

# Titanium and its alloys

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## Subjects of interest

- *Introduction/Objectives*
- *Extraction and melting of titanium*
- *Alloying system & classification of titanium and its alloys*
- *Commercial pure titanium,  $\alpha$  and near  $\alpha$  titanium alloys*
- *$\alpha+\beta$  titanium alloys*
- *$\beta$  titanium alloys*
- *Forming and casting of titanium alloys*
- *Welding of titanium alloys*
- *Properties of titanium alloys*



# Objectives

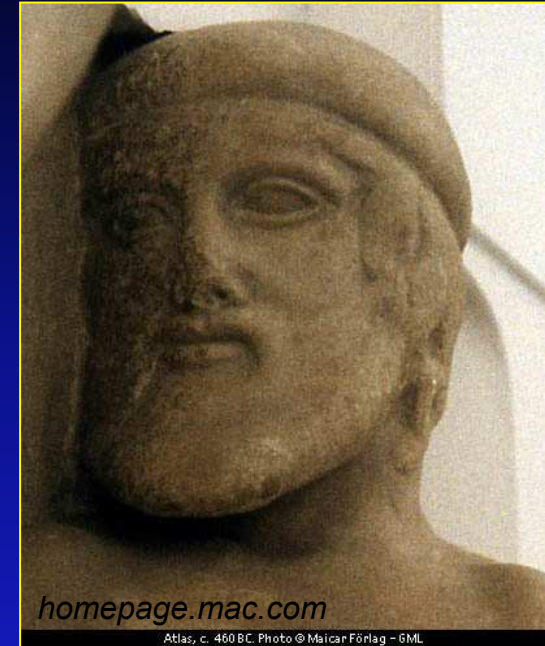
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- This chapter provides fundamental knowledge of different methods of productions / heat treatments of titanium alloys and the use of various types of cast and wrought titanium alloys.
- The influences of alloy composition, microstructure and heat treatment on chemical and mechanical properties of titanium alloys will be discussed in relation to its applications.



# Introduction- **Titanium and its alloys**

- **Titanium** is named after the **Titans**, the powerful sons of the earth in Greek mythology.
- Titanium is the **forth abundant metal** on earth crust (~ 0.86%) after aluminium, iron and magnesium.
- Not found in its free, pure metal form in nature but as **oxides**, i.e., ilmenite ( **$FeTiO_3$** ) and rutile ( **$TiO_2$** ).
- Found only in small amount in Thailand.
- Have similar **strength as steel** but with a **weight nearly half of steel**.



homepage.mac.com

Atlas, c. 460 BC. Photo © Maicar Förlag - GML

**Titans**



**Ilmenite ( $FeTiO_3$ )**



**Rutile ( $TiO_2$ )**



# Physical properties of titanium

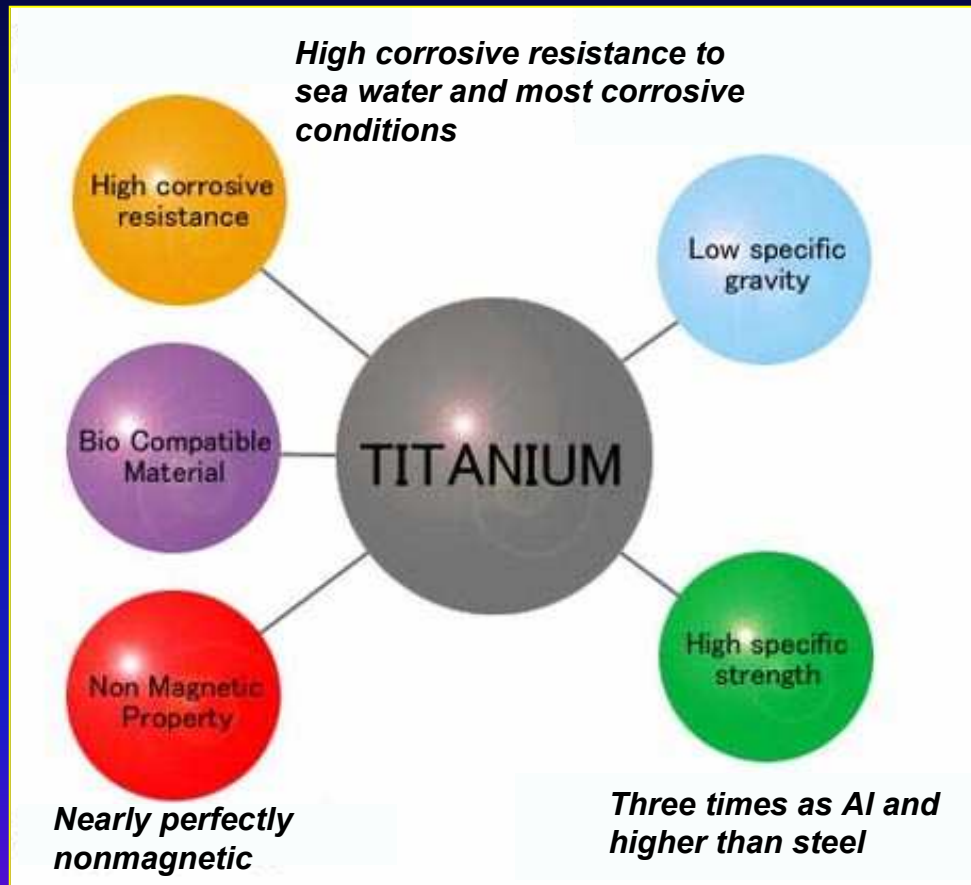
Crystal structure	HCP (<882.5°C) BCC (>882.5°C)
Atomic diameter	0.320
Density (g.cm <sup>-3</sup> )	4.54
Melting point (°C)	1667

22	HCP,BCC
<b>Ti</b>	
Titanium	
47.87	

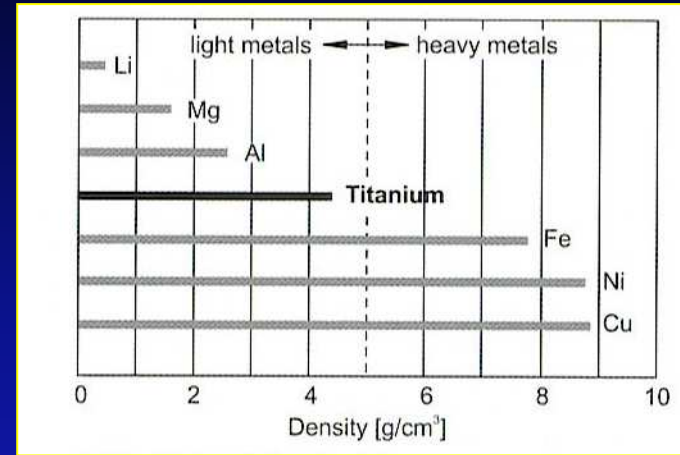
- Experiences **allotropic transformation** ( $\alpha \rightarrow \beta$ ) at 882.5°C.
- Highly react with oxygen, nitrogen, carbon and hydrogen.
- Difficult to extract  $\rightarrow$  **expensive**.
- Used mainly in wrought forms for **advanced applications** where cost is not critical.
- High strength and toughness.



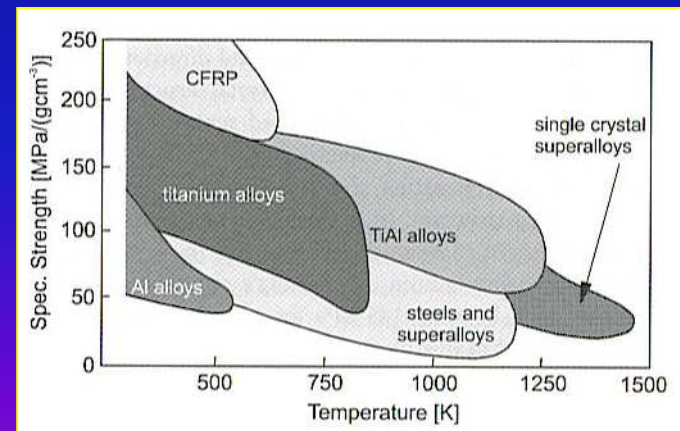
# Advantages of titanium alloys



[www.daido.co.jp](http://www.daido.co.jp)



**Density of selected metals**



**Specific strength vs temperature**

# Applications of titanium alloys

- Used mainly in aerospace, marine, chemical, biomedical applications and sports.



**Turbine blades**

**National science centre, Scotland**



**Hip-joint component**

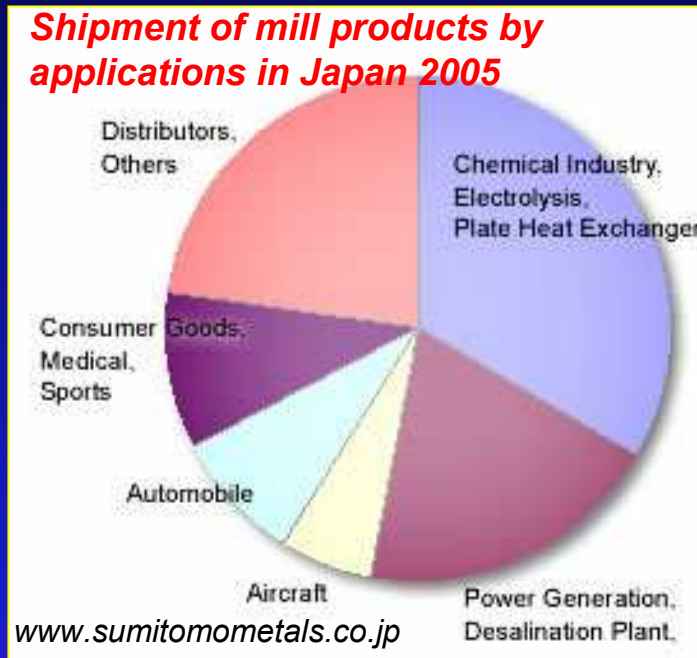
**Shape memory alloy**



**Titanium cladded Guggenheim Bilbao museum, Spain at sunset.**



# Applications of titanium alloys



## AEROSPACE

- Civil
- Military
- Space

## INDUSTRIAL

- Petrochemical
- Offshore
- Subsea
- Metal Finishing
- Pulp & Paper
- General Engineering

## MEDICAL

- Orthopaedic Implants
- Bone Screws
- Trauma Plates
- Dental Fixtures
- Surgical Instruments

## SPECIALIST

- Body Jewellery
- Ultrasonic Welding Components
- Marine
- Bicycle
- Sports Equipment



# ***Production of titanium alloys***

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- ***Extraction processes***

- Kroll extraction process

- ***Melting processes***

- Electroslag Refining (ESR)
- Vacuum Arc Remelting (VAR)
- Electron Beam Melting (EBM)
- Plasma Arc Melting (PAM)
- Induction Skull Melting

- ***Casting processes***

- Casting : investment casting, laser fabrication

- ***Forming processes***

- Forming process such as rolling, extrusion, forging.

- ***Heat treatments***



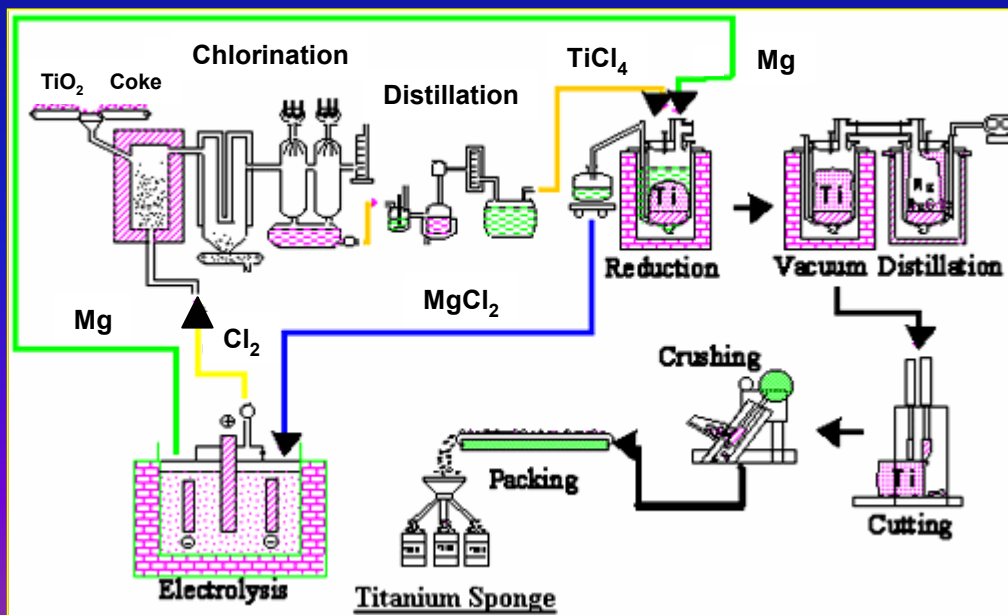
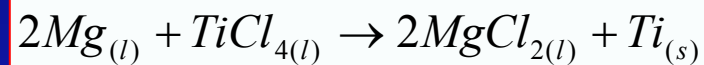
# Extraction of titanium

**Titanium ore – rutile ( $TiO_2$ )** is converted into titanium sponge by

1) Passing  $Cl_2$  gas through charge the ore, resulting in colourless titanium tetrachloride  $TiCl_4$ .  $TiO_2 + 2Cl_2 + C \rightarrow TiCl_4 + CO_2$

2)  $TiCl_4$  is purified by fractional distillation.

3) The liquid form of  $TiCl_4$  is reacted with either  $Mg$  or  $Na$  under an inert ( $Ar$ ) atmosphere to obtain **titanium sponge** while  $Mg$  or  $Na$  is recycled.



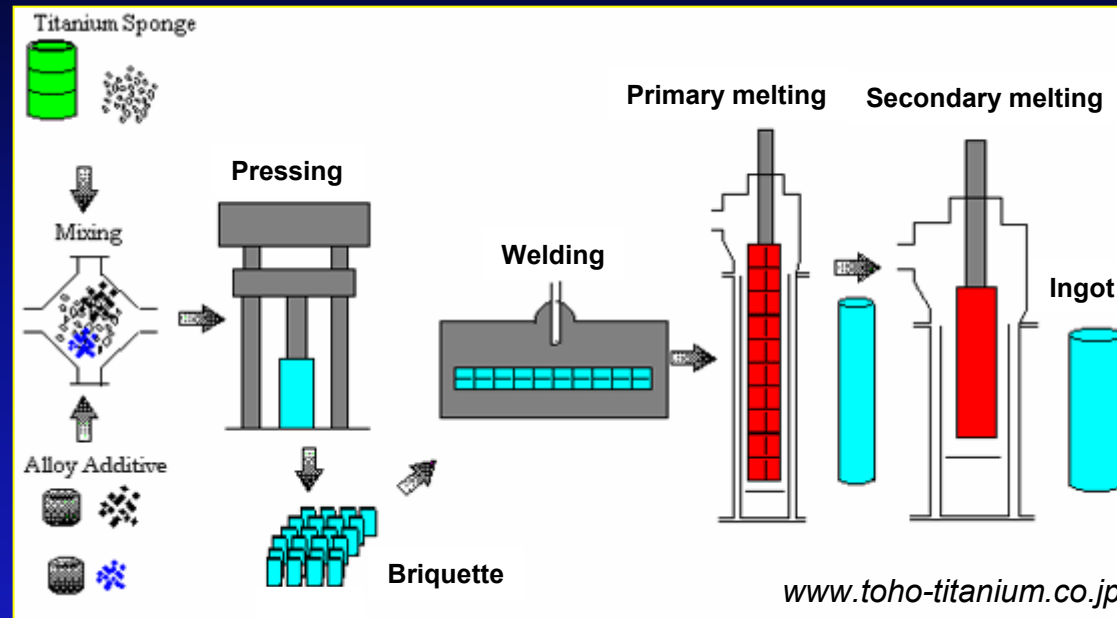
**Titanium sponge**

**Ti sponge  
production based  
on Kroll process**



# Melting of titanium alloys

## Vacuum Arc Refining (VAR) - Process



- **Sponge** and **alloying elements** are blended together and then hydraulically pressed to produce blocks (briquette). **Revert** or scrap can also be used.
- The **briquettes** are welded together to produce **first melt electrode** or 'stick'.
- The electrode is **double or triple melted** in the VAR furnace to produce sound ingot.

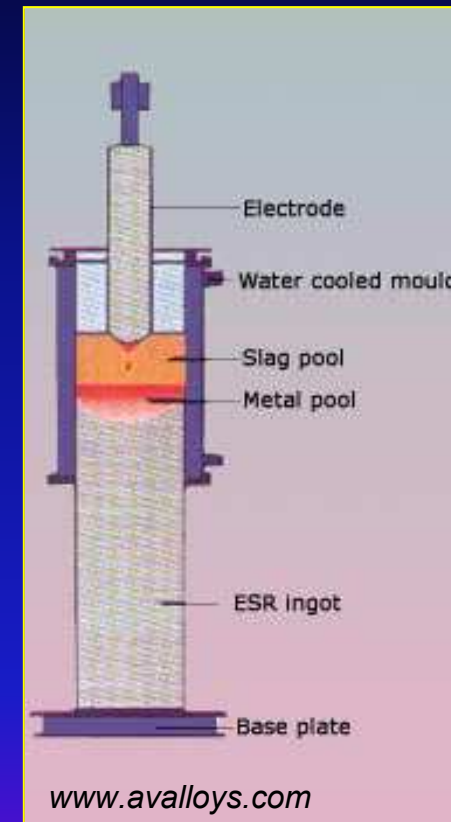




# Melting of titanium alloys

## Electroslag Refining (ESR)

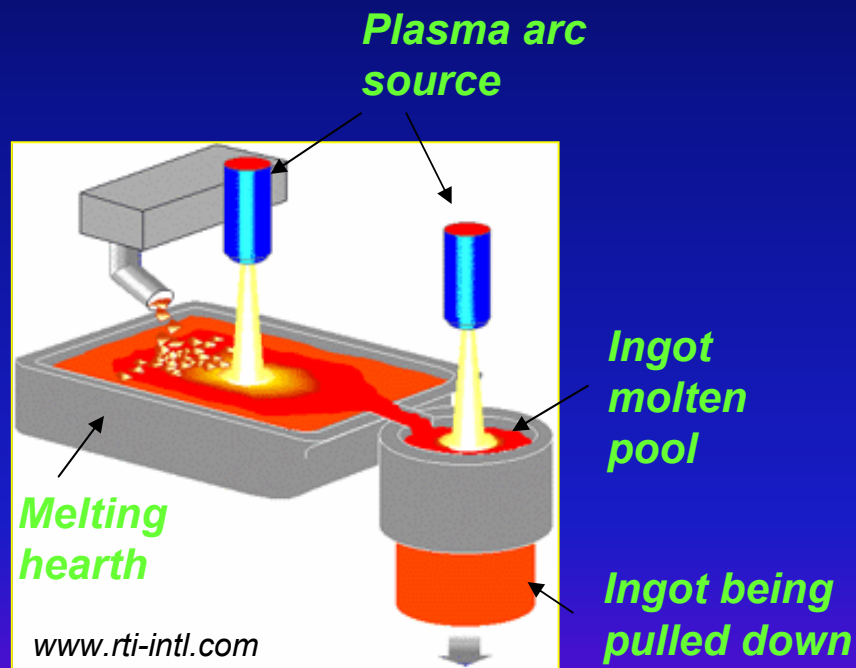
- The continuous billet serves as an **electrode** where its end dips into the slag pool heated by **AC current**.
- Molten metal reacts with **super heated slag** having composition adapted to the molten alloy.
- The intended molten metal drop down through the slag to form **metal pool** and then **solidify** to give ESR ingot.
- The molten metal is refined and **inclusions** are absorbed during the reaction.



