Titanium and its alloys

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

• 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 (\(\text{FeTiO}_3\)) and rutile (\(\text{TiO}_2\)).
- Found only in small amount in Thailand.
- Have similar **strength as steel** but with a **weight nearly half of steel**.
Physical properties of titanium

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

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystal structure</td>
<td>HCP (&lt;882.5\textdegree C)</td>
</tr>
<tr>
<td></td>
<td>BCC (&gt;882.5\textdegree C)</td>
</tr>
<tr>
<td>Atomic diameter</td>
<td>0.320</td>
</tr>
<tr>
<td>Density ((\text{g.cm}^{-3}))</td>
<td>4.54</td>
</tr>
<tr>
<td>Melting point ((\text{oC}))</td>
<td>1667</td>
</tr>
</tbody>
</table>

\(\text{Ti}  \\
\text{Titanium}  \\
47.87\)
Advantages of titanium alloys

- High corrosive resistance to sea water and most corrosive conditions
- Nearly perfectly nonmagnetic
- Low specific gravity
- Bio Compatible Material
- High specific strength
- Three times as Al and higher than steel

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.

Aerospace
Motorcycle
Sports

www3.lehigh.edu
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Applications of titanium alloys

**AEROSPACE**
- Civil
- Military
- Space

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

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

**SPECIALIST**
- Body Jewellery
- Ultrasonic Welding
- Motor Racing Components
- Marine
- Bicycle
- Sports Equipment

*Shipment of mill products by applications in Japan 2005*

www.sumitomometals.co.jp
Production of titanium alloys

- 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 ($\text{TiO}_2$) is converted into titanium sponge by

1) Passing Cl$_2$ gas through charge the ore, resulting in colourless. titanium tetrachloride $\text{TiCl}_4$.

\[
\text{TiO}_2 + 2\text{Cl}_2 + C \rightarrow \text{TiCl}_4 + \text{CO}_2
\]

2) $\text{TiCl}_4$ is purified by fractional distillation.

3) The liquid form of $\text{TiCl}_4$ is reacted with either Mg or Na under an inert (Ar) atmosphere to obtain titanium sponge while Mg or Na is recycled.

\[
2\text{Mg}_{(l)} + \text{TiCl}_4_{(l)} \rightarrow 2\text{MgCl}_2_{(l)} + \text{Ti}_{(s)}
\]

Titanium 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

**Vacuum Arc Refining (VAR)** - melting

- **Electrode** made from compacted briquette of nominal alloy composition is held in the **VAR** by a stub and first melted in a **water-cooled copper crucible**.

- A **molten metal pool** is on the top of the new ingot.

- The **melting variables** such as melting rate, molten pool depth, stirring, contamination is carefully control to obtain **homogeneity** and **soundness** of ingots.

VAR furnace

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**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.

**Note:** Used for melting of reactive materials such as Ti, Ni, Ta, Zr.
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 skull melting](www.dmgbm.com)

**Charged metal melted with ISM**

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Alloying system of titanium alloys

Basic types of phase diagrams for titanium alloys

- **α phase**
  - HCP structure

- **β phase**
  - BCC structure

**Allotropic transformation**

882.3 °C

**Alloying elements**

- **Alpha stabilisers**
  - Al, O, N

- **Beta stabilisers**

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

- **Neutral**
  - Zr, Si, Sn

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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 $M_T$.
- For **highly alloyed Ti**, rapid quenching from the $\beta$ phase field gives lowest strength but after ageing, the maximum strength is obtained.
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.*

Solute content
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 α phase structure

HCP α phase structure with β 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, H₂SO₄, H₃PO₄**.
- Less expensive

**Applications:**

- Airframes, heat exchangers, chemicals, marine, surgical implants.
## Compositions and applications of commercially pure (CP) titanium alloys

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

**Alpha titanium alloy**

- **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 **α 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** (α₂), which is coherent to lattice. → **deleterious ductility**.
- **Sn** and **Zr** are also added in small amount to stabilise the **α** phase and give **strength**.

**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 β 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 ($\text{Ti}_3\text{Al}$) $\rightarrow$ 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.

