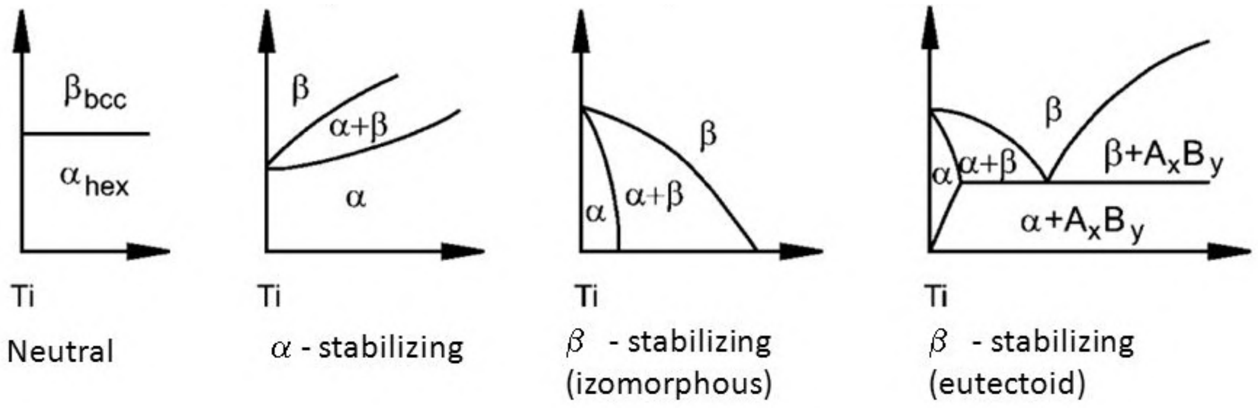
Course goal: Describe phase transformation in Ti and Zr alloys during heating and cooling at different rates and explain how this can change the properties of the material.

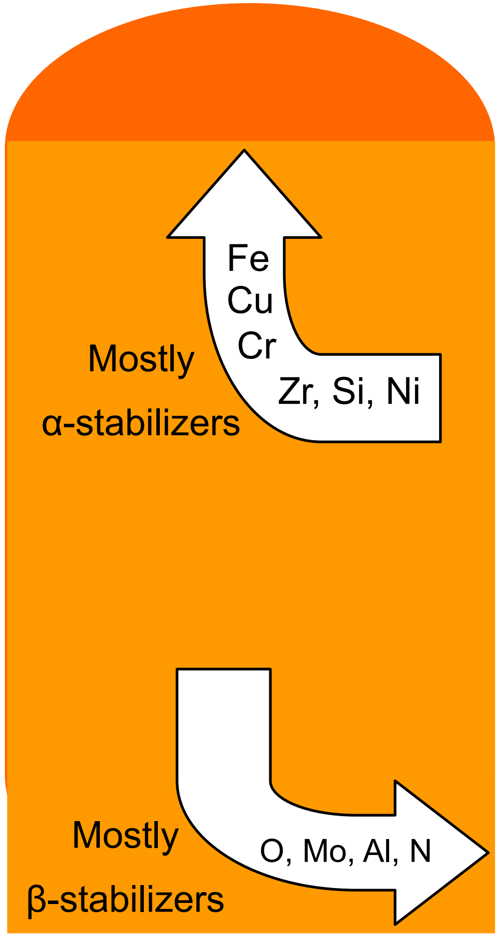
Learning outcomes:

- ***Describe the effect of different alloying additions on the phase structure of Ti (and Zr) alloys***



α-stabilising increase β-transus
β-stabilising decrease β-transus
Isomorphous – completely soluble in solid solution
Eutectoid – intermetallic particles are created

Melting – Element Segregation Trends



- Subsequent heat treatment / forging will not reduce any macro segregation → ***re-melting.***
- For 'difficult' alloys product chemistry and structure is more reliable than ingot analysis.
- For good melt practice oxygen 'pick up' is small (< 150 ppm).

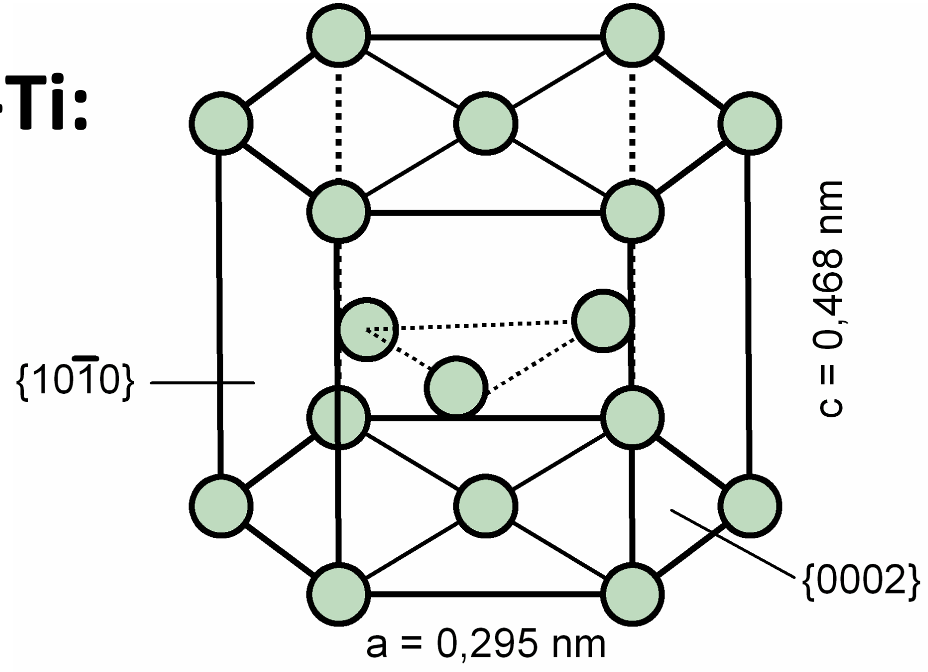
When used in aeroengines, melting defects can cause component failure – very rare today.

Allotropic transformation of pure Ti (and Zr)

T < 880ºC

hcp

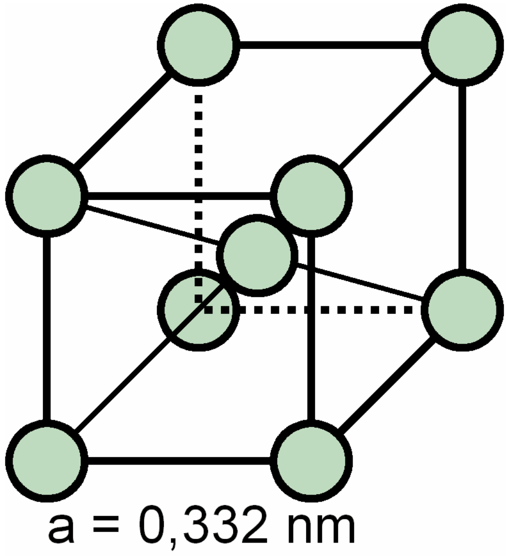
α-Ti:



T > 880ºC

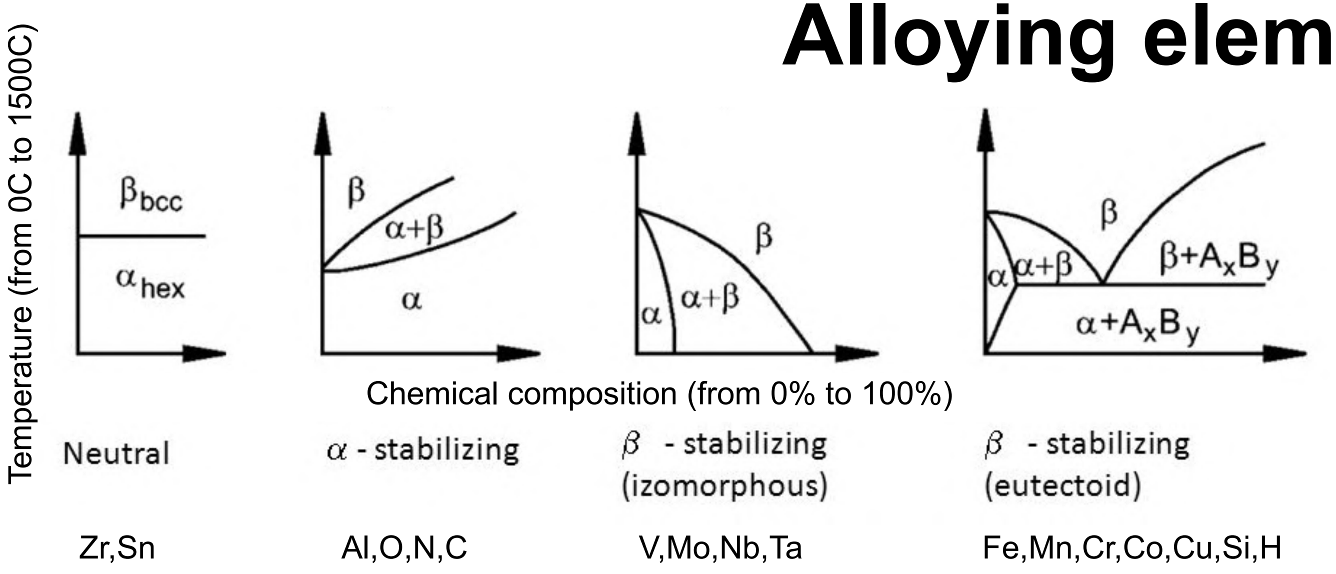
bcc

β-Ti:



Live lecture – Which crystal structure has higher density?

Alloying elements in Ti



α-stabilising increase β-transus
β-stabilising decrease β-transus
Isomorphous – completely soluble in solid solution
Eutectoid – intermetallic particles are created

α-stabiliser

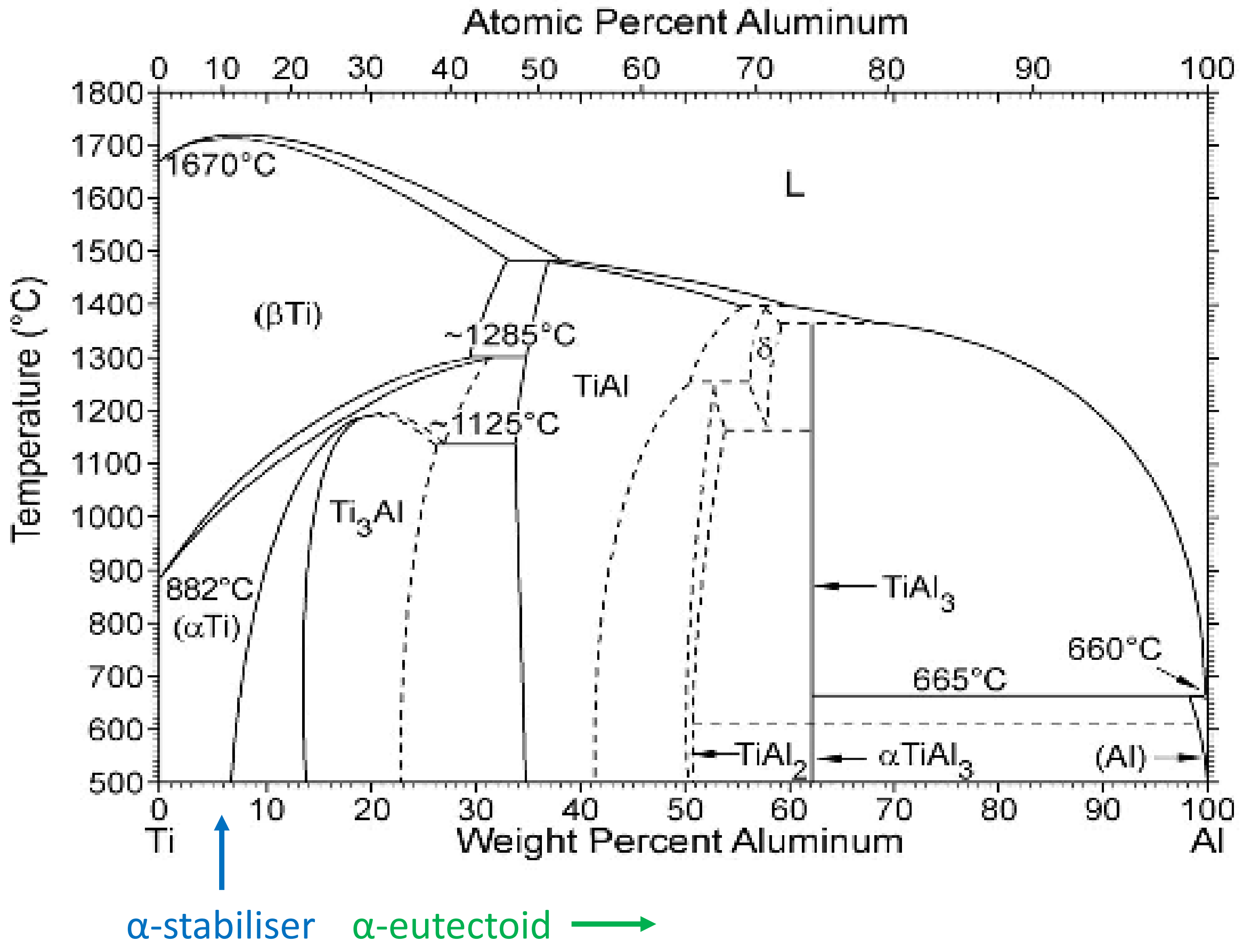
- Stabilise the α-phase at room temperature.
- Eg. Aluminium, Oxygen etc.

β-stabiliser

- Stabilise the β-phase at room temperature.
- Eg. Vanadium, Niobium, Molybdenum, etc.

