Nonferrous Alloys

- Aluminum Alloys
- Copper Alloys
- Magnesium
- Beryllium Alloys
- Nickel and Cobalt Alloys
- Titanium Alloys
- Refractory and Precious Metals

Aluminum Alloys

- High specific modulus (ratio of modulus to density) and high specific strength, (ratio of strength to density)
- High electrical and thermal conductivity (in annealed condition),
- Non-magnetic material,
- Good resistance to corrosion and oxidation by **Al_2O_3 film** on its surface,
- Low endurance limit,
- Low service temperature; low strength at elevated temperatures,
- Low hardness and poor wear resistance.

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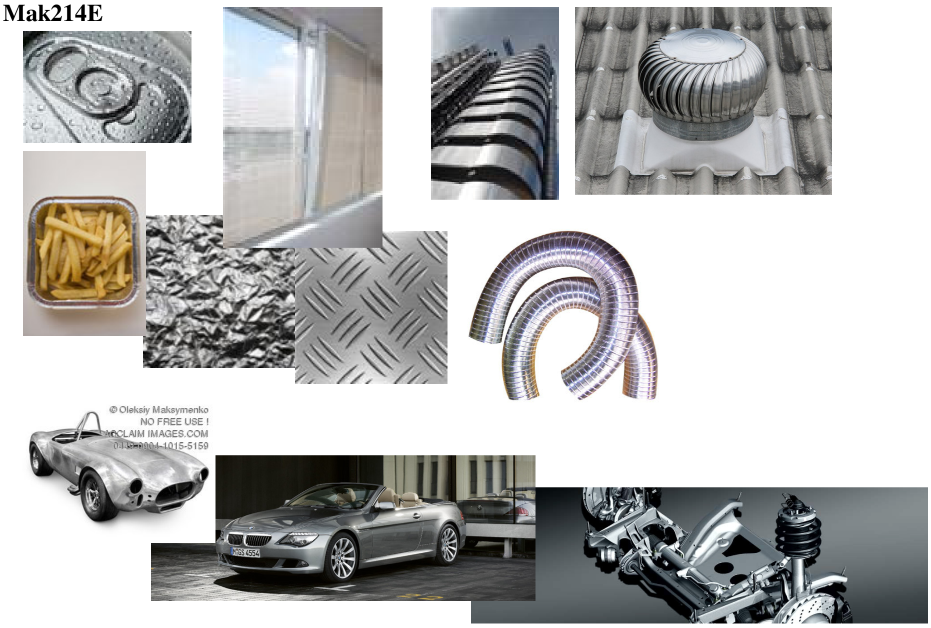

3

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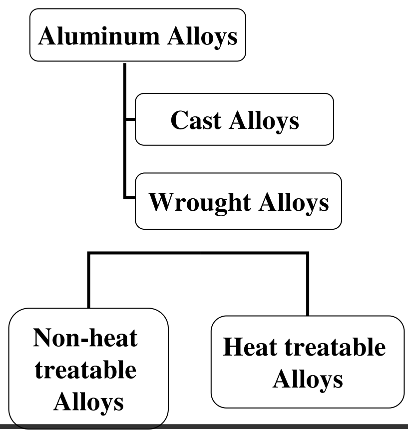

TABLE 13-2 ■ ***The effect of strengthening mechanisms in aluminum and aluminum alloys***

Material	Tensile Strength (psi)	Yield Strength (psi)	% Elongation	Ratio of Alloy-to-Metal Yield Strengths
Pure Al	6,500	2,500	60	1
Commercially pure Al (at least 99% pure)	13,000	5,000	45	2.0
Solid-solution-strengthened Al alloy	16,000	6,000	35	2.4
Cold-worked Al	24,000	22,000	15	8.8
Dispersion-strengthened Al alloy	42,000	22,000	35	8.8
Age-hardened Al alloy	83,000	73,000	11	29.2

4

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Strengthening mechanisms

- Solid solution hardening (alloying) Cr, Mg, Si, Cu, Zn, etc.
- Strain hardening (cold deformation)
- Precipitation (Age) hardening Cu, Zn, Li, etc.
- Dispersion hardening SiC, Al_2O_3, etc.
- Grain refinement (small grain size) B, Ti, etc.

Alloys: X30 stronger than pure Al.

