HEAT TREATMENT

- **Heat Treatment**
  - Purpose
  - Principle
  - Stages
  - Types
- **Heat Treatment & Procedures**
  - Carbon Steel
  - Aluminium Alloy
  - Titanium Alloy
  - Magnesium Alloy
- **Case Hardening**
  - Types, Procedure
  - Stress Reliving Procedures
  - Protective Treatments

Heat Treatment Process

- **Heat treatment** is the **controlled heating and cooling** of metals for the purpose of **altering their properties.**
- The Properties of metals and alloys can be changed as desired by the **heat treatment process**
- Since heat treatment can **greatly alter** the **mechanical** and **physical properties** of metals and alloys, therefore its widely used in Manufacturing process

Purpose of Heat Treatment

- To **relieve internal stress** due to cold working, welding, casting, forging…etc
- To **improve Machinability**
- To **refine grain size**
- To **soften the metal**
- To **improve hardness** of the metal surface
- To **improve Mechanical properties** like tensile strength, ductility, etc.
- To **improve magnetic and electrical** properties
- To **increase resistance to wear** and **corrosion**
- To **improve toughness**
- To change the **chemical composition**

Definition

Heat treatment may be defined as an operation or combination of operations **involving heating and cooling** of metal/ alloys in **solid state to obtain desirable properties**

Principles of heat treatment

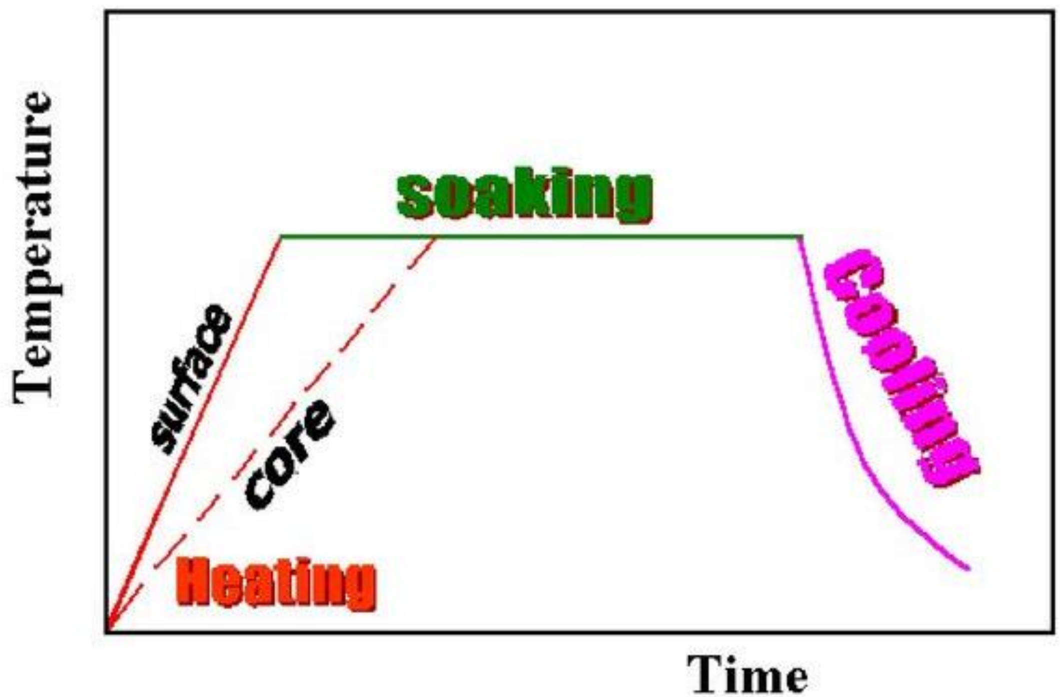
- The theory of heat treatment is based on the fact that a **change takes place in internal structure** of metal by **heating and cooling** which induce **desired properties** in it

- The **rate of cooling is the controlling factor** in developing **hard or soft structure**. **Rapid cooling** from the critical range results in **hard structure** whereas **very slow cooling** produces a **soft structure.**

- Factors
  - Method of heating and cooling
  - Rate of heating and cooling
  - Furnaces used
  - Quenching medium used

Stages of Heat treatment

- Heating
- Soaking
- Quenching



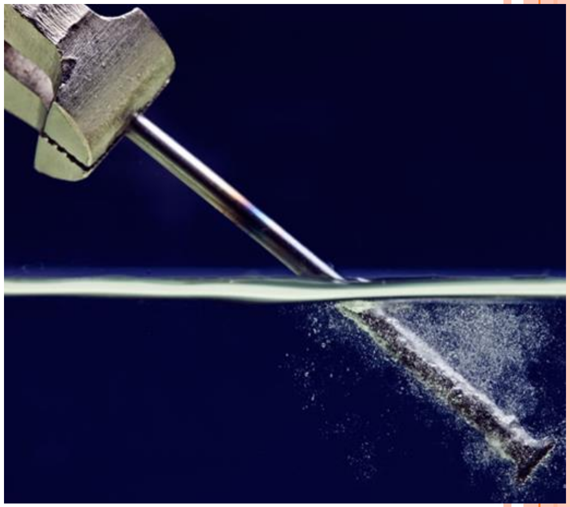
Heating

- **Heating the metal slowly to ensure a uniform temperature**
- The primary objective in the heating stage is to **maintain uniform temperatures.**
- If **uneven heating** occurs, one section of a part can **expand faster than another** and result in **distortion or cracking**. Slow heating attains uniform temperatures.
- **Heating rate** of a part depends on several factors. One important factor is the **heat conductivity of the metal**.
- A metal with a **high-heat conductivity** heats at a **faster rate** than one with a **low conductivity**. Also, the condition of the metal determines the rate at which it may be heated

SOAKING

- **Soaking (holding)** the metal at a **given temperature for a given tim**e and **cooling the metal to room temperature.**
- After the metal is heated to the proper temperature, it is **held at that temperature until the desired internal structural changes** take place. This process is called **SOAKING**.
- The **length of time held** at the proper temperature is called the **SOAKING PERIOD**.
- The soaking period depends on the chemical analysis of the metal and the mass of the part.

QUENCHING

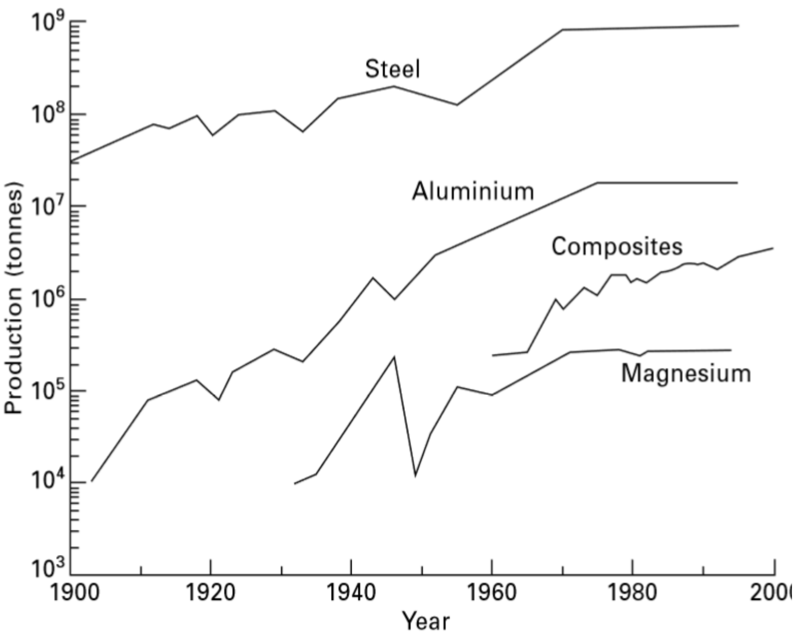


- **Cooling the metal to room temperature**
- After a **metal has been soaked**, it must **be returned to room temperature** to complete the heat treating process.
- To cool the metal, you can place it in **direct contact with a COOLING MEDIUM** composed of a **gas, liquid, solid, or combination** of these.
- The rate at which the metal is cooled depends on the metal and the properties desired.
- **Rate of cooling** depends on the **medium**; Therefore, the choice of a **cooling medium** has an important **influence on the desired properties**.

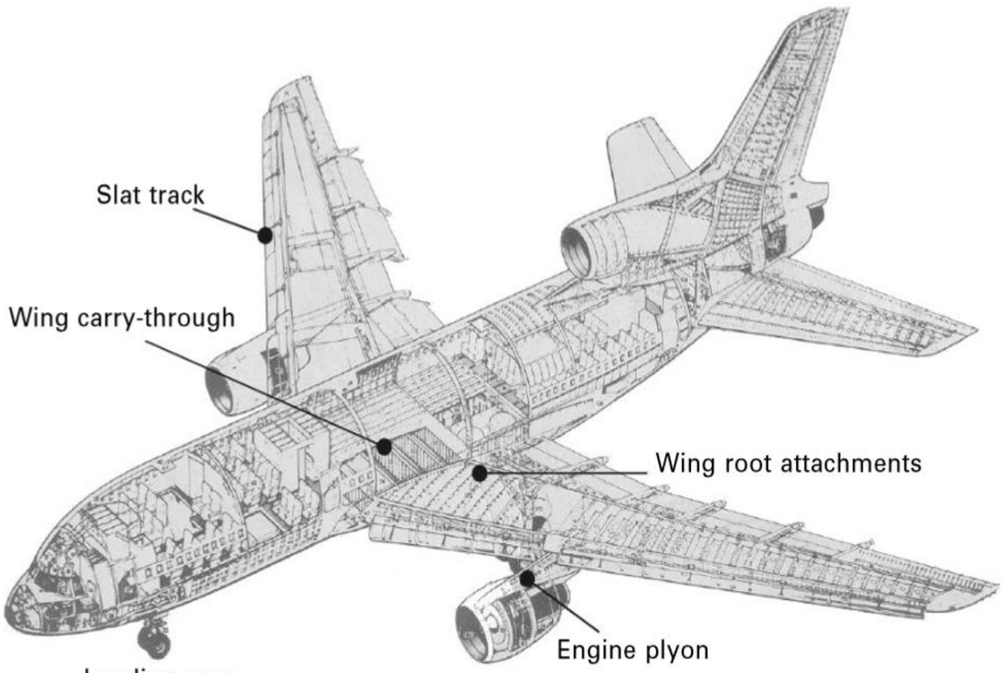
Steels for aircraft structures

- **Steel is an alloy of iron** containing **carbon** and **one (or) more** other alloying elements.
- The world-wide **consumption** of **steel is around 100 times** greater than **aluminium**, which is the second most used structural metal.
- Production of **steel, aluminium, magnesium and composites** over the course of the 20th century, and the **usage of steel amounts to more than 90%** of all metal consumed.
- Although steel is used extensively in many sectors, its **usage in aerospace is small in comparison to aluminium** and composite material.
- The use of **steel in aircraft and helicopters** is often limited to just **5–8% of the total airframe weight** (or 3–5% by volume).

STEELS FOR AIRCRAFT STRUCTURES



Production figures (approximate) for aluminium, magnesi
steel and composites.



- **Aircraft structural components are made using high-strength steel includes**
  - **Undercarriage landing gear**
  - **Wing-root attachments**
  - **Engine pylons**
  - **Slat track components**

Heat Treatment of Steel

Mild Steels (also called **Low-Carbon Steels**) contain **less than about 0.2% carbon** and are hardened mainly by **cold working**. Mild steels have **moderate yield strength (200–300 MPa)**. Therefore **too soft for aircraft structural applications**

High-Strength Low-Alloy (HSLA)

- Steels contain a **small amount of carbon (under 0.2%)** like mild steels, and also contain **small amounts of alloying elements**
  - (Like Copper, Nickel, Niobium, Vanadium, Chromium, Molybdenum and Zirconium).
- **HSLA steels** are referred to as **micro-alloyed steels** because they are **alloyed at low concentrations** compared with other types of steels.
- The **yield strength of HSLA steels** is **250–600 MPa** and they are used in automobiles, trucks and bridges amongst other applications.
- The use of HSLA steels in aircraft is rare because of **low specific strength and poor corrosion resistance**.

Medium-carbon steels

- It contain somewhere between **0.25 and 0.5% carbon** and are **hardened by thermo-mechanical treatment** processes to strengths of **300–1000 MPa.**
- This group of steels is used in the greatest quantities **for structural applications.**
- **Applications** includes motor cars, rail carriages, structural members of buildings and bridges, ships and offshore structures and, in small amounts, aircraft.

Medium-carbon low-alloy steels

- **Medium-carbon low-alloy steels** also contain somewhere **between 0.25 and 0.5% carbon** but have a **higher concentration of alloying elements** to **increase hardness and high-temperature strength**.
- Alloying elements includes nickel, chromium, molybdenum, vanadium and cobalt.
- At the higher alloy contents, these steels are used as **tool steels (e.g. tool bits, drills, blades and machine parts)** which require hardness and wear resistance at high temperature. Strength levels **up to 2000 MPa** can be achieved.
- These steels are used in aircraft, typically for undercarriage parts.

Maraging steels

- **Maraging steels** have a **high alloy content**, but with virtually no **carbon (less than 0.03%)**.
- Alloying together with heat treatment (which, unlike that for the other steels described above, **includes age-hardening**) **produces maraging steels** with the unusual **combination of high strength, ductility and fracture toughness**.
- The strength of maraging steels is within the range of **1500–2300 MPa,** which puts them amongst the **strongest metallic materials**.
- **Maraging steel** is used in heavily loaded aerospace components.

