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Titanium and Titanium Alloys

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Outline



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- Titanium and Titanium Alloys
 - Introduction (Ti alloys)
 - Influence of alloying elements
 - Classification (Ti alloys)
 - Phase transformations
 - Applications of Titanium Alloys
 - Titanium welding problems of $\alpha+\beta$
 - Titanium alloy welding problems of β
 - Alloys defects in Titanium welding

Titanium and Titanium Alloys



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– Important Properties

- High strength to weight ratio
- Excellent combination of strength and toughness
- Excellent corrosion resistance
- Low coefficient of thermal expansion and low thermal conductivity

Titanium and Titanium Alloys



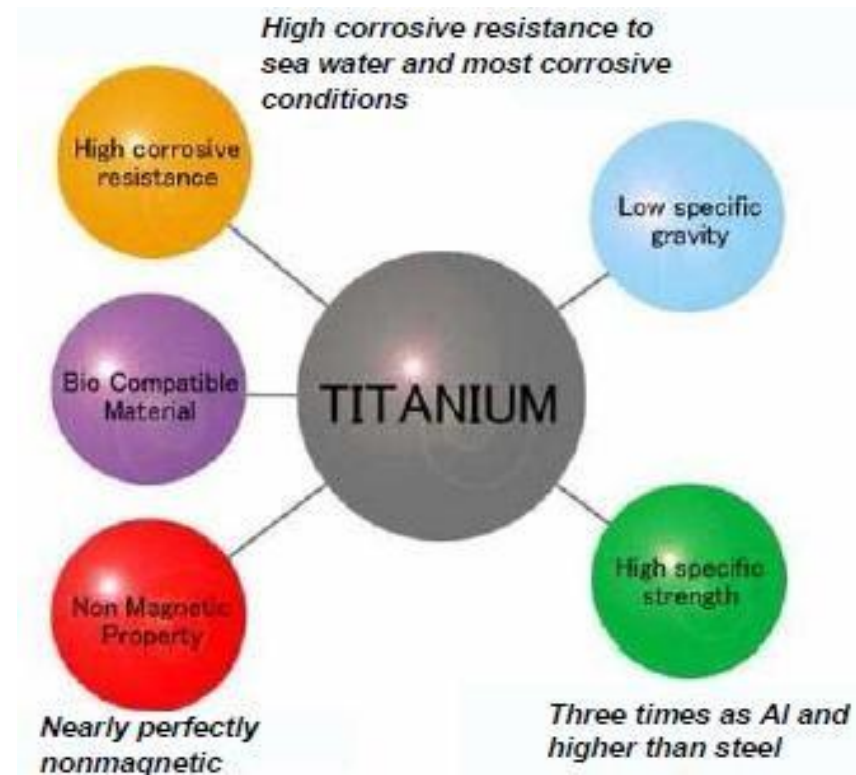
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– Applications

- Aerospace industry
- Pressure vessels
- Aircraft-turbine and compressor blades and disks
- Surgical implants (Medical field)
- Chemical industry
- Marine and Petrochemical industries
- Manufacture of sports equipment

Titanium and Titanium Alloys

– Introduction



Titanium and Titanium Alloys



– Introduction

- Pure titanium is a silver-colored metal (~correct weld should be silver as well)
- Melting point 1670°C (3035°F), Boiling point 3260°C (5900°F).
- The average coefficient of thermal expansion is 8.41 $\mu\text{m}/\text{m}/^\circ\text{C}$ at 20°C (68°F).
- Titanium density: 4.51 g/cm^3
- Titanium has a strong chemical affinity for oxygen, forms a tight microscopic oxide film on prepared surfaces at RT
- The oxide film makes titanium passive to further reactivity.
- This accounts for the excellent corrosion resistance of titanium to aqueous salt or oxidizing acid solutions and to an above-average resistance to corrosion caused by mineral acids.

Titanium and Titanium Alloys



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– Introduction

Cost of Titanium: A Comparison^a

Item	Material (\$/lb)		
	Steel	Aluminum	Titanium
Ore	0.02	0.01	0.22 (rutile)
Metal	0.10	1.10	5.44
Ingot	0.15	1.15	9.07
Sheet	0.30–0.60	1.00–5.00	15.00–50.00

^a2015 Contract prices. The high cost of titanium compared to aluminum and steel is a result of (a) high extraction costs and (b) high processing costs. The latter relates to the relatively low processing temperatures used for titanium and the conditioning (surface regions contaminated at the processing temperatures, and surface cracks, both of which must be removed) required prior to further fabrication.

Metal Consumption

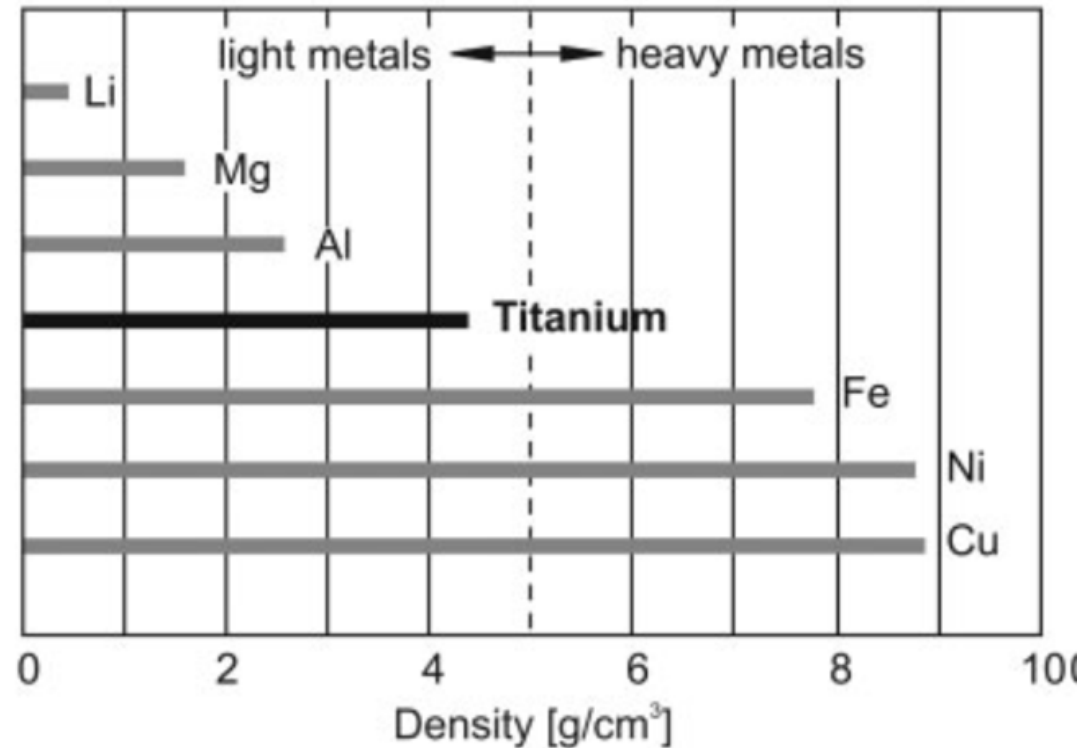
Structural Metals	Consumption/Year (10 ³ Metric Tons)
Ti	50
Steel	700,000
Stainless steel	13,000
Al	25,000

Titanium and Titanium Alloys



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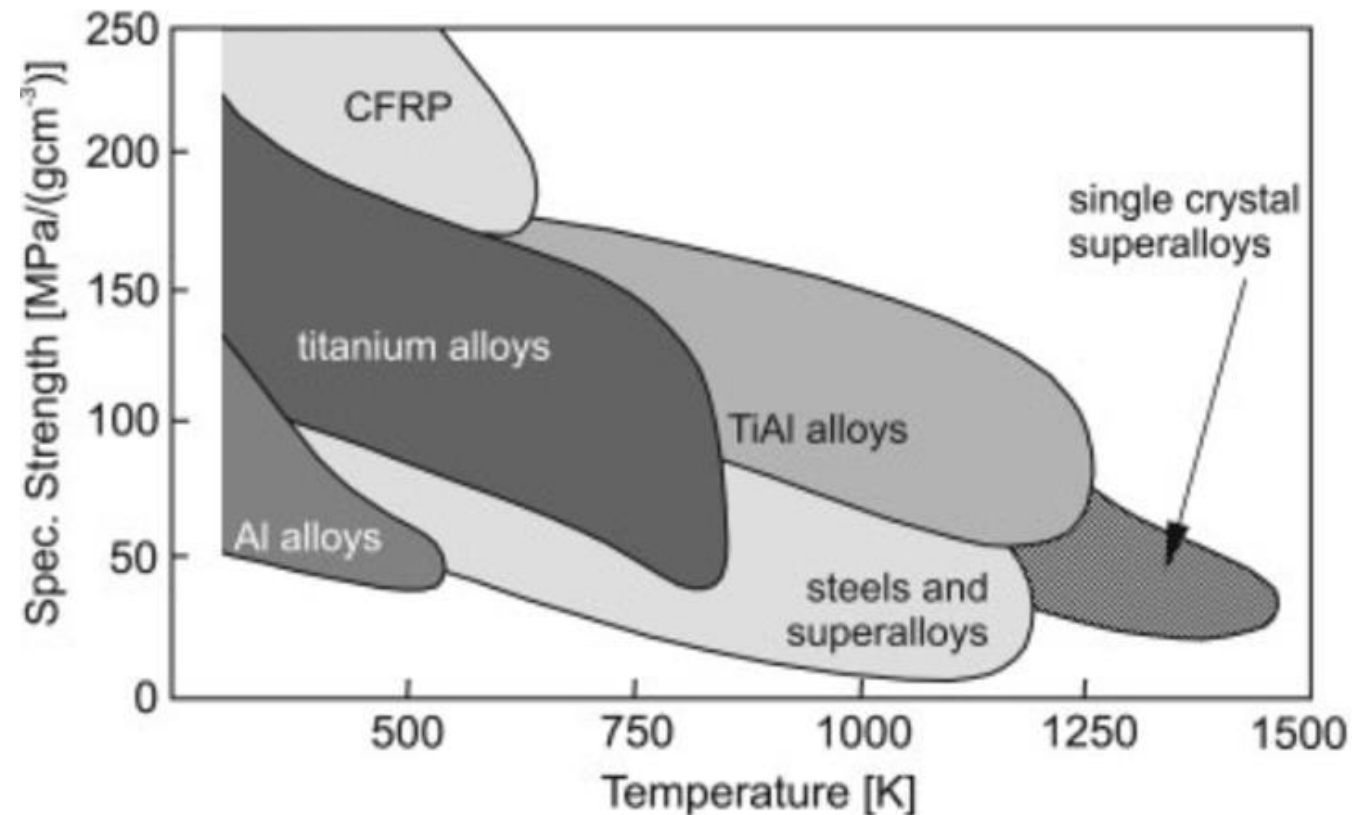
- Density comparison
 - Showing selected only



Titanium and Titanium Alloys

– Specific strength vs temperature

Specific strength versus use temperature of selected structural materials compared with titanium alloys and aluminides.