# Melting of titanium alloys

## Plasma Arc Melting (PAM)

- Improved method over VAR



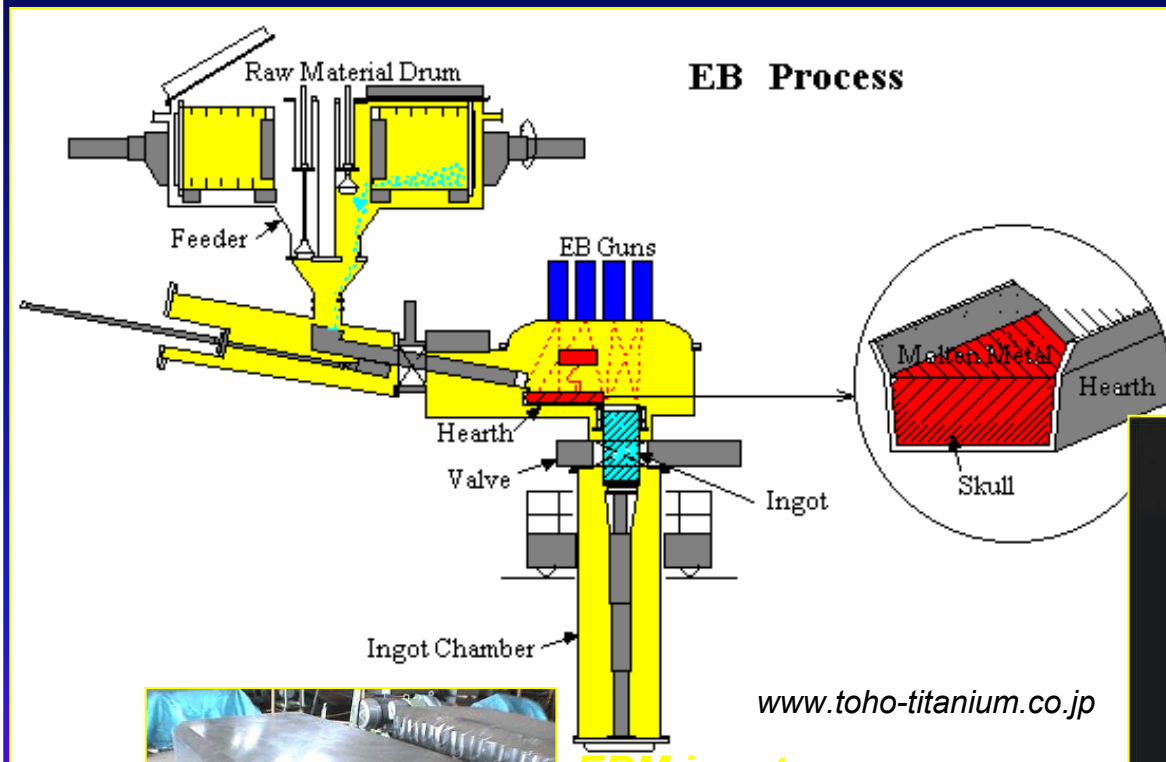
- The metal is melted in a **water-cooled copper vessel (hearth)** using the heat source (**plasma torch or electron beam**).
- The **skull** (solid Ti) is contacted with the hearth and leave the molten titanium alloy floating on the top, preventing **contamination** from the hearth.
- High density **inclusions** are separated on to the bottom of the hearth.



# Melting of titanium alloys

## Electron Beam Melting (EBM)

- Material is fed through the hearth and melted by heat source provided by electron beam similar to PAM.



- The floating metal is on the top of the skull, giving a sound ingot.



**EBM ingot**



[www.antares.com.ua](http://www.antares.com.ua)

**Note:** Used for melting of reactive materials such as Ti, Ni, Ta, Zr.

May-Aug 2007



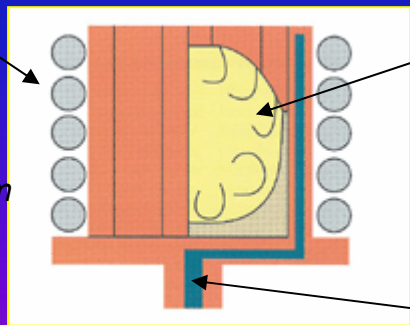
# Melting of titanium alloys

## Induction Skull Melting

- A **water-cooled copper crucible** is used to avoid contamination of reactive materials.
- Metal is charged inside the crucible by induction power source applied by magnetic field.
- The charge is melted and freeze along the bottom and wall, producing a shell or **skull** with molten metal in it.
- **Revert or scrap** can be used.
- Low cost, high quality titanium alloy production.

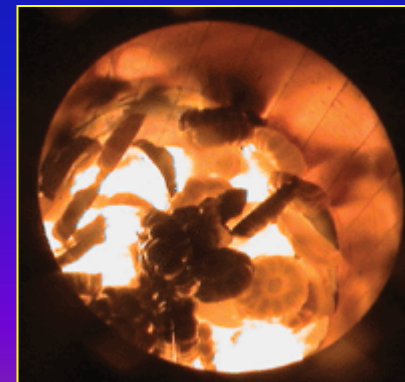
Induction coils

[www.dmgbm.com](http://www.dmgbm.com)



Molten metal in the skull

Water-cooled system

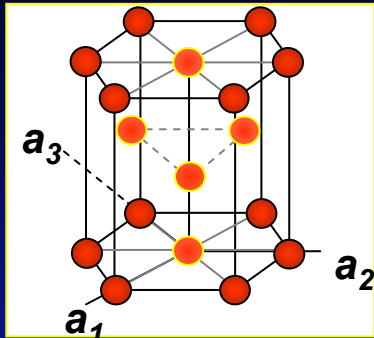


Charged metal melted with ISM

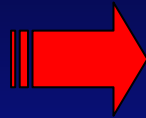
Induction skull melting



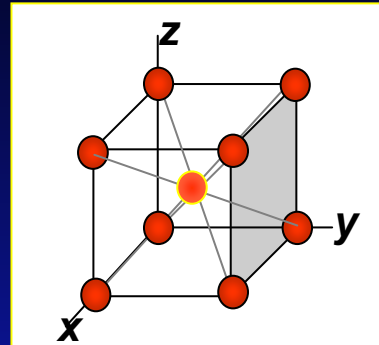
# Alloying system of titanium alloys



Allotropic transformation

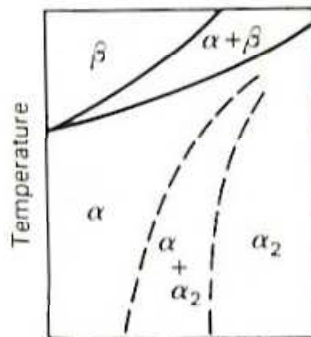


882.3 °C

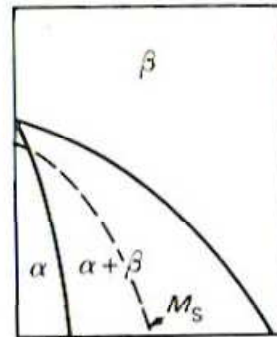


$\alpha$  phase  
HCP structure

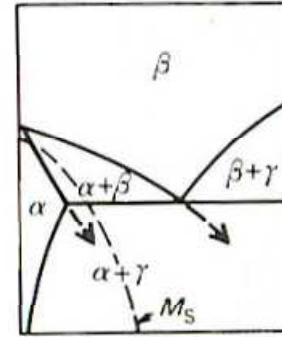
$\beta$  phase  
BCC structure



(a)  $\alpha$  stabilising



(b) Isomorphous  
 $\beta$  stabilising



(c) Eutectoid  
 $\beta$  stabilising

## Alloying elements

### Alpha stabilisers

Al, O, N

### Beta stabilisers

Isomorphous: **Mo, V, W, Nb, Ta.**

Eutectoid: **Fe, Cr, Cu, Ni, Co, Mn.**

### Neutral

**Zr, Si, Sn**



Basic types of phase diagrams for titanium alloys

Suranaree University of Technology

Tapany Udomphol

May-Aug 2007

# Classification of titanium alloys

- **Commercially pure (CP) titanium alpha and near alpha titanium alloys**

- Generally non-heat treatable and weldable
- Medium strength, good creep strength, good corrosion resistance

- **Alpha-beta titanium alloys**

- Heat treatable, good forming properties
- Medium to high strength, good creep strength

- **Beta titanium alloys**

- Heat treatable and readily formable
- Very high strength, low ductility

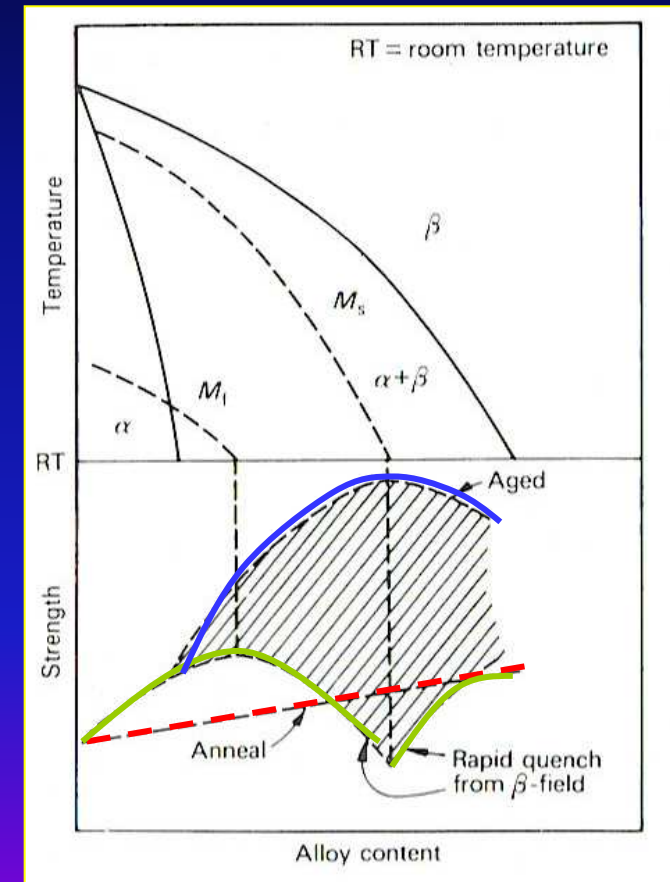
***Different crystal structures and properties → allow manipulation of heat treatments to produce different types of alloy microstructures to suit the required mechanical properties.***



# Basic principal of heat treatment

Heat treatment is mainly applied to  $\alpha/\beta$  and  $\beta$  titanium alloys due to the  $\alpha$ - $\beta$  transformation (typically in the  $\beta$  isomorphous Ti alloy group).

- **Strength** of annealed alloys increases gradually and linearly with increasing **alloy contents**.
- **Quenching** from the  $\beta$  phase field gives a **martensitic transformation** with improved strength (depending on composition).
- For **lowly alloyed Ti**, rapid quenching from the  $\beta$  phase field gives **maximum strength** at  $M_r$ .
- For **highly alloyed Ti**, rapid quenching from  $\beta$  phase field gives lowest strength but after ageing, the **maximum strength** is obtained.



Heat treatment diagram of  $\beta$  isomorphous titanium alloys



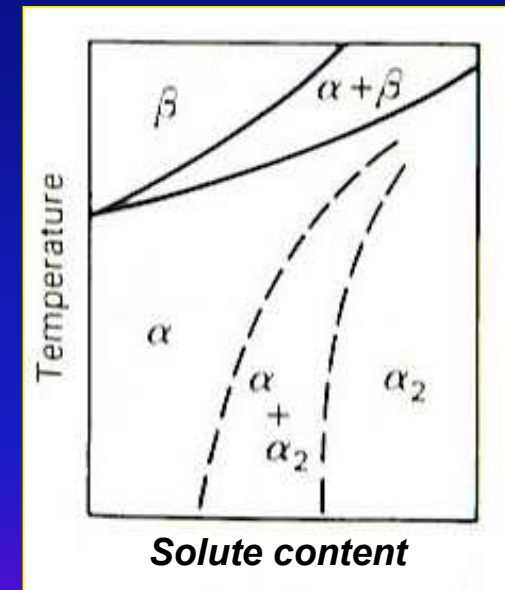
# Commercially pure (CP) titanium and alpha/near alpha alloys

Microstructure contains **HCP**  $\alpha$  phase and can be divided into;

- **Commercially pure titanium alloys**
- **Alpha titanium alloys**
- **Near alpha titanium alloys**

## Characteristics:

- Non-heat treatable
- Weldable.
- Medium strength
- Good notch toughness
- Good creep resistance at high temperature.



**Phase diagram of  $\alpha$  stabilised Ti alloy.**

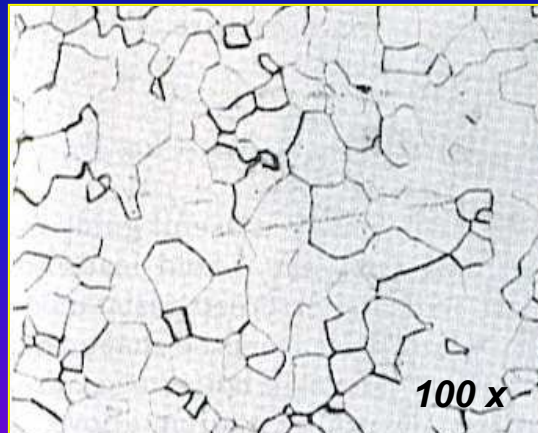


# Microstructure of commercially pure (CP) titanium alloys

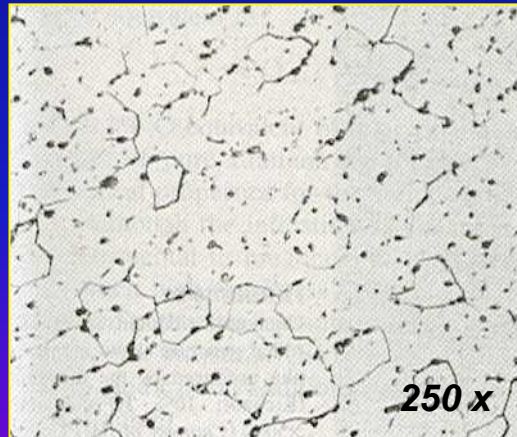
- Purity 99.0-99.5%, **HCP** structure.
- **Main elements** in unalloyed titanium are **Fe** and interstitial elements such as **C, O, N, H**.
- **O** content determines the **grade** and **strength**.
- **C, N, H** present as **impurities**. **H** → embrittlement.

**Oxygen equivalent**

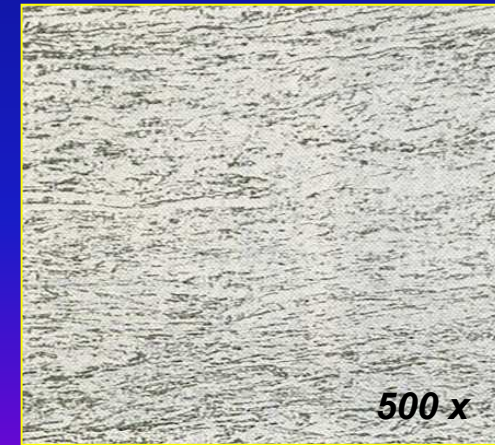
$$\%O_{equiv} = \%O + 2.0\%N + 0.67\%C$$



**HCP  $\alpha$  phase structure**



**HCP  $\alpha$  phase structure with  $\beta$  spheroidal particles due to 0.3% Fe as impurity**



**Hot-rolled structure**



# Properties and typical applications of commercially pure (CP) titanium alloys

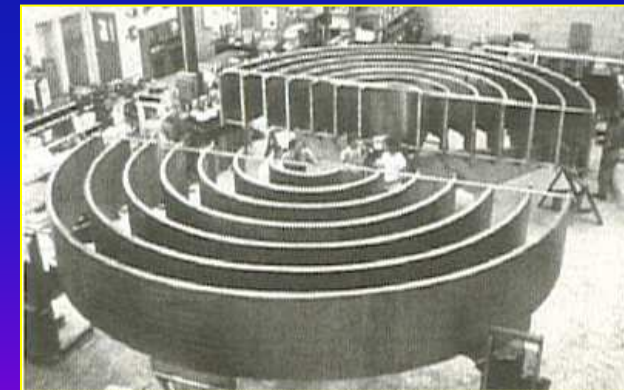
## Properties

- Lower strength, depending on contents of **O, N**.
- Corrosion resistance to nitric acid, moist chlorine.
- 0.2% **Pd** addition improves corrosion resistance in **HCl, H<sub>2</sub>SO<sub>4</sub>, H<sub>3</sub>PO<sub>4</sub>**.
- Less expensive

## Applications:

- Airframes, heat exchangers, chemicals, marine, surgical implants.

**Plate and frame heat exchanger**



**Large structure used in bleaching section of pulp and paper**



# Compositions and applications of commercially pure (CP) titanium alloys

Chemical compositions (maximum values) and typical applications of unalloyed titanium†

% Ti	Grade	ASTM No.	% C	% Fe	% N	% O	% H	Typical applications
99.5	1	B265	0.08	0.20	0.03	0.18	0.015	Airframes; chemical, desalination, and marine parts; plate-type heat exchangers; cold-spun or pressed parts; platinized anodes; high formability.
99.2	2	B265	0.08	0.25	0.03	0.20	0.015	Airframes; aircraft engines; marine chemical parts; heat exchangers; condenser and evaporator tubing; formability.
99.1	3	B265	0.08	0.25	0.05	0.30	0.015	Chemical, marine, airframe, and aircraft engine parts which require formability strength, weldability, and corrosion resistance.
99.0	4	B265	0.08	0.50	0.05	0.40	0.015	Chemical, marine, airframe, and aircraft engine parts; surgical implants; high-speed fans; gas compressors; good formability and corrosion resistance, high strength.

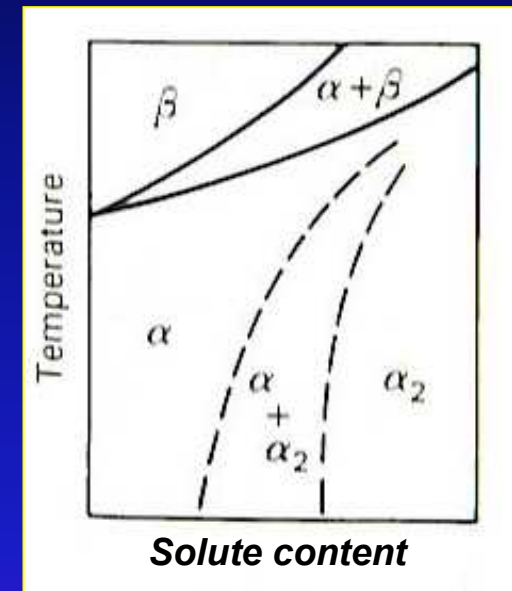
† After "ASM Databook," published in *Met. Prog.*, mid-June, vol. 114, no. 1, 1978.



# Alpha titanium alloy

$\alpha$  stabilisers are more soluble in the  $\alpha$  phase and raise the  $\beta$  transus temperature.

- **Al** and **O** are the main **alloying elements**, which provide **solid solution strengthening**. **O** and **N** present as impurities give **interstitial hardening**.
- The amount of  **$\alpha$  stabilisers** should not exceed 9% in the **aluminium equivalent** to prevent embrittlement due to ordering.
- 5-6% **Al** can lead to a finely dispersed, **ordered phase** ( $\alpha_2$ ), which is coherent to lattice. → **deleterious ductility**.
- **Sn** and **Zr** are also added in small amount to stabilise the  $\alpha$  phase and give **strength**.



