AIRCRAFT MATERIALS AND PROCESSES

MODULE VI – HIGH TEMPERATURE MATERIALS

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High Temperature Materials: Characteristics

(1) High temperature materials should withstand loading at operating temperature (T_{oper}) close to its melting temperature (T_m)

stress / unstressed

$$\tau = \frac{T_{oper}}{T_m} \geq 0.6$$ Temperature in K

Examples: Ni-base alloy
T_{oper} = 1000 °C, T_m = 1455°C, τ = 0.75

What about Ice?
T_{oper}= - 45 °C, T_m = 0 °C
τ = 0.84

(2) High temperature materials should show a sustainable resistance to mechanical degradation over extended period of time.

a time dependent, inelastic, irrecoverable
Creep should be considered

(3) High temperature materials should show a high tolerance of severe operating environments

Example: hot gas generated in a coal-fired electricity-generating turbine are highly corrosive due to highly sulphur levels in the charge.

Introduction to High Temperature Materials

Material	max. use temperature (ΥC)	max. use temp. / melting temp.
Carbon steel	425*	0.27
Latest 12% Cr steel (HCM 12A)	650*	0.41
Nickel – 20% chromium alloy	400*	0.3
Single crystal nickel superalloy (CMSX4)	1050*	0.79
Oxidation res. nickel alloy (Brightray H)	1250#	0.9

* Stressed applications

Unstressed applications

Introduction to High Temperature Materials

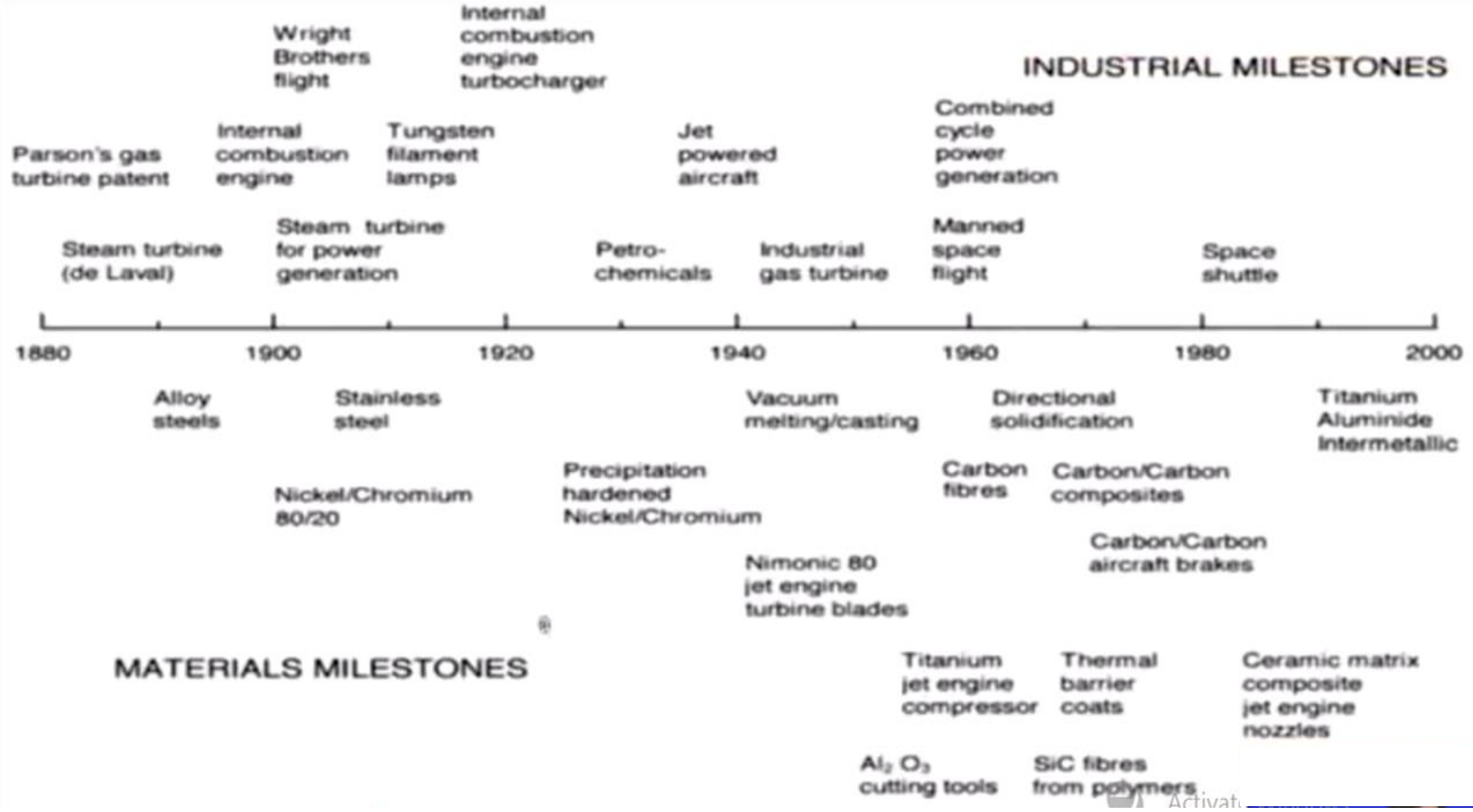
Environmental Resistance
- oxidation
- sulphidation
- salt/ash deposit corrosion
- carburisation

Physical Properties
- density
- thermal expansion coefficient
- thermal conductivity

Mechanical Properties
- zero time deformation
- creep
- mechanical fatigue
- thermo-mechanical fatigue
- corrosion fatigue
- hardness
- young modulus

Erosion

Wear


INDUSTRIAL MILESTONES
Parson's gas turbine patent
Steam turbine (de Laval)
Internal combustion engine
Wright Brothers flight
Steam turbine for power generation
Tungsten filament lamps
Internal combustion engine turbocharger
Petro-chemicals
Jet powered aircraft
Industrial gas turbine
Combined cycle power generation
Manned space flight
Space shuttle
1880
1900
1920
1940
1960
1980
2000
Alloy steels
Stainless steel
Nickel/Chromium 80/20
Precipitation hardened Nickel/Chromium
Vacuum melting/casting
Nimonic 80 jet engine turbine blades
Al2 O3 cutting tools
Titanium jet engine compressor
Carbon fibres
Directional solidification
Carbon/Carbon composites
Carbon/Carbon aircraft brakes
Thermal barrier coats
SiC fibres from polymers
Titanium Aluminide Intermetallic
Ceramic matrix composite jet engine nozzles
MATERIALS MILESTONES