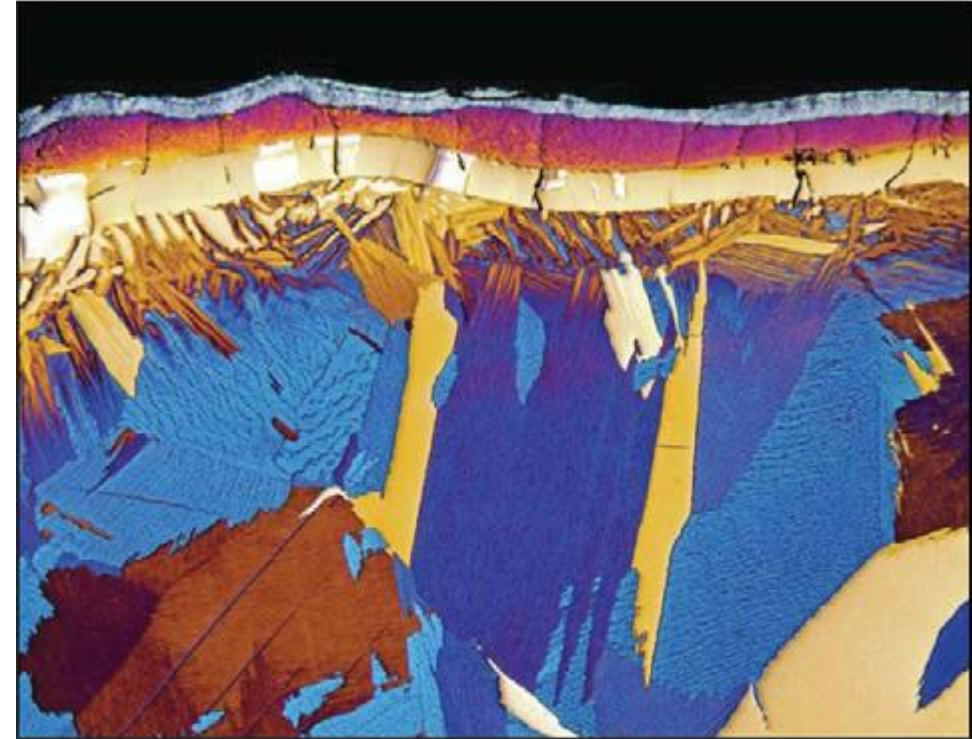


Titanium and Titanium Alloys

- The oxide film makes titanium passive to further reactivity.
- Providing excellent corrosion resistance to aqueous salt or oxidizing acid solutions



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Micrograph courtesy of E-Imaging Consulting

Figure 6.2—Micrograph of Forged Grade 2 Titanium Showing an Oxide Layer Formed on the Surface (Top Layer) (X200, DIC-Light, Stain Etched)

Titanium and Titanium Alloys



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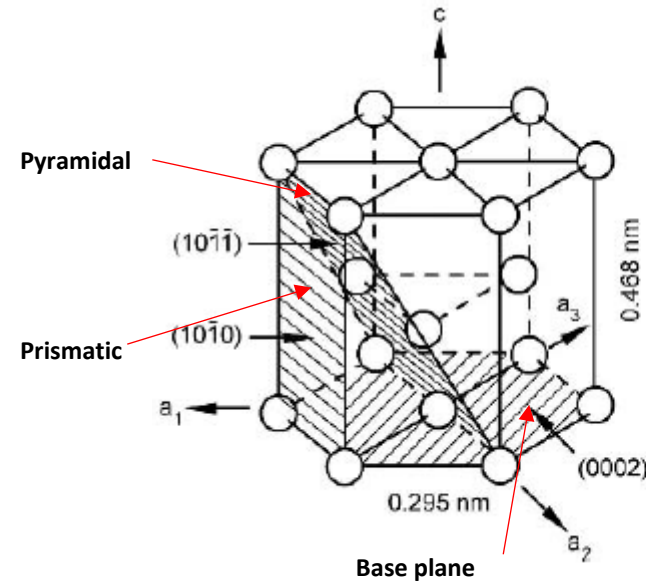
- Titanium crystal structures
 - **HCP (α) at low temperatures**
 - **BCC (β) at high temperatures**
- $\alpha \leftrightarrow \beta$ allotropic transformation
 - **Occurs at 882°C in pure Ti**
 - This temp is known as **transformation temperature**
 - Transformation mode
 - Slow cooling > Diffusional (α)
 - Fast cooling > Martensitic (α')
 - Alloying elements influence transformation temperature
- Alloying elements
 - α stabilizers (**Al, C, O, N**) elements soluble in α phase
 - β stabilizers (elements soluble in β phase)
 - Isomorphous (**Nb, Mo, V, Ta**)
 - Eutectoid (**Cr, Ni, Co, Fe, Mn, Cu, Si, Pd, H**)
 - Neutral elements (**Zr, Sn**)
- The temperature at which allotropic transformation takes place is called beta transus

Titanium and Titanium Alloys

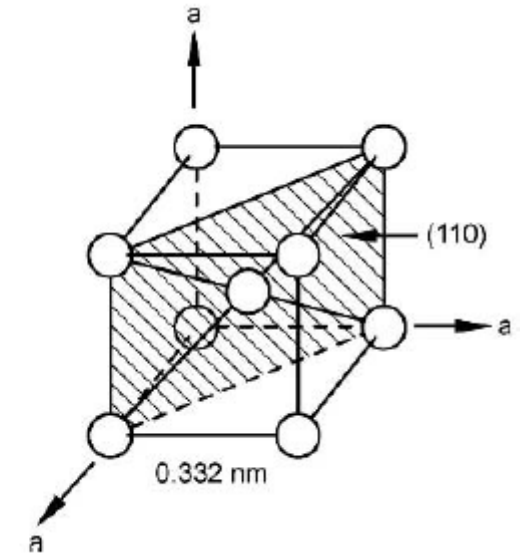


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- Titanium crystal structures
 - HCP (α) at low temperatures
 - BCC (β) at high temperatures
- $\alpha \leftrightarrow \beta$ allotropic transformation
 - **Occurs at 882°C in pure Ti**
- The hexagonal unit cell of the α phase indicating also the RT values of the lattice parameters a (0.295 nm) and c (0.468 nm).
- Similarly for beta phase shown



Unit cell of alpha phase

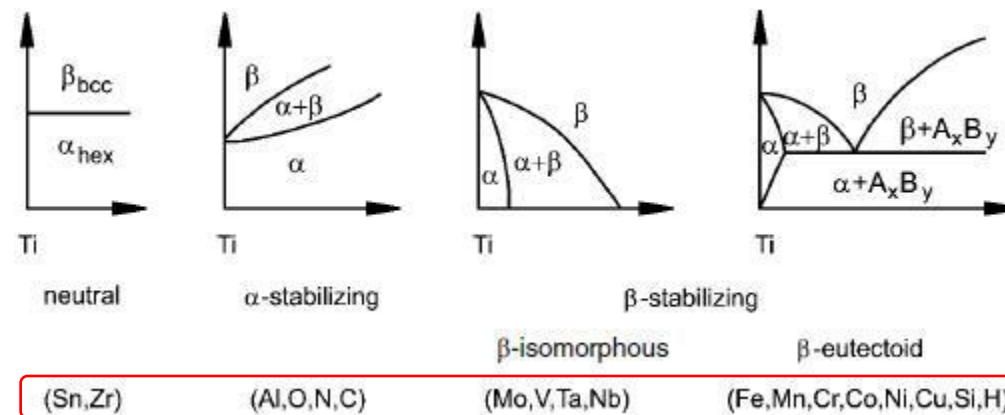


Unit cell of beta phase

Titanium and Titanium Alloys

– Influence of alloying elements

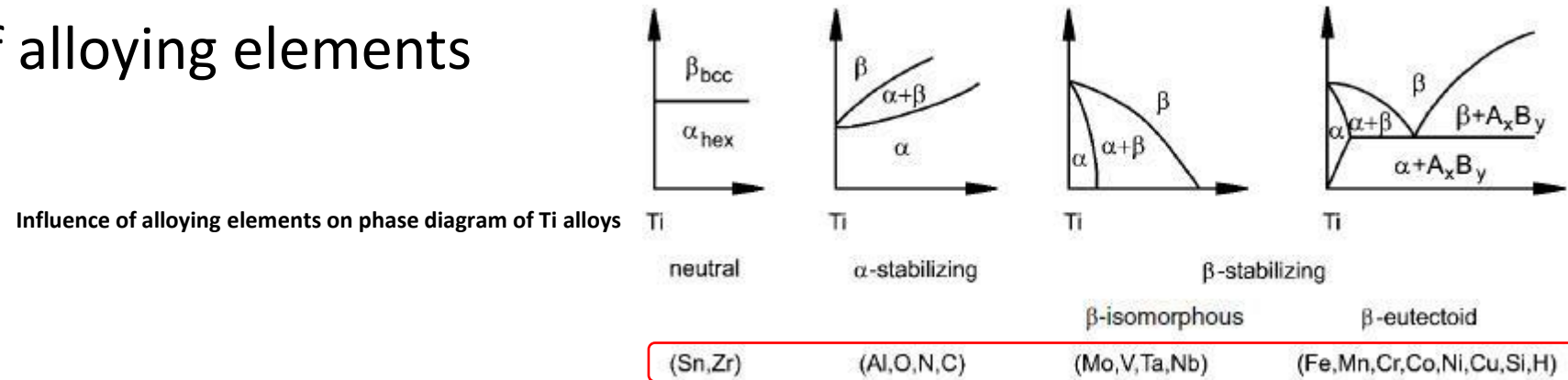
- Depending on the influence of the alloying elements added, titanium alloys are classified as follows: (a) CP Ti (b) α alloys, (c) near α alloys (d) α - β alloys and (e) β alloys
- Elements soluble in α phase (α stabilizers) and elements soluble in β phase (β stabilizers)



Influence of alloying elements on phase diagram of Ti alloys

Titanium and Titanium Alloys

– Influence of alloying elements



- α stabilizers raise the beta transus temperature by stabilizing α phase
- β stabilizers are elements that lower the beta transus temp
 - β isomorphous: Beta-isomorphous elements exhibit complete mutual solubility with beta titanium (solubility of the element in Ti in the β form is unlimited). Increasing the addition of the solute element progressively depresses the transformation temperature. Mo and V are the most important beta isomorphous elements, while Nb and Ta have also found application in some alloys
 - β eutectoid: eutectoid mixture of alpha and a compound form

Titanium and Titanium Alloys



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– Beta stabilizing Titanium alloys

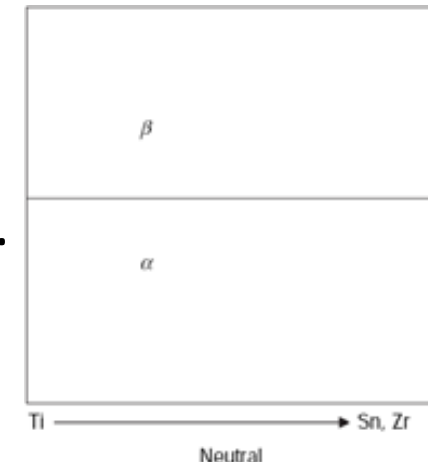
- Mo is an important beta stabilizer that promotes hardness and short time elevated-temperature strength.
- V is another important beta stabilizer, although it is less effective than molybdenum in providing elevated-temperature strength.
- Nb improves oxidation resistance at high temperatures.
- Sn and Zr are neutral elements because they neither rise nor lower the beta transus temp
- Intermetallic compounds will not form during HT and welding of Ti-Mn, Ti-Fe and Ti-Cr alloys; however,
- Heat treatment or welding of Ti-Cu, Ti-Ni and Ti-Si alloys will result in the formation of intermetallics (metallic impurities).
- Only Cr and Fe are used as beta-stabilizing elements in commercial titanium alloys (to avoid compound impurities).
- Small Si additions produce fine silicides in these alloys, which improve elevated temperature properties.

Titanium and Titanium Alloys



– Neutral elements

- Sn and Zr are neutral elements because they neither rise nor lower the beta transus temperature (used as strengthening elements in 3 types of Ti alloys)
- Tin has extensive solid solubility in both the alpha and beta phases
- Tin (element – Sn) is used as a solid-solution strengthener in conjunction with Al to achieve higher strength without embrittlement.
- Solute atoms of elements such as Al or Sn, which have atomic diameters that are approximately the same (i.e., within $\pm 15\%$) as Ti, will form substitutional solid solutions (filling gaps where Ti is absent).
- Zr forms a continuous solid solution with Ti and increases strength at low and intermediate temperatures.

