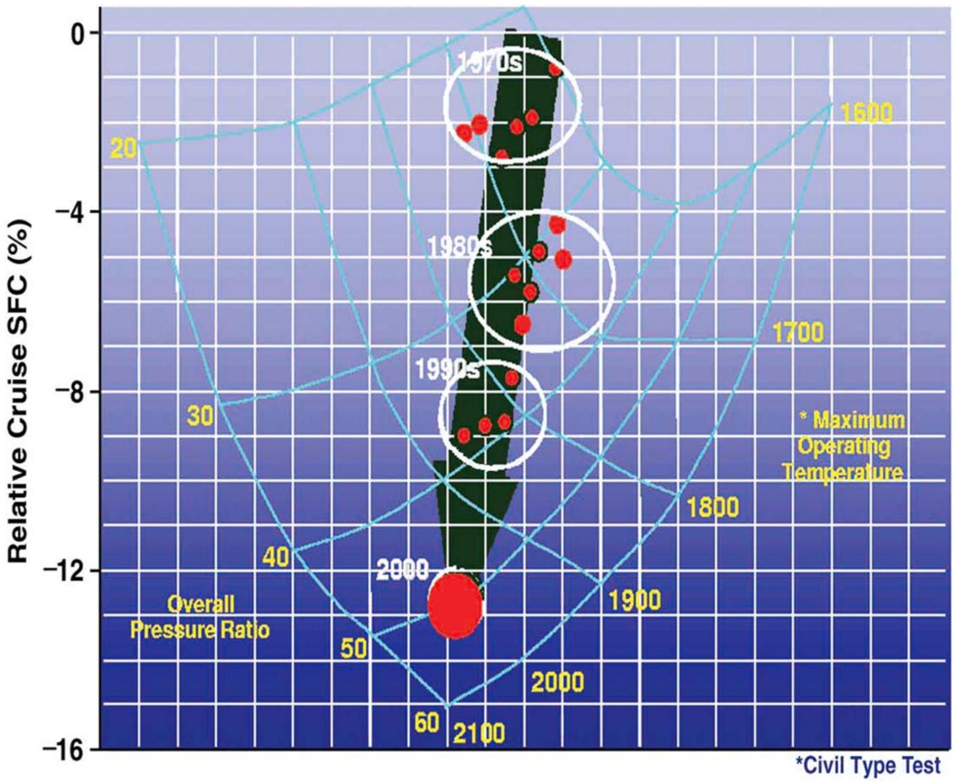
High temperature materials

José M. Torralba
Universidad Carlos III de Madrid (Spain)
josemanuel.torralba@madrid.org

Materials competition for high temperature

Improvement in efficiency with increasing turbine operating temperatures and pressures

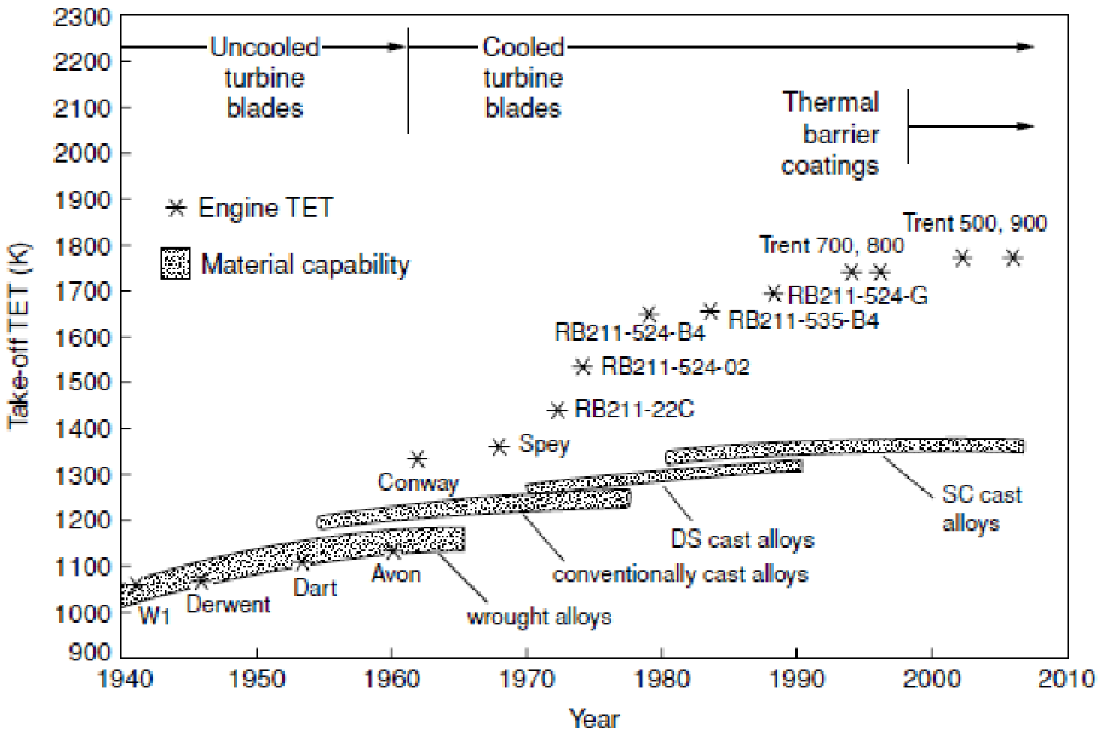


- Specific fuel Consumption (SFC) is a function of:
  - overall pressure ratio (OPR)
  - turbine entry temperature (TET)
  - component efficiency
  - propulsive efficiency
  - installed drag

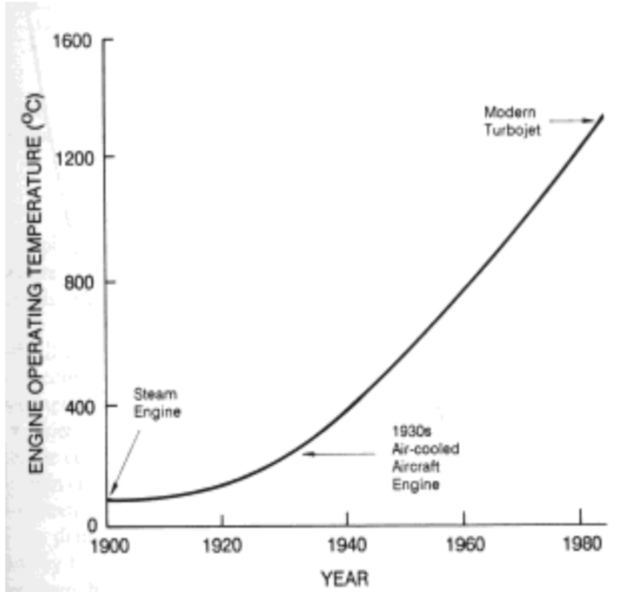
Why is temperature important? The efficiency of the engine is very sensitive to hot zone temperature. Even small increases in the temperature to which turbine blades can be exposed produces significant gains in engine efficiency