(per cent)		
0.05	Dead mild steel	Sheet and strip for presswork, car bodies, tin-plate; wire, rod, and tubing
0.08-0.15	Mild steel	Sheet and strip for presswork; wire and rod for nails, screws, concrete reinforcement bar
0.15	Mild steel	Case carburising quality
0.1-0.3	Mild steel	Steel plate and sections, for structural work
0.25-0.4	Medium carbon steel	Bright drawn bar
0.3-0.45	Medium carbon steel	Shafts and high-tensile tubing
0.4-0.5	Medium carbon steel	Shafts, gears, railway tyres
0.55-0.65	High carbon steel	Forging dies, railway rails, springs
0.65-0.75	High carbon steel	Hammers, saws, cylinder linings
0.75-0.85	High carbon steel	Cold chisels, forging die blocks
0.85-0.95	High carbon steel	Punches, shear blades, high-tensile wire
0.95-1.1	High carbon steel	Knives, axes, picks, screwing dies and taps, milling cutters
1.1-1.4	High carbon steel	Ball bearings, drills, wood-cutting and metal-cutting tools, razors

Heat-Treatment

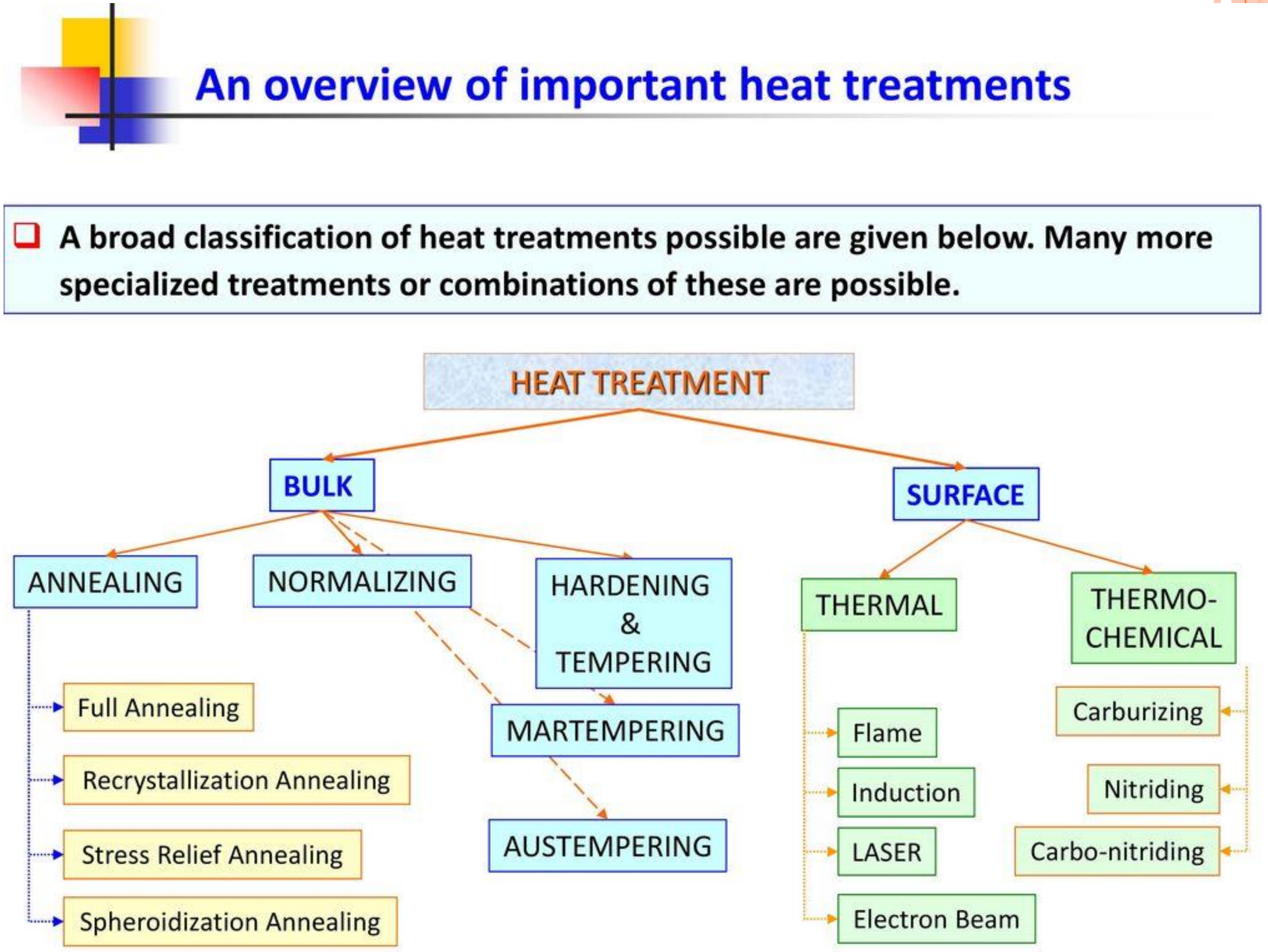
- **Heat treatment** is a process in which **metal/alloy is heated beyond the critical temperature and cooled at controlled rates** to get **different microstructures** and hence **desired mechanical properties**.
- It involves the **use of heating or chilling**, normally to extreme temperatures.
- To achieve a desired result such as **hardening** **or** **softening** **of a material**.
- It applies only to processes where the **heating and cooling are done for the specific purpose** of altering properties intentionally.

Stages of heat treatment process

- **Stage 1:** Heating a metal/alloy **beyond the critical** temperature.
- **Stage 2:** Holding at that temperature for **sufficient period of time** to allow necessary changes to occur.
- **Stage 3:** Cooling metal/alloy **(quenching)** at a rate necessary to obtain the **desired properties**.

Types of Heat treatment

- **Annealing**
- **Normalizing**
- **Hardening**
- **Tempering**



ANNEALING

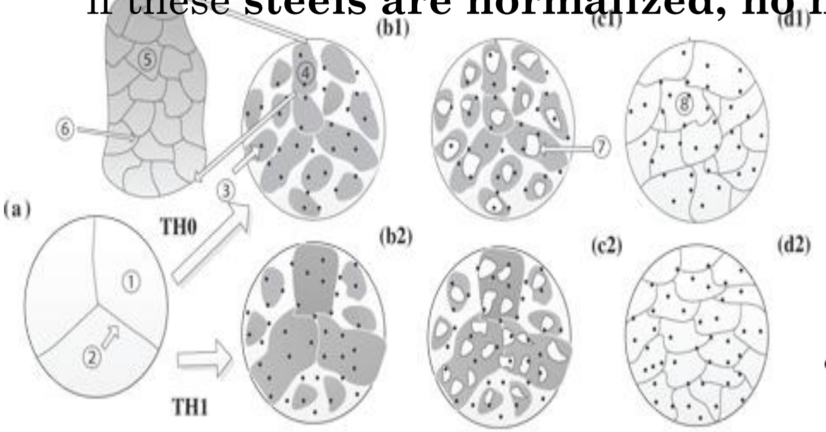
- **Process of heating** solid metal to **high temperatures and cooling it slowly** so that its **particles arrange into a defined lattice.**
- **Annealing** is performed **to reduce hardness, remove residual stresses, improve toughness, restore ductility,** and to alter various mechanical, electrical or magnetic properties of material trough refinement of grains.
- **Cooling rate is very slow** around **10˚C per hour**. Process is carried out in a **controlled atmosphere of inert gas to avoid oxidation.**

CAUSES OF RESIDUAL STRESSES

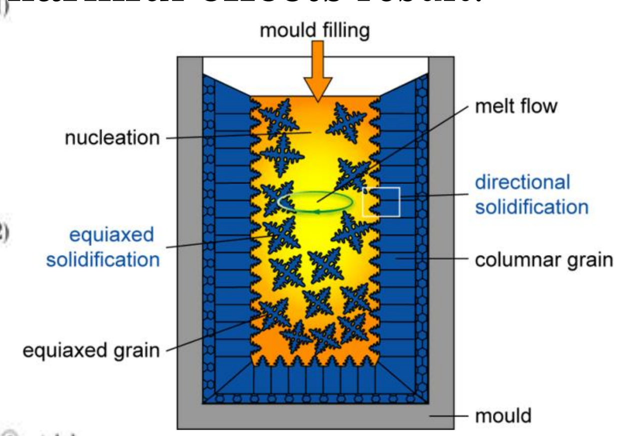
- **Thermal factors** (e.g., thermal stresses caused by temperature gradients within the workpiece during heating or cooling).
- **Mechanical factors** (e.g., cold-working).
- **Metallurgical factors** (e.g., transformation of the microstructure).

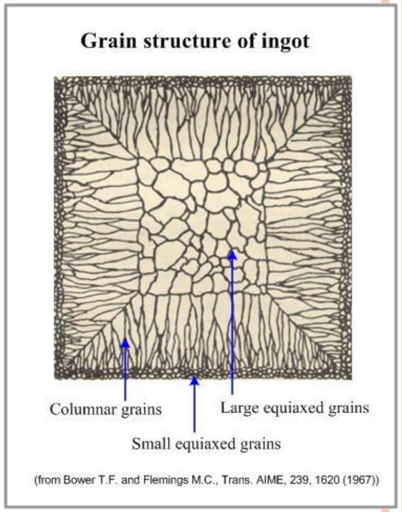
NORMALIZING

- **Normalizing** is a **type of heat treatment** applicable to **ferrous metals only.** It differs from annealing in that the metal is heated to a **higher temperature and then removed from the furnace** for **air cooling**.
  - Gives a uniform fine-grained structure and to avoid excess softening in steel.
  - The **purpose of normalizing** is **to remove the internal stresses induced by heat-treating, welding, casting, forging, forming, or machining.**
- Heating the steel just above its upper critical point **creates austenitic grains (much smaller than the previous ferritic grains),** which during cooling, form **new ferritic grains with a further refined grain** size.
- The process produces a **tougher, more ductile material**, and **eliminates columnar grains and dendritic segregation** that sometimes occurs during casting.
- Before hardening steel, you should **normalize it first to ensure the maximum desired results**. Usually, **low-carbon steels do not require normalizing**; however, if these **steels are normalized, no harmful effects** result.



① = austenite, ② = prior austenite boundary, ③ = precipitates, ④ = ferrite, ⑤ = ferrite grain, ⑥ = triple junction, ⑦ = new austenite nucleation, ⑧ = austenite after double phase transformation



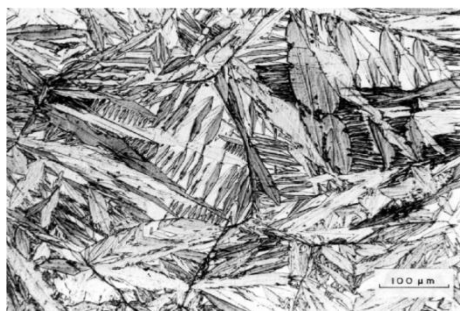


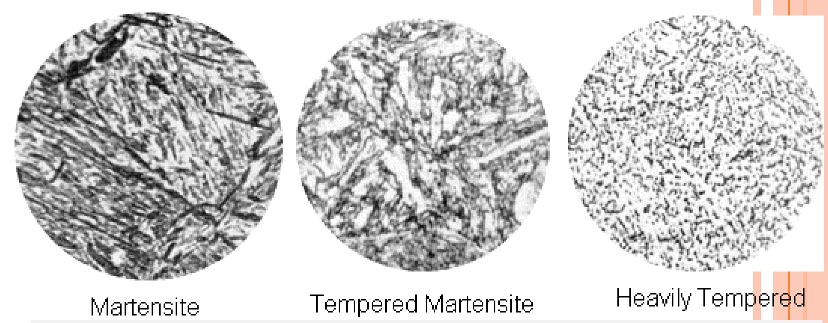
Hardening

- When a **piece of steel**, containing **sufficient carbon,** is **cooled rapidly (**from above its upper critical temperature) it becomes **considerably harder** than it would be if allowed to cool slowly.
- The degree of hardness produced can vary.
- It is dependent upon such factors as :
  - initial quenching temperature
  - size of the work
  - constitution
  - Properties
  - temperature of the quenching medium
  - degree of agitation
  - final temperature of the quenching medium.