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Casting Aluminum Alloys

Important

- Effects of **Si** on the casting alloys
  1. Lower the melting point,
  2. Increase the fluidity,
  3. Increase the castability.
- **Fluidity:** The ability of liquid metal to flow and fill the die cavity without premature solidification.
- **Castability:** The ease to make good casting, related to fluidity.

Advanced applications

- **Al-Li alloys:** ρ_{Li}; 0.54 gr/cm^3,
  - lower density (10%),
  - good fatigue resistance,
  - good toughness at cryogenic temp,
  - higher modulus of elasticity,
  - formability with super-plasticity,
  - Especially good for aerospace applications.

- **Dispersion strengthening** by powder metallurgy,
- **Thixocasting** to break dentritic structure and cast large complex geometries.
- **SAP- (sintered Al powders)**, metal matrix composites with SiC, Al_2O_3, etc.
- **Al clad products in composite technology**.

Example 13.4

Design a casting process to produce automotive wheels having reduced weight and consistent and uniform properties.

SOLUTION

Thixocasting process in which the material is **stirred during solidification, producing a partly liquid**, partly solid structure that behaves as a solid when no external force is applied, **yet flows as a liquid under pressure**. We would **select an alloy with a wide-freezing range** so that a significant portion of the **solidification process occurs by the growth of dendrites.** A **hypoeutectic aluminum-silicon alloy** might be appropriate. In the thixocasting process, the dendrites are broken up by stirring during solidification. The billet is later reheated to cause melting of just the eutectic portion of the alloy, and it is then **forced into the mold in its semi-solid condition at a temperature below the liquidus temperature.**

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Copper and Its Alloys

- Heavier than iron,
- Some alloys has excellent ductility,
- Corrosion resistance,
- Specific strength is less than Al and Mg but have better creep, fatigue, and wear resistance,
- **Good thermal and electrical conductivity**,
- Easy processing (fcc structure).
- Applications for Cu-based alloys include
  - Electrical components (such as wire), pumps, valves, and plumbing parts.
  - Cartridges,
  - Decorative applications

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Commercially pure Cu:

- Impurities less than 1%; good for electrical applications.

Alloys:

- Decorative colors in a large spectrum: pure Cu; red, alloys with Zn; yellow, alloys with Ni, silver, etc.
- Better mechanical properties.
- Usually Cheaper..

Important

Common alloys

- **Brass** - A group of Cu-Zn alloys,
  - **α Brass -** upto 30%Zn known as cartridge brass (deep drawing cups)
  - **α+β Brass** – upto-40% Zn known as forging Brass (plumbing, pump parts)
- **Bronze** –(alloying elements other than Zn).
  - Tin Bronzes (Phosphor Bronze) mostly in cast structure due to limited formability- naval applications.
  - Lead Bronzes (Sliding bearings) – upto 5% Pb, machinable parts
  - Al Bronze (upto 6% Al) good formability, strength and toughness.
- Be-Cu – Age hardenable alloys –springs, non-sparking tools
- Cr-Cu– Age hardenable – Spot welding electrodes
- Ni-Cu – Cupro nickel– Alman gümüşü

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Copper Alloys

- Cast Alloys
- Wrought Alloys

TABLE 13-7 ■ ***Properties of typical copper alloys obtained by different strengthening mechanisms***

Material	Tensile Strength (psi)	Yield Strength (psi)	% Elongation	Strengthening Mechanism
Pure Cu, annealed	30,300	4,800	60	None
Commercially pure Cu, annealed to coarse grain size	32,000	10,000	55	Solid solution
Commercially pure Cu, annealed to fine grain size	34,000	11,000	55	Grain size
Commercially pure Cu, cold-worked 70%	57,000	53,000	4	Strain hardening
Annealed Cu-35% Zn	47,000	15,000	62	Solid solution
Annealed Cu-10% Sn	66,000	28,000	68	Solid solution
Cold-worked Cu-35% Zn	98,000	63,000	3	Solid solution + strain hardening
Age-hardened Cu-2% Be	190,000	175,000	4	Age hardening
Quenched and tempered Cu-Al	110,000	60,000	5	Martensitic reaction
Cast manganese bronze	71,000	28,000	30	Eutectoid reaction

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Magnesium Alloys

- Lighter than Al with a density of 1.7 g/cm^3,
- Not as strong as Al, but its strength to weight ratio close to it,
- **Poor fatigue**, creep and wear resistance,
- Good corrosion and oxidation resistance by **MgO film** on its surface,
- Low elasticity modulus,
- Low melting point,
- Easily burns under O_2 atmosphere: Dangerous,
- Poor ductility (HCP structure): But may be improved with alloying,
- **Difficulty in processing** (forming, machining and casting),
- **Extracted electrolytically from $MgCl_2$ in sea water**.

