Titanium and its alloys

Important properties

Appearance: Silvery gray-white

Melting point: 1668 °C

Density: 4.506 g/cc

Crystal structure: HCP

CTE: 8.6×10^{-6} /°C

Thermal conductivity: 21.9 W/m.K

Young's modulus: 116 GPa

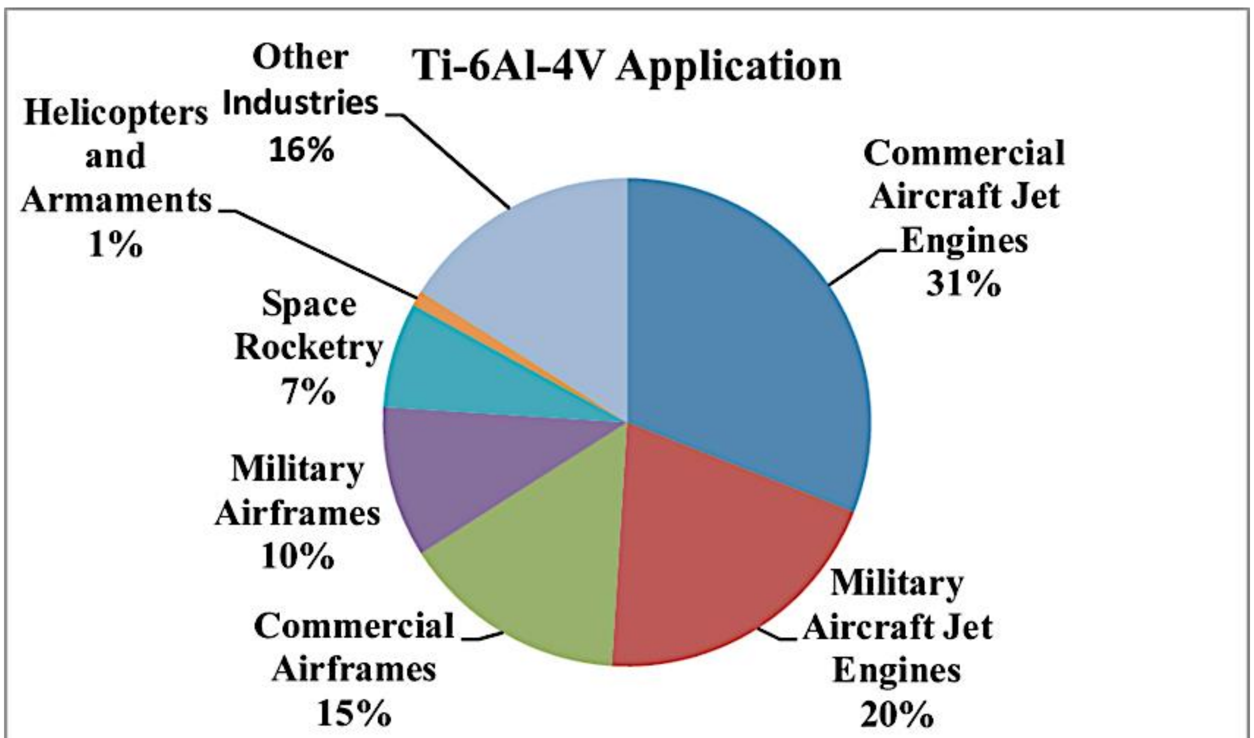
Shear modulus: 44 GPa

Titanium and its alloys

- Titanium is the fourth most abundant element in the earth's crust. It is however relatively expensive to extract titanium from ores
- Because of its lower density with respect to steel, titanium alloy structures have a high specific strength
- Titanium has excellent corrosion resistance upto around 500 °C
- At room temperature it has a HCP structure (α-titanium), which converts to BCC structure at 882 °C (β-titanium)

Titanium and its alloys

- In comparison to titanium alloys, commercially pure titanium is lower in strength and more corrosion resistant
- Typical applications include chemical process piping, valves and tanks, aircraft firewalls etc.