- **Water quenching of a steel** containing sufficient carbon produces an **extremely hard structure** called **martensite,** which appears under the microscope as a **mass of uniform needle-shaped crystals**
- The **quenching medium is chosen** according to the rate at which it is desired to cool the steel.
- The following list of media is arranged in order of quenching speeds:

➢ 5% Caustic soda
➢ 5-20% Brine
➢ Cold water
➢ Warm water
➢ Mineral oil
➢ Animal oil
➢ Vegetable oil





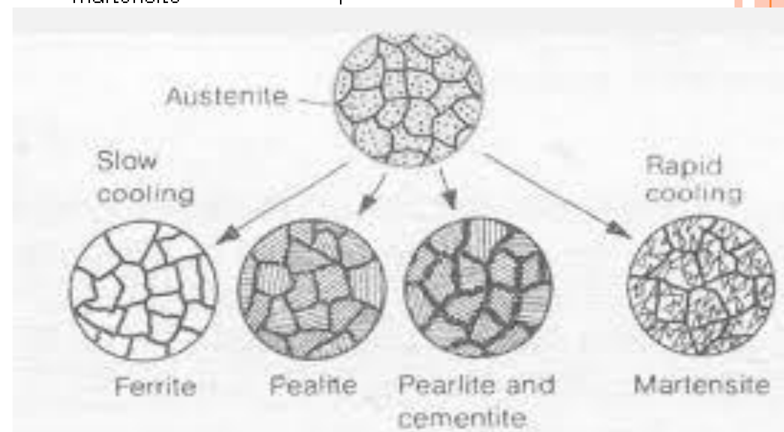


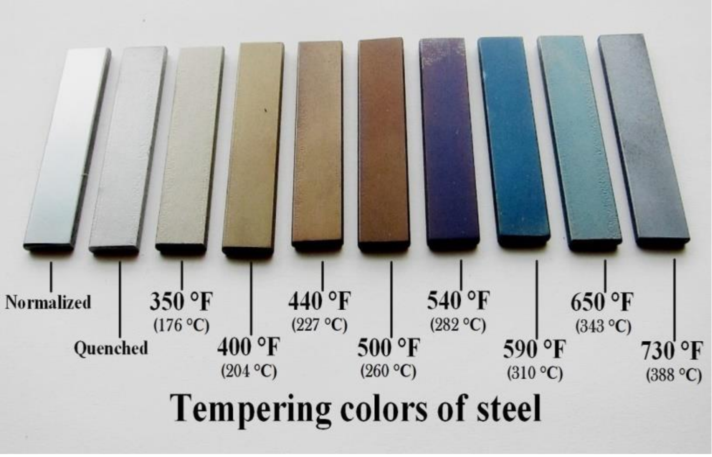
Fig. 3.637 Retransformation of the austenite structure.

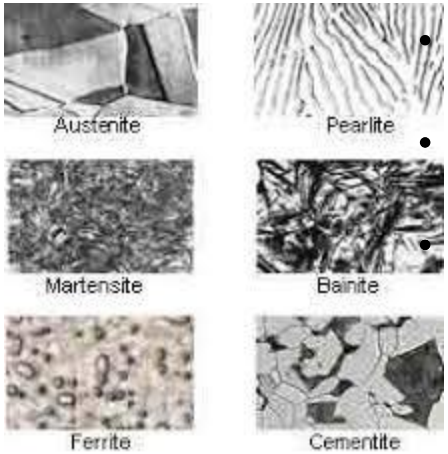
To harden a piece of steel, then, it must be **heated to between 30 and 50˚C above its upper critical temperature** and then **quenched in some medium** which will produce in it the **desired rate of cooling**.

Tempering

- A fully **hardened carbon tool steel is relatively brittle**, and the **presence of stresses set up by quenching** make its use, in this condition, in advisable except in cases where extreme hardness is required.
- Hence it is customary to **re-heat—or 'temper'** the quenched component so that **internal stresses will be relieved and brittleness reduced**.
- **Medium-carbon** constructional steels are also tempered but here the **temperatures are somewhat higher** so that **strength and hardness are sacrificed** to some extent in **favour of greater toughness and ductility**.

- **During tempering**, which is always carried out ***below the lower* critical temperature**, **martensite tends to transform to the equilibrium structure** of **ferrite and cementite**.
- The **higher the tempering temperature** the more closely will the **original martensitic structure revert to this ferrite cementite mixture** and so strength and hardness fall progressively.



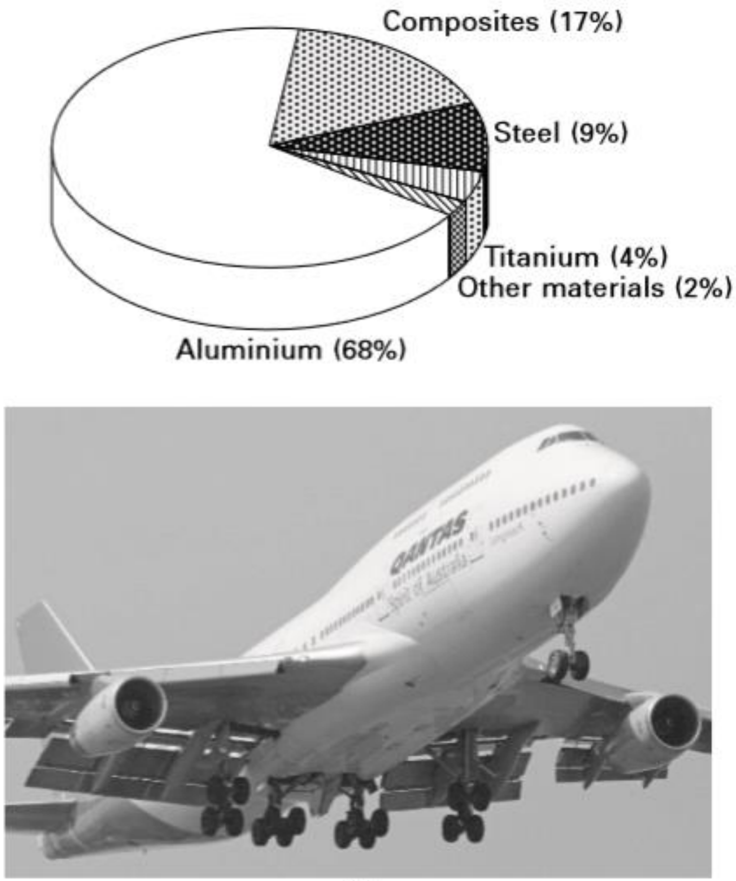


- The first one, on the left, is **normalized** steel.
- The second is **quenched, untempered martensite.**
- The remaining pieces have been tempered in an oven to their corresponding temperature, for an hour each.

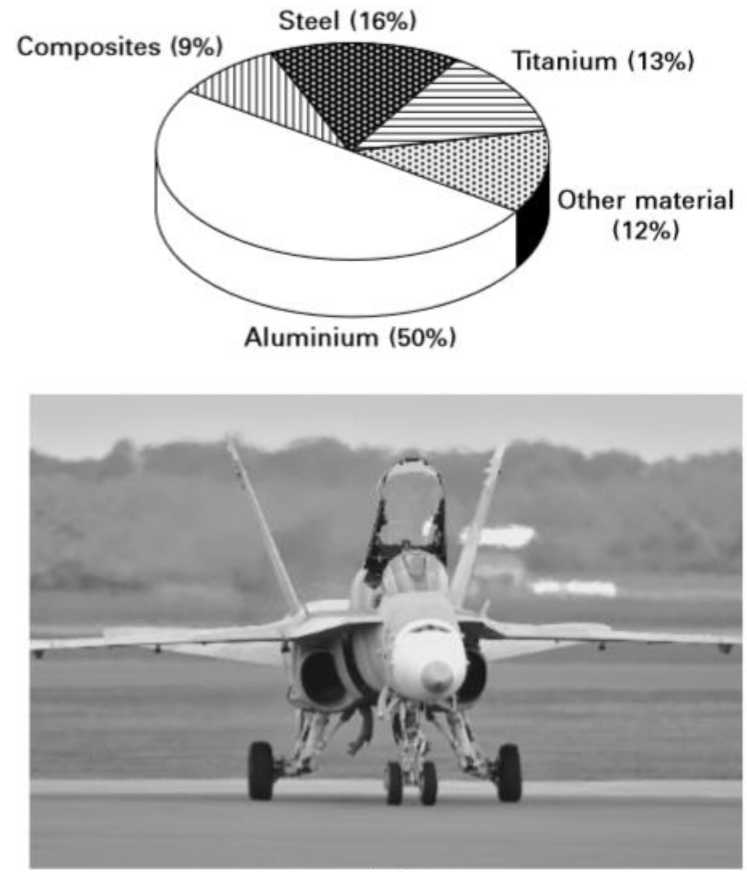
- http://ecoursesonline.iasri.res.in/mod/page/view.php?id=3804

Aluminium alloys for aircraft structures

- **Aluminium** has been an **important aerospace structural material** in the **development of weight-efficient airframes** for aircraft **since the 1930s**.
  - The development of aircraft capable of flying at **high speeds and high altitudes** would have been difficult **without the use of high-strength aluminium alloys** in major airframe components such as the **fuselage and wings.**
- Aluminium accounts for **60–80% of the airframe weight** of most **modern aircraft, helicopters and space vehicles**.
- **Aluminium** is likely to remain an **important structural material** despite the growing use of composites in large passenger airliners such as the **Airbus 380 and 350XWB and the Boeing 787**.
  - Many types of airliners continue to be constructed mostly of aluminium, including aircraft built in large numbers such as the **Boeing 737, 747 and 757 and the Airbus A320 and A340.**
- Competition between **aluminium and composite as the dominant structural material** is likely to intensify over the coming years, **although aluminium remains central to weight-efficient airframe** construction.

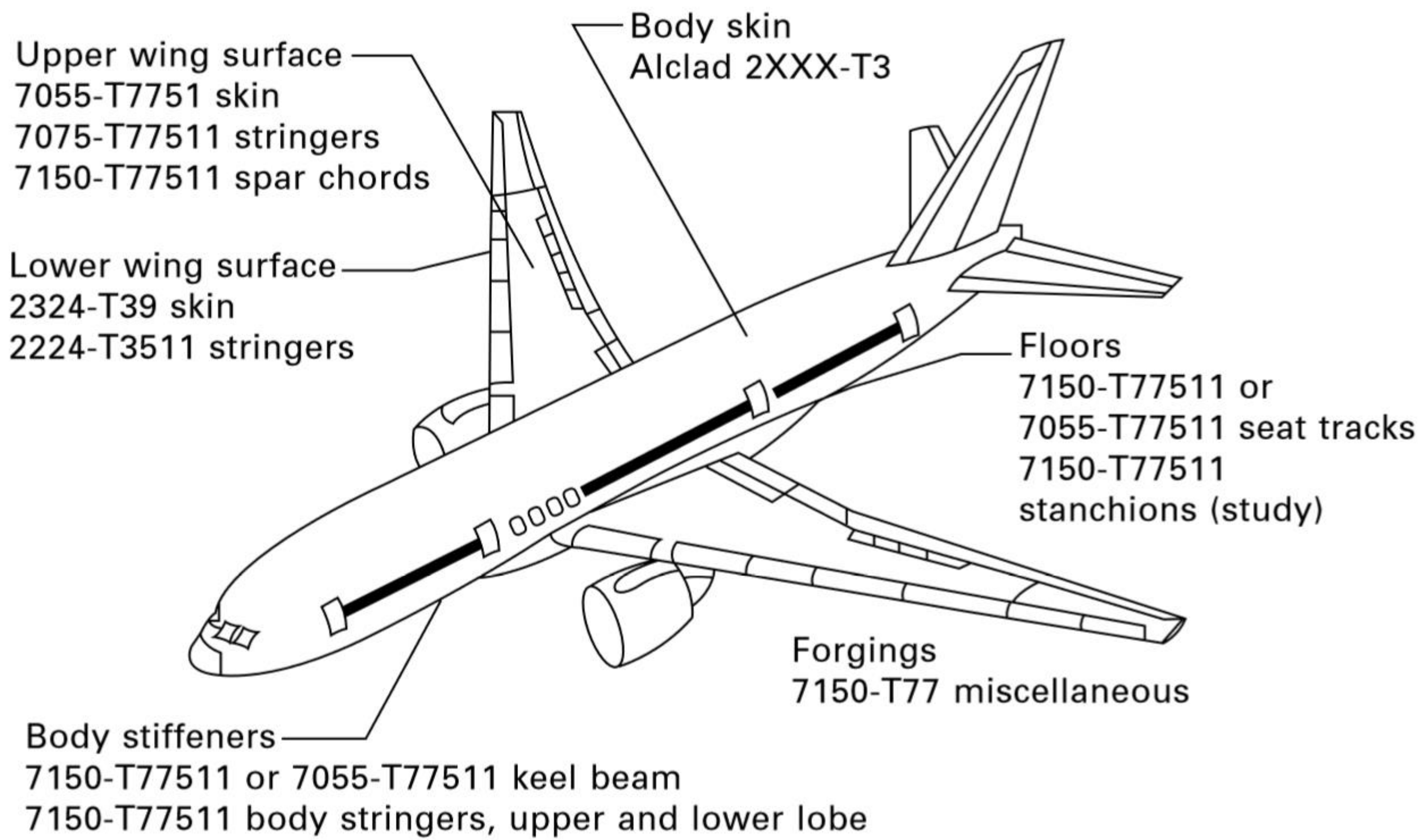


(a)



(b)

Use of aluminium alloys and other structural materials in (a) the Boeing 747 and (b) Hornet F/A-18.