Applications
- Aerospace industry,
- **High speed machinery**,
- Transportation and materials handling equipments.

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19

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Magnesium Alloys: Designation

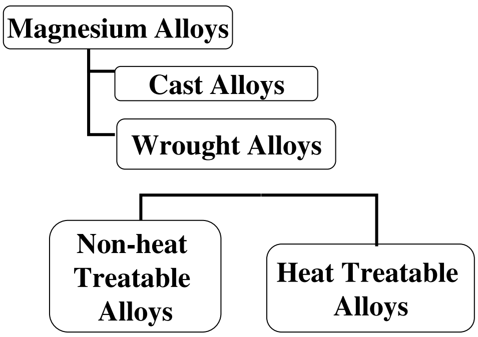

TABLE 13-6 ■ *Properties of typical magnesium alloys*

Alloy	Composition	Tensile Strength (psi)	Yield Strength (psi)	% Elongation
Pure Mg:				
Annealed		23,000	13,000	3–15
Cold-worked		26,000	17,000	2–10
Casting alloys:				
AM 100-T6	10% Al-0.1% Mn	40,000	22,000	1
AZ81A-T4	7.6% Al-0.7% Zn	40,000	12,000	15
ZK61A-T6	6% Zn-0.7% Zr	45,000	28,000	10
Wrought alloys:				
AZ80A-T5	8.5% Al-0.5% Zn	55,000	40,000	7
ZK40A-T5	4% Zn-0.45% Zr	40,000	37,000	4
HK31A-H24	3% Th-0.6% Zr	38,000	30,000	8

20

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Beryllium Alloys

- **Lighter than Al** with a density of 1,85 g/cm^3,
- **Very high modulus of elasticity** (higher than steel, 290 GPa),
- Yield Strength of 210-350 MPa,
- High specific strength and particularly specific modulus (6 times greater than those of steel); good for stiff and light parts,
- **Good properties at high temperature**,
- **Brittle** (hcp), limited ductility at room T,
- Reactive and toxic,
- **Rapidly oxidizes** at high temperature forming toxic BeO.
- Needs special manufacturing techniques such as vacuum casting, vacuum forging, powder metallurgy, etc.
- **Expensive**.

21

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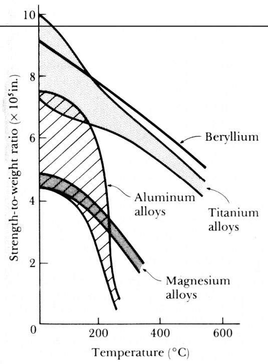
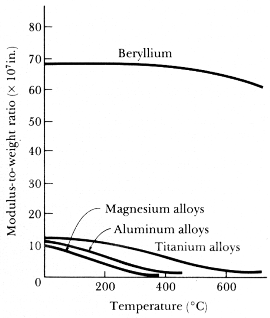
Applications:

- Instrument grade Be is used in inertial guidance systems where the elastic deformation must be minimal,
- Mirror for satellite signaling,
- Structural grades for aerospace and nuclear applications,
- Transparency to electromagnetic radiation,
- Non sparking tools made off by **Cu-Be** alloys





22

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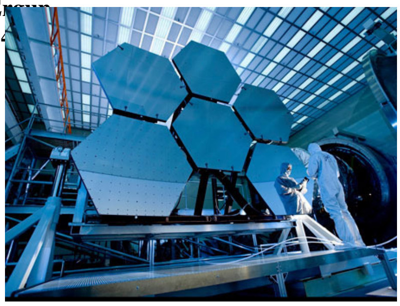

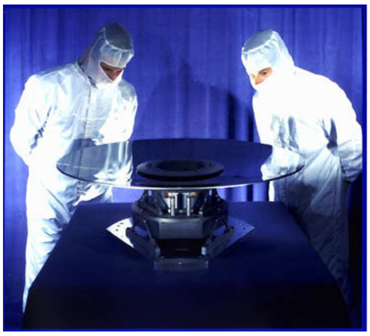

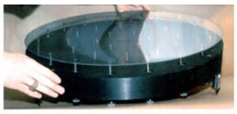

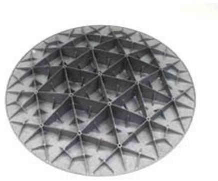

23

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Nickel and its Alloys

- Commercially pure Ni, very high corrosion resistance,
- High corrosion resistance even at high-temperature,
  - ✓ Good for high temperature applications,
- High melting temperature,
- **Nickel;** fcc structure, good formability,
- High strengths.