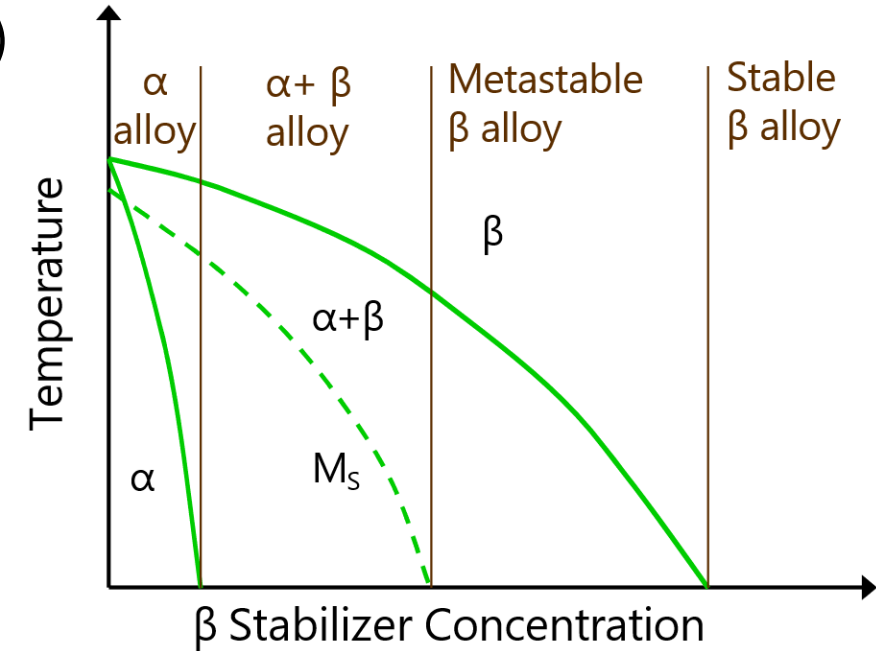


Titanium and Titanium Alloys



– Classification of Titanium alloys

- CP Titanium (Commercially Pure)
 - Different grades depending on oxygen content (up to 0.4%)
 - Pd additions for improved corrosion resistance (Grades 7)
- α alloys
 - Ti-3Al-2.5V (half-alloy)
 - Ti-5Al-2.5Sn
- Near- α alloys
 - Ti-6Al-2Sn-4Zr-2Mo
 - Ti-6Al-5Zr-0.5Mo-0.25Si (IMI685)
 - Ti-5.8Al-4Sn-3.5Zr-0.7Nb-0.5Mo-0.3Si-0.06C (IMI 834)



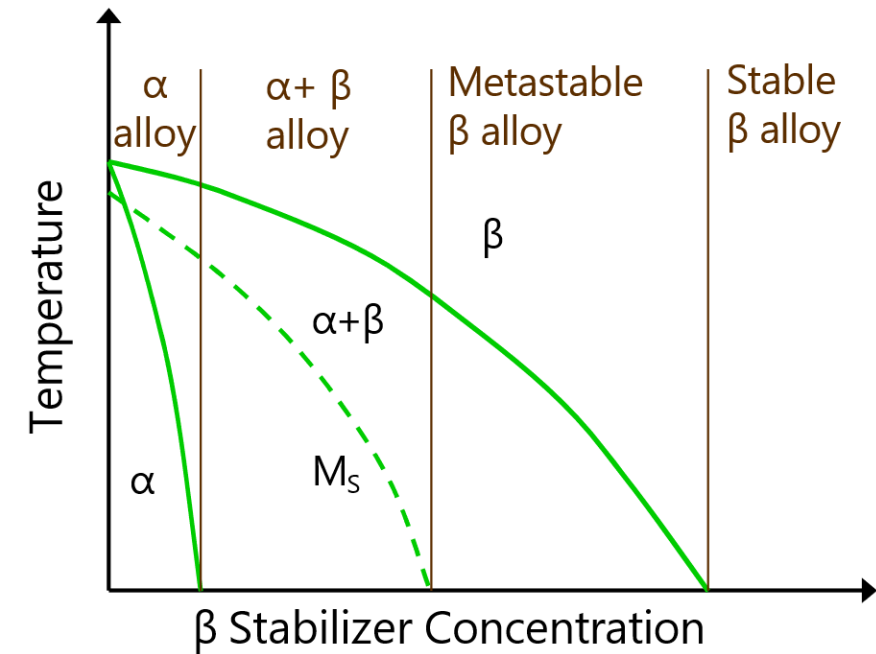
Pseudo binary section through a β isomorphous phase diagram

Titanium and Titanium Alloys



– Classification of Titanium alloys

- α - β alloys
 - Ti-6Al-4V
 - Ti-8Al-1Mo-1V
 - Ti-4Al-2Sn-4Mo-0.5Si (IMI550)
- Metastable β alloys
 - Ti-6Al-2Sn-4Zr-6Mo
 - Ti-10V-2Fe-3Al
 - Ti-15V-3Cr-3Al-3Sn
 - Ti-15Mo-2.7Nb-3Al-0.2Si (Beta 21S)
- Stable β alloys
 - Ti25V-15Cr-0.2Si (Ti-40)



Pseudo binary section through a β isomorphous phase diagram

Titanium and Titanium Alloys



– Classification of Titanium alloys

- Depending on the influence of the alloying elements added, titanium alloys are classified as follows: (a) α alloys, (b) near α alloys, (c) α - β alloys and (d) β alloys
- **CP Ti:** Different grades depending on oxygen content (up to 0.4%). Pd additions for improved corrosion resistance (Grades 7)
- **α alloys:** These alloys contain aluminium as the principal alloying element and tin as it does not influence the transformation temperature significantly but causes considerable solid solution strengthening. Al also contributes to the high strength to weight ratio. These alloys have good stability, good high temperature properties but are not controllable to heat treatment for microstructural modifications.

Titanium and Titanium Alloys



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– Classification of Titanium alloys

- **Near α alloys:** These alloys contain small amount of β stabilizers, generally up to 2 % by weight, which stabilize small volume fraction of the β phase. **They possess higher creep resistance compared to the other class of titanium alloys.**
- **α - β alloys:** These alloys contain significant amount of β stabilizers (6 %). They may also contain some amount of Zr and Sn as solid solution strengtheners. These alloys are amenable to heat treatment and hence their properties can be altered over a wide range. They have higher short time high temperature strength compared to other class of titanium alloys.
- **β alloys:** These alloys contain sufficient amount of β stabilizers (>10 %) to retain β in metastable form. Due to the good **ductility** of the β phase, the β alloys have excellent **formability** and this is the main attraction of these alloys. These alloys have excellent forgeability, cold rolling capabilities, and can be cold formed in sheet form more readily than other alloys.

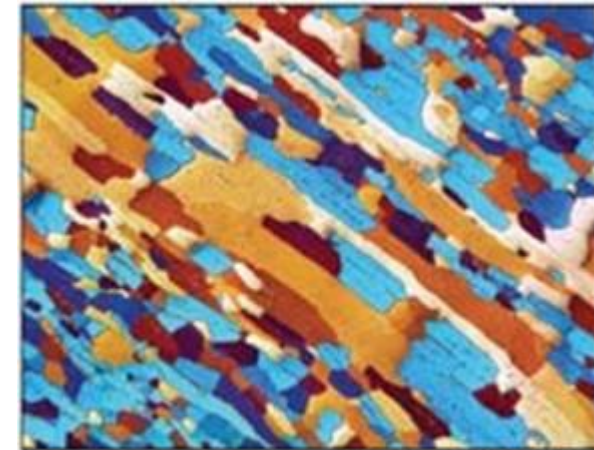
Titanium and Titanium Alloys



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– CP Titanium alloys

- Pure Ti (CP Ti) is quite ductile
 - Primarily for applications requiring corrosion resistance and high ductility for fabrication but relatively low strength in service.
 - YS (240-550 MPa) UTS (262-621 MPa) at RT
 - Pure Ti is quite ductile (Elongation: 15-25%)
 - Adding limited amounts of O, C and N in a solid solution will significantly strengthen titanium
 - Carbon also contributes to strengthening, but less intensive effect on Ti
 - Excessive quantities of O and N leads to embrittlement
 - Hydrogen also promotes embrittlement in titanium when present above specific limits.
 - Strengthening by coldworking is possible (not popular) i.e., without adding any elements
 - Example of CP Ti: Ti-0.2 Pd, addition of Pd provides improved corrosion resistance, but no effect on mechanical properties

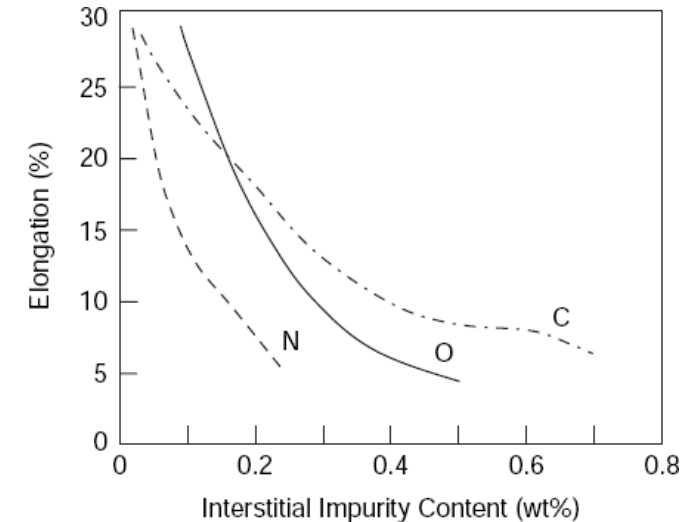
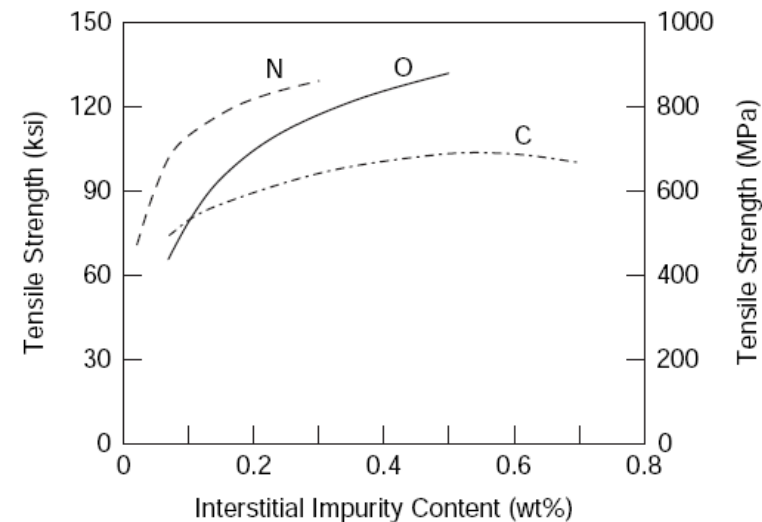


Micrograph courtesy of E-Imaging Consulting
Microstructure of Commercially Pure
Grade 2 Titanium Plate (X200, Stain Etched)

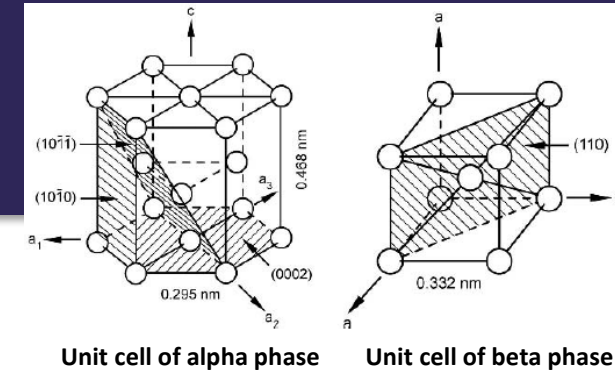
Titanium and Titanium Alloys



- CP Titanium alloys: Effect of interstitial content
 - C, H, N and O form an interstitial solid solution with Ti
 - (C has limited solubility in both alpha and beta phases) O and N have extensive solubility in α phase, with O having greater (α stabilizers)
 - H more soluble in beta phase (β stabilizing element)
 - Insufficient protection of hot Ti from the atmosphere promotes absorption of O
 - Ti has great affinity for interstitial elements (O, N) readily absorbs them at elevated Temperatures, which increases strength and reduces ductility
 - N is more effective strengthener, O is next to it, followed by C

