FS 2024/25

MSE-422 – Advanced Metallurgy

7-Ti-based alloys

Christian Leinenbach

Some basic facts about Ti

- Ti is the 4th most common element in the earth's crust (0.5-1%)
- The main resources of titanium are the various forms of TiO_2, i.e. anatase, brookite, rutile, and the iron-titanate ilmenite ($FeTiO_3$)
- With a density of 4.51 g/cm^3, Ti is a light metal
- Physical properties:
  - Melting point 1'670°C
  - Electrical conductivity 2.5 MS/m (4% of pure Cu); Thermal conductivity 22 W/mK (5.5% of pure Cu)

Anatase

Brookite

Rutile

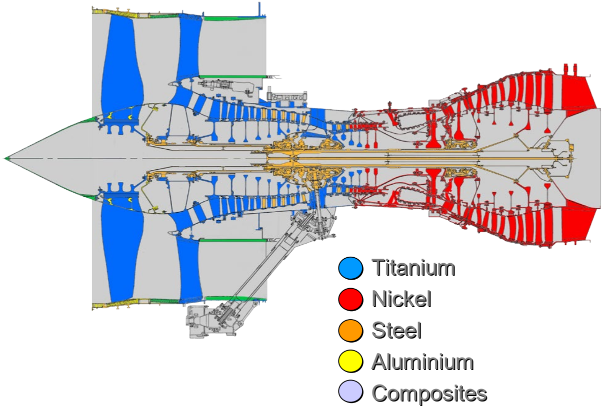
Mining of ilmenite in Australia

Some basic facts about Ti

- Despite Ti was discovered already in 1791, Ti and Ti alloys are a comparably new class of engineering materials and are only used since ~1950
- The reason is the fairly complex processing route
  - Reduction of titanium ore with C and Cl_2 according to $TiO_2 + 2Cl_2 + C \rightarrow TiCl_4 + CO/CO_2$ to a porous form of Ti metal, referred to as sponge
  - The $TiCl_4$ is subsequently purified and mixed with Mg to form $MgCl_2$.
  - Vacuum arc melting (VAM) of sponge to form an ingot
  - Primary fabrication when ingots are converted into general kinds of mill products
  - Secondary fabrication of the mill products into finished shapes
- The $MgCl_2$ is recycled by electrolysis, leading to Mg and Cl_2 that is then reused for the next batch of TiO_2
- Ti is a relatively expensive material. This is not related to the lack of available Ti ore or the price of the starting material TiO_2. The high production costs are related to the use of VAM as well as the recycling of the facilitators, i.e. Cl_2 and Mg
- Worldwide annual production of Ti sponge is about 0.4 Mt (compared to 1'870 Mt of steel, 100 Mt of Al and 20 Mt of Cu)

Ti-alloys for aerospace applications

- Ti alloys combine high strength (R_m >1'000 MPa) with low density (4.5 g/cm^3) and good corrosion resistance
- They are therefore used for a variety of aerospace applications (e.g. compressor blades and vanes, structural parts)



Ti-alloys for racing car applications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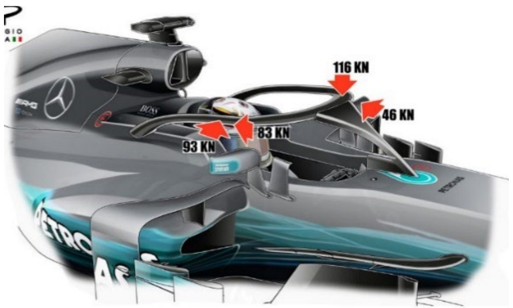
Romain Grosjean's 'life saved' by halo after remarkable escape at Bahrain GP

- Frenchman's car split in half after big collision with barriers
- Driver walks away with only second degree burns to hands

Use case: halo
A 7 kg device is able to withstand up to 125 kN


Charles Leclerc was saved by the new addition at the Belgian GP while Ferrari made their power advantage pay

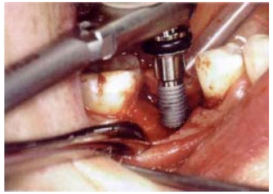
The dramatic crash with Fernando Alonso landing on top of Charles Leclerc during the Belgian Grand Prix showed the value of the halo. Photograph: John Thys/AFP/Getty Images



Ti-alloys for biomedical applications

- Besides their good corrosion resistance and mechanical properties, Ti alloys have an excellent biocompatibility
- They are therefore also used for a variety of temporary and permanent implants

Dental implants

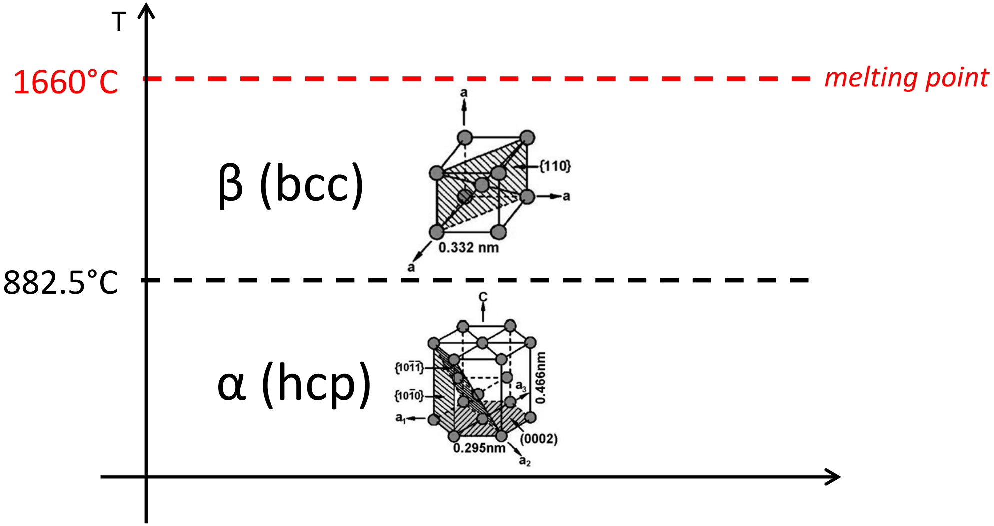


Orthopaedic implants

Spinal implants

Crystal structures of Ti

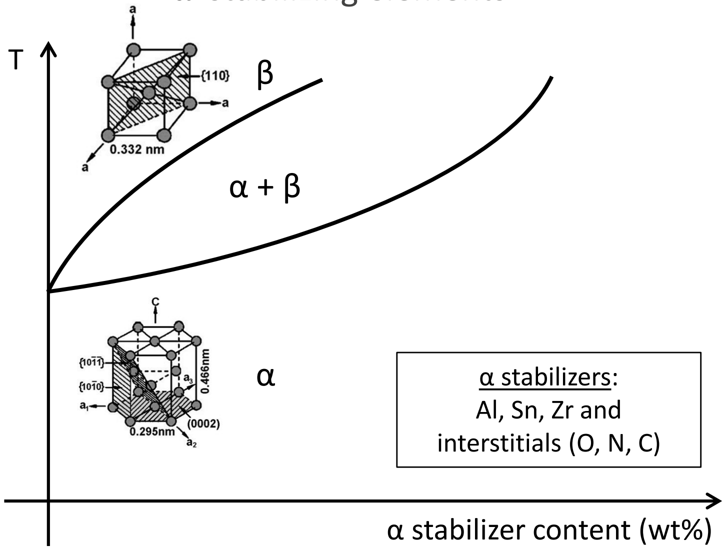
- Ti has two elemental crystal structures: hcp-α and bcc-β
- Pure titanium undergoes a phase transformation from α to β at 882.5°C



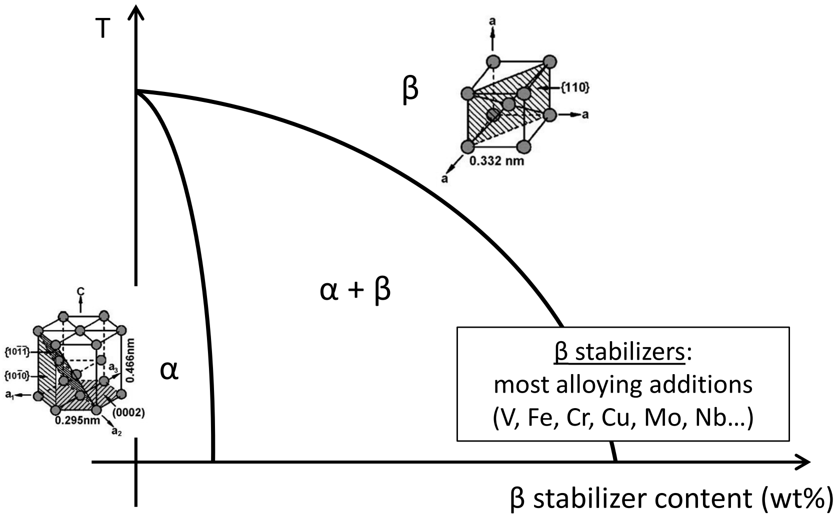
Role of alloying elements in Ti

- The addition of α stabilizers (Al, Sn, Zr, O, N, C) increases the transformation temperature
- The addition of β stabilizers (V, Fe, Nb, Cr, Cu, Mo, Ta…) decreases the transformation temperature

