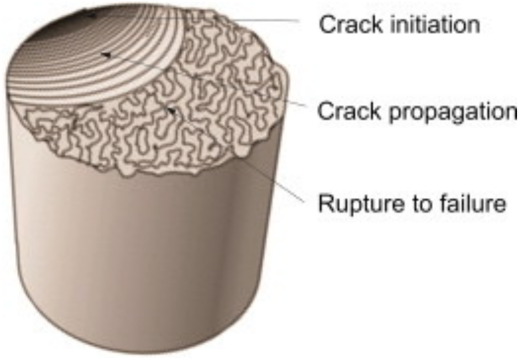
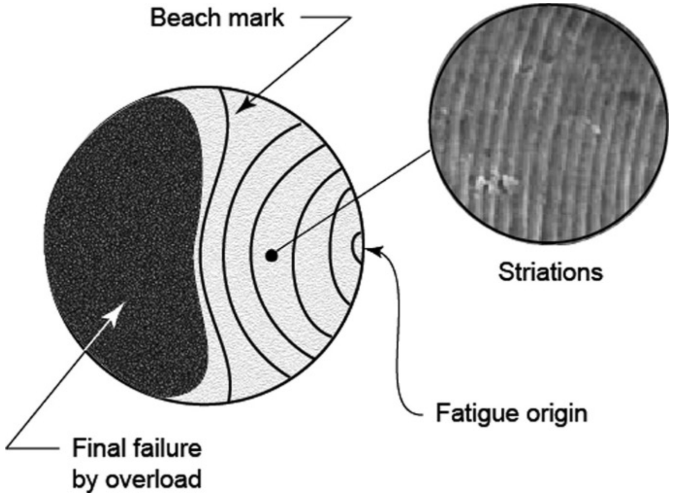
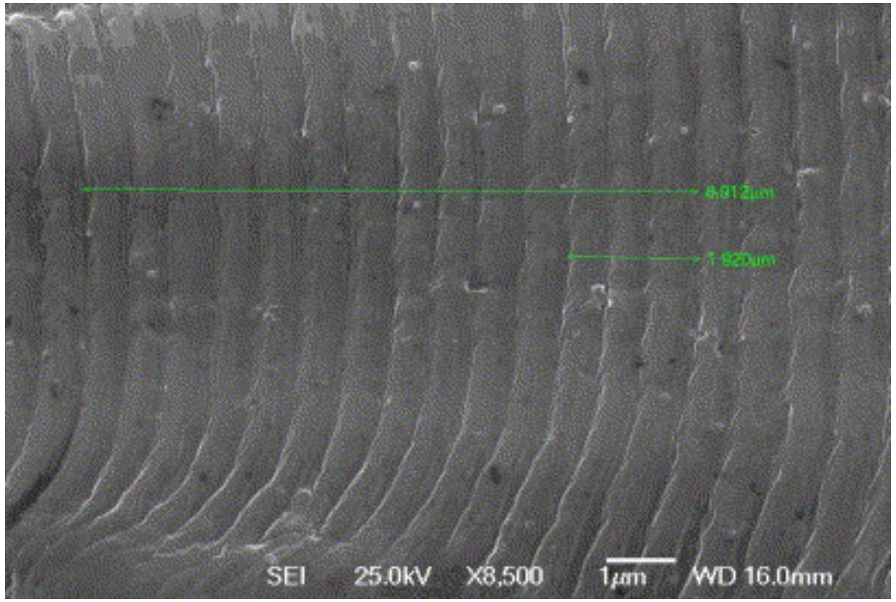


Fatigue crack propagation has distinct features



Within beachmarks are **striations**

These are microscopic and have to be seen with an electron microscope



Can think of each striation as the amount of crack growth per stress cycle

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Fatigue crack initiation and propagation