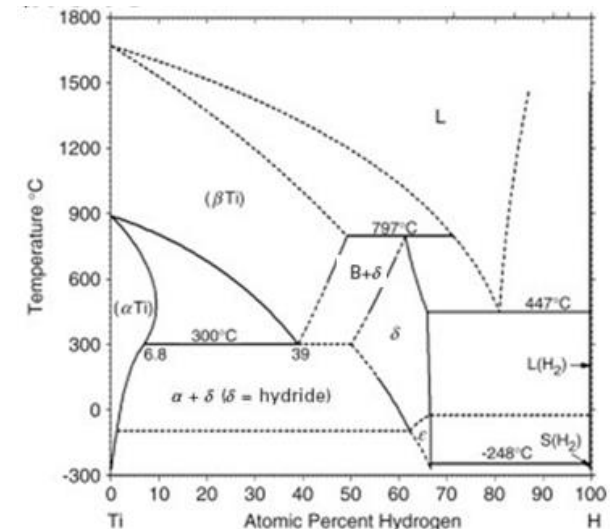
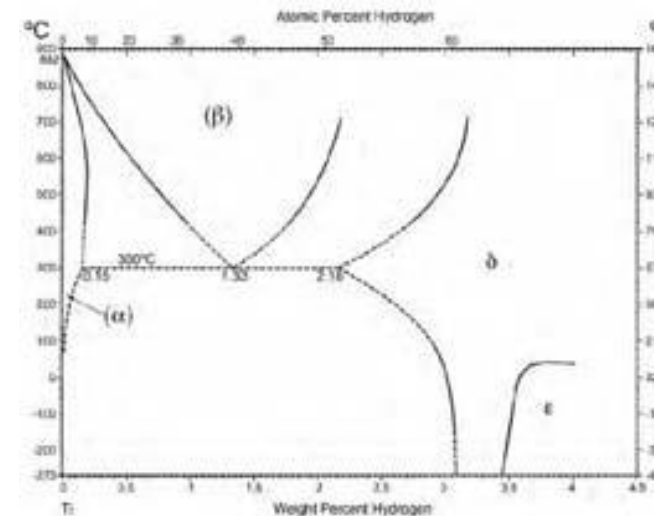


Titanium and Titanium Alloys



– Hydrogen Solubility

- β has much higher solubility for hydrogen than α , thus, α alloys are more prone to hydride formation
- The higher solubility, rapid diffusion of hydrogen in the beta titanium results from BCC structure (especially at elevated temperatures)
- Hydrogen enters the tetrahedral holes which are larger in BCC than HCP
- The presence of hydrogen in solid solution in both α and β phases results in lattice expansions



Titanium and Titanium Alloys

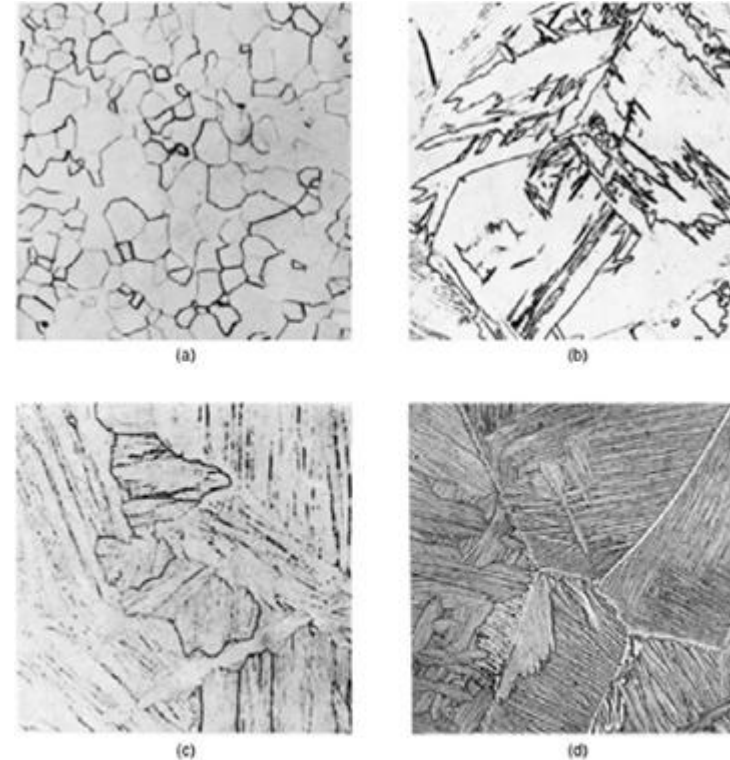


– Hydrogen Solubility

- Hydrogen is always minimized in titanium alloys because it causes hydrogen embrittlement by the precipitation of hydrides, so the **maximum limit allowed** is approximately **0.015 wt% (~100 ppm)**.
- When the solubility limit of hydrogen in titanium (~100 to 150 ppm for CP Ti) is exceeded, hydrides begin to precipitate.
- Absorption of several hundred ppm of hydrogen results in embrittlement and the possibility of SCC (stress corrosion cracking)
- H and O can be absorbed if moisture is present
- Residual oils, cleaning agents, other contaminating substances on the work piece should be removed

Titanium and Titanium Alloys

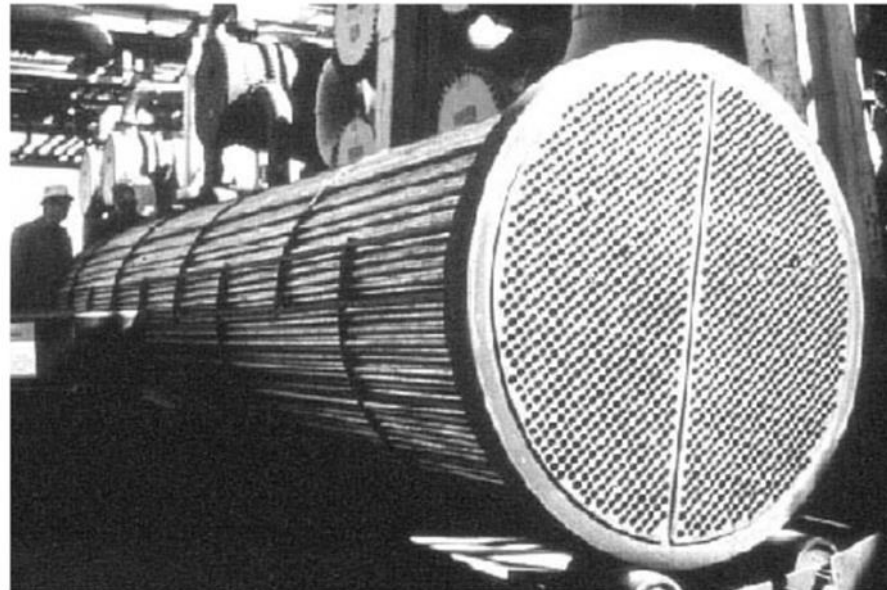
– CP Titanium alloys: Microstructure



Microstructure of CP titanium: (a) annealed 1 h at 700 °C showing equi-axed grains of α ($\times 100$); (b) quenched from β -phase field showing martensitic α' ($\times 150$); (c) air-cooled from the phase field showing Widmanstatten plates of α ($\times 100$) (courtesy W. K. Boyd); (d) near- α alloy IMI 685 air-cooled from the phase field showing a basket weave configuration of Widmanstatten plates of the α -phase delineated by small amounts of the β -phase (courtesy IMI Titanium) ($\times 75$).

Titanium and Titanium Alloys

– CP Titanium alloys



Shell type heat exchanger containing welded CP titanium tubes (courtesy J. A. Hall)

Titanium and Titanium Alloys



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– Titanium alloys

Composition of Titanium Alloys in Commercial Production

Designation	Nominal Composition, wt %					Impurity Limits (max.), wt %				
	Al	Sn	Zr	Mo	Others	N	C	H	Fe	O
Unalloyed Grades										
ASTM Grade 1	—	—	—	—	—	0.03	0.10	0.015	0.20	0.18
ASTM Grade 2	—	—	—	—	—	0.03	0.10	0.015	0.30	0.25
ASTM Grade 3	—	—	—	—	—	0.05	0.10	0.015	0.30	0.35
ASTM Grade 4	—	—	—	—	—	0.05	0.10	0.015	0.50	0.40
ASTM Grade 7	—	—	—	—	0.2 Pd	0.03	0.10	0.015	0.30	0.25
ASTM Grade 11	—	—	—	—	0.12–0.25 Pd	0.03	0.10	0.015	0.20	0.18
ASTM Grade 12	—	—	—	0.3	0.6–0.9 Ni	0.03	0.10	0.015	0.30	0.25

Titanium and Titanium Alloys



– Alpha Titanium alloys

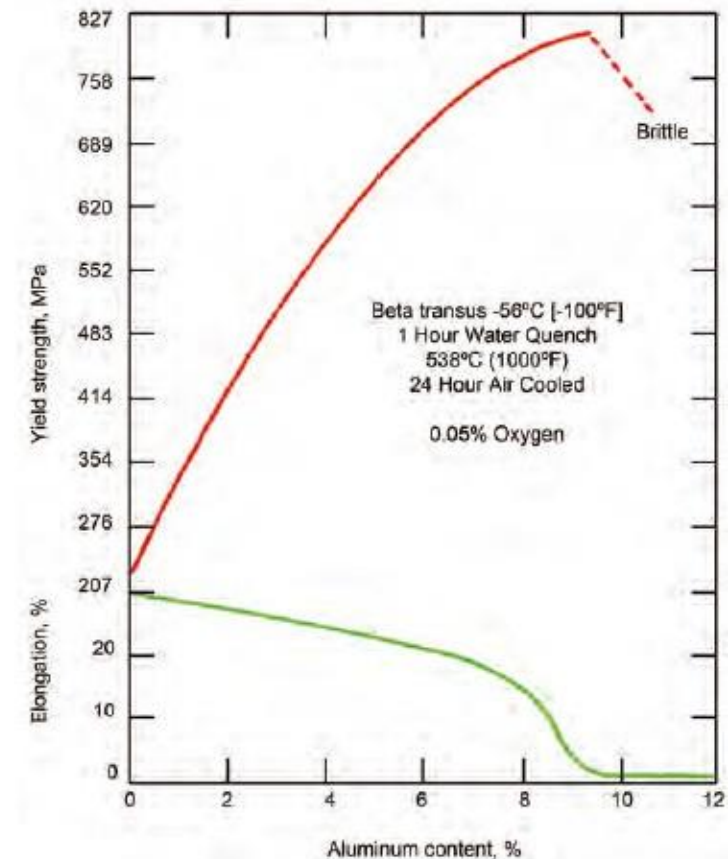
- Aluminium as the principal alloying element
- Zr and Sn are used as substitutional α strengtheners
- Good high temperature properties and weldability
- Not controllable to heat treatment for microstructural modifications
- Primarily used in the chemical and process engineering industry
- Used in cryogenic applications and when corrosion resistance is needed

Titanium and Titanium Alloys



– Alpha Titanium alloys

- Ductility is excellent up to 8% Al, where a sufficient amount of Al can cause embrittlement.
- Outstanding elevated temperature properties, but this comes with the loss of ductility and toughness at RT
- Upper limit of Al in commercial Ti alloys (6-8% Wt.%) for retaining ductile nature
- Neutral elements Sn and Zr, in combination with Al, also cause embrittlement or lack of ductility after creep exposure.
- There is a practical limit to the amount of α -stabilizing elements that may be added to titanium since the alloys tend to embrittle because of an ordering reaction that occurs if the '**aluminium equivalent**' exceeds about 9%.