α -stabilizing elements

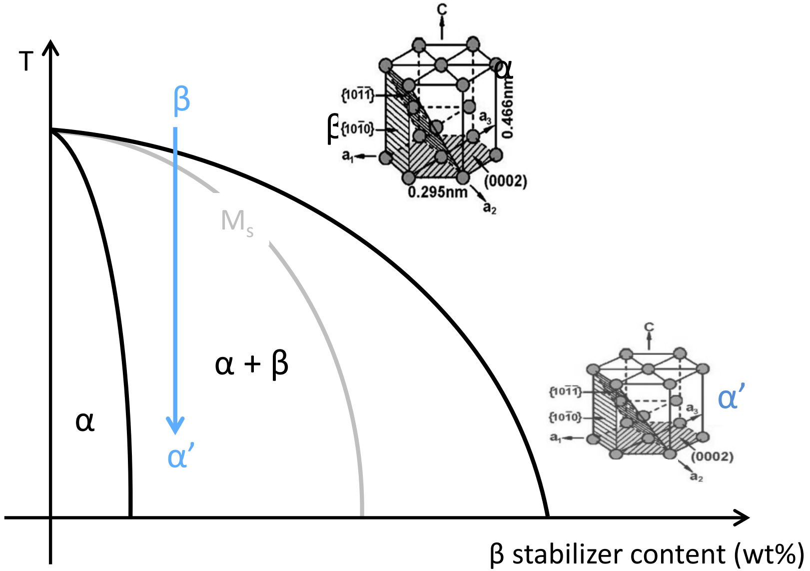


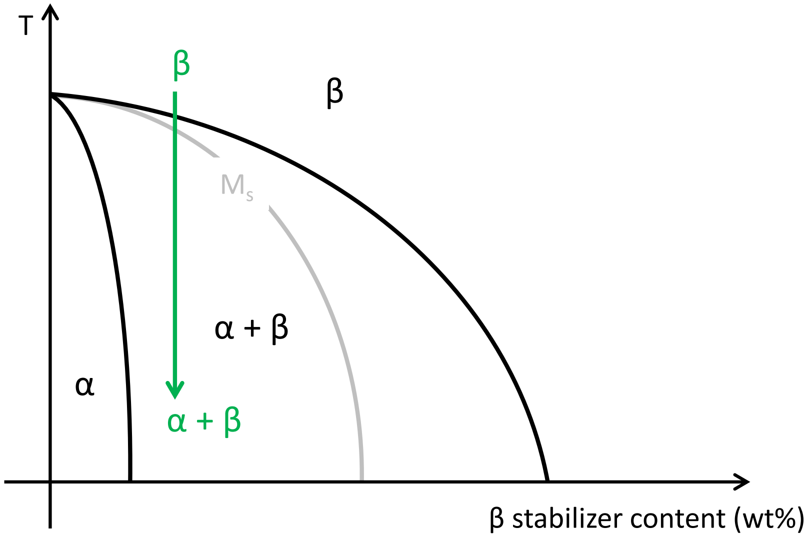
β-stabilizing elements



Role of alloying elements in Ti

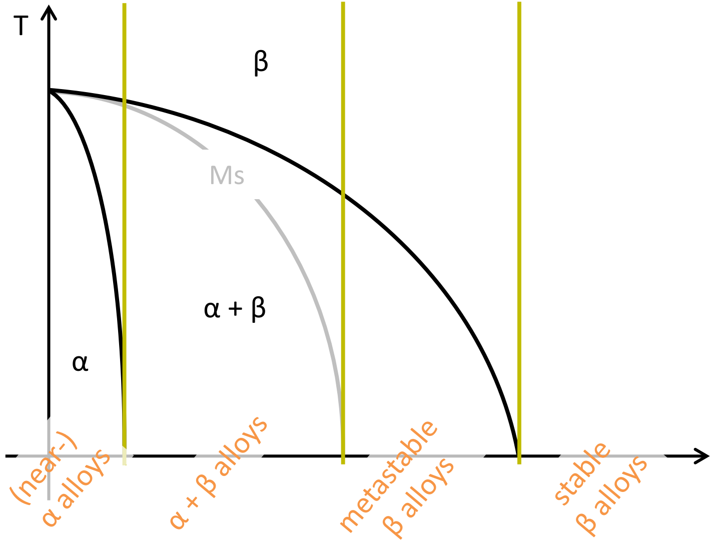
- Ti alloys exhibit a martensitic transformation
- Upon fast cooling through Ms, β is transformed to α’-martensite
- α’-martensite is enriched in β-stabilizers and has a slightly distorted hcp lattice; it is fairly soft
- Upon slow cooling , β is transformed to α+ β





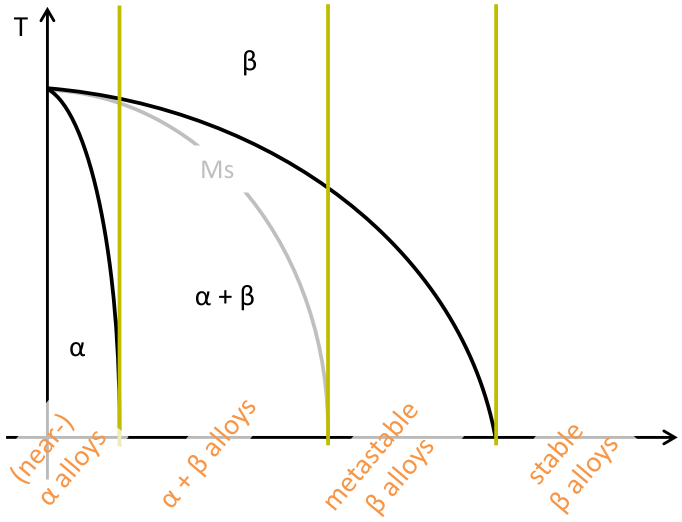
Classification of Ti alloys

- There are more than 100 Ti alloys, but only 20-30 are commercially available and used in applications
- Titanium alloys can be classified in 4 large categories:
  - α-alloys and near α-alloys (including “commercially pure” (cp) titanium)
  - α + β alloys
  - metastable β-alloys
  - stable β-alloys
- cp-Ti makes up for approximately 25%
- The by far most widely used Ti-alloy is the α+β alloy TiAl6V4 (~55%)



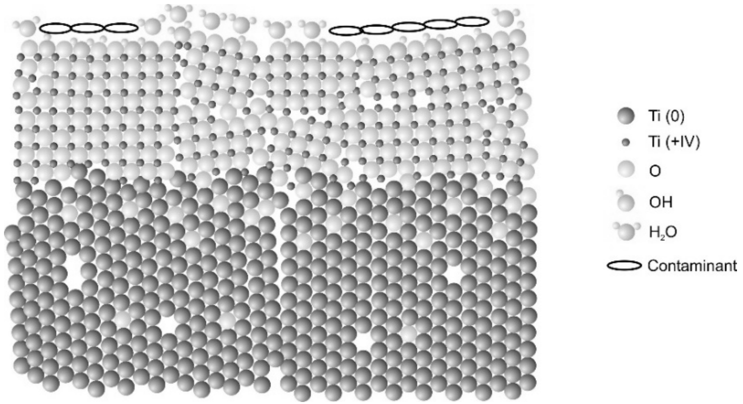
Strengthening mechanisms in Ti alloys

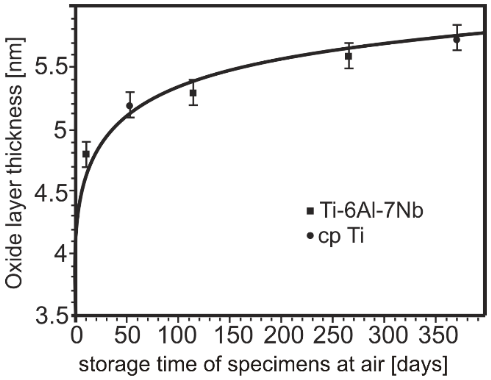
- Solid solution strengthening
  - Pronounced effect in α, α + β and β alloys
- Dislocation strengthening
  - Only weak to mild effect in all Ti alloys
- Grain boundary strengthening
  - Pronounced effect in cp-Ti
  - Mild effect in other Ti alloys
- Particle strengthening
  - IM precipitate formation in some metastable β alloys
- Texture strengthening
  - Because of the hcp lattice, α-Ti can exhibit pronounced textures after thermo-mechanical treatment



Titanium surface

- In comparison with other metals, Ti alloys have in general a high corrosion resistance against acids (nitric, chloric, sulfuric, and phosphoric acids, exemption: hydrofluoric acid)
- The reason is the spontaneous formation of a thin (4-6 nm), but dense TiO_2 layer, even at rather low oxygen contents
- This oxide layer gives Ti also ist biocompatibility → cells 'see' the TiO2, not the Ti