High Temperature Materials: Characteristics

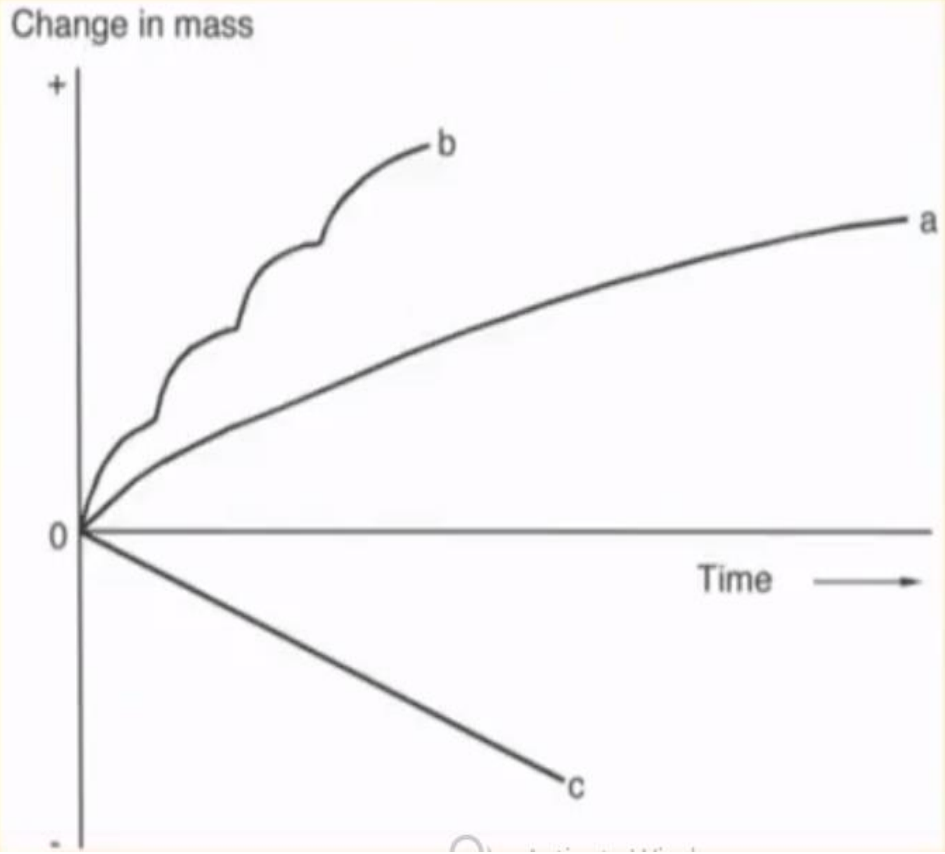
Environmental Resistance

oxidation

- a- parabolic (Cr_2O_3 on stainless steel)
- b- spallation of scale
- c- protection ineffective (volatile oxides)

sulphidation

- occur in presence of SO_2/SO_3 (oxidizing) or H_2/H_2S (reducing)
- when sulphide compounds of alloying elements are thermodynamically more stable than their oxides
- sulphide scales are non protective
- rate is very high



High Temperature Materials: Characteristics

Environmental Resistance

carburisation

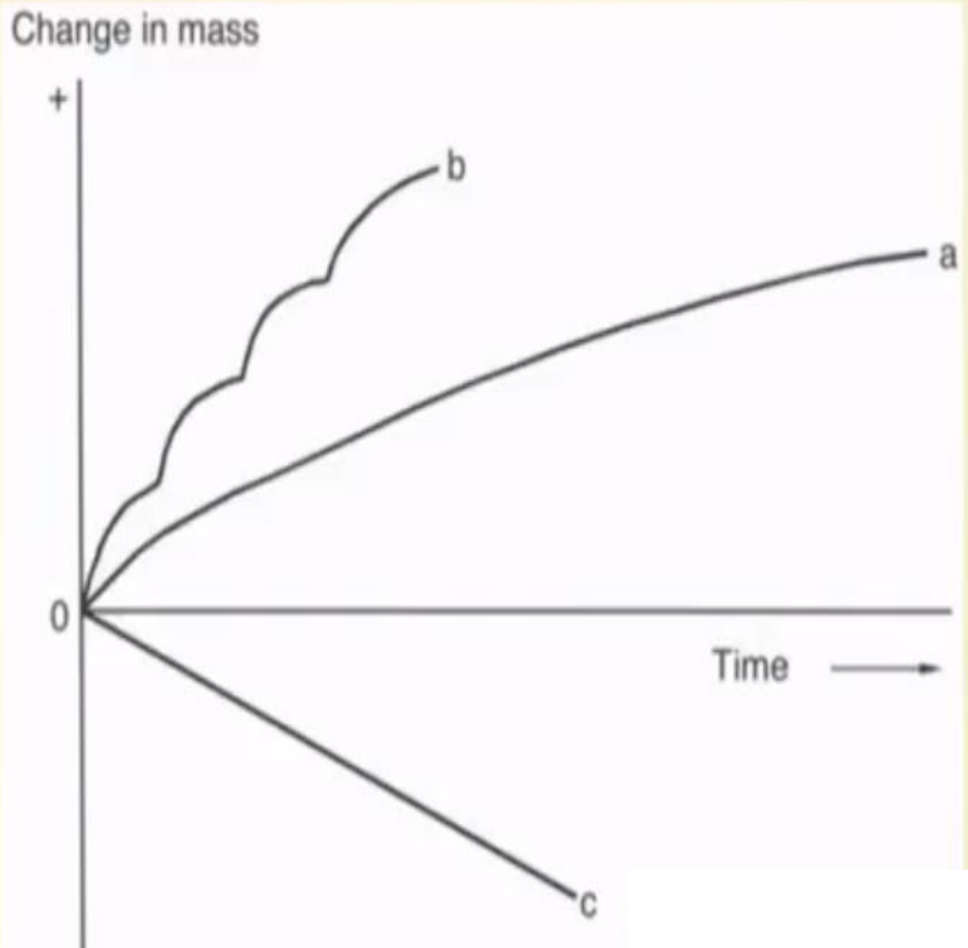
- occurs at low P_{O2} with CO, hydrocarbons
- C absorbed from atmosphere->carbide
- > 800 °C; metal dusting at 650 °C

Erosion

- moving fluid with solid particles + corrosion
- Coatings are rarely effective

Wear

- Relative movement of parts
- Poor oxide adherence accelerate the wear
- Wear + corrosion aggrieves the condition



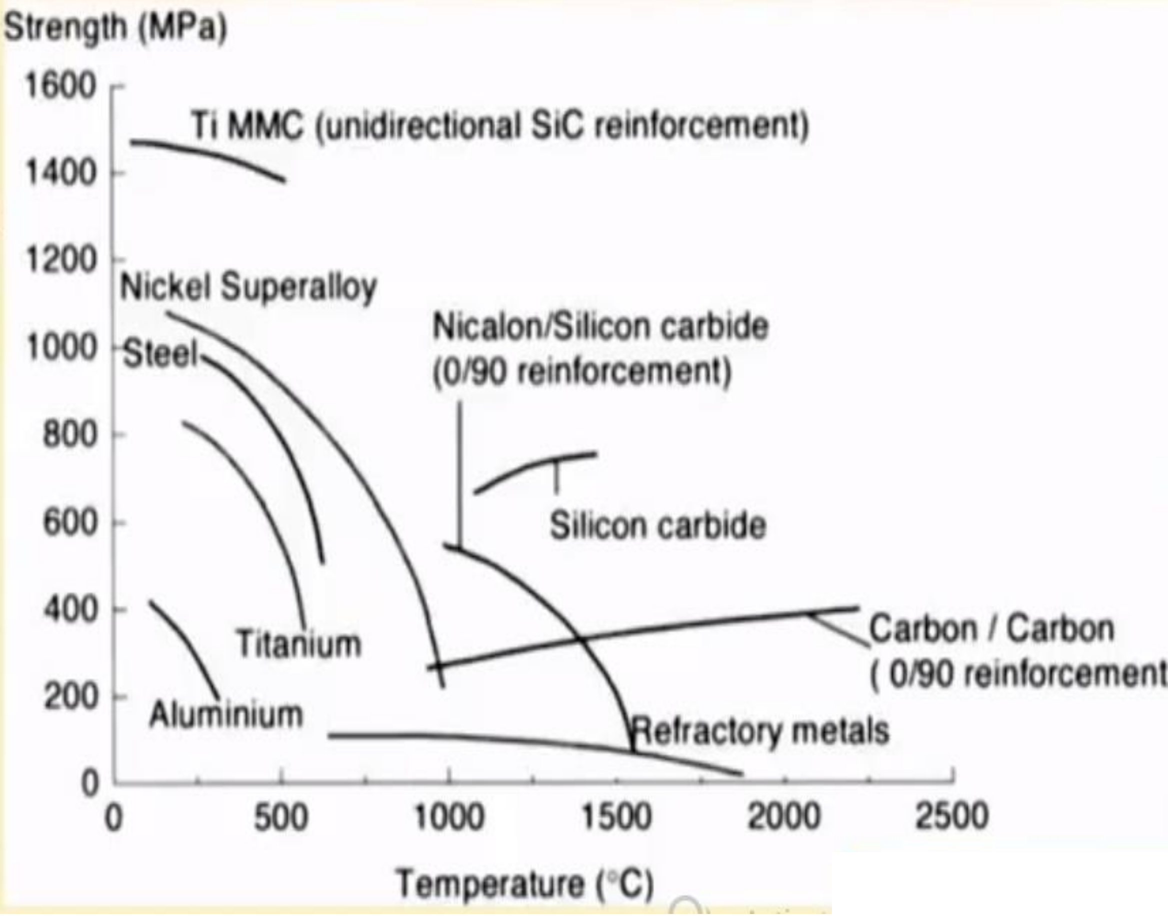
High Temperature Materials: Mechanical Behavior