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**Chemical compositions and typical applications of α titanium alloys†**

<table>
<thead>
<tr>
<th>α Alloys</th>
<th>Condition</th>
<th>Typical applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>5% Al, 2.5% Sn</td>
<td>Annealed</td>
<td>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.</td>
</tr>
<tr>
<td>5% Al, 2.5% Sn (low O₂)</td>
<td>Annealed</td>
<td>Special grade for high-pressure cryogenic vessels operating down to −423°F.</td>
</tr>
</tbody>
</table>

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.
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.
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.

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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).*
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

(a) 1\degree C/min  
(b) 100\degree C/min  
(c) 8000\degree C/min
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.

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Chemical compositions and typical applications of near-α titanium alloys†

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

**Alpha-beta titanium alloys**

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

- 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.

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

![Image 1: Air-cooled from $\beta$ phase field giving transformed $\beta$ phase (acicular) 250 x](image1)

![Image 2: Air-cooled from $\alpha+\beta$ phase field, showing primary $\alpha$ grains in a matrix of transformed $\beta$ (acicular) 250 x](image2)
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.

*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.

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

If enough $\beta$ stabilisers

- Lath martensite colonies
- Lenticular or twinned martensite

Increasing solute content

Metastable $\beta$

- (body-centred cubic)
- (may contain athermal $\omega$)
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).

**Below $M_s$**

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

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

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.

\[
\begin{align*}
\alpha' \text{ martensite} & \\
\beta\text{-isomorphous alloys} & \alpha' \rightarrow \alpha + \beta \\
\text{Alloys with} & \text{ slow eutectoid reactions} \\
e.g. Ti-Mn & \alpha' \rightarrow \alpha + \beta \rightarrow \alpha + \text{compound} \\
\beta\text{-eutectoid alloys} & \text{Alloys with fast eutectoid reactions} \\
e.g. Ti-Cu & \alpha' \rightarrow \alpha + \text{compound} \\
& \text{(may form in several stages)} \\
\alpha'' \text{ martensite} & \\
\text{Alloys with high} M_s(\alpha'') \text{ temperature} \\
\alpha'' \rightarrow \alpha'' + \alpha \rightarrow \alpha'' + \alpha + (\alpha + \beta) \rightarrow \alpha + \beta & \text{(cellular reaction)} \\
\text{Alloys with low} M_s(\alpha'') \text{ temperature} & \alpha'' \rightarrow \beta \rightarrow \text{products} \\
& \text{(see Section 6.3.4)}
\end{align*}
\]
Decomposition of metastable $\beta$

- **Retained $\beta$** obtained after quenching decomposes when subjected to ageing at elevated temperatures → 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.

### Possible reactions

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

$\beta$ 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

Lamellar, β annealed
Lamellar, β forged
bimodal, water quenching
bimodal, air cooling

fine globular
coarse globular
Anisotropic properties of Ti-6Al-4V alloys

(a) Slip planes in HCP α 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 × 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)

<table>
<thead>
<tr>
<th>Testing directions</th>
<th>0.2% proof stress (MPa)</th>
<th>Tensile strength (MPa)</th>
<th>Elastic modulus (GPa)</th>
<th>Elongation (%)</th>
<th>Approximate fatigue strength at 10^7 cycles (± MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal</td>
<td>834</td>
<td>910</td>
<td>114</td>
<td>17.5</td>
<td>496</td>
</tr>
<tr>
<td>Long transverse</td>
<td>934</td>
<td>986</td>
<td>128</td>
<td>17.0</td>
<td>427</td>
</tr>
<tr>
<td>Short transverse</td>
<td>893</td>
<td>978</td>
<td>114</td>
<td>12.5</td>
<td>565</td>
</tr>
</tbody>
</table>
# Composition and applications of \(\alpha+\beta\) titanium alloys