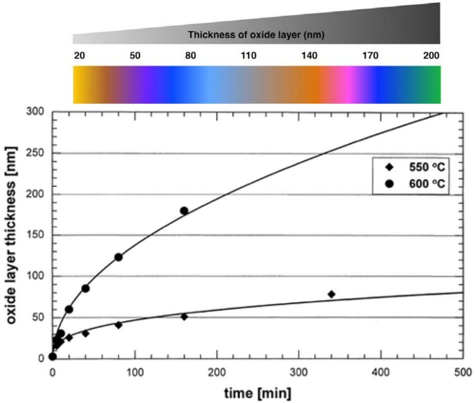


/Sittig, 1998/

Oxidation of titanium alloys

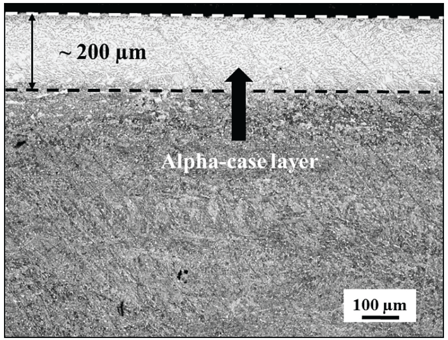
- Ti alloys exhibit a high affinity towards oxygen and pronounced growth of the oxide layer at elevated temperatures
  - Short-term growth at 300°C<T<600°C results in colorful oxide layers with thicknesses 20-200 nm
  - Long-term exposure of near-α and α+β alloys at T>600°C results in the further thickening of the oxide layer and finally diffusion of oxygen into the Ti and a stabilization of a O-saturated α-region, leading to a pronounced embrittlement of the near-surface region ('α-case')

→ Heat-treatments should be performed in high-purity inert atmospheres (e.g. Ar) or in Vacuum



/D. Velten et.al, J. Biomed. Mater. Res. 59(1) (2002) 18-28/

Alpha-case layer in Ti-6Al-4V
700 °C/500 h



/B. Sefer et.al, Proc. 13th World Conference on Titanium, 2016/

Commercially pure (cp) titanium

- cp-Ti has typically relatively low strength that depends significantly on the level of interstitial alloying elements (O, N), Fe, grain size and degree of cold working.
- The corrosion resistance of cp-Ti can be further improved by addition of 0.2% of palladium.

Composition of cp-Ti [wt.%]

Grade	Ti	O	N	Fe	C	H
Ti cp-1	>99.5	0.18	0.03	0.15	0.1	0.015
Ti cp-2	>99.4	0.25	0.03	0.20	0.1	0.015
Ti cp-3	>99.2	0.35	0.05	0.25	0.1	0.015
Ti cp-4	>99.0	0.45	0.05	0.30	0.1	0.015

α and near-α-Ti alloys

- α and near-α alloys are stabilized with Al and the interstitials O and N.
- Solid solution strengthening due to these elements and the neutral elements Zr and Sn
- The amount of Al is limited to 8 wt.% due to the formation of Ti_3Al, which leads to embrittlement
- Near α-alloys may contain up to 2 wt. % of β-stabilizers

Composition of some (near)α-alloys [wt.%]

Grade	Al	Sn	Zr	Mo	O	N	C	H	Others
Ti-5Al-2.5Sn	5.5-6.5	2.2-2.7	---	---	0.2	0.05	0.08	0.015	---
Ti-6Al-2Sn-4Zr-2Mo	5.5-6.5	1.5-2.5	3.5-4.5	1.5-2.5	0.2	0.05	0.08	0.015	---
Ti-8Al-1Mo-1V	7.5-8.5	0.2	---	0.8-1.2	0.2	0.05	0.08	0.009	1V
Ti-5Al-5Sn-2Zr-2Mo	5-6	11	1.5-2.5	1.5-2.5	0.15	0.05	0.05	0.01	0.25Si

α+β-Ti alloys

- In α+β alloys, Al is added as a solid solution strengthener and to stabilize the α phase while V or other β-stabilizing elements (Nb, Mo, Mn, Ta) are added to retain a significant amount of β-phase at RT
- Further solid solution strengthening is achieved by adding ‘neutral’ elements such as Sn, Zr and maintaining a certain amount of the interstitial elements O, N and C
- The most well-known example is Ti-6Al-4V

Composition of some α+β-alloys [wt.%]

Grade	Al	Sn	Zr	Mo	O	N	C	H	Others
Ti-6Al-4V	5.5-6.5	---	---	---	0.2	0.05	0.08	0.015	4V
Ti-6Al-7Nb	5.5-6.5	---	---	---	0.2	0.05	0.08	0.015	7Nb
Ti-6Al-2Sn-4Zr-6Mo	7.5-8.5	2	4	6	0.2	0.05	0.08	0.01	---
Ti-7Al-4Mo	6.5-7.5	---	---	4	0.15	0.05	0.05	0.01	---

Metastable β-Ti alloys

EPFL

- There are only a few β-Ti alloys commercially available, which are used for niche products
- All relevant β-Ti alloys are metastable alloys; they contain significant amounts of the β-stabilizing elements Mo, Nb, Ta as well as solid solution strengtheners such as Zr and Fe
- The interest in the metastability is driven by the hardening potential due to the formation of precipitation phases upon solutionizing and ageing

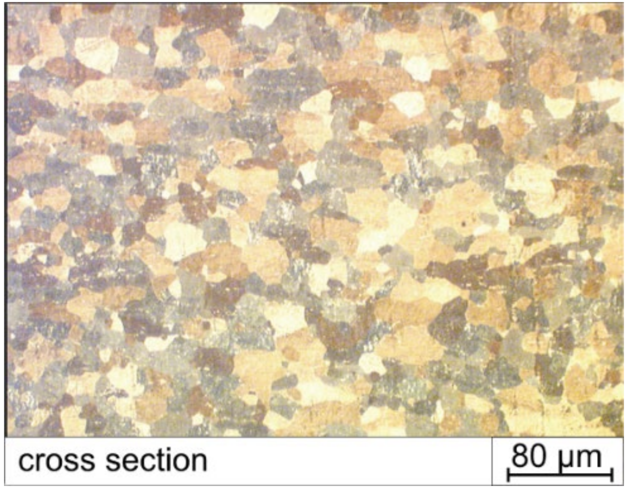
Composition of some metastable β-alloys [wt.%]

[wt.-%]	Mo/Ta	Nb	Fe	Zr	O	N	C	H	Other
Ti-15Mo	15.0	---	0.1	---	0.15	0.01	0.05	0.015	
Ti-15Mo-2.7Nb-3Al-0.2Si	15.0	2.5-3.0	0.1	---	0.10	0.01	0.08	0.02	3 Al, 0.2 Si
Ti-12Mo-6Zr-2Fe	12.0	---	2.0	6.0	0.18	0.01	0.02	0.02	
Ti-29Nb-13Ta-4.6Zr	13.0	29.0	0.03	4.6	0.14	0.03	0.02	0.02	

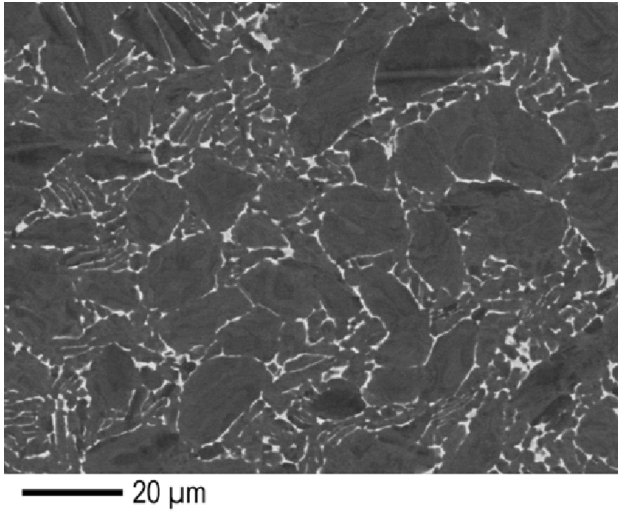
Microstructures (near-)α-Ti alloys

- cp-Ti and near-α Ti alloys exhibit a single-phase microstructure upon solutionizing and cooling or they contain smaller amounts of β primarily on the grain boundaries

OM – cp-Ti grade 2



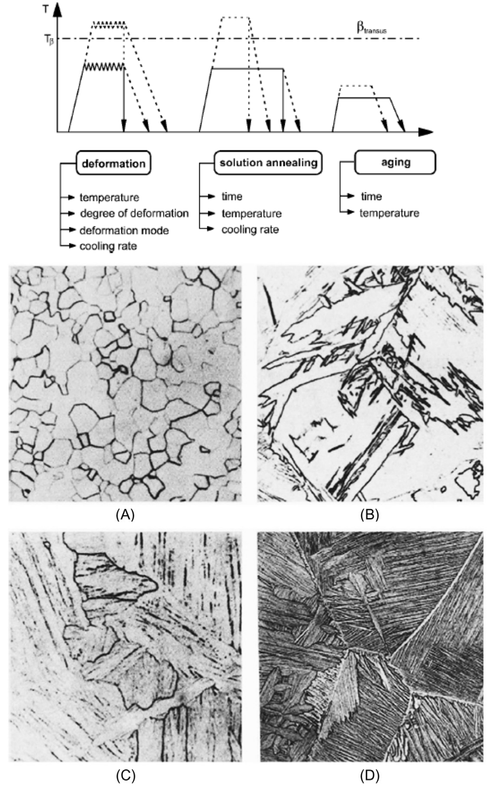
SEM – Ti-8Al-1Mo-1V



Microstructures of (near-)α-Ti alloys

Influence of thermo-mechanical treatment

- Due to the hexagonal lattice of the α-phase, a small grain size is required for decent plastic forming capacity.
  - hot working and annealing is often performed in the α or the α+β region
  - extended heat treatment in the β-region is avoided to prevent excessive grain growth
- The heat treatment affects the microstructure
  - Annealing in the α-field leads to equiaxed grains (A)
  - Quenching from the β-field leads to martensitic α’ (B)
  - Air-cooling from the β-field leads to Widmannstätten (plate-like) α-grains growing from the former β-grain boundaries into the grain.
  - Slow cooling from the α+β region in near α- alloys leads to finely dispersed β-phase in an α-matrix (Duplex annealed).