Strength: zero time deformation

- design stress = % of YS (steel)
  =% of PS (non-ferrous)

-strength improves when slip is difficult

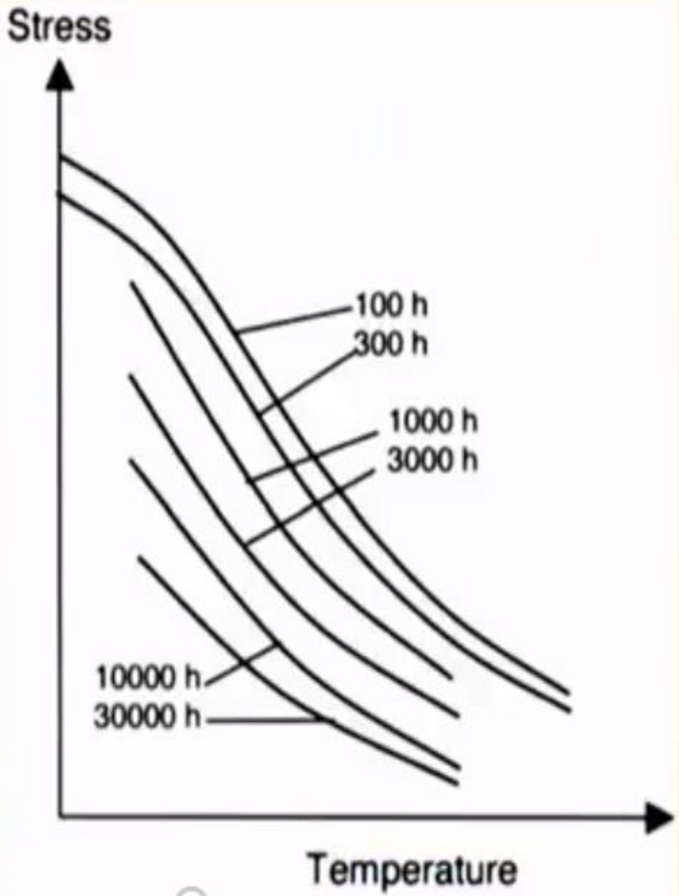
-slip helps redistribution of local stress and avoid stress concentration, higher defect tolerance



High Temperature Materials: Mechanical Behavior

Creep: real time deformation

- Slow, continuous, time dependent deformation at T> 0.3-0.4 T_m under a constant stress
- **At low temperature**, creep is restricted by microstructural features, such as, grain boundaries or precipitates restricting dislocation movement
- **At higher temperature**; dislocations can climb out of their blocked slip plane and continue the creep process. Here, diffusion is the controlling process in dislocation climb with the activation energies for creep and self-diffusion being similar for many crystalline solids
- Material comparison using empirical relationships such as that due to **Larson and Miller** approach



Typical creep-rupture data correlating stress, temperature and life

High Temperature Materials: Mechanical Behavior

Fatigue: mechanical

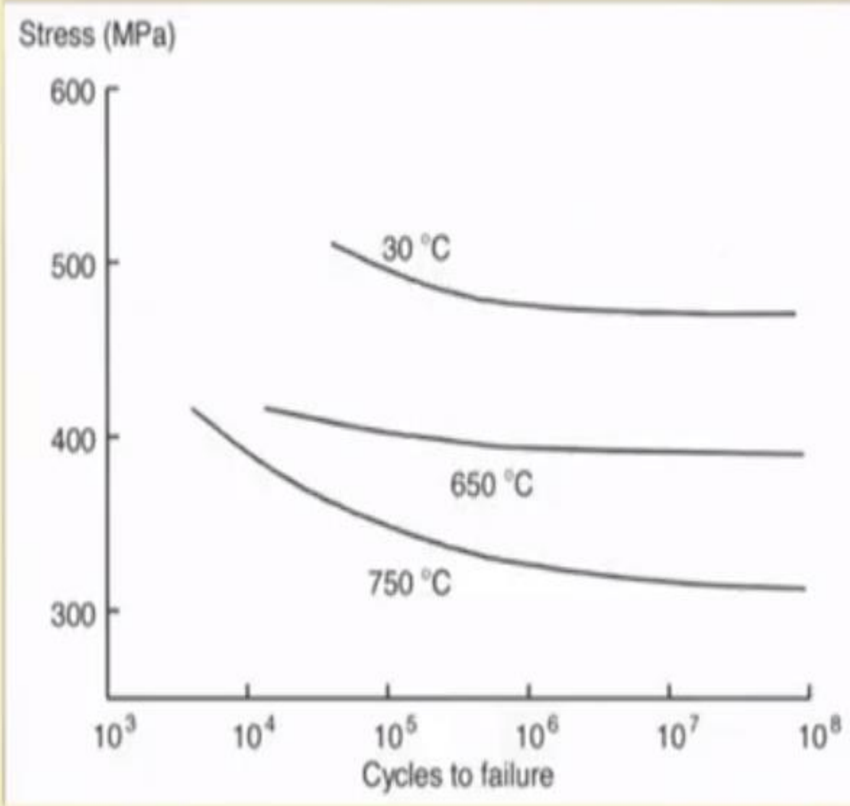
- failure can occur at stresses well below tensile strength, under repeated stress or strain cycles: vibrational stress in a turbine blade
- high-cycle fatigue (HCF) at $N>10^4$ and low cycle fatigue (LCF)

Fatigue: thermo-mechanical

- Combination of thermal stresses with periods of dwell on-load at temperature results in creep fatigue interactions: in-phase or out-of-phase

Fatigue: corrosion

- interactions with corrosion lead to failure
- furnace walls of boilers suffers due to high temperature corrosive environment and the cyclic stressing of the fire-side: cyclic operation of plant



S-N curves of nickel superalloy, IN 625

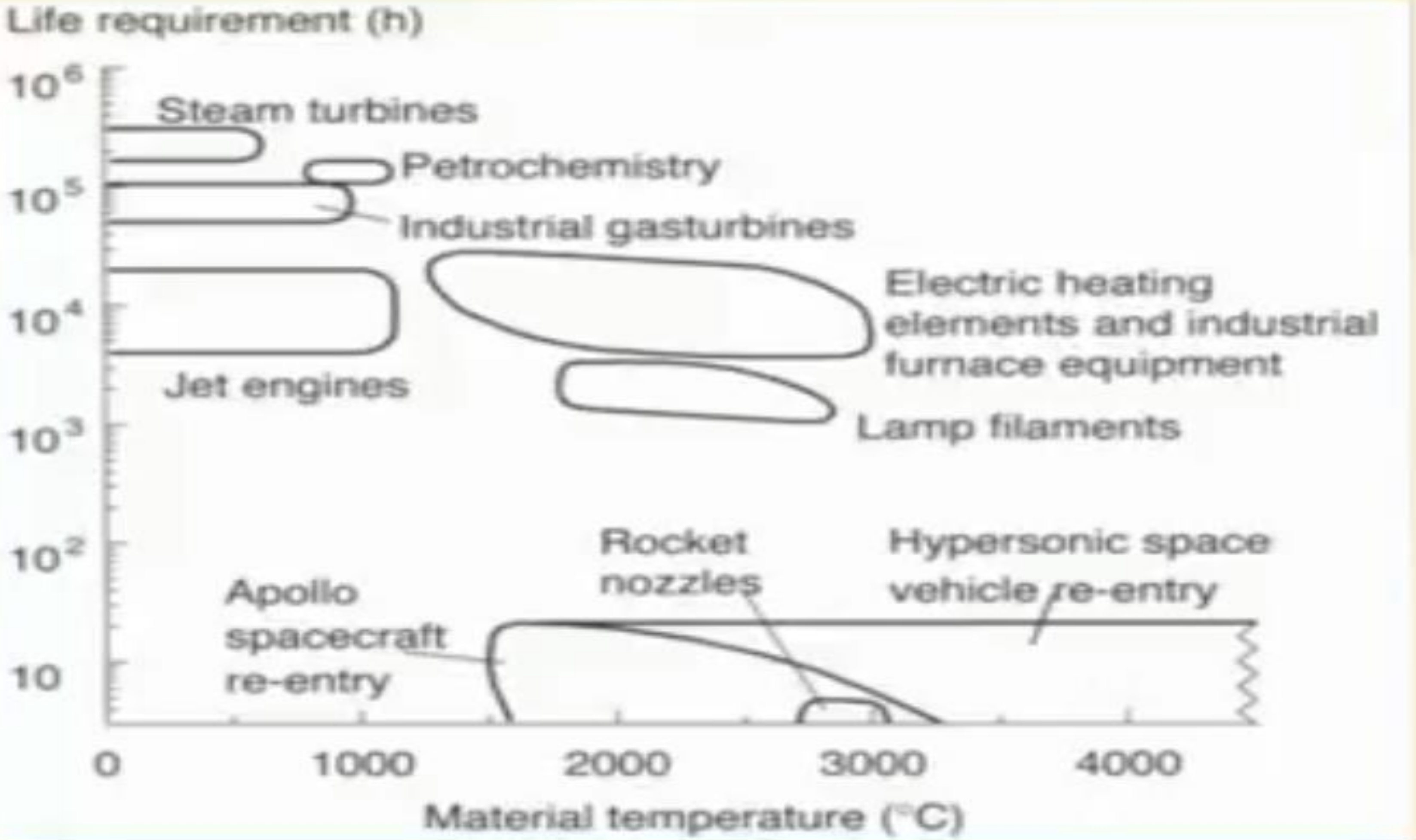
High Temperature Materials: Enhanced Capability