Phase diagram of  $\alpha$  stabilised Ti alloy

**Aluminium equivalent**

$$\%Al_{equiv} = Al + \frac{1}{3}Sn + \frac{1}{6}Zr + 10(O + C + 2N) \leq 9\%$$



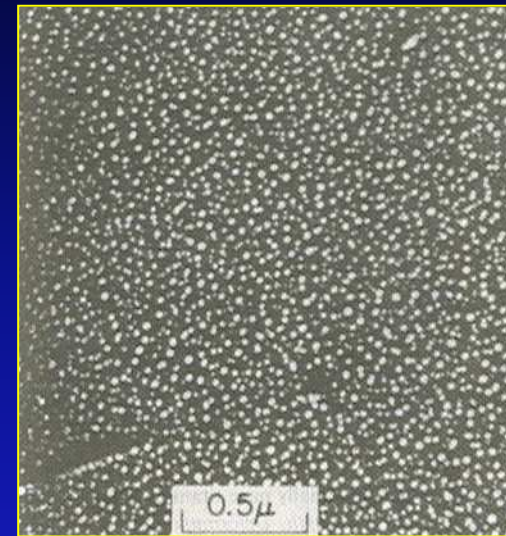
# Alpha titanium alloys

## Microstructure



*Ti-5%Al-2.5% Sn alloy in sheet form*

- **Sn** is added to improve ductility.
- Spheroidal  **$\beta$**  phase is due to 0.3% **Fe** as impurity.



*Homogeneous  $\alpha_2$  precipitation on dislocations in aged Ti 8%Al with 1780 ppm of O*

- >5-6% **Al** addition produces coherent ordered  $\alpha_2$  phase ( **$Ti_3Al$** )  $\rightarrow$  embrittlement.
- **Co-planar dislocations** are produced  $\rightarrow$  early fatigue cracking.



# Alpha titanium alloys

## Properties

- Moderate strength.
- **Strength** depends on **O** and **Al** contents. (**Al** <5-6%).
- **Al** also reduces its density.
- **Good oxidation resistance** and strength at 600 to 1100°F.
- Readily weldable.

## Applications:

- Aircraft engine compressor blades, sheet-metal parts.
- High pressure cryogenic vessels at -423°C.

Chemical compositions and typical applications of  $\alpha$  titanium alloys†

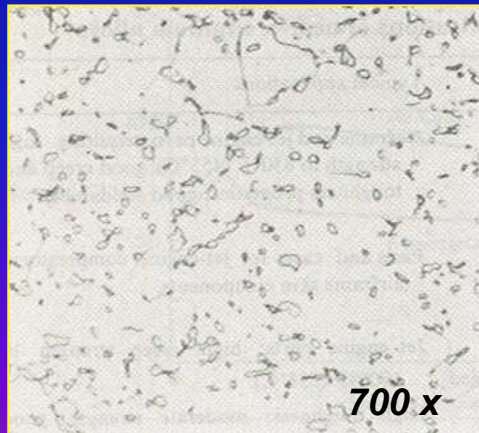
$\alpha$ Alloys	Condition	Typical applications
5% Al, 2.5% Sn	Annealed	Weldable alloy for forgings and sheet-metal parts such as aircraft engine compressor blades and ducting; steam turbine blades; good oxidation resistance and strength at 600 to 1100°F; good stability at elevated temperatures.
5% Al, 2.5% Sn (low O <sub>2</sub> )	Annealed	Special grade for high-pressure cryogenic vessels operating down to -423°F.

† After "ASM Databook," published in *Met. Prog.*, mid-June, vol. 114, no. 1, 1978.

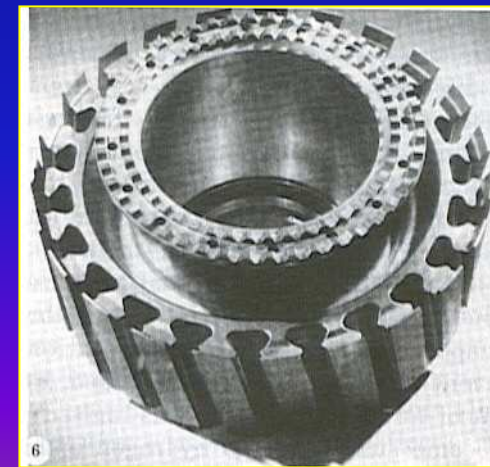


# Near-alpha titanium alloys

- Small amounts of  $\beta$  stabilisers (**Mo, V**) are added, giving a **microstructure** of  $\beta$  phase dispersed in the  $\alpha$  phase structure.  
→ improved performance and efficiency.
- **Sn** and **Zr** are added to compensate **Al** contents while **maintaining strength** and ductility.
- Show **greater creep strength** than fully  $\alpha$  Ti alloy up to 400°C.
- **Ti-8Al-1Mo-1V** and **Ti-6Al-2Sn-4Zr-Mo** alloys are the most commonly used for aerospace applications, i.e., airframe and engine parts.



**Duplex annealed Ti-8Al-1Mo-1V**



**Forged compressor disc made from neat alloy IMI 685**

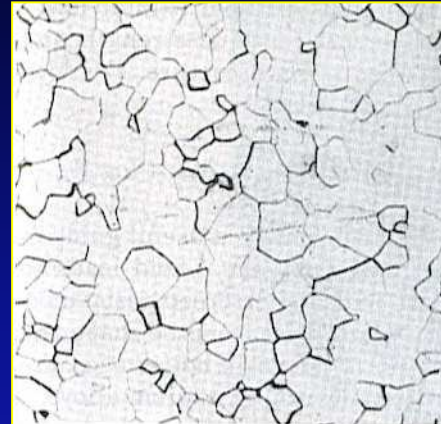


# Heat treatment in CP and alpha titanium alloys

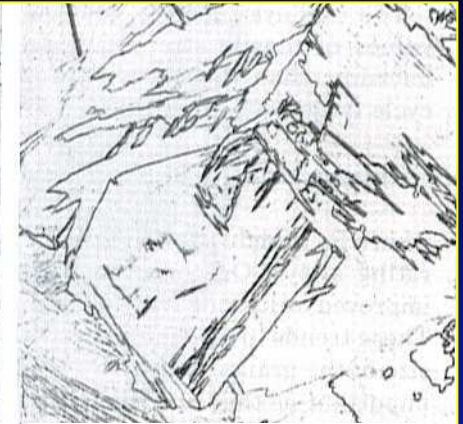
## Treatment from the $\beta$ phase field

- **Annealing of CP Ti** at high temperature gives a **HCP  $\alpha$**  phase structure, *fig (a)*.
- **Quenching of CP Ti** from the  $\beta$  phase field change the **HCP** structure to the **hexagonal martensitic  $\alpha'$**  phase with remained  $\beta$  grains, *fig (b)*.
- **Air-cooling of CP Ti** from the  $\beta$  phase field produces **Widmanstätten  $\alpha$**  plates, *fig (c)*.

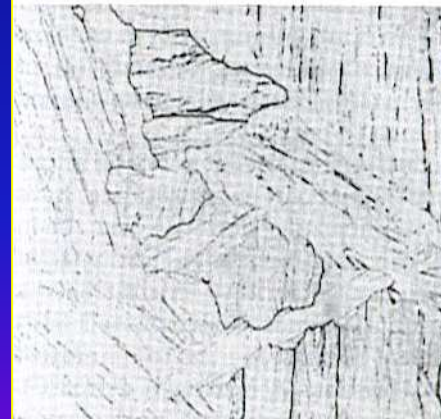
*Note: This transformation contribute to only little strength.*



(a) Annealed at 700°C/1h.



(b) Quenched from  $\beta$  phase field.



(c) Air-cooled from  $\beta$  phase field.

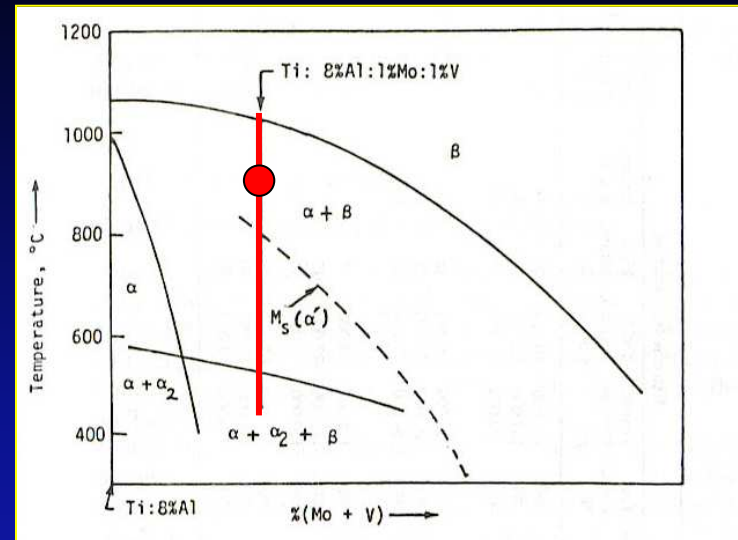
**Microstructure of CP Ti alloy.**



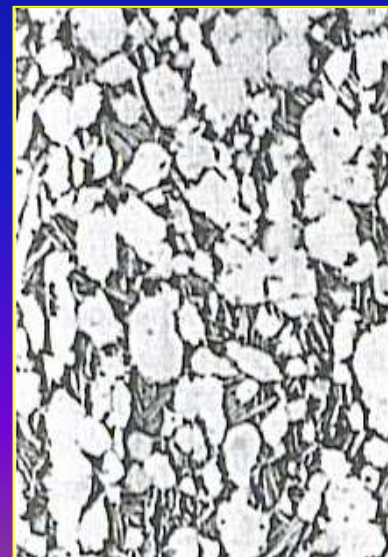
# Heat treatment in near $\alpha$ titanium alloys

## Heat-treated from $\alpha+\beta$ phase field

- Alloys should contain **high amount of  $\alpha$  stabilisers** without severe loss of ductility.
- Small amounts of **Mo** or **V** (beta stabilisers) are added to promote the **response to heat-treatment**.
- The alloy is heated up to **T** to obtain equal amount of  $\alpha$  and  $\beta$  phases.
- Air-cooling** gives equiaxed primary  $\alpha$  phase and **Widmanstätten  $\alpha$**  formed by nucleation and growth from the  $\beta$  phase, **fig.**
  - Faster cooling** transforms  $\beta$  into martensitic  $\alpha'$  which gives higher strength.



Pseudo-binary diagram for Ti-8%Al with Mo and V addition



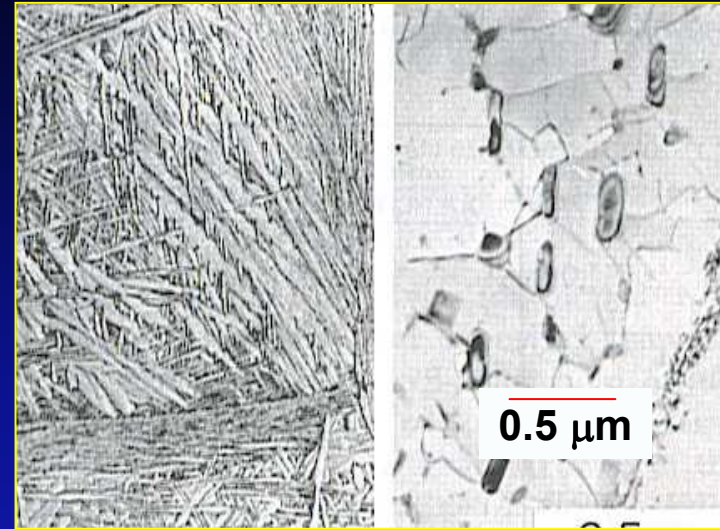
IMI679 Air-cooled from  $\alpha+\beta$  phase field, having white primary  $\alpha$  phase and Widmanstätten  $\alpha$



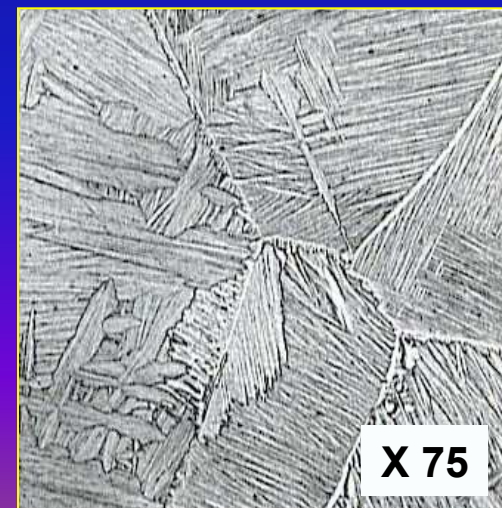
# Heat treatment in near $\alpha$ titanium alloys

## Heat-treated from $\beta$ phase field

- **Quenching** from the  $\beta$  phase field produces laths of martensitic  $\alpha'$ , which are delineated by thin films of  $\beta$  phase.
- **Ageing** causes precipitation of fine  $\alpha$  phase dispersion.
- **Air-cooling** from the  $\beta$  phase field gives a basket weave structure of **Widmanstätten**  $\alpha$  phase delineated by  $\beta$  phase, *fig (b)*.



(a) Near  $\alpha$  Ti (IMI 685) oil-quenched,  
(b) quenched from  $\beta$  phase field and aged at 850°C



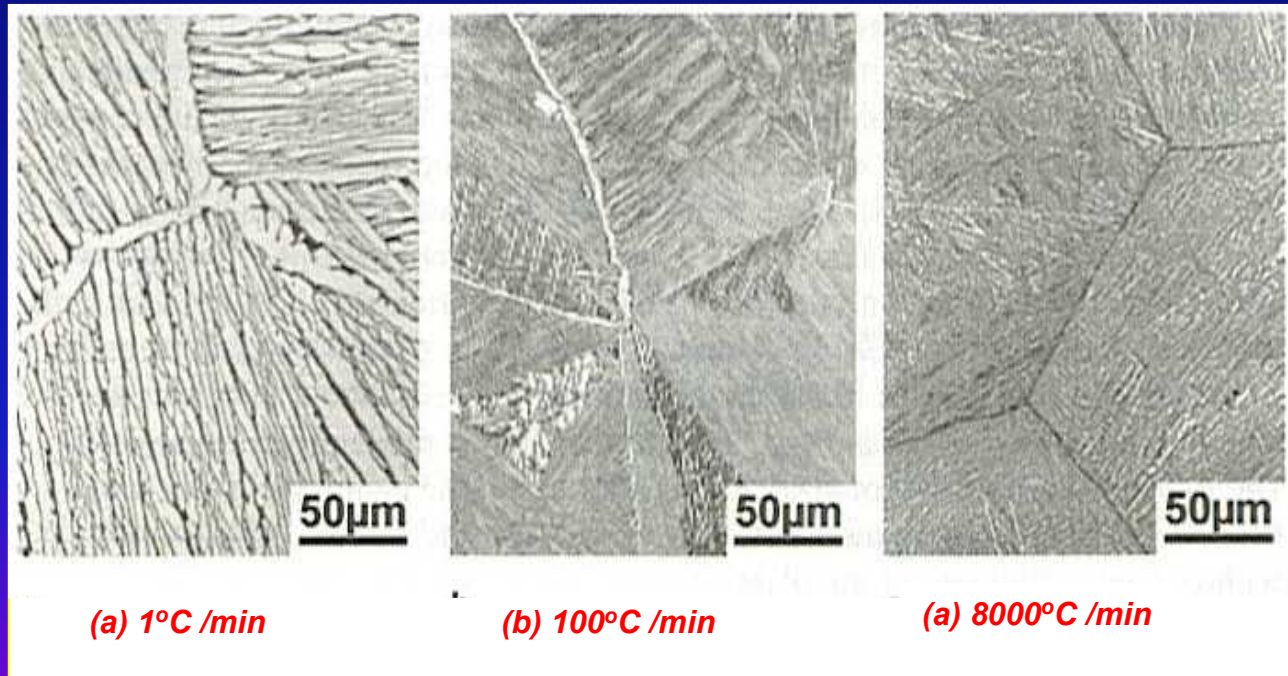
(b) Near  $\alpha$  Ti (IMI 685) air-cooled from the  $\beta$  phase field



# Heat treatment in near $\alpha$ titanium alloys

Effects of cooling rate from  $\beta$  phase field in lamellar microstructure

Increasing cooling rate



Effects of cooling rate from the beta phase field on lamellar microstructure in Ti 6242 alloy

# Near alpha titanium alloys

## Properties

- **Moderately high strength** at **RT** and relatively **good ductility** (~15%).
- High toughness and good creep strength at high temperatures.
- Good weldability.
- Good resistance to **salt-water** environment.

## Applications:

- Airframe and jet engine parts.

Chemical compositions and typical applications of near- $\alpha$  titanium alloys†

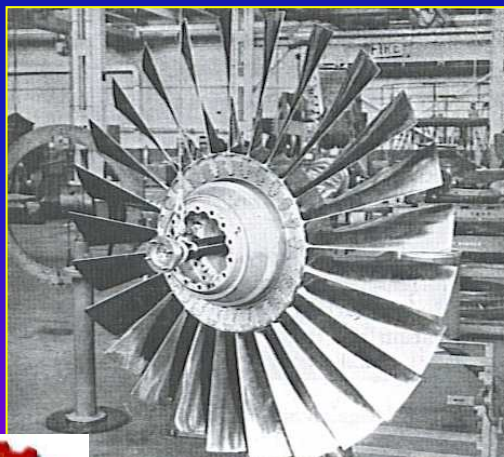
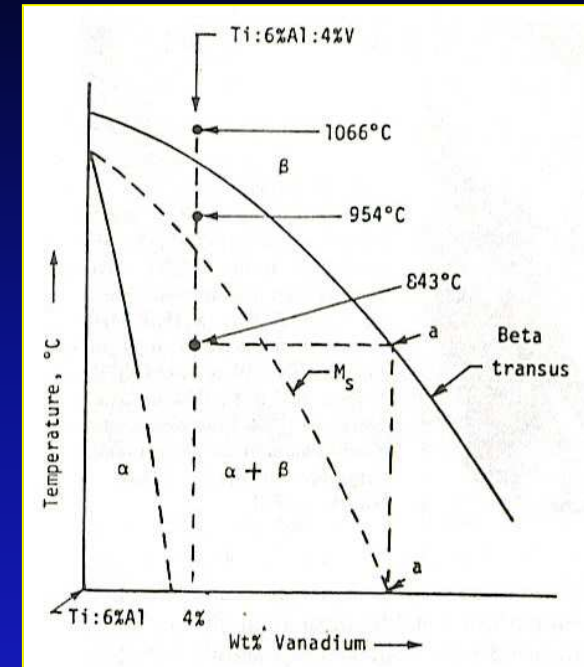
Composition	Condition	Typical applications
8% Al-1% Mo-1% V	Duplex-annealed	Airframe and jet-engine parts requiring high strength to 850°F (455°C); good creep and toughness properties; good weldability.
6% Al-2% Sn-4% Zr-2% Mo		Parts and cases for jet-engine compressors; airframe skin components.
5% Al-5% Sn-2% Zr-2% Mo-0.25% Si	975°C ( $\frac{1}{2}$ h) air-cooled, + 600°C (2h) air-cooled	Jet engine parts; high creep strength to 1000°F (538°C).
6% Al-1% Mo-2% Cb-1% Ta	As-rolled, 1-in plate	High toughness; moderate strength; good resistance to sea water and hot-salt stress corrosion; good weldability.

† After "ASM Databook," published in *Met. Prog.*, vol. 114, no. 1, mid-June 1978.