Materials competition for high temperature

Increases in working temperature in airplane engines



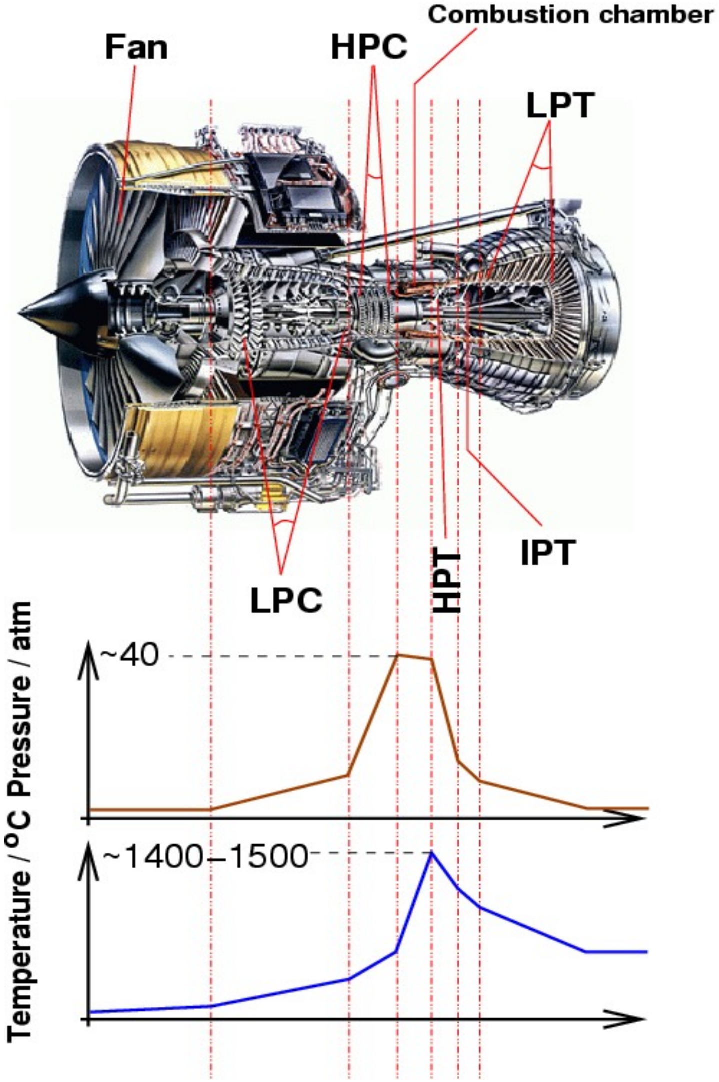
Evolution of the turbine entry temperature (TET capability of Roll-Royce´s civil Aero engines, from 1940 to the present day



URE 1.2 The steep climb in operating temperatures of engines during this centur
e possible by modern materials.

Materials competition for high temperature

The gas turbine



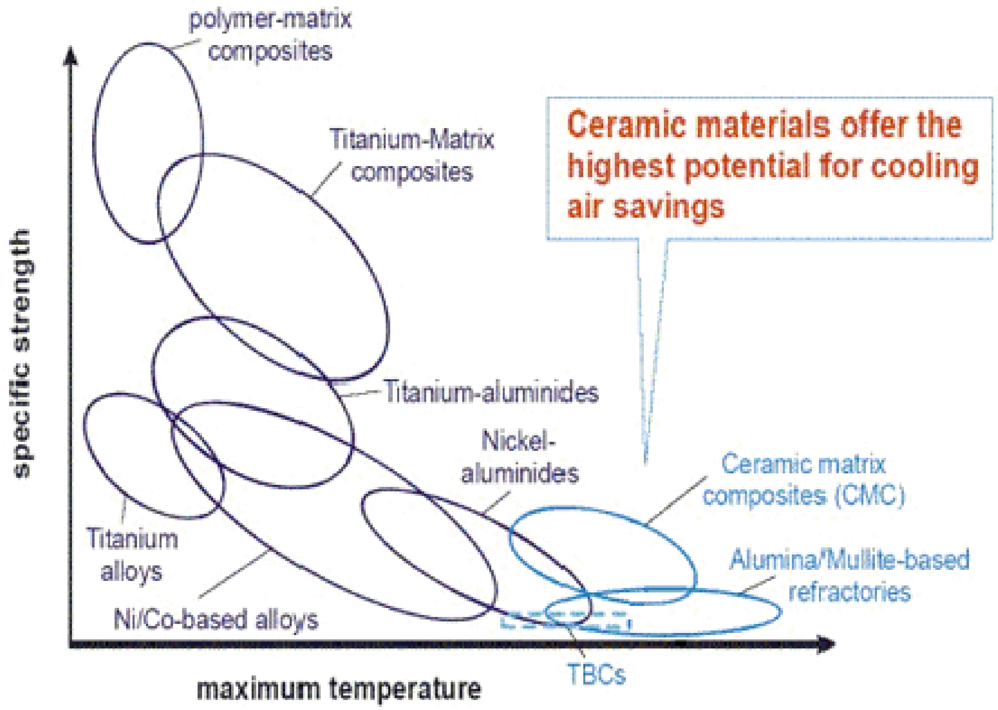
Pressure and temperature distributions in the gas turbine

Materials competition for high temperature

Main requirements in materials for gas turbines

- ❑ High melting point
- ❑ Good oxidation/corrosion behaviour
- ❑ High temperature performance
- ❑ Microstructural stability at high temperature
- ❑ Low density
- ❑ High stiffness
- ❑ Easy to process
- ❑ Cost

Materials competition for high temperature



Refractory Materials (Engines)

	T_{melt}	
Carbon	3800	oxidizes
Tungsten	3650	oxidizes
MgO	3100	brittle (room T)
SiC	3000	brittle (room T)
Mo	2880	oxidizes
Nb	2740	oxidizes
Al_2O_3	2290	brittle (room T)
Cr	2160	brittle
Zr	2125	expensive (nuclear fuel elements)
Pt	2042	expensive (crucibles)
Fe	1808	oxidizes
Ni	1726	√

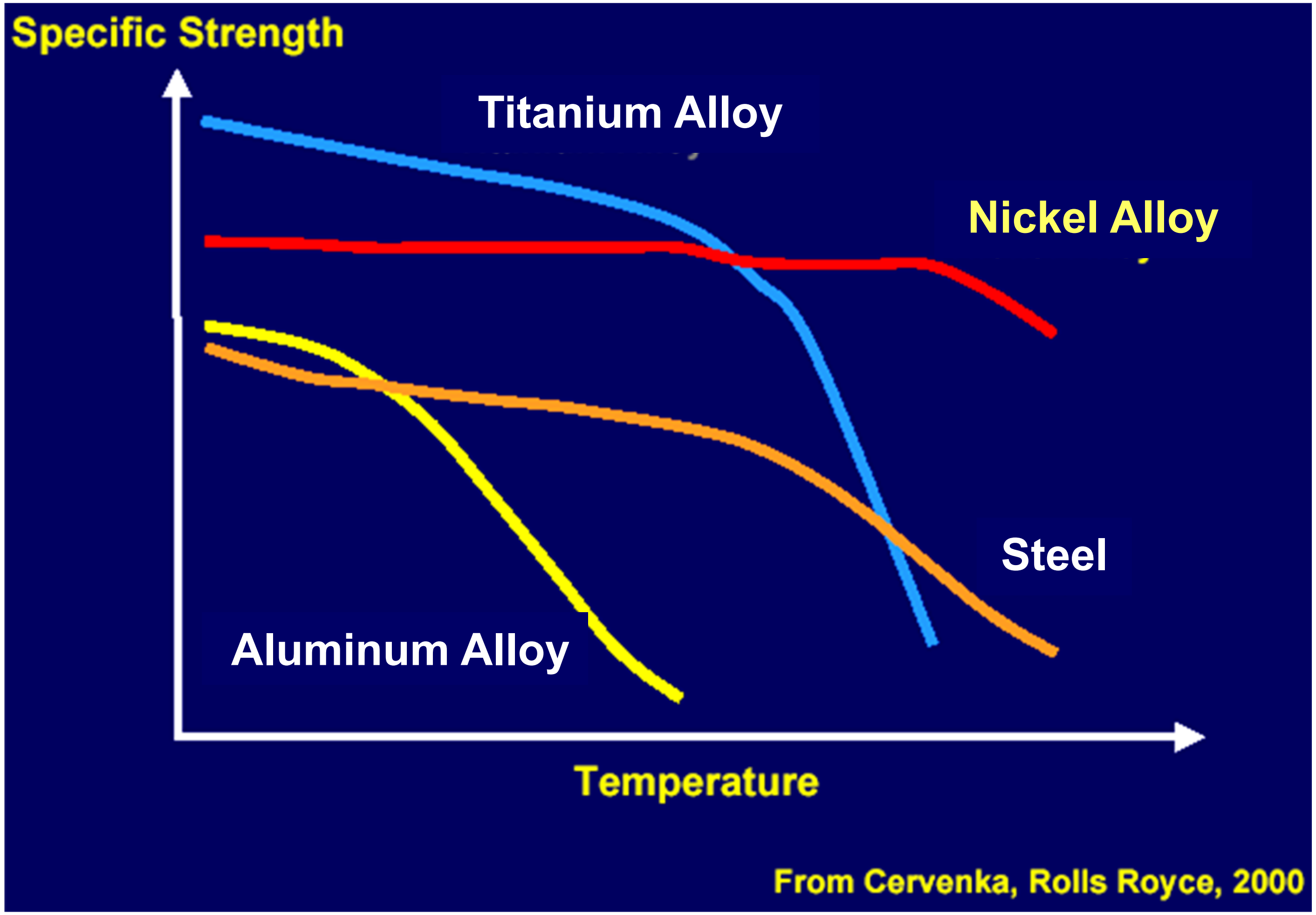
Materials competition for high temperature