New aluminium alloys and tempers used on the Boeing 777

Aluminium is a popular aerospace structural material for many important reasons, including:

- Moderate cost
- Ease of fabrication, including casting, forging and heat-treatment
- Light weight (density of only 2.7 g/cm^3)
- High specific stiffness and specific strength
- Ductility, fracture toughness and fatigue resistance;
- Good control of properties by mechanical and thermal treatments

As with any other aerospace material, there are several disadvantages of using aluminium alloys in aircraft structures including:

- Low mechanical properties at elevated temperature (softening occurs above ~150 °C)
- Susceptibility to stress corrosion cracking
- Corrosion when in contact with carbon-fibre composites
- Age-hardenable alloys cannot be easily welded

Aluminium alloy types

Casting and wrought alloys

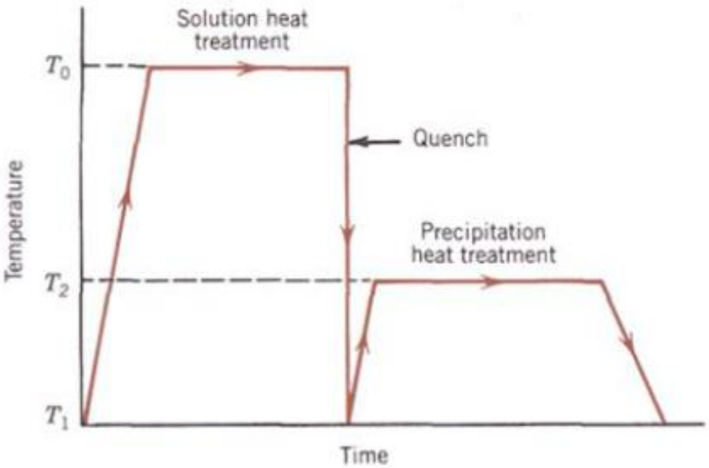
- Aluminium alloys are classified as **casting alloys, wrought non-heat-treatable alloys or wrought heat-treatable alloys**.
- Casting alloys are used in their **cast condition without any mechanical or heat treatment** after being cast.
- The mechanical properties of casting alloys are generally **inferior to wrought alloys**, and are not used in aircraft structures.
- Casting alloys are sometimes used in **small, non-load-bearing components on aircraft**, such as parts for control systems.
- Nearly all the aluminium used in **aircraft structures** is in the form of **wrought heat-treatable alloys**.
- The strength properties of wrought alloys can be **improved by plastic forming** (e.g. extrusion, drawing, rolling) and heat treatment.

- Heat treatment, refers to **heating and cooling operation** which alters
  - the metallurgical structure (e.g. crystal structure, grain size, dislocation density, precipitates)
  - Mechanical properties (e.g. yield strength, fatigue resistance, fracture toughness)
  - Environmental durability (e.g. corrosion resistance, oxidation resistance) or the internal residual stress state.
- When '**heat treatment**' is applied to **wrought aluminium alloys** it usually implies that heating and cooling operations are used **to increase the strength** via the process called **age hardening** or **(precipitation hardening)**.
- There are **two major groups** of wrought aluminium alloys:
  - Non-Age hardenable and Age-hardenable alloys.
- The distinguishing characteristic of **non-age-hardenable alloys** is that when heat treated they **cannot be strengthened by precipitation hardening**.

- **Non-Age-hardenable** alloys derive their strength from solution solid strengthening, work hardening and refinement of the grain structure.
- The **yield strength** of most non-age-hardenable alloys is **below about 300 MPa**, which is inadequate for aircraft structures.
- **Age-hardenable** alloys achieve high strength from the combined strengthening mechanisms of solid solution hardening, strain hardening, grain size control and, most importantly, precipitation hardening.
- The **yield strength** of Age-hardenable alloys is typically in the range of **450 to 600 MPa**.
- The combination of low cost, light weight, ductility, high strength and toughness makes **age-hardenable alloys suitable** for use in a wide variety of **structural and semi structural parts** on aircraft.

HEAT TREATMENT OF ALUMINIUM

- **Solution Heat Treating** involves heating the material to a temperature that puts all the **elements in solid solution** and then **cooling very rapidly to freeze the atoms** in place.
  - Heat
  - Soak
  - Quench



- **Aging or Precipitation Hardening**
  - **Aging** is a relatively **low-temperature heat treatment** process that **strengthens a material** by causing the precipitation of components or phases of alloy from a **super-saturated solid solution condition**.
  - **Precipitation Heat Treatment** is the three step process of solution treating, quenching, and age hardening to increase the **strength or hardness** of an alloy.

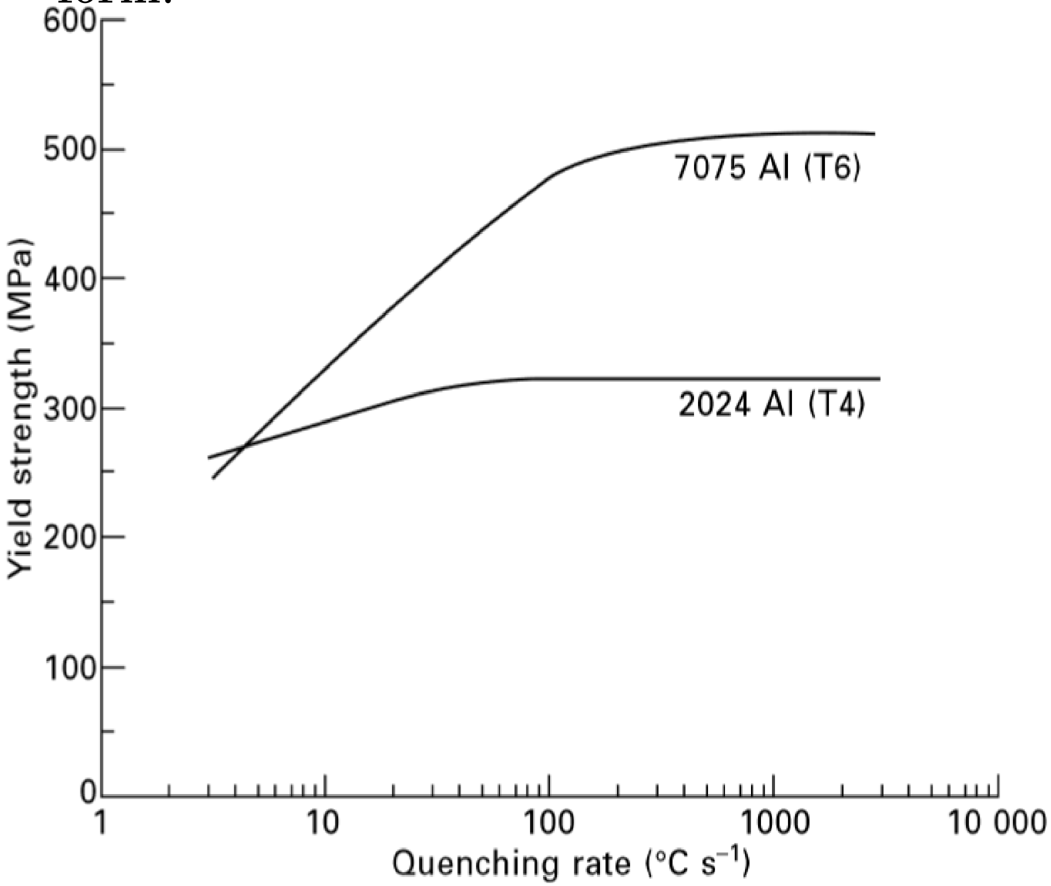
Solution treatment of aluminium

- Solution treatment is the **first stage** in the heat-treatment process, and is performed **to dissolve any large precipitates** present in the **metal after casting**.
- These precipitates can **seriously reduce the strength, fracture toughness and fatigue life** of aluminium, and therefore it is essential they are removed before the **metal is processed into an aircraft structure**.
- The precipitates are formed during the casting process. As the metal cools inside the casting mould, the **alloying elements react with the aluminium to form intermetallic precipitates**.
- The **purpose** of the solution treatment process **is to dissolve the large precipitates**, and thereby **minimise the risk of fracture**.
- The solution treatment process involves heating the aluminium to a sufficiently **high temperature to dissolve the precipitates** without melting the metal.

- The **rate at which the precipitates dissolve** and the **solubility** of **the alloying elements** in solid aluminium both increase with temperature, and therefore it is desirable to solution treat the metal at the highest possible temperature that does not cause melting.
- The solution treatment temperature is determined by the **alloy composition, and allowances** are made for unintended temperature variations of the furnace.
- Control of the temperature during solution treatment is essential to ensure good mechanical properties.
- When the **temperature is too low, the precipitates do not completely dissolve**, and this may cause a loss in ductility and toughness.
- When the **temperature is too high**, **local (or eutectic) melting can occur** that also lowers ductility and other mechanical properties.
- The treatment temperature for most aluminium alloys is within the **range of 450–600 °C**.

- The **alloy is held at the treatment** temperature for a sufficient period, known as the ‘**soak time**’, to **completely dissolve the precipitates** and allow the alloying elements to **disperse evenly through the aluminium matrix**.
- The **soak time may vary** from a few minutes to one day, depending on the **size and chemical composition** of the part.
- After the alloy has been solution treated it is ready to be quenched.
- Quenching is performed by **immersing the hot aluminium in cold water** or spraying the metal with water, and this cools thin sections in less than a few seconds.
- However, with aluminium **components with a complex shape** it is often necessary to **quench at a slower rate to avoid distortion** and **internal (residual) stress**.
- **Slow quenching** is done using **hot water or some other fluid** (e.g. oil, brine).
- However, when **slow cooling rates are used some precipitation can occur**, and this reduces the ability to strengthen the alloy by thermal ageing.

- Ideally, the aluminium alloy should be in **a supersaturated solid solution condition with the alloying elements** uniformly spread through the aluminium matrix after quenching.
- After quenching, the **aluminium is soft and ductile**, and this is the best condition to **press, draw and shape the metal into the final product** form.



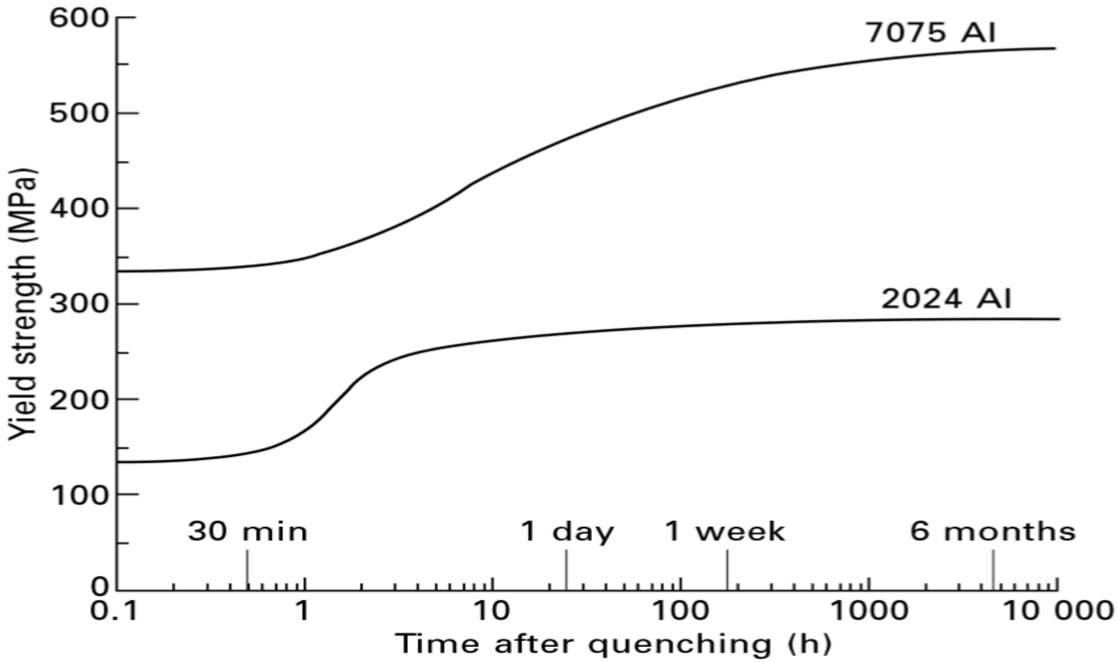
Effect of average quenching rate on the final yield strength of aerospace alloys 2024 Al and 7075 Al.

Thermal ageing of aluminium

- **Ageing** is the process that **transforms the supersaturated solid solution to precipitate particles** that can greatly enhance the **strength properties**.
- It is the **formation of precipitates** that provide aluminium alloys with the mechanical properties required for aerospace structures.
- Ageing can occur at **room temperature**, which is known as **natural ageing**, or at **elevated temperature**, which is called **artificial ageing.**
- **Natural ageing** is a slow process in most types of **age-hardenable alloys**, and the effects of the ageing process may only become significant after many months or years.
  - Natural ageing can occur, albeit very slowly, at temperatures **as low as –20 °C.**
  - For this reason, it is sometimes **necessary to chill aluminium below this temperature** immediately after quenching **to suppress or delay the ageing process.**

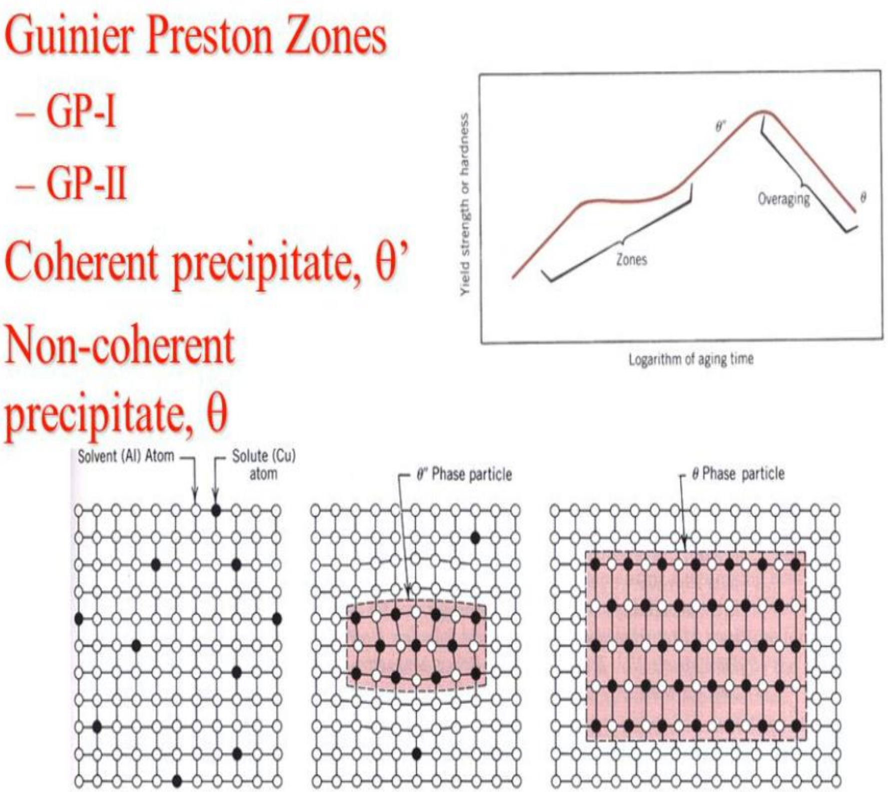
NATURAL AGEING

- It is sometimes **necessary to postpone ageing** when manufacturing aircraft components and, therefore, the metal must be **refrigerated immediately after quenching**.
- For example, it is common practice to **refrigerate 2024 Al rivets** until they are ready to be driven into **aircraft panels to maintain their softness** which allows them to **deform more easily in the rivet hole**.
- More often, however, the **alloy is artificially aged immediately** or shortly after quenching.