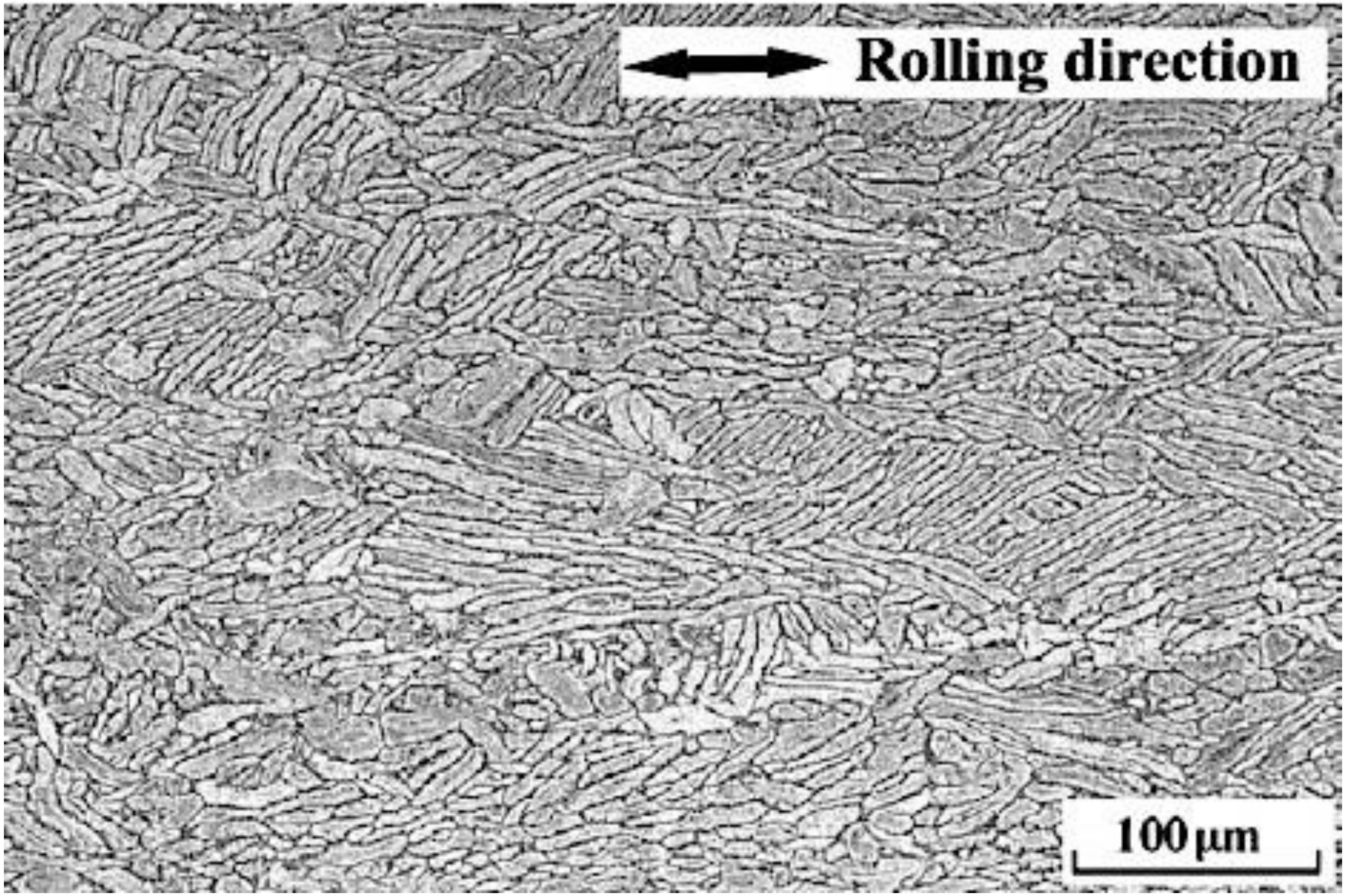
Titanium and its alloys

- Addition of alloying elements to titanium influences the alpha to beta transition temperature
- The alloying elements are classified as either alpha or beta stabilizers
  - An alpha stabilizer raises the alpha to beta transformation temperature. Aluminum is an alpha stabilizer
  - A beta stabilizer lowers the transformation temperature. Important beta stabilizers are chromium, molybdenum, vanadium, manganese and iron

Titanium and its alloys

- The relative amounts of alpha and beta stabilizers in an alloy and the heat treatments determine whether an alloy is single (α/β) phase or two phase (α-β)
- The properties of the titanium alloys are directly related to microstructure
- The single phase alloys are weldable with good ductility. Some two phase alloys are also weldable, but their welds are less ductile
- α-β alloys are stronger than the single phase α-alloys, simply because the BCC β phase is stronger than HCP α phase
- The two phase α-β alloys can be stregthened by heat treatment