# Alpha-beta titanium alloys

- **Alpha-beta titanium alloys** contain both  $\alpha$  and  $\beta$ .
- **$\alpha$  stabilisers** are used to give strength with 4-6%  **$\beta$  stabilisers** to allow the  $\beta$  phase to retain at *RT* after quenching from  $\beta$  or  $\alpha+\beta$  phase field.
- Improved strength and formability in comparison to  $\alpha$ -Ti alloys.
- **Ti-6Al-4V** (IMI 318) is the most widely commercially used.



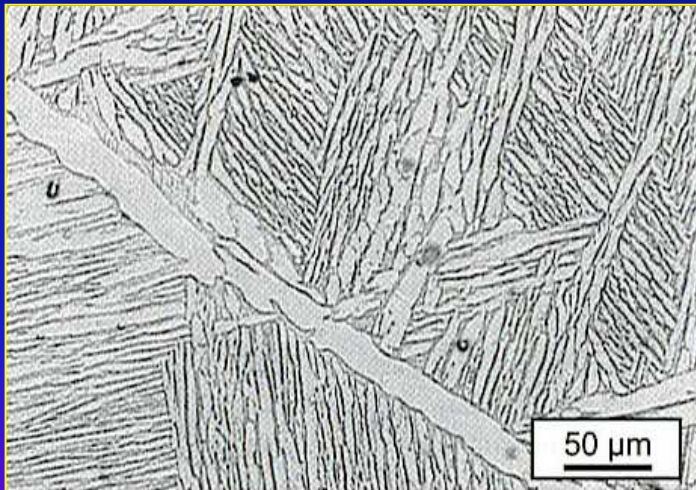
**Forged Ti-6-4 blades**

- Microstructure depends on **chemical composition**, **processing history and heat treatments**, i.e., annealing, quenching and tempering.
- **Heat treatment** can be done in corporation with **thermo-mechanical processes** to achieve desired microstructure/properties.



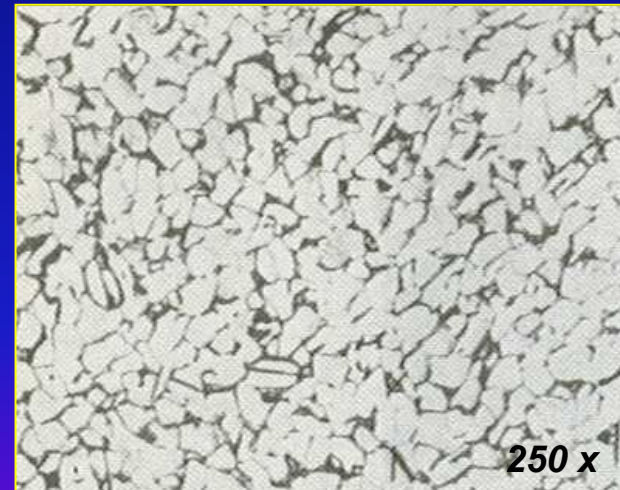
# Annealing from $\beta$ or $\alpha+\beta$ phase field

- **Annealing** from the  $\beta$  phase field ( $\beta$  annealed) causes a transformation from  $\beta$  to  $\alpha$  microstructure containing **lamellar structure** of similar crystal orientation.



Annealed from  $\beta$  phase field, showing transformed  $\beta$  phase or lamellar (basket weaves) microstructure of Ti-6Al-4V

- **Annealing** from the  $\alpha+\beta$  phase field (mill annealed) produces microstructure approaching equilibrium equiaxed primary  $\alpha$  phase surrounding with **retained  $\beta$  phase**.

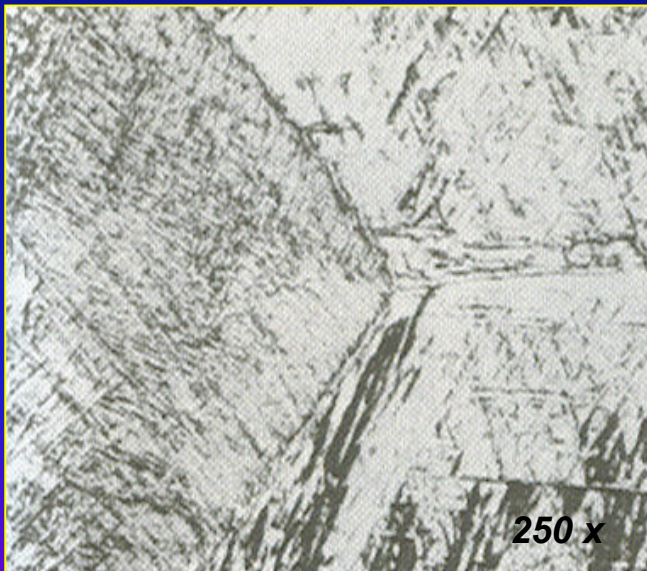


Annealed from  $\alpha+\beta$  phase field, showing equiaxed  $\alpha$  grains (light) with intergranular retained beta (dark)



# Air cooling from $\beta$ and $\alpha+\beta$ phase field.

- **Air cooling** provides intermediate cooling rates.
- **Air cooling** from the  **$\beta$  phase** field produces ***fine acicular  $\alpha$*** , which is transformed from the  **$\beta$  phase** by nucleation and growth.
- **Air cooling** from the  **$\alpha+\beta$  phase field** provides equiaxed ***primary  $\alpha$  phase*** in a matrix of ***transformed  $\beta$  phase*** (acicular).



**Air-cooled from  $\beta$  phase field giving transformed  $\beta$  phase (acicular)**

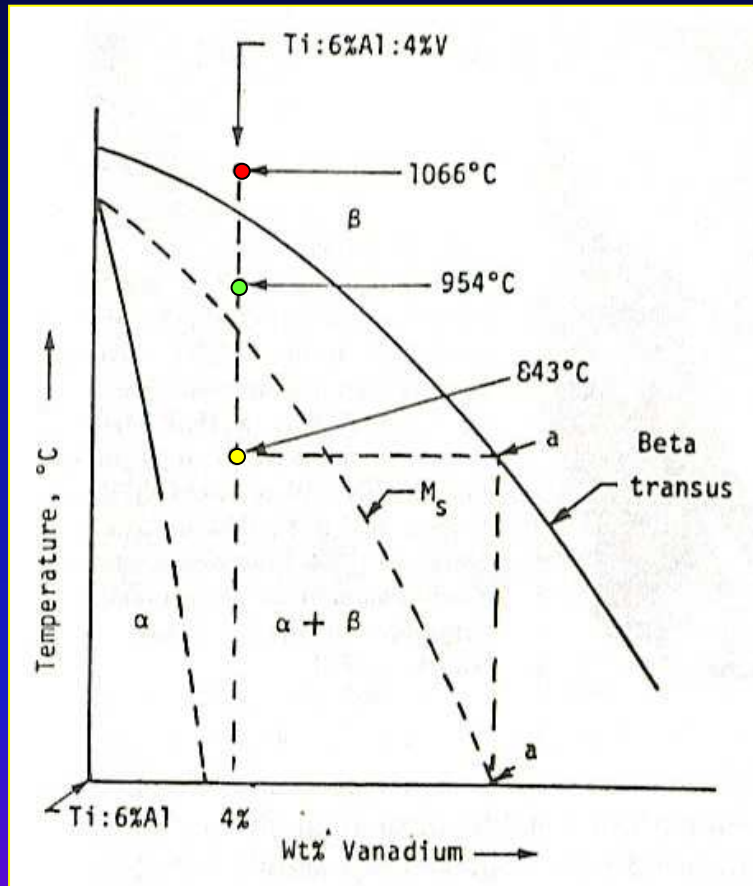


**Air-cooled from  $\alpha+\beta$  phase field, showing primary  $\alpha$  grains in a matrix of transformed  $\beta$  (acicular)**



# Alpha-beta titanium alloys

## Heat treatment

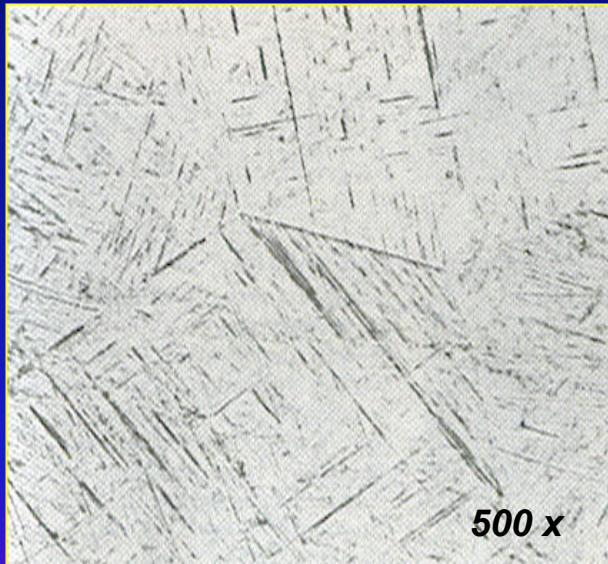


- Annealing from the  $\beta$  and  $\alpha + \beta$  phase field.
- Air cooling from the  $\beta$  and  $\alpha + \beta$  phase field.
- Quenching from  $\beta$  and  $\alpha + \beta$  phase fields.
- Tempering of titanium martensite
- Decomposition of metastable  $\beta$



# Quenching from $\beta$ phase field

- The alloy experiences *martensitic transformation* when quenched from the  $\beta$  phase field passing through  $M_s$ .
- **Martensite  $\alpha'$**  consists of individual platelets which are heavily twinned and have **HCP** crystal structure.



*Ti-6-4 alloy solution-heat-treated at 1066°C/30min and water quenched*

Rapid transformation increases dislocation density



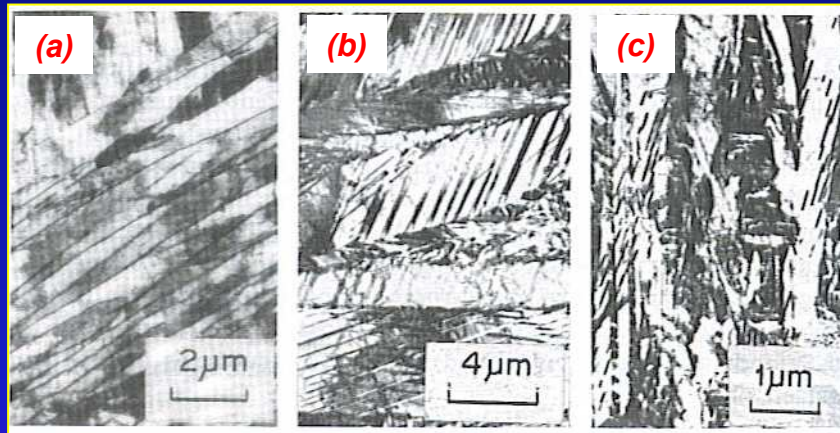
Increase hardness (strength) but not as high as in steel.

**Note:** Following tempering and ageing at elevated temperature lead to decomposition of martensite.

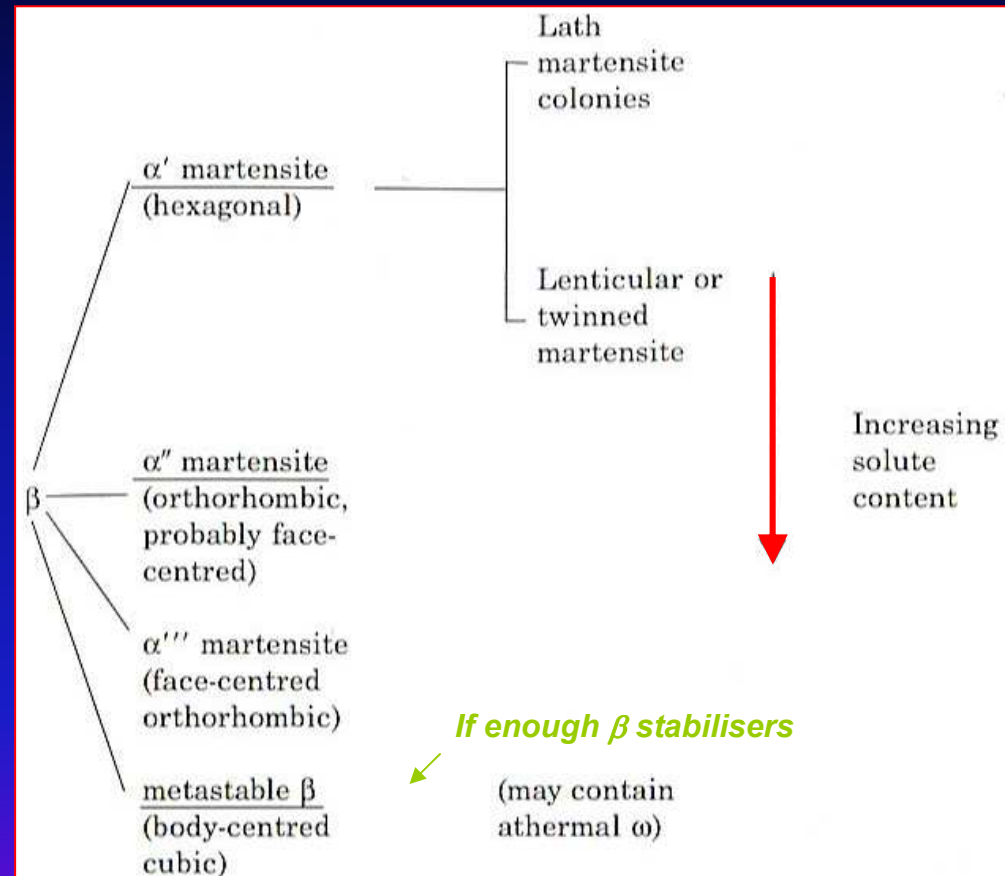


# Quenching from $\beta$ phase field

- **Martensite** of different crystal structure.
- Increasing solute,  $\alpha' \rightarrow \alpha''$



(a) Hexagonal  $\alpha'$  lath, (b) hexagonal lenticular  $\alpha'$ , (c) orthorhombic  $\alpha''$



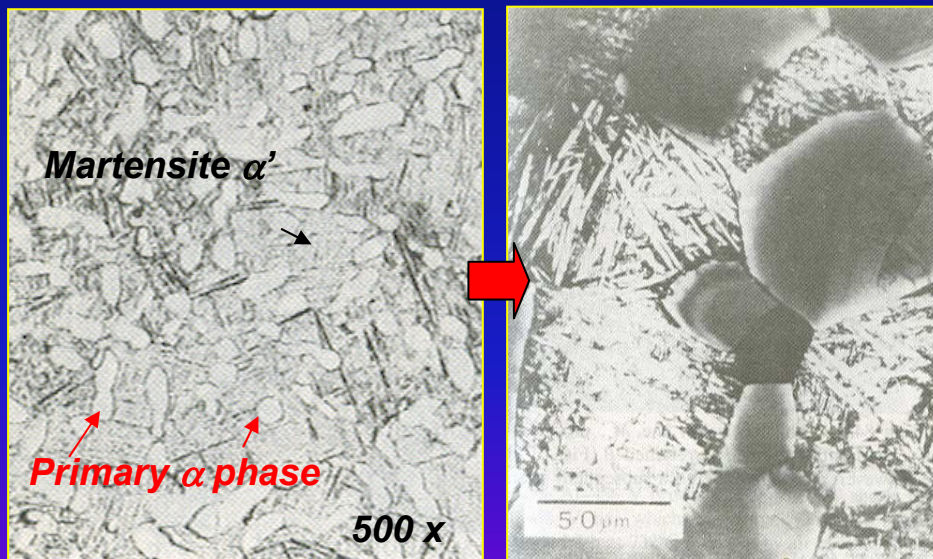
**Possible reactions due to quenching from the  $\beta$  phase field**



# Quenching from $\alpha+\beta$ phase field

**Below  $\beta$  transus but above  $M_s$**

- Microstructure consists of **primary  $\alpha$**  phase embedded in **transformed  $\beta$**  phase ( $\alpha'$  martensite).



**Ti-6-4 alloy solution treated at 954°C and then water quenched**

**Below  $M_s$**

- Microstructure consists of **primary  $\alpha$**  phase and small amount of **retained or untransformed  $\beta$** .



**Ti-6-4 alloy solution treated at 843°C and then water quenched**



# Tempering of titanium martensite

- **Decomposition of martensitic structure** occurs when a quenched alloy is subject to subsequent elevated temperature treatments.
- Decomposition reaction depends upon **martensite crystal structure** and **alloy composition**.

<i>α'</i> martensite		
β-isomorphous alloys	$\alpha' \rightarrow \alpha + \beta$	
	Alloys with slow eutectoid reactions e.g. Ti-Mn	$\alpha' \rightarrow \alpha + \beta \rightarrow \alpha + \text{compound}$
β-eutectoid alloys		
<i>α''</i> martensite		
	Alloys with high $M_s(\alpha'')$ temperature	$\alpha'' \rightarrow \alpha'' + \alpha \rightarrow \alpha'' + \alpha + (\alpha + \beta) \rightarrow \alpha + \beta$ (cellular reaction)



# Decomposition of metastable $\beta$

- **Retained  $\beta$**  obtained after quenching **decomposes** when subjected to ageing at elevated temperatures.  $\rightarrow$  developing high tensile strength.
- The **metastable  $\beta$**  is transformed into **equilibrium  $\alpha$  phase** at high ageing temperatures due to difficulty in nucleating **HCP  $\alpha$  phase** on **BCC  $\beta$  matrix**.

## Medium alloy content

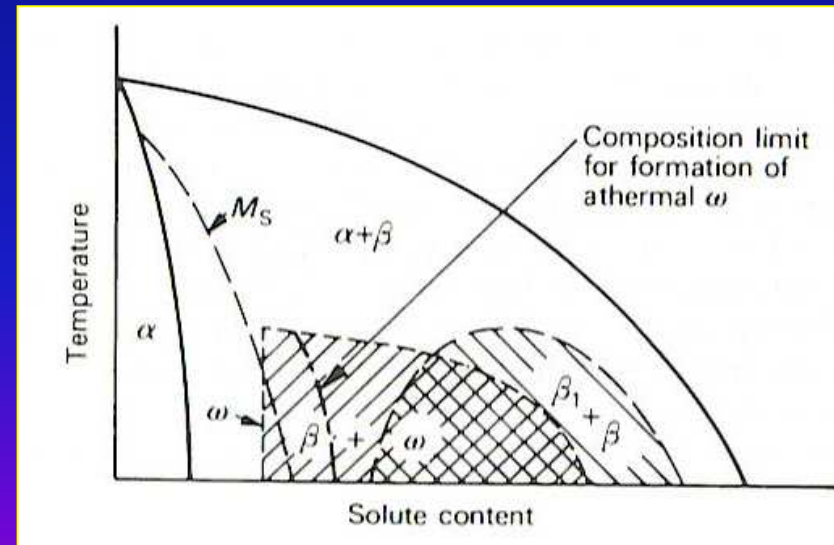
100- 500°C       $\beta \rightarrow \beta+\omega \rightarrow \beta+\alpha$

## Concentrated alloys

200- 500°C       $\beta \rightarrow \beta+\beta_1 \rightarrow \beta+\alpha$   
> 500°C           $\beta \rightarrow \beta+\alpha$

## Possible reactions

- $\omega$  phase formation
- $\beta$  phase separation
- Equilibrium  $\alpha$  phase formation



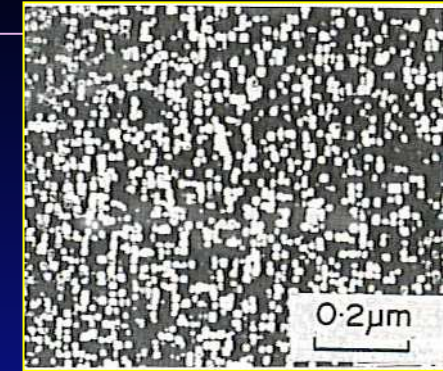
**$\beta$  isomorphous alloy phase diagram**



# Decomposition of metastable $\beta$

$\omega$  phase  $\rightarrow$  embrittlement

- Appears as *very fine dispersion particles* after *metastable  $\beta$*  is isothermally aged at 100-500°C
- Avoided by controlling *ageing conditions*, temp (475°C), composition.