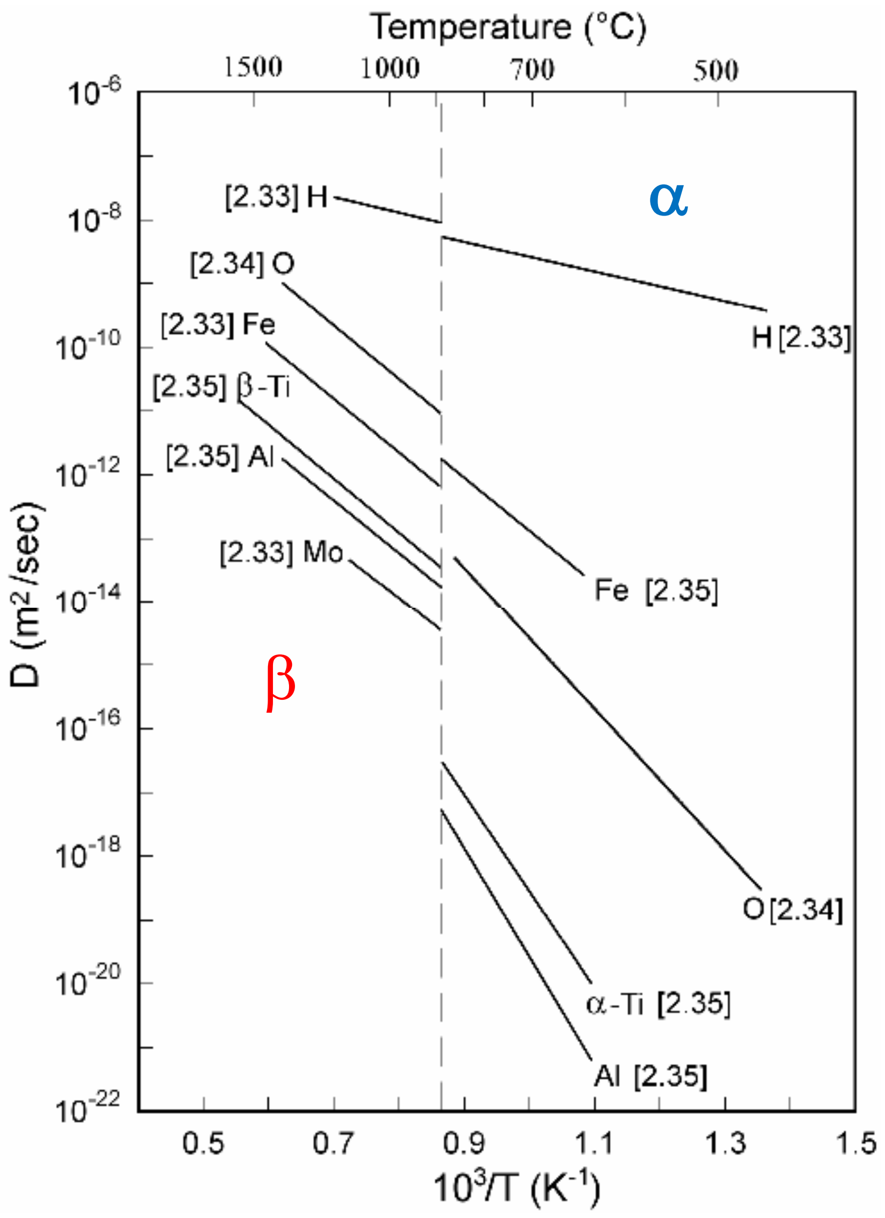
Ti-Al Phase Diagram

- ***Thermodynamics*** → calculation of system energy at equilibrium → phase diagram
- How fast changes happen? → ***Kinetics***
  - ***- Cooling rate***
  - ***- Element diffusion***



Diffusion in Ti / Zr

- Arrhenius diagram of titanium self-diffusion and various alloying elements
- Zirconium displays very similar behaviour *(although Nb is a much slower diffusing species in Zr).*

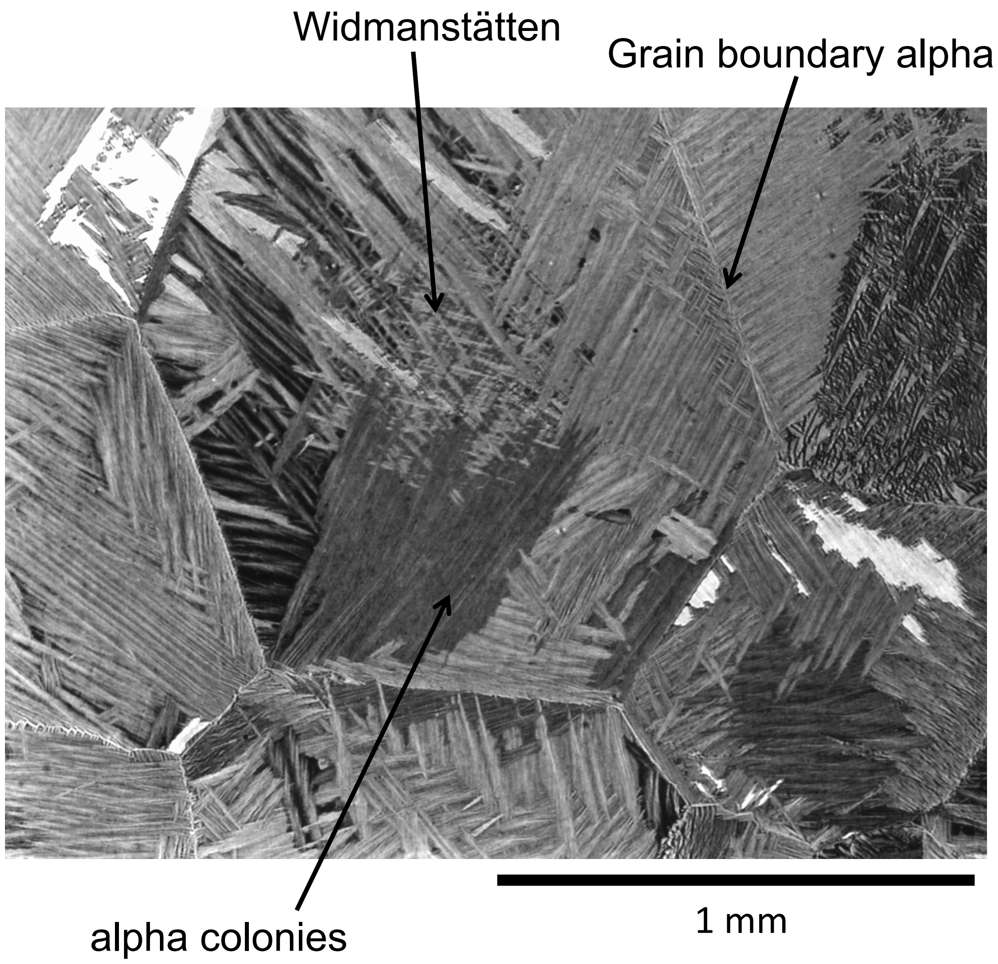


Slower diffusing species

Course goal: Describe phase transformation in Ti and Zr alloys during heating and cooling at different rates and explain how this can change the properties of the material.

Learning outcomes:

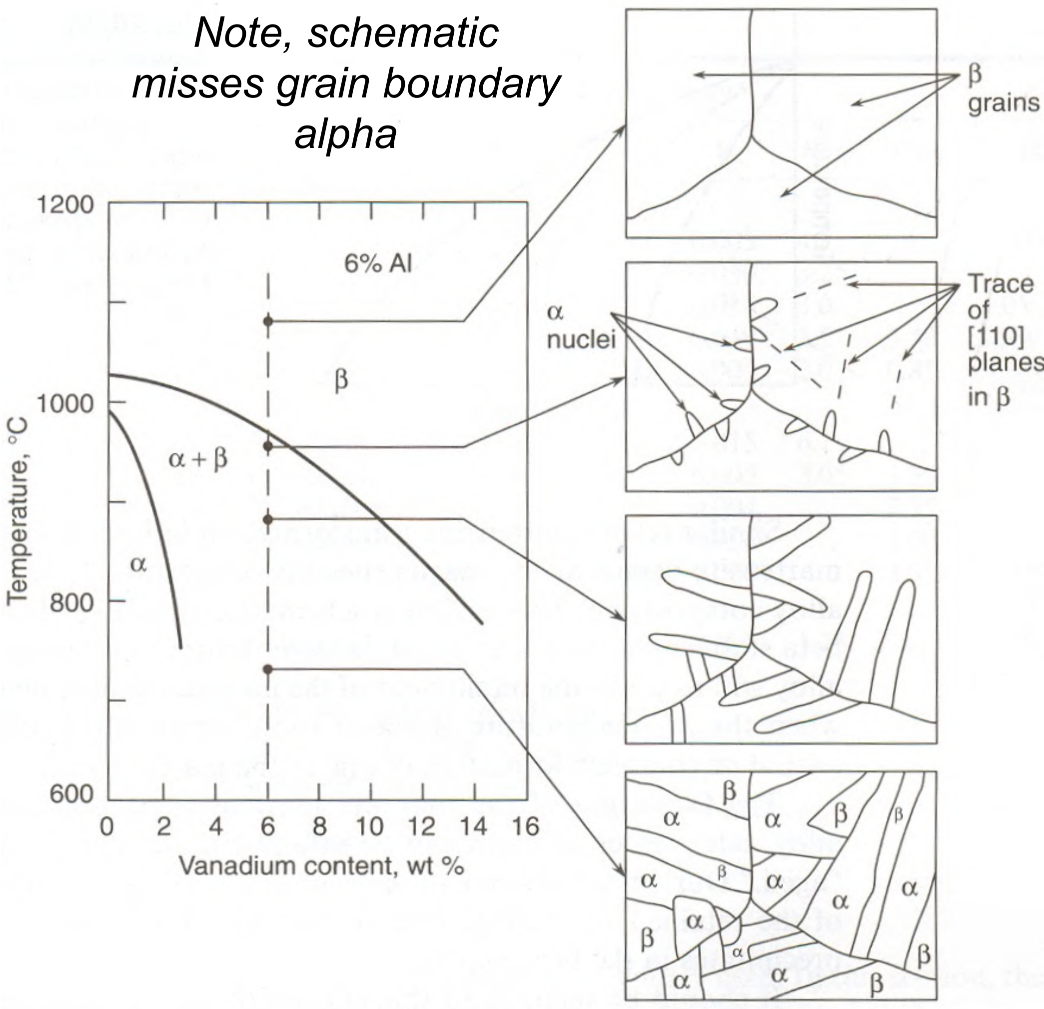
- Describe the effect of different alloying additions on the phase structure of Ti (and Zr) alloys.
- ***Describe phase transformation and microstructural changes during heating and cooling of Ti and Zr alloys at different rates.***



Identification of different microstructural features in a Ti alloy at room temperature.

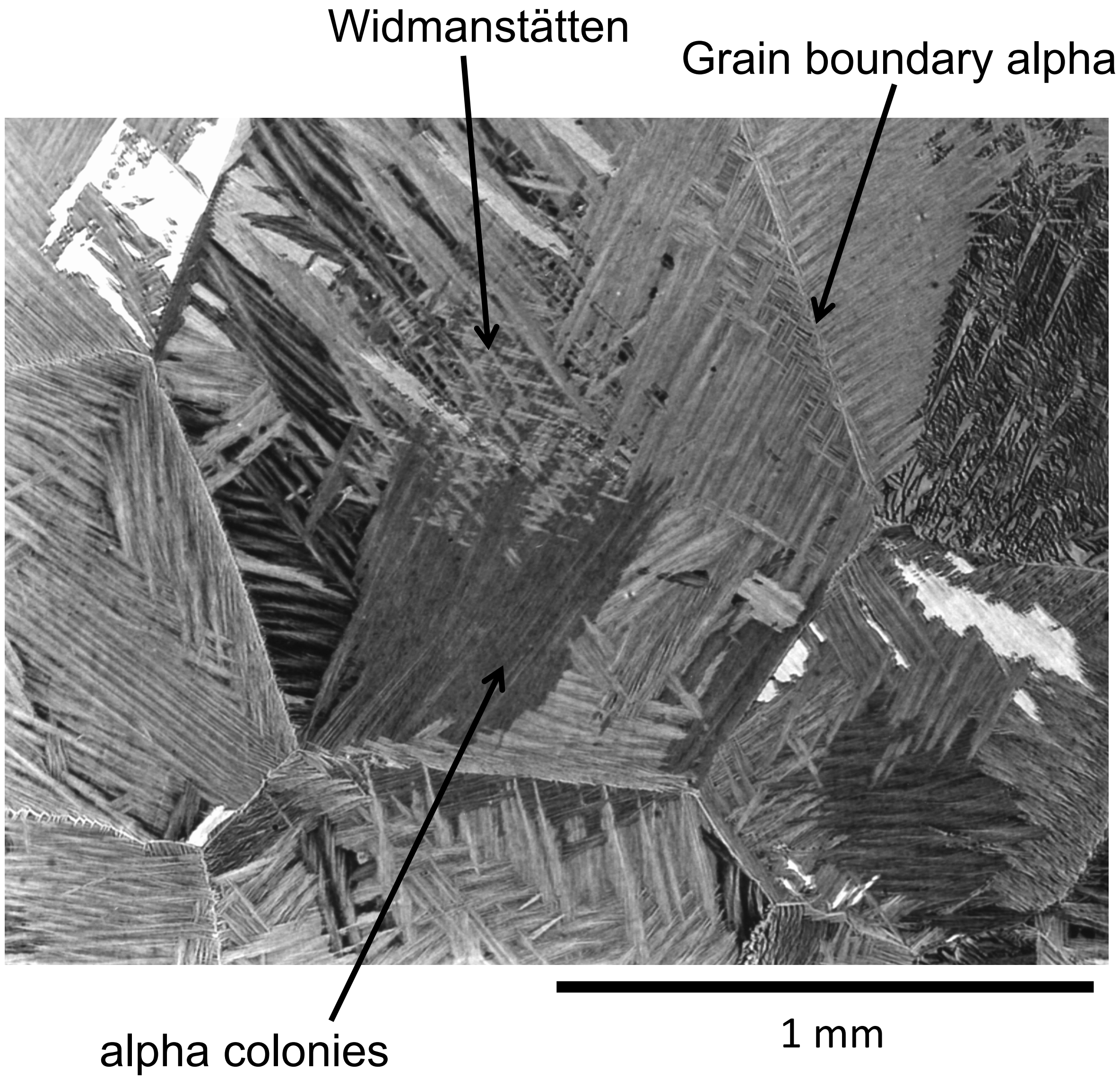
Phase Transformation during Cooling

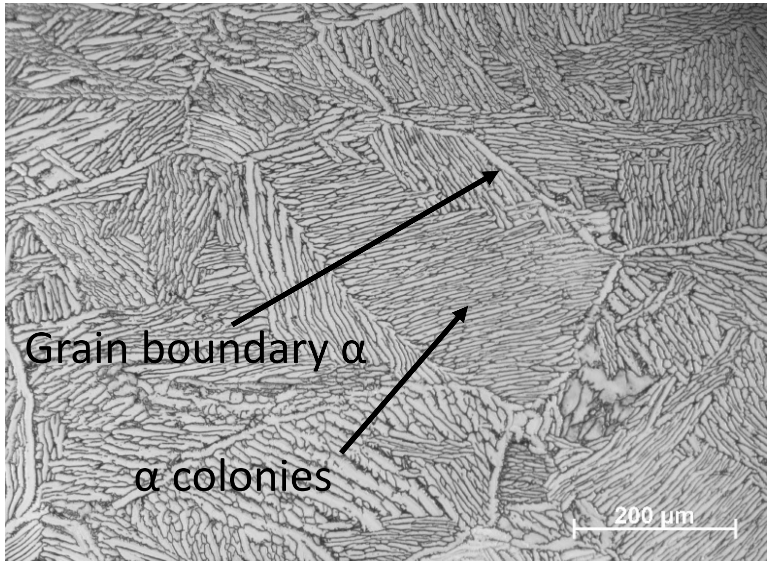
- When casting Ti or Zr alloys the high temperature β-phase forms first *(also important when welding and additive manufacturing)*
- These alloys are single β-phase at very high temperatures
  (≳ 900°C in Zr, ≳ 1000°C in Ti).
- α-Ti/Zr tends to form first on the β grain boundaries, before α-lamellae grow into the β-grains.
- α-lath structure forms by epitaxial growth (similar growth of Pearlite in Steel).
- In α + β alloys, β-ligaments remain in-between α-laths when cooled to room temperature.