Titanium and Titanium Alloys



- Alpha Titanium alloys
 - Increased Al content causes embrittlement

Composition of Titanium-Aluminum Systems According to Phase

Phase	Aluminum, wt %
(β Ti)	0 to 33.8
(α Ti)	0 to 32
Ti ₃ Al	14 to 26
TiAl	34 to 56.2
Ti ₃ Al ₅	44 to 49
TiAl ₂	51 to 54
α TiAl ₂	—
δ	57 to 59.8
TiAl ₃	63
α TiAl ₃	63
(Al)	98.8 to 100

Titanium and Titanium Alloys



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– Alpha Titanium alloys

Industrial uses for titanium because of good corrosion resistance

Industry	Equipment	Environment
Power generation	Condensers, heat exchangers, flue gas scrubbers	Aqueous solutions of various purity, SO ₂ containing gases
Water plants	Desalinization heat exchangers	Sea water
Petrochemical industry	Heat exchangers, well heads, pipe and down hole hardware	H ₂ S containing brines
Pulp and paper	Diffusion washers in bleaching section of process	Chlorides containing liquids
Chemical industry	Dimensionally stable electrodes	Cl ₂ and Cl ₂ compounds
Metal production	Cathodes for electrowinning Cu, Au, and Zn	Various aggressive aqueous solutions
Mineral dressing	Pressure vessels at high T and P	Various aggressive aqueous solutions
Biomedical devices	Orthopedic implants, surgical implants, surgical implements	Human body and autoclave sterilizers
Spacecraft	Cryogenic tanks	N ₂ O ₄ , liquid O ₂ , liquid H ₂

Titanium and Titanium Alloys



- Near-Alpha Titanium alloys
 - Contain small amount of β stabilizers (up to 2 % by weight)
 - Possess **higher creep resistance**
 - Majority of these alloys contain **silicon for enhanced creep resistance**
 - Operating temperature is limited to about 500 to 550°C

Alloy	Chemical Composition [wt. %]	T_p [°C]	Developer	Year	Hardness [HV]	E [GPa]	YS [MPa]	TS [MPa]	%El	K_k [MPa m ^{1/2}]
<i>Near-α Titanium Alloys</i>										
Ti-6-2-4-2-S	Ti-6Al-2Sn-4Zr-2Mo-0.1Si	995	RMI, USA	1970	340	114	990	1010	13	70
TIMETAL 1100	Ti-6Al-2.7Sn-4Zr-0.4Mo-0.4Si	1010	Timet, USA	1988		112	900–950	1010–1050	10–16	60–75
TIMETAL 685	Ti-6Al-5Zr-0.5Mo-0.25Si	1020	IMI, UK	1969		120	850–910	990–1020	6–11	68
TIMETAL 834	Ti-5.8Al-4Sn-3.5Zr-0.5Mo-0.7Nb-0.35Si-0.06C	1045	IMI, UK	1984	350	120	910	1030	6–12	45

Titanium and Titanium Alloys



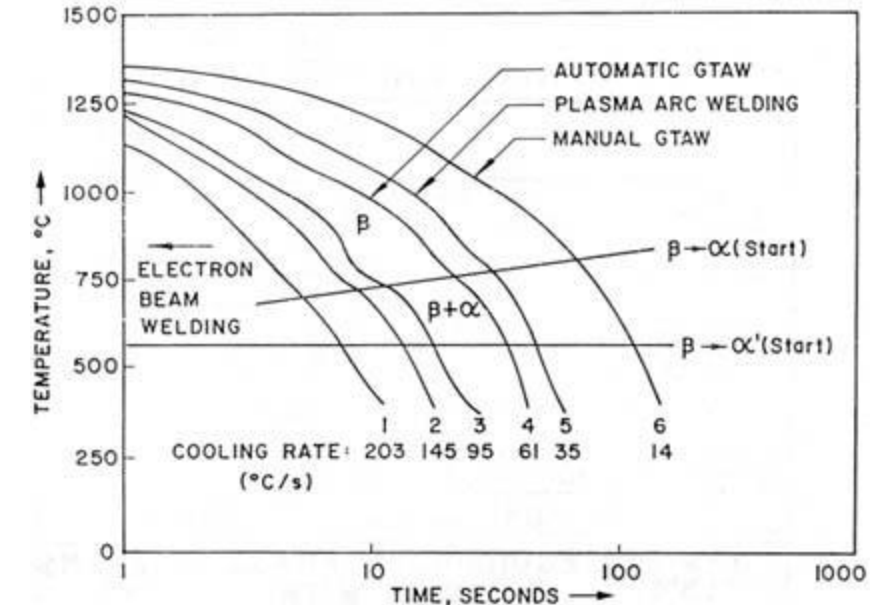
– Alpha-Beta Titanium alloys

- Contain significant amount of β stabilizers (up to 6 % by weight)
- Also contain some amount of Zr and Sn as solid solution strengthening
- Controllable for heat treatment
- Creep strength is lower than near- α alloys
- Used either in annealed or ST (solution treated) and aged condition
- Exhibit outstanding high strength-to-weight ratios in HT condition and excellent fracture toughness when annealed

Alloy	Chemical Composition [wt. %]	T_p [°C]	Developer	Year	Hardness [HV]	E [GPa]	YS [MPa]	TS [MPa]	%El	K_{Ic} [MPa m ^{1/2}]
<i>α-β Titanium Alloys</i>										
Ti-6-4	Ti-6Al-4V	995	miscellaneous	1954	300-400	110-140	800-1100	900-1200	13-16	33-110
Ti-6-6-2	Ti-6Al-6V-2Sn	945	miscellaneous		300-400	110-117	950-1050	1000-1100	10-19	30-70
Ti-6-2-2-2-2	Ti-6Al-2Sn-2Zr-2Mo-2Cr-0.25Si					110-120	1000-1200	1100-1300	8-15	65-110
Ti-6-2-4-6	Ti-6Al-2Sn-4Zr-6Mo	940	Pratt & Whitney, USA		330-400	114	1000-1100	1100-1200	13-16	30-60
Ti-17	Ti-5Al-2Sn-2Zr-4Mo-4Cr	890	GE, USA	1968	400	112	1050	1100-1250	8-15	30-80

Titanium and Titanium Alloys

- Alpha-Beta Titanium alloys: Continuous cooling effect
 - Cooling effect from Beta > Alpha transition
 - The microstructure phase transformations during welding can be well understood using the concept of continuous cooling transformations (CCT) diagrams.
 - During continuous cooling, principally decomposition of β phase occurs. Such transformations include diffusion controlled nucleation and growth of α and other phases such as martensite (α') and duplex.



Continuous cooling transformation diagram for Ti-6Al-6V-2Sn for different welding processes

Titanium and Titanium Alloys



– Beta Titanium alloys

- Contain a sufficient amount of β stabilizers (>10 %) to retain β
- Due to the good ductility of β phase, β alloys have excellent formability
- Excellent forgeability and cold-rolling capabilities
- These alloys are denser than other Ti alloys (high density comes from large additions of heavy β stabilizers (Mo, V and Cr))
- Weldable in the annealed condition.

Alloy	Chemical Composition [wt. %]	T_p [°C]	Developer	Year	Hardness [HV]	E [GPa]	YS [MPa]	TS [MPa]	%El	K_{Ic} [MPa m ^{1/2}]
<i>Metastable β Titanium Alloys</i>										
SP 700	Ti-4.5Al-3V-2Mo-2Fe	900	NKK, J	1989	300–500	110	900	960	8–20	60–90
Beta III	Ti-11.5Mo-6Zr-4.5Sn	760	Colt/Crucible, USA	1960	250–450	83–103	800–1200	900–1300	8–20	50–100
Beta C	Ti-3Al-8V-6Cr-4Mo-4Zr	795	RMI, USA	1969	300–450	86–115	800–1200	900–1300	6–16	50–90
Ti-10-2-3	Ti-10V-2Fe-3Al	800	Timet, USA	1976	300–470	110	1000–1200	1000–1400	6–16	30–100
Ti-15-3	Ti-15V-3Cr-3Al-3Sn	760	Timet, USA	1981	300–450	80–100	800–1000	800–1100	10–20	40–100

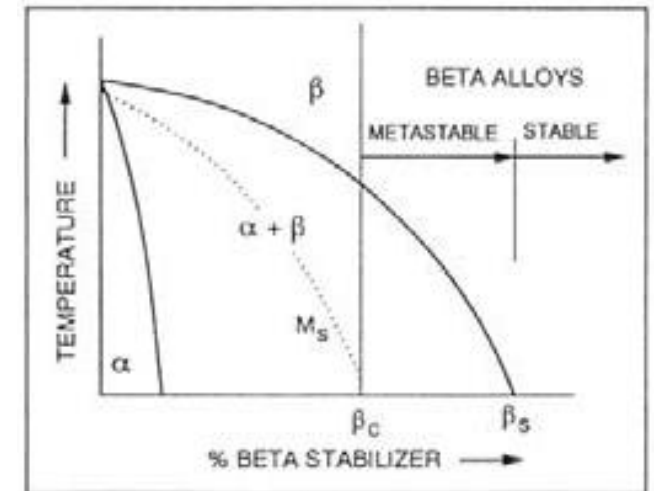
Titanium and Titanium Alloys



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– Beta and Metastable beta Titanium alloys

- β -titanium alloys are defined as those containing enough total alloying elements that enable the β phase to be retained in either a metastable or stable condition after cooling to RT during HT.
- This implies that the amount of these elements is sufficient to avoid passing through the martensite start line (M_s).
- Alloy compositions that place them between the critical minimum level (β_c) of these stabilizing elements (i.e. where the M_s line intersects the room temperature axis) and the similar intersection point of the β - transus line (β_s), are commonly referred to as metastable β -titanium alloys because they will precipitate a second phase (usually alpha) upon ageing.
- More highly alloyed compositions to the right of β_s are considered to be stable β -alloys and should not be able to be hardened by heat treatment. Such alloys are less commonly used.



Phase diagram showing metastable and stable beta alloys

Titanium and Titanium Alloys



– Beta and Metastable beta Titanium alloys

- Mo content in beta stabilization plays crucial role in determining beta-titanium type
- Measured as MoE (Mo-Equivalence) (Molybdenum equivalency)
 - Alloys with $0 \leq \text{MoE} < 5$ are beta-rich
 - Alloys with $5 \leq \text{MoE} < 10$ are near-beta
 - Alloys with $10 \leq \text{MoE} < 30$ are metastable β
 - Alloys with $\text{MoE} > 30$ are denoted stable β .

β stabilization:

Table: Concentration of some transition metals needed to retain the β phase at room temperature in binary titanium alloys:

	V	Nb	Ta	Cr	Mo	W	Mn	Fe	Co	Ni
Wt%	15	36	50	8	10	25	6	4	6	8

Titanium and Titanium Alloys



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– Beta and Metastable beta Titanium alloys

- $0 \leq \text{MoE} < 5$ are beta-rich
- $5 \leq \text{MoE} < 10$ are near-beta
- $10 \leq \text{MoE} < 30$ are metastable β
- $\text{MoE} > 30$ are denoted stable β

The molybdenum equivalency (MoE) and beta transus temperatures (T_β) of several model binary and commercially important beta Ti alloys. Compositions of the alloys are given in wt. %.