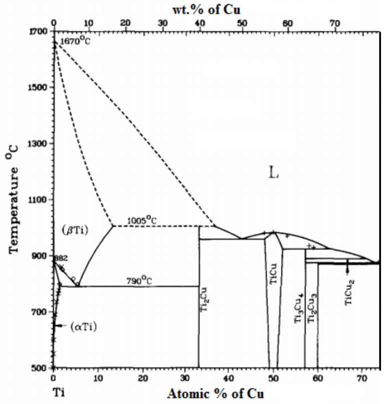


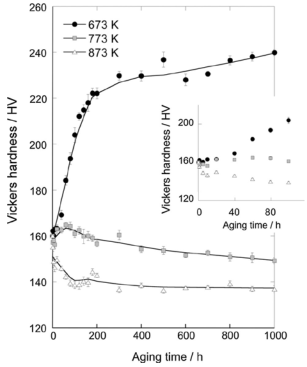
/I. Polmear et al. Light Alloys, 5th Edition (2017), Elsevier/

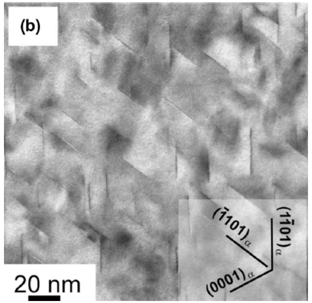
Precipitation hardening of α-Ti alloys

The system Ti-Cu

- Precipitation hardening is comparably rarely used in Ti alloys. The only system that has some significance is the Ti-Cu system.
- The solubility limit of copper drops from 2.1 wt.% at the eutectoid temperature (805°C) to virtually zero at 400°C.
- The precipitate observed is at any rate Ti_2Cu that precipitates as platelets on the {1101} planes.
- During aging at 400°C the hardness increases by 200-300 MPa.





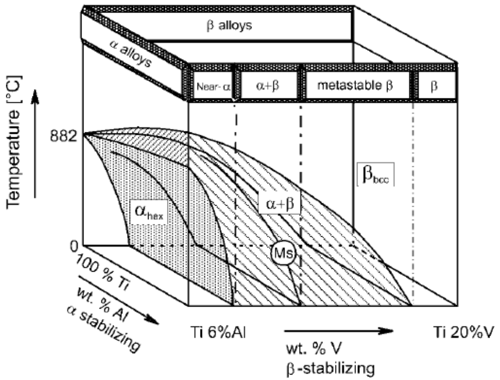


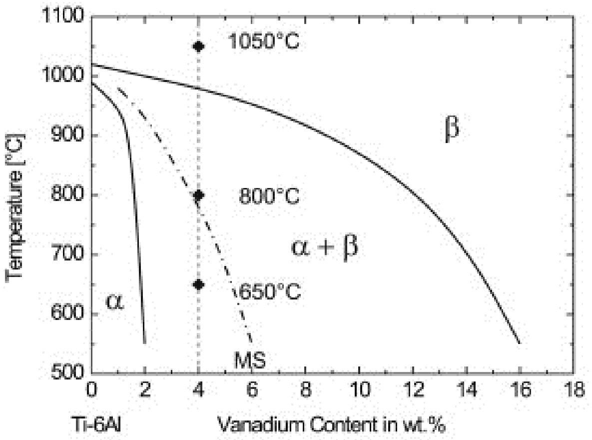
/M. Mitsuhara et al., Metall. Mater. Trans., 47A (2016) 1544/

Microstructures of α+β-Ti alloys

The alloy Ti-6Al-4V

- Ti−6Al−4V was invented during the period from 1952 to 1954 in the United States
- Ti−6Al−4V is a multi-purpose Ti alloy and is used for a variety of applications in aerospace technology, racing cars, biomedical technology etc.
- Two grades of Ti−6Al−4V are produced commercially, Grade 5 and Grade 23 (Extra Low Interstitial, ELI) with lower amounts of O, N and H
- Grade 5 offers higher strength but lower ductility than Grade 23
- The specifications of Grade 5 allow Al to vary from 5.5% to 6.75% and V from 3.5% to 4.5%
  - Higher amounts give highest strength
  - Lower amounts improve weldability





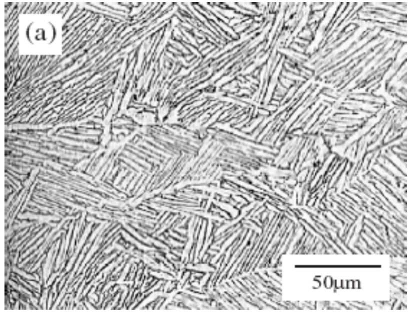
/M. Peters, in Titanium and Titanium Alloys. Fundamentals and Applications Edited by Christoph Leyens, Manfred Peters, Wiley (2003)/

Microstructures of α+β-Ti alloys

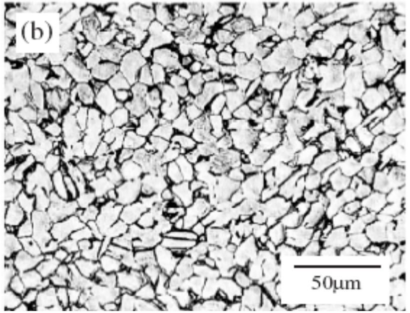
Influence of thermo-mechanical treatment on the ms of Ti-6Al-4V

- Depending on the thermo-mechanical pre-treatment, Ti-6Al-4V (and other α+β alloys) exhibit a variety of different microstructures
  - Slow cooling from the β-region results in lamellar α-grains, rapid quenching in a martensitic structure
  - Strong plastic deformation at RT followed by recrystallization in the upper α+β-region results in equiaxed grains
  - Deformation and solution heat treatment just below the β-transus temperature results in bimodal microstructures that consist partly of equiaxed (primary) α in a lamellar α+β matrix

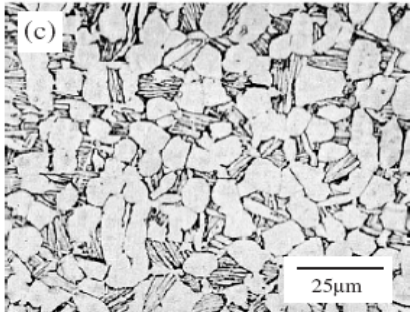
lamellar (Widmanstätten)



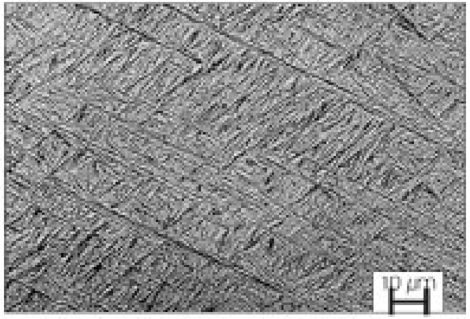
globular



bimodal



martensitic

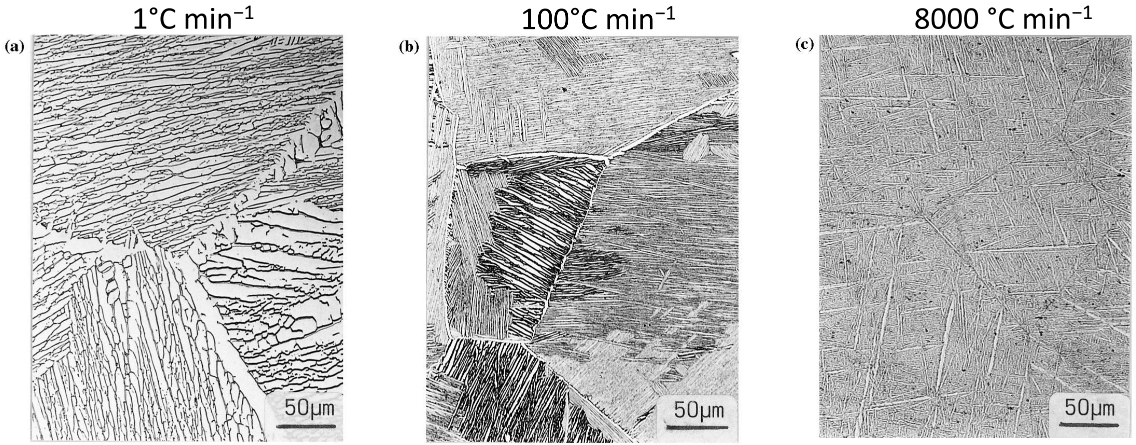


/Donachie, 1982/

Microstructures of α+β-Ti alloys

Influence of cooling rate on ms in Ti-6Al-2Sn-4Zr-6Mo

- In α+β-Ti alloys, a critical parameter determining the width of the α-lamellae in the lamellar structure within the β grains and the extent of the continuous α-layer at β grain boundaries is the cooling rate from the homogenization temperature.