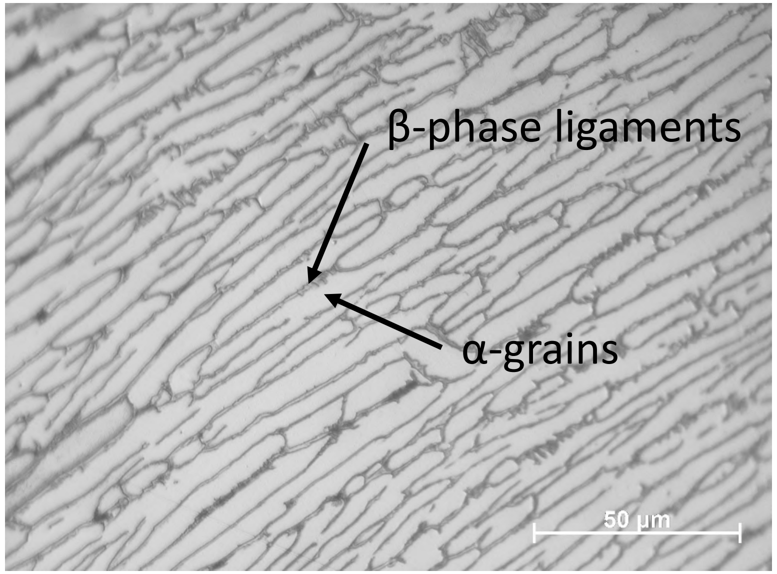


Phase Transformation during Cooling

Phase Transformation during Cooling

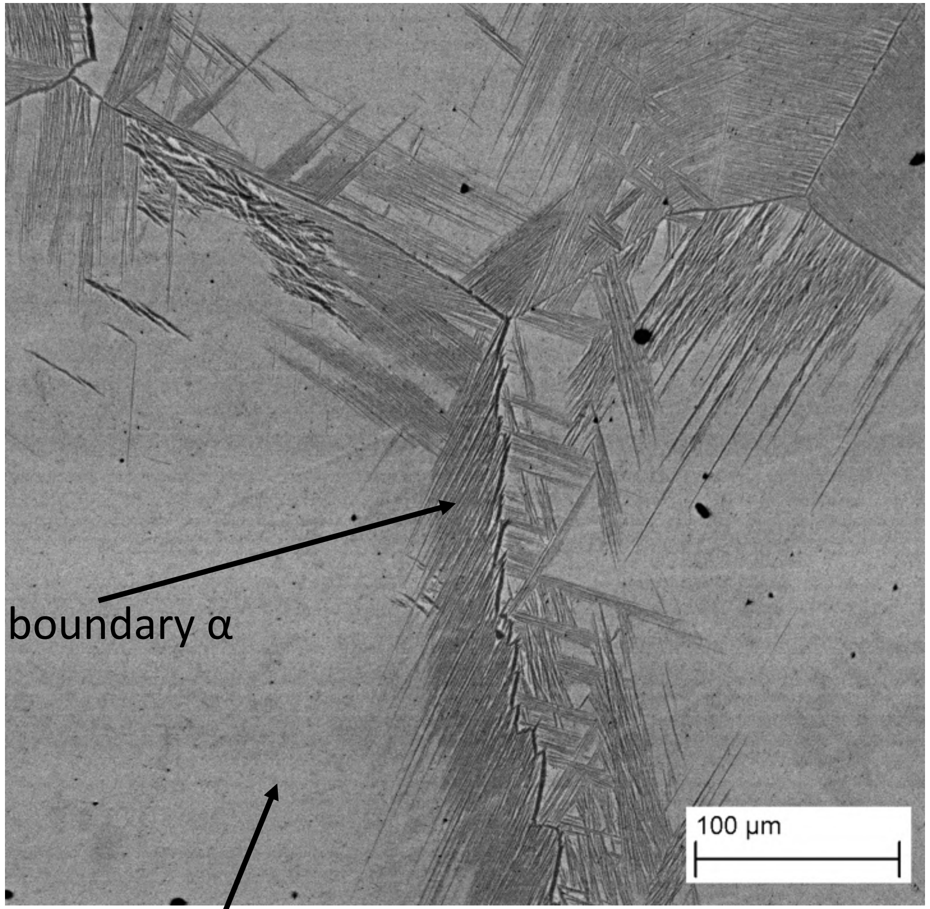






Phase Transformation during Cooling

Microstructure at 800℃



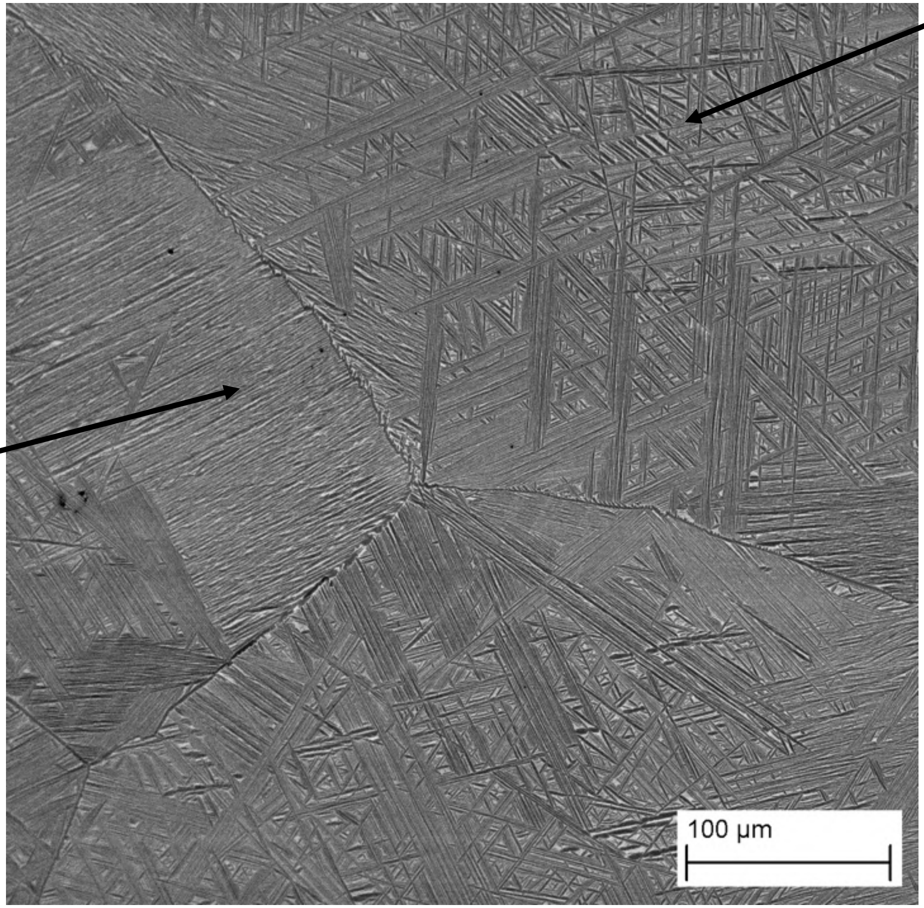
Grain boundary α

Retained β-phase

Microstructure at 700℃

Widmanstätten/
basketweave

α colonies

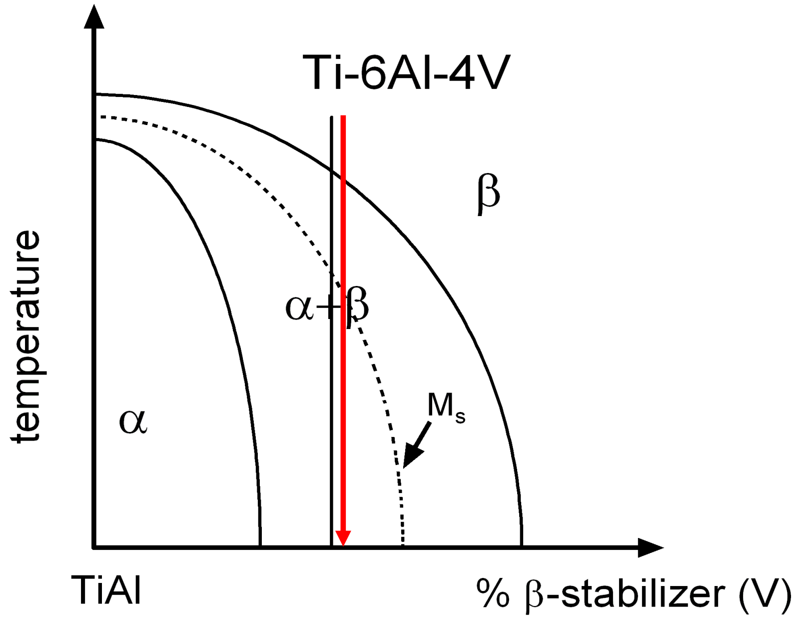


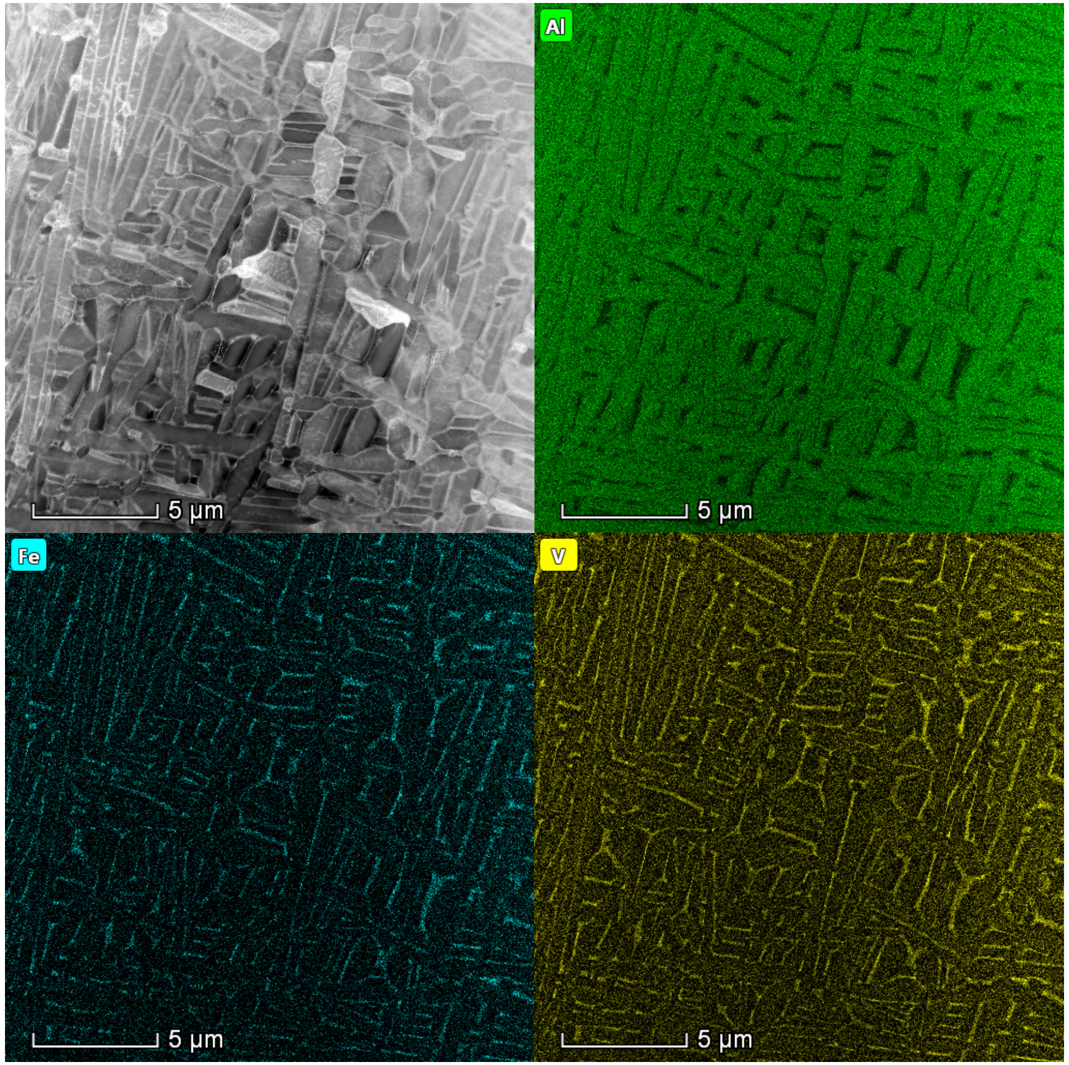
Live lecture – Why can we see these microstructures at RT?

Where do the Alloying Additions Go?

- As temperatures drops, β-phase requires more β-stabilising content to remain stable.
- β-stabilisers diffuse to β-phase
- α-stabilisers diffuse to α-phase

→ *Thermodynamics determine equilibrium phase fraction.*
→ *Diffusion controls kinetics.*



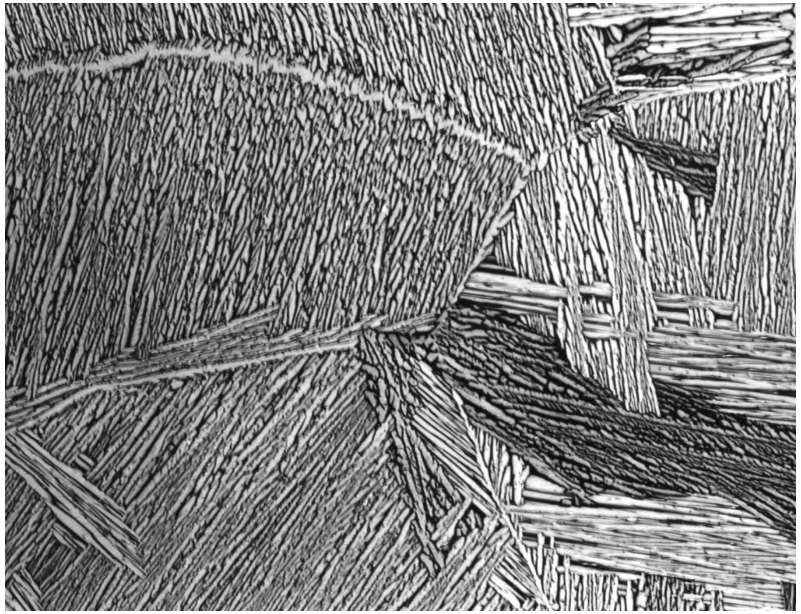


Effect of Cooling Rate

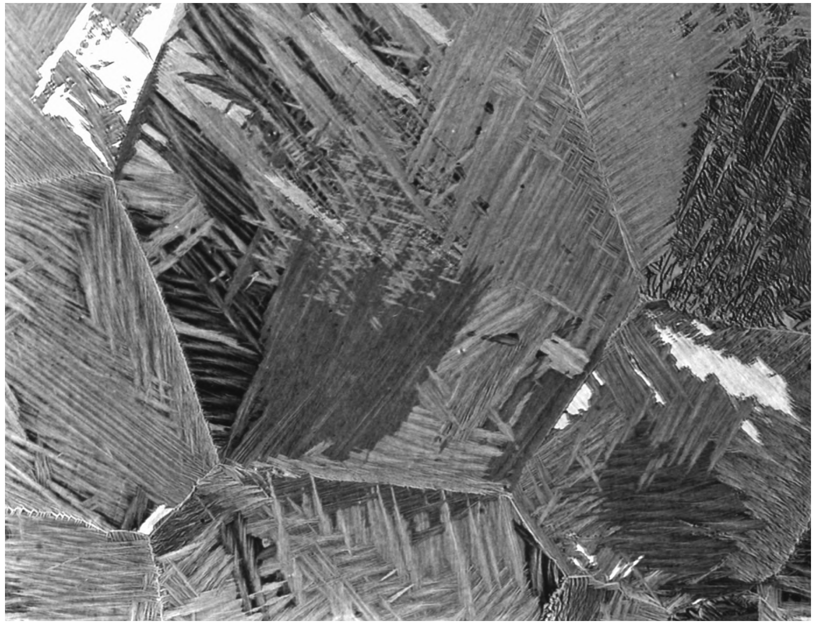
- **Nucleation versus growth;**

- ***At slow cooling rates***, *α-Ti (or Zr) tends to form first on the β grain boundaries, before α-lamellae* ***grow*** *into the β-grains.*
- ***At very fast cooling rates***, *fine α-Ti (or Zr) grains can also* ***nucleate*** *at sites throughout the β-grains.*