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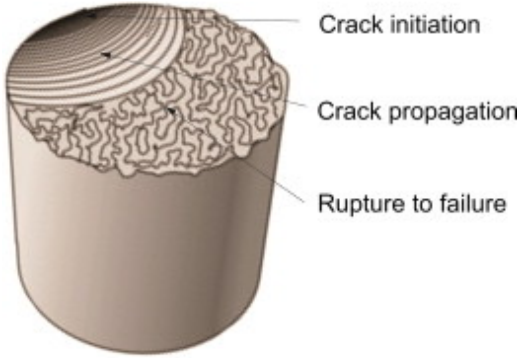
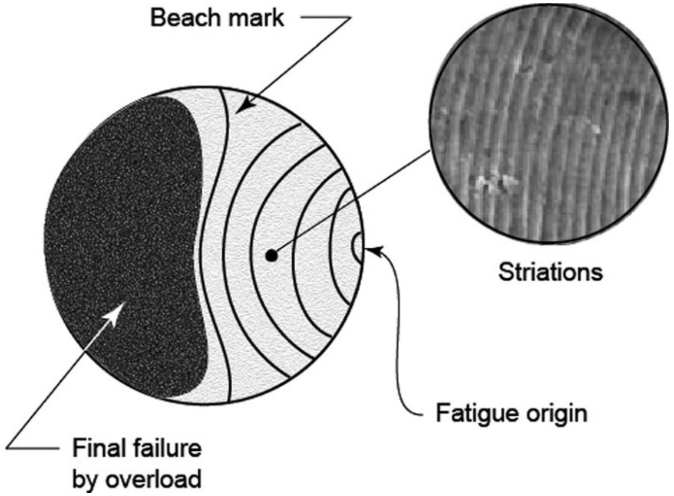


Fatigue crack propagation has distinct features



Beachmarks: Macroscopic

Striations: Microscopic

If beachmarks/striations are observed on fracture surface
→ Fatigue played a role in fracture

If beachmarks/striations are NOT observed on fracture surface → Fatigue could have played a role in fracture also

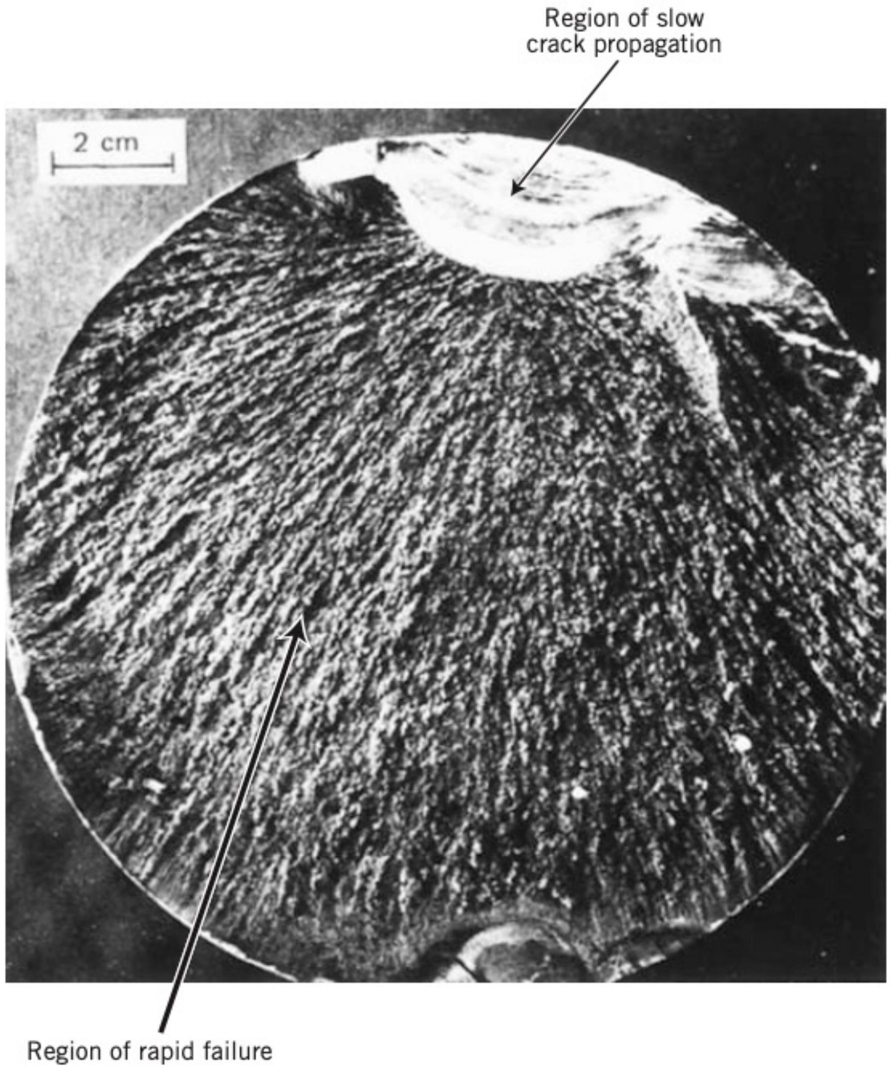
Fatigue crack initiation and propagation