Applications

- ✓ Corrosion resistant parts: Valves, pumps, vanes
- ✓ Heat exchangers, shafts, impellers,
- ✓ Heat treatment equipments,
- ✓ Gas turbines,
- ✓ Chemical reactor components,
- ✓ Alloying element.

24

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Cobalt

- Allotropic metal: hcp up to 417°C, fcc above 417°C.
- Corrosion resistant
- Its alloys: high strength and hardness, high wear resistant,
- Resistant to human body fluid: **Biomaterial** applications as implant/ prosthetic devices.
- Used in superalloys: Hynes

25

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Super-alloys

Important

- A group of Ni, Fe-Ni, and Co-based alloys.
- Large amount of alloying elements to produce strong and stable phases at high temperatures.
- Heat resistance, creep resistance, and corrosion resistance up to 1000°C. Event though the melting point similar to that of steel.
- **Applications:** Vanes and blades for turbines and other jet engine parts, chemical reaction vessels, heat treatment equipments, heat exchangers.

26

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- **Monel**: Ni-Cu alloy about with 60% Ni: High strength, high corrosion at elevated temperatures, resistance to sea water (thermocouples, heating elements, decorative stuff (silver like color- alman gümüşü).
- Udimed, Inconel: Ni-based superalloys
- **Invar**: Fe-Ni base superalloy having almost no thermal expansion between ±100^{o}C. (Measuring devices and equipments)

27

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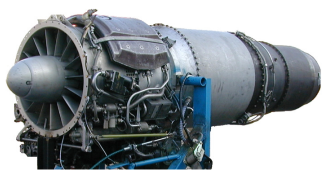

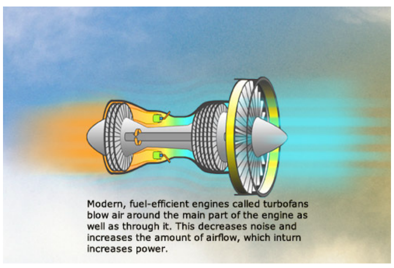

28

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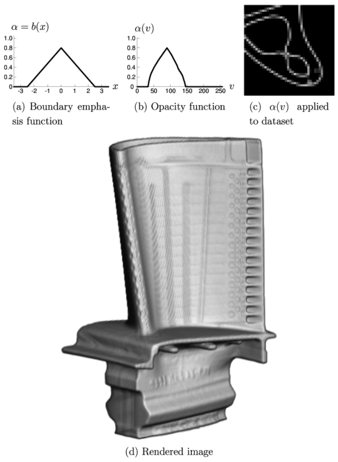

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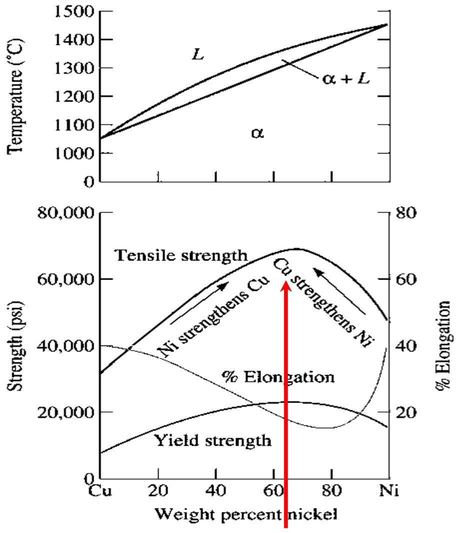

The mechanical properties of Cu-Ni alloys. **<u>Monel:</u>** 60% Ni -40% Cu.

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Strengthening Mechanisms

Important

How to strengthen superalloys working at high Temp?
Creep is important mechanism at high temperature!!