Optical Micrographs of samples quenched from β field and aged for different times; bright α-Ti, dark β-Ti

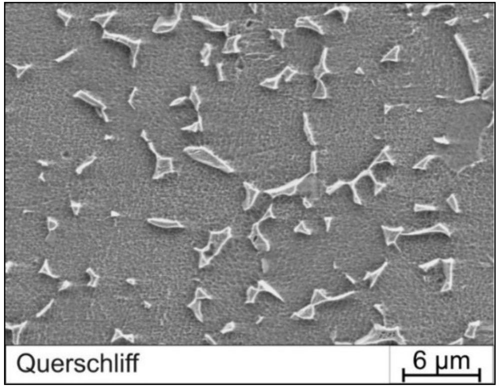
/G. Lütjering, MSEA 243 (1998) 32-45/

Microstructures of α+β-Ti alloys

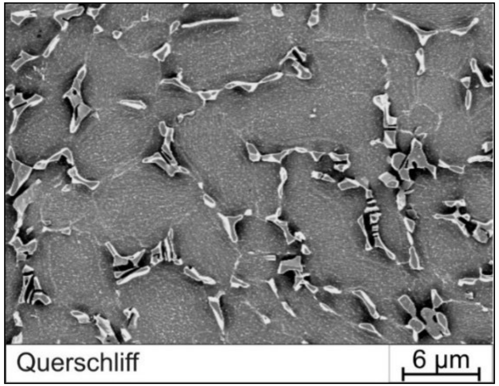
Ti-6Al-4V vs. Ti-6Al-7Nb

- The β-stabilizer V and its oxide V_2O_5 are cyto-toxic in its pure form
- Because V can be locally enriched in the β-phase in implants made from Ti-6Al-4V, it has been debated for a long time whether this can have a long-term impact
- In order to mitigate the potential negative impact of V, the alloy Ti-6Al-7Nb with similar properties than Ti-6Al-4V was developed in the 1980s

Ti-6Al-4V ELI



Ti-6Al-7Nb



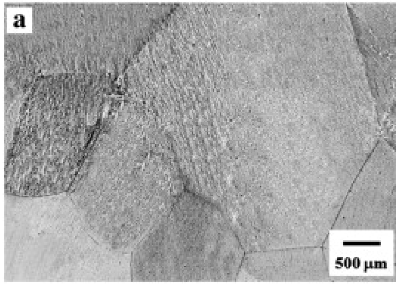
/C. Leinenbach, 2004/

Microstructures of other metastable β-Ti alloys

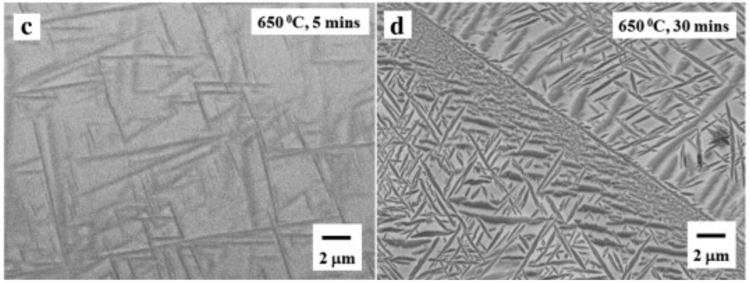
Influence of ageing on microstructure

- Metastable β-Ti alloys exhibit a single-phase microstructure upon solutionizing and cooling
- After ageing α-Ti forms predominantly on the grain boundaries (GB-α) and intra-granular α-laths
- Besides, hardening can be achieved by the formation of the meta-stable ω-phase and the (coherent, spinodal) separation on short length scale into solute lean and solute rich β-phase (β')
- Which of these phases (ω, β', or α) are formed depends on the composition and the annealing temperature.

As deformed grain structure



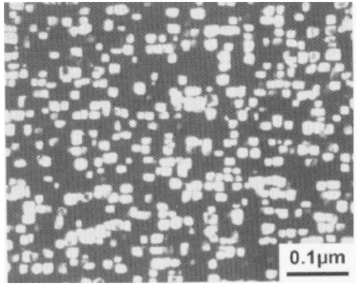
SEM micrographs of samples quenched from β field and aged for different times; bright β-Ti, dark α-Ti



Ti–5Al–5Mo–5V–3Cr

/S.K. Kar et al., Mater. Charact. 81 (2013) 37-48/

TEM dark field; cuboidal ω-precipitates



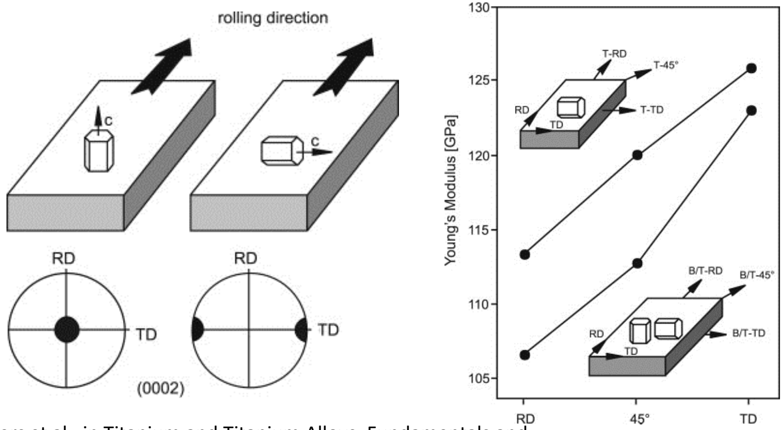
Ti-8Fe 400°C/4h

/G. Lütjering, J.C. Williams: Titanium, 2nd Ed. Springer 2010/

Textures in (near-)α and α+β-Ti alloys

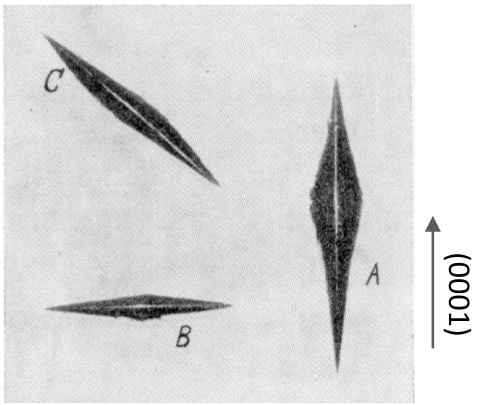
- Ti alloys can have a pronounced anisotropy of properties, which can be directly related to the inherent anisotropy of the hexagonal crystal structure of α.
- These crystallographic textures develop upon deformation (deformation texture) and can be further pronounced by a subsequent recrystallization annealing (recrystallization texture).

Basal and transverse textures of
of Ti-alloys and influence on Young's modulus



M. Peters et al., in Titanium and Titanium Alloys. Fundamentals and Applications .Edited by Christoph Leyens, Manfred Peters, Wiley (2003)/

Asymmetric hardness tip indenter
mark in a Ti single crystal



Mechanical properties of (near-)α Ti alloys

Grade	$R_{p0.2}$ [MPa]	R_m [MPa]	A_5 [%]
Ti cp-1	200	290-410	30
Ti cp-2	250	390-540	22
Ti cp-3	320	460-590	18
Ti cp-4	390	540-740	16

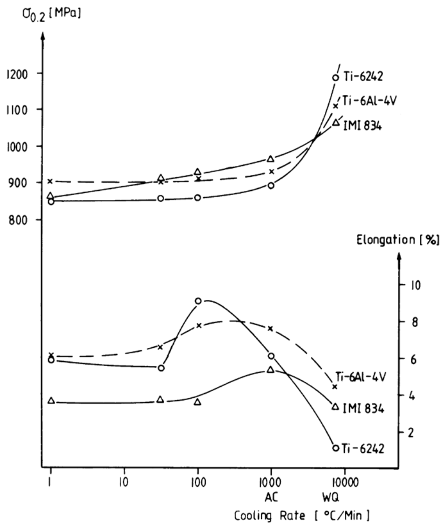
Grade	$R_{p0.2}$ [MPa]	R_m [MPa]	A_5 [%]
Ti-5Al-2.5Sn	710-860	760-880	16
Ti-6Al-2Sn-4Zr-2Mo	890-940	930-990	10
Ti-8Al-1Mo-1V	950-970	1030	16
Ti-5Al-5Sn-2Zr-2Mo	800-850	900-950	10

Mechanical properties of α+β-Ti alloys

EPFL

- α+β-Ti alloys offer in general a balanced mix of high strength and ductility
- Besides the composition, the mechanical properties are strongly effected by the amount, size and shape of the two phases α and β
- The most influential microstructural parameter on the mechanical properties is the size of the α-regions
  - α-grain size in globular microstructures
  - Width of the α-colonies in fully lamellar microstructures

	$R_{p0.2}$ [MPa]	R_m [MPa]	A_5 [%]
Ti-6Al-4V	800-1070	920-1140	10-18
Ti-6Al-7Nb	800-1010	870-1130	10-16
Ti-6Al-2Sn-4Zr-6Mo	1000-1100	1100-1200	10-16
Ti-7Al-4Mo	950-1100	1100-1200	8-10