Fatigue failure is characterized by:

1. **Crack initiation** where a small crack forms at some point of high stress concentration

2. **Crack propagation** where the crack advances incrementally with each stress cycle

3. **Failure** once the crack reaches a critical size



The rapid failure region can be ductile or brittle.

Plastic deformation will be observed if it was a ductile fracture

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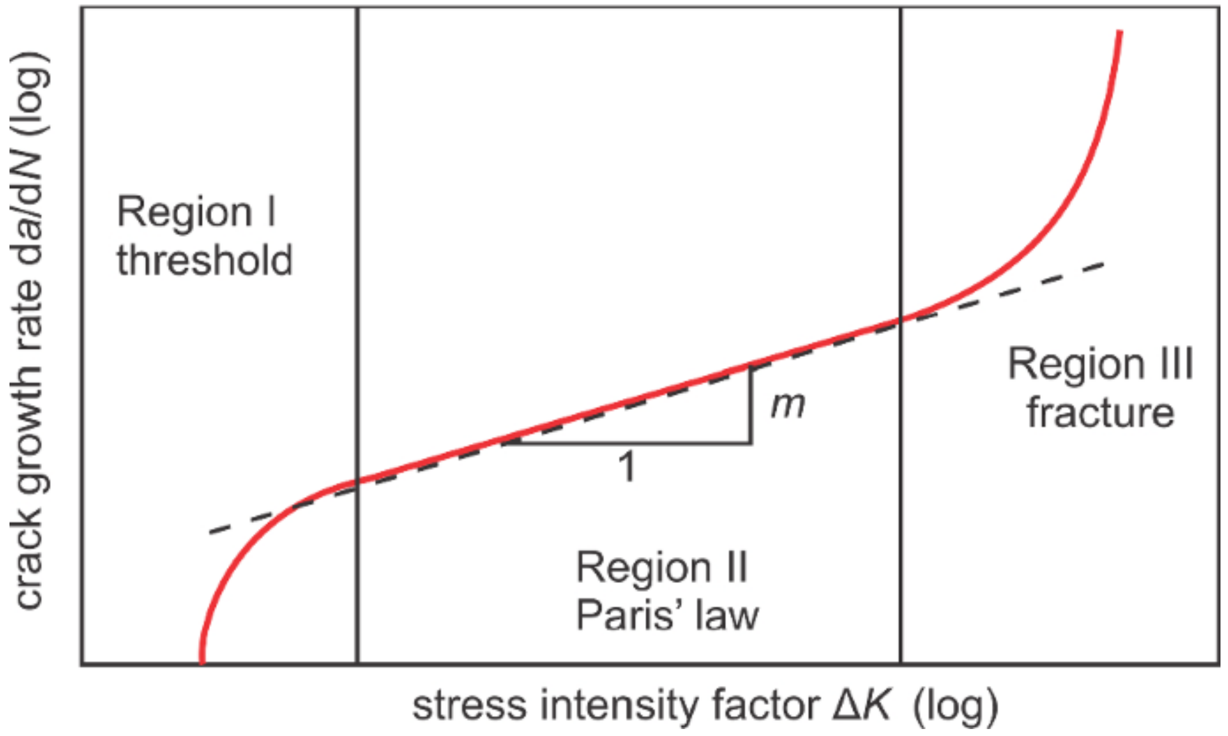
Paris' Law (Crack growth equation)