Main requirements in materials for gas turbines

- ❑ High melting point
- ❑ Good oxidation/corrosion behaviour
- ❑ High temperature performance
- ❑ Microstructural stability at high temperature
- ❑ Low density
- ❑ High stiffness
- ❑ Easy to process
- ❑ Cost
- ❑ Reliable performance

Materials competition for high temperature

Strength as function of the temperature in metals



Materials competition for high temperature

Main materials used in high temperature applications

- Ti base alloys
- Superalloys
- Intermetallics
- Ceramic matrix composites

Superalloys

What is a Superalloy?

- A superalloy is a metallic alloy which can be used at unusually high homologous temperatures, often in excess of 0.8 Tm
- Amazing property of superalloys: they become stronger at higher temperature :
  - Able to maintain high strengths
  - Good corrosion and oxidation resistance (Cr, Al)
  - Good resistance to creep and rupture
  - Good fatigue behaviour
- 3 main classes of superalloys:
  - Ni – Base
  - Ni-Fe – Base
  - Co – Base

Superalloys

Ni-based superalloys

- "Superalloys" originated with the Ni-Cr alloys used for heating elements in furnaces.
- They are based on the Ni-Cr-Al ternary system but have many other alloy additions (can have up to 14 different alloying elements).
- Since 1950, these alloys have predominated in the range 750-980° C.
- Are "super" because of the γ ' precipitate strengthening.
  γ ' ("gamma-prime") = Ni_3Al is an intermetallic compound (ordered fcc structure) that is coherent with the matrix and whose strength increases with temperature.

Superalloys

Nickel-Iron Base Superalloys

- Fe is added to replace some of Ni as it has lower cost. Lowering the properties as compared with nickel base superalloy.
- Most Ni-Fe-based superalloys designed so that they have an austenitic FCC matrix :
  - Contain 25-45%Ni and 15-60%Fe.
  - 28 %Cr – oxidation resistance
  - 1-6 %Mo - solid solution strengthening
- Solid solution strengtheners: – Cr, Mo, Ti, Al, Nb
- Precipitation strengtheners:
  - Ti, Al, Nb
  - combine with Ni to form intermetallic phases
- Lower nickel contents mean they cannot be used at as high temperatures as the Ni-base superalloys (650-815° C)

Superalloys

Compositional ranges of mayor alloying additions in superalloys

Element	Range, %	
	Fe-Ni- and Ni-base	Co-base
Cr	5–25	19–30
Mo, W	0–12	0–11
Al	0–6	0–4.5
Ti	0–6	0–4
Co	0–20	. . .
Ni	. . .	0–22
Nb	0–5	0–4
Ta	0–12	0–9
Re	0–6	0–2

Superalloy commercial names:

NiMonic, Hastelloy, Inconel, Incoloy, Rene, Udimet,

Pyromet, Haynes, MAR, Astroloy, Discaloy

Superalloys

Major phases in Superalloys

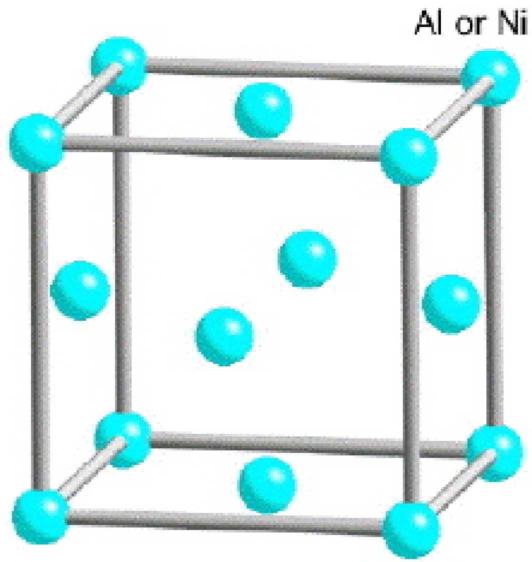
The major phases present in the nickel-base superalloys:

- γ (gamma) phase – the continuous matrix of FCC.
- γ’ (gamma prime) phase – the major precipitate phase
- Carbides –various types, mainly $M_{23}C_6$ and MC. M = metal
- γ’’ (gamma double prime) phase – Ni and Nb combine to form a BCT Ni_3Nb coherent precipitate found in Ni-Fe alloys.
  - Provides strength at low and intermediate temperatures
  - Unstable above 650 ° C
- Borides formed at grain boundaries
- Topologically close-packed (TCP) type phases-

Superalloys

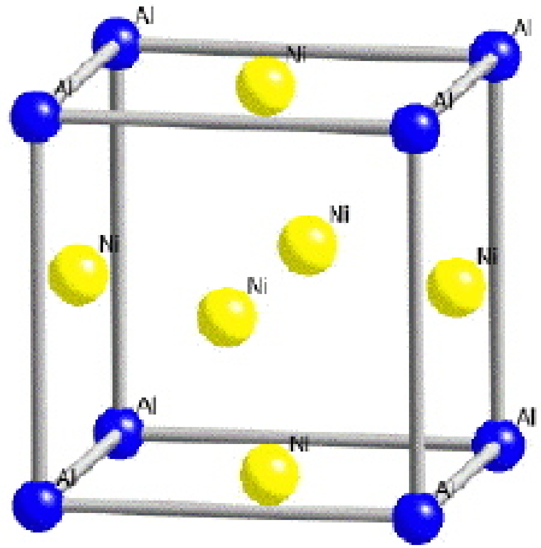
Major phases in Superalloys

γ **(gamma**) = face-centered-cubic (FCC) nickel-based continuous **matrix** with high percentage of solid solution elements (Co, Cr, Mo, and W)



γ**' = gamma prime** Ni_3X precipitate (X = Al, Ti and Si)

- Same crystal structure (FCC)
- Similar lattice parameter (coherent precipitate)
- Ni_3X ordered FCC structure