Dense dispersion of cuboids of  $\omega$  phase

$\beta$  phase separation  $\rightarrow$  not significantly important

- $\beta$  phase separation into two **BCC** phases  $\beta \rightarrow \beta_{(enrich)} + \beta_{1(depleted)}$  occurs in *high  $\beta$  stabiliser containing alloy* to prevent  $\omega$  formation.
- This  $\beta$  phase will slowly transform into equilibrium  $\alpha$  phase

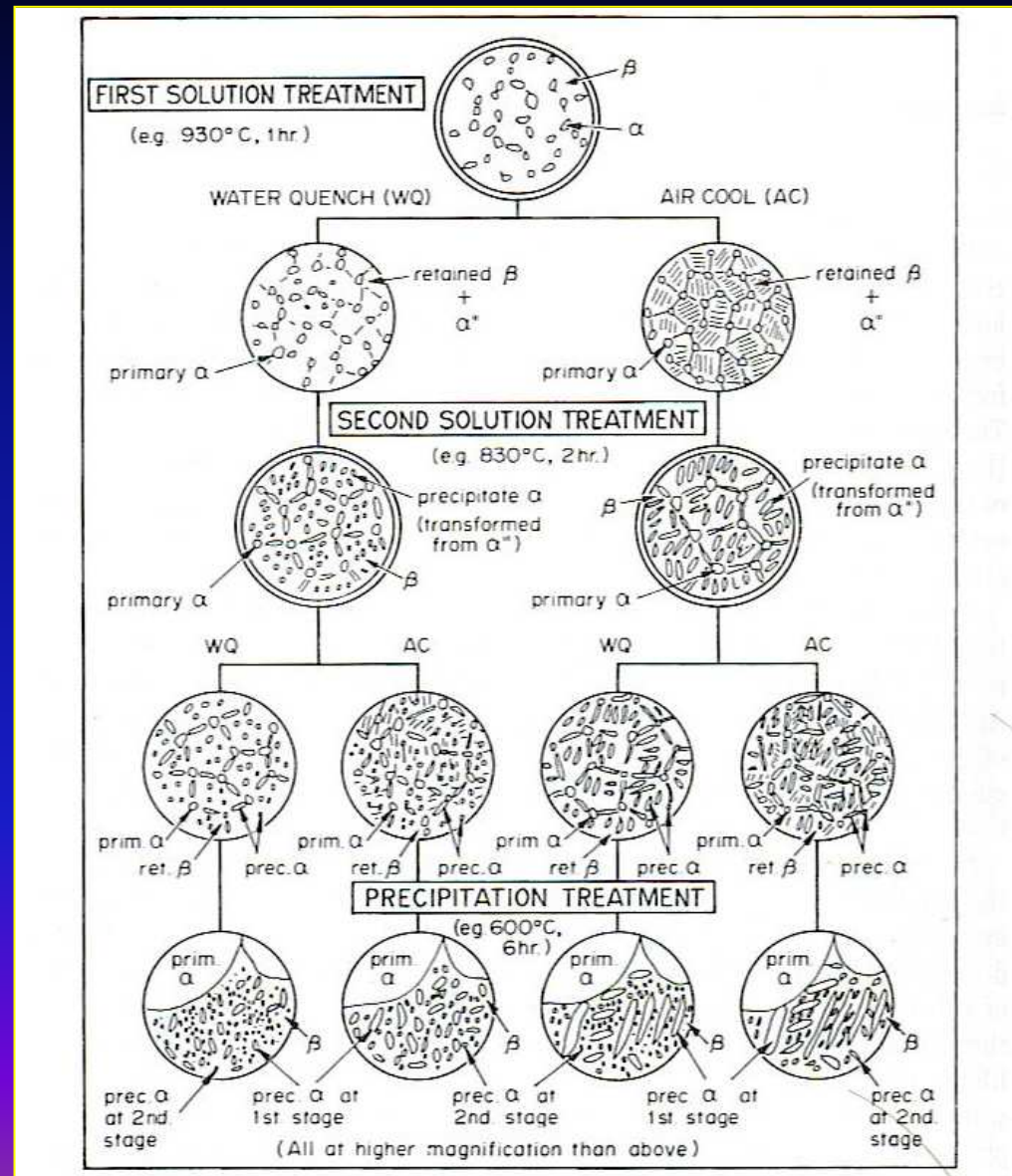
Equilibrium  $\alpha$  phase formation  $\rightarrow$  strength

- Equilibrium  $\alpha$  phase can form directly from  $\beta$  phase or indirectly from  $\omega$  or  $\beta_1$ .

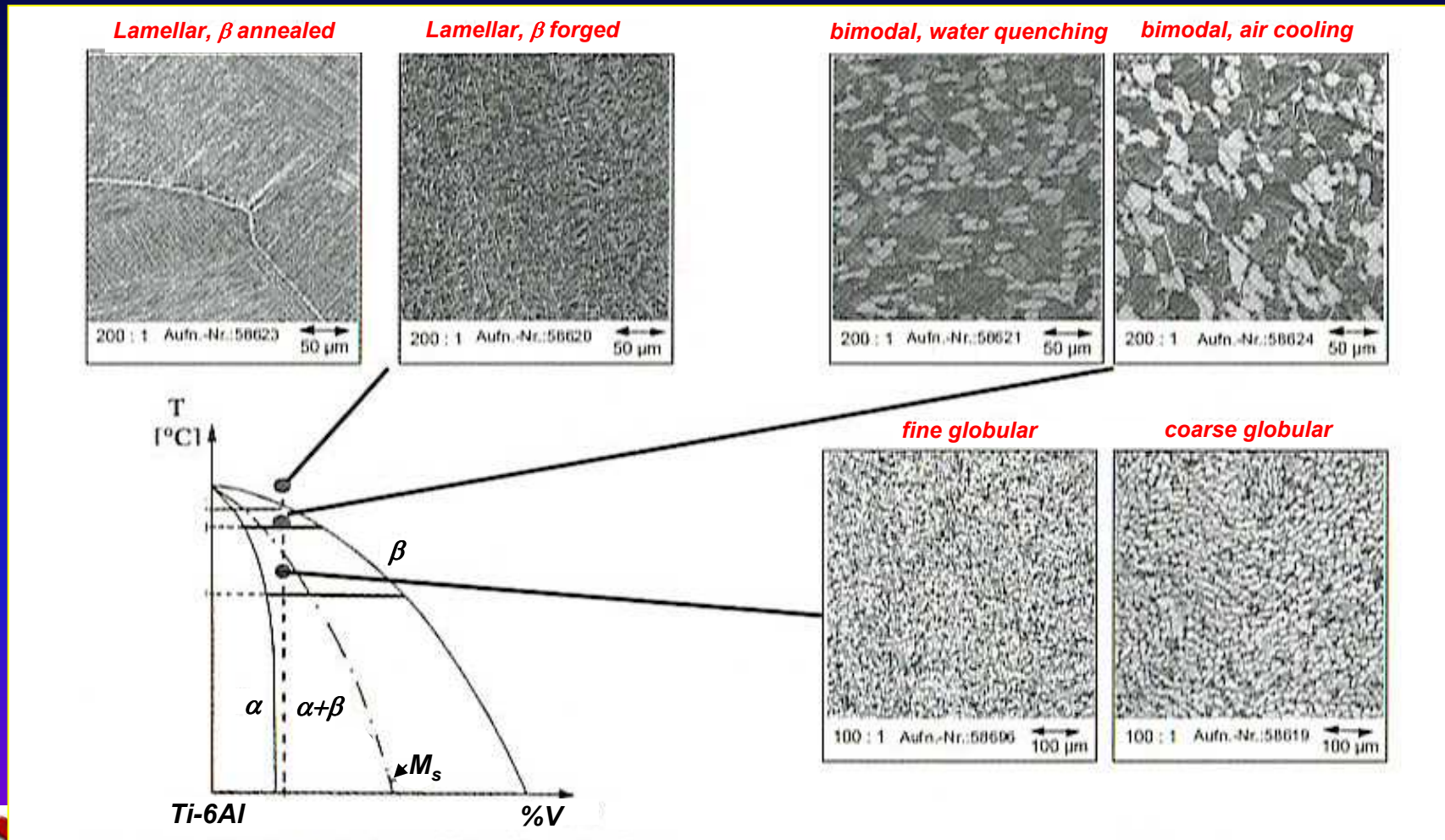
- Laths of Widmanstätten  $\alpha$
- Finely dispersed  $\alpha$  particles



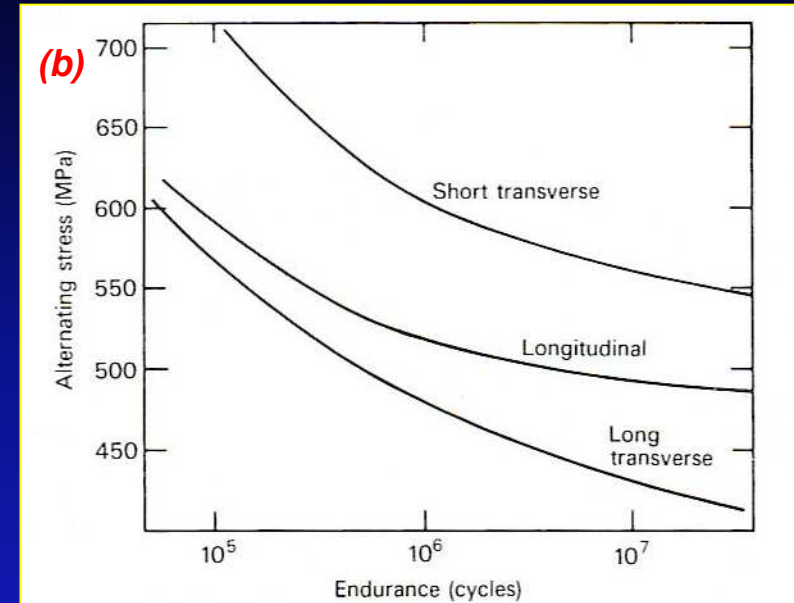
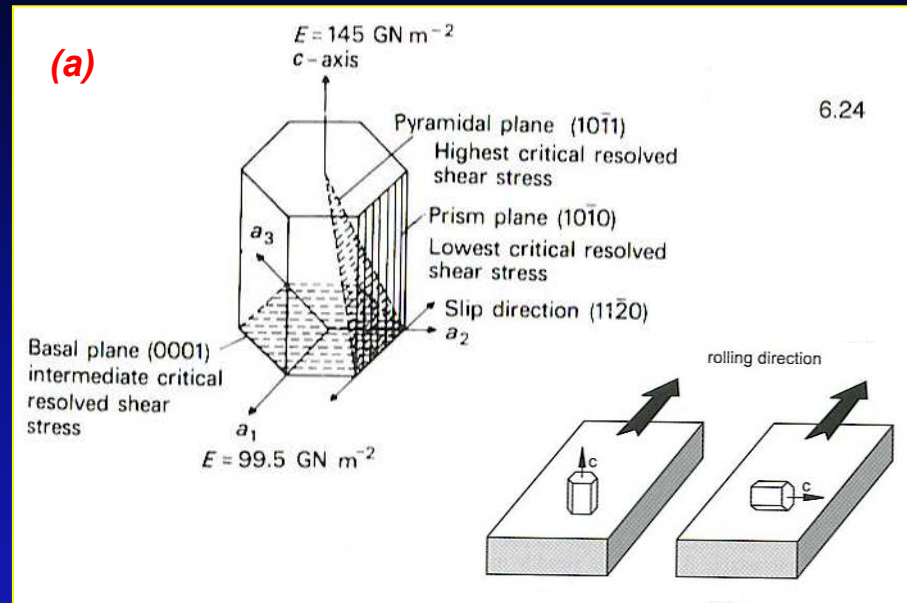
# Double solution treatments



# Microstructure vs heat treatment in Ti-6Al-4V alloys



# Anisotropic properties of Ti-6Al-4V alloys



(a) Slip planes in HCP  $\alpha$  Ti alloy and alignment of unit cell showing strongly preferred orientation.

(b) Fatigue endurance limit of three different conditions in Ti-6Al-4V alloy.

**Table 6.5** Mechanical properties of 57 mm thick  $\times$  235 mm wide forged and annealed Ti-6Al-4V bar (from Bowen, A. W., in *Titanium Science and Technology*, R. I. Jaffee and H. M. Burte (Eds), Plenum Press, New York, Volume 2, 1973; p. 1271)

Testing directions	0.2% proof stress (MPa)	Tensile strength (MPa)	Elastic modulus (GPa)	Elongation (%)	Approximate fatigue strength at $10^7$ cycles ( $\pm$ MPa)
Longitudinal	834	910	114	17.5	496
Long transverse	934	986	128	17.0	427
Short transverse	893	978	114	12.5	565



# Composition and applications of $\alpha+\beta$ titanium alloys

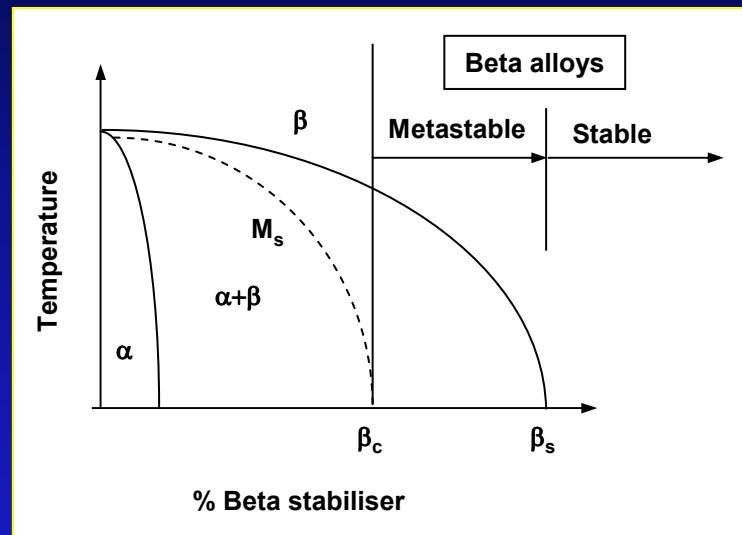
Chemical compositions and typical applications of  $\alpha-\beta$  titanium alloys†

Alloy composition	Condition	Typical applications
6% Al, 4% V	Annealed; solution + age	Rocket motor cases; blades and disks for aircraft turbines and compressors; structural forgings and fasteners; pressure vessels; gas and chemical pumps; cryogenic parts; ordnance equipment; marine components; steam-turbine blades.
6% Al, 4% V (low O <sub>2</sub> )	Annealed	High-pressure cryogenic vessels operating down to -320°F
6% Al, 6% V, 2% Sn	Annealed; solution + age	Rocket motor cases; ordnance components; structural aircraft parts and landing gears; responds well to heat treatments; good hardenability.
7% Al, 4% Mo	Solution + age	Airframes and jet engine parts for operation at up to 800°F; missile forgings; ordnance equipment.
6% Al, 2% Sn, 4% Zr, 6% Mo	Solution + age	Components for advanced jet engines.
6% Al, 2% Sn, 2% Zr, 2% Mo, 2% Cr, 0.25% Si	Solution + age	Strength, fracture toughness in heavy sections; landing-gear wheels.
10% V, 2% Fe, 3% Al	Solution + age	Heavy airframe structural components requiring toughness at high strengths.
8% Mn	Annealed	Aircraft sheet components, structural sections, and skins; good formability, moderate strength.
3% Al, 2.5% V	Annealed	Aircraft hydraulic tubing, foil; combines strength, weldability, and formability.



# Beta titanium alloys

- **Beta stabilisers** are sufficiently added to retain a **fully  $\beta$  structure** (avoid martensite formation) when quenched from the  $\beta$  phase field.



$\beta$ -Stabilizer	Type	$\beta_c$ (wt.%) <sup>a</sup>	$\beta_1$ Suppression ( $^{\circ}\text{C}$ ) <sup>b</sup>
Mo	Isomorphous	10.0	-8.3
V		15.0	-5.5
W		22.5	-13.8
Nb		36.0	-10.6
Ta		45.0	-15.6
Fe	Eutectoid	3.5	0.0
Cr		6.5	-2.8
Cu		13.0	-5.6
Ni		9.0	4.4
Co		7.0	3.3
Mn		—	21.1

**Molybdenum equivalent**

**Metastable  $\beta$  alloys : Mo Eq. <25**

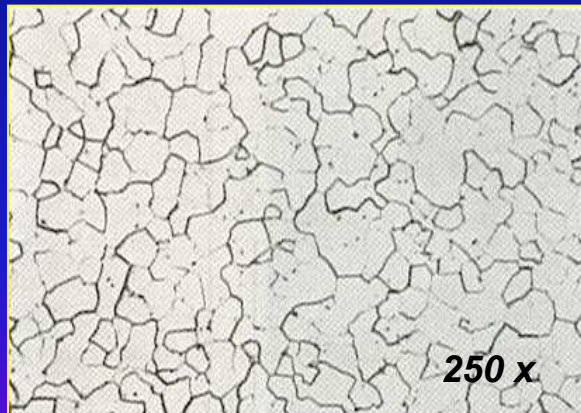
**Stable  $\beta$  alloys : Mo Eq. 25-40.**

$$Mo_{equiv} \% = 1.0Mo + 0.67V + 0.44W - 0.28Nb + 0.22Ta + 1.6Cr + \dots - 1.0Al$$

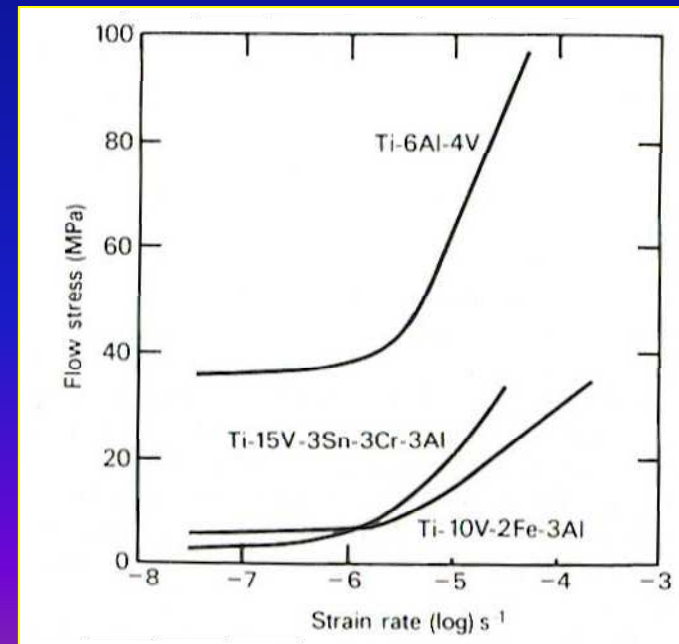


# $\beta$ titanium alloys

- $\beta$  titanium alloys possess a **BCC** crystal structure, which is readily cold-worked (than **HCP**  $\alpha$  structure) in the  $\beta$  phase field.
- Microstructure after quenching contains **equiaxed  $\beta$  phase**.
- After solution heat treating + quenching  $\rightarrow$  giving **very high strength** (up to 1300-1400 MPa).
- **Metastable  $\beta$  Ti alloys** are hardenable while **stable  $\beta$  Ti alloys** are non-hardenable.