Crack growth equations are used to calculate the size of a fatigue crack growing from cyclic loads



Typical plot of crack growth vs stress intensity range

$\Delta K = K_{max} - K_{min}$ Maximum and minimum stress intensity factors in a stress cycle

Paris' Law

$$\frac{da}{dN} = C(\Delta K)^m$$

C and *m* are determined experimentally

Paris' law only holds for mid-range of crack growth.

Can be used to estimate cycles to failure

Paris' Law in action

A large plate contains a crack of length 2_{a0} = 10 mm in the center

The plate is subjected to a constant amplitude cyclic tensile stress ranging from 100 MPa to 200 MPa.

Assume the fatigue crack growth rate is given by Paris' Law with:

$$\frac{da}{dN} = 0.42 \times 10^{-11} (\Delta K)^3$$

1) What is the crack growth rate?

2a = 10 mm

$$\Delta K = K_{max} - K_{min}$$

$$K = Y\sigma\sqrt{\pi a}$$

$$\Delta K = Y\Delta\sigma\sqrt{\pi a}$$

$$\Delta K = 1(100)\sqrt{\pi\, 0.005}$$

$$\Delta K = 12.53\ MPa\sqrt{m}$$

$$\frac{da}{dN} = 0.42 \times 10^{-11} (12.53)^3 = 8.26 \times 10^{-9} \text{ m/cycle}$$

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Assume the fatigue crack growth rate is given by Paris' Law with:

$$\frac{da}{dN} = 0.42 \times 10^{-11} (\Delta K)^3$$

2) Assuming that the fracture toughness of this material is 60 MPa$\sqrt{m}$, estimate the number of cycles to failure

2a = 10 mm

$$K_{IC} = 60\ MPa\sqrt{m}$$

Let us first determine the critical crack size under these conditions

$$K_{IC} = Y\sigma_{max}\sqrt{\pi a_c}$$

$$a_c = 28.7\times10^{-3}\text{m}$$

At these conditions, complete and rapid fracture occurs at a crack length of 28.7 x 10^{-3} m.

Paris' Law in action

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The plate is subjected to a constant amplitude cyclic tensile stress ranging from 100 MPa to 200 MPa.

Assume the fatigue crack growth rate is given by Paris' Law with:

$$\frac{da}{dN} = 0.42 \times 10^{-11} (\Delta K)^3$$

Knowing a_c, how do we find the cycles to failure?

$$a_c = 28.7 \times 10^{-3} \mathrm{m}$$

$$\int_0^{N_f} dN = \int_{a_0}^{a_c} \frac{da}{0.42 \times 10^{-11} (\Delta K)^3}$$

$$N_f = \int_{5\times10^{-3}}^{28.7\times10^{-3}} \frac{da}{0.42 \times 10^{-11} (\Delta K)^3}$$

$$\Delta K = Y \Delta\sigma \sqrt{\pi a}$$

$$\Delta K = 1(100)\sqrt{(3.14)a}$$

$$\Delta K = 177.2\sqrt{a}$$

$$N_f = \int_{5\times10^{-3}}^{28.7\times10^{-3}} \frac{da}{2.34\times10^{-5}. a^{\frac{3}{2}}}$$

EPFL

Paris' Law in action

A large plate contains a crack of length 2_{a0} = 10 mm in the center

The plate is subjected to a constant amplitude cyclic tensile stress ranging from 100 MPa to 200 MPa.