Metallic Materials/Alloys
- solid solution strengthening
- precipitation strengthening
- dispersion strengthening
- grain size and GB effects
- environmental resistance

Ceramic Materials
- phase control
- defect tolerance
- thermal shock resistance

Composite Materials
- Titanium matrix
  (requirements: strength, stiffness)
- Carbon-carbon
  (requirements: defect tolerance, reliability, stiffness, oxidation)
- Ceramic matrix
  (requirements: defect tolerance, reliability)

High Temperature Materials



High Temperature Materials

Steels
- Ferritic heat resistant steels
- Martensitic creep resisting steels
- Austenitic steels with high strength and corrosion resistance
- Controlled transformation stainless steels

Cast Iron
- Grey cast iron
- Spheroidal graphite iron
- Austenite Irons

Superalloys
Ni-base
Co-base
FeNi-base

Intermetallics
- Aluminides (Ti, Ni, Fe)
- Silicides

Cermet, Ceramics and Composites

High Temperature Materials: Steels

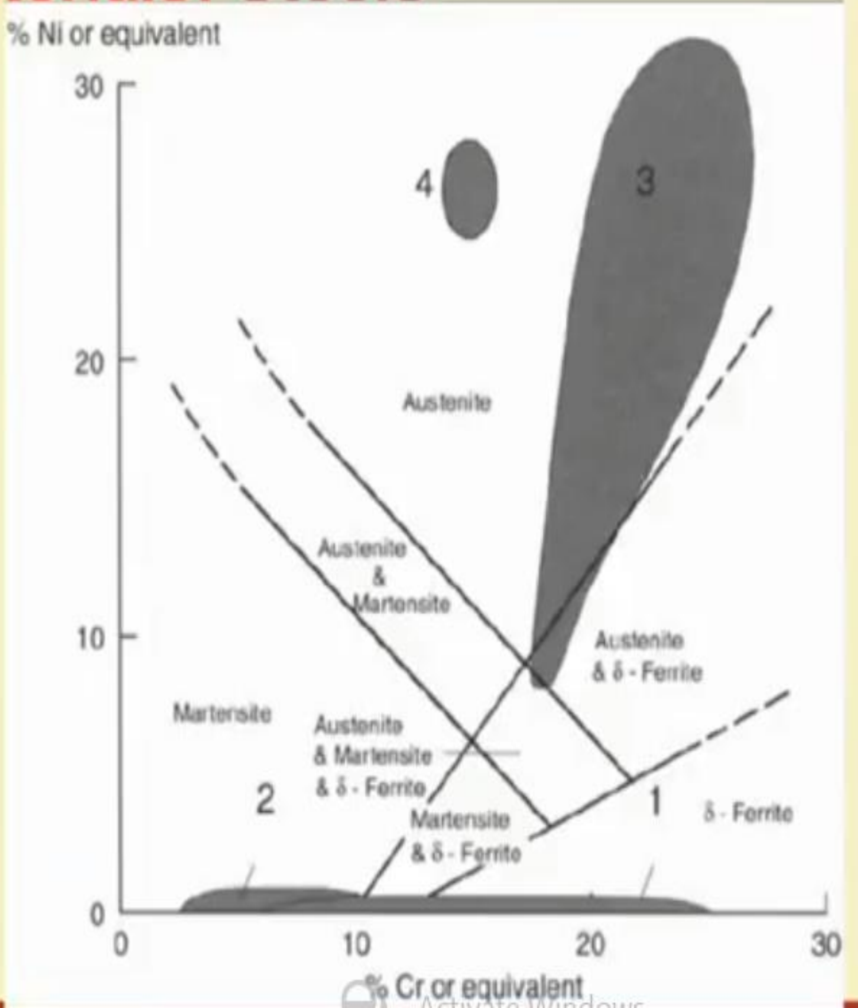
Steels

(1) Ferritic heat resistant steels

(2) Martensitic creep resisting steels

(3) Austenitic steels corrosion resistance

(4) High strength austenitic steels



High Temperature Materials: Steels

(1) Ferritic heat resistant steels

The ferritic steels (high Cr and low C) have been developed to provide resistance to high temperature corrosion and oxidation.

Cr is ferrite stabilizer, can not be strengthened upon heat treatment

Additions of Si, Al and small amounts of rare earth elements reduce oxide spallation, particularly during thermal cycling.

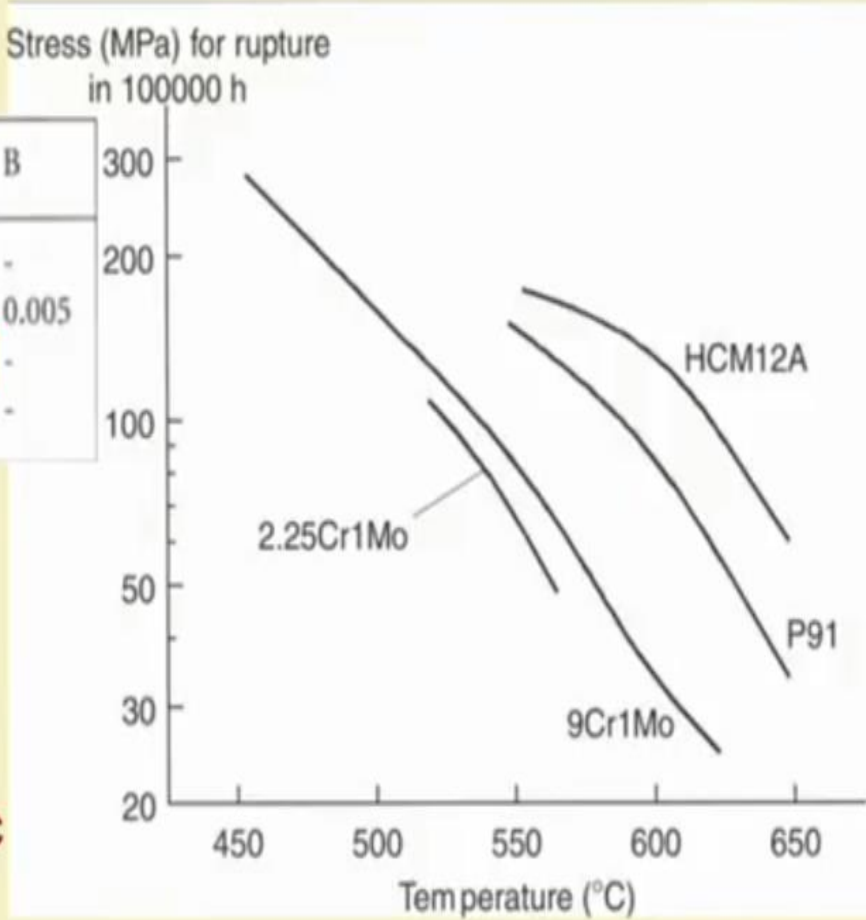
The excellent oxidation resistance of the FeCrAl has been achieved due to the formation of a protective Al_2O_3 film.