Artificial ageing

- The **artificial ageing process** is performed at one or more elevated temperatures, which are usually in the **range of 150 to 200 °C**.
- The **alloy is heated** for times between **several minutes to many hours**, depending on the **part size and the desired amount** of **hardening**.
- During ageing, the alloy undergoes a **series of chemical and microstructural transformations** that have a profound impact on the mechanical and corrosion properties.



The **order of occurrence** of the transformations is:

- Supersaturated solid solution (a_{ss})
- Solute atom clusters ((Guinier Preston) GP1 and GP2 zones)
- Intermediate (coherent) precipitates
- Equilibrium (incoherent) precipitates.

Magnesium alloys

- Magnesium alloys are classified as **wrought or casting alloys**. **Wrought alloys** account for only a **small percentage (under 15%)** of the total consumption of magnesium, and these alloys are **not used in aircraft**.
  - **A problem** with wrought alloys is their **low yield strength** (typically less than 170 MPa).
- Most magnesium alloys that are used commercially, including those in **aircraft and helicopters, are casting alloys**.
- The **casting alloys** are often used in the **tempered condition**; that is **heat-treated and work hardened**, under conditions similar to the **tempering of aluminium alloys**.
- There are **two broad classes of magnesium alloys** that are strengthened by **cold working or solid solution hardening** combined with precipitation hardening.

Magnesium alloys

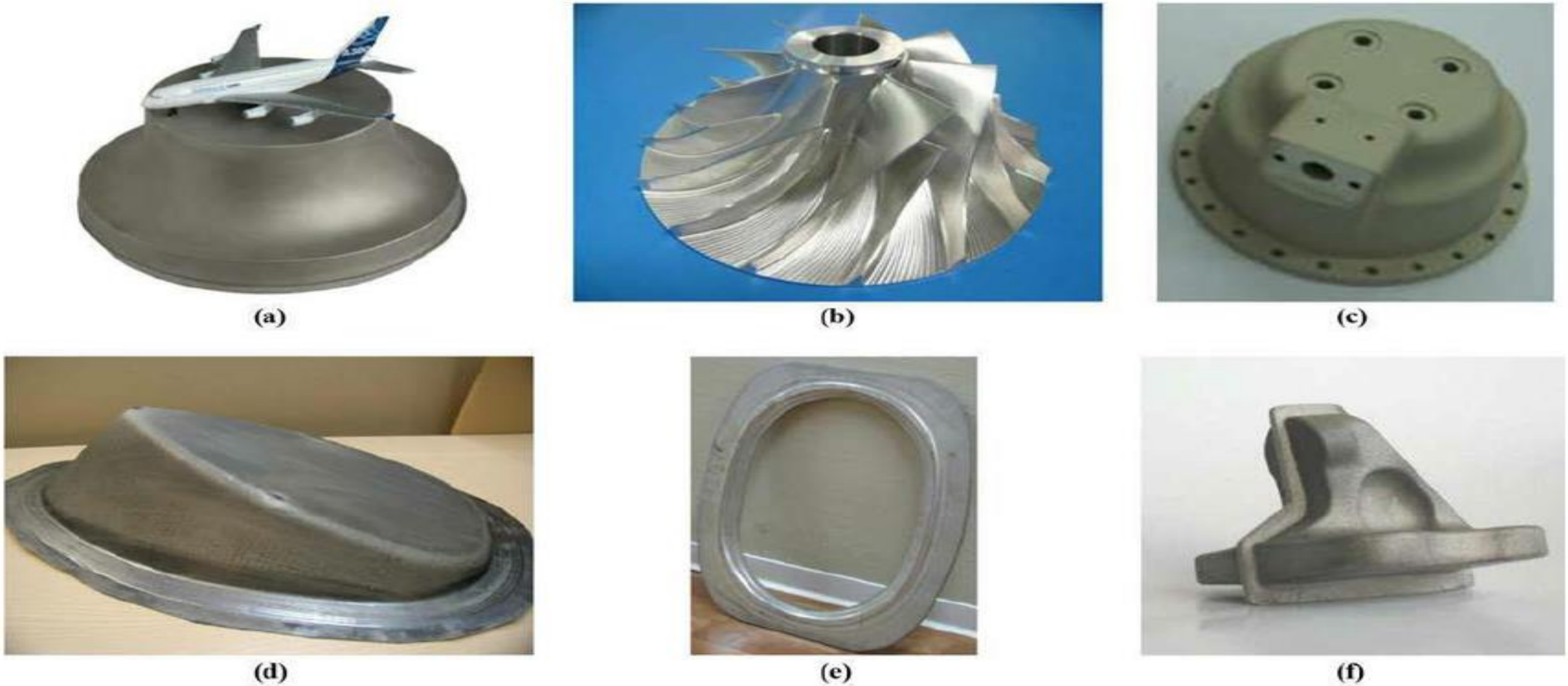
- **Till 1970s Magnesium** was extensively used in **structural components of aircraft, helicopters and spacecraft** because of its light weight.
  - **Magnesium** was used extensively in **airframes, aviation instruments and low-temperature engine** components for aircraft, especially fighters and military helicopters, and **semi-structural parts** for spacecraft and missiles.
- However, the use of magnesium has **declined owing to high cost, poor corrosion resistance** and other factors, and it is now rarely used in aircraft, spacecraft and missiles.
- The use of **magnesium alloys** is now largely confined to engine parts, and common applications are **gearboxes and gearbox housings for aircraft** and the **main transmission housing** for helicopters.
  - Magnesium has **good damping capacity** and therefore is often the material of choice in **harsh vibration environments**, such as **helicopter gearboxes**.

- As mentioned, it is difficult to **greatly increase the strength of magnesium by cold working** owing to the **hcp crystal structure**, and therefore the majority of magnesium alloys used in aerospace applications are strengthened by the **combination of solid solution and precipitation hardening**.

- The **strength properties** of magnesium are **improved by a large number of different alloying elements**, and the main ones are aluminium and zinc.

- A typical **heat-treatment cycle** involves **solution treating at about 440 °C**, quenching, and then **thermally ageing at 180–200 °C** for 16–20 h.

- These heat-treatment conditions are similar to those used to **strengthen age-hardenable aluminium alloys**.
- However, the response of magnesium to precipitation hardening is much **less effective than aluminium**.



Notes: (a) AZ80 compressor wheel produced by closed-die forging; (b) WE43 impeller with twisted blades; (c) WE43 compressor upper case for air conditioning system produced by closed-die forging; (d) AZ31B eurocopter antenna support produced by deep drawing; (e) AZ80-forged airbus window frame; (f) AZ80-forged door stop fitting

Helicopter gearbox casing made of magnesium alloy.

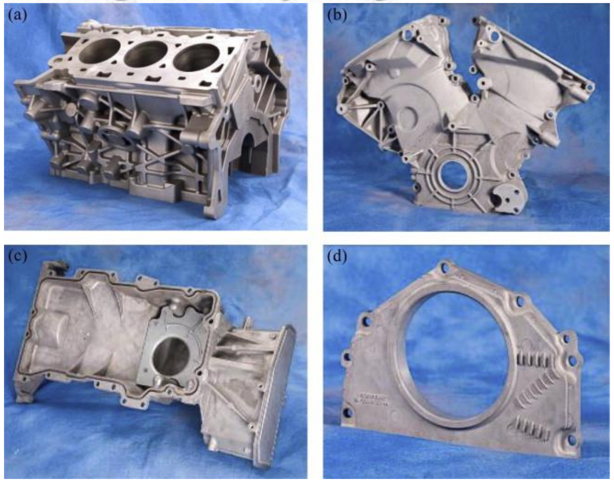


Table 10.1 ASTM lettering system for magnesium alloys

A: Aluminium	B: Bismuth	C: Copper	D: Cadmium
E: Rare earths	F: Iron	H: Thorium	K: Zirconium
L: Lithium	M: Manganese	N: Nickel	P: Lead
Q: Silver	R: Chromium	S: Silicon	T: Tin
W: Yttrium	Z: Zinc		

Table 10.2 Composition and properties of pure magnesium and its alloys used in aircraft and helicopters

Alloy	Composition	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)
Pure Mg (annealed)	>99.9% Mg	90	160	15
Pure Mg (cold-worked)	>99.9% Mg	115	180	10
WE43 (T6)	Mg–5.1Y–3.25Nb–0.5Zr	200	285	4
ZE41 (T5)	Mg–4.2Zn–1.3E–0.7Zr	135	180	2
QE21 (T6)	Mg–2.5Ag–1Th–1Nb–0.7Zr	185	240	2
AZ63 (T6)	Mg–6Al–3Zn–0.3Mn	110	230	3
AK61 (T6)	Mg–6Zn–0.7Zr	175	275	5

Table 10.3 Aerospace applications for magnesium alloys

Alloy	Application
RZ5	Helicopter transmission; aircraft gearbox casings; aircraft generator housing (e.g. A320, *Tornado*, *Concorde*)
WE43	Helicopter transmission (e.g. *Eurocopter* EC120, NH90; *Sikorsky* S92)
ZE41	Helicopter transmission
QE21	Aircraft gearbox casing; auxiliary gearbox (e.g. F-16, *Eurofighter*, *Tornado*)
ZW3	Aircraft wheels; helicopter gearbox (e.g. Westland *Sea King*)

Titanium alloys for aerospace structures and engines

- **Titanium alloys** are used in **airframe structures, landing gear components and jet engine parts** for their unique combination of properties:
  - **Moderate density, high strength & fracture toughness, long fatigue life, creep strength, and excellent resistance** to **corrosion and oxidation.**
- Titanium alloys also have **good mechanical performance at high temperature (up to 500–600 °C)**, which is well above the operating temperature limit of lightweight aerospace materials such as aluminium alloys, magnesium alloys and fibre–polymer composites.
- The earliest use of titanium was in **compressor discs and fan blades for gas turbine engines**, which require **excellent creep resistance** at high operating temperature.

- The **use of titanium** was significant in the early development of **jet engines**, which were originally built using **heat-resistant steels and nickel alloys**.
- Both **steels and nickel alloys are 'heavy materials'**, and their replacement with titanium in **discs and blades** reduced the weight of early jet engines by **more than 200 kg**.
    - Titanium is also used in the **engine frames, casings, manifolds, ducts and tubes.**
- It is **not possible to use titanium** in all parts of the engine, and it is unsuitable within the **combustion chamber** and other sections **where the temperature exceeds 600 °C**.
- Above this temperature, **titanium rapidly softens, creeps and oxidises,** and more heat-resistant materials such as nickel alloys are required.
- Titanium is used in a wide variety of structures on commercial aircraft, including **wing boxes, wings and undercarriage** parts.

- **Titanium** is also used in **helicopters** for the **main rotor hub**, **tail rotor hub, pivots, clamps, and blade tips** which require high strength and fracture toughness.
- Titanium alloys are also used in **solid-fuel & liquid-fuel engines, high-pressure gas and fuel storage tanks** and, in some cases, the skin of rockets.
- **Aerospace is the single largest market** for titanium products; with the industry consuming about **80% of the global production** of the metal.
- The **aerospace applications of titanium** in the USA are approximately:
  - jet engines for commercial aircraft: 37%;
  - jet engines for military aircraft: 24%;
  - airframes for commercial aircraft: 18%;
  - airframes for military aircraft: 12%;
  - rockets and spacecraft: 8%;
  - helicopters and armaments: 1%.

Heat treatment of Ti & Ti - alloys

Titanium and titanium alloys are heat treated in order to:

- Reduce residual stresses developed during fabrication **(stress relieving)**
- Produce an optimum combination of ductility, machinability, and dimensional & structural stability **(annealing)**
- Increase strength **(solution treating and aging)**
- Optimize properties such as fracture toughness, fatigue strength, and high-temperature creep strength.