Alpha titanium alloys



Optical micrograph of Ti-5Al-2.5Sn alloy

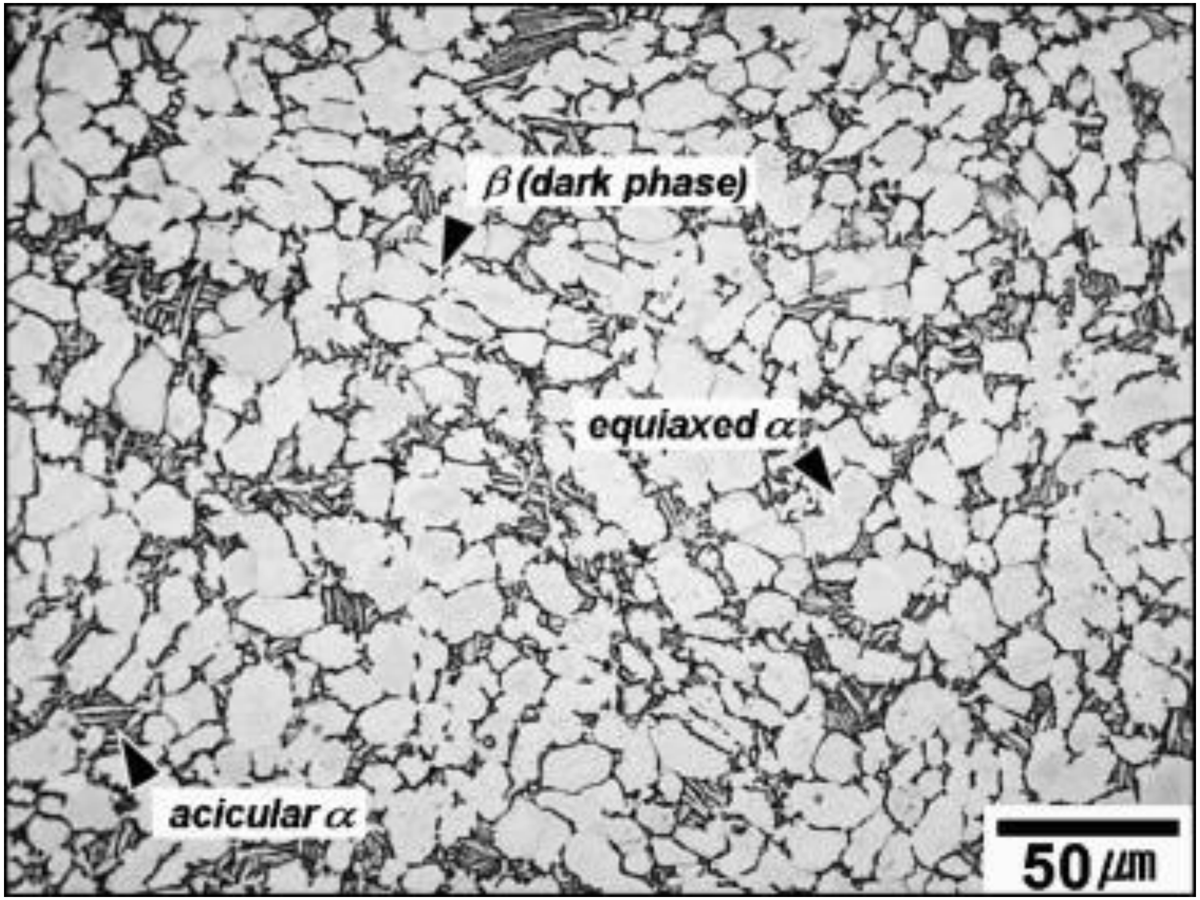
Beta titanium alloys

Optical micrograph of Ti-3Al-8V-6Cr-4Zr-4Mo beta alloy

Alpha beta titanium alloys

- α-β alloys contain a mixture of α and β phases at room temperature
- They may contain 10 – 50 wt.% β-stabilizers. If the content of β-stabilizers > 20 wt.%, weldability decreases
- Aluminum is added as α-phase stabilizer and hardener due to its solid solution strengthening effect.
- Vanadium stabilizes the ductile β-phase, providing hot workability of the alloy
- The most important α-β alloy is Ti-6Al-4V
- Titanium α-β alloys have high tensile strength and fatigue strength, good hot formability and creep resistance upto 425 °C

Alpha beta titanium alloys



Optical micrograph of Ti-6Al-4V

Applications of titanium alloys

Aerospace applications

- Due to its combination of light weight and high strength, Ti is used to reinforce airframes and enable better performance in jet engines
- Ti alloys, due to their high corrosion resistance, high specific strength and good heat resistance, is used for different spacecraft parts

Chemical industry

- Tanker trucks carrying sodium hypochlorite and sodium chromate use Ti due to its light weight, corrosion resistance and high strength
- Ti is safe and economical material for heat exchangers

Applications of titanium alloys

Biomedical applications

Main benefits of Ti for application as biomedical implants are:

- Lightweight and high strength
- Corrosion resistance
- Cost efficiency
- Non-toxic and bio-compatible
- Long lasting
- Non-ferromagnetic
- Flexibility and elasticity comparable to that of human bone