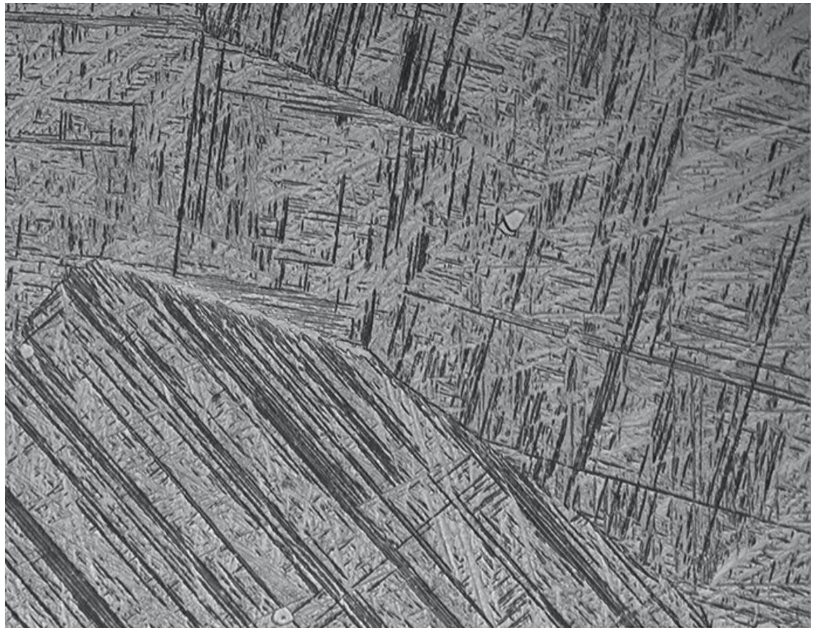
500 microns



slow cooling / furnace cooling
0.1 °C/s



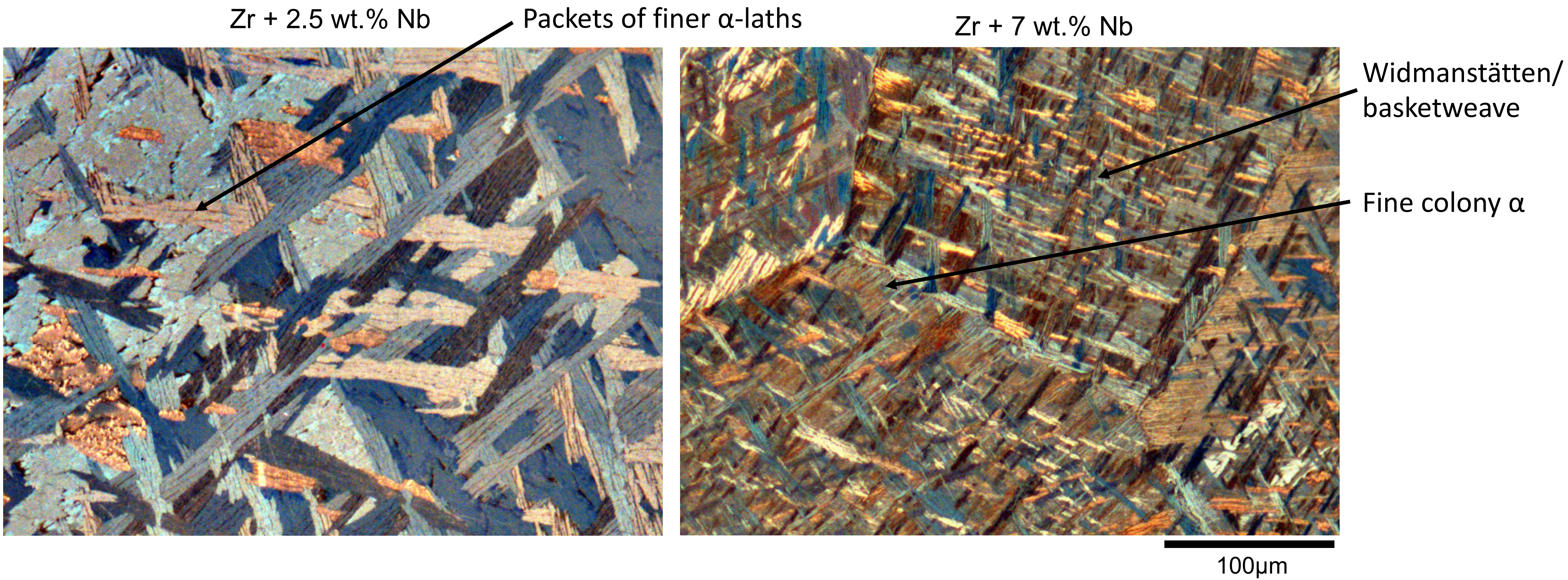
fast cooling / air cooling
1 °C/s



very fast cooling / water quench
> 10 °C/s

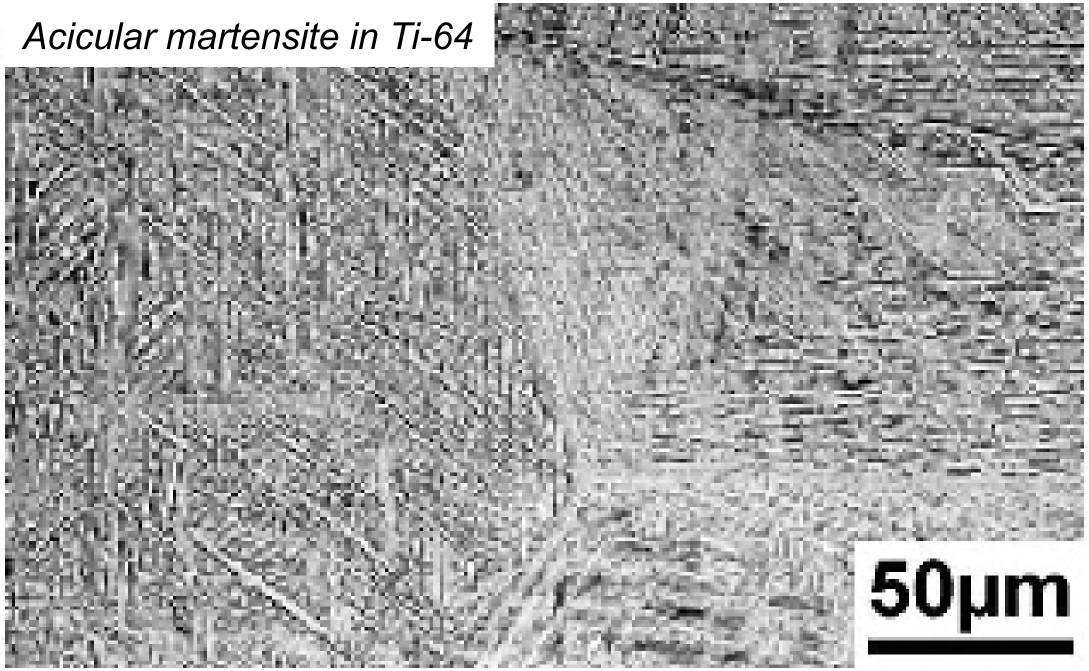
Effect of Alloying Addition

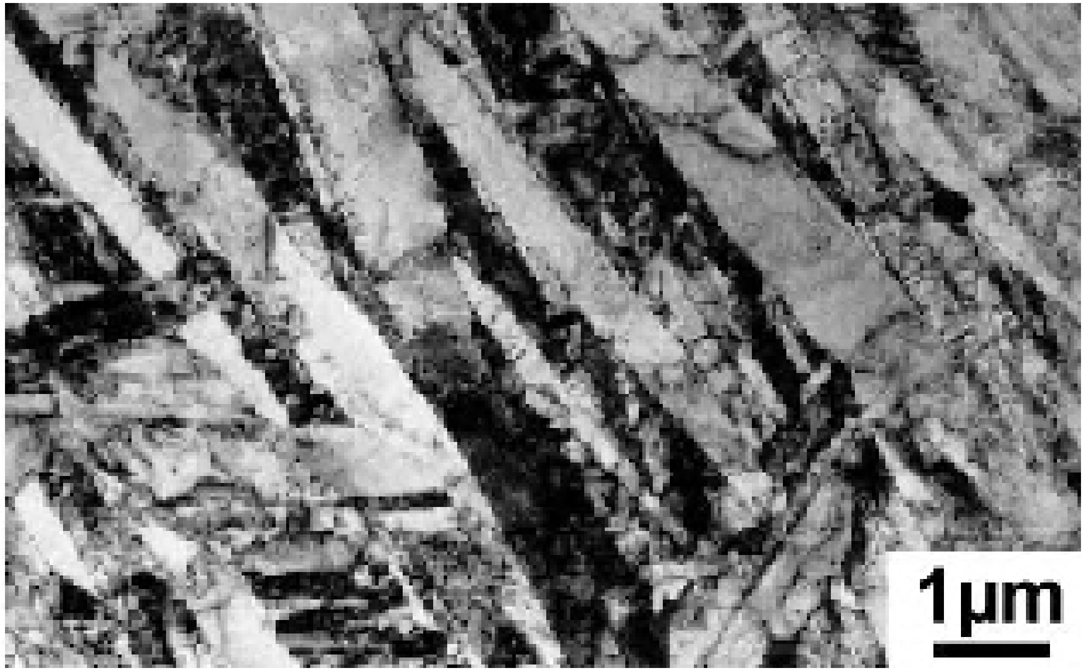
- *Diffusion of alloying elements controls growth (kinetics).*
- *Finer α-laths appear in Zr alloys due to slower diffusing Nb elements (undercooling effect).*



Allotropic Martensite Transformation (V. Fast Cooling)

- When Ti/Zr is quenched from the beta phase region a martensitic (diffusionless transformation) can occur.
- In contrast to steel, the martensitic transformation in Ti/Zr does not produce a heavily distorted crystal cell.
- Strengthening mechanism in this case mainly results from the grain refinement
  – very fine lamellar (plate) microstructure



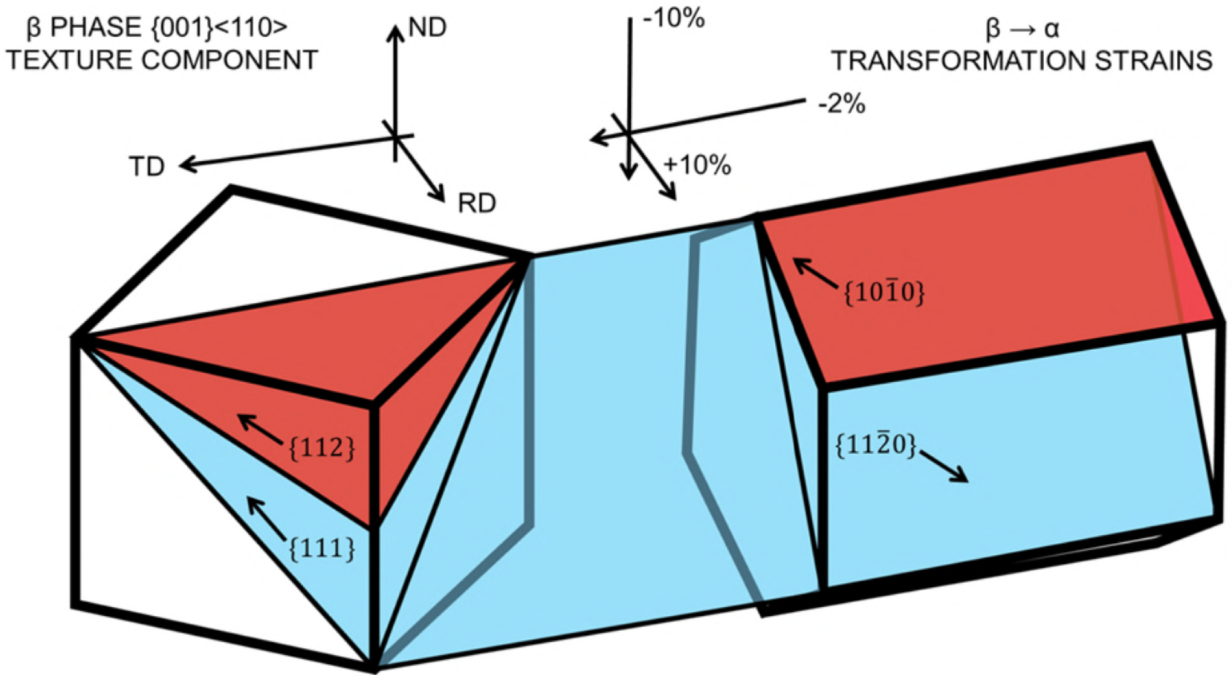


In application, Titanium martensitic microstructures are mainly seen in welds.

Course goal: Describe phase transformation in Ti and Zr alloys during heating and cooling at different rates and explain how this can change the properties of the material.

Learning outcomes:

- Describe the effect of different alloying additions on the phase structure of Ti (and Zr) alloys.
- Describe phase transformation and microstructural changes during heating and cooling of Ti and Zr alloys at different rates.
- ***Recall the Burgers Orientation Relationship (BOR), describing crystallographic relationship between α and β phases, and predict 'variant' orientations.***



Schematic of the Burgers Orientation Relationship (BOR), showing phase transformation in Zr and Ti Alloys.