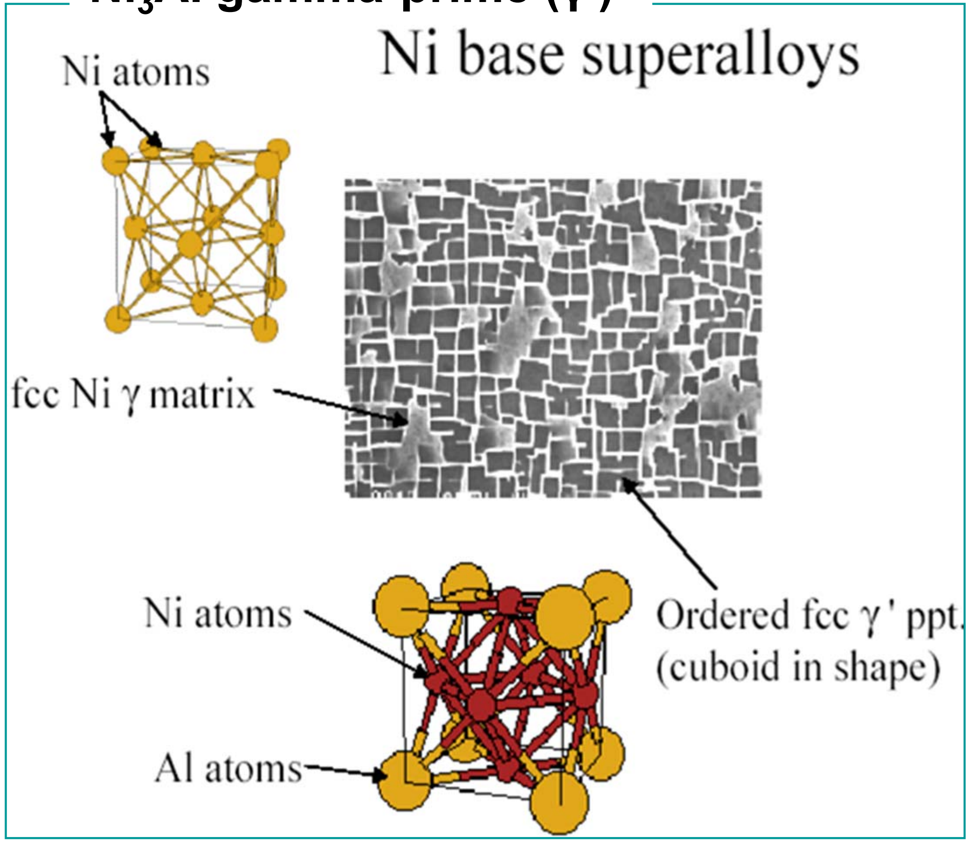


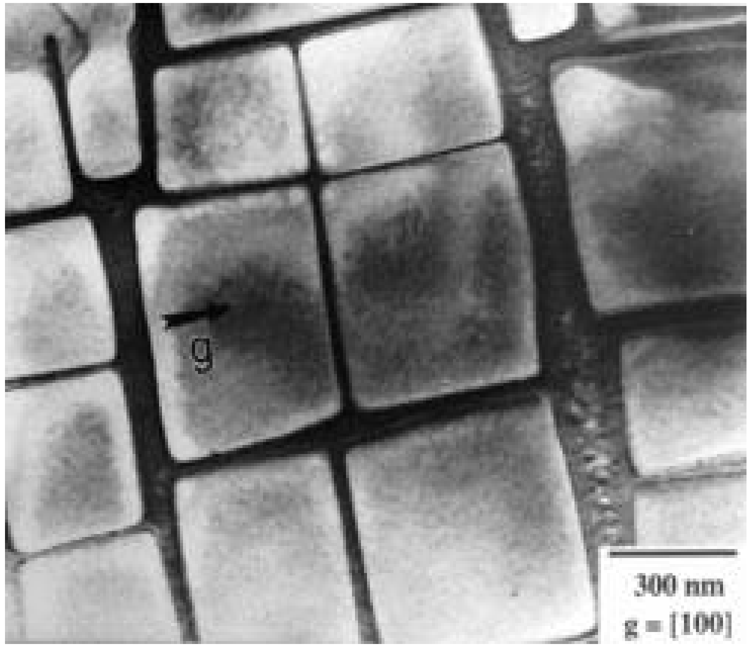
Superalloys

Microstructure and Strengthening Mechanisms

Major phases in Superalloys

Ni_3Al gamma-prime (γ')





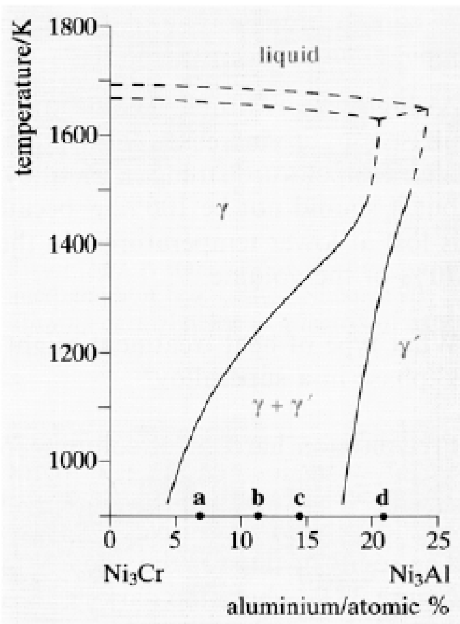
TEM micrograph showing a large fraction of cuboidal γ' particles in a γ matrix

The phase relationships allow a very large volume fraction of cuboidal γ' to be precipitated in the matrix: this is a very effective barrier to dislocation creep

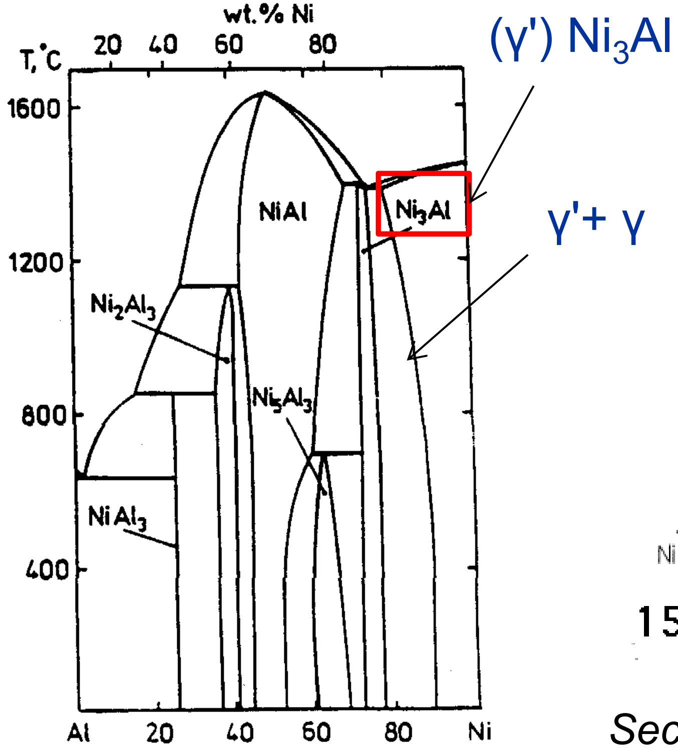
Superalloys

Major phases in Superalloys

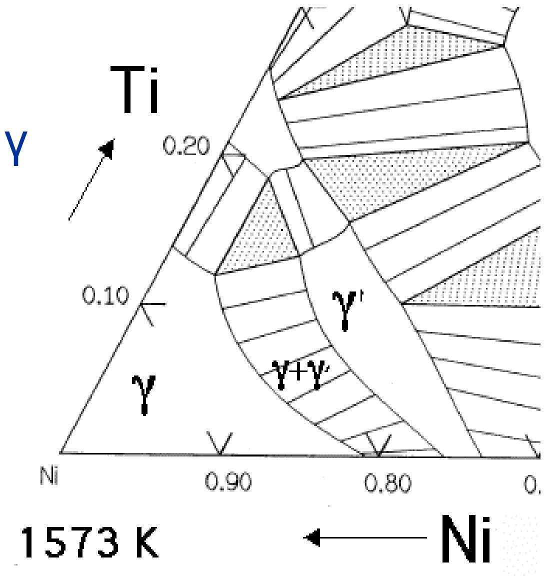
- Solutes in nickel based superalloys: Cr, Al, Ti
- Two-phase equilibrium microstructure: gamma (γ) and gamma-prime (γ') Ni3Al.