Nickel and its alloys

Important properties

Appearance: Silver with a gold tinge

Melting point: 1455 °C

Density: 8.908 g/cc

Crystal structure: fcc

CTE: 13.4×10^{-6} /°C

Thermal conductivity: 90.9 W/m.K

Young's modulus: 200 GPa

Shear modulus: 76 GPa

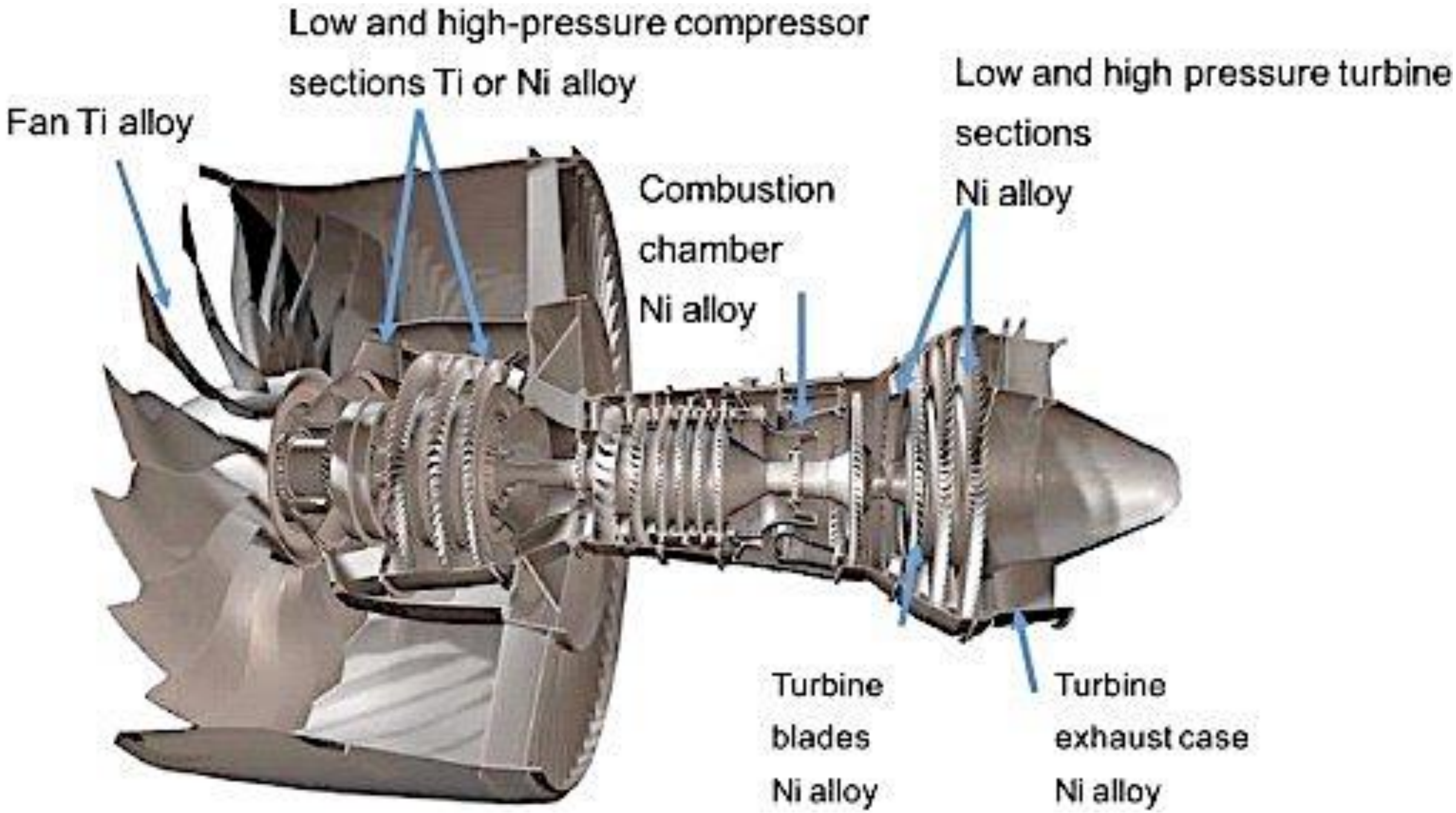
Nickel and its alloys

- Nickel is characterized by good resistance to corrosion and oxidation
- Nickel possess good workability and good mechanical properties
- Nickel forms tough, ductile solid solution alloys with many of the common metals
- Because of its high corrosion resistance and hardness, nickel makes an ideal coating for parts subjected to corrosion and wear
- The electrical conductivity of nickel, while not so high like copper and aluminum, is satisfactory for current carrying leads in many applications