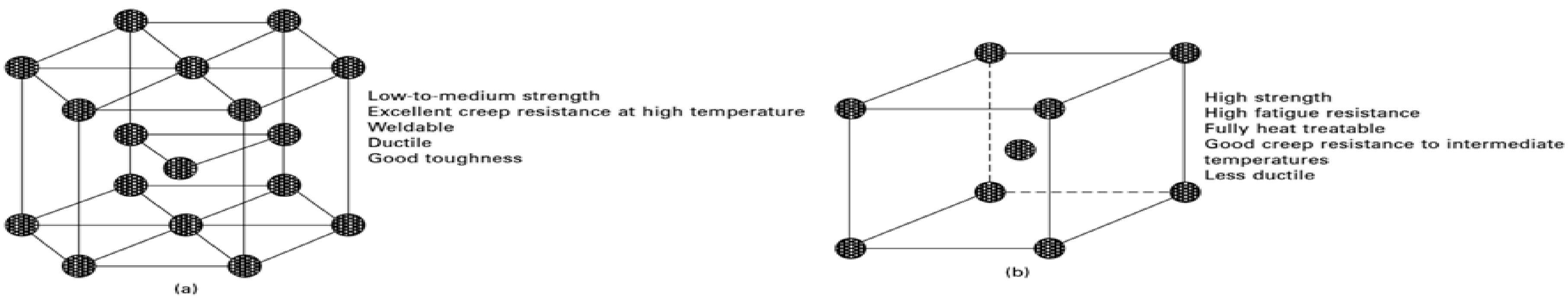
- Various types of **annealing treatments** (single, duplex, (beta), and recrystallization annealing), **solution treating and aging treatments**, are imposed to **achieve selected mechanical properties**.
- Stress relieving and annealing may be employed
  - To **prevent preferential chemical attack** in some corrosive environments
  - To **prevent distortion** (a stabilization treatment)
  - To condition the **metal for subsequent forming** and fabricating operations.

TYPES OF TITANIUM ALLOY

Phases of titanium

- In **pure titanium**, the **alpha phase** is characterized by a **hexagonal close packed** crystalline structure. It is stable from room temperature to approximately **882°C (1620°F).** The **beta phase** in pure titanium has a **body-centered cubic** structure and is stable from approximately **882°C (1620°F)** to the melting point of about **1688°C (3040°F)**.
- **Unalloyed titanium** is **allotropic**. Its **close-packed hexagonal structure (α phase)** changes to a **body-centered cubic, structure (β-phase)** at **885°C (1625°F),** and this structure persists at **temperatures up to the melting point**.
- With respect to their effects on the **allotropic transformation**, alloying elements in titanium are classified as **α stabilizers** or **β stabilizers.**
- **Alpha stabilizers**, such as **oxygen and aluminum**, raise the **α-to-β transformation temperature. Nitrogen and carbon** are also stabilizers, but these elements usually are not added intentionally in alloy formulation.
  - **tin and zirconium**, behave as **neutral solutes** in titanium and have little effect on the transformation temperature, acting as **strengtheners of the alpha phase**.

Crystal structure and properties of (a) α-titanium and (b) β-titanium.

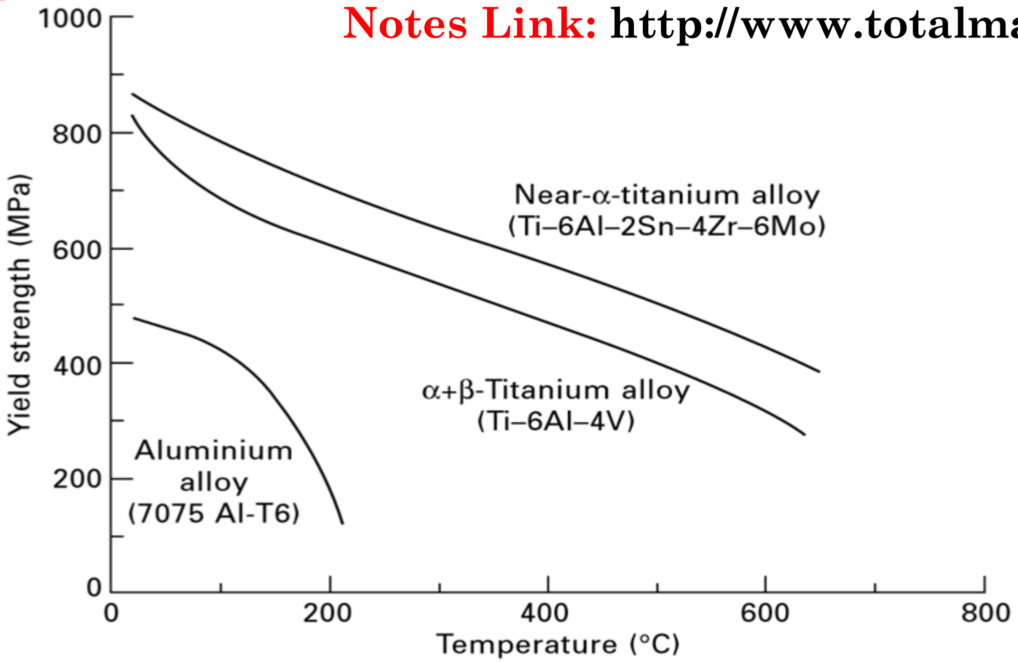


- Certain alloying additions, notably **aluminum and interstitials** (O, N,C), tend to stabilize the alpha phase, (i.e., raise the temperature at which the **alloy will be transformed** completely to the **beta phase**). This temperature is known as the **beta transus temperature**.
- There are **two major groups of alpha titanium alloys**
  - **Super-alpha and Near-alpha.**
- **Super-alpha alloys** contain a large amount of **α-stabilising alloying elements** (>5 wt%) and are composed entirely of **α-Ti grains**.
- **Near-alpha alloys** contain a large amount of **α-stabilisers** with a smaller quantity **of β -stabilising elements** (<2 wt%).
  - Near-alpha alloys have **higher strength properties than super-alpha alloys** (owing to the small amount of the **hard β -Ti phase**) and also have **excellent creep resistance** at high temperature.
- For this reason, near-alpha alloys are preferred over super-alpha alloys in components for **gas turbine engines and rocket propulsion systems** required to operate for **long times at 500–600 °C**.
- Strengthening of **α -Ti alloys** is achieved by **work hardening, solid solution hardening and grain-size refinement**.
  - **Work hardening** by plastic forming processes such as rolling or extrusion can more than double the tensile strength from about **350 to 800 MPa.**
  - **Solid solution hardening** increases the tensile strength between 35 and 70 MPa for every 1% of alloying element.

- **β stabilizers**, such as manganese, chromium, iron, molybdenum, vanadium, and niobium, **lower the α-to-β transformation temperature** and, depending on the amount added, may result in the **retention of some β phase** at room temperature.
  - The strength and fatigue resistance of β-Ti alloys is generally higher than the α -Ti alloys.
  - However, the use of **β-Ti alloys is very low**; accounting for less than a few percent of all the titanium used by the aerospace industry owing to their **low creep resistance at high temperature**.
- α + β -Ti alloys are the most important group of titanium alloys used in aircraft. These alloys are produced by the **addition of α -stabilisers and β -stabilisers** to promote the formation of both **α -Ti and β -Ti grains** at room temperature.
- The popularity of **α + β -Ti alloys** stems from their excellent high temperature creep strength, ductility and toughness (from the **α -Ti phase**) and high tensile strength and fatigue resistance (from the **β -Ti phase**).

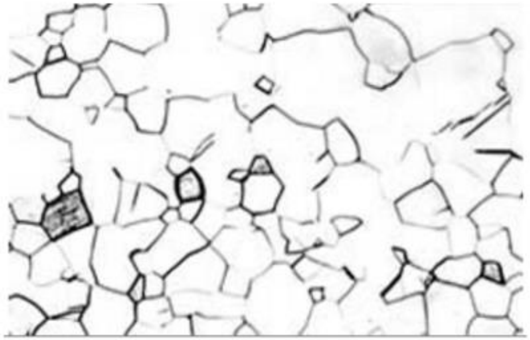
- The mechanical properties of **α + β -Ti alloys** are often between those of **α -Ti and β -Ti alloys.**
- The strength of **α + β -Ti alloys** is derived from several hardening processes, including **solid solution hardening, grain boundary strengthening and work hardening**, although the most important is **precipitation hardening** of the **β -Ti grains**.
- As with **β -Ti alloys**, the thermal ageing of **α + β -Ti** alloys cause some of the **β -phase to transform into α -Ti particles** and ω precipitates which raise the strength.

Notes Link: **http://www.totalmateria.com/Article97.htm**



Effect of temperature on the yield strength of titanium and aluminium alloys.

Titanium alloy microstructures are characterized by the various alloy additions and processes.

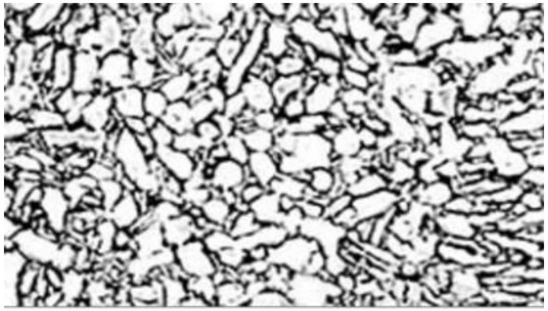


Unalloyed Ti 200X

Commercially pure plate,

0.03% iron 732°C (1350°F)/30 Min.;

Air Cool (Mill-annealed condition)



Ti 5Al-2.5Sn 200X Alpha Alloy

Hot roll 51mm (2 in.) round bar

816°C (1500°F)/2 Hr.;

Air Cool (Mill-annealed condition)

Ti-6Al-2Sn-2Zr-

2Mo-2Cr-Si 200X

Alpha-beta alloy

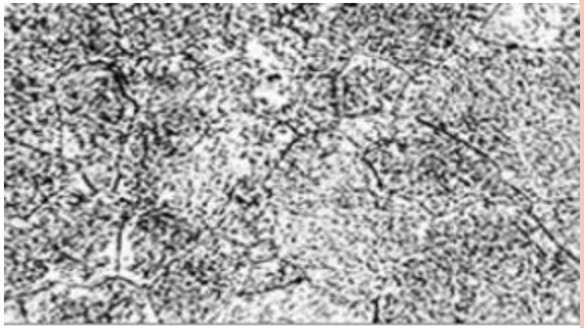
1.6mm (.063 in.) sheet

900°C (1650°F)/30 Min.;

Air Cool + 510°C (950°F)

/10 Hr.; Air Cool

(Solution treated and aged)



Ti-3Al-8V-6Cr

-4Zr-4Mo 250X

Beta alloy 16mm

(0.625 in.) dia. bar

816°C (1500°F)/15 Min.;

Air Cool +566°C (1050°F)

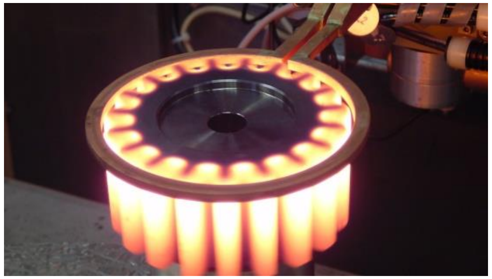
/6 Hr.; Air Cool

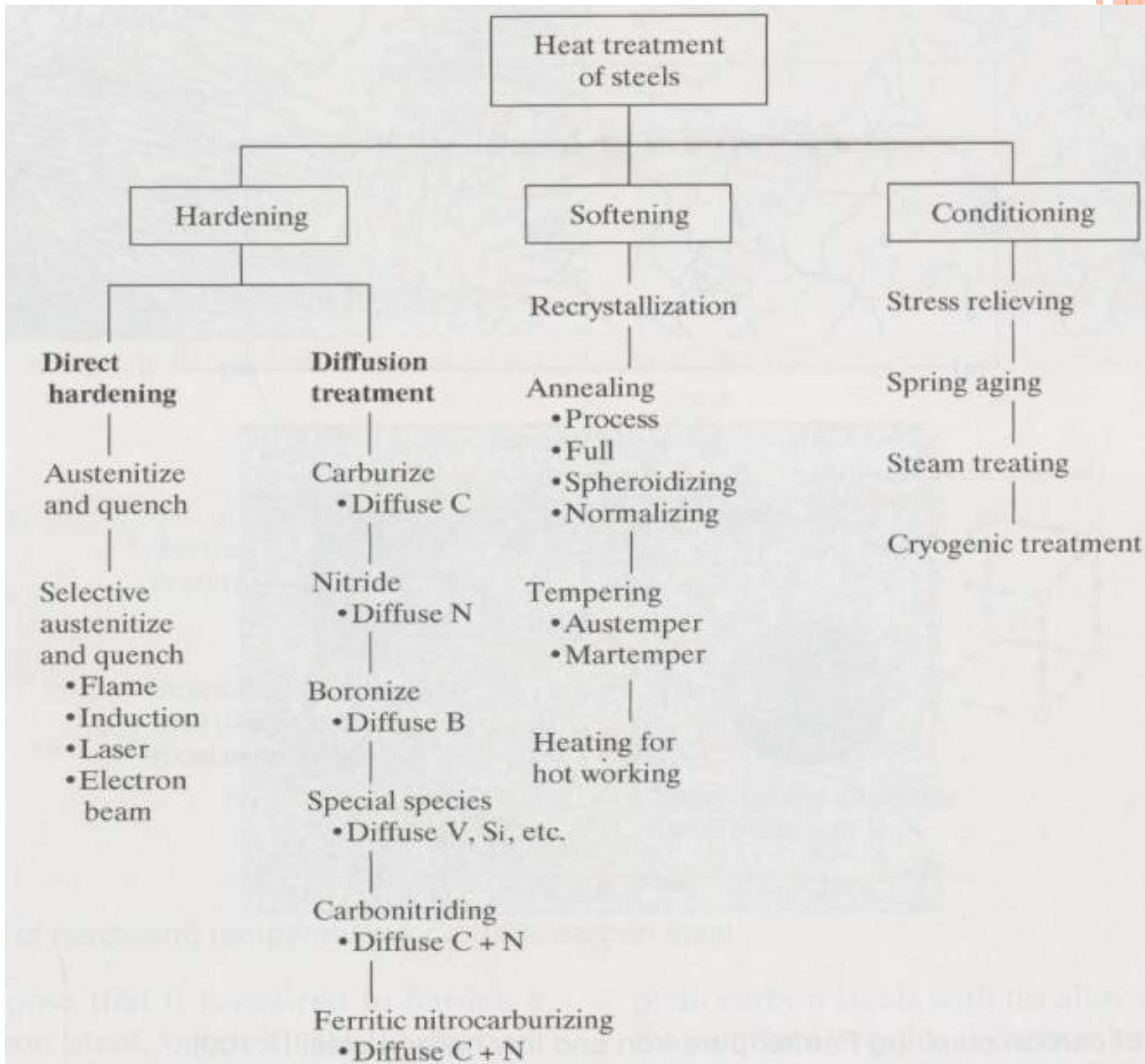
(Solution treated and

aged condition)