Burgers Orientation Relationship (BOR)

- Phase transformation governed by Gibbs Free Energy

↓

- Small shifts in atomic positions

↓

- New crystallographic phase

- **Crystallographic relationship between α and β phase;**

$$\{110\}_\beta \parallel (0002)_\alpha \text{ and } \langle 111\rangle_\beta \parallel [11\bar{2}0]_\alpha$$

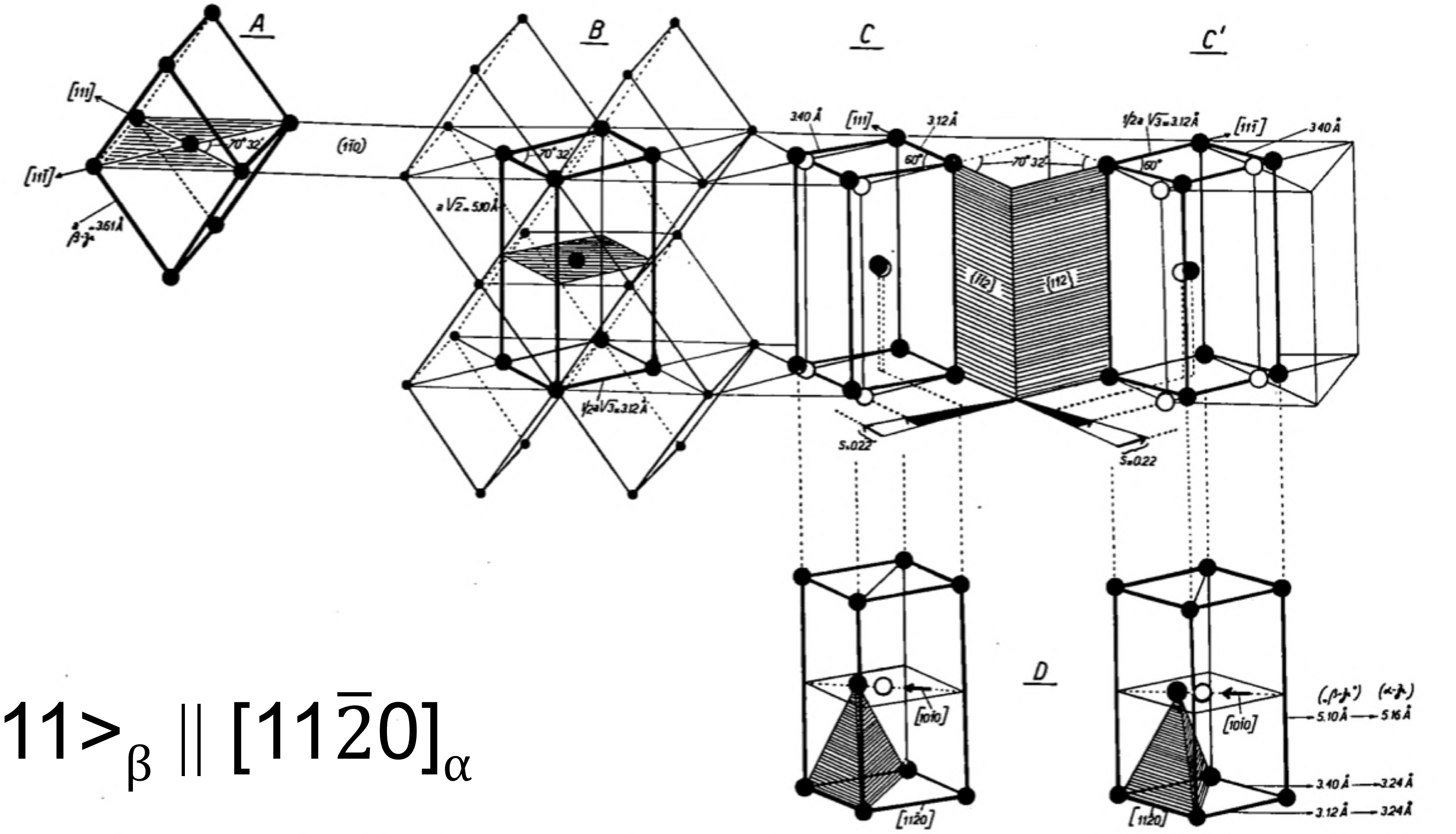
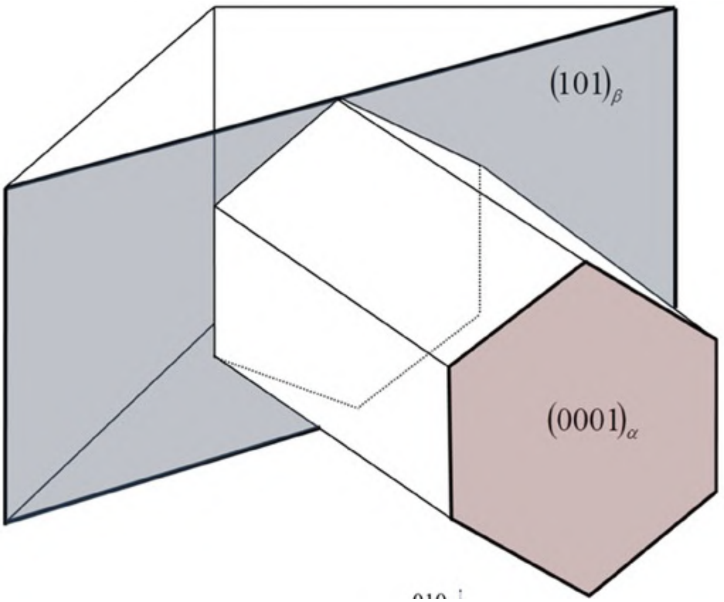


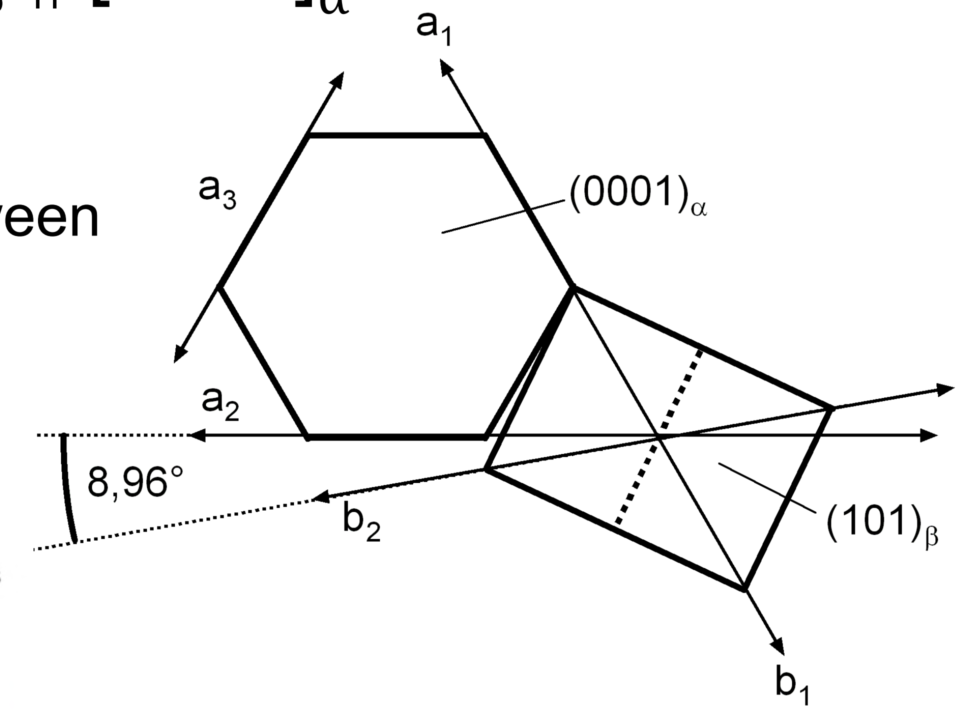
Fig. 5. Transition of the cubic-body-centred into the hexagonal-close-packed lattice in Zirconium-crystals. The figure illustrates how *two* positions of the hexagonal lattice correspond to *one* definite {110}-plane.

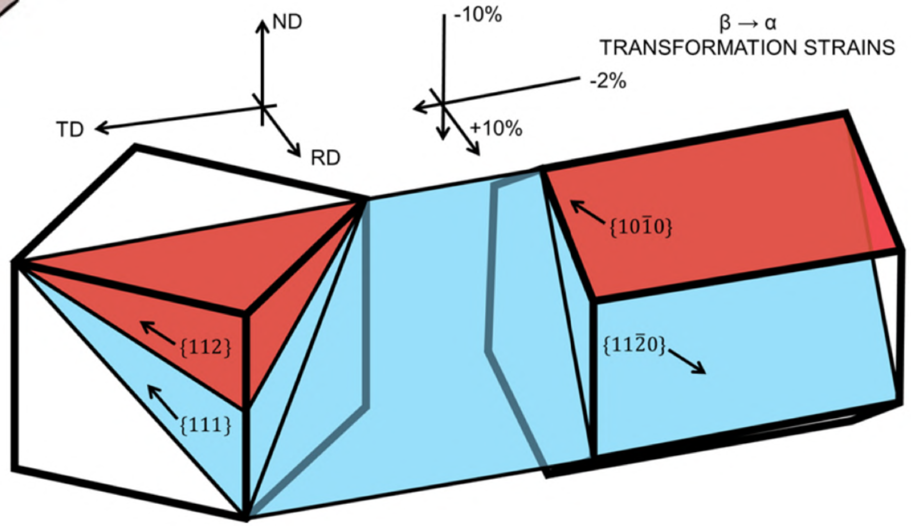
Burgers Orientation Relationship (BOR)

$$\{110\}_\beta \parallel (0002)_\alpha \text{ and } \langle 111\rangle_\beta \parallel [11\bar{2}0]_\alpha$$



Small angular difference between $\langle 111\rangle_\beta \parallel [1120]_\alpha$ alignment



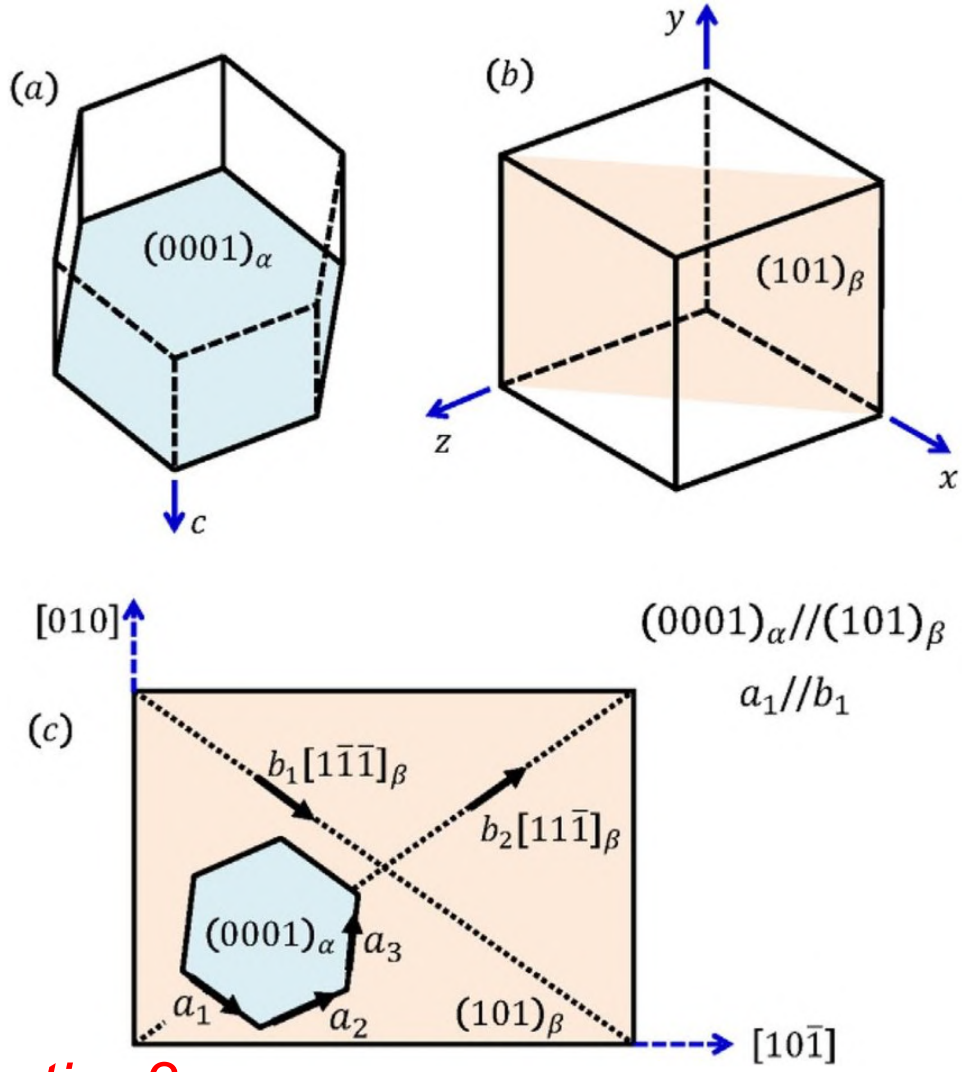


Burgers Orientation Relationship (BOR)

β-phase has;

- six different 110 planes
- each 110 plane contains two 111 directions

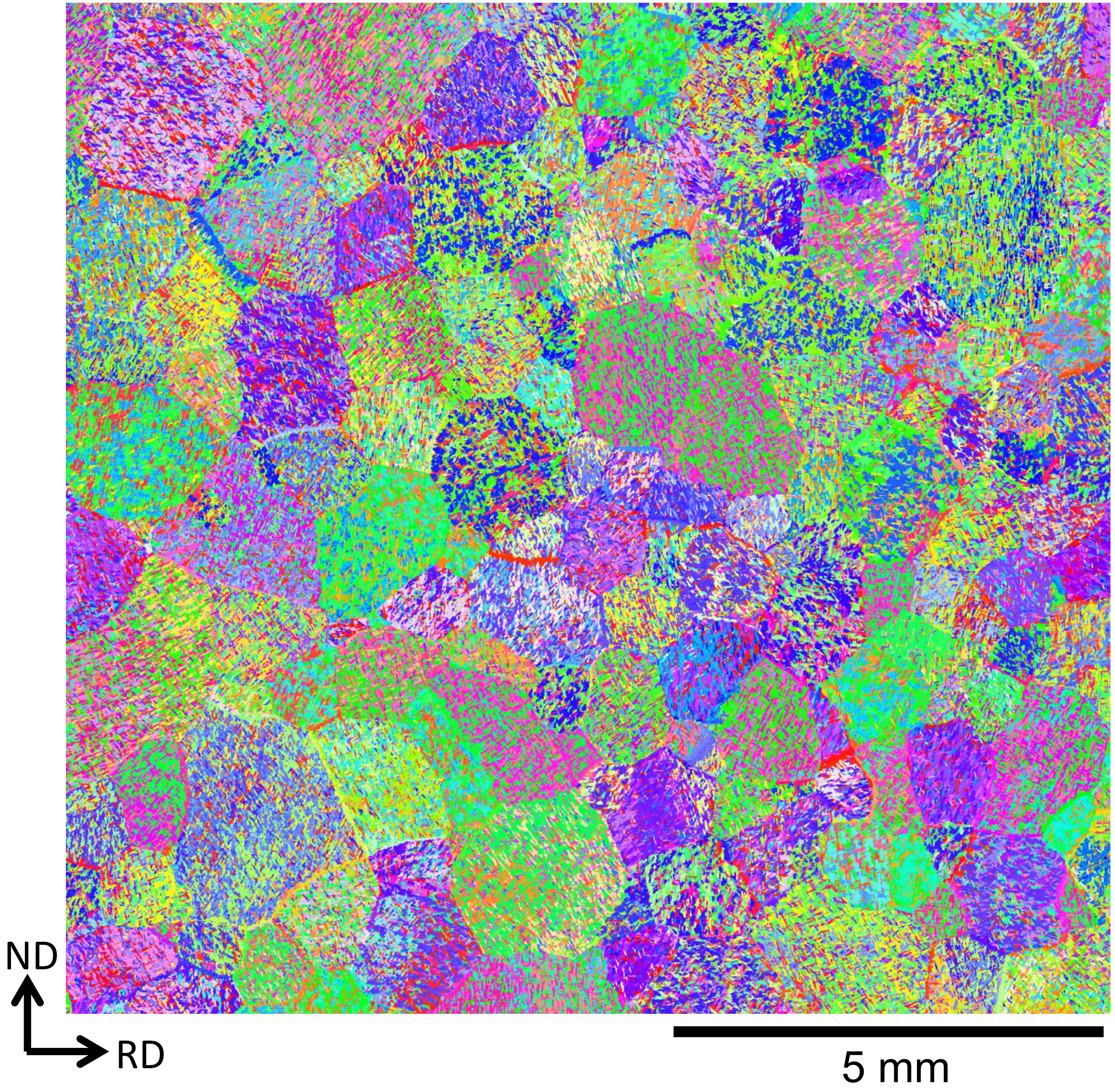
→ 12 different α variants from a single β grain.