Alloy	Name	Application	Type	MoE	Beta Transus (°C)
Ti-13Nb-13Zr	-	Biomedical	Beta-rich	1.4	735
Ti-20Nb-10Zr-5Ta	TN2T	Biomedical	Near-Beta	5.0	-
Ti-5Al-5Mo-5V-3Cr	Ti-5553	Aircraft	Near-Beta	8.2	855–870
Ti-11.5Mo-6Zr-4.5Sn	TMA	Biomedical	Near-Beta	9.0	-
Ti-10V-2Fe-3Al	Ti-10-2-3	Aircraft	Near-Beta	9.5	790–805
Ti-35Nb-5Ta-7Zr	-	Biomedical	Near-Beta	9.7	-
Ti-29Nb-13Ta-4.6Zr	-	Biomedical	Metastable	10.2	-
Ti-15V-3Cr-3Al-3Sn	-	Aircraft	Metastable	10.9	750–770
Ti-15Mo-3Al-3Nb-0.2Si	Beta 21S	Aircraft	Metastable	12.8	795–810
Ti-15Mo	-	Model Binary	Metastable	15.0	-
Ti-3Al-8V-6Cr-4Mo-4Zr	Beta C	Aircraft/Oilfields	Metastable	16.0	715–740
Ti-12Mo-6Zr-2Fe	-	Biomedical	Metastable	16.8	-
Ti-13V-11Cr-3Al	B120 VCA	Aircraft	Metastable	23.0	650
Ti-30Mo	-	Model Binary	Stable	30.0	-
Ti-40Mo	-	Model Binary	Stable	40.0	-
Ti-35V-15Cr	Alloy C	Aircraft	Stable	47.5	unknown

Titanium and Titanium Alloys



AILEEN

- Beta and Metastable beta Titanium alloys
 - Another measure for beta alloys is;
 - Approximately 3.5 wt.% Fe added to titanium is required to retain the beta phase, while nearly 45 wt.% Ta is required before 100% beta can be retained at room temperature

Alloying element	Minimum alloy content to retain 100% beta after quenching (β_c)	
	U.S. data	
	wt%	at.%
Mn	6.5	5.6
Fe	3.5	3.0
Cr	6.3	5.8
Co	7.0	5.8
W	22.5	6.7
Ni	9	7.5
Mo	10.0	5.3
V	15.0	14.2
Cb	36.0	22.5
Ta	45.0	17.8

Titanium and Titanium Alloys



AILEEN

- Beta and Metastable beta Titanium alloys: Characteristics
 - **β -Titanium** alloys possess BCC crystal structure, which is readily cold worked (than HCP α structure) in the β -phase field.
 - Microstructure after quenching contains uniform β phase.
 - After solution heat treating + quenching + ageing > gives high strength (1300 – 1400 MPa)
 - Metastable β -Titanium alloys are hardenable while stable β -Titanium alloys are non-hardenable
 - Excellent fabrication ability
 - Excellent tensile strength up to 370°C. Poor creep strength above 370°C.
 - Good weldability in the solution-treated condition
 - Beta 1 alloy (Ti-13V-11Cr-3Al) is used successfully on SR-71, Mach 3 aeroplane

Titanium and Titanium Alloys



– Beta and Metastable beta Titanium alloys: Characteristics

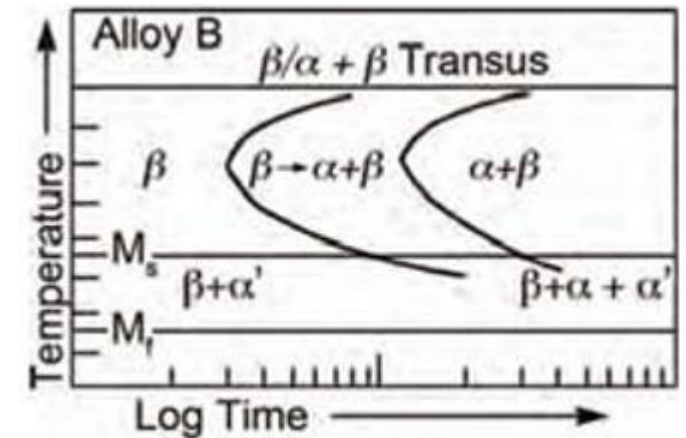
- **Metastable beta** titanium alloys, e.g., Ti-15V-3Al-3Sn-3Cr and Ti-3Al-8V- 6Cr-4Mo-4Zr (BetaC™), contain high percentages of beta phase stabilizing elements. (before beta stable)
- This results in transformation so sluggish that during processing (e.g., air cooling) the microstructure is retained as 100% beta phase at room temperature.
- In beta-Ti alloys, subsequent ageing in a temperature range from about 480°C to 595°C results in precipitation of fine alpha. Ageing within this range produces a significant increase in strength.
- Although an extremely high strength-to-weight ratio can be achieved with ageing at low temperatures, but ductility and fracture toughness are reduced.
- Metastable-beta alloys are used frequently in fasteners and springs, where they exhibit exceptional work-hardening characteristics. Metastable beta titanium alloys in current use, such as Ti-15Mo-2.7Nb-3Al-0.2Si (Beta-21S), exhibit excellent oxidation resistance and good elevated-temperature properties.

Titanium and Titanium Alloys



– Metastable beta Titanium alloys: Heat treatment

- Ageing
 - Ageing treatment leads to increase in strength, but there is an accompanying loss of ductility.
 - During ageing of alloys at relatively low ageing temperatures (200-500°C), embrittlement occurs due to decomposition of beta phase (changing) to other.
 - Done in steps
 - First step ageing with 200 or 300°C
 - Second step with high 500°C
 - It is desirable to have some coarse α platelets prior to ageing, especially in high-strength alloys
 - Coarse α platelets needed for ductility
 - Fine α platelets needed for strength



Titanium and Titanium Alloys



AILEEN

- Metastable beta Titanium alloys: Heat treatment
 - Prolonged treatment may lead to a remarkable loss of mechanical properties owing to the coarsening of β grains.
 - Intermediate treatment results in higher yield & tensile strengths

Titanium and Titanium Alloys



AILEEN

– Summary: Characteristics of Titanium alloys

Typical Characteristics of Commercial Titanium Alloys

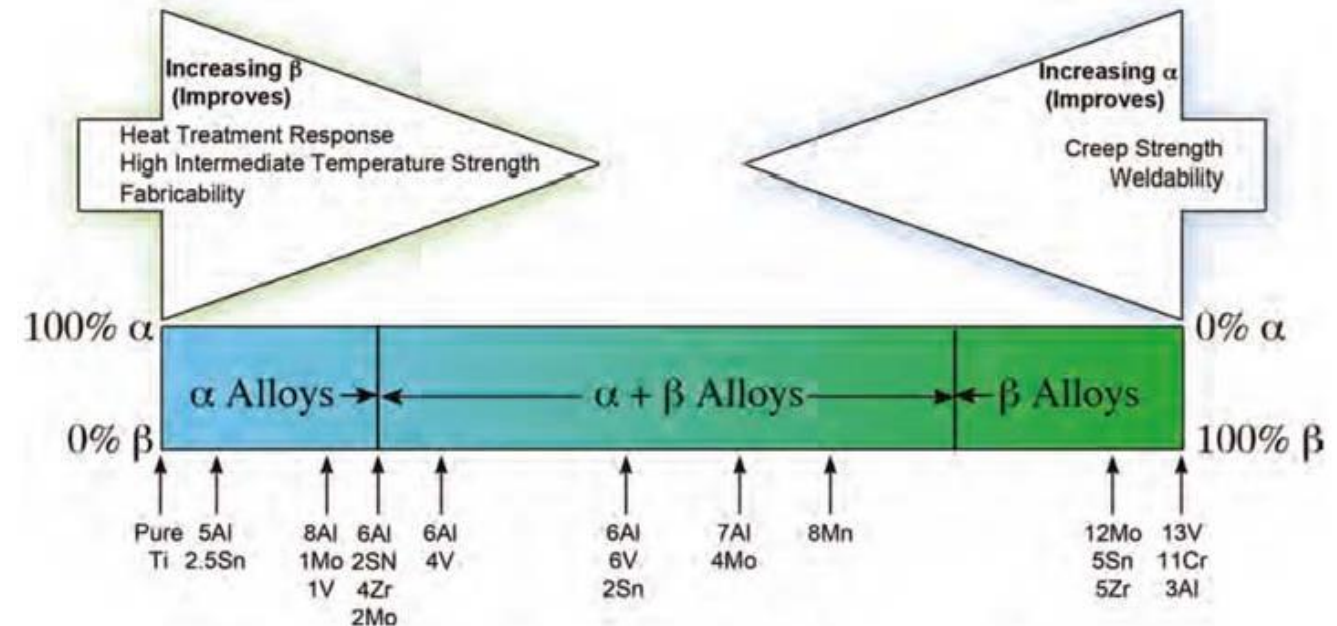
α Alloys	α/β Alloys (Including Near- α Alloys)	Near- β and Metastable β Alloys
• Not heat treatable • May contain small amount of β for microstructure refinement • Satisfactory room temperature strength • Good creep resistance • Good toughness • Weldable • Poor fabricability	• Heat treatable • At equilibrium $\alpha + \beta$ • Increasing room temperature strength, decreasing creep resistance and decreasing fabricability with increasing β stabilization • Good toughness • Weldable at β • Good producibility	• Heat treatable • At equilibrium $\alpha + \beta$ • High room temperature strength • Low creep resistance • Good toughness • Poor weldability • Excellent fabricability

Titanium and Titanium Alloys



AILEEN

- Summary: Characteristics of Titanium alloys
 - Composition relationship



- Converting pure Ti into alloy: line starts at the left and represents alloys containing 100% alpha
- Moving toward the right represents an increasing amount of beta phase
- Extreme right are metastable beta alloys that retain 100% beta at RT

Titanium and Titanium Alloys



– Mechanical Properties of Ti and Ti alloys

Designation	Commerically Pure Titanium	Medium Strength Alloys	High Strength Alloys	Highest Strength
Alloy Type	Alpha	Alpha-Beta	Alpha-Beta	Beta
0.2% Proof Stress MPa	345 - 480	480 - 550	725 - 1000	1100 - 1400
Tensile Strength MPa	480 - 620	600 - 650	830 - 1100	1200 - 1500
Elongation %	20 - 25	15 - 20	8 - 15	6 - 12
Tensile Modulus GPa	103	104	110 - 120	69 - 110
Torsion Modulus GPa	45	43	40 - 48	38 - 45
Hardness HV	160 - 220	200 - 280	300 - 400	360 - 450
Density kg/l	4.51	4.48 - 4.51	4.43 - 4.60	4.81 - 4.93
Thermal Expansion $10^{-6}/^{\circ}\text{C}$	8.9	8.3	8.9	7.2 - 9.5
Conductivity W/mK	22	8.0	6.7	6.3 - 7.6
Specific Heat J/kg/ $^{\circ}\text{C}$	525	544	565	490 - 524

Titanium and Titanium Alloys

– Applications of Titanium alloys

- Aerospace
- Defence



Forged Ti-6Al-4V jet engine fan disks are 890 mm in diameter and weigh 249 kg

Titanium and Titanium Alloys

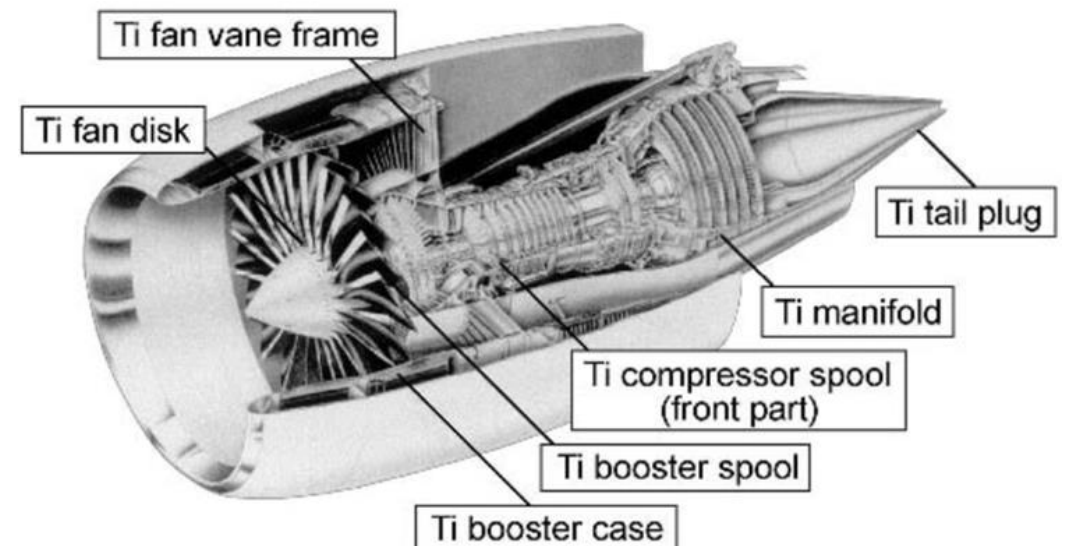
– Applications of Titanium alloys

- Aerospace
 - In modern aero-engines, the weight share of titanium is about 25% (mainly in fan and compressor sections)

Made of Titanium or armored steel
(Flight Data Recorder or Black Box)



Titanium alloy blades in aircraft engines



Titanium and Titanium Alloys



- Applications of Titanium alloys
 - Construction



Fukuoka stadium dome with retractable titanium roof

Titanium and Titanium Alloys



– Applications of Titanium alloys

- Consumer goods: spectacle frames, cameras, watches, jewelry
- Sporting goods: golf clubs, tennis rackets, bicycle frames, spikes in sprinter's running shoes
- The β alloy Ti-15-3 is now being used for handlebars and seat posts of mountain bikes



Titanium and Titanium Alloys



– Applications of Titanium alloys

- Automotive
- Beta Titanium alloy with high-strength and low-modulus for automotive suspension spring coil, rotor, connector applications.
- Currently many parts used for automobiles were made of steel and can be replaced with beta titanium alloy
- Drastically weight reductions in vehicle body due to the light weight of titanium and simultaneous increment in performance can be achieved.