The "pseudo-binary" phase diagram for certain Ni-Al-Cr alloys



Ni-Al phase diagram



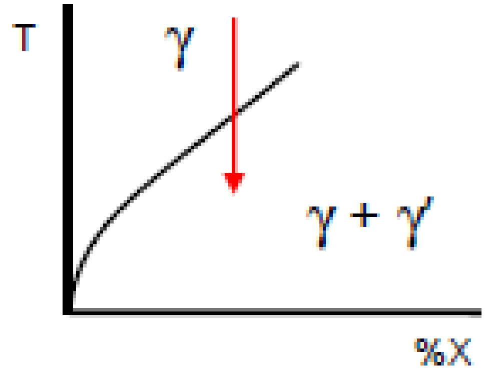
Section of ternary Ni-Al Ti phase diagram

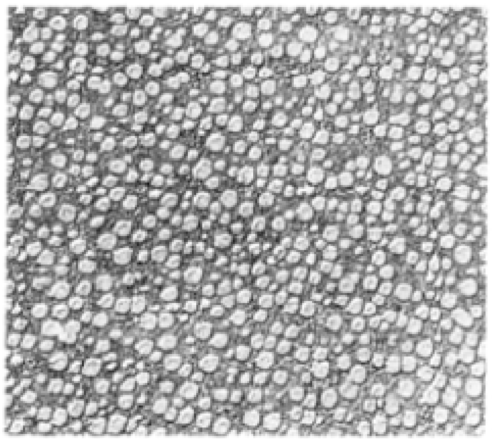
Superalloys

Major phases in Superalloys

Ni_3Al gamma-prime (γ')

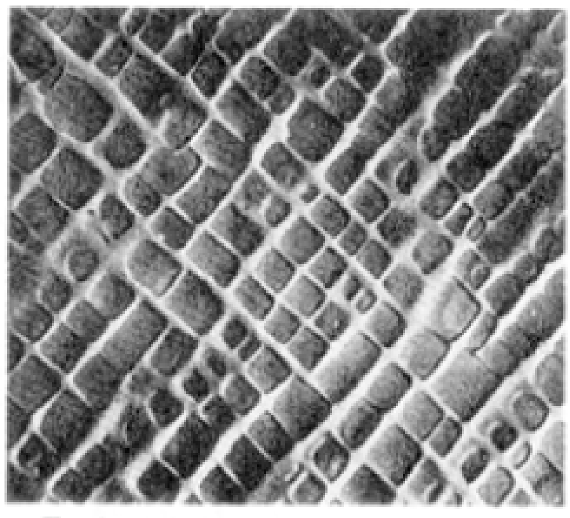
- Fully coherent across all interfacial planes
- Very low energy
- Very good creep resistant properties
- Remain coherent with different shapes
- Change in morphology related to a matrix-precipitate m
  - Spheroids for 0 to 0.2% mismatches
  - Cuboidal for mismatches of 0.5 to 1%
  - Plate like at mismatches above about 1.25%.





Spheroids in Udinet 500, typical of early low f alloys

Cuboids IN 100, typical of later high f alloys



Superalloys

Microstructure and Strengthening Mechanisms

Major phases in Superalloys

Topologically Close-Packed Phases (TCP's)

These are generally undesirable, brittle phases that can form during heat treatment or service:

- TCPs (Sigma (σ), Mu (μ), Laves, etc.) usually form as plates or needles
- TCPs are potentially damaging for two reasons: they tie up γ and γ' strengthening elements in a non-useful form, thus reducing creep strength, and they can act as crack initiators because of their brittle nature.

Superalloys

Microstructure and Strengthening Mechanisms

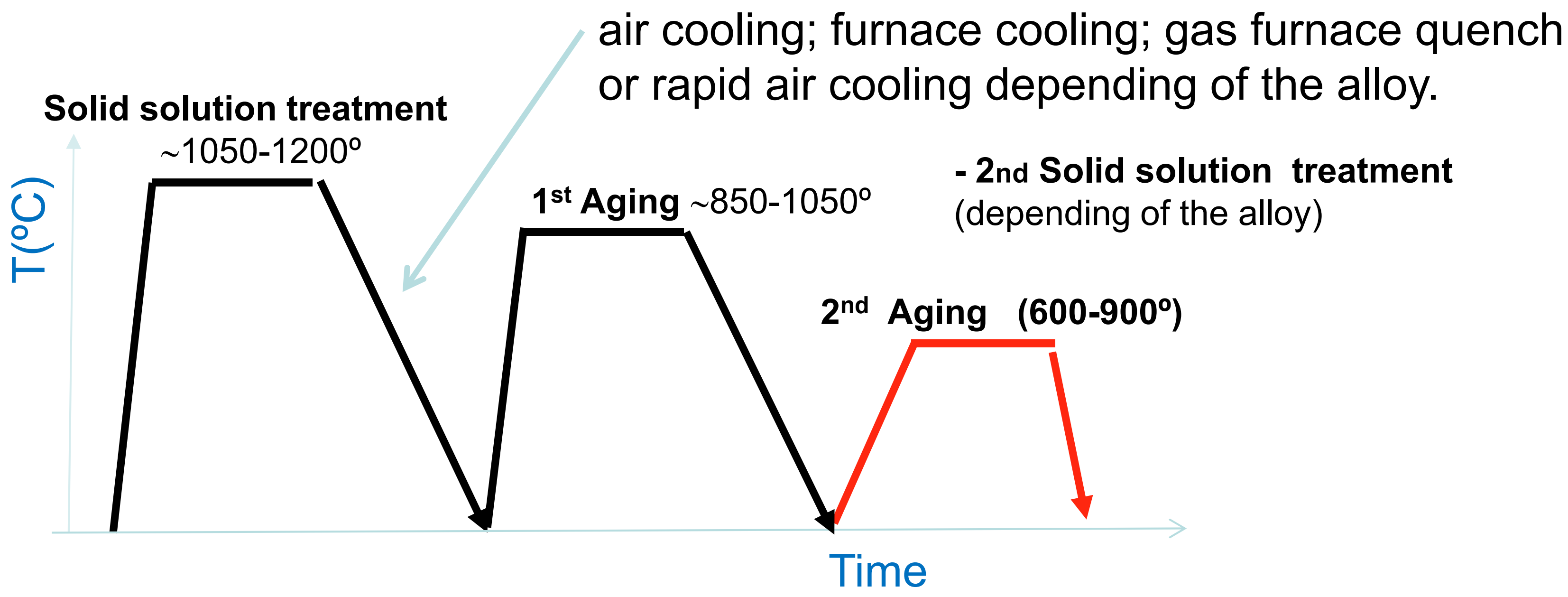
Strengthening mechanisms in superalloys:

- Solid solution strengthening (Mo and W)
- Addition of elements, e.g., Co which decrease the solubility of others to promote precipitation of intermetallics
- Al and Ti to form ordered FCC intermetallic precipitates of γ' -phase [Ni_3Al], [Ni_3Ti]
- Carbides on grain boundaries (pin boundaries to stop shear) i.e. control grain boundary sliding
- Small additions of B and Zr which segregate to the grain boundaries and retard sliding process and grain boundary diffusional process
- Large grains; columnar grains; single crystal – to stop grain boundary shear

Superalloys

Microstructure and Strengthening Mechanisms

Precipitation Hardening

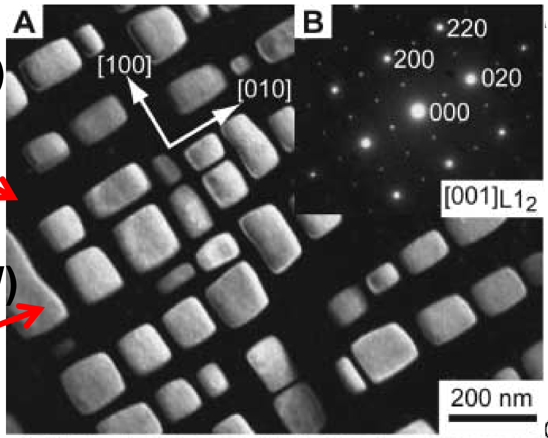


γ' phase – precipitated in nickel superalloys by precipitation hardening heat treatments

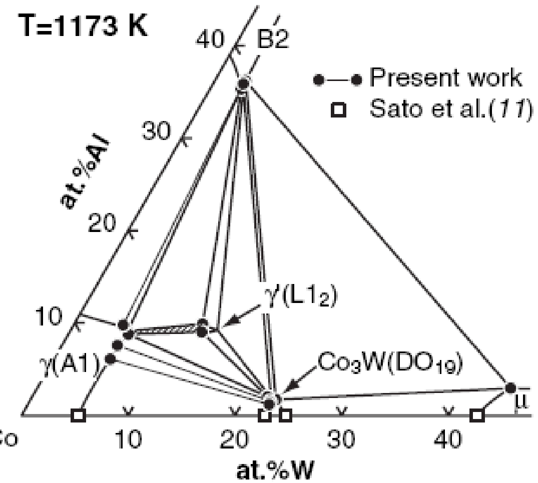
- Solution heat treatment to dissolve nearly all γ' and carbides. Some γ' can form upon air cooling from the solution treatment temperature
- 1st Aging: coarsen the γ' that is formed upon cooling, and precipitate additional γ'
- 2nd Aging: precipitate finer γ'

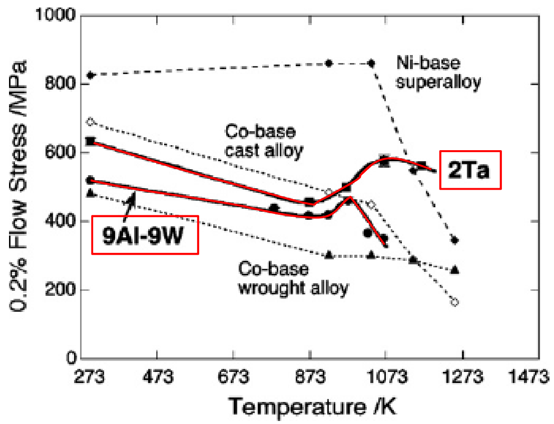
New Co-base alloys

Co-Al-W system



Sato et al., Science, 312, 2006, 90





Suzuki et al., Scr. Mater., 56, 2007, 38

- $\gamma - \gamma$' alloys having similar microstructure to Ni-base superalloys
- Proper alloying addition results in superior strength than Ni-base superalloys at high temperatures

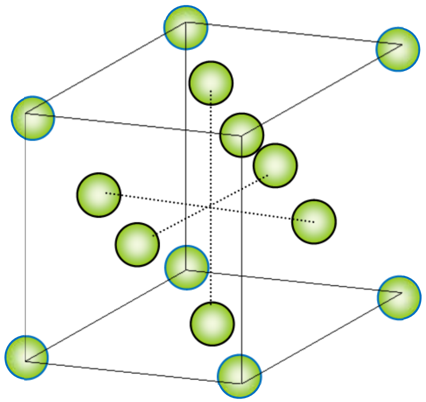
New Co-base alloys

Gamma (γ) & Gamma Prime (γ')

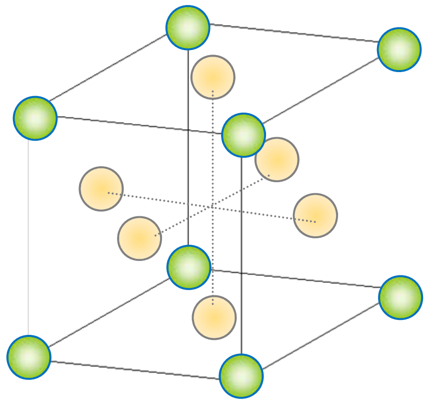
FCC Co –base nonmagnetic phase that usually contains a high percentage of solid-solution elements

Strengthening phase in Co-based superalloys is Co3(Al,W), and is called gamma prime (γ **').**

It is a coherently precipitating phase (i.e., the crystal planes of the precipitate are in registry with the gamma matrix) with an ordered FCC crystal structure.



Co, Al, W



Al, W

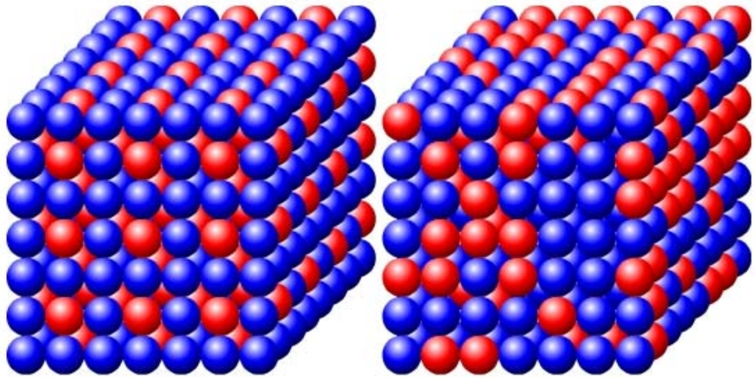
Intermetallics

What is an intermetallic?

- It is ‘an intermediate compound’, usually with fix stochiomethy.
- Solid phases containing two or more metallic elements, with optionally one or more non-metallic elements, whose crystal structure differs from that of the other constituents.
- It is an ‘alloy’, but without metallic bonding: usually ionic or covallent bonding (ceramic character).
- They combine good properties from metals and ceramics.
- The structure should have substructures.
- Net parameters of big order, with difficult paths for dislocations.
- Good high temperature performance.