## Chemical compositions and typical applications of \(\alpha-\beta\) titanium alloys

<table>
<thead>
<tr>
<th>Alloy composition</th>
<th>Condition</th>
<th>Typical applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>6% Al, 4% V</td>
<td>Annealed; solution + age</td>
<td>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.</td>
</tr>
<tr>
<td>6% Al, 4% V (low O₂)</td>
<td>Annealed</td>
<td>High-pressure cryogenic vessels operating down to (-320^\circ F)</td>
</tr>
<tr>
<td>6% Al, 6% V, 2% Sn</td>
<td>Annealed; solution + age</td>
<td>Rocket motor cases; ordnance components; structural aircraft parts and landing gears; responds well to heat treatments; good hardenability.</td>
</tr>
<tr>
<td>7% Al, 4% Mo</td>
<td>Solution + age</td>
<td>Airframes and jet engine parts for operation at up to (800^\circ F); missile forgings; ordnance equipment.</td>
</tr>
<tr>
<td>6% Al, 2% Sn, 4% Zr, 6% Mo</td>
<td>Solution + age</td>
<td>Components for advanced jet engines.</td>
</tr>
<tr>
<td>6% Al, 2% Sn, 2% Zr, 2% Mo, 2% Cr, 0.25% Si</td>
<td>Solution + age</td>
<td>Strength, fracture toughness in heavy sections; landing-gear wheels.</td>
</tr>
<tr>
<td>10% V, 2% Fe, 3% Al</td>
<td>Solution + age</td>
<td>Heavy airframe structural components requiring toughness at high strengths.</td>
</tr>
<tr>
<td>8% Mn</td>
<td>Annealed</td>
<td>Aircraft sheet components, structural sections, and skins; good formability, moderate strength.</td>
</tr>
<tr>
<td>3% Al, 2.5% V</td>
<td>Annealed</td>
<td>Aircraft hydraulic tubing, foil; combines strength, weldability, and formability.</td>
</tr>
</tbody>
</table>
Beta titanium alloys

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

### Metastable β alloys: Mo Eq. <25

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

- **Stable β alloys** : Mo Eq. 25-40.

<table>
<thead>
<tr>
<th>β-Stabilizer</th>
<th>Type</th>
<th>$\beta_c$ (wt.%)$^a$</th>
<th>$\beta_i$ Suppression (°C)$^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mo</td>
<td>Isomorphous</td>
<td>10.0</td>
<td>-8.3</td>
</tr>
<tr>
<td>V</td>
<td></td>
<td>15.0</td>
<td>-5.5</td>
</tr>
<tr>
<td>W</td>
<td></td>
<td>22.5</td>
<td>-13.8</td>
</tr>
<tr>
<td>Nb</td>
<td></td>
<td>36.0</td>
<td>-10.6</td>
</tr>
<tr>
<td>Ta</td>
<td></td>
<td>45.0</td>
<td>-15.6</td>
</tr>
<tr>
<td>Fe</td>
<td>Eutectoid</td>
<td>3.5</td>
<td>0.0</td>
</tr>
<tr>
<td>Cr</td>
<td></td>
<td>6.5</td>
<td>-2.8</td>
</tr>
<tr>
<td>Cu</td>
<td></td>
<td>13.0</td>
<td>-5.6</td>
</tr>
<tr>
<td>Ni</td>
<td></td>
<td>9.0</td>
<td>4.4</td>
</tr>
<tr>
<td>Co</td>
<td></td>
<td>7.0</td>
<td>3.3</td>
</tr>
<tr>
<td>Mn</td>
<td></td>
<td>—</td>
<td>21.1</td>
</tr>
</tbody>
</table>
**β titanium alloys**

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

Fig. 2.1 Schematic phase diagram of metastable beta alloy [9].
**β titanium alloys**

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

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

**Effect of pre-aging on microstructure of heavily stabilised β alloys**

Beta 21S (Ti-15Mo-2.6Nb-3Al-0.2Si)

- **(a) 690°C/8h** + **650°C/8h.**
- **(b) 500°C/8h** + **725°C/24h.**
- **(c) 725°C/24h.**
**Composition and applications of β titanium alloys**