Titanium and Titanium Alloys

– Applications of Titanium alloys

- Bio-Applications

- Hip or knee prostheses - good corrosion stability in the human body, high fatigue resistance, high strength-to-weight ratio, good ductility, low elastic modulus, excellent wear resistance, low cytotoxicity, and a negligible tendency to provoke allergic reactions
- beta Ti alloys - low elastic modulus compared to alpha or alpha+beta Ti alloys
- Low elastic modulus is of particular relevance because an important requirement of bone-replacing



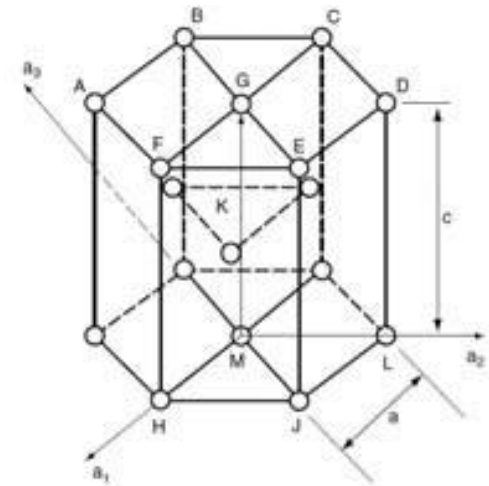
Titanium and Titanium Alloys



AILEEN

– Welding of Titanium alloys

- Problems...
- Titanium readily picks up **N, O, H and C** at temp, **exceeding 430°C**
- Occupy interstitial sites
- The presence of these elements in the interstices (i.e., sites located between titanium atoms) inhibits plastic deformation and increases strength, and also results in a substantial **loss of ductility (>brittle)**.
- c/a ratio of hexagonal α lattice increases (face height/width)
- When contamination exceeds certain levels, the stresses generated during welding may cause cracking of the weld metal. Levels of oxygen on the order of 3000 ppm in the weld metal may result in transverse cracking i.e., in HAZ



Contamination Cracking in a Weld in Grade 2 Titanium Plate

Titanium and Titanium Alloys



AILEEN

– Welding of Titanium alloys

- Titanium tends to oxidize rapidly when heated in air to temperatures above 650°C
- At elevated temperatures, dissolving discrete amounts of oxide into weld solution.
- Welding of titanium requires the use of protective shielding, such as an inert gas atmosphere, to prevent contamination and embrittlement from oxygen and nitrogen
- The relatively low coefficient of thermal expansion and conductivity of titanium reduces the possibility of distortion caused by welding compared to other commonly welded metals.
 - The thermal conductivity of Ti alloys is one-half of stainless steels and one-tenth of Al alloys
 - The linear coefficient of thermal expansion of Ti is lower than Al alloys and steels
 - The electrical resistivity of Ti is lower than PH stainless steels and 10 times greater than Al alloys

Titanium and Titanium Alloys



– Welding of Titanium alloys

- Hydrogen and oxygen can be absorbed if moisture is present.
- If not removed, residual oils, cleaning agents, and other contaminating substances on the workpieces will result in hydrogen and carbon contamination of titanium.
- Weld metal toughness of the CP Ti that are strengthened by oxygen may be significantly decreased by high hydrogen content, due to the formation of brittle titanium hydride platelets.
- The presence of small amounts of iron and certain other beta stabilizers is beneficial, probably due to the formation of beta grains of high hydrogen solubility.

Titanium and Titanium Alloys



- Welding of Titanium alloys
 - Extremely reactive and sensitive to contamination
 - GTAW, GMAW, PAW, EBW, LBW, FW
 - No serious hot cracking problems
 - Matching fillers possible
 - Limited availability of filler wires
 - Undermatching fillers with generous reinforcement
 - Go for EBW and LBW
 - Most alloys suffer from poor weld ductility
 - Remedies:
 - High purity shielding gases, backing and trailing gas arrangements, glove box welding, remove surface films, thoroughly degrease the weld joint

Titanium and Titanium Alloys



AILEEN

- Problems in welding Alpha-Beta Titanium alloys
 - Titanium readily picks up gases (oxygen, hydrogen, nitrogen) which can lead to mechanical property degradation
 - The poor ductility of welds is generally attributed to a large prior β grain size
 - The ductility cannot be improved under usual welding conditions by merely altering the heat input during welding, because a high energy input coarsens the prior- β grains while a low heat input results in faster cooling and increases the aspect ratio of the grains microstructure.
 - Therefore, Post-weld heat treatment becomes necessary to improve the weld metal ductility to an acceptable level.

Titanium and Titanium Alloys



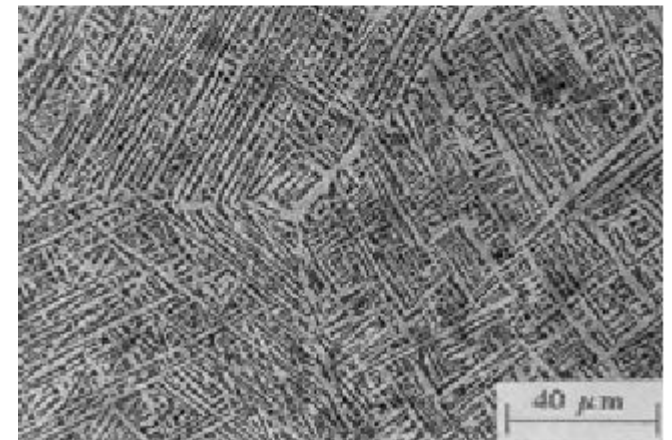
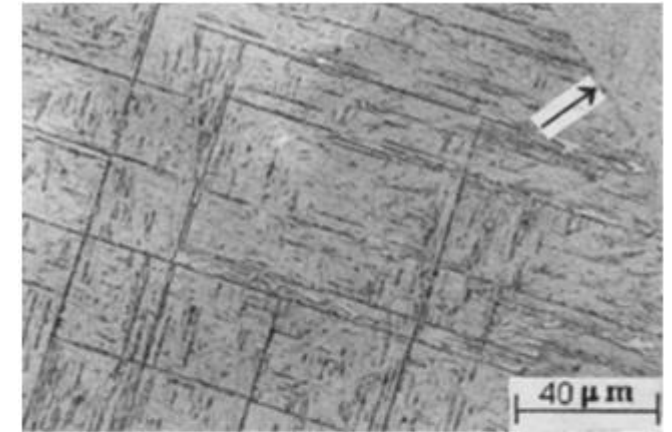
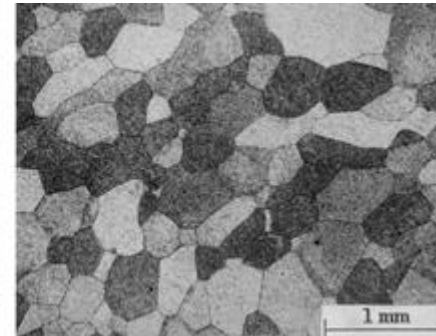
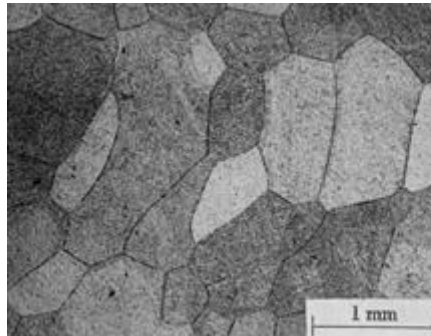
– Problems in welding Alpha-Beta Titanium alloys

- Post weld heat treatment (PWHT) is carried out for...
 - Relief of residual stresses produced during welding operation
 - Modification of the metastable weld zone microstructure
 - Stabilization of the microstructure for weld structure application at elevated temperatures.
 - The ultimate aim of post-weld heat treatments (PWHT)s is to enhance the mechanical properties.
 - Heat treatment of rapidly cooled welds in α - β alloys at relatively low temperatures between 400 and 550 °C results in micro precipitation of β phase

Titanium and Titanium Alloys

- Problems in welding Alpha-Beta Titanium alloys
 - Grain refinement with current pulsing (causing heating)

Example: Comparison of Ti-6242 welded grain size refinement before and after pulsing at same scales



Titanium and Titanium Alloys



AILEEN

– Problems in welding Alpha-Beta Titanium alloys

- Post weld heat treatment (PWHT)
 - Some different procedures for different treatments

HEAT TREATMENT DESIGNATION	HEAT TREATMENT CYCLE ^(A)	MICROSTRUCTURE
DUPLEX ANNEAL	SOLUTION TREAT AT 50-75 °C (90-135 °F) BELOW T _β , AIR COOL AND AGE FOR 2-8 H AT 540-675 °C (1000-1250 °F)	PRIMARY α, PLUS WIDMANSTÄTTEN α - β REGIONS
SOLUTION TREAT AND AGE	SOLUTION TREAT AT ~40 °C (70 °F) BELOW T _β , WATER QUENCH AND AGE FOR 2-8 H AT 535-675 °C (995-1250 °F)	PRIMARY α, PLUS TEMPERED α' OR A β - α MIXTURE
BETA ANNEAL	SOLUTION TREAT AT ~15 °C (30 °F) ABOVE T _β , AIR COOL STABILIZE AT 650-760 °C (1200-1400 °F) FOR 2 H	WIDMANSTÄTTEN α - β COLONY MIXTURE
BETA QUENCH	SOLUTION TREAT AT ~15 °C (30 °F) T _β , WATER QUENCH AND TEMPER AT 650-760 °C (1200-1400 °F) FOR 2 H	TEMPERED α'
RECRYSTALLIZATION-ANNEAL	925 °C (1700 °F) FOR 4 H, COOL AT 50 °C/H (90 °F/H) TO 760 °C (1400 °F), AIR COOL	EQUIAXED α WITH β AT GRAIN-BOUNDARY TRIPLE JOINTS
MILL ANNEAL	α - β HOT WORK PLUS ANNEAL AT 705 °C (1300 °F) FOR 30 MIN TO SEVERAL HOURS AND AIR COOL	INCOMPLETELY RECRYSTALLIZED α WITH A SMALL VOLUME FRACTION OF SMALL β PARTICLE

Titanium and Titanium Alloys



– Problems in welding Beta Titanium alloys

- No serious cracking problems
- Main problems
 - α -grains formation during either weld metal cooling or post-weld ageing (PWA)
 - Segregation, especially in heavily-stabilized alloys
 - Non-uniform formation of strengthening precipitates
 - The presence of an alpha phase with a continuous grain boundary can promote intergranular fracture, which results in reduced ductility and toughness. Strength < base metal
- We must compromise on either strength or ductility
 - Low strength in as-welded condition
 - Serious loss of ductility after PWA

Titanium and Titanium Alloys



- Problems in welding Beta Titanium alloys
 - Post-weld aging mitigation
 - Use as-welded condition (No PWA to avoid ductility loss, but with less strength)
 - Use CP-Ti or highly stabilized beta-Ti fillers in welding to mitigate low strength
 - Refine the grain structure of the fusion zone either by mechanical agitation during solidification or by adding suitable grain refiners
 - Addition of nickel to fusion zone is reported to refine the grain size of Ti welds, when present in the filler metal

Titanium and Titanium Alloys



- Post weld heat treatment in Beta Titanium alloys
 - Similar to metastable beta Ti alloys treatment
 - Two-step ageing or controlled heating to ageing temperature
 - It is desirable to have some coarse α platelets prior to aging, especially in high-strength alloys
 - Coarse α platelets needed for ductility
 - Fine α platelets needed for strength
 - In essence, multiple thermal treatments under carefully controlled conditions are required for achieving optimum properties

Titanium and Titanium Alloys



– Weldability issues comparison

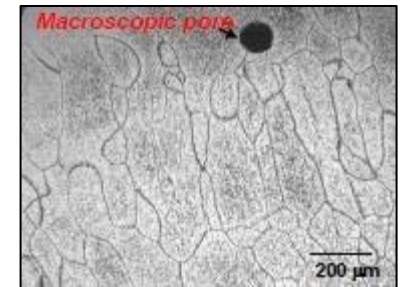
Material	Weldability Issues
CP Ti and α alloys	Weldable Good ductility (α forms, but it is not brittle (low β stabilizing elements))
$\alpha + \beta$ alloys	Weldable Inferior ductility (large amount of α)
Metastable β alloys	Weldable Good as-welded ductility Low strength (Grain boundary α Problem) Segregation problems Post Weld Ageing > thickens the grain boundary α and forms precipitate free zone (PFZ) adjacent to grain boundary α

Titanium and Titanium Alloys



– Defects in Titanium Welding

- Titanium and titanium alloys are highly reactive to oxygen. 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 defect** 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, avoid areas near steel fabrication.