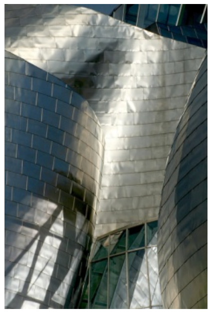
Intermetallics

Crystal structures: **ordered atom distribution**



Intermetallic | Standard Alloy

Bonding Strength (Ti-Al)>> Bonding Strength (Ti-Ti/Al-Al)



METALS

Intermediate position between

- **-High melting point**
- **-Good resistance against corrosion**
- **-Low density**

CERAMICS

Intermetallics

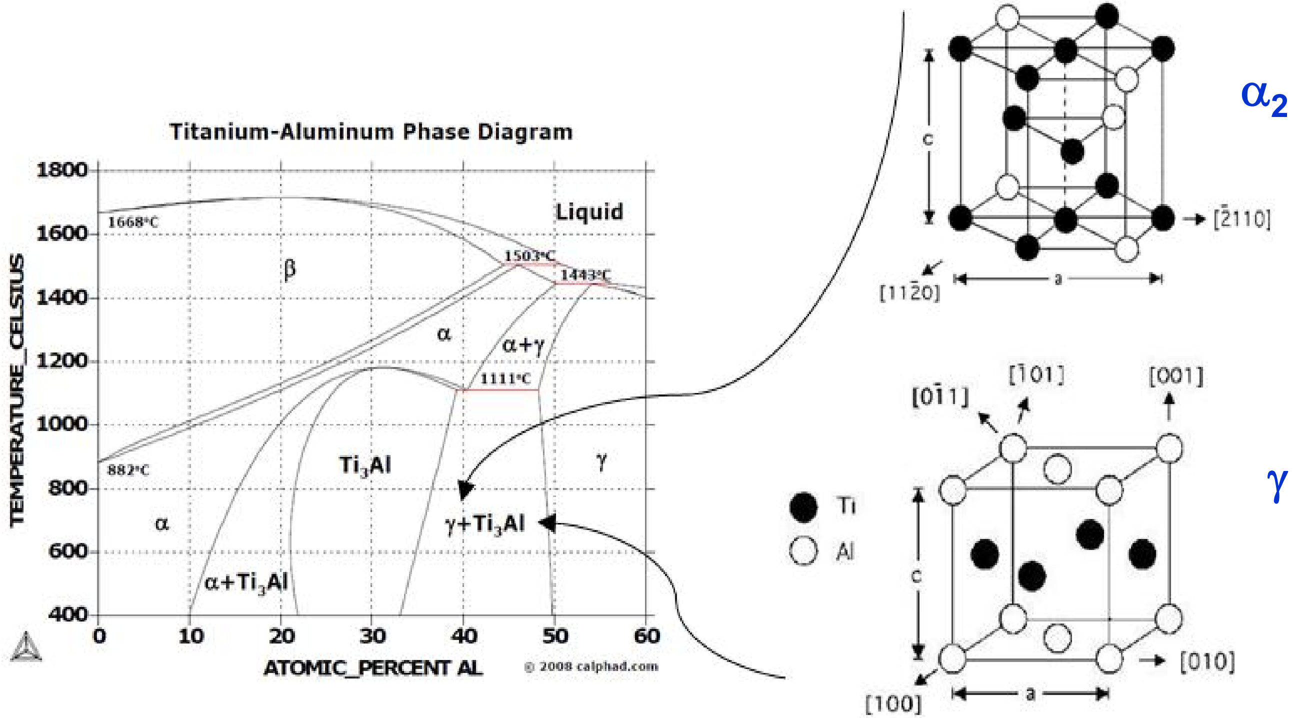
Alloy	Crystal structure	Critical ordering temperature (T_c)	Melting point (T_m)	Material density	Young's modulus
		° C	° C	g/cm^3	Gpa
Ni_3Al	$L1_2$ (ordered fcc)	1390	1390	7.50	179
NiAl	B2 (ordered bcc)	1640	1640	5.86	294
Fe_3Al	$D0_3$ (ordered bcc)	540	1540	6.72	141
	B2 (ordered bcc)	760	1540	. . .	. . .
FeAl	B2 (ordered bcc)	1250	1250	5.56	261
Ti_3Al	$D0_{19}$ (ordered hcp)	1100	1600	4.2	145
TiAl	$L1_0$ (ordered tetragonal)	1460	1460	3.91	176
$TiAl_3$	$D0_{22}$ (ordered tetragonal)	1350	1350	3.4	. . .

Properties of nickel, iron, and titanium aluminides

Intermetallics

Titanium Aluminides

- α_2: Ti_3Al; γ = TiAl



α_2: Ti_3Al

γ = TiAl

Intermetallics

Titanium Aluminides

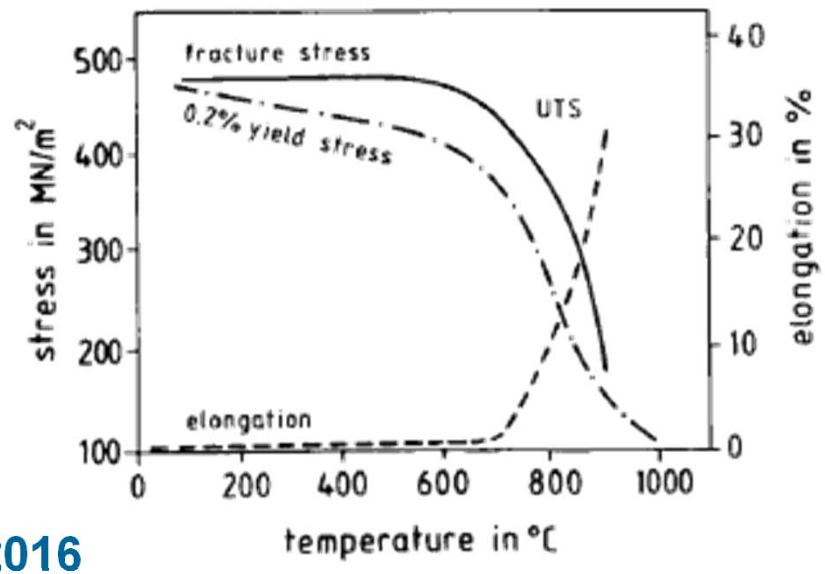
	Ti	Ti_3Al	TiAl	Ni-base
Density (g/cm^3)	4.54	4.28	3.83	8.45
Stiffness (GPa)	110	145	175	206
Max T/creep °C	535	815	900	1095
Ductility @ 25°C (%)	20	2-4	1-3	3-10

Intermetallics

γ-TiAl

- High melting point of 1460°C
- Low density (4 g/cm³);
- High stiffness (E=175 GPa at 20°C to 150GPa at 700°C);
- High specific properties (similar to cast Ni-based alloys);
- High temperature strength and oxidation resistant up to 750°C;
- Low diffusion coefficient
- Good structural stability
- High ignition resistance when compared with conventional titanium alloys.

Ultimate tensile strength (UTS), 0.2% yield stress, and elongation, as a function of temperature for single-phase, polycrystalline TiAl with 54 at.% Al



Intermetallics

γ-TiAl

Engineering alloys based on the (TiAl) phase usually have Al concentrations of 45–48 at%

Ti-(45–48)Al-(0.1–10)X (at%)

X =Cr, Nb, Mn, V, Ta, Mo, Zr, W, Si, C, and B

Strengthening mechanism: Solid solution strengthening Precipitation hardening (α_2 phase)

- Nb: strengthening and oxidation resistance
- Cr, V, Mn: enhance ductility
- W, Mo, Si: creep resistance
- B: grain refinement

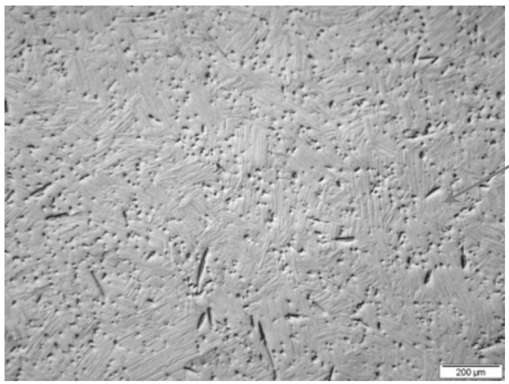
- Main drawbaks of γ TiAl:
  - Brittleness
  - Difficult fatigue analysis
  - Low elongation (1 – 2%)