https://usa-titanium.com/basic-titanium-metallurgy/

Case Hardening





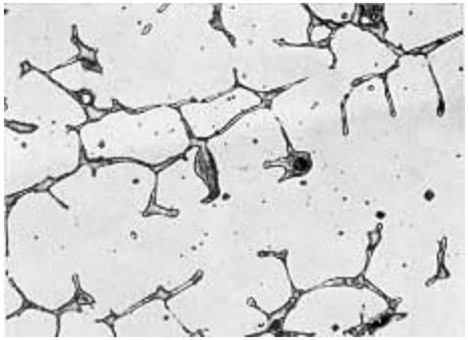
Case Hardening

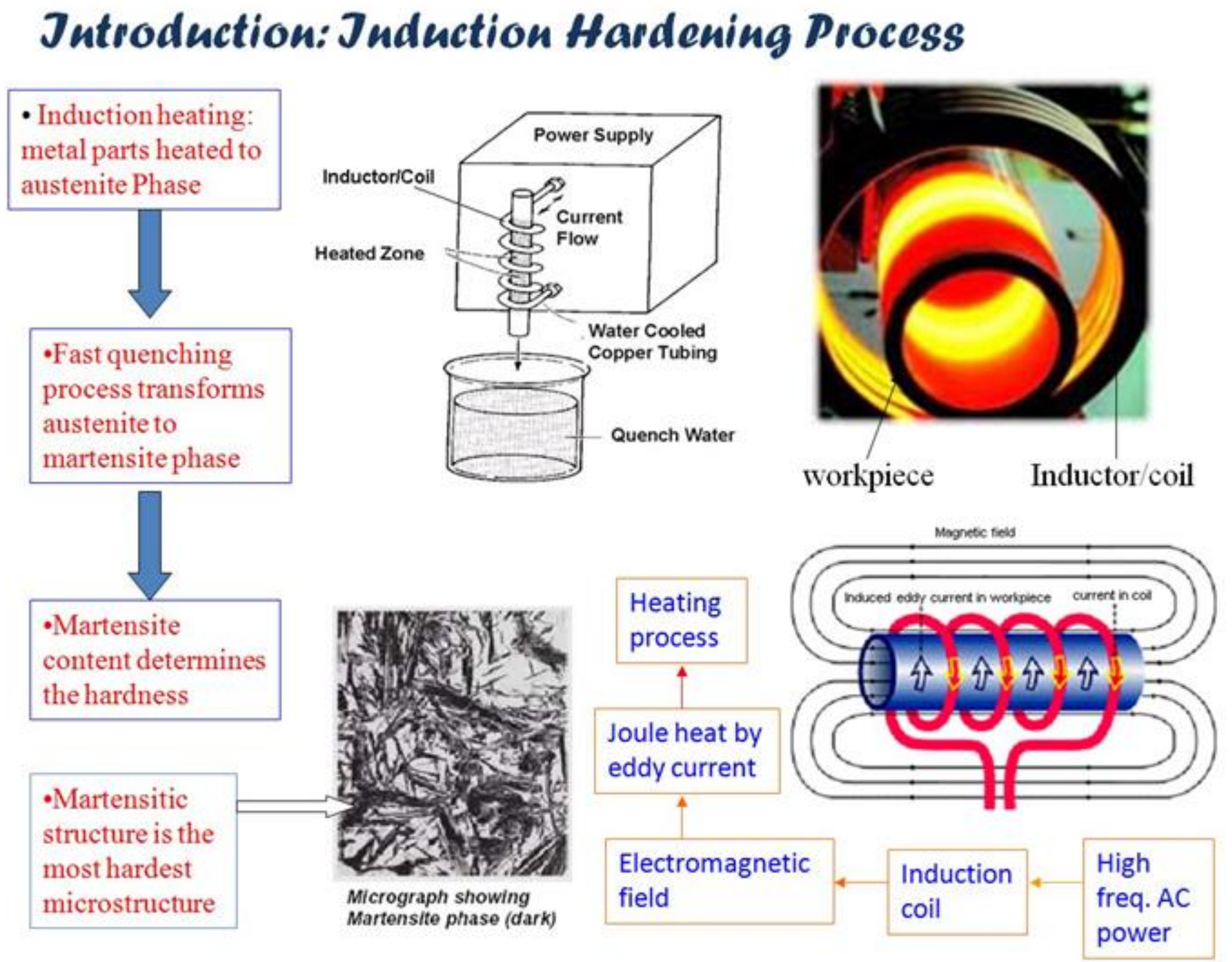
- **Case Hardening** is also known as **Surface Hardening**. Sometimes also are known as the **Face Hardening**. The process of **hardening the surface** of the components is known as the **Case Hardening**.
- The **process of Hardening the surface** of the machined components **to resists wear and tear** by keeping the **core material remains soft to withstand the shock loads** known as the **Case hardening or the Surface Hardening** process. This Case Hardening process will be applied to the **final shaped machine** components.
- **Purpose**
  - **Improve the brittleness** uniformly throughout the body of the material. sometimes we do not require this uniform brittleness. Here we use case **hardening to harden the outer layer and kept the core material soft for absorbs the shock loads**.
  - It helps the components **not to crack during the shock loads** due to core material softness.
  - For **gears and railway wheels, ball bearings** etc.
- Types:
  - Carburising
  - Nitriding
  - Cyaniding
  - **Induction Hardening (Direct)**
  - **Flame Hardening (Direct)**

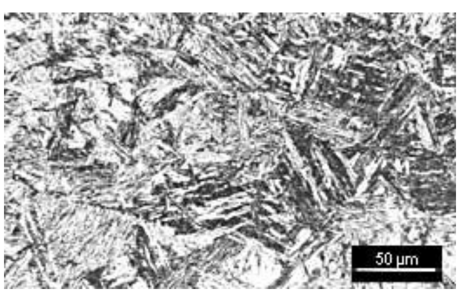
https://www.tec-science.com/material-science/heat-treatment-steel/surface-hardening-case-hardening/

Direct Hardening – Austenitizing and quench:

- *Austenitizing –taking a steel with 6% carbon or greater and heating to the austenite region.*
- ***Rapid quench to trap the carbon*** *in the crystal structure – called* ***martensite****.*
- *Types: Induction hardening and Flame hardening,*

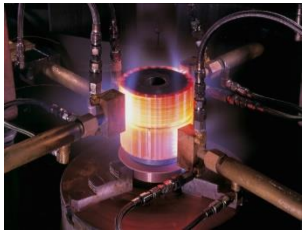


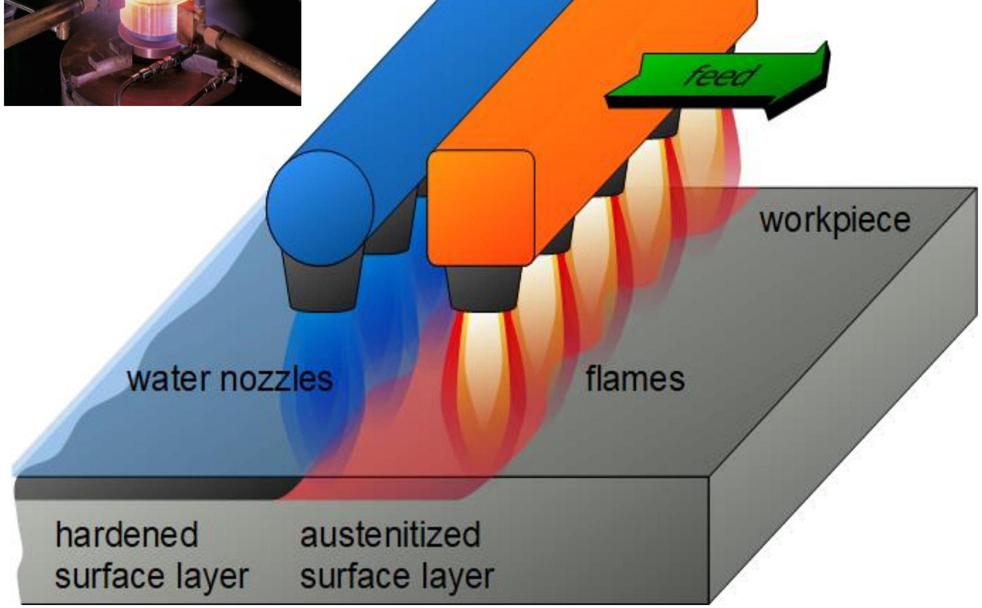




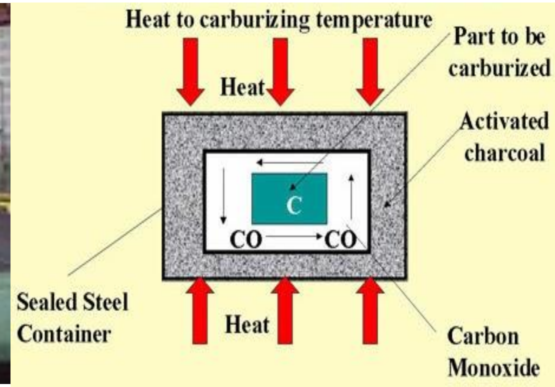
FLAME HARDENING

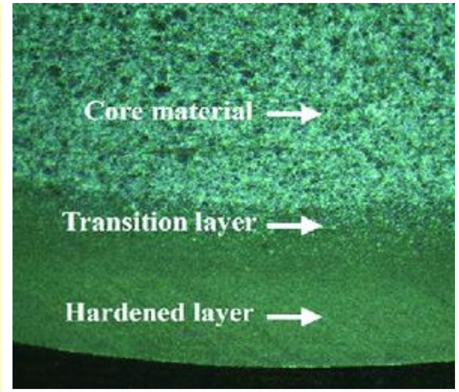
- Harden the surface of metal parts. When you **use an oxyacetylene flame**, a thin layer at the surface of the part is **rapidly heated to its critical temperature** and then **immediately quenched** by a **combination of a water spray** and the cold base metal.
- This process produces a **thin, hardened surface**, and at the same time, the internal parts **retain their original properties**.

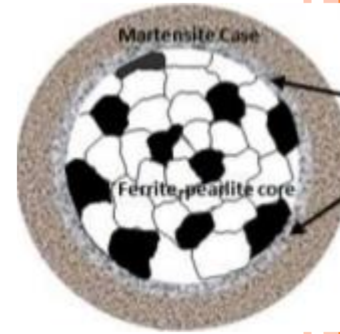




- The parts will be heated rapidly with Oxy-gas flame or induction heating and cooled rapidly with the help of water.
- The hardness of the part will depend on the **Duration of the heating, composition of the metal** is being heat treated, the design of the flame head.





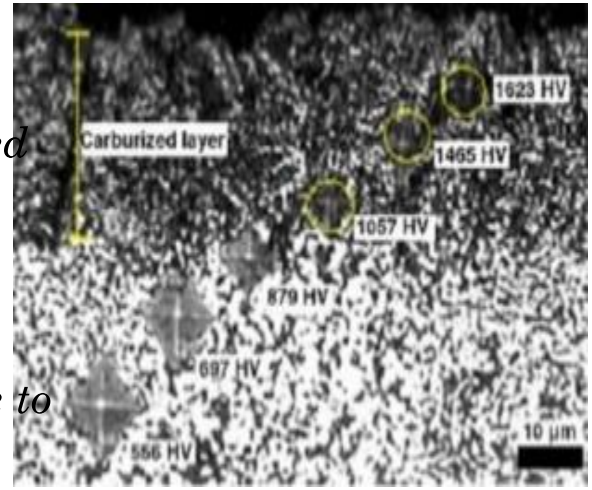


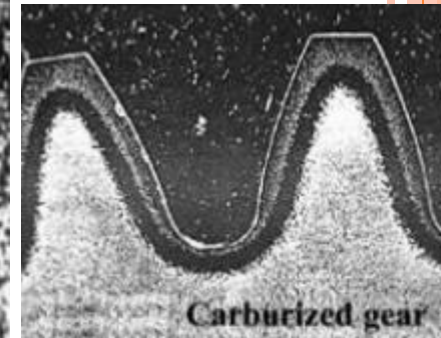
CARBURIZING

- The **Steel is heated** in the presence of **carbon environment (charcoal or carbon monoxide)** for some time and then quenched so that the carbon can be **deposited on the surface** of the steel. this process is called **Carburising**.
- Simply **repeatedly heat the part surfaces** with the **Aceline torch** (Flame torch) and **quenched in the Carbon contained fluid or oil** is also known as the **carburising process**.
- Mostly this Carburising process used to **harden the Low carbon steel** Components.
- This **carburising** is applied to the preferred surface such as **gear tooths** and the remaining portion no needs to be hardened.