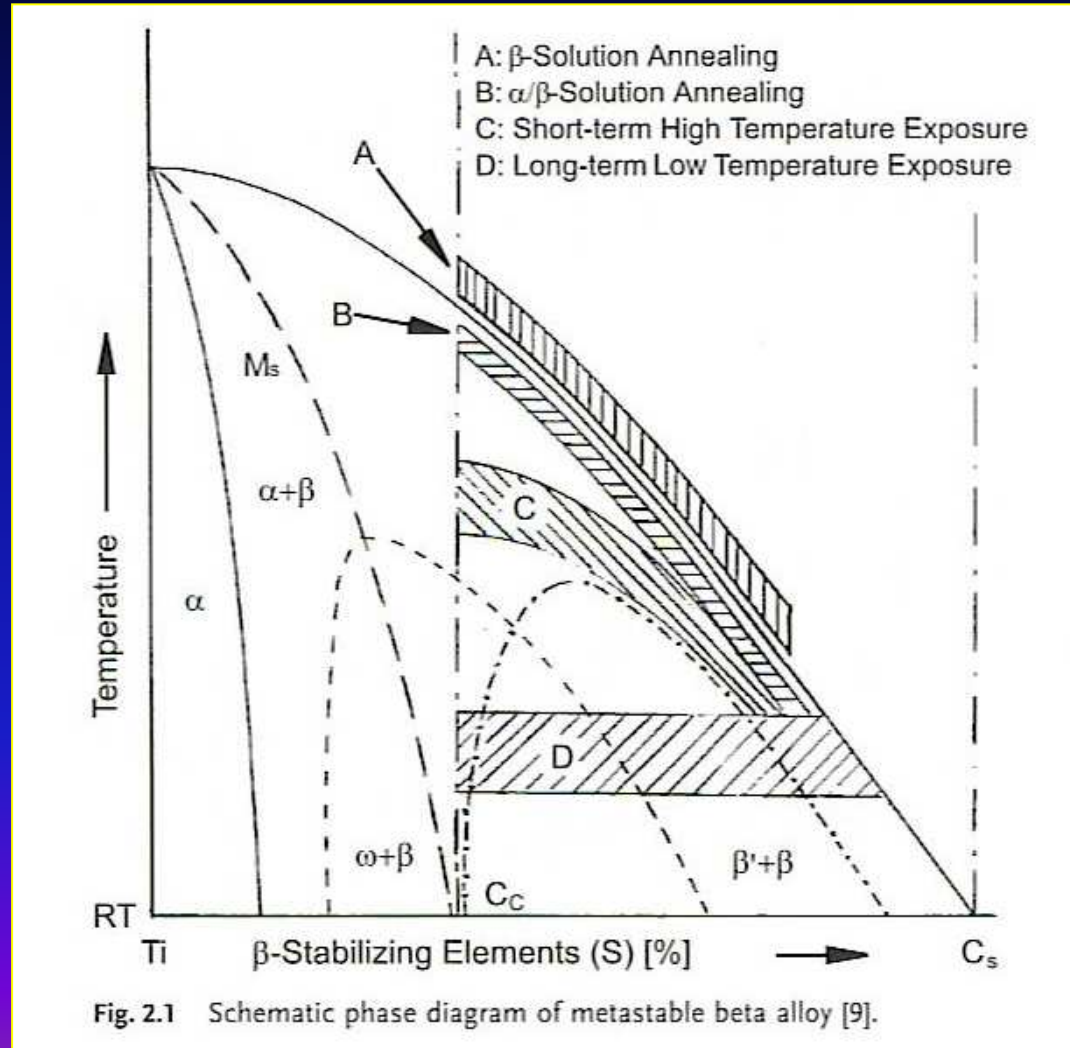
**Ti-13V-11Cr-3Al alloy solution heat-treated at 788°C/30min and water-quenched**



**Flow stress for Ti alloys hot-worked at 810°C**

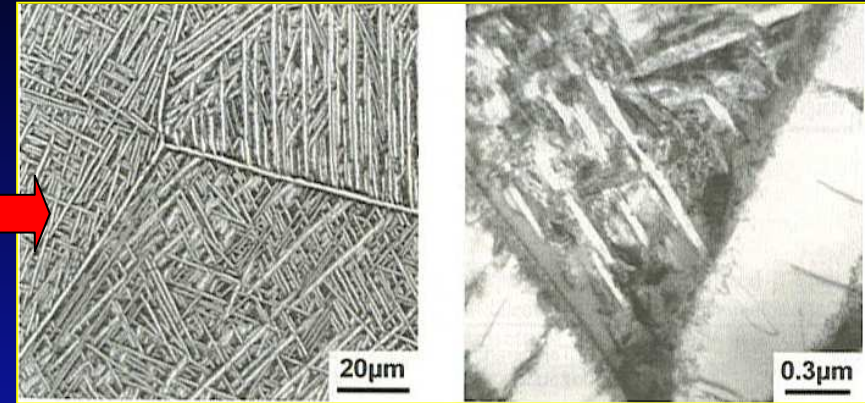


# Heat treatment scheme for $\beta$ titanium alloys



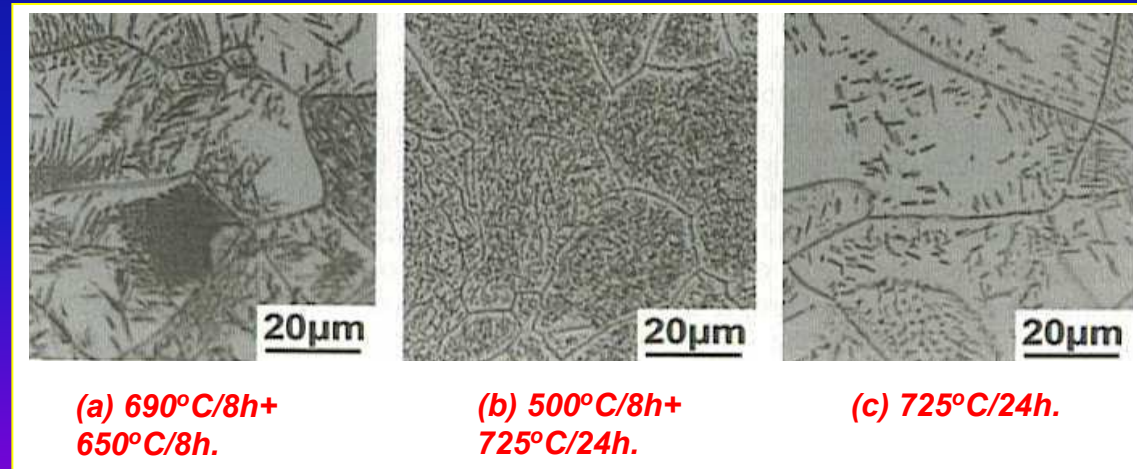
# $\beta$ titanium alloys

- **Most  $\beta$  titanium alloys** are **metastable** and tend to transform into
  - (1) coarse  **$\alpha$  platets** after heat-treated in the  $\alpha+\beta$  phase field or
  - (2)  **$\alpha$  phase precipitation** after long-term ageing at elevated temperature.



**$\beta$  annealed microstructure,  $\beta$  CEZ (Ti-5Al-2Sn-2Cr-4Mo-4Zr)- beta rich**

- This effect gives **higher strength** to the alloy but can cause **embrittlement** and not desirable when ductility is required.



**(a) 690°C/8h+  
650°C/8h.**

**(b) 500°C/8h+  
725°C/24h.**

**(c) 725°C/24h.**

**Effect of pre-aging on microstructure of heavily stabilised  $\beta$  alloys  
Beta 21S (Ti-15Mo-2.6Nb-3Al-0.2Si)**



# Composition and applications of $\beta$ titanium alloys

Alloy composition	Commercial name	Category (Mo equivalent)	$T_{\beta}$ (°C)	Actual and potential applications	Year introduced (company)
Ti-35V-15Cr	Alloy C	Beta (47)		Burn resistant alloy	1990 (P&W)
Ti-40Mo		Beta (40)		Corrosion resistance	1952 (RemCru)
Ti-30Mo		Beta (30)		Corrosion resistance	1952 (RemCru)
Ti-6V-6Mo-5.7Fe-2.7Al	TIMETAL 125	Metastab (24)	704	High strength aircraft fasteners	1990 (TIMET)
Ti-13V-11Cr-3Al	B120 VCA	Metastab (23)	650	Airframe, landing gear, springs	1952 (RemCru)
Ti-1Al-8V-5Fe	1-8-5	Metastab (19)	825	Fasteners	1957 (RMI)
Ti-12Mo-6Zr-2Fe	TMZF	Metastab (18)	743	Orthopedic implants	1992 (Howmedica)
Ti-4.5Fe-6.8Mo-1.5Al	TIMETAL LCB	Metastab (18)	800	Low cost, high strength alloy	1990 (TIMET)
Ti-15V-3Cr-1Mo-.5Nb-3Al-3Sn-.5Zr	VT35	Metastab (16)		High strength airframe castings	n.a. (Russian)
Ti-3Al-8V-6Cr-4Mo-4Zr	Beta-C	Metastab (16)	795	Oil-fields, springs, fasteners	1969 (RMI)
Ti-15Mo	IMI 205	Metastab (15)	727	Corrosion resistance	1958 (IMI)
Ti-8V-8Mo-2Fe-3Al	8-8-2-3	Metastab (15)	775	High strength forgings	1969 (TIMET)
Ti-15Mo-2.6Nb-3Al-0.2Si	Beta 21S	Metastab (13)	807	Oxidation/corrosion resist, MMC	1989 (TIMET)
Ti-15V-3Cr-3Sn-3Al	15-3	Metastab (12)	760	Sheet, plate airframe castings	1978 (USAF)
Ti-11.5Mo-6Zr-4.5Sn	Beta III	Metastab (12)	745	High strength	1969 (Crucible)
Ti-10V-2Fe-3Al	10-2-3	Metastab (9.5)	800	High strength forgings	1971 (TIMET)
Ti-5V-5Mo-1Cr-1Fe-5Al	VT22	Metastab (8)	850	High strength forgings	n.a. (Russian)
Ti-5Al-2Sn-2Zr-4Mo-4Cr	Ti-17	Beta-rich (5.4)	885	High strength, medium temperature	1968 (GEAE)
Ti-4.5Al-3V-2Mo-2Fe	SP700	Beta-rich (5.3)	900	High strength, SPF	1989 (NKK)
Ti-5Al-2Sn-2Cr-4Mo-4Zr-1Fe	Beta CEZ	Beta-rich (5.1)	890	High strength, medium temperature	1990 (CEZUS)
Ti-13Nb-13Zr		Beta-rich (3.6)		Orthopedic implants	1992 (Smith&Neph)



# $\beta$ titanium alloys

Tab. 2.1 Advantages and disadvantages of beta titanium alloys [3].

## *Advantages*

- high strength-to-density ratio
- low modulus
- high strength/high toughness
- high fatigue strength
- good deep hardenability
- low forging temperature
- strip producible – low-cost TMP\* (some alloys)
- cold formable (some alloys)
- easy to heat treat
- excellent corrosion resistance (some alloys)
- excellent combustion resistance (some alloys)

## *Disadvantages*

- high density
- low modulus
- poor low and high temperature properties
- small processing window (some alloys)
- high formulation cost
- segregation problems
- high springback
- microstructural instabilities
- poor corrosion resistance (some alloys)
- interstitial pick up

\* TMP: thermomechanical processing



# *Forming of titanium alloys*

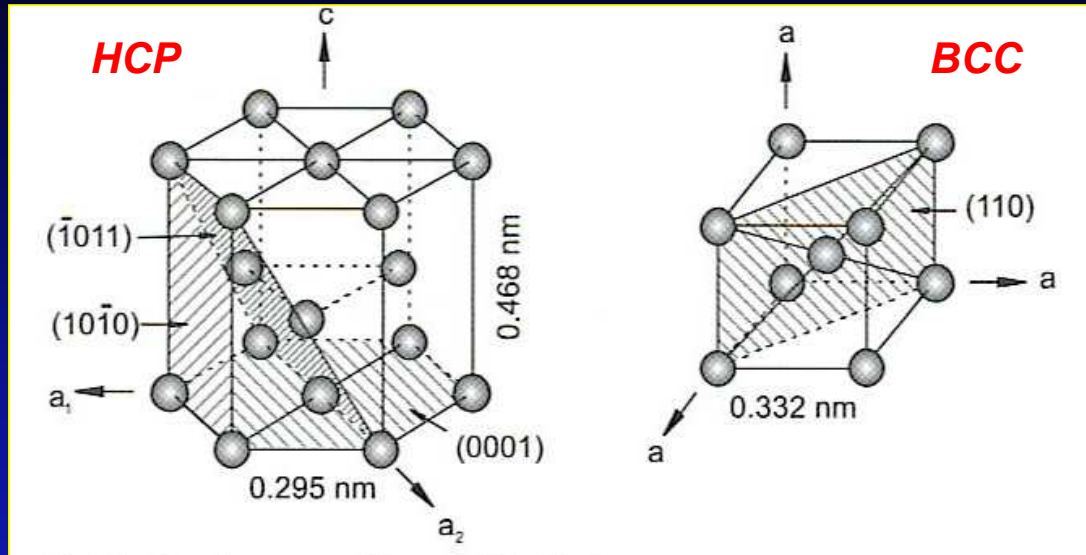
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*Most of titanium products are mechanically deformed by the following processes.*

- *Forging*
- *Sheet and ring rolling*
- *Machining*
- *Power metallurgy*
- *Superplastic forming/diffusion bonding*



# Deformation of titanium alloys



Crystal structure and slip systems in HCP and BCC crystal structures

**HCP  $\alpha$  Ti alloys**

Deformation is limited on available slip systems and relies on **twinning\*** deformation at RT.

**BCC  $\beta$  Ti alloys**

Deformation relies on more available slip systems with quite limited **twinning** deformation.  $\rightarrow$  hot-working.

Structure type	N	CN	P	Slip planes		Slip system per unit cell	Atom density of slip plane	$b_{min}/a$
				indices	numbers			
hcp ( $c/a=1,633$ )	6	12	74%	{0001}	1	$1 \times 3 = 3$	$\approx 91\%$	1
				{11 $\bar{2}$ 0}	3			
bcc	2	8	68%	{110}	6	$6 \times 2 = 12$	$\approx 83\%$	$1/2 \sqrt{3}$ $\approx 0,87$
				{111}	2			
fcc	4	12	74%	{111}	4	$4 \times 3 = 12$	$\approx 91\%$	$1/2 \sqrt{2}$ $\approx 0,71$
				{110}	3			

N – no. of atoms per unit cell, CN – Coordination number, P – Packing density,  $b_{min}/a$  – minimal slip component.



**Note:** FCC metals have the most activated slip system  $\rightarrow$  most ductile.

# Forging of titanium alloys

- **Ti alloys** have much higher flow stress than **Al alloys** or **steels**. → requiring high forging pressure, capacity.
- Near net shape is obtained using precision die forging.



- **Initial working** is done about 150°C above the **beta transus temperature** to about 28-38% strain, depending on alloy types and prior heat treatments. Subsequent deformation processes can be done in the  **$\alpha+\beta$  region**.



**Forged Ti connecting rod and implant prosthesis**



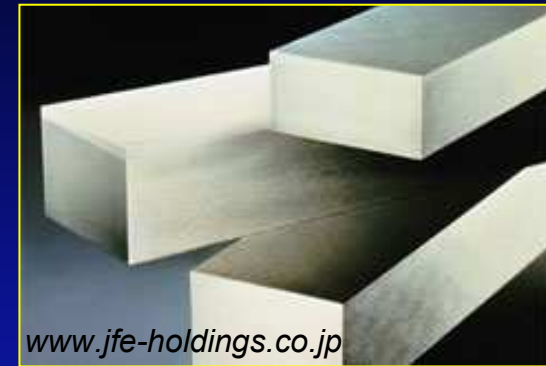
**Titanium forged golf club**



# Rolling of titanium alloys

- **Titanium alloy sheet** is normally pack-rolled to avoid surface oxidation.
- A group of titanium sheet blanks are sealed with steel retort and rolled as a group.
- **Parting agent** is filled between individual blanks to prevent sheet bonding.
- After hot rolling, the sheets are extracted, pickled and flattened for finishing process.

- Titanium alloys are **ring rolled** to produce large cylinders for fan casing or pressure vessels.



**Hot-rolled Ti clad steel plates used in condenser in power station**



**Titanium ring rolling**



# Machining of titanium alloys

- **Titanium and titanium alloys** are relatively more difficult to machine (especially  $\beta$  Ti alloys) in comparison to **steels** and **aluminium alloys** for all conventional methods such as milling, turning, drilling etc.
- Titanium's **low thermal conductivity** reduces heat dissipation at metal-workpiece interface → **decreased tool life, welding or galling at tool-workpiece interface**.
- **Machining tools** are critical → carbide or ceramic toolings.
- Avoid loss of **surface integrity** due to tool damage → dramatically reduce properties especially **fatigue**.



[www.manufacturingcenter.com](http://www.manufacturingcenter.com)



[www.sstool.com](http://www.sstool.com)

**Machined titanium parts -defence satellites**



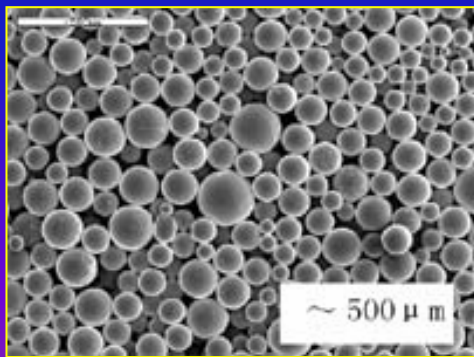
# Powder metallurgy of titanium alloys

- **Titanium PM parts** are made from pressing and sintering, giving **near-net shape products**.

- Production of titanium powder is quite difficult due to high **reactivity of titanium with oxygen**. → expensive.

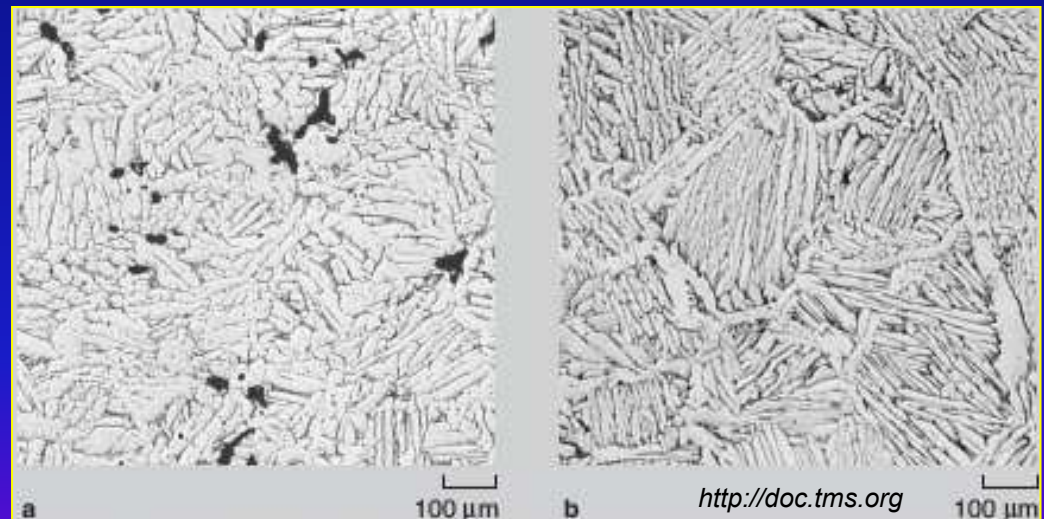
- The whole process (atomisation, pressing and sintering) requires prevention from **atmospheric contamination**.