/G. Lütjering, MSEA 243 (1998) 32-45/

Mechanical properties of metastable β-Ti alloys

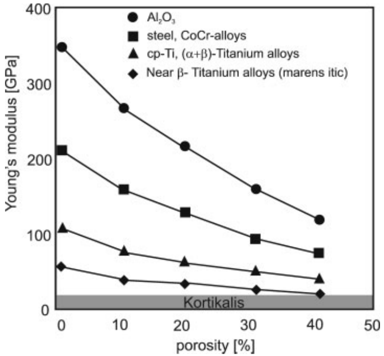
- Due to the significant hardening by precipitated α, ω, or β'-phase, the β-Ti alloys can achieve a higher yield and tensile strength than their α or α+β counterparts, depending on the processing route
- At high amounts of continuous GB-α layers, the ductility can be significantly decreased

	$R_{p0.2}$ [MPa]	R_m [MPa]	A_5 [%]
Ti-15Mo	800-1070	920-1140	8-18
Ti-15Mo-2.7Nb-3Al-0.2Si	880-1350	930-1450	5-15
Ti-12Mo-6Zr-2Fe	800-1010	870-1130	11-16
Ti-29Nb-13Ta-4.6Zr	600-1000	650-1050	5-25

Mechanical properties of metastable β-Ti alloys

- (near-)β-Ti have in general a lower Young's modulus than α and α+β alloys
- Several recently developed β-Ti alloys containing high amounts of Nb (up to 35 wt.%) and/or Ta (up to 25 wt.%) exhibit extremely low Young's moduli (40-70 GPa)
- This can be exploited e.g. for light-weight springs in cars or for iso-elastic orthopaedic implants (E_{bone} = 10-30 GPa)

/www.dierk-raabe.com/



/J. Breme et al., in Titanium and Titanium Alloys. Fundamentals and Applications Edited by Christoph Leyens, Manfred Peters, Wiley (2003)/

Alloy Designation	Type alloy	E (Gpa)
Ti-19Nb-14Zr	Near β	14
Ti–24Nb–4Zr–7.9Sn	β	33
Ti-29Nb-6Ta-5Zr	β	43
Ti-35Nb-4Sn	β	44
Ti35Nb2Ta3Zr	β	<50
Ti-10Zr-5Ta-5Nb	β	51.97
Ti–(18-20)Nb–(5-6)Zr	Near β	45-55
Ti-25Ta-25Nb	β	55
Ti-29Nb-13Ta-7.1Zr	β	55
Ti-35Nb-7Zr-5Ta	Near β	55
Ti–35Nb–5.7Ta–7.2Zr	β	57
Ti-28Nb-13Zr-2Fe	Near β	58
Ti–28Nb–13Zr–0.5Fe	Near β	58
Ti-29Nb-11Ta-5Zr	β	60
Ti-29Nb-13Ta-2Sn	β	62
Ti-12Mo-5Zr	β	64
Ti-29Nb-13Ta-4.5Zr	β	65
Ti–25Nb–2Mo–4Sn	Near β	65
Ti-29Nb-13Ta-4.6Sn	β	66
Ti–35Nb–5Ta–7Zr–0.40	β	66
TLM Alloy	β	67
Ti–12Mo–5Ta	Near β	74
Ti-29Nb-13Ta-4Mo	β	74
Ti-29Nb-13Ta-6Sn	β	74

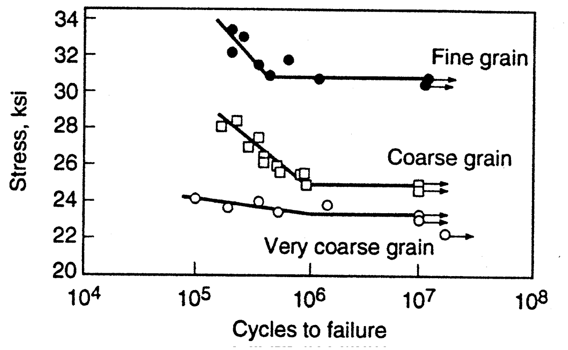
Fatigue behaviour of (near-)α-Ti alloys

EPFL

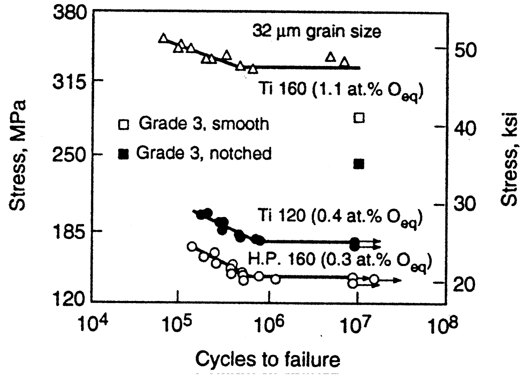
- The hardening mechanisms that are efficient to increase the static strength (grain refinement, increase of oxygen conten, cold working can be also applied to increase the cyclic strength of cp-Ti and (near-) α-Ti alloys

Influence of different parameters on fatigue performance of cp-Titan

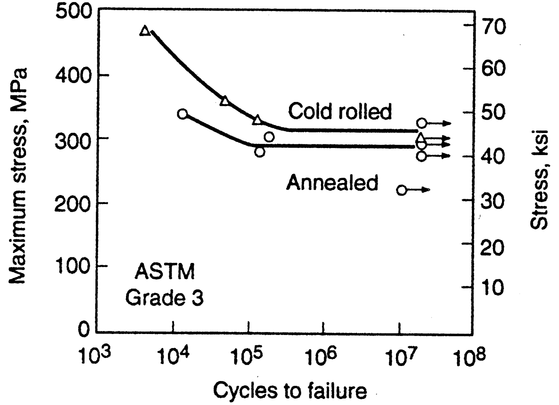
Grain size, R=-1



Oxigen content, R=-1



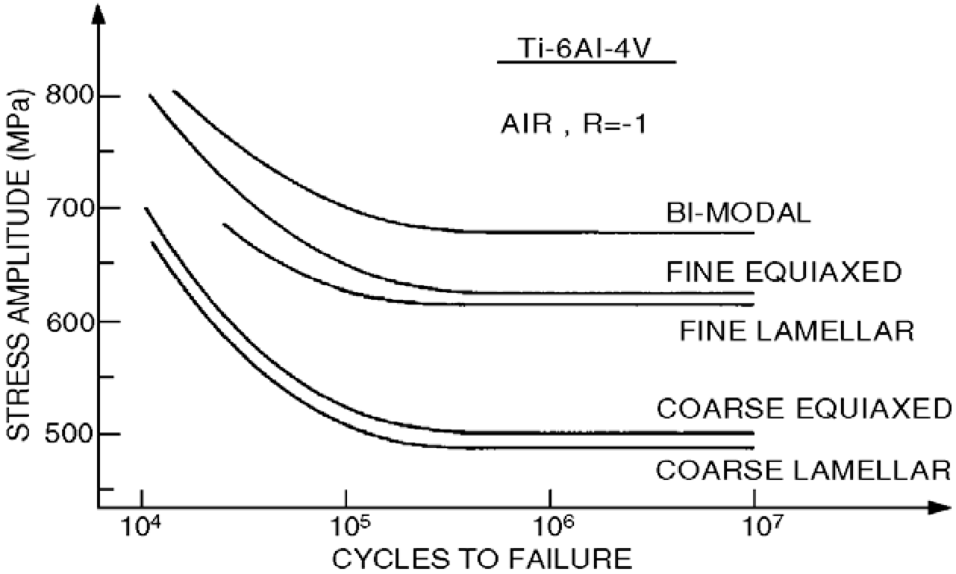
Cold deformation, R=0.1



/L. Wagner, in Titanium and Titanium Alloys. Fundamentals and Applications .Edited by Christoph Leyens, Manfred Peters, Wiley (2003)/

Fatigue behaviour of Ti-6Al-4V

- Qualitatively, the bi-modal microstructure offers the best fatigue properties, followed by the equiaxed and the lamellar microstructures
- The fatigue properties are strongly influenced by the grain/lamellae size



/Jaffee et al., 1987/

Fatigue behaviour of Ti-6Al-4V

EPFL

- Qualitatively, the bi-modal microstructure offers the best fatigue properties, followed by the equiaxed and the lamellar microstructures
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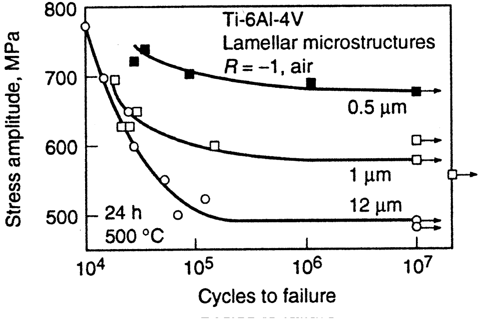
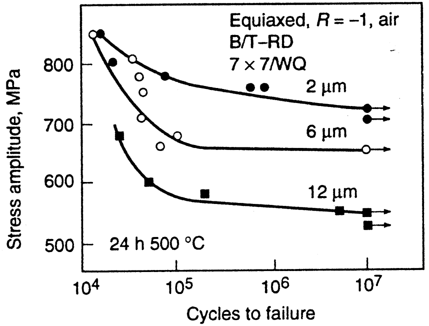
Lamellar microstructure – width of α lamellae [μm]