1. Single crystal or directional solidification.
2. Solid solution strengthening of the matrix
3. Carbide dispersion along grain boundaries
4. γ' phase dispersion (intermetallic phase)

Solid solution strengthening:

- Large addition of Cr, Mo, W and small addition of Ta, Zr, Nb, and B for solid solution strengthening
- No catastrophic softening occurs during heating: stable at high temperatures and provides creep resistance.

31

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Strengthening Mechanisms

Precipitation hardening:

- Al and Ti addition causes the precipitation of coherent γ' (intermetallic) phase (Ni_3Al, and Ni_3Ti).
- Lattice parameters of this precipitate is close to Ni matrix therefore not much increase in strength, but this phase is stable and hard at high temperatures providing strength at high temperatures therefore **resistance to creep** for long periods of time.

Dispersion Strengthening:

- **Carbide;** All alloys have small amount of C to combine with the alloying elements and form a network of fine carbide.
- Oxide: **TD Nickel**: Dispersion of 2%ThO_2: Used at very high T ≈1000°C
- Prevents the dislocation motion and grain boundary sliding.
- Important carbides: TiC, B_4C, ZrC, TaC, Cr_7C_3, $Cr_{23}C_6$, Mo_6C, W_6C, etc.
  - Stellite 6B, a Co-base superalloy, good wear resistance at high T. due to this carbides.

32

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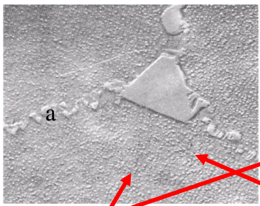
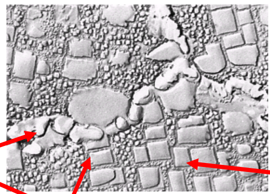
Strengthening Mechanisms

- Age hardenable alloys: small amount of **Ti** and **Al** to precipitate coherent **γ' phase**: **Ni_3Ti**, **Ni_3Al**: doubles the tensile properties.
- γ' (gamma prime) precipitates resistant to overaging up to 200-450°C.





Matrix Strengthened with solid solution strengthening

Strengthened with Carbide precipitation along the grain boundaries

Strengthened with precipitation of γ' phase

(a) Microstructure of a superalloy, with carbides at the grain boundaries and γ´ precipitates in the matrix. (b) Microstructure of a superalloy aged at two temperatures, producing both large and small cubical γ´ precipitates.

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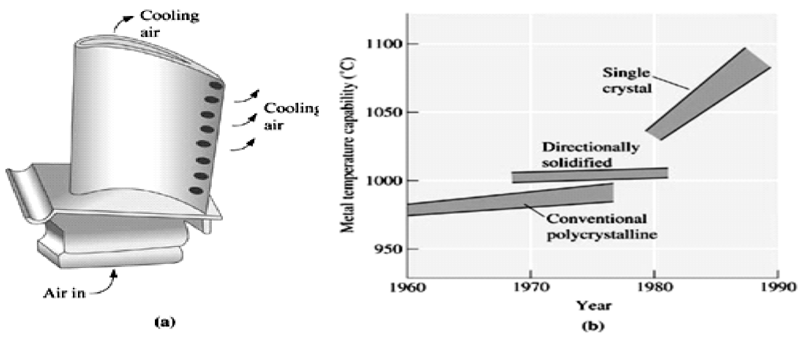
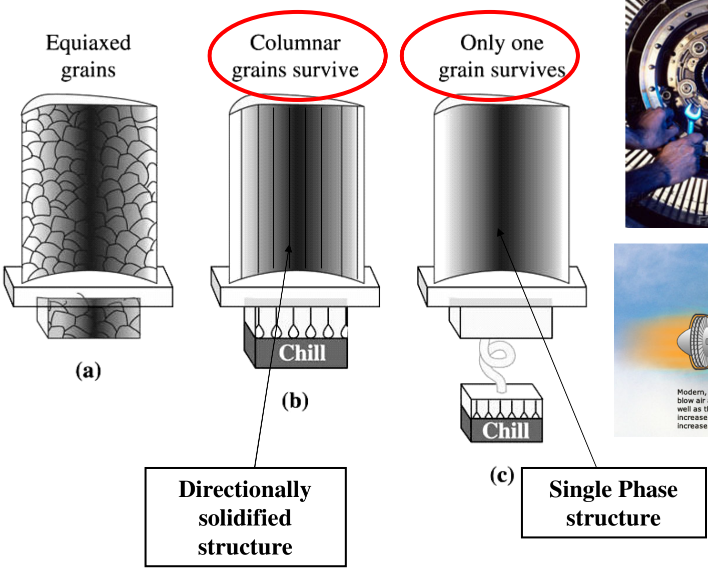
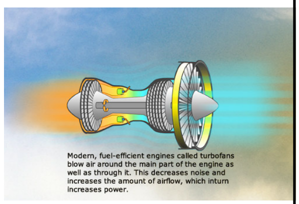
Design/Materials Selection for a High-Performance Jet Engine Turbine Blade