- **Blending of Ti sponge and master alloys.**
- **CIPing at  $T > \beta$  transtus upto 95% density.**
- **HIPing to improve mechanical properties.**



**Titanium powder (SEM)**

Suranaree University of Technology



**(a) Ti-6Al-4V alloy produced from CIPing and sintering of blended CP sponge and AL-V master alloy**

**(b) Same material after HIPing, showing no porosity**



# Superplastic forming and diffusion bonding of titanium alloys

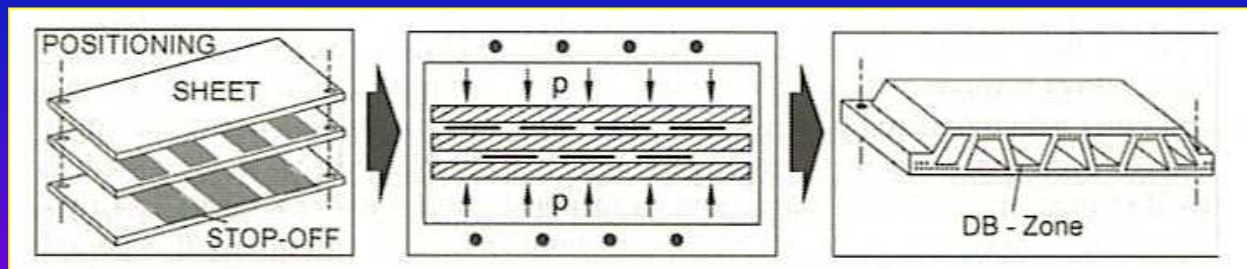
## Advantages:

- Produce **complex** and **light-weight** components with good **integrity** and **stiffness**.
- Reduce production steps.
- Reduce the use of fasteners, i.e., rivets → eliminating stress concentrations.

## Disadvantages:

- **Expensive** and cannot be used for **critical load bearing structures**.

- **Stop-off agent** is used for bonding of regions of the sheet, followed by pressurisation to separate unbonded regions of the sheet.



SPF/DB process



SPF/DB structure



# Casting of titanium alloys

*Titanium castings* contribute to small amount of titanium products recently used. There are several methods as follows;

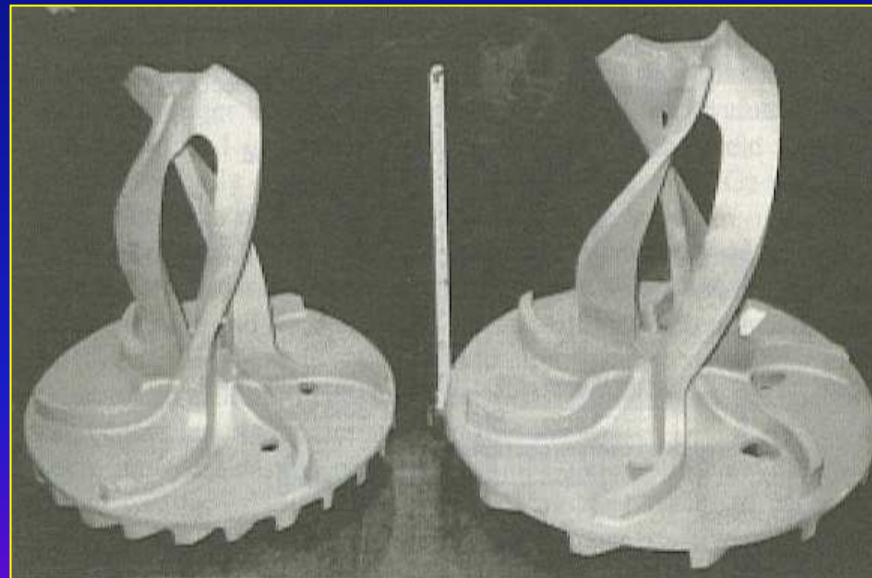
- **Conventional casting**
- **Investment casting**
- **Vacuum casting**

**Note:** *Titanium castings are normally near net shape products with minimised metal waste, which can occur during mechanical processing and machining.*



# Conventional casting

- **Rammed graphite** is used as the mould rather than sand due to its minimal tendency to react with molten titanium.
- Produce intricate shapes with good surface finish condition.



**Rammed graphite casting made from CP Ti grade 2**



# Investment casting

This process begins with

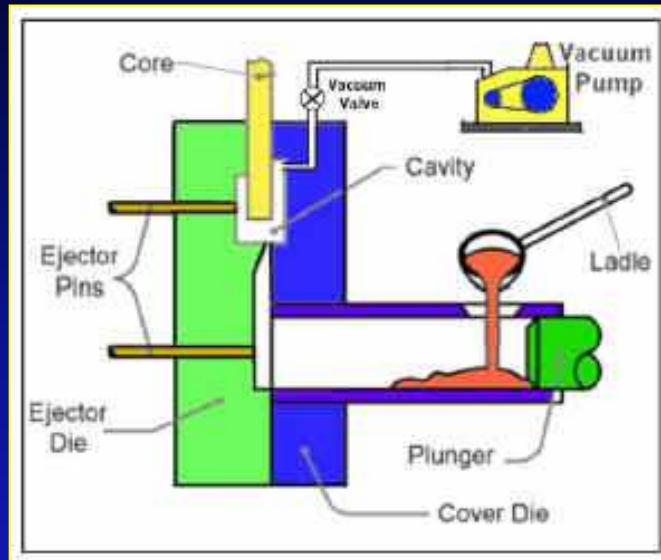
- 1) Duplicating a wax part from engineering drawing of the specific part.
- 2) Dipping in ceramic slurry until a shell is formed.
- 3) The wax is then melted out and the fired shell is filled with molten metal to form a part near to the net shape of the drawing.

- **Most widely used for titanium castings**
- **Cost effective**
- **Precise dimensional control**

*Used for structural applications requiring metallurgical integrity and sports applications such as golf heads.*



# Vacuum die casting



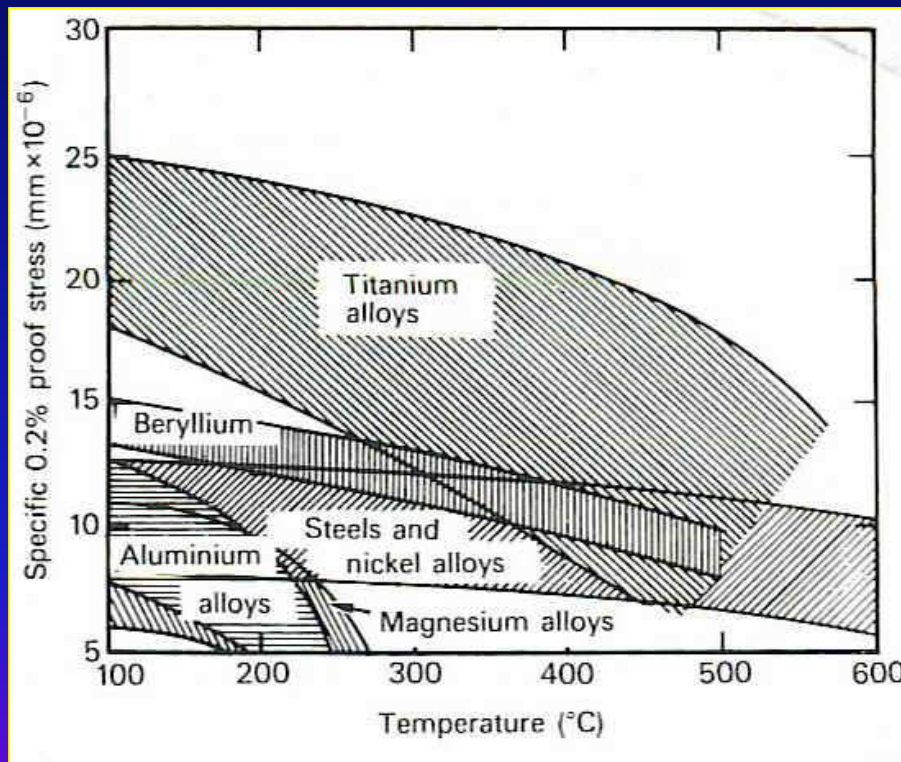
**Vacuum** is applied for die casting to reduce gas entrapment during metal injection and to decrease porosity in the casting.

- **Reduce porosity in the castings**
- **Provide high quality parts**

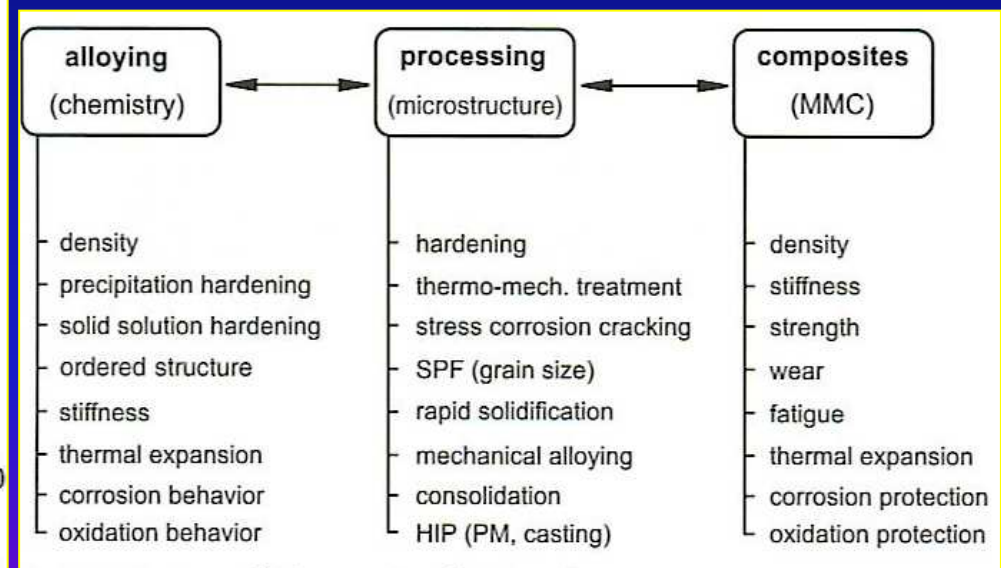


# Properties of titanium alloys

**Material strength, creep resistance and fatigue properties are the main properties usually required for applications of titanium alloys.**



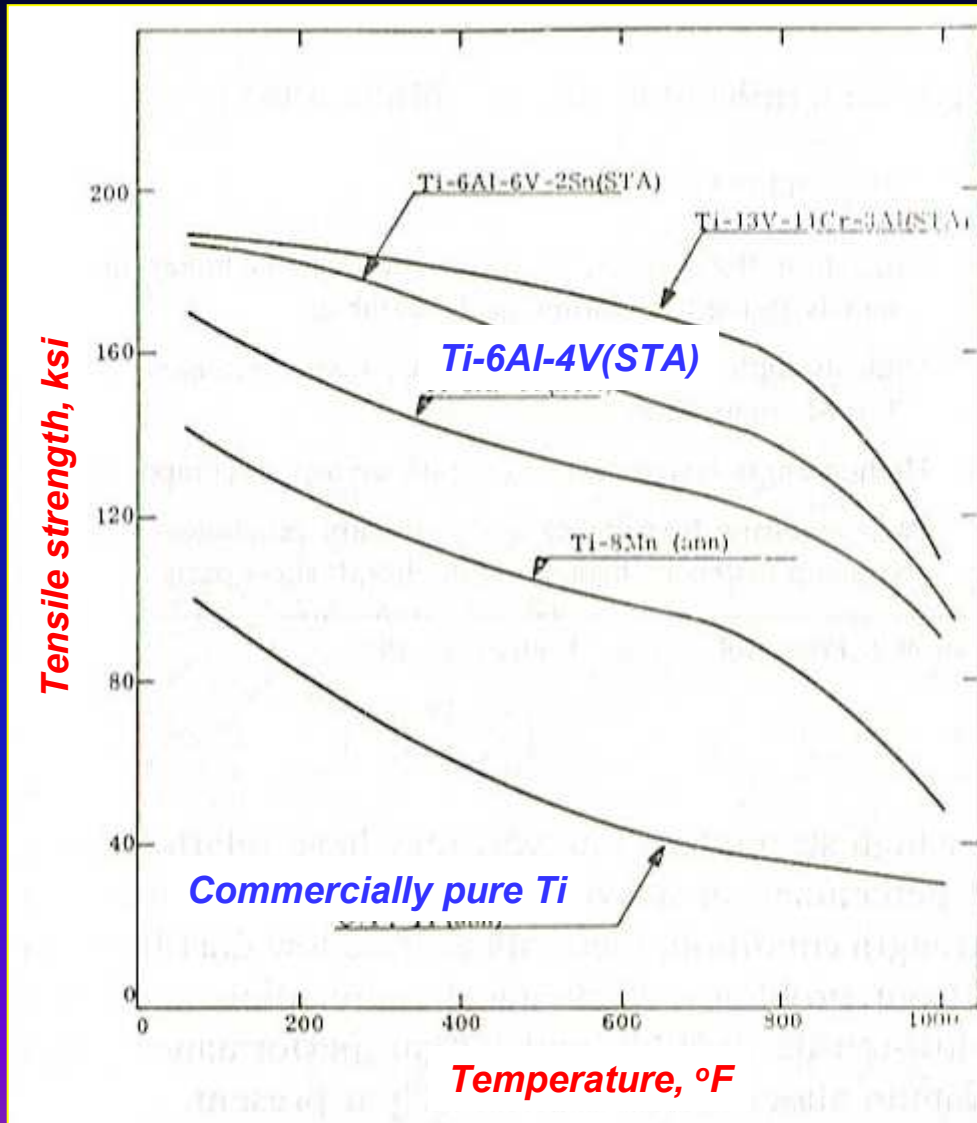
- Titanium alloys provide superior specific yield strength (high strength to weight ratio) than other alloys.



**Specific proof stress of various materials**

**Approaches to modify the properties of titanium alloys**

# Strength and toughness of titanium alloys



Tensile strength of different Ti alloys at a range of temperatures



# Strength and toughness of titanium alloys

Yield strength and plane-strain fracture toughness of various titanium alloys\*

Alloy	$\alpha$ morphology or processing method	Yield strength		Plane-strain fracture toughness ( $K_{Ic}$ )	
		MPa	ksi	MPa $\sqrt{m}$	ksi $\sqrt{in}$
Ti-6 Al <sub>4</sub> V	Equiaxed	910	130	44-66	40-60
	Transformed	875	125	88-110	80-100
	$\alpha - \beta$ rolled + mill annealed(a)	1095	159	32	29
Ti-6 Al-6 V-2 Sn	Equiaxed	1085	155	33-55	30-50
	Transformed	980	140	55-77	50-70
Ti-6 Al-2 Sn-4 Zr-6 Mo	Equiaxed	1155	165	22-23	20-30
	Transformed	1120	160	33-55	30-50
Ti-6 Al-2 Sn-4 Zr-2 Mo forging	$\alpha + \beta$ forged, solution treated and aged	903	131	81	74
	$\beta$ forged, solution treated and aged	895	130	84	76
Ti-17 <sup>†</sup>	$\alpha - \beta$ processed	1035-1170	150-170	33-50	30-45
	$\beta$ processed	1035-1170	150-170	53-88	48-80

\* After *Metals Handbook*, 10th ed., vol. 2, ASM International, 1990, p. 622.

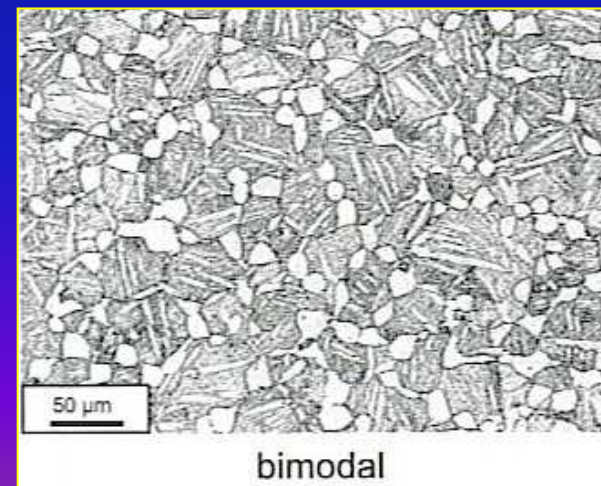
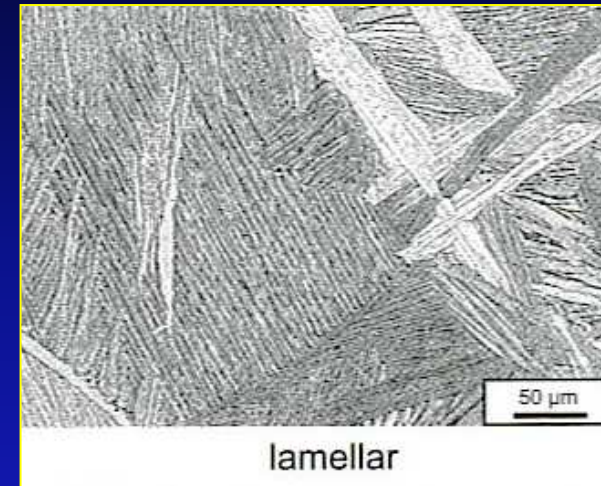
<sup>†</sup> Ti-17 has the composition Ti-5 Al-2 Sn-2 Zr-4 Mo-4 Cr.



# Microstructure and tensile properties of titanium alloys

Table 5.7. Tensile properties at room temperature and 600°C of the  $\alpha$ + $\beta$  alloy IMI 834

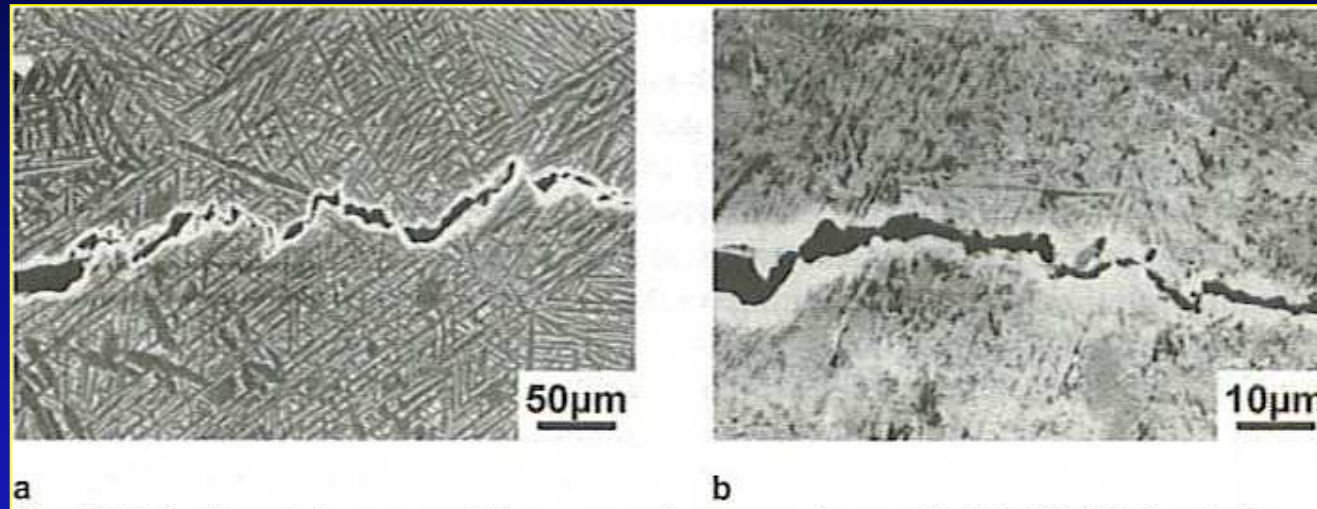
Microstructure	Test Temp.	$\sigma_{0.2}$ (MPa)	UTS (MPa)	$\sigma_F$ (MPa)	El. (%)	RA (%)
Lamellar	RT	925	1 015	1 145	5	12
Bi-modal (20 vol% $\alpha_p$ )	RT	995	1 100	1 350	13	20
Bi-modal (30 vol% $\alpha_p$ )	RT	955	1 060	1 365	13	26
Lamellar	600°C	515	640	800	10	26
Bi-modal (10 vol% $\alpha_p$ )	600°C	570	695	885	10	30
Bi-modal (40 vol% $\alpha_p$ )	600°C	565	670	910	14	36



- **Bimodal microstructure** is more resistant to fracture due to equiaxed  $\alpha$  phase  $\rightarrow$  giving higher strength.
- **Equiaxed  $\alpha$  phase** is also more resistant to nucleation of voids  $\rightarrow$  higher ductility.