Assume the fatigue crack growth rate is given by Paris' Law with:

$$\frac{da}{dN} = 0.42 \times 10^{-11} (\Delta K)^3$$

$$N_f = \int_{5\times10^{-3}}^{28.7\times10^{-3}} \frac{da}{2.34\times10^{-5}.\, a^{\frac{3}{2}}}$$

$$N_f = 42791 \int_{5\times10^{-3}}^{28.7\times10^{-3}} a^{-\frac{3}{2}}\ da$$

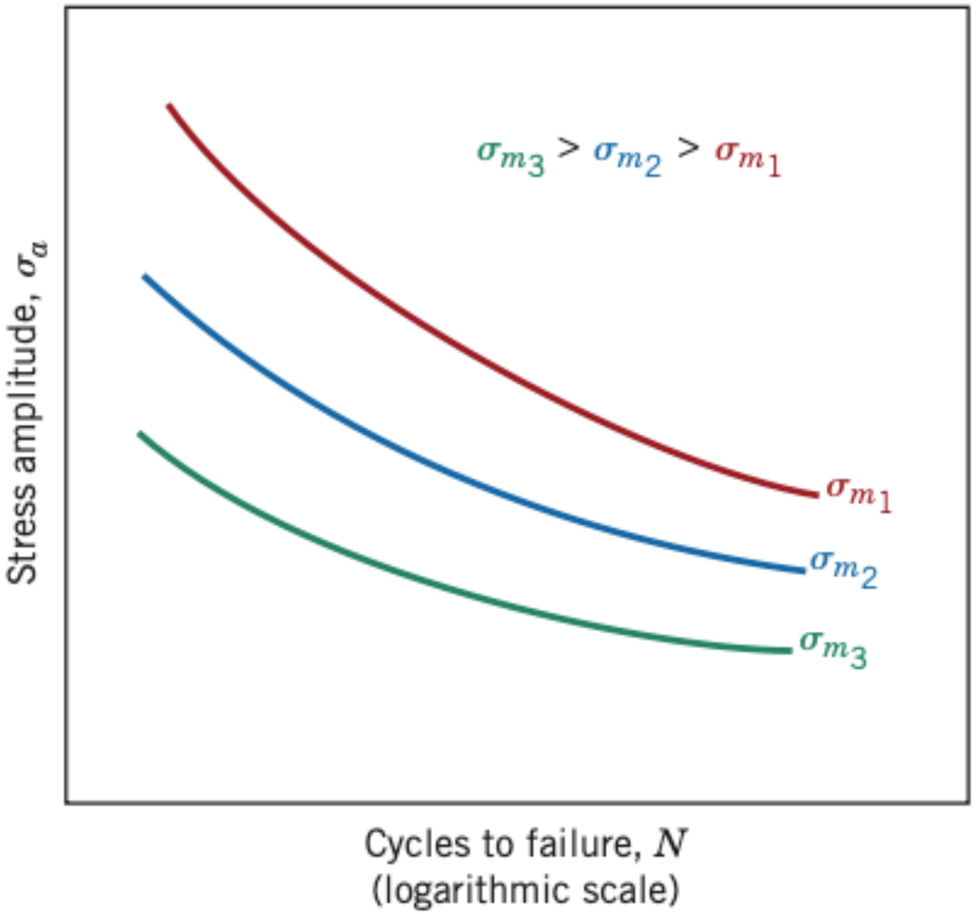
$$N_f = 42791 \left[(-2)a^{-\frac{1}{2}}\right]_{5\times10^{-3}}^{28.7\times10^{-3}}$$