Important

Design a nickel-based superalloy for producing turbine blades for a gas turbine aircraft engine that will have a particularly long creep-rupture time at temperatures approaching 1100°C.







SOLUTION

First, we **need a very stable microstructure**. **Addition of Al or Ti** permits the **precipitation of up to 60 vol% of the γ´ phase** during heat treatment and may permit the alloy to **operate at temperatures approaching 0.85 times the absolute melting temperature**.

Second, we might produce **a directionally solidified or even single-crystal** turbine blade (Chapter 8). In directional solidification, only columnar grains.

We would then heat treat the casting to assure that the **carbides and γ´ precipitate** with the **correct size and distribution**.

Finally, the blade might contain small cooling channels along its length. Air for combustion in the engine can pass through these channels, providing active cooling to the blade, before reacting with fuel in the combustion chamber.

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Refractory Metals

- Tungsten, molybdenum, tantalum, and niobium (or columbium),
- Very high-melting temperatures (above 1925°C)
- Good for high-temperature applications.
- Applications:
  - Filaments for light bulbs, rocket nozzles, nuclear power generators, tantalum and niobium-based electronic capacitors, and chemical processing equipment.
- Tungsten oxidizes between 200-425°C- then rapidly contamination and embrittlement.
- Special protection during processing and using in service
  1. **Inert atmosphere** during processing (casting, hot working, welding, or powder metallurgy) or during the service.
  2. **Coating** with silicides or aluminates to protect up to 1650°C or (coating: high melting T, be compatible with the metal, provide diffusion barrier, and compatible thermal expansion coef.)

37

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TABLE 13-10 ■ ***Properties of some refractory metals***

			T = 1000°C		
Metal	Melting Temperature (°C)	Density (g/cm^3)	Tensile Strength (psi)	Yield Strength (psi)	Transition Temperature (°C)
Nb	2468	8.57	17,000	8,000	−140
Mo	2610	10.22	50,000	30,000	30
Ta	2996	16.6	27,000	24,000	−270
W	3410	19.25	66,000	15,000	300

38

Precious Metals

- Gold, silver, palladium, platinum, and rhodium.
- From an engineering viewpoint,
  - ✓ High corrosion and make
  - ✓ Very good conductors of electricity.

Titanium Alloys

Important

- Light weight with a density of 4.5 g/cm^3
- High specific strength, 2x of strengthened low alloy steel.
- Low elasticity modulus
- UTS above 1000MPa,
- Allotropic: hcp-α up to 882°C, bcc-β at above 882°C.
- Excellent corrosion resistance with a coherent TiO_2 layer on its surface; up to 535°C at which layer breaks and becomes unprotected to O, C, N, and H: So good high temperature characteristics up to 535°C.
- Relatively brittle due to its hcp structure.
- Expensive-difficulties of extraction form the ore, and following processing.
- Biocompatible (i.e., they are not rejected by the body). Implant/prosthesis material.

Applications:

- High strength aerospace material for airframe and jet engine components.
- Machinery parts, sporting goods, bicycle, eyeglass etc. frames.
- Chemical processing equipment,
- Marine components,
- Biomedical implants such as hip prostheses.
- Shape memory alloys: with 50% Ni

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Main Alloying elements

- Zr, Sn — Solid solution strengthening
- **Al**, O, H — α stabilizing elements
- **V**, Ta, Mo, Nb — β stabilizing elements
- Mo, Cr, Fe — Promoting α + β structure.