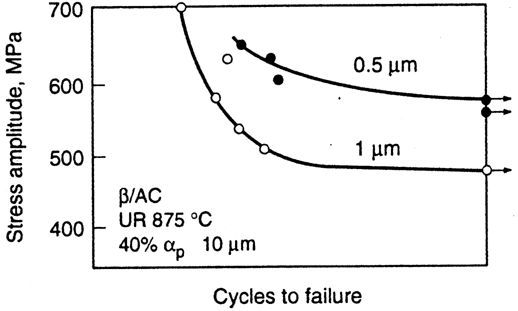
0.5 - $R_{p0,2}$=1040MPa, A=16%
1 - $R_{p0,2}$= 980MPa, A=18%
12 - $R_{p0,2}$= 930MPa, A=14%

Globular microstructure – size of α grains [μm]



2 - $R_{p0,2}$=1120MPa, A=46%
6 - $R_{p0,2}$=1070MPa, A=44%
12 - $R_{p0,2}$=1060MPa, A=43%

Bimodal microstructure – width of α lamellae[μm]



0,5 - $R_{p0,2}$=1045MPa, A=39%
1 - $R_{p0,2}$= 975MPa, A=34%

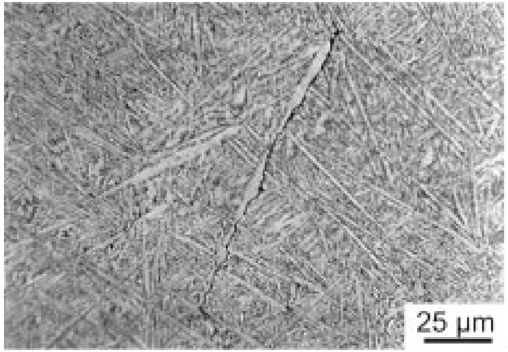
/L. Wagner, in Titanium and Titanium Alloys. Fundamentals and Applications .Edited by Christoph Leyens, Manfred Peters, Wiley (2003)/

Fatigue behaviour of Ti-6Al-4V

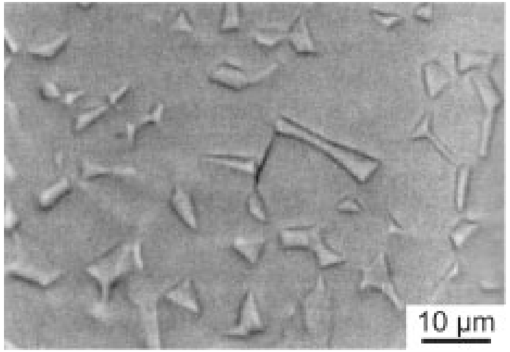
Influence of microstructure on fatigue crack formation

- The lifetime of Ti parts is determined by their resistance to crack nucleation as well as the propagation behaviour of short and long cracks
- Crack nucleation depends primarily on the first dislocation motion and therefore mostly on the yield stress
- The propagation behavior of microcracks depends on the dislocation slip length; with increasing slip length, the microcrack propagation rate in these slip bands is increased

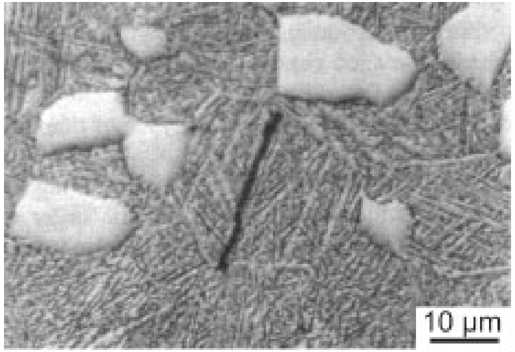
Lamellar microstructure



Globular microstructure



Bimodal microstructure



Ti-6Al-4V, σ_a = 775 MPa, R=–1

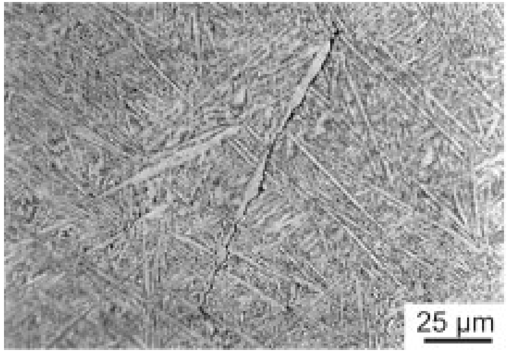
/L. Wagner, in Titanium and Titanium Alloys. Fundamentals and Applications Edited by Christoph Leyens, Manfred Peters, Wiley (2003)/

Fatigue behaviour of Ti-6Al-4V

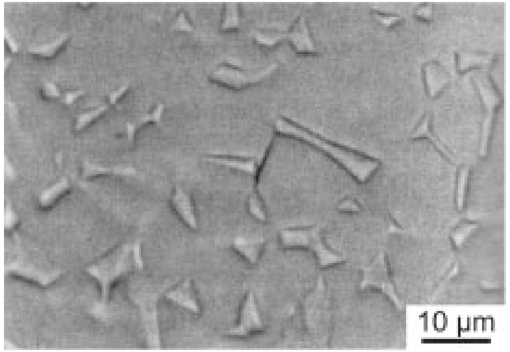
Influence of microstructure on fatigue crack formation

- In lamellar microstructures, fatigue cracks initiate at slip bands within the α lamellae or at α along prior β grain boundaries
- For equiaxed structures, fatigue cracks nucleate along slip bands within α grains
- In duplex structures, fatigue cracks can either initiate in the lamellar matrix, at the interface between the lamellar matrix and the primary α phase, or within the primary α phase, depends on the cooling rate, and the volume fraction and size of the primary α phase

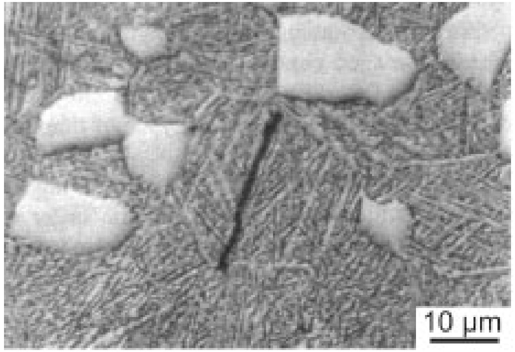
Lamellar microstructure



Globular microstructure



Bimodal microstructure



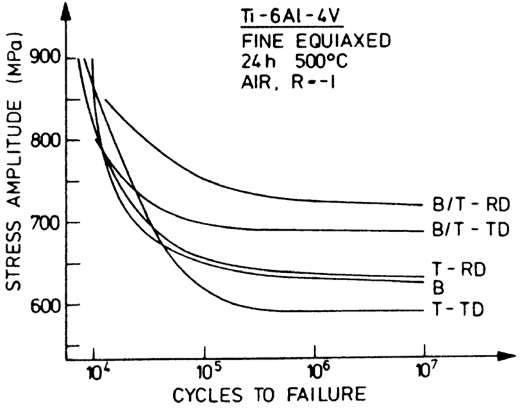
Ti-6Al-4V, σ_a = 775 MPa, R=–1

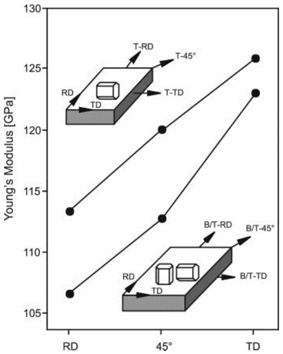
/L. Wagner, in Titanium and Titanium Alloys. Fundamentals and Applications Edited by Christoph Leyens, Manfred Peters, Wiley (2003)/

Fatigue behaviour of Ti-6Al-4V

Influence of textures

- Textured polycrystalline materials with high volume fractions of α phase can reveal quite anisotropic fatigue behavior
- A B/T texture loaded parallel to the rolling direction (RD) showed the highest fatigue strength while the lowest values were found for a T texture loaded perpendicular to RD in the rolling plane (TD)
- The difference in the endurance limit values can be signifcant (725 MPa vs. 580 MPa)



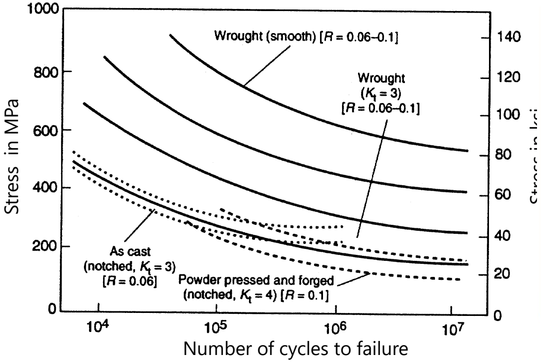


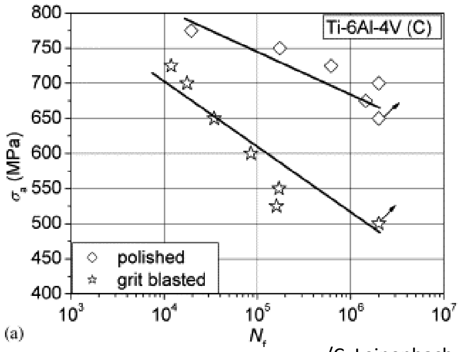
/L. Wagner, in Titanium and Titanium Alloys. Fundamentals and Applications .Edited by Christoph Leyens, Manfred Peters, Wiley (2003)/