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

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>high strength-to-density ratio</td>
<td>high density</td>
</tr>
<tr>
<td>low modulus</td>
<td>low modulus</td>
</tr>
<tr>
<td>high strength/high toughness</td>
<td>poor low and high temperature properties</td>
</tr>
<tr>
<td>high fatigue strength</td>
<td>small processing window (some alloys)</td>
</tr>
<tr>
<td>good deep hardenability</td>
<td>high formulation cost</td>
</tr>
<tr>
<td>low forging temperature</td>
<td>segregation problems</td>
</tr>
<tr>
<td>strip producible – low-cost TMP*</td>
<td>high springback</td>
</tr>
<tr>
<td>(some alloys)</td>
<td></td>
</tr>
<tr>
<td>cold formable (some alloys)</td>
<td>microstructural instabilities</td>
</tr>
<tr>
<td>easy to heat treat</td>
<td>poor corrosion resistance (some alloys)</td>
</tr>
<tr>
<td>excellent corrosion resistance (some alloys)</td>
<td>interstitial pick up</td>
</tr>
<tr>
<td>excellent combustion resistance (some alloys)</td>
<td></td>
</tr>
</tbody>
</table>

*TMP: thermomechanical processing*
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 \textit{twinning}* deformation at RT.

BCC \( \beta \) Ti alloys
Deformation relies on more available slip systems with quite limited \textit{twinning} deformation. \( \rightarrow \) hot-working.

Note: FCC metals have the most activated slip system \( \rightarrow \) most ductile.

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<table>
<thead>
<tr>
<th>Structure type</th>
<th>( N )</th>
<th>( CN )</th>
<th>P</th>
<th>Slip planes</th>
<th>Slip directions</th>
<th>Atom density per unit cell</th>
<th>Atom density of slip plane</th>
<th>( b_{min}/a )</th>
</tr>
</thead>
<tbody>
<tr>
<td>hcp (c/a=1.633)</td>
<td>6</td>
<td>12</td>
<td>74%</td>
<td>{0001}</td>
<td>( \frac{1}{3}, \frac{2}{3}, \frac{1}{3} )</td>
<td>( \approx 91% )</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>bcc</td>
<td>2</td>
<td>8</td>
<td>68%</td>
<td>{110}</td>
<td>( \frac{1}{2}, \frac{1}{2}, \frac{1}{2} )</td>
<td>( \approx 83% )</td>
<td>( \frac{1}{2} \sqrt{3} )</td>
<td></td>
</tr>
<tr>
<td>fcc</td>
<td>4</td>
<td>12</td>
<td>74%</td>
<td>{111}</td>
<td>( \frac{1}{4}, \frac{1}{4}, \frac{1}{4} )</td>
<td>( \approx 91% )</td>
<td>( \frac{1}{2} \sqrt{2} )</td>
<td></td>
</tr>
</tbody>
</table>

\( N \) – no. of atoms per unit cell, \( CN \) – Coordination number, \( P \) – Packing density, \( b_{min}/a \) – minimal slip component.
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 **α+β 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.
Machining of titanium alloys

• *Titanium and titanium alloys* are relatively more difficult to machine (especially *β 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*.
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 > β transtus upto 95% density.**
- **HIPing to improve mechanical properties.**

(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

Titanium powder (SEM)

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http://doc.tms.org

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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**

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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 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.
**Strength and toughness of titanium alloys**

Tensile strength of different Ti alloys at a range of temperatures

- **Commercially pure Ti**
- **Ti-6Al-4V(STA)**
- **Ti-13Y-1.0Cr-3.5Al(STA)**

*Graph showing tensile strength vs. temperature for different titanium alloys.*
## Strength and toughness of titanium alloys