Material	Temperature capability (°C)	Applications
Fe-6Cr	650	Petrochemical plant
Fe-10Cr-2Si	750	Internal combustion engine valves
Fe-15Cr-4.5Al	1050	Chemical plant
Fe-25Cr-5Al-0.3Y	1400	Heat treatment furnace equipment, heating elements

High Temperature Materials: Steels

(2) Martensitic creep resisting steels

Steel	Fe	C	Cr	Ni	Mo	V	Nb	W	Co	Cu	N	B
FV448	bal	0.15	11	0.7	0.7	0.25	0.3	-	-	-	0.06	-
FV535	bal	0.07	10.5	0.3	0.7	0.25	0.3	-	6	-	0.02	0.005
P91	bal	0.1	9	-	1	0.2	0.06	-	-	-	0.05	-
HCM12A	bal	0.1	12	-	0.5	0.2	0.05	1.8	-	1	0.06	-



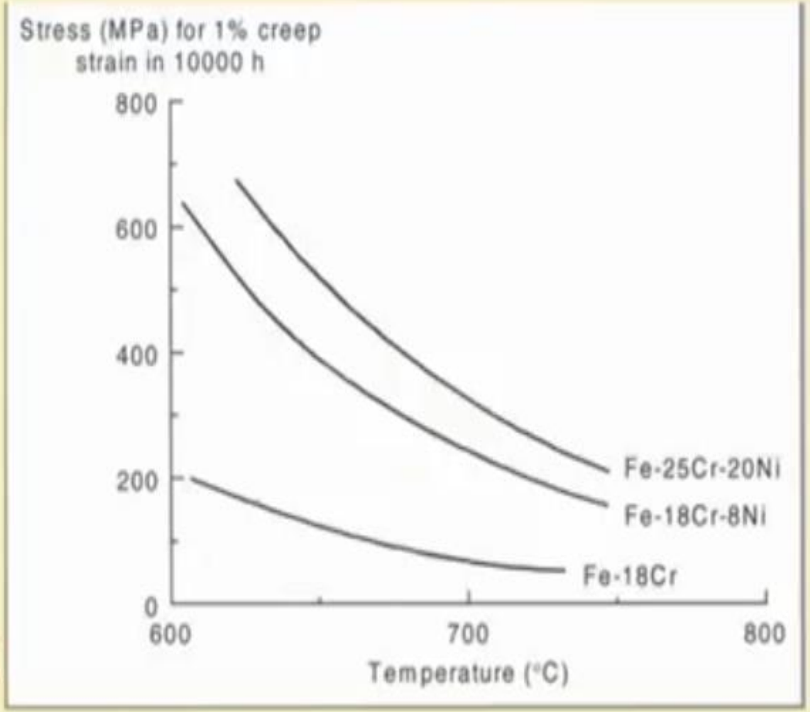
Microstructure: Tempered martensite + carbide
Use: power plant (critical, sub and super critical)
The creep strength has allowed the main pressurised parts of super-critical power plants operating at temperatures up to 590°C to be made from martensitic steel.

High Temperature Materials: Steels

(3) Austenitic steels with corrosion resistance

The addition of small quantities of Ti (Type 321) or Nb results in the formation of TiC or NbC and avoids the problem - the "sensitisation" to local corrosion is reduced. An alternative approach is to reduce the carbon content (304L or 317L).

The general corrosion resistance of austenitic steels is better than ferritic steels, but low resistance to stress corrosion cracking (SCC) and pitting corrosion. Mo is added to improve resistance to pitting (Types 316 and 317) while higher Ni contents as in Incoloy 800 (20Cr/32Ni) gave increased resistance to SCC. Increase in Ni Mo, Cu additions increase corrosion resistance in reducing environments.

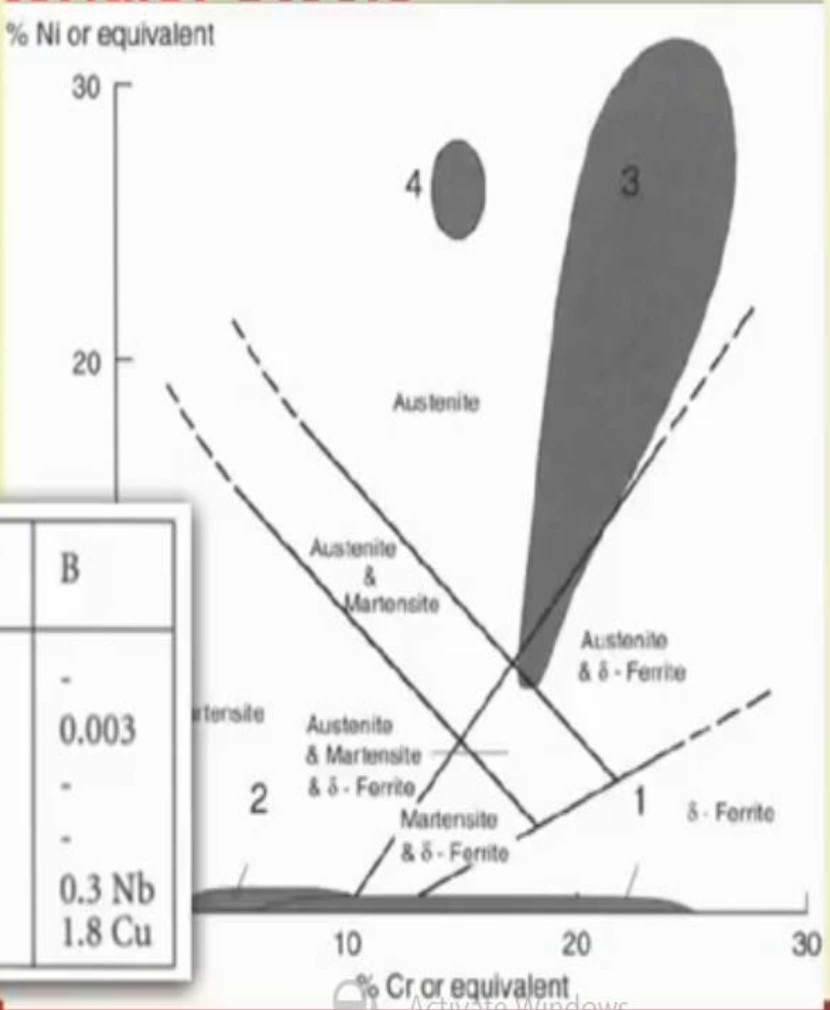


High Temperature Materials: Steels

(4) Austenitic steels with high strength

The strength has been increased by precipitation hardening with $Ni_3(Ti,Al)$. These alloys were derived from Tinidur. Materials such as A286 and Discaloy were used for turbine discs in early US jet engines and are still widely used for discs in industrial turbines.

	C	Cr	Ni	Mo	Ti	Al	B
Tinidur	0.04	15	26	-	2.2	0.15	-
A286	0.05	15	26	1.25	2.15	0.2	0.003
Discaloy	0.04	13.5	26	2.75	1.75	0.1	-
AM350	0.10	17	4	2.75	-	-	-
FV520	0.05	16	5.5	1.8	-	-	0.3 Nb 1.8 Cu



Superalloys

A superalloy is a high-performance alloy and exhibits excellent strength at high temperature, resistance to thermal creep deformation, good surface stability, and resistance to corrosion or oxidation

Any high temperature alloy can be called as SUPERALLOY? NO.