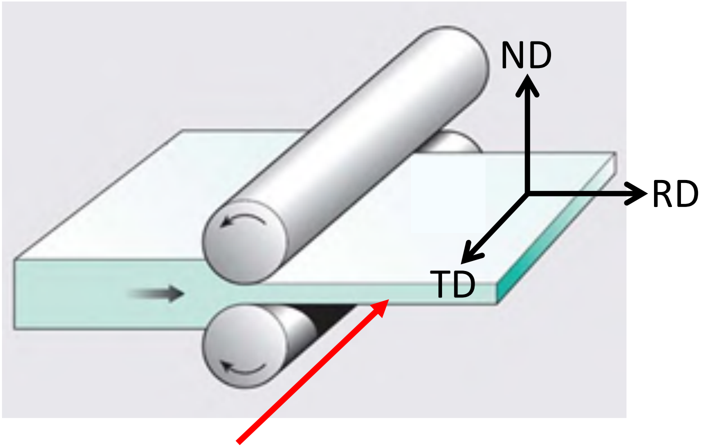


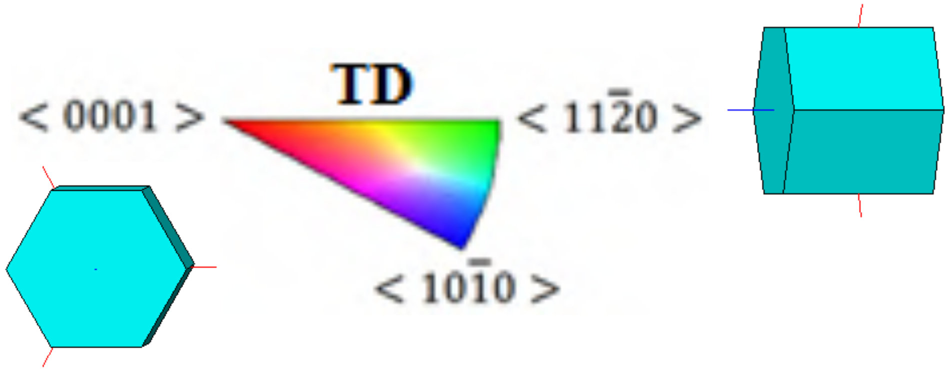
- *Note, BOR is maintained during* ***Heating*** *and* ***Cooling***

Live lecture – How many possible variants during heating?

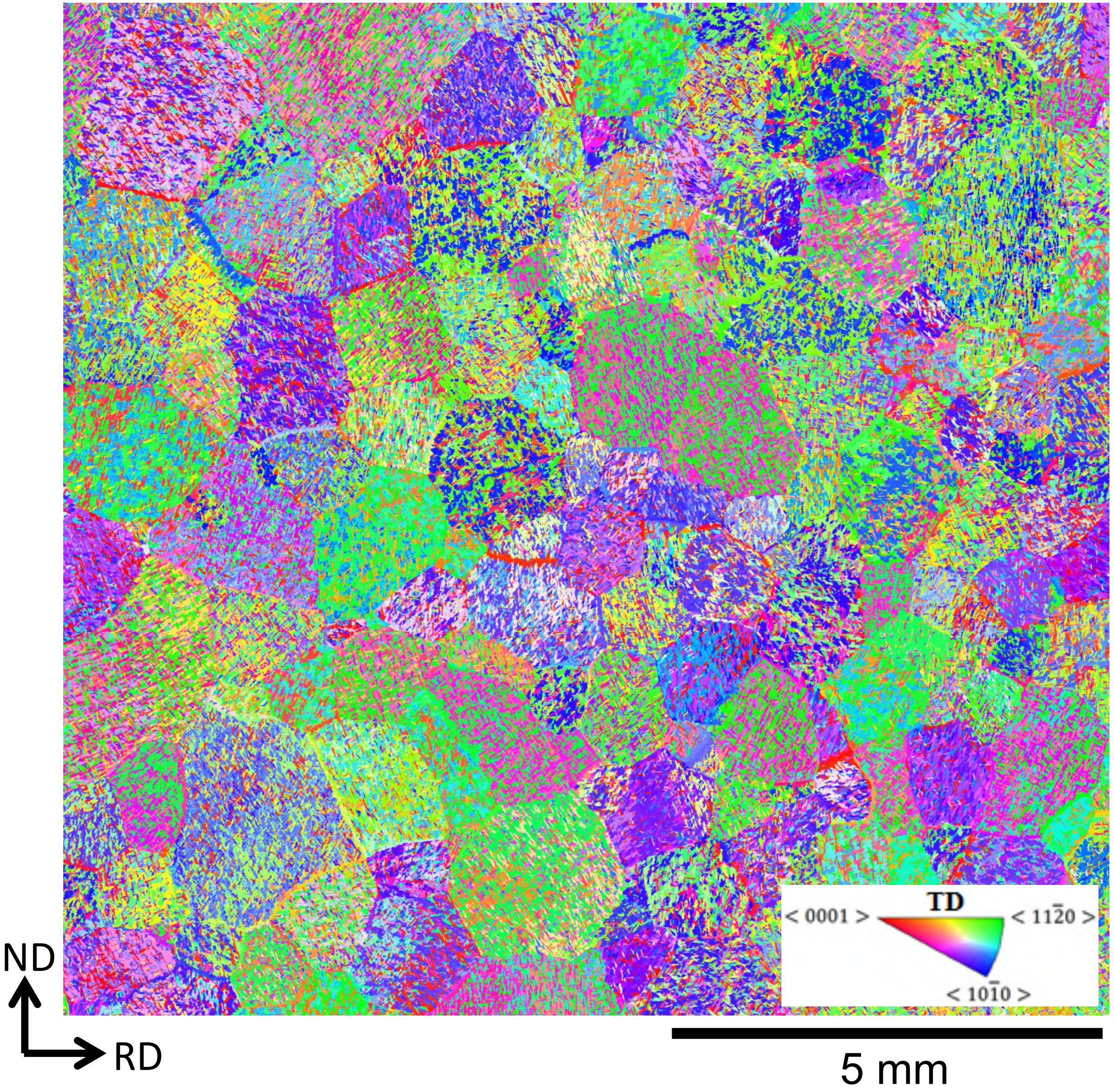
Orientation map recorded by Electron Backscatter Diffraction (EBSD)

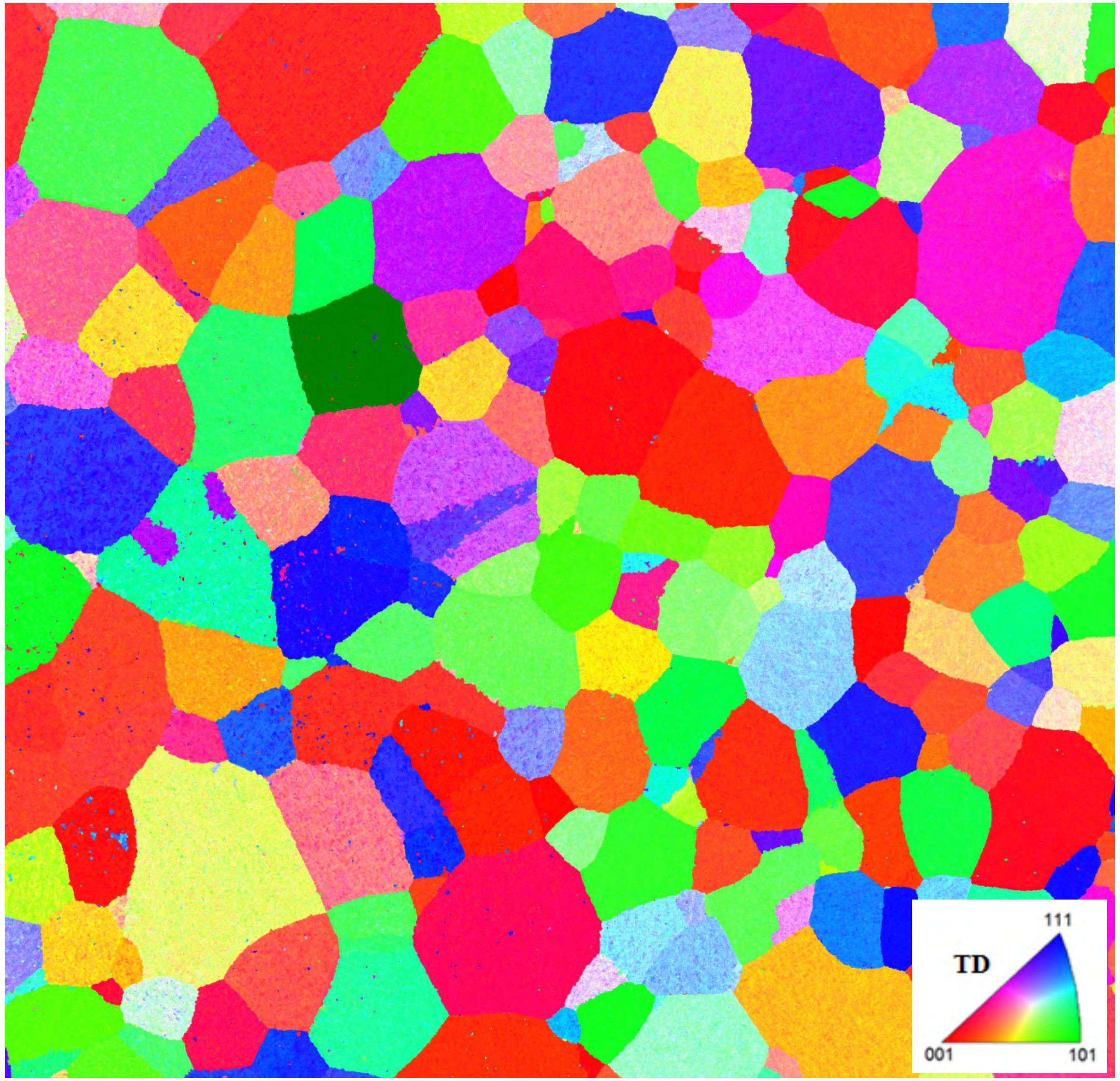






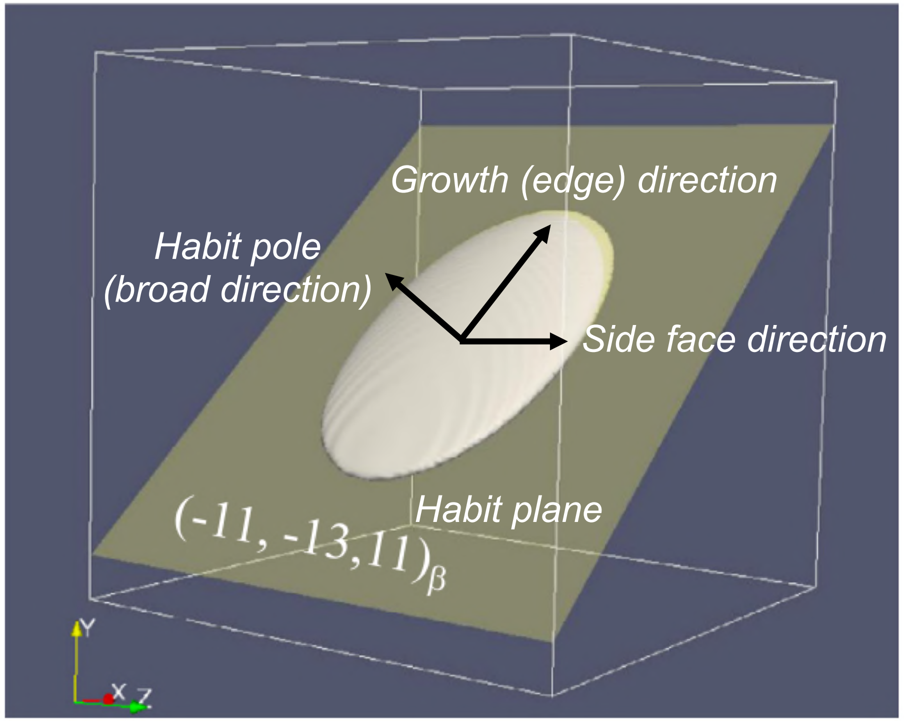
Reconstruction of high temperature β-phase microstructure

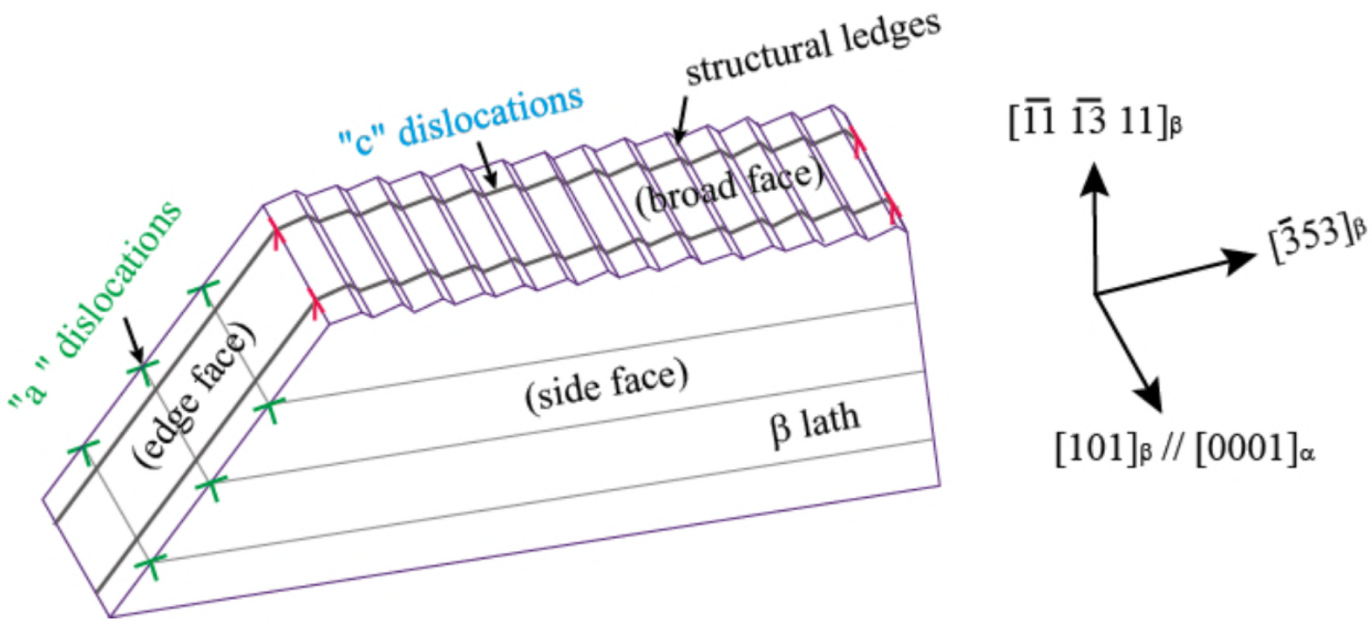




Habit (Growth) Plane

- α-laths are 3D structures. *(But, we often only see them as 2D slices.)*
- Habit plane defines broad face (containing length and breadth directions).
- Growth direction close to ~ $\langle 1\bar{1}1\rangle_\beta || \langle 11\bar{2}0\rangle_\alpha$