### Properties of various Ti alloys

<table>
<thead>
<tr>
<th>Alloy</th>
<th>α morphology or processing method</th>
<th>Yield strength</th>
<th>Plane-strain fracture toughness (K&lt;sub&gt;IC&lt;/sub&gt;)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>MPa</td>
<td>ksi</td>
</tr>
<tr>
<td>Ti–6 Al–4 V</td>
<td>Equiaxed</td>
<td>910</td>
<td>130</td>
</tr>
<tr>
<td></td>
<td>Transformed</td>
<td>875</td>
<td>125</td>
</tr>
<tr>
<td></td>
<td>α – β rolled + mill annealed(a)</td>
<td>1095</td>
<td>159</td>
</tr>
<tr>
<td>Ti–6 Al–6 V–2 Sn</td>
<td>Equiaxed</td>
<td>1085</td>
<td>155</td>
</tr>
<tr>
<td></td>
<td>Transformed</td>
<td>980</td>
<td>140</td>
</tr>
<tr>
<td>Ti–5 Al–2 Sn–4 Zr–6 Mo</td>
<td>Equiaxed</td>
<td>1155</td>
<td>165</td>
</tr>
<tr>
<td></td>
<td>Transformed</td>
<td>1120</td>
<td>160</td>
</tr>
<tr>
<td>Ti–6 Al–2 Sn–4 Zr–2 Mo</td>
<td>forging</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>α + β forged, solution treated and aged</td>
<td>903</td>
<td>131</td>
</tr>
<tr>
<td></td>
<td>β forged, solution treated and aged</td>
<td>895</td>
<td>130</td>
</tr>
<tr>
<td>Ti–17&lt;sup&gt;†&lt;/sup&gt;</td>
<td>α–β processed</td>
<td>1035–1170</td>
<td>150–170</td>
</tr>
</tbody>
</table>

<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

**Bimodal microstructure** is more resistant to fracture due to equaixed \(\alpha\) phase \(\rightarrow\) giving higher strength.

**Equiaxed \(\alpha\) phase** is also more resistant to nucleation of voids \(\rightarrow\) higher ductility.

<table>
<thead>
<tr>
<th>Microstructure</th>
<th>Test Temp</th>
<th>(\sigma_0.2) (MPa)</th>
<th>UTS (MPa)</th>
<th>(\sigma_F) (MPa)</th>
<th>El. (%)</th>
<th>RA (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lamellar</td>
<td>RT</td>
<td>925</td>
<td>1015</td>
<td>1145</td>
<td>5</td>
<td>12</td>
</tr>
<tr>
<td>Bi-modal (20 vol% (\alpha_\beta))</td>
<td>RT</td>
<td>995</td>
<td>1100</td>
<td>1350</td>
<td>13</td>
<td>20</td>
</tr>
<tr>
<td>Bi-modal (30 vol% (\alpha_\beta))</td>
<td>RT</td>
<td>955</td>
<td>1060</td>
<td>1365</td>
<td>13</td>
<td>26</td>
</tr>
<tr>
<td>Lamellar</td>
<td>600°C</td>
<td>515</td>
<td>640</td>
<td>800</td>
<td>10</td>
<td>26</td>
</tr>
<tr>
<td>Bi-modal (10 vol% (\alpha_\beta))</td>
<td>600°C</td>
<td>570</td>
<td>695</td>
<td>885</td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>Bi-modal (40 vol% (\alpha_\beta))</td>
<td>600°C</td>
<td>565</td>
<td>670</td>
<td>910</td>
<td>14</td>
<td>36</td>
</tr>
</tbody>
</table>
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 tortuous path in coarse lamellar microstructure leads to higher energy dissipation during fracture \(\rightarrow\) higher toughness.
Fatigue properties of titanium alloys

• Smaller equiaxed α grains are more beneficial to fatigue strength.

• Crack nucleates within the lamellar region more easily than in the equiaxed α phase region.

• But crack propagation is more difficult in the lamellar structure.

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

Crack initiation at lamellar region in bi-modal microstructure

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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. $\rightarrow$ better low cycle fatigue (high stress).

• Duplex structure of 30% equiaxed $\alpha$ and $\alpha$ platelets provides high temperature applications.

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

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

FCG curves for $\beta$ and $\alpha+\beta$ annealed conditions
Corrosion of titanium alloys

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

- 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

www.alba.no/whytitanium/
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 → macro/micro segregation.

- Tungsten Inert Gas Welding
- Electron Beam Welding
- Laser Beam Welding
- Friction welding
**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.*
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
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.
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.
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°C. → need effective shielding.

  • **Contamination cracking**
    - Due to iron contamination → reducing corrosion resistance, separate from steel fabrication.
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

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