Ni based superalloys

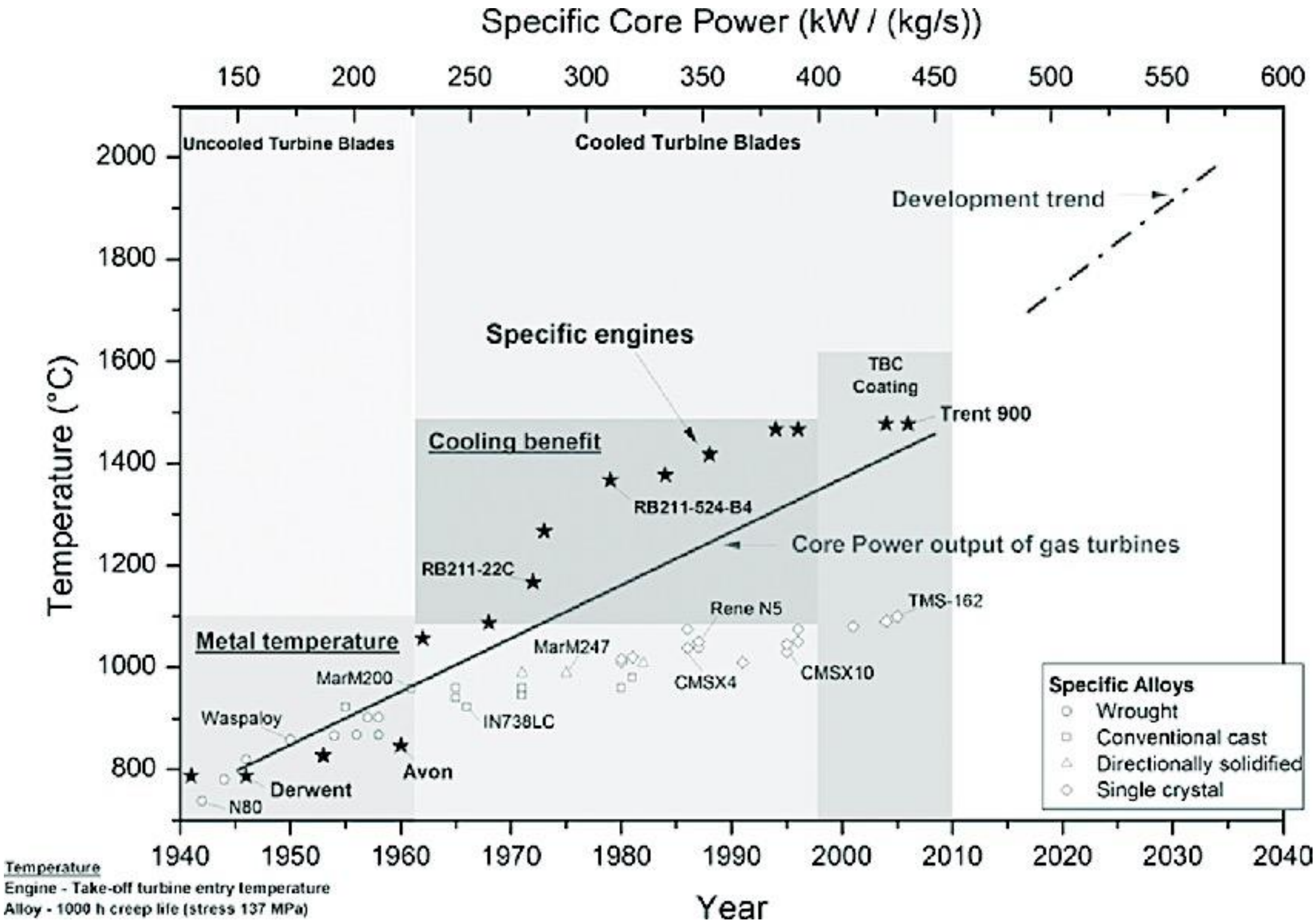
- Nickel based superalloys are a class of metallic material with exceptional properties
- These materials possess an exceptional combination of high temperature strength, toughness and resistance to degradation in corrosive or oxidizing environments
- Ni-based superalloys are widely used in aircraft and power generating turbines, rocket engines, nuclear power and chemical processing plants
- Some superalloys can even tolerate average temperatures over 1050 °C with occassional excursions above 1200 °C

Ni based superalloys



Ni-based superalloys in a jet engine

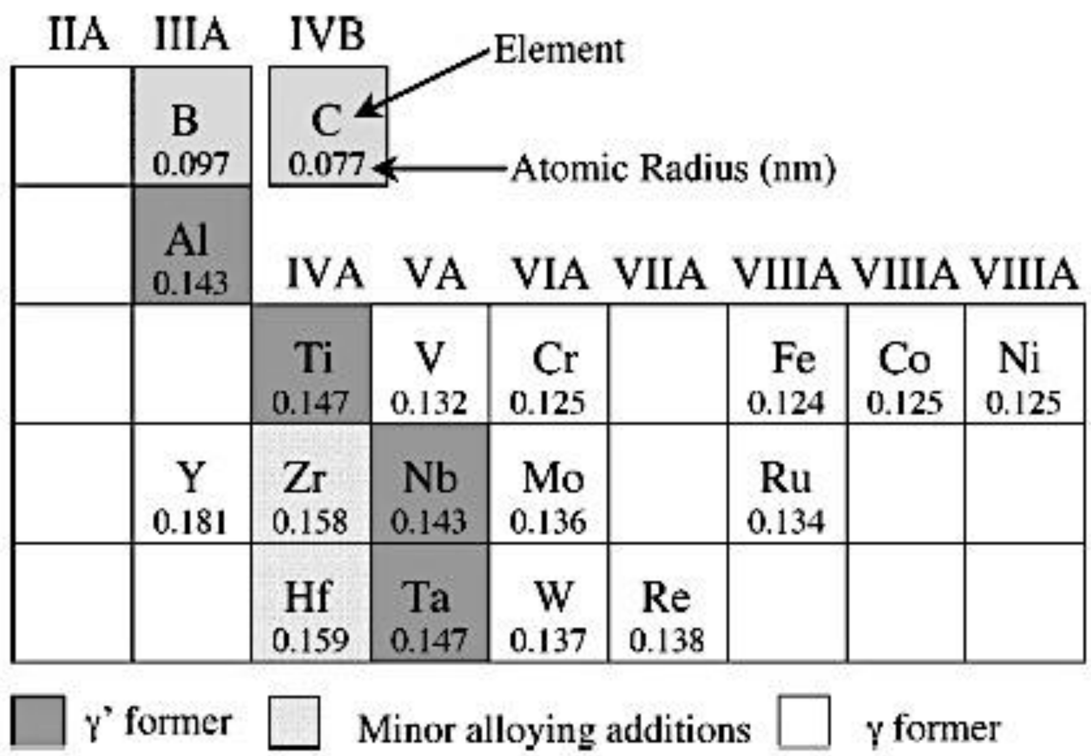
Ni based superalloys



Development trend of Ni-base superalloys

Physical metallurgy of Ni-superalloys

- FCC nickel is the main constituent of Ni-based superalloys
- Apart from nickel, superalloys contain upto 40 wt.% of five to ten other alloying elements
- The main alloying elements in superalloys are marked below