Common features of Superalloys:

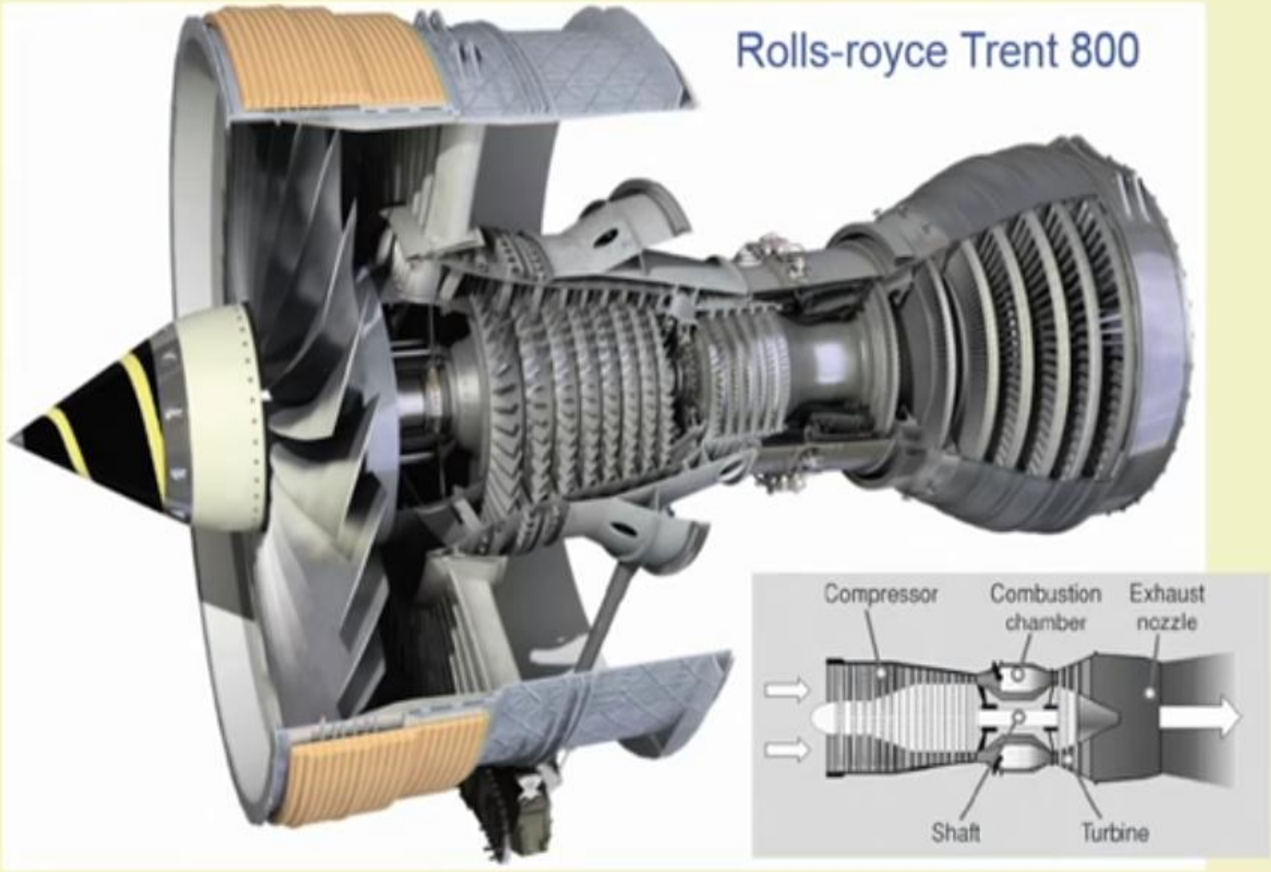
- FCC structure (Ni, Co, Fe) of matrix phase
- solid solution strengthening
- precipitation strengthening
- used for gas turbine engine (GTE)

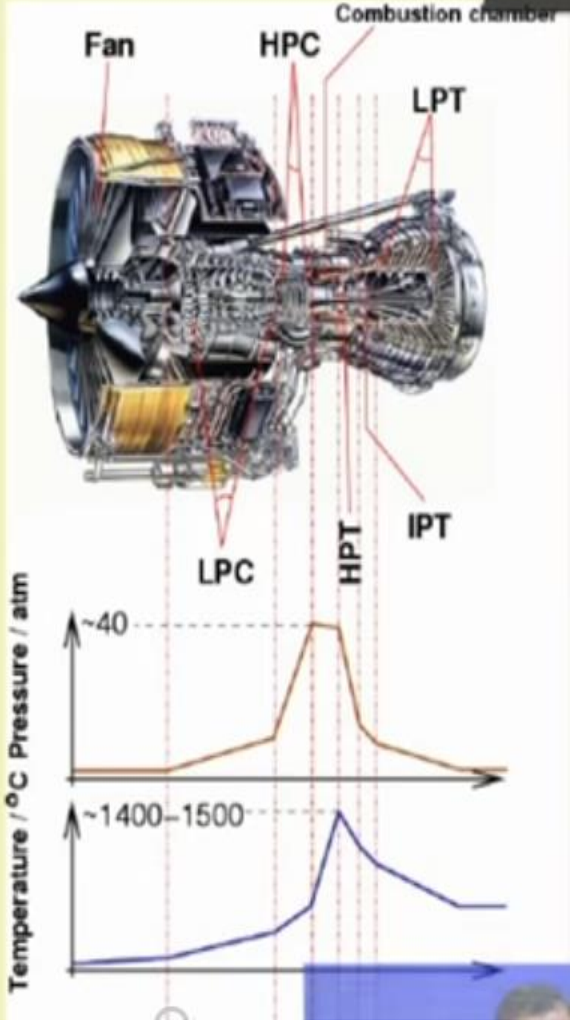
Superalloys

"Superalloys" belong to a group of alloys for use in turbo-superchargers and aircraft gas turbine engines that required high performance at elevated temperatures. The use of these alloys has subsequently expanded too many other areas, including land-based gas turbines, rocket engines, chemical, and petroleum plants. These alloys are particularly well suited for these demanding applications because of their ability to retain most of their strength even after long exposure times above 650 °C. Their versatility stems from the fact that they combine high strength with good low-temperature ductility and excellent surface stability.

Superalloys

What is a gas turbine engine (GTE)