Intermetallics

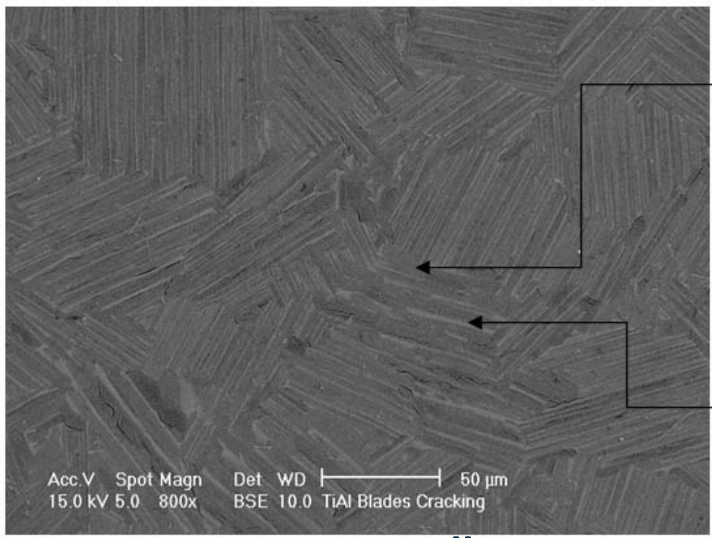
γTiAl: Microstructure

Microstructure depending on heat treatment:

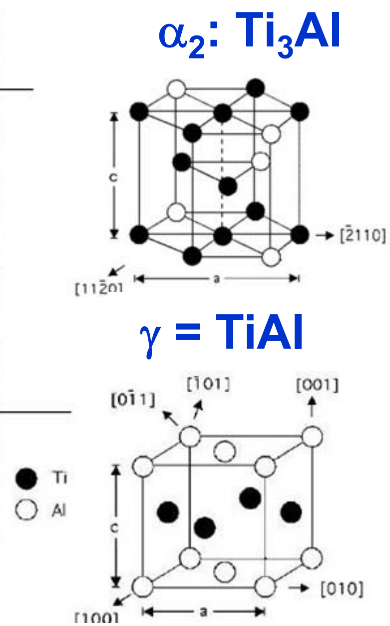
- **Fully lamellar :** lamellas of γ TiAl and α_2 Ti_3Al
- **Nearly lamellar**
- **Duplex** or bimodal microstructures with varying volume fraction of lamellar grains
- **Near gamma** microstructures



→Effects of boron: Refine and stabilize lamellar structure

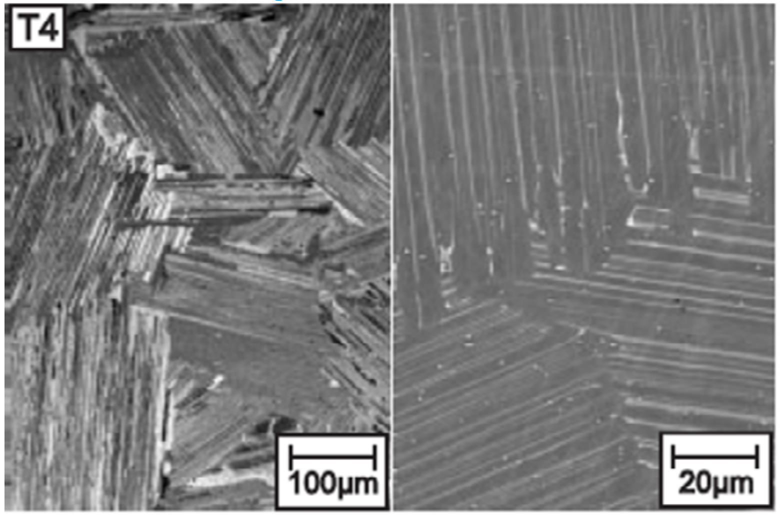


Lamellar structure

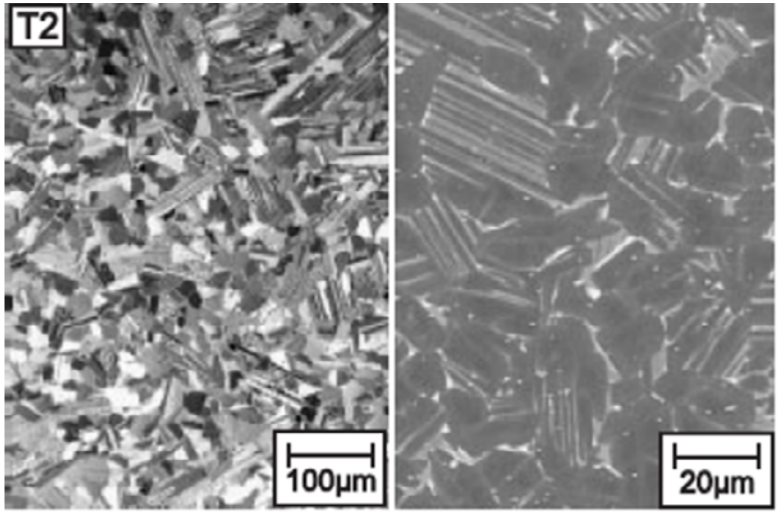


Intermetallics

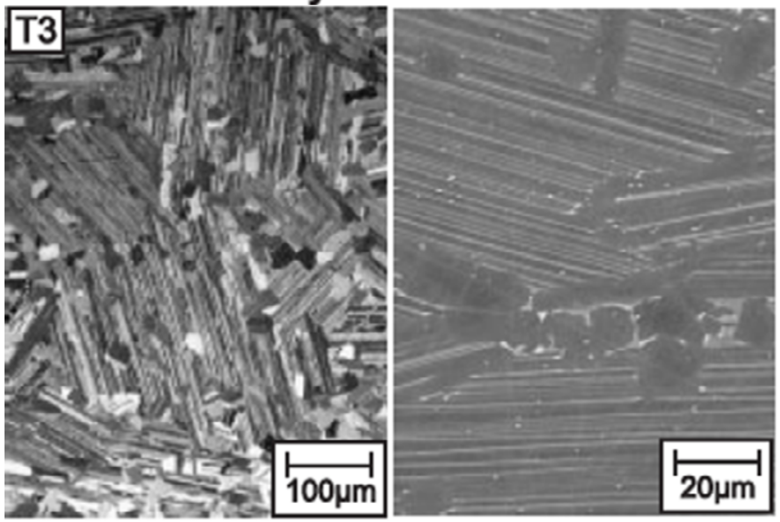
γTiAl: Microstructure



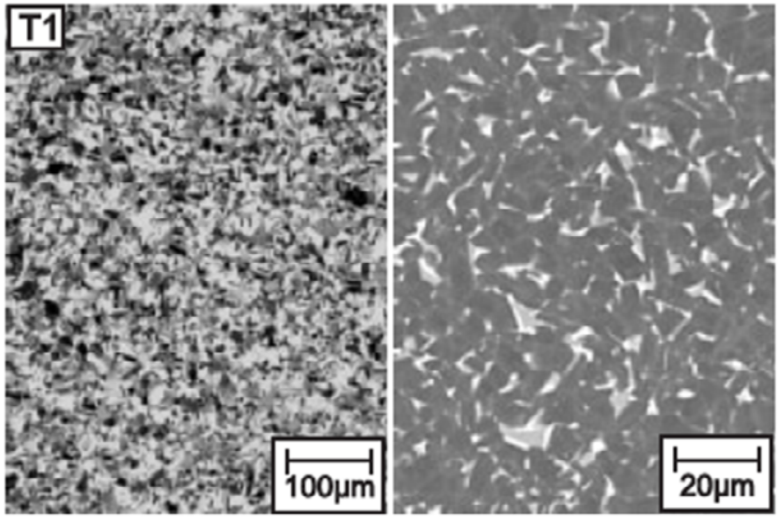
Fully Lamellar



Duplex