Physical metallurgy of Ni-superalloys

Most Ni-based superalloys contain 10-20 wt.% Cr, up to 8 wt.% Al and Ti, 5-10 wt.% Co and small amounts of B, Zr and C

Table I. Chemical compositions (wt%) of selected aerospace Ni-based superalloys.[4]

Alloy	Ni	Cr	Co	Mo	W	Zr	Ti	Al	Fe	C	Other
CM247LC	Bal.	8.0	9.0	0.5	10	0.01	0.7	5.6		0.07	1.4Hf, 3.2Ta, 0.015B
N18	Bal.	11.5	15.5	6.5	–	–	4.3	4.3	–	0.02	0.015B, 0.5Hf
RR1000	Bal.	15.0	18.5	5.0	–	0.06	3.6	3.0	–	0.027	0.015B, 2Ta, 0.5Hf
Astroloy	Bal.	15.0	15.0	5.25	–	0.06	3.5	4.4	<0.3	0.06	0.03B
Udimet 720	Bal.	18.0	14.8	3.0	1.25	0.03	5	2.5	–	0.035	–
René 41	Bal.	19.0	11.0	10.0	–	–	3.1	1.5	<0.3	0.09	0.01B
Waspaloy	Bal.	19.5	13.5	4.3	–	0.09	3.0	1.4	2.0	0.07	0.06B

Physical metallurgy of Ni-superalloys

- The Ni-Al system is the binary basis for compositions of Ni-based superalloys
- As the level of Al added to γ-Ni increases, a precipitate phase with nominal composition of Ni_3Al and designated as γ' is formed
- The precipitation and growth kinetics of γ' are strongly dependent upon the rate at which the alloy is cooled through the solvus temperature
- The γ and the γ' phases are the main constituents of Ni-based superalloys and the presence of a high volume fraction of γ' phase is key to strengthening of these materials.

Physical metallurgy of Ni-superalloys

- Generally refractory elements with atomic radii compared to that of Ni, such as Mo, W, Nb and Re are added in superalloys for soild solution strengthening of the γ-phase
- Additions of Ti, Ta and Nb contribute to the formation and strengthening of the Ni_3(Al, Ti, Ta, Nb) γ' phase
- Additions of Cr, Y, La typically enhance the oxidation/corrosion resistance
- Minor additions of B, C, Hf and Zr form borides and carbides located at grain boundaries. They are important in controlling the grain size
- C exhibits a strong affinity for elements such as Zr, Ti, Ta, Nb etc. and form carbides