Superalloys

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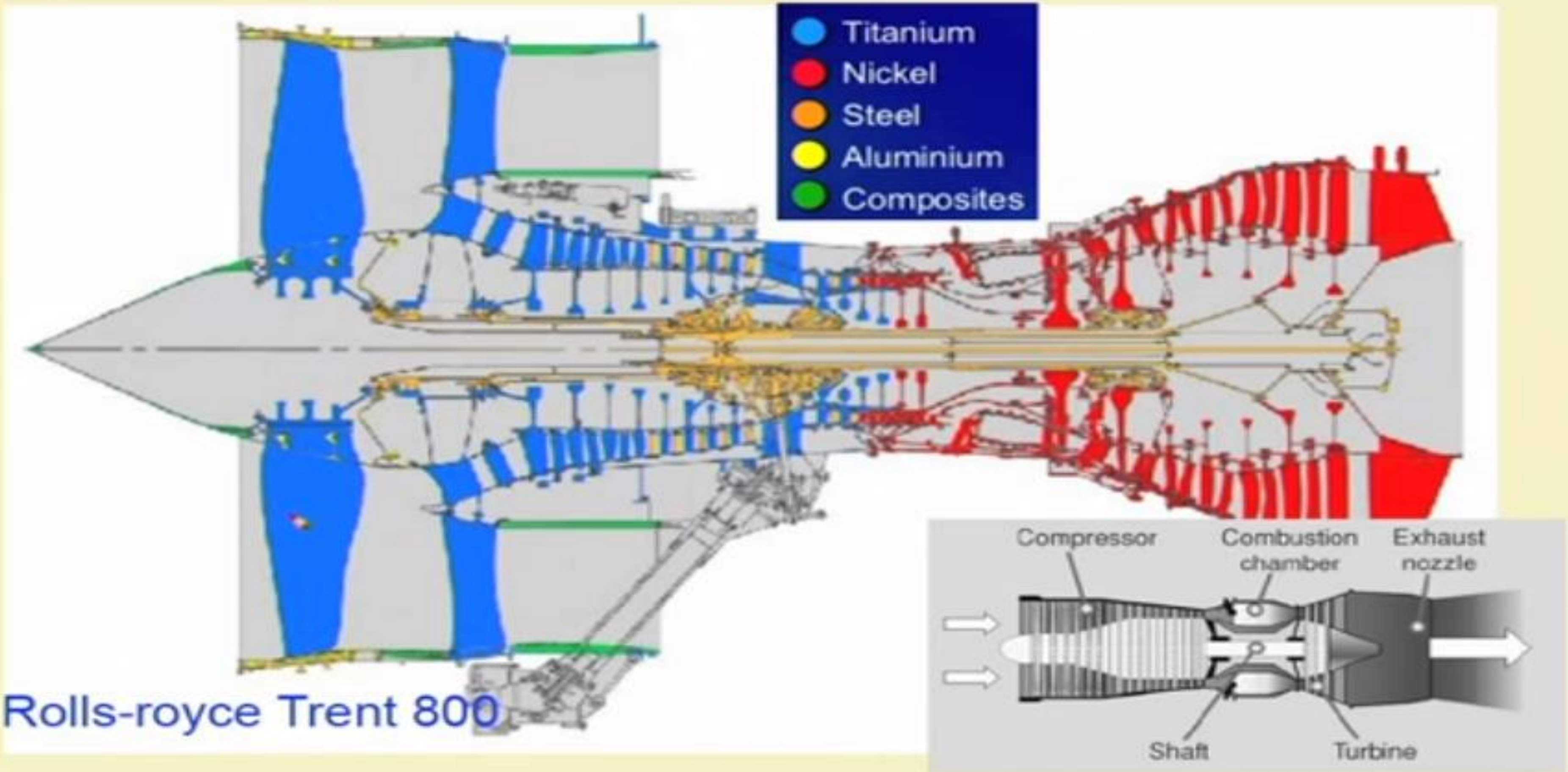


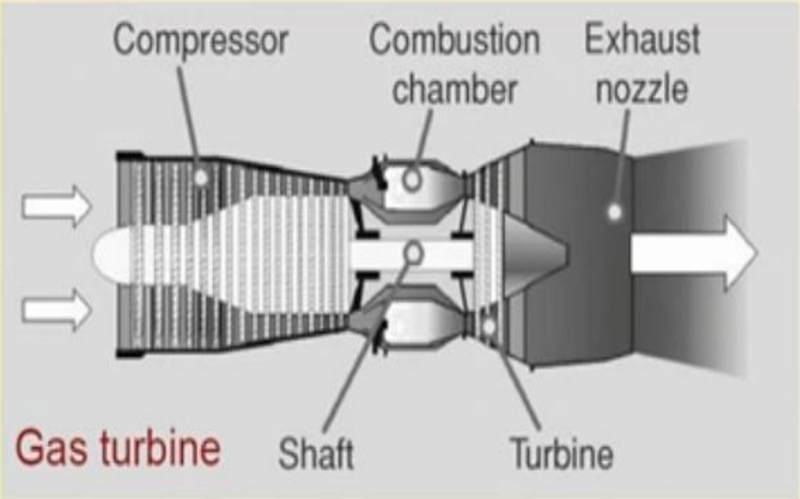
Rolls-royce Trent 800

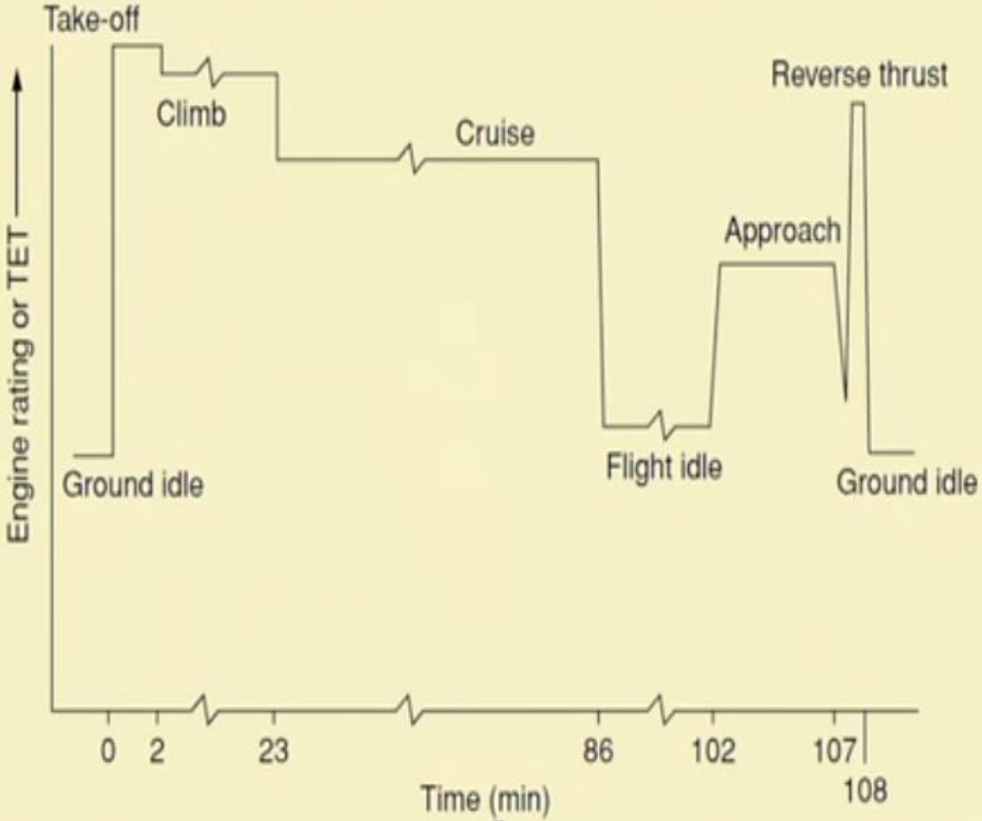
Superalloys

Turbine entry temperature (TET): Temperature of hot gases entering into the turbine arrangement. The temperature falls when mechanical work is extracted from the gas stream

Gas turbine: Jet propulsion Rolls-royce Trent 800
>800°C General Electric GE90 Boeing 777