$$N_f = 7.05 \times 10^5$$

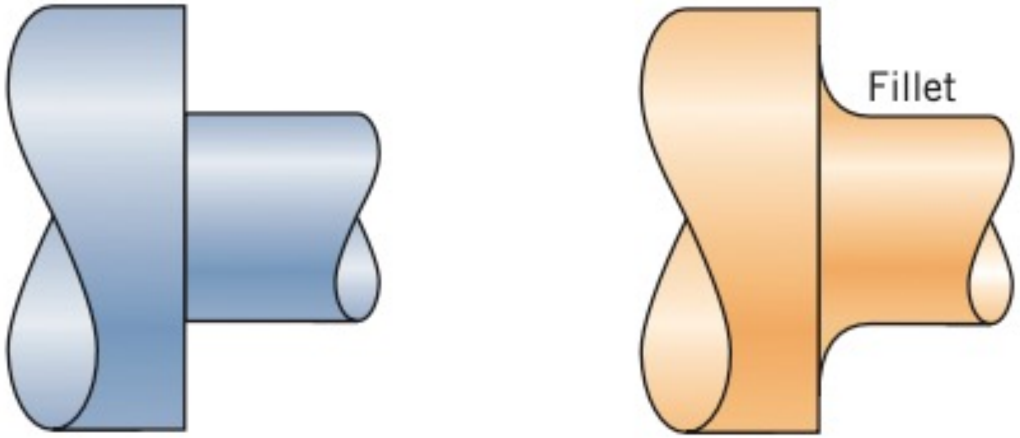
EPFL

What affects fatigue?