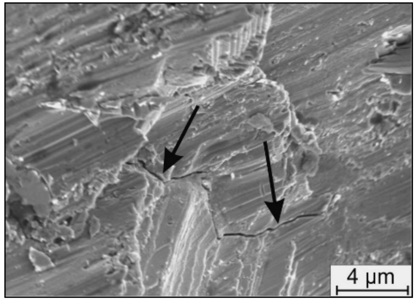
Fatigue behaviour of Ti-6Al-4V

Influence of notches and surface roughness

- α+β-Ti exhibit a pronounced notch sensitivity under cyclic loading; macroscopic notches and even microscopic surface roughness lead to a local stress concentration
- In comparison to fcc or bcc lattices, the hcp lattice of α-Ti has a lower number of slip systems and thus limited possibilities for dislocation glide
- If grains are "unfavorably" oriented with regard to the external load, the high stress cannot be dissipated as plastic strain and micro-cracks are initiated







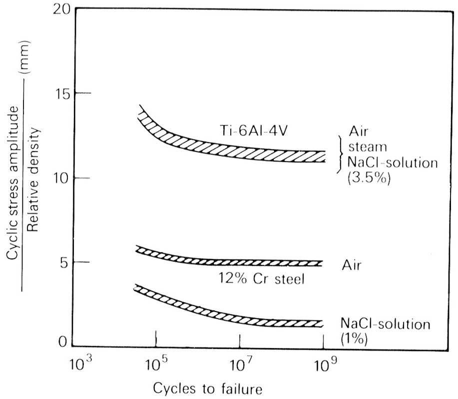
/C. Leinenbach et.al, Biomaterials 27(8) (2006) 1200-1208/

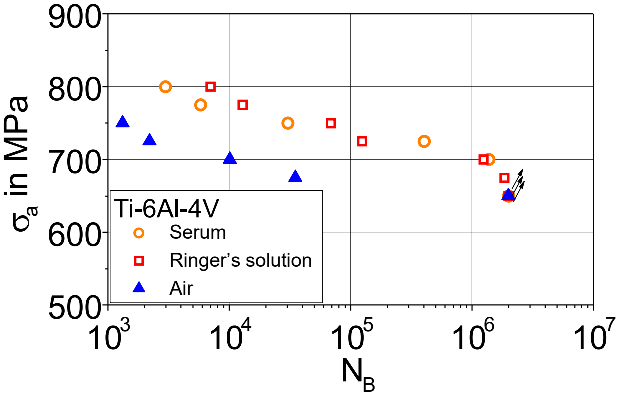
/L. Wagner, in Titanium and Titanium Alloys. Fundamentals and Applications Edited by Christoph Leyens, Manfred Peters, Wiley (2003)/

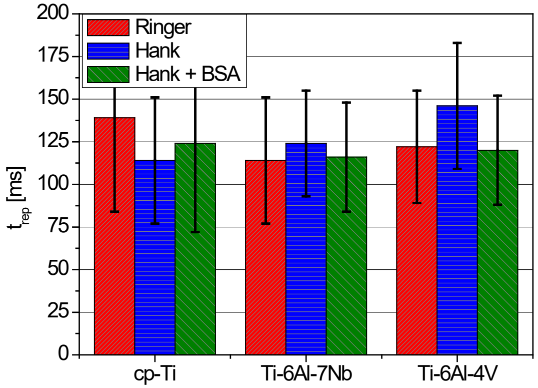
Fatigue behaviour of Ti-6Al-4V

Influence of environmental conditions

- Ti alloys outperfom most other engineering materials both for fatigue resistance in many aggressive environments (e.g. the human body)
- This is also because of the ability of Ti to repassivate very quickly if the surface oxide layer is damaged

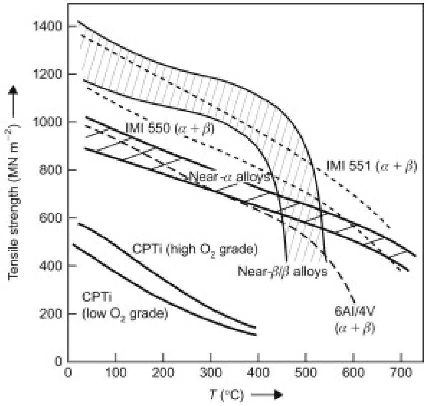




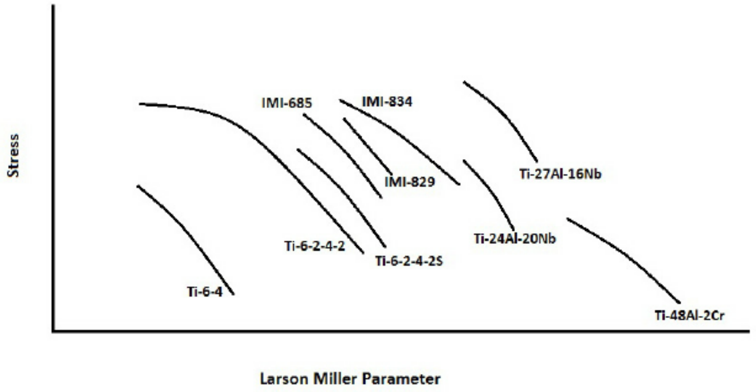


HT mechanical performance of Ti alloys

- Near-α Ti alloys exhibit a better high-T strength and creep performance than α+β-Ti or β-Ti alloys and are thus used for applications with service temperatures up to 550°C
- Reasons for
  - High amount of efficient solid solution strengtheners Al, Sn, which stabilize α
  - The hcp lattice is inherently less prone to high-T slip mechanisms (cross slip) than the bcc lattice
  - Some alloys contain small amounts of Si, which form nanometric Ti silicides
- Ti-6Al-4V is usually applied up to 400°C



/R.E. Smallman, A.H.W. Ngan, in Modern Physical Metallurgy (Eighth Edition), 2014/



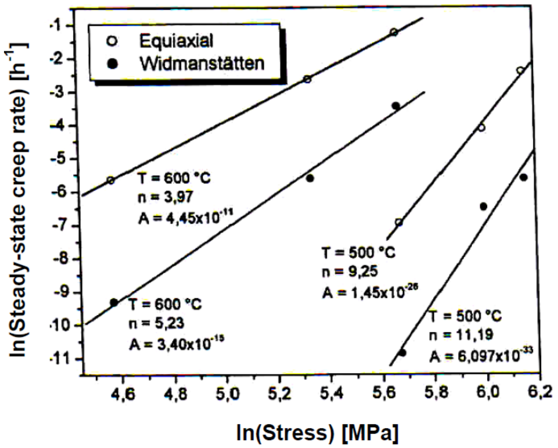
/N.R. Muktinutalapati, Materials for Gas Turbines – An Overview, in: E. Benini, Advances in Gas Turbine Technology, Intech Open, 2011/

HT mechanical performance of Ti alloys

Creep behaviour of Ti-6Al-4V

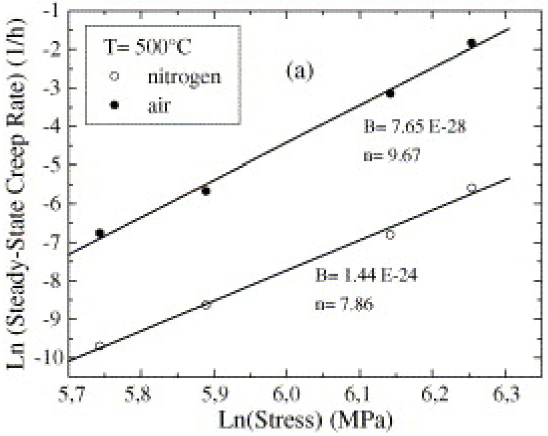
- The creep properties of Ti-6Al-4V are influenced by the microstructure
- Because of the pronounced oxidation tendency at T>500°C, the presence of oxygen can significantly incrase the creep rates

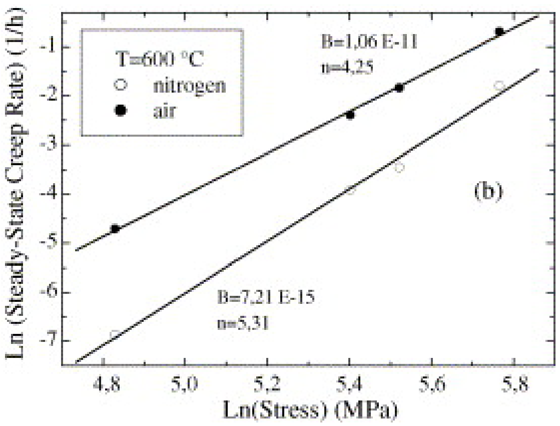
Influence of microstructure



/T. Sugahara et al., Mater. Sci. Forum 636/637 (2010) 657-662/

Influence of atmosphere





/D.A.P. Reis et al., MSEA 399 (2005) 276-280/

Learning objectives

- Classification of Ti alloys (α, β and α+β Ti alloys)
- Main alloying elements in Ti alloys and their effect on
  - Solid solution strengthening
  - Precipitation strengthening
- Typical microstructures of α, β and α+β Ti alloys
- Main properties of α, β and α+β Ti alloys with regard to their application (static & cyclic mechanical, fatigue)
- Surfaces on Ti alloys & reactivity
- Plasticity in hex crystals, implications on deformation behavior and notch sensitivity