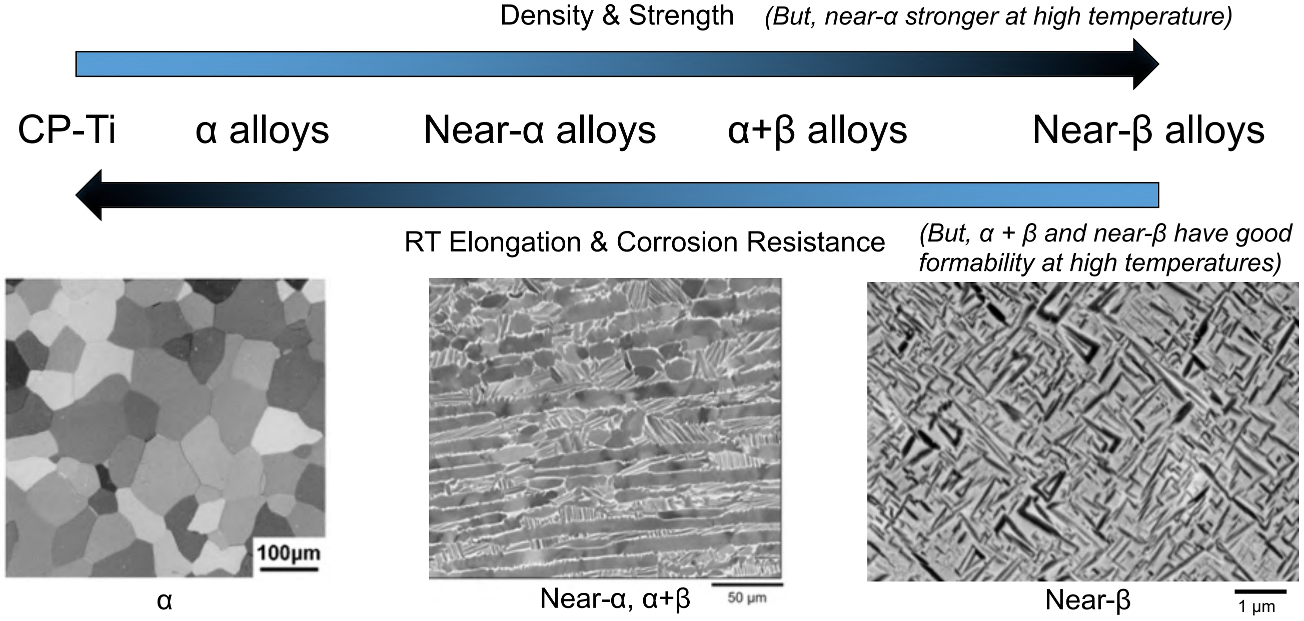


Classification of Ti Alloys

Course goal: Describe phase transformation in Ti and Zr alloys during heating and cooling at different rates and explain how this can change the properties of the material.

Learning outcomes:

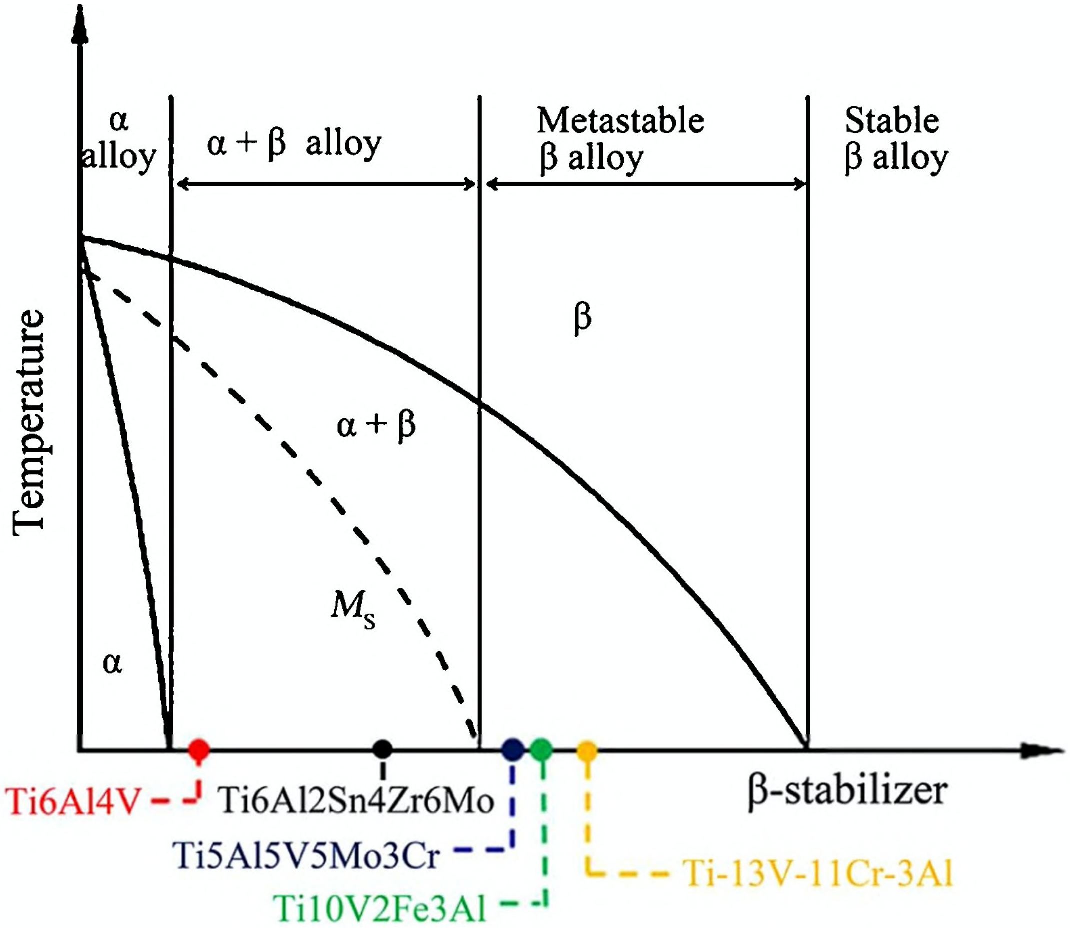
- Describe the effect of different alloying additions on the phase structure of Ti (and Zr) alloys.
- Describe phase transformation and microstructural changes during heating and cooling of Ti and Zr alloys at different rates.
- Recall the Burgers Orientation Relationship (BOR), describing crystallographic relationship between α and β phases, and predict 'variant' orientations.
- ***Classify different Ti alloys and summarise their different properties and applications.***



General trends in the different classes of Ti alloys.

Classification of Ti Alloys

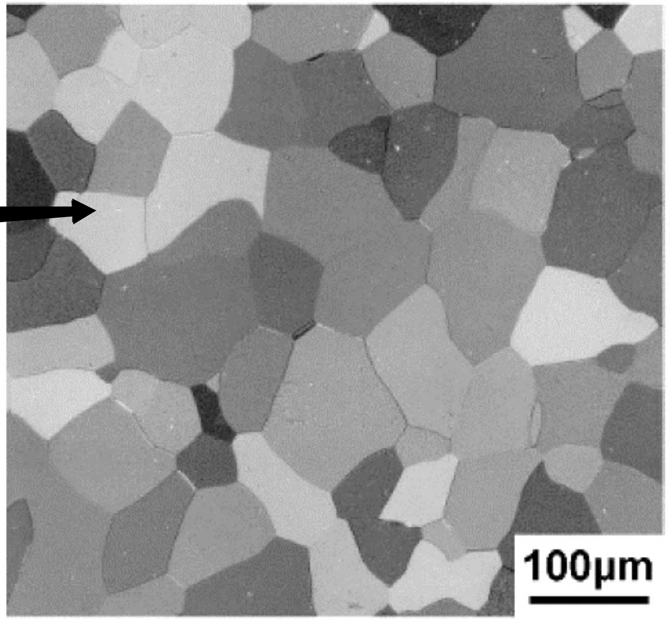
- Commercially Pure Titanium (CP-Ti)
- Single-phase α-Titanium alloys
- Near-α Titanium alloys
- Two-phase $\alpha + \beta$ Titanium alloys
- Near-β *(Metastable)* Titanium alloys

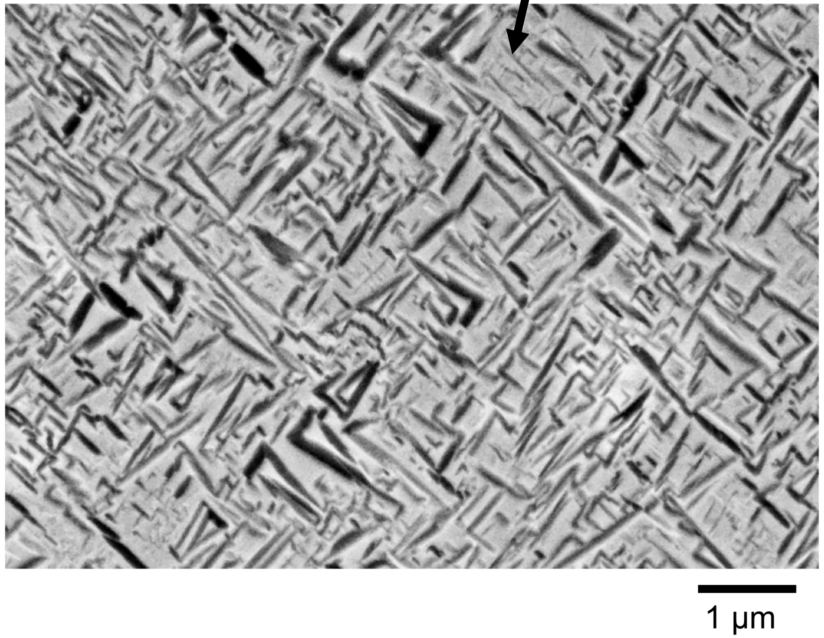


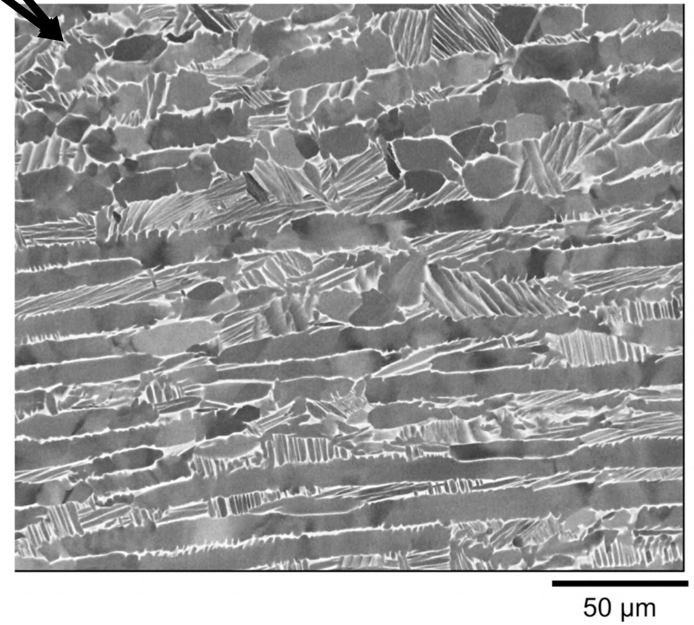
Titanium Classes – Microstructures

α → α + β →

- commercially pure (CP) titanium
- α alloys
- near-α alloys
- α + β alloys
- near-β alloys







Note the difference in scales!

Commercially Pure Titanium (CP-Ti)

- ***Applications:*** Chemical and Petrochemical industries as piping, heat exchangers, pumps and valves.
- ***Properties:*** Superior corrosion resistance, high formability, good weldability. Low strength.
- *CP-Ti (Grade 1 and 2) can be cold-rolled.*

Pipework for offshore use made from CP-Ti

Grade or Alloy	O (max.)	Fe (max.)	$\sigma_{0.2}$ (MPa)
CP Titanium			
CP Titanium Grade 1	0.18	0.20	170
CP Titanium Grade 2	0.25	0.30	275
CP Titanium Grade 3	0.35	0.30	380
CP Titanium Grade 4	0.40	0.50	480

↓ *Reduced elongation (%) and ductility*

Single-phase α-Titanium alloys

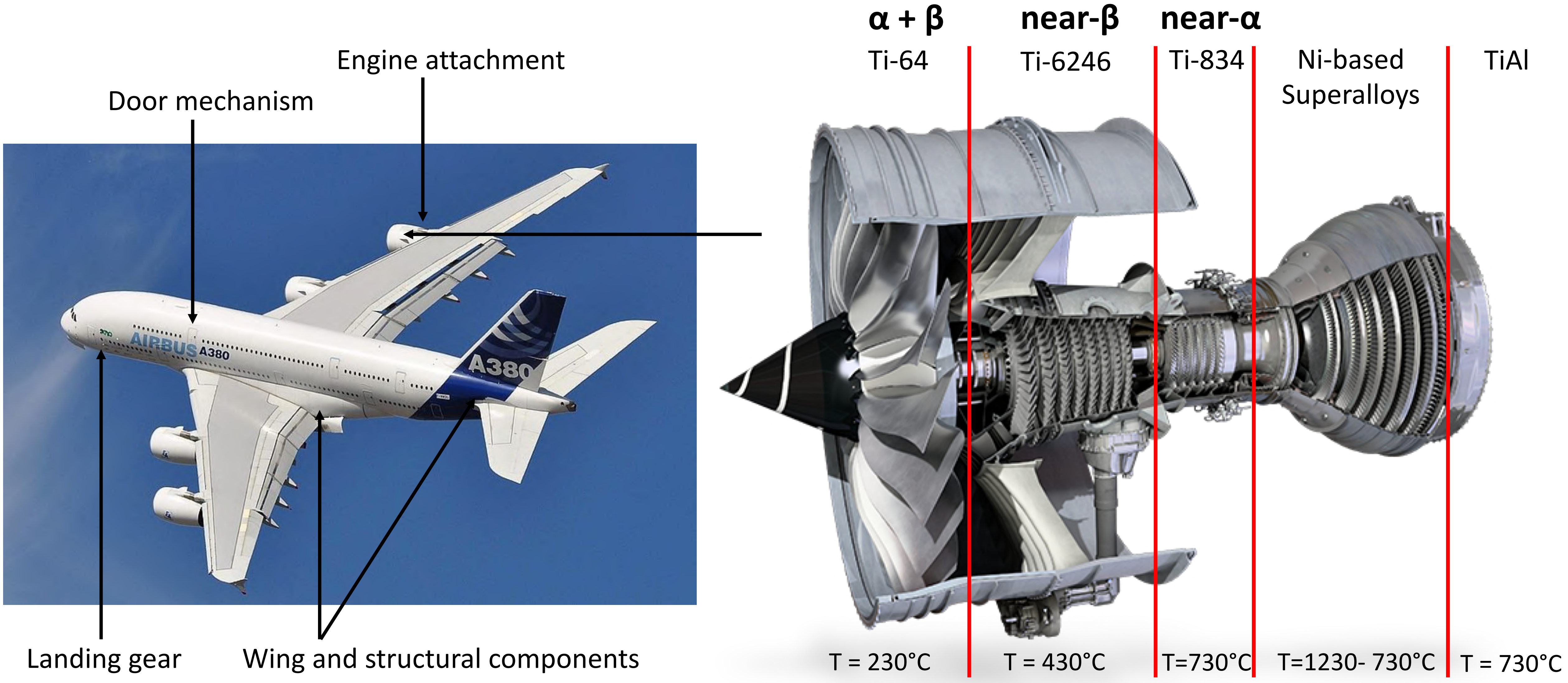
- ***Applications:*** Cryogenic applications (with low level of interstitials). Otherwise, not very common as difficult to process.
- ***Properties:*** Good strength, toughness, creep properties and weldability. Good corrosion behaviour. Poor formability at low temperatures.
- *Strengthened via alloying additions, and thermomechanical processing.*