# ***Microstructure and fracture toughness properties of titanium alloys***

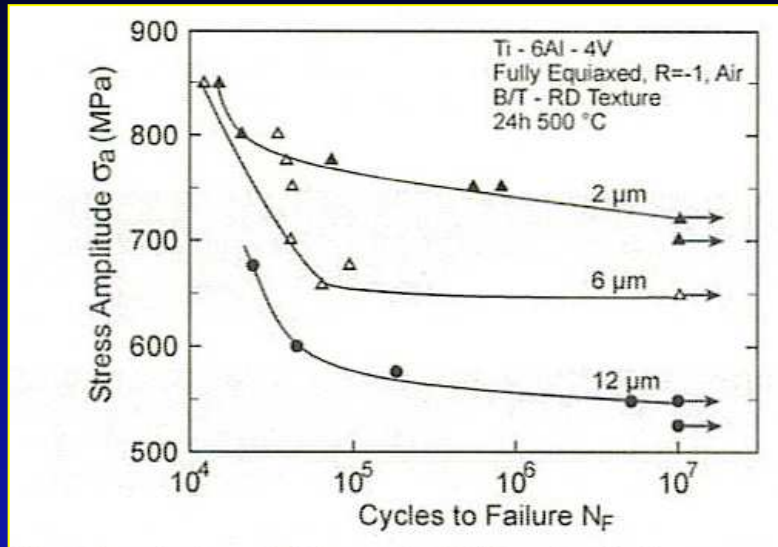


***Crack paths in the centre of fracture toughness Ti-6Al-4V specimens  
(a) coarse lamellar and (b) fine lamellar***

- *More torturous path in coarse lamellar microstructure leads to higher energy dissipation during fracture → higher toughness.*



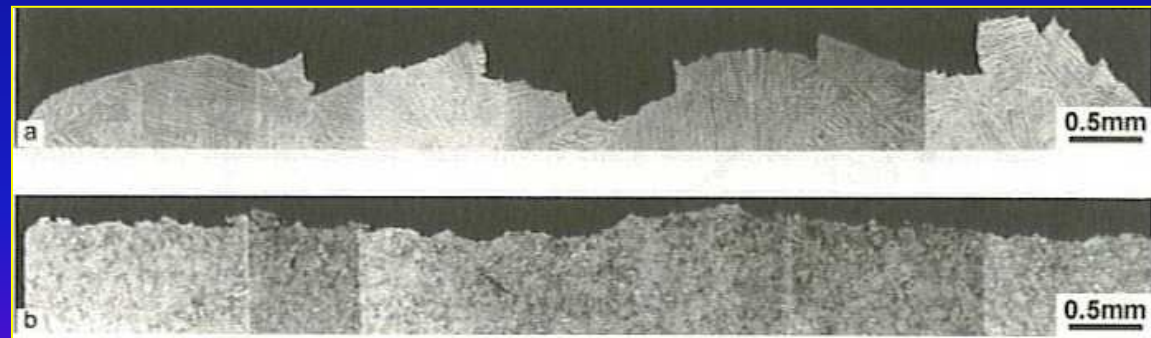
# Fatigue properties of titanium alloys



- **Smaller equiaxed  $\alpha$  grains** are more beneficial to fatigue strength.
- Crack nucleates within the **lamellar region** more easily than in the **equiaxed  $\alpha$  phase region**.
- But crack propagation is more difficult in the **lamellar structure**.



**Crack initiation at lamellar region in bi-modal microstructure**



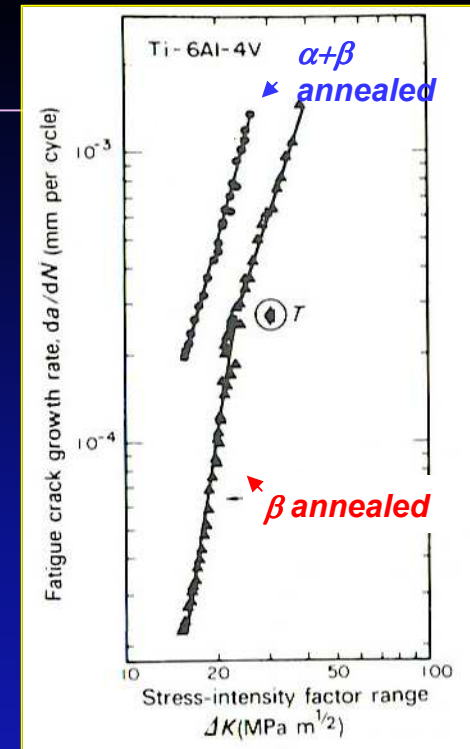
**Crack propagation paths in (a) lamellar and (b) bi-modal structures**



# Fatigue properties of titanium alloys

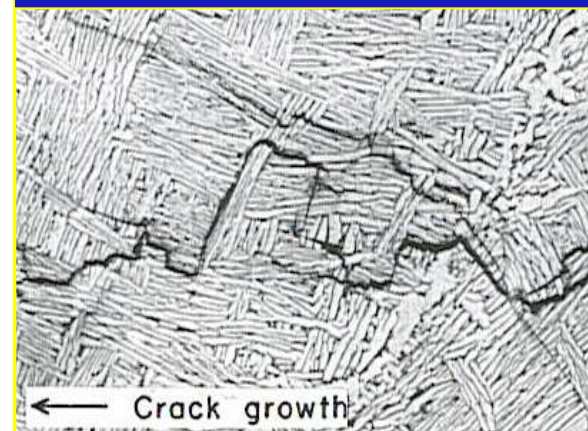
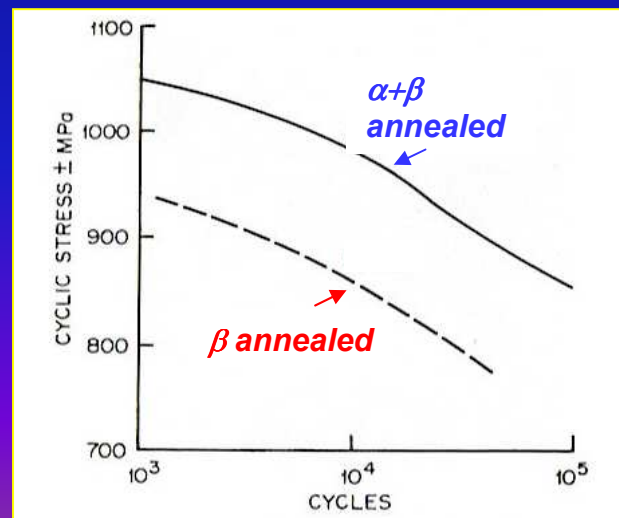
## Properties of annealed Ti-6Al-4V (forging)

- Moderate tensile strength.
- **$\beta$  annealed** has superior fatigue along **platelets of  $\alpha$** .
- **$\alpha+\beta$  annealed** is more **fatigue resistance** due to slower crack propagation rate to fatigue crack initiation.  
→ better low cycle fatigue (high stress).
- **Duplex structure** of 30% **equiaxed  $\alpha$**  and  **$\alpha$  platelets** provides high temperature applications.



FCG curves for  $\beta$  and  $\alpha+\beta$  annealed conditions

LCF of Ti-6Al-4V in  $\alpha+\beta$  annealed and  $\beta$  annealed



Crack propagation path in  $\beta$  annealed Ti-6-4



# Corrosion of titanium alloys



• *When fresh titanium is exposed to environment containing oxygen, it will develop oxide films which are*

- 1) Stable
- 2) Tenacious
- 3) Inert
- 4) Self-healing or re-form

• Good corrosive resistance to salt water and marine, acids, alkalis, natural waters and chemicals.



# Welding of titanium alloys

- $\alpha$  and  $\alpha+\beta$  titanium alloys are readily weldable.
  - $\beta$  titanium alloys are not readily weldable due to high amounts of alloying element  $\rightarrow$  *macro/micro segregation*.
- **Tungsten Inert Gas Welding**
  - **Electron Beam Welding**
  - **Laser Beam Welding**
  - **Friction welding**



[www.sms-vt.com](http://www.sms-vt.com)

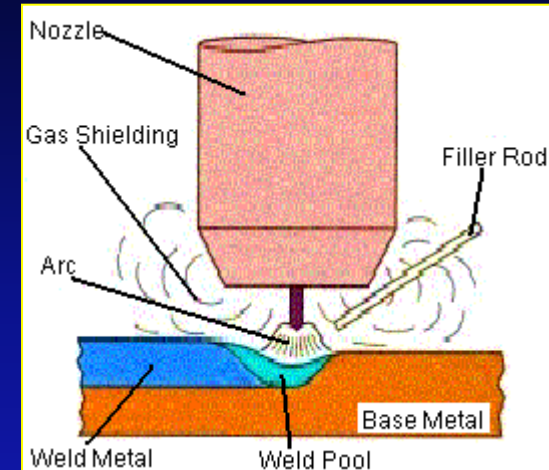


# Tungsten inert gas welding

**Arc is produced between a non-consumable tungsten electrode and the metals in the presence of shielding gas (He, Ar).**

- *Most widely used technique for titanium welding.*
- *Require no vacuum*
- *Lower operating cost*
- *Provide relatively coarser weld structure than those obtained from EBW and LBW.*
- *High heat input → relatively high distortion.*

**Note: Also called Tungsten Inert Gas welding or TIG welding.**



**Tungsten inert gas welding.**

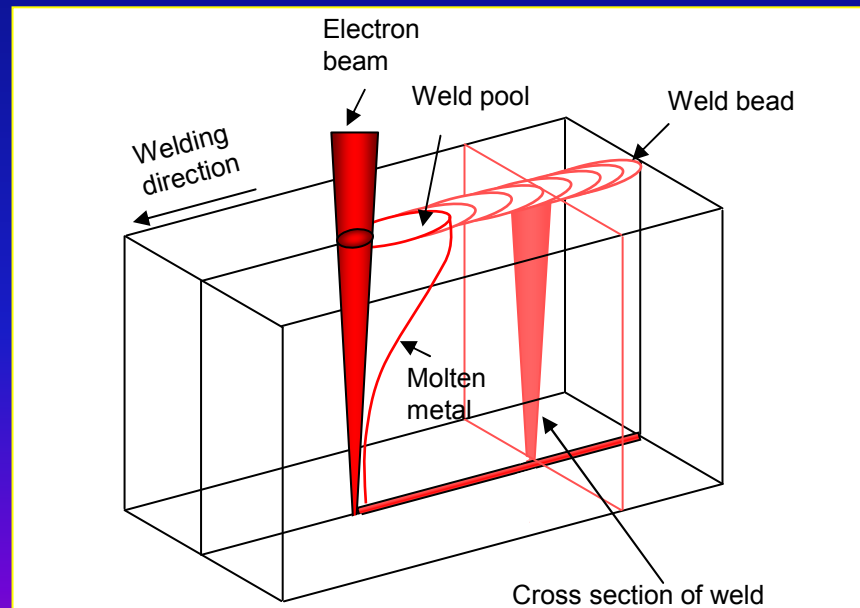


# Electron beam welding

- *Electron beam is used as a heat source.*
- *Vacuum and non-vacuum process → clean.*
- *Relatively high operating cost and equipment.*
- *Multiple or single -pass arc welding*
- *Low heat input → minimum distortion*



**Electron beam welding**



**Mobile electron beam welding unit**

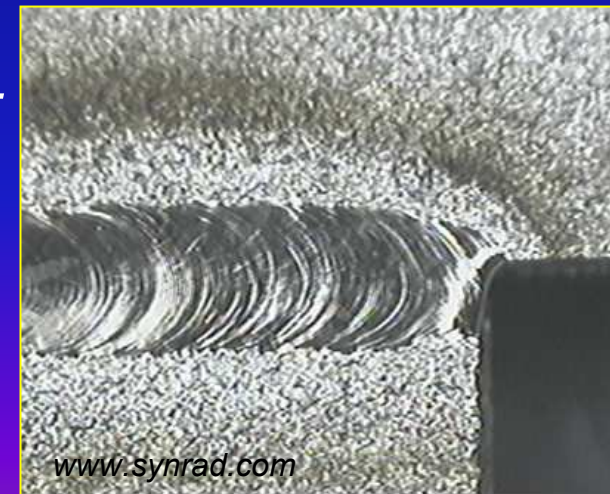


# Laser beam welding

- *Laser is used as a heat source.*
- *Correct choice of shielding gas*
- *Adequate shielding methods*
- *Pre-cleaning (de-greasing)*
- *Good joint surface quality*

## Advantages of laser beam welding

- *High productivity (nearly 10 times faster than TIG).*
- *Low heat input and therefore low distortion.*
- *Ease of automation for repeatability.*
- *No need for filler wire, thus reducing costs.*



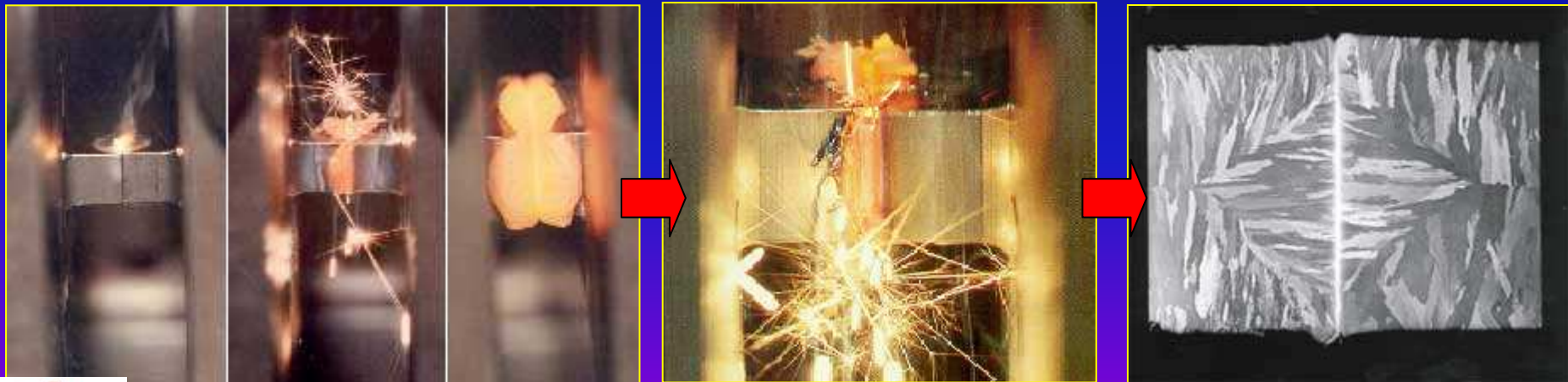
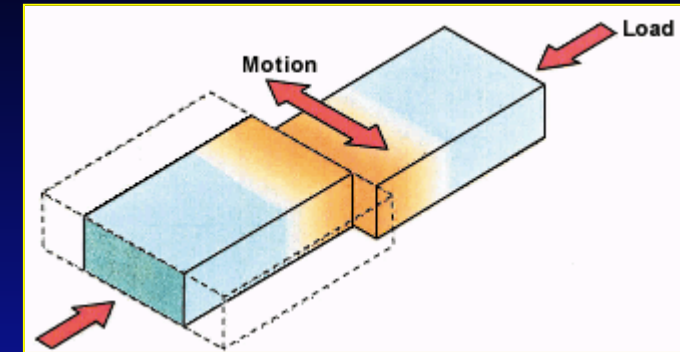
**Laser welding of titanium alloy**



# Friction welding

**Friction welding is carried out by moving one part in a linear reciprocating motion to effect the heat at the joint.**

- High cost of welding machines.
- Can use to join dissimilar metals.
- Very small distortion.
- Limited to non-round and non-complex component.



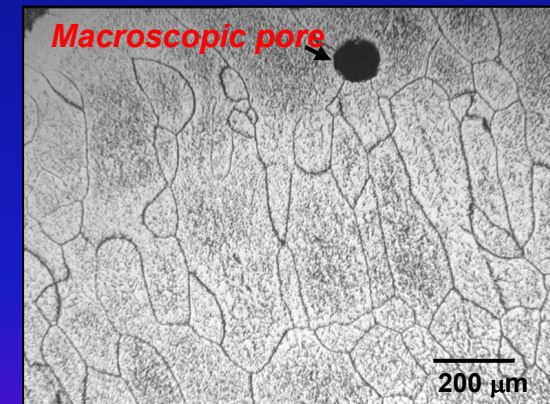
**Friction welding process**

**Weld structure obtained from friction welding**



# Defects in titanium welding

- **Titanium and titanium alloys** are highly reactive to oxygen, therefore care must be taken for titanium welding. Should be carried out in vacuum or appropriate shielding gas such as **Ar or He**.
- The main defects occur in titanium welding are;
  - **Weld metal porosity**
    - Most frequent defects caused by gas bubbles trapped between dendrites during solidification.
  - **Embrittlement**
    - Due to oxygen, nitrogen or hydrogen contamination at  $T > 500^{\circ}\text{C}$ . → need effective shielding.
  - **Contamination cracking**
    - Due to iron contamination → reducing corrosion resistance, separate from steel fabrication.



**Macroscopic pore observed in TIG welding of beta titanium alloy**

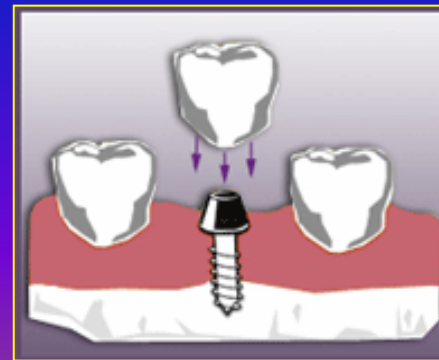
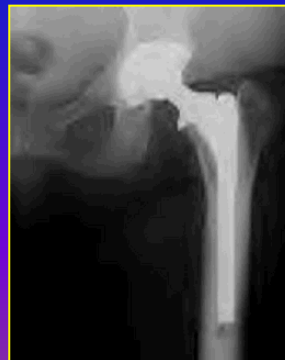


# Applications of titanium alloys in summary

- Aeroengines
- Automotive and road transport
- Dental alloys
- Electrochemical anodes
- Geothermal plant
- Marine
- Military hardware
- Offshore production tubulars
- Airframes
- Condensers
- Desalination plant
- Flue gas desulphurisation
- Nuclear and environmental safety
- Petrochemical refineries
- Architectural
- Cryogenic logging tools
- Food, brewing and pharmaceutical
- Jewellery manufacture
- Metal extraction equipment
- Offshore piping systems
- Pulp and paper
- Heat exchangers
- Medical implants



## Titanium implants



# References

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