Pack carburizing:

- *Part surrounded by **charcoal treated with activating** chemical – then heated to austenite temperature.*
- *Charcoal forms CO_2 gas which reacts with excess carbon in charcoal to form CO.*
- *CO reacts with low-carbon steel surface to form atomic carbon*
- *The atomic carbon diffuses into the surface*
- *Must then be quenched to get hardness*





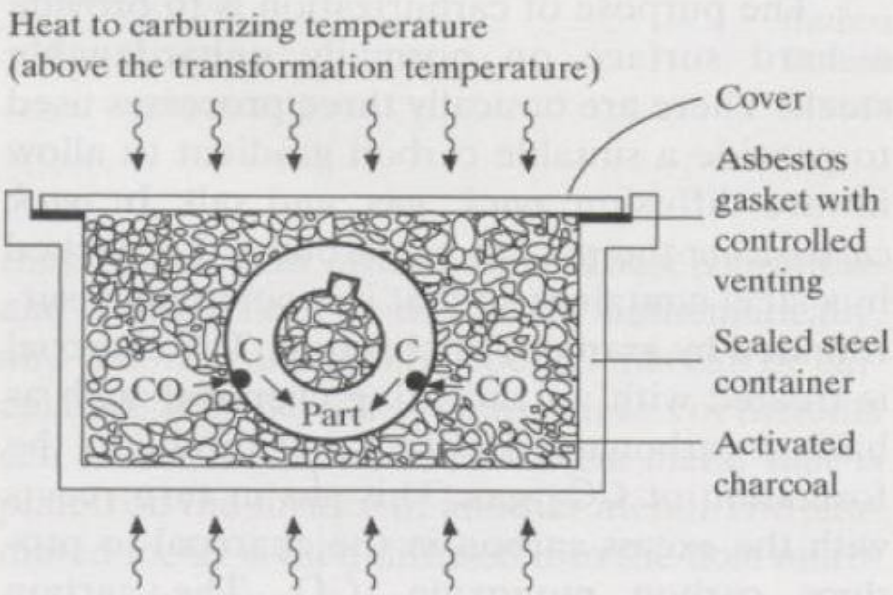


Figure 10–21
Pack carburizing

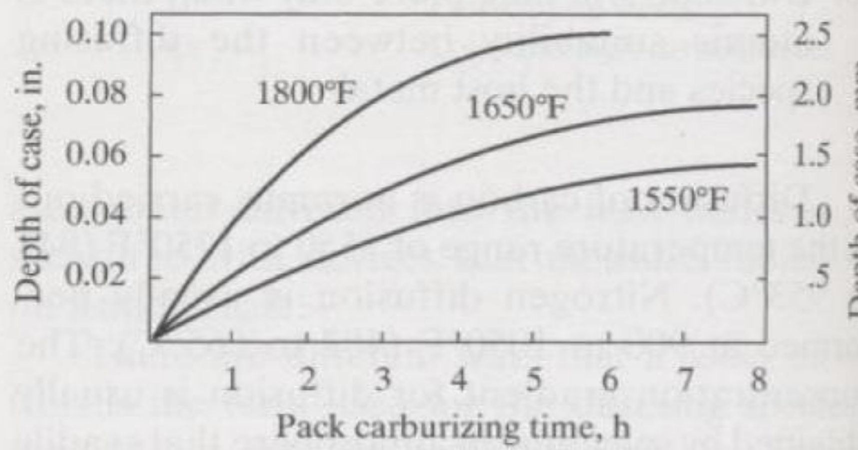


Figure 10–22
Effect of carburizing temperature on case depth
Source: G. M. Enos and W. E. Fontaine. *Elements of Heat Treatment*. New York: John Wiley & Sons, Inc., 1963.

Nitriding

- **The diffusion of nitrogen into the surface layers of low carbon steels at elevated temperature.**
- In **Nitriding** process, the parts will be **heated up to the 482°C–621°C** in the **presence of ammonia** to **form nitrides** to achieve the hardness.
- To form Nitride we must use one of these nitride forming elements: **chromium, molybdenum, aluminium**.
- Nitride is suitable to do **after Quenching or Tempering**, or **Machined**.
- No further quenching require after nitriding. (***No quenching is required*** *- no worry about warping or other types of distortion)*
- To case harden items, such as **gears, cylinder sleeves, camshafts and other engine parts, that need to be wear resistant** and **operate in high-heat** areas.

➢ Nitrogen is diffused into the surface of the component being treated.

➢ Nitriding Temperature: 500-600°C [2]

➢ $2NH_3 \xrightarrow[\blacktriangle]{} 2N + 3H_2$ [2]

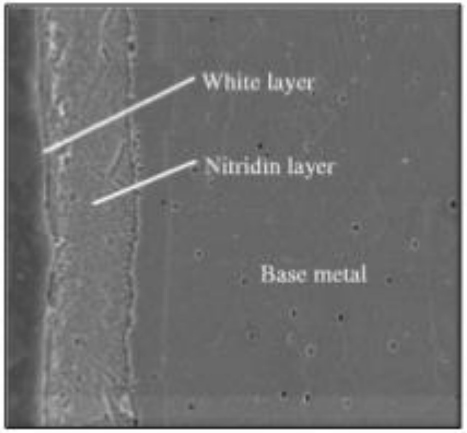


Figure 5: Microstructure of nitrided component [3]

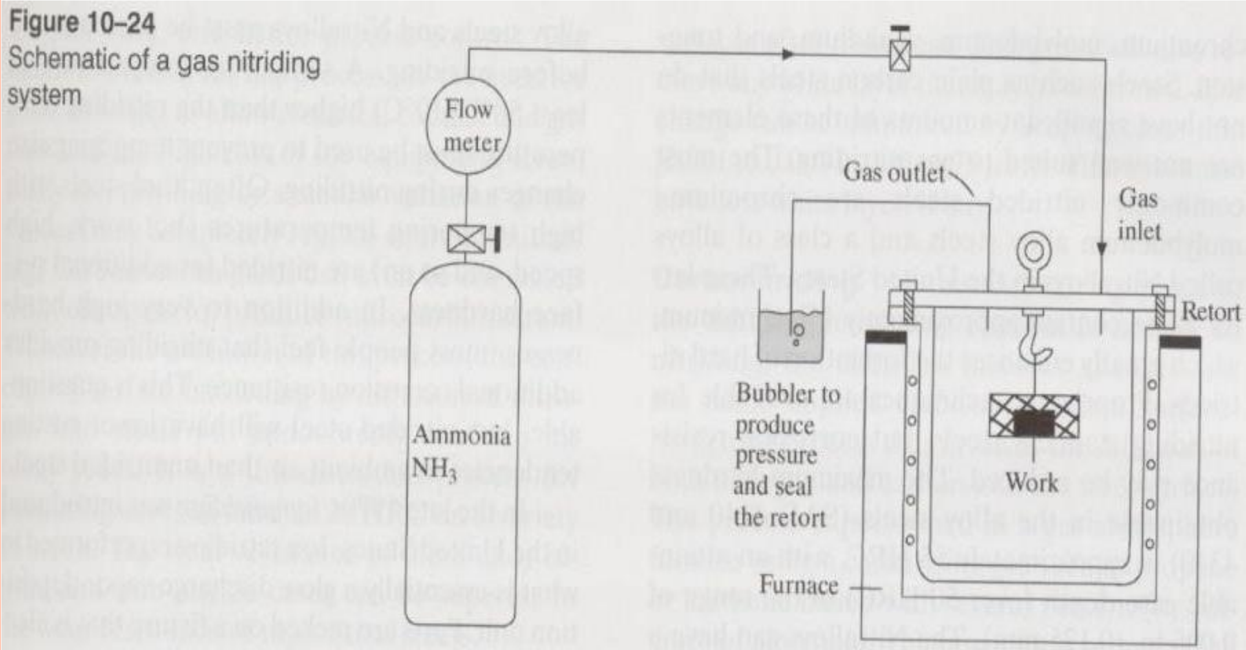
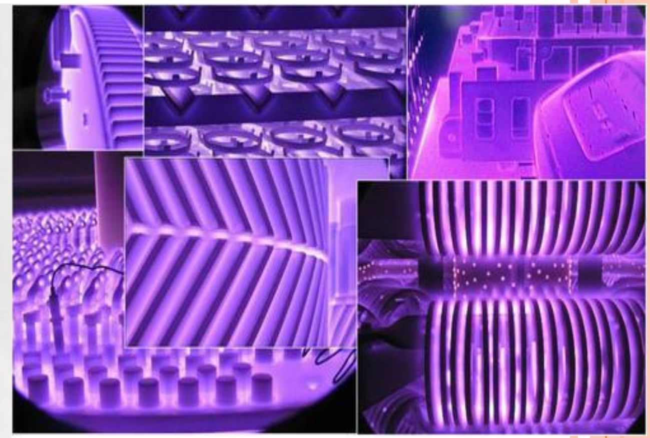
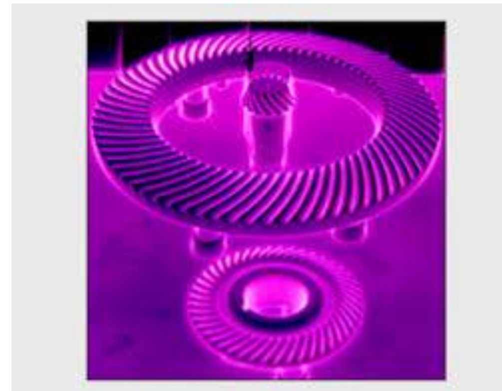


Figure 10–24 Schematic of a gas nitriding system





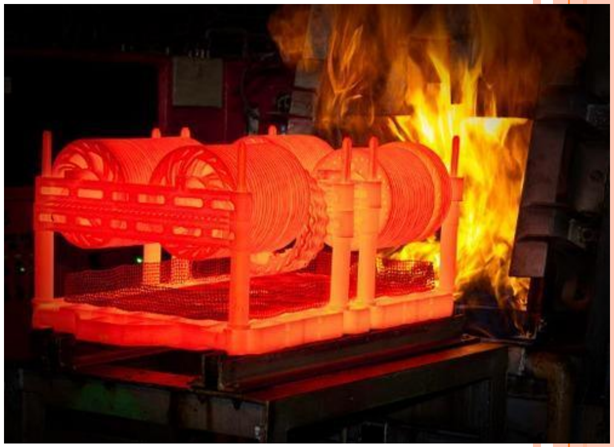
CARBONITRIDING

- Involves Diffusion of **both nitrogen and carbon** into the steel surface.
- Also called as **gas-cyaniding/dry cyaniding**, since use of mixture of hydrocarbons and ammonia.
- Suitable for **low carbon alloyed** steel.
- Carburizing gas (Propane/Methane), Ammonia (Source of Nitrogen).
- Work piece is heated to **850°C for 2 to 10Hrs** in the mixture and Quenched **(increase hardness)**, tempered at 180 °C **(reduce brittleness)**.

CYANIDING

- In the Cyaniding process, the parts will be **heated up to the 871°C-954°C** in the presence of **Sodium Cyanide and quenched** with the water or oil to remove the **residual cyanide.**
- Preheated steel is dipped into a **heated cyanide bath and allowed to soak**. Upon removal, it is quenched and then rinsed to remove any residual cyanide.
- This process produces a **thin, hard shell** that is harder than the one produced by carburizing (completed in **20 to 30 minutes**)
- Used for the low Carbon Steels.
- The cyaniding process is the **fast and most efficient** surface hardening process.
- Cyanide salts are a **deadly poison**.

Stress Relieving



- **Stress relieving** is performed on metal products **to minimize residual stresses** in the structure, thereby **reducing the risk of dimensional changes** during further **manufacturing or final use** of the component.
- **Machining, and cutting,** as well as **plastic deformation**, will cause a build up of **stresses in a material**. These stresses could cause **unwanted dimension changes** if released uncontrolled, for example during a subsequent heat treatment.
- **Stress relieving** is normally done after **rough machining**, but before **final finishing** such as **polishing or grinding**.
- Parts that have **tight dimensional tolerances**, and are going to be further processed, for example by **nitrocarburising,** must be **stress relieved.**
- **Welded** structures can be made **tension free by stress relieving**.

Process

- The **stress relieving temperature** is normally between **550 and 650°C** for steel parts. **Soaking time** is about **one to two hours**.
- After the **soaking time** the components should be **cooled down slowly** in the furnace or in air.
- A **slow cooling speed** is important to avoid **tensions caused by temperature differences** in the material, especially for larger components.
- If necessary, stress relieving can be **performed in a furnace** with **protective gas**, to **protect surfaces from oxidation**. In extreme conditions vacuum furnaces can be used. The temperature for **copper** parts is, depending on the alloy, **150-275°C** and for **brass** components **250-500°C.**

Application & materials

- **Stress relieving does not change** the **material's structure** and **does not** significantly **affect its hardness**.
- **Hardened and tempered** parts to be stress relieved must be treated at a **temperature around 50°C below** the temperature used for **previous tempering to avoid an impact on the hardness**.
- **Stress relieving** before **nitrocarburising** should be executed at temperatures **> 600°C.**