Mean stress level



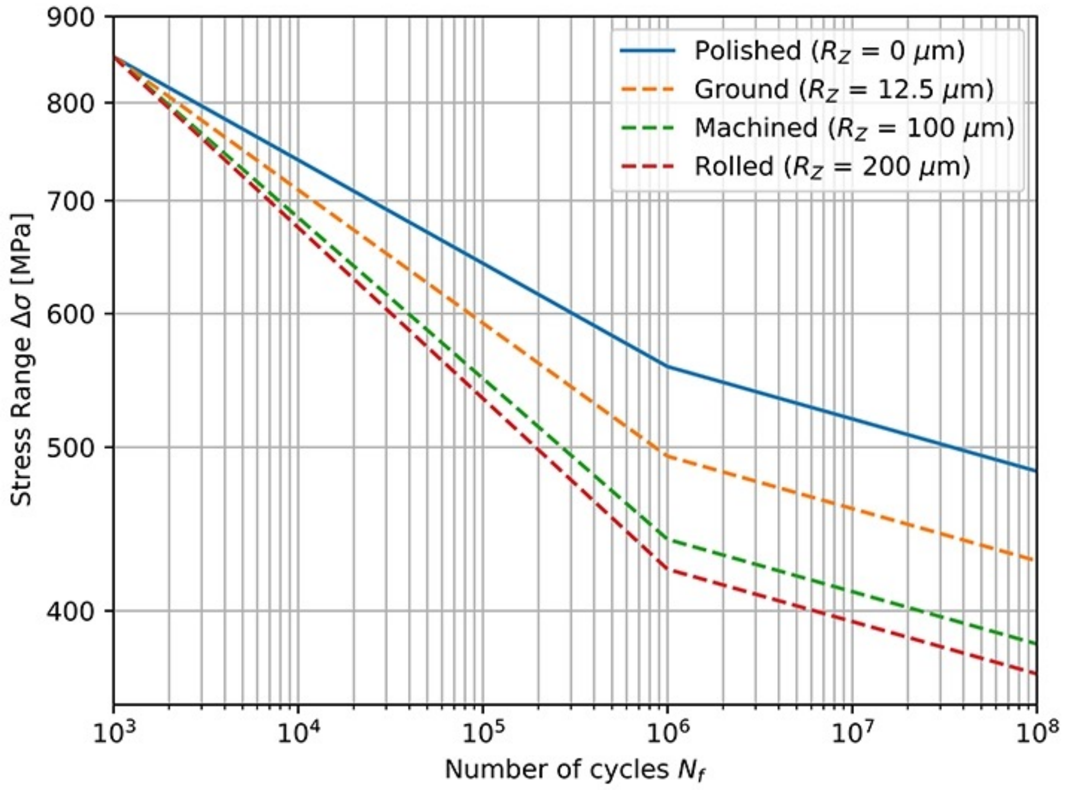
Design of part



Sharp corners can act as stress concentrators and initate a surface crack. This surface crack can initiate fatigue crack propagation

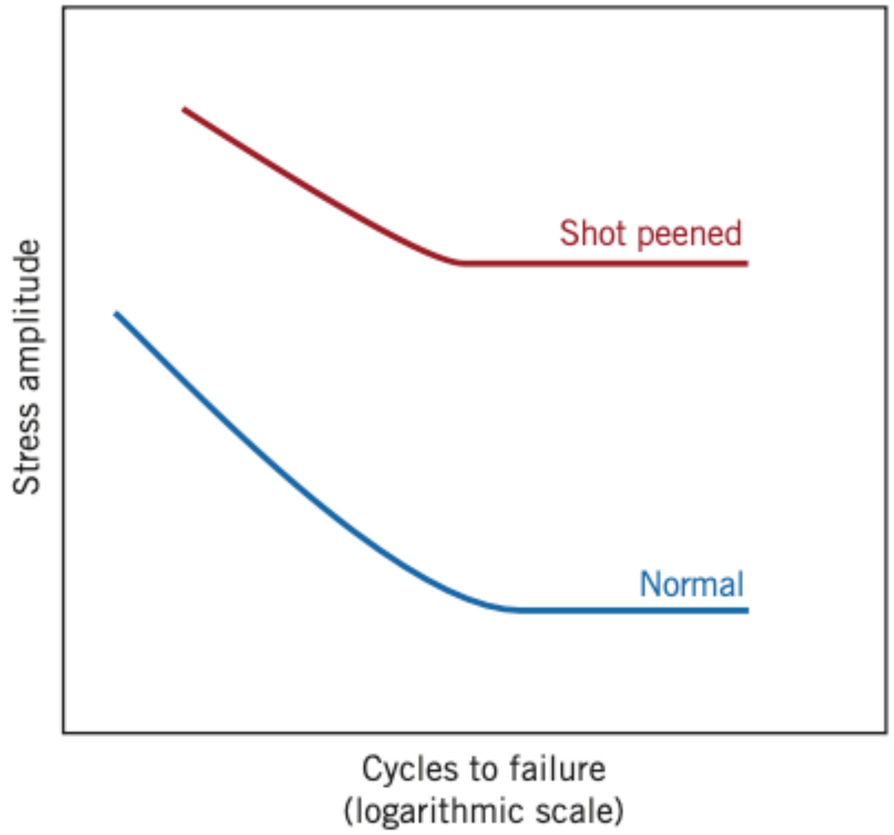
What affects fatigue?

Surface Treatment
(Polishing)



Polishing removes surface flaws that could initiate fatigue cracking

Surface Treatment
(Shot peening)



Cracks can only grow in tension

Shot peening induces a compressive stress onto the surface. Need to overcome this stress before crack can grow

EPFL

Week 10 Learning Objectives

- Understand what a CCT diagram is and how it differs from a TTT diagram
- Understand how to qualitatively use a CCT diagram to predict the microconstituents of a cooling alloy
- Understand the difference between brittle and ductile fracture
- Understand what the fracture toughness of a material is
- Use the fracture toughness of a material to predict of a material will fracture
- Understand what fatigue is
- Be able to use Miner's rule to predict fatigue failure
- Be able to use Paris' Law to predict fatigue failure
- Understand the factors that affect fatigue fracture