Grade or Alloy	O (max.)	Fe (max.)	Other Additions	$\sigma_{0.2}$ (MPa)
α Titanium Alloys				
Ti-0.3Mo-0.9Ni (Grade 12)	0.25	0.30	0.2-0.4Mo, 0.6-0.9Ni	345
Ti-3Al-2.5V (Grade 9)	0.15	0.25	2.5-3.5Al, 2.0-3.0V	485
Ti-3Al-2.5V-0.05Pd (Grade 18)	0.15	0.25	2.5-3.5Al, 2.0-3.0V, (+Pd)	485
Ti-3Al-2.5V-0.1Ru (Grade 28)	0.15	0.25	2.5-3.5Al, 2.0-3.0V, (+Ru)	485
Ti-5Al-2.5Sn (Grade 6)	0.20	0.50	4.0-6.0Al, 2.0-3.0Sn	795
Ti-5Al-2.5Sn ELI	0.15	0.25	4.75-5.75Al, 2.0-3.0Sn	725

↓ *Solid Solution Strengthening*

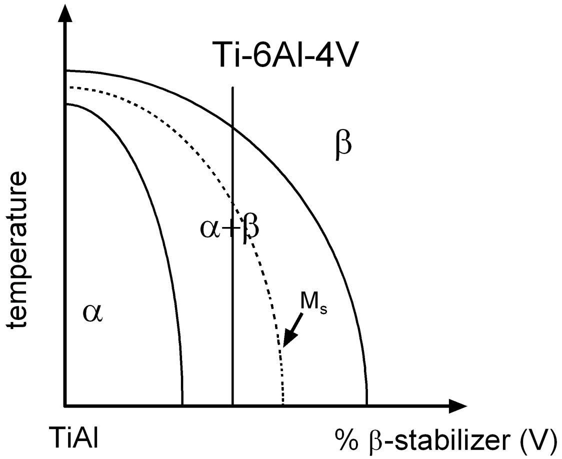
↓ *Reduced elongation (%) and ductility*

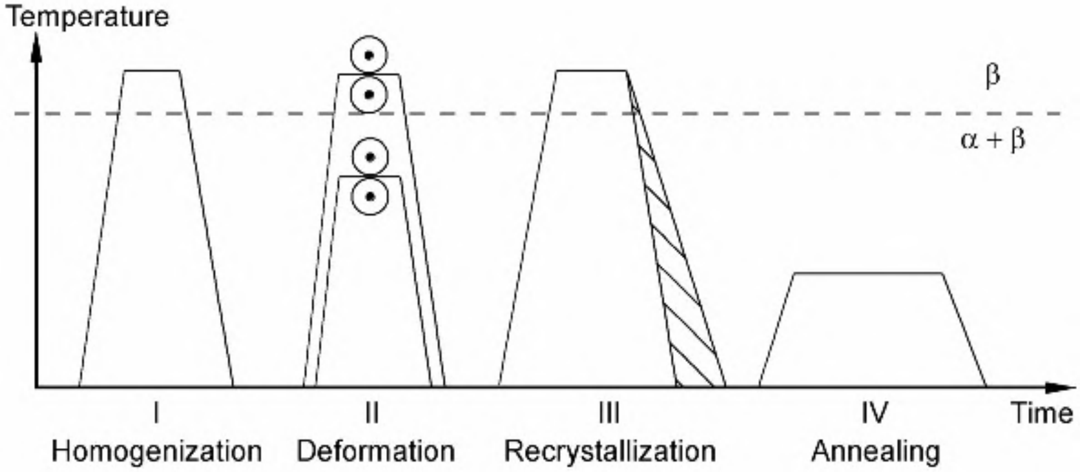
Ti Alloys in the Aerospace Industry



Two-phase α + β Titanium alloys

- ***Applications:*** Aerospace industry (blades, compressor discs, fasteners). Offshore industry (heat exchanger). Elevated temperature applications (up to 400℃)
- ***Properties:*** Higher strength (stronger than CP-Ti and α-Ti). Ok corrosion resistance. Poorer creep behaviour. Properties highly dependent on microstructure!
- *Thermomechanical processed at high temperatures, with sufficient amount of β-phase.*
- *Ti-6Al-4V (Ti-64) is the work horse of all Ti alloys.*





Near-α Titanium alloys

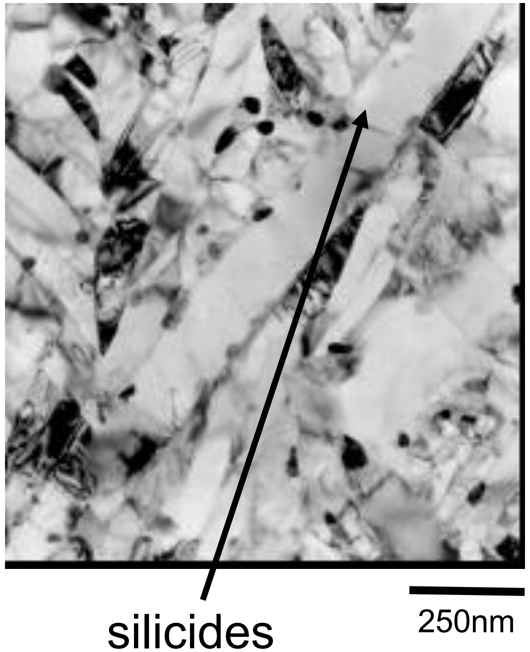
- ***Applications:*** Medium compressor parts in jet engine (aerospace industry)

- ***Properties:*** High strength (comparable to Ti-64) and improved creep behaviour. Capable of operating at higher temperatures (up to 700℃). Difficult to process, machine and weld (than Ti-64).

- *Less β-stabiliser (than Ti-64) → increased strength and volume of more creep-resistant α-phase at high temp. → improved high temperature capability.*

- *Si Additions: contribute to solid solution strengthening and formation of silicides (to improve creep properties)*

High pressure compressor disk made of Timetal-834



Important Near-α and α + β and Ti alloys

Common Name	Alloy Composition (wt%)	T_β (°C)
α+β Alloys		
Ti-811	Ti-8Al-1V-1Mo	1040
IMI 685	Ti-6Al-5Zr-0.5Mo-0.25Si	1020
IMI 834	Ti-5.8Al-4Sn-3.5Zr-0.5Mo-0.7Nb-0.35Si-0.06C	1045
Ti-6242	Ti-6Al-2Sn-4Zr-2Mo-0.1Si	995
Ti-6-4	Ti-6Al-4V (0.20O)	995
Ti-6-4 ELI	Ti-6Al-4V (0.13O)	975
Ti-662	Ti-6Al-6V-2Sn	945
IMI 550	Ti-4Al-2Sn-4Mo-0.5Si	975

Near-β Ti alloys

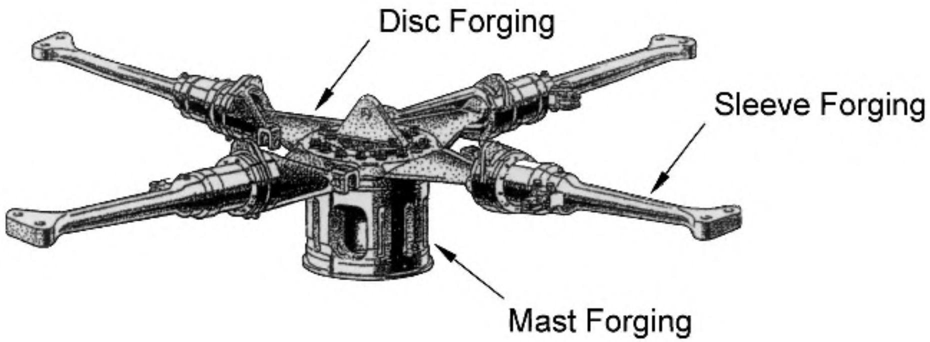
- ***Applications:*** Larger compressor parts, landing gear, sheets, fasteners, helicopter rotor.

- ***Properties:*** Good weldability and formability. Hardened to very high strength. Improved corrosion resistance (better than Ti-64, worse than α-Ti). High hydrogen tolerance.

- *Can retain 100% β-phase when quenched.*

- *Excellent formability in solution treated condition.*

A380 landing gear



Helicopter rotor

Important Near-β Ti alloys

Common Name	Alloy Composition (wt%)	T_{β} (°C)
β Alloys		
Ti-6246	Ti-6Al-2Sn-4Zr-6Mo	940
Ti-17	Ti-5Al-2Sn-2Zr-4Mo-4Cr	890
SP-700	Ti-4.5Al-3V-2Mo-2Fe	900
Beta-CEZ	Ti-5Al-2Sn-2Cr-4Mo-4Zr-1Fe	890
Ti-10-2-3	Ti-10V-2Fe-3Al	800
Beta 21S	Ti-15Mo-2.7Nb-3Al-0.2Si	810
Ti-LCB	Ti-4.5Fe-6.8Mo-1.5Al	810
Ti-15-3	Ti-15V-3Cr-3Al-3Sn	760
Beta C	Ti-3Al-8V-6Cr-4Mo-4Zr	730
B120VCA	Ti-13V-11Cr-3Al	700

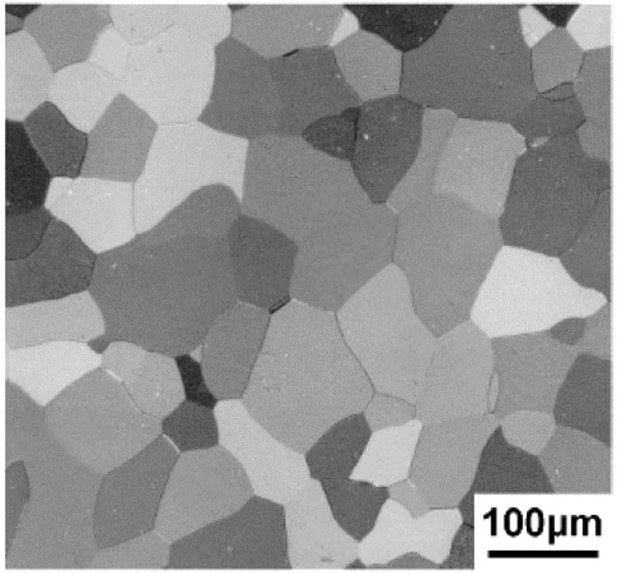
Lower β-transus with more β-stabilising addition.

Titanium Alloy Class General Trends

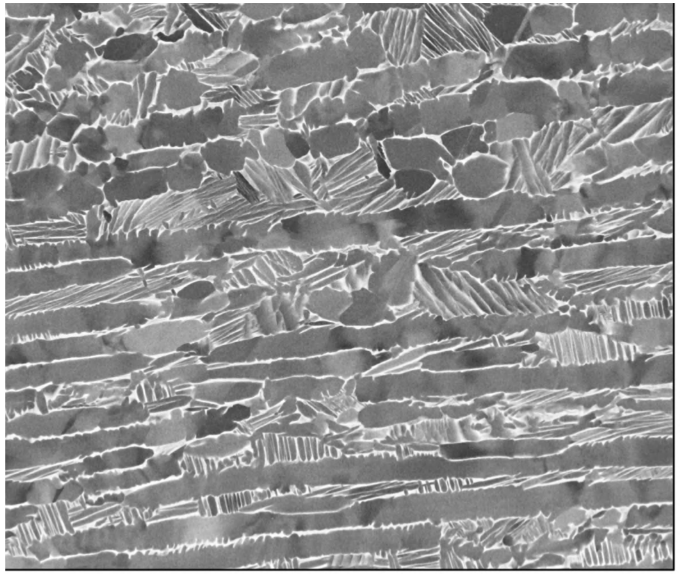
Density & Strength *(But, near-α stronger at high temperature)*

CP-Ti α alloys Near-α alloys α+β alloys Near-β alloys

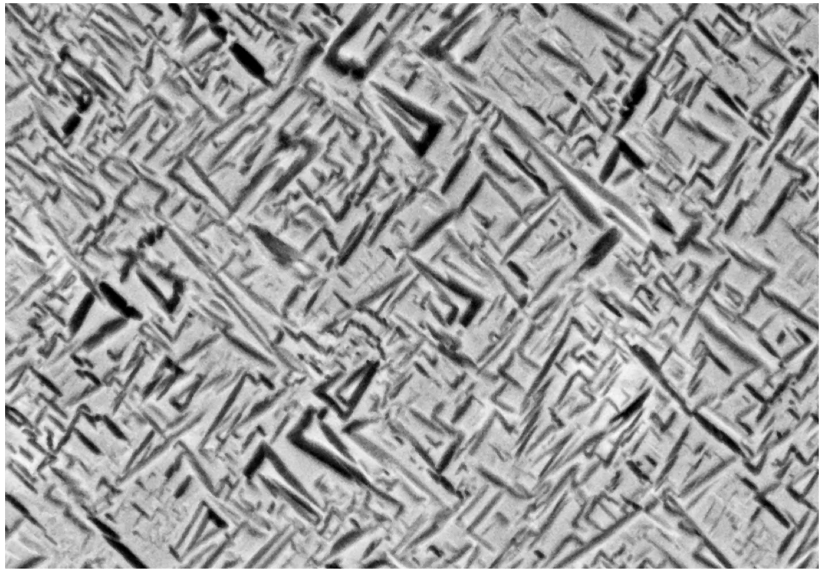
RT Elongation & Corrosion Resistance *(But, α + β and near-β have good formability at high temperatures)*



α



Near-α, α+β 50 µm



Near-β 1 µm