TABLE 13-9 ■ ***Properties of selected titanium alloys***

Material	Tensile Strength (psi)	Yield Strength (psi)	% Elongation
Commercially pure Ti:			
99.5% Ti	35,000	25,000	24
99.0% Ti	80,000	70,000	15
Alpha Ti alloys:			
5% Al-2.5% Sn	125,000	113,000	15
Beta Ti alloys:			
13% V-11% Cr-3% Al	187,000	176,000	5
Alpha-beta Ti alloys:			
6% Al-4% V	150,000	140,000	8

Heat treatment is possible

43

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Types of Titanium Alloys

Important

1. **Commercially pure titanium;**
   - ✓ Superior corrosion resistance.
   - ✓ Oxygen for solid solution strengthening.
   - ✓ Mech. properties quickly decreases at elevated T.
   - ✓ Applications:
     - ➢ Heat exchangers, pipes, reactor parts, pumps/valves for chemical and petrol-chemical industries (where resistance against corrosion is crucial)

44

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Important

2.Alpha (α) titanium alloys; (low stress applications)

- Solid solution strengthening of α
- Maintains mech properties at high T.
- Good weldability,
- Good ductility and formability even its hcp structure.
- ***Heat treatment***: Heating to β then
  - ✓If rapid cooling: fine acicular (needle like) α grains: good fatigue properties-low stress applications.
  - ✓If furnace cooling: plate like α grains: good creep properties-low stress applications.

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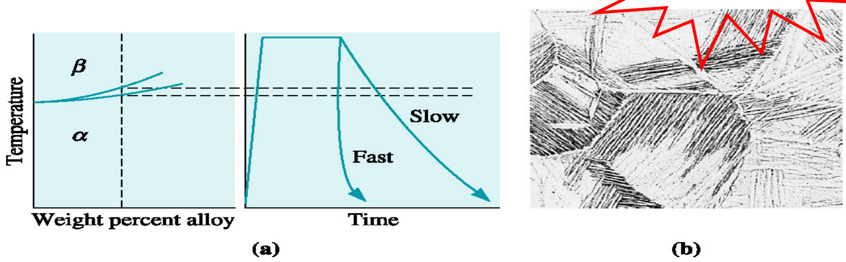
Important



(a) Annealing and (b) microstructure of rapidly cooled α Ti. Both the grain boundary precipitate and the Widmanstätten plates are α.

Important

3.Alpha + Beta (α+β) titanium alloys; (High strength applications)

- ✓V and Mo for entirely β structure,
- ✓In annealed condition, strength derived from solid solution.
- ✓Aged hardening for high strength applications
- ✓Applications:
  - ➢ Fasteners, beams and other fitting for aerospace applications.

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Important

- Annealing for high ductility, uniform properties and good strength.
- **Heat treatments**: Heat below to β transus
  1. If slow cooling — **Equiaxed α** grains. Near- β alloys.
     - ➢ Good ductility, and formability,
     - ➢ Difficulty in fatigue crack nucleation.
  2. If fast cooling — **Needle like α** phase. Near- α alloys.
     - ➢ Easy fatigue crack initiation
     - ➢ Slow fatigue crack growth
     - ➢ Good toughness
     - ➢ Good resistance to creep

4. Alpha + Beta (α+β) Titanium alloys;

- A mixture of α and β at room T.

3 different heat treatments can be applied to α-β Titanium alloys

1. Annealing for high ductility, uniform properties and good strength.
2. Controlling the cooling rate from just below β transus to obtain **Equiaxed α** or **Needle like α** grains
3. Tampered or aged structure can be obtained

- **Controlling the cooling rate: The alloy is first heated to just below the β transus;**

1. If slow cooling — **Equiaxed α** grains. Near- β alloys.
   - Good ductility, and formability,
   - Difficulty in fatigue crack nucleation.
2. If fast cooling — **Needle like α** phase. Near- α alloys.
   - Good toughness, and creep resistance,
   - Easy fatigue crack initiation,
   - Slow fatigue crack growth.