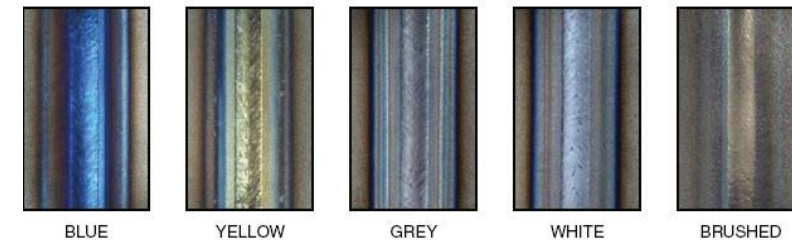


Macroscopic pore observed in TIG welding of beta titanium alloy

Titanium and Titanium Alloys

– Defects in Titanium Welding

- Titanium weld colors
 - For interpretation



Interpretation of Surface Color in Titanium Welds

Color	Interpretation	Action
Silver	Correct shielding	None
Light straw to dark straw	Slight surface contamination, acceptable	Remove surface oxide by brushing, correct shielding
Purple	Moderate surface contamination, unacceptable	Remove weld bead by grinding, correct shielding
Dark blue to light blue	Heavy contamination, unacceptable	Remove weld bead
Yellow to gray to white	Very heavy contamination, unacceptable	Remove weld bead and 0.8 mm (0.031 in.) to 6 mm (0.250 in.) of the material beneath

Titanium and Titanium Alloys



– Defects in Titanium Welding

- Tolerance limits in welding
 - Oxygen, nitrogen, and carbon are interstitial elements that cause significant hardening of titanium and must be strictly controlled
 - The maximum tolerable limits in weld metal have been estimated as 0.3% oxygen, 0.15% nitrogen and 150 ppm hydrogen so scrupulous cleanliness is essential for both parent metals and filler wires.
 - Degreasing the weld preparation followed by stainless steel wire brushing and a further degrease is generally sufficient.
 - Heavily oxidised components may need to be pickled in a nitric/hydrofluoric acid mixture to remove the oxide layer.

Titanium and Titanium Alloys

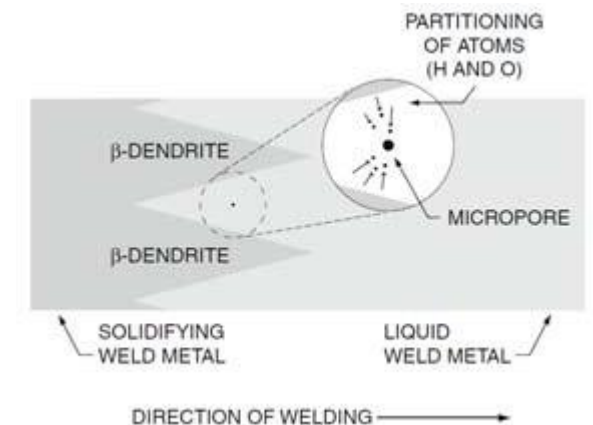


– Defects in Titanium Welding

- Tolerance limits in welding
 - Degreasing of the filler wire for TIG welding should be done as a matter of course and the cleaned wire handled with clean cotton gloves; grease and perspiration from the fingers can cause local contamination and/or porosity.
 - For critical titanium welds that require very high quality, pickling of the weld joint and surrounding metal may be necessary. Workpieces should be rinsed in a solution of 2% to 4% hydrofluoric acid and 30% to 40% nitric acid, followed by thorough rinsing with deionized water, and drying.

– Defects in Titanium Welding

- **Porosity:** hydrogen from moisture in the arc environment or contamination on the filler and parent metal surface, is the most likely cause of porosity
- Porosity in the weld metal originates at the trailing edge of the weld pool, where interstitial elements (oxygen or hydrogen) are partitioned.
- Atoms combine to form molecules of H_2 and O_2 , which, in turn, combine to form micropores.
- The formation of micropores of diatomic gas (e.g., H_2 and O_2)
~1 to 3 μm in diameter



Titanium and Titanium Alloys



– Defects in Titanium Welding

- To avoid porosity...
- It is essential that the joint and surrounding surface areas are cleaned by first degreasing either by steam, solvent, alkaline or vapour degreasing.
- Any surface oxide should then be removed by pickling (HNO_3 , solution), light grinding or scratch brushing with a clean, stainless steel wire brush.
- On no account should an ordinary steel brush be used.
- After wiping with a lint-free cloth, care should be taken not to touch the surface before welding.
- When TIG welding thin section components (<3mm), the joint area should be dry-machined to produce a smooth surface finish

Titanium and Titanium Alloys



– Defects in Titanium Welding

- **Embrittlement** can be caused by weld metal contamination by either gas absorption or by dissolving contaminants such as dust (iron particles) on the surface.
- At temperatures above 500°C, titanium has a very high affinity for oxygen, nitrogen and hydrogen. The weld pool, heat affected zone and cooling weld bead must be protected from oxidation by an inert gas shield (argon or helium).

Titanium and Titanium Alloys



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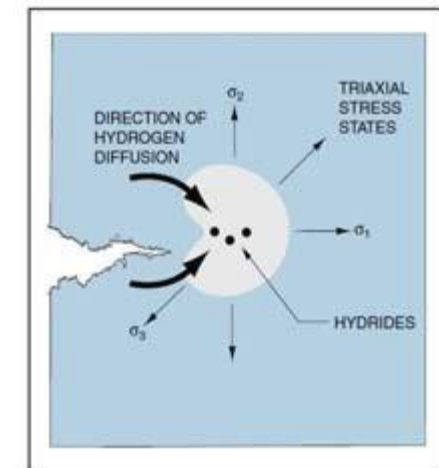
- Defects in Titanium Welding
 - Formation of Titanium Hydrides precipitates
 - Hydrogen > 100 ppm can cause problems
 - Sources of hydrogen
 - moisture in shielding gas
 - moisture on plate or filler wire
 - oil on plate or filler wire
 - hydrogen dissolved in plate or filler wire
 - surface residue from cleaning solvents
 - Remedies
 - Minimum exposure to moisture or hydrocarbons
 - Shielding gases
 - Cleaning of fillers materials

Titanium and Titanium Alloys



– Defects in Titanium Welding

- Formation of Titanium Hydrides precipitates
- Assuming a micro crack is present in the weld, hydrogen atoms will diffuse to the tip of the crack.
- At the tip, stresses produce large holes in the lattice that easily accommodate hydrogen atoms. Hydrogen diffusing to the crack can form diatomic gas (H_2) resulting in gas pressure again advancing the crack



Titanium and Titanium Alloys



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– Defects in Titanium Welding

- Formation of Titanium Hydrides precipitates
- Air and water vapor are particularly detrimental to titanium and can lead to oxygen and hydrogen contamination. Hydrogen absorption can occur upon heating in gases containing water vapour (by the decomposition of water vapour into O and H or hydrocarbons)
- Using shielding gas with a sufficiently low dew point (-50°C) and low oxygen content (below 60 ppm);

Dew Point

Temperature at which water vapor in air begins to condense.

<u>Dew Point ($^{\circ}\text{C}$)</u>	<u>Water Vapor (ppm)</u>
-10	740
-20	422
-30	235
-40	128
-50	67
-60	34

Titanium and Titanium Alloys



– Defects in Titanium Welding

- Ductility-dip cracking
 - when abruptly cooled from above the beta transition temperature
 - The loss in ductility occurs in the HAZ during the thermal cycle of the weld.
 - When shrinkage and thermal strains are sufficiently severe, cracking may result.
 - Alloy Ti-6211 (6Al-2Nb-1Ta-0.8Mo) exhibits the largest ductility dip, and it will likely crack during weld cooling when the welding stresses are high

Titanium and Titanium Alloys



– Defects in Titanium Welding

- Contamination cracking in Alpha-Ti alloys
 - Removing surface films from the joint area with a stainless-steel wire brush or with a new aluminum-oxide or silicon-carbide grinding wheel
 - Thoroughly degreasing the joint prior to welding, using acetone or another solvent that does not leave a residue
 - Providing sufficient inert gas shielding during welding, and maintaining the shielding until the weld and surrounding areas have cooled below **430°C**
 - Using shielding gas with a sufficiently low dew point (-50°C) and low oxygen content (below 60 ppm)
 - Discarding contaminated stickout of filler metal wire after each weld when using GMAW, or after it becomes discolored when using GTAW

Titanium and Titanium Alloys



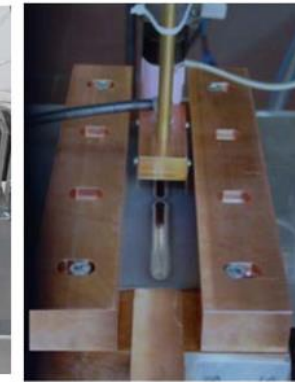
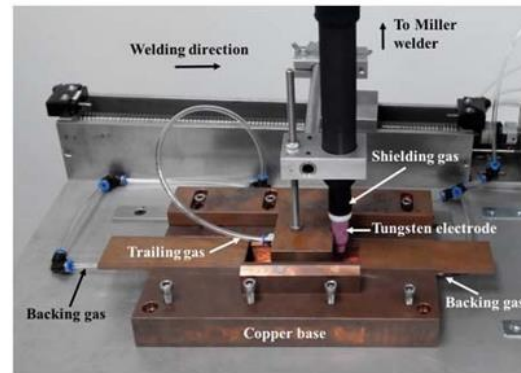
– Fillers in Titanium Welding

ASTM Grade	Composition	UTS (min) MPa	Filler	Comments
1	Ti-0.150	240	ERTi-1	Commercially pure
2	Ti-0.200	340	ERTi-2	Commercially pure
3	Ti-0.350	550	ERTi-4	Commercially pure
7	Ti-0.200 -0.2Pd	340	ERTi-7	Commercially pure
9	Ti-3Al-2.5V	615	ERTi-9	Tube components
5	Ti-6Al-4V	900	ERTi-5	'Workhorse' alloy
23	Ti-6Al-4V ELI	900	ERTi-5ELI	Low interstitials
25	Ti-6Al-4V-0.06Pd	900	ERTi-25	Corrosion resistant grade

Titanium and Titanium Alloys

- Titanium Welding
 - Setup example

Ti Welding Fixture with Trailing and Backing gas



Torch gas : Ar, Ar + He
Backing gas, Trailing gas : Ar

GTA Welding parameters

joint preparation	HF/HNO ₃ pickle + acetone degrease
arc voltage	9-15 volts
travel speed	electrode negative
pulsed current time (t _{high} /t _{low})	150 ms / 100 ms
pulse frequency	4-6 hz
arc current (I _{high} /I _{low})	0% Hydrogen (135-270 amps) 5-7.5% hydrogen(125-250amps)

Color used to indicate oxygen contamination

silver
light straw
dark straw
light blue
dark blue
gray blue
gray
white

↑
Increase in contamination
↓

Thank You



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