Physical metallurgy of Ni-superalloys

Roles of various alloying elements in Ni-based superalloys

Solid-solution strengtheners: Co, Cr, Fe, Mo, W, Ta

Carbide formers: W, Ta, Ti, Nb, Mo, Cr

γ' formers: Al, Ti

Hardening precipitates/intermetallics: Al, Ti, Nb

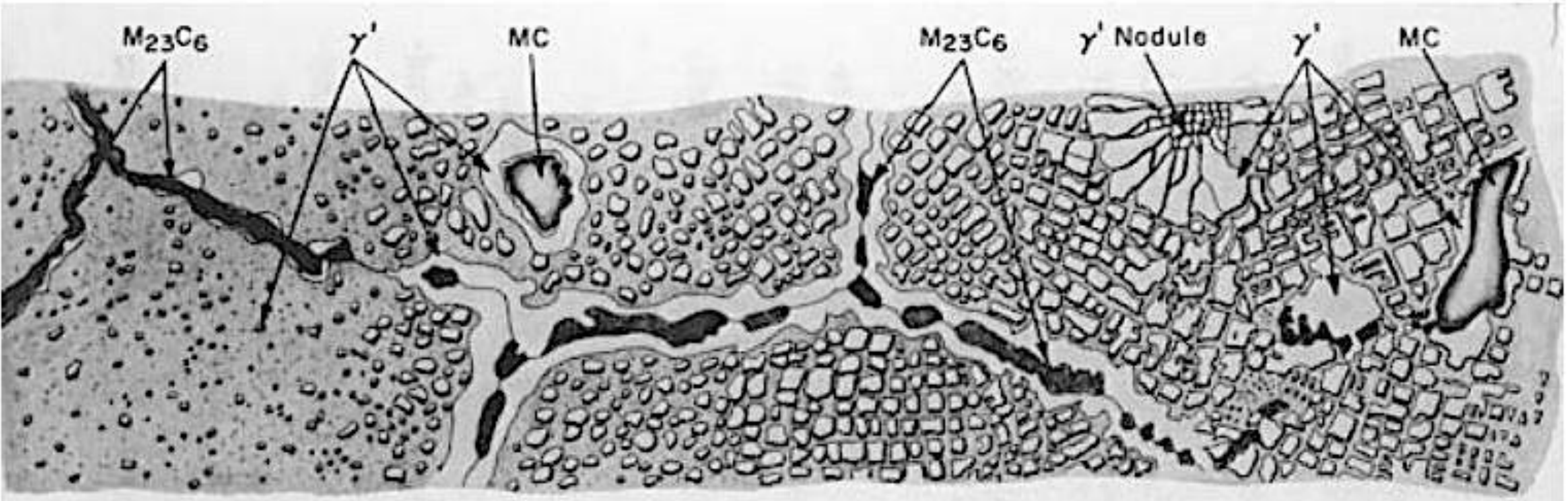
Oxidation resistance: Cr, Y, La

Improves hot corrosion resistance: La, Th

Causes grain boundary segregation: B, C, Zr, Hf

Sulfidation resistance: Cr

Physical metallurgy of Ni-superalloys

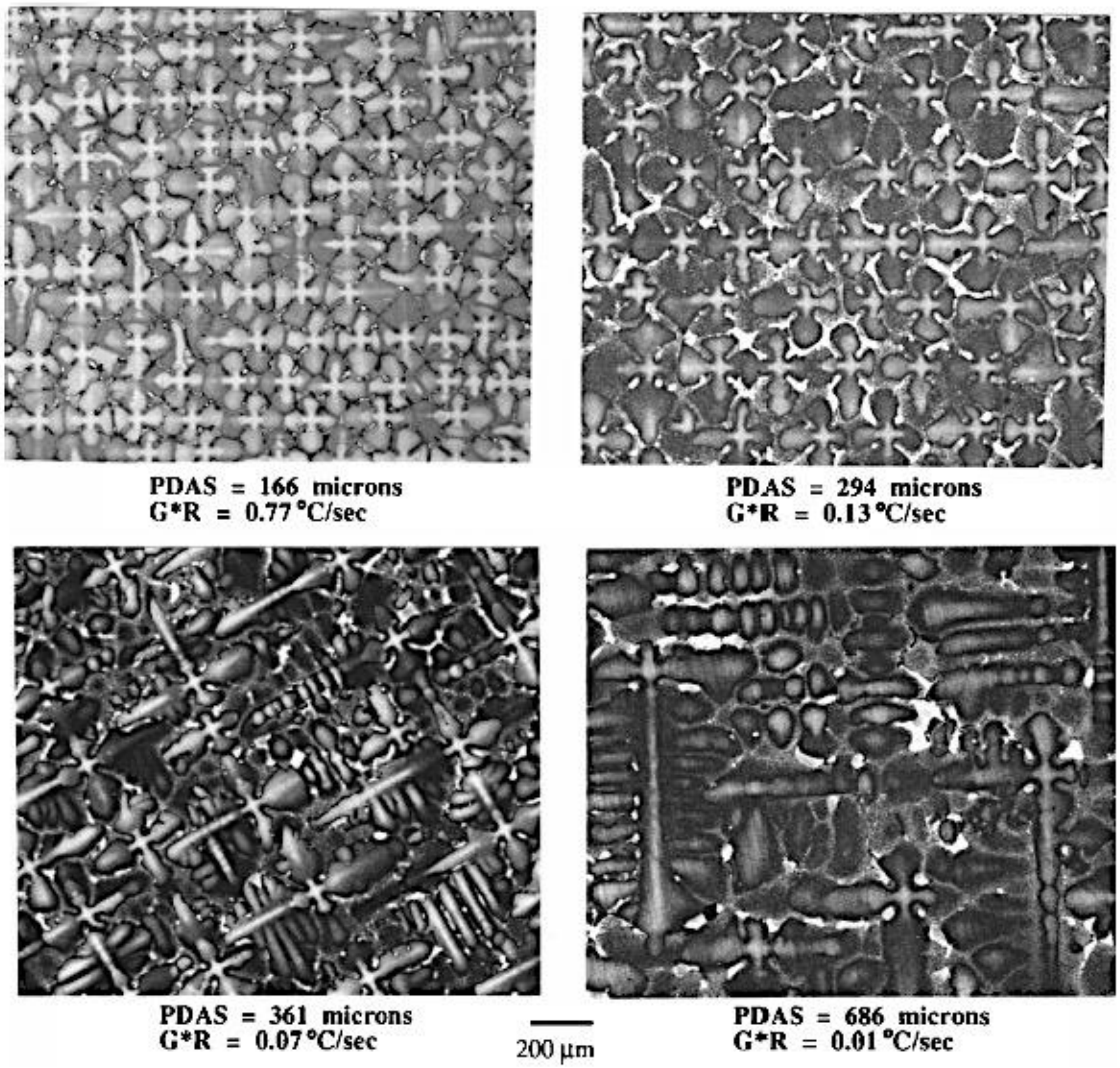


Schematic of the evolution of microstructure in Ni-based superalloys, labeled with different carbides and other phases

Processing aspects of Ni-superalloys

- In terms of processing, Ni-based superalloys classified into following categories: cast alloys, directionally solidified alloys and wrought alloys
- Investment casting is the primary casting process for fabrication of Ni-based superalloy components with complex shapes
- Castings may be equiaxed, columnar grained or single crystal
- In all casting processes the final microstructure and properties are sensitive to the thermal conditions present during solidification of the casting
- Solidification during casting is dendritic in nature and associated with it is segregation of alloying elements