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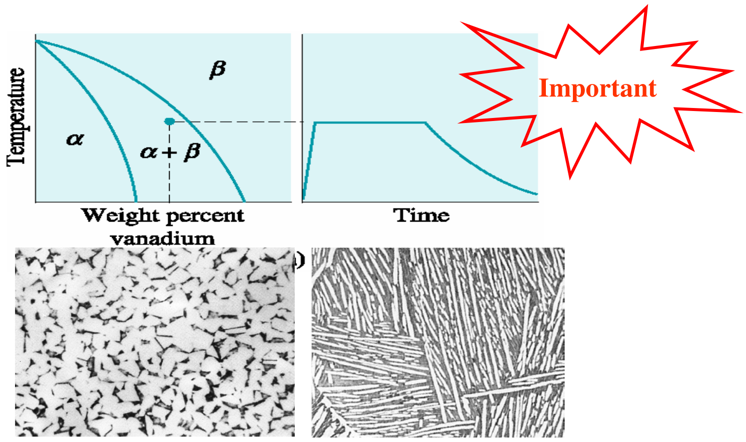

a) Annealing just below the *α–β* transformation temperature,
b) Slow cooling gives equiaxed *α* grains, and
c) Rapid cooling yields acicular *α* grains.

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3. Quenching

- Heat treatment for more alloyed α + β alloys.
- For **Low V (α rich) alloy**
  - ✓ Heat just below β transition temperature
  - ✓ Quench to form titanium martensite α'(titanium martensite).
  - ✓ Tempering, α_m' ⇨ α + β
- For **High V (β rich) alloy**
  - ✓ Heat just below β transition temperature
  - ✓ Quenching: β_{ss}' supersaturated solid solution.
  - ✓ Aging – β_{ss}' → α + β transformations
- Higher strength, fracture toughness.
- Applications: airframes, rockets, jet engines, landing gears.

Titanium martensite is very soft phase

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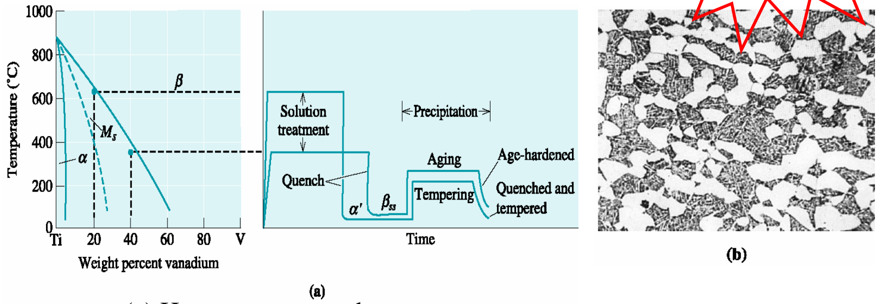
Important



(a) Heat treatment and

(b) Microstructure of the α-β Ti alloys.

(c) The structure contains primary *α* (large white grains) and a dark *β* matrix with needles of *α* formed during aging (250).

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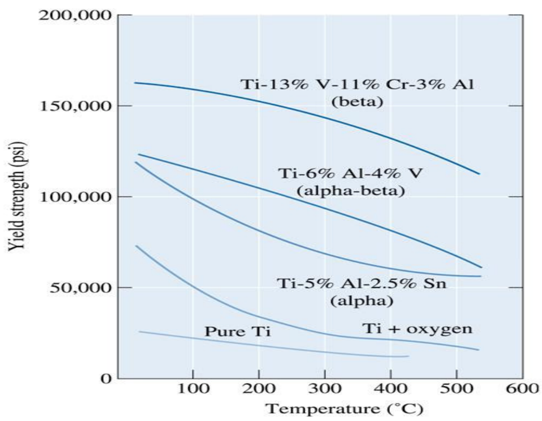

The effect of temperature on the yield strength of selected titanium alloys.

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Processing of Titanium Alloys

Important

Processing:

- ✓ Casting
- ✓ Forming
- ✓ Joining: welding

- Special care should be given when processing above 535°C
- Vacuum furnace or inert gas protection to minimize the contamination
- Superplasticity is possible in Ti6Al4V alloys: 1000% during the slow forming process under gas protection.
- Superplastic deformation + diffusion bonding for aircraft parts..

55

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Design a high-performance connecting rod for the engine of a racing automobile.

Important

Example 13.9 SOLUTION

To achieve high strengths, we might consider an alpha-beta titanium alloy. Because of its availability, the Ti-6% Al-4% V alloy is a good choice. The alloy is heated to about 1065°C, which is in the all-***β*** portion of the phase diagram.

When the heat treatment is performed in the all-***β*** region, the tempered martensite has an acicular structure, which reduces the rate of growth of any fatigue cracks that might develop.

56