Gas turbine: Electricity Generation 250 MW
>800°C city of a million people





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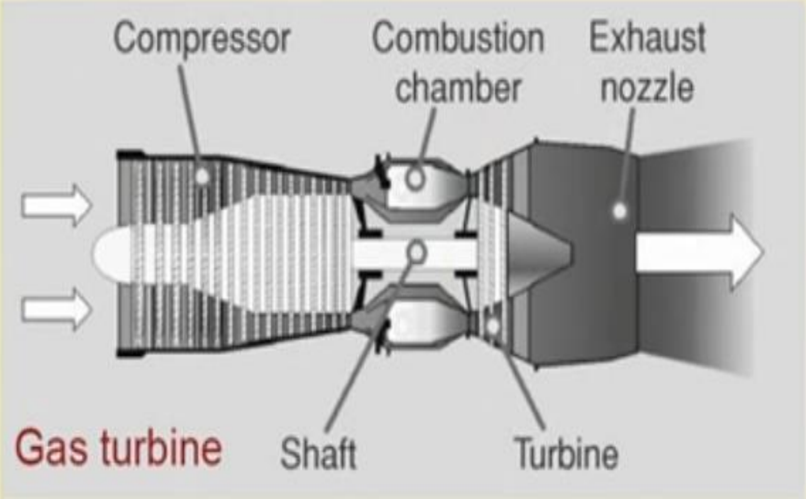
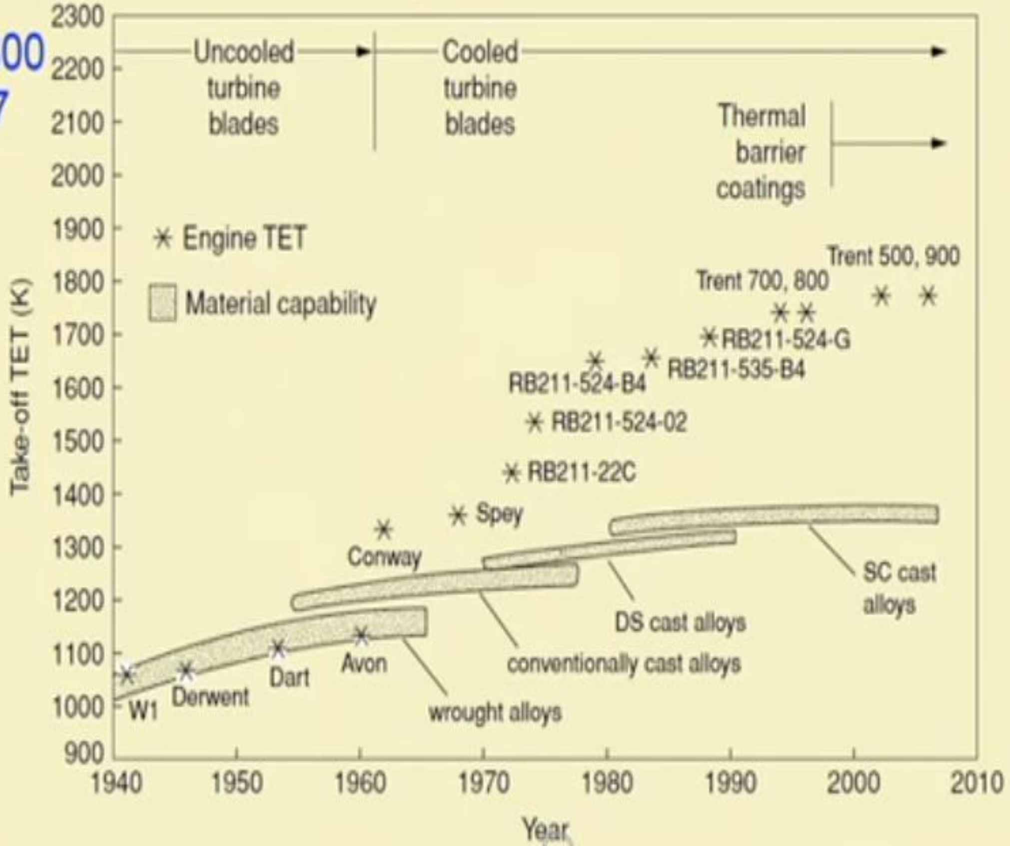
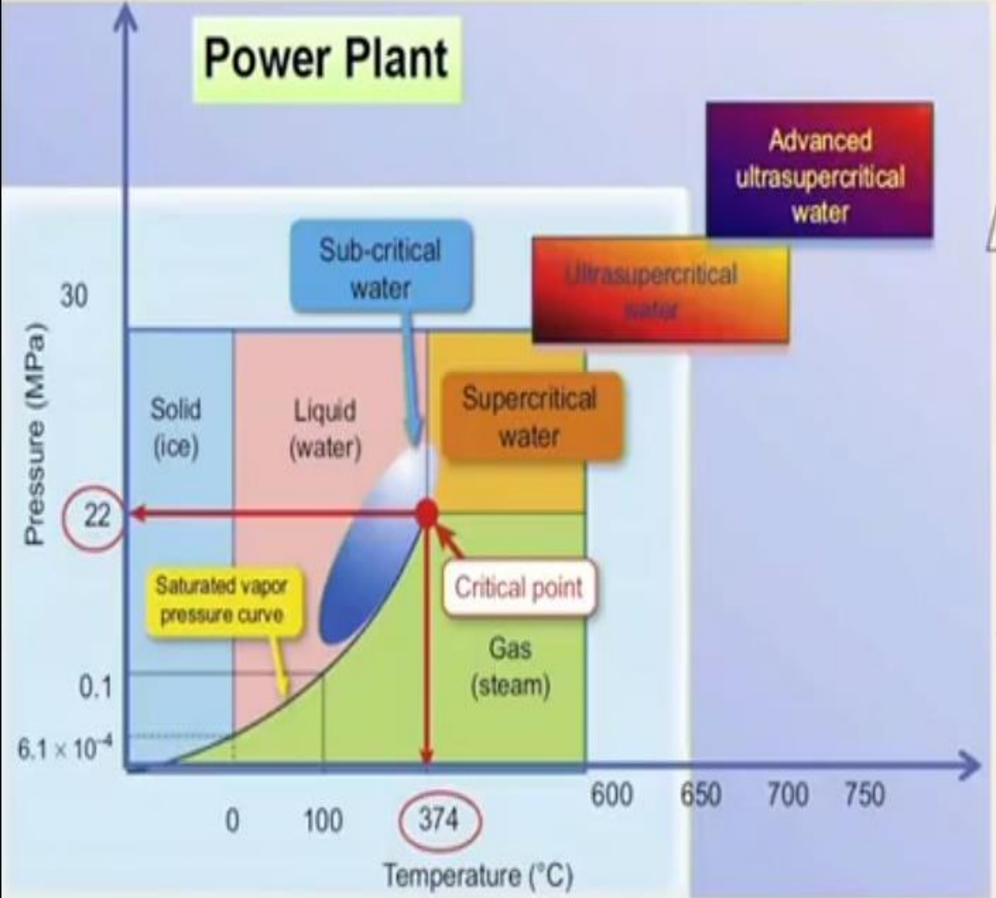
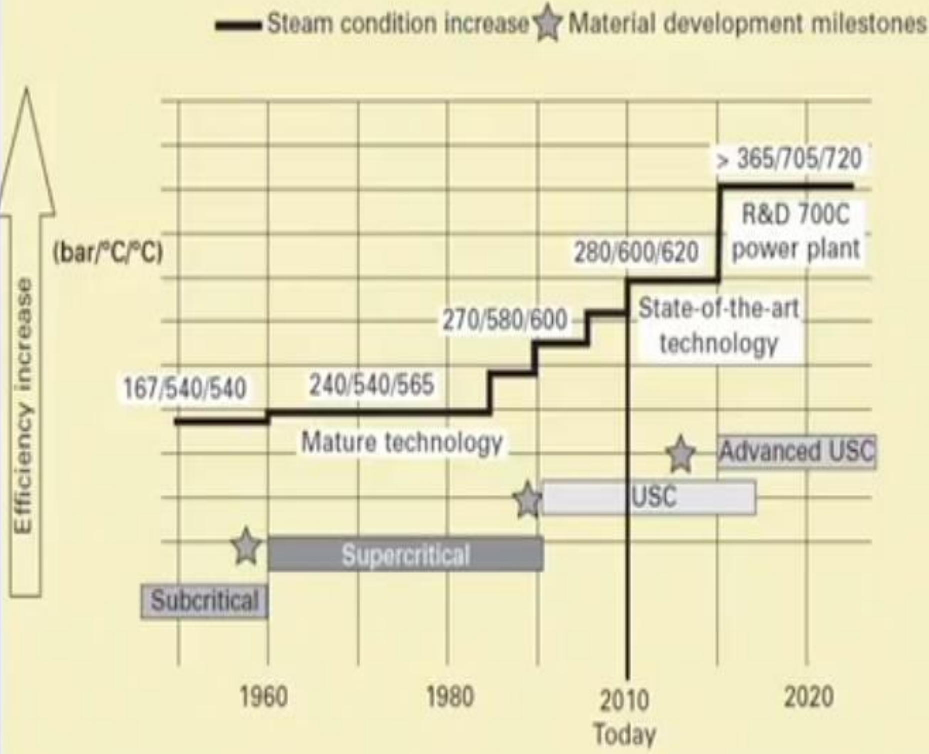




High Temperature Materials

Demand: High efficiency low emission (HELE) with carbon capture and storage (CCS)





2.1 The evolution of steam turbine operating conditions (USC = ultra supercritical).