Processing aspects of Ni-superalloys



Variation in dendritic arm spacing with cooling rate in cast Ni-superalloys

Processing aspects of Ni-superalloys

- Although cast Ni-based superalloys possess good high temperature properties, improved processing characteristics can result into better properties
- Creep rupture resistance can be improved by orienting the grain boundaries parallel to the direction of applied stress, or completely removing the boundaries
- This can be achieved by directionally solidification processing

Processing aspects of Ni-superalloys

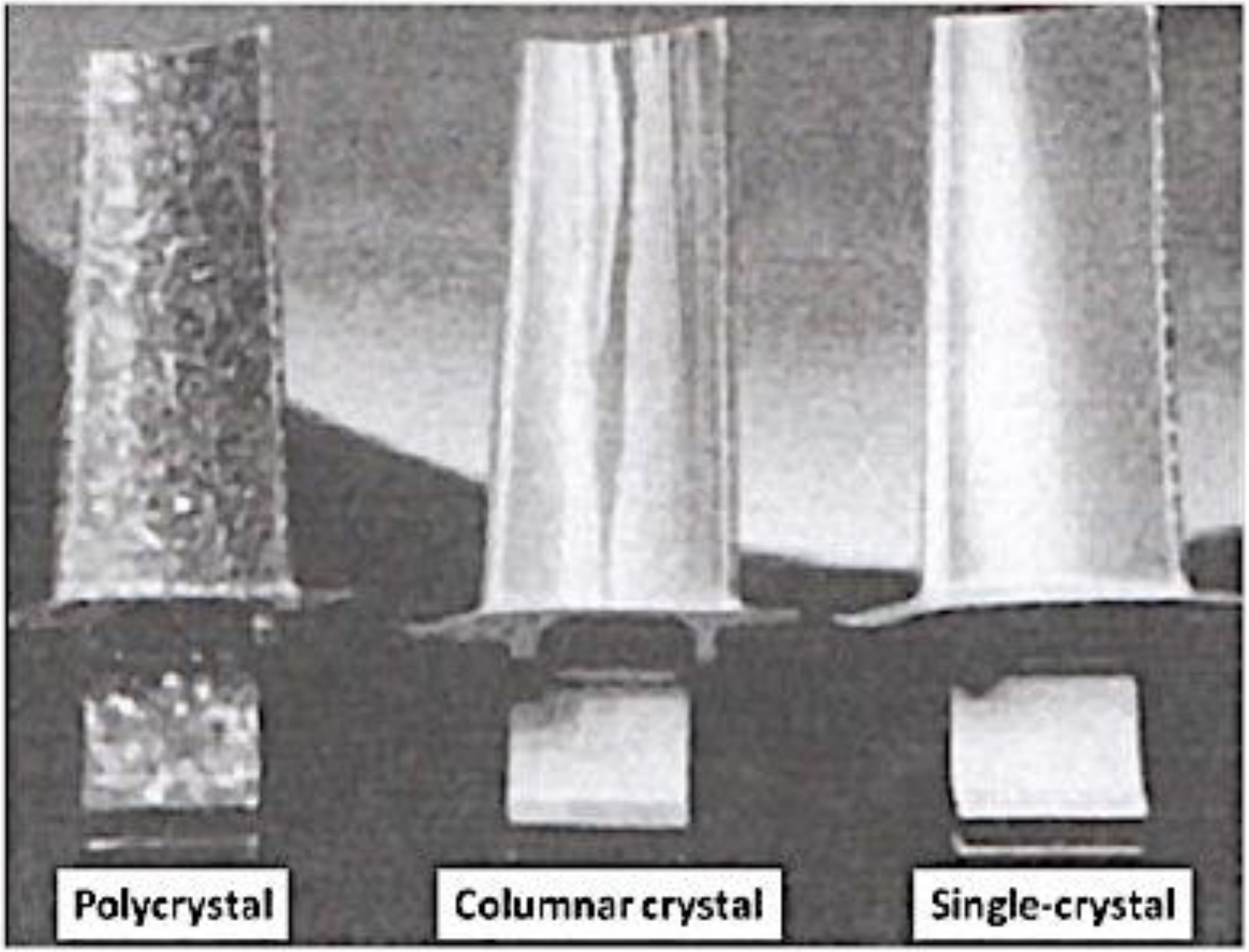


Fig. 13 - Turbine blades made of nickel base alloys with various grain structures [17].

Processing aspects of Ni-superalloys

- Wrought alloys are fabricated by remelting the cast ingots to form a secondary ingot or powder for further deformation processing
- This secondary processing is necessary as the high temperature properties of the superalloys are very sensitive to the structural inhomogenities, which are typically present in large cast ingots
- Powder metallurgy routes have been developed to overcome the difficulties associated with casting defects and it is a viable route for fabrication of advanced high strength Ni-based superalloy components

Properties of Ni-based superalloys

- Superalloys constitute a large fraction of materials for construction in turbine engines due to their unique combination of physical and mechanical properties
- Ni-based superalloys have relatively high yield strength and ultimate tensile strengths, with yield strengths in the range of 900-1300 MPa and ultimate tensile strengths in the range of 1200-1600 MPa at room temperature
- Strengthening in two phase superalloys arises from multiple sources → solid solution strengthening, grain size strengthening and interaction of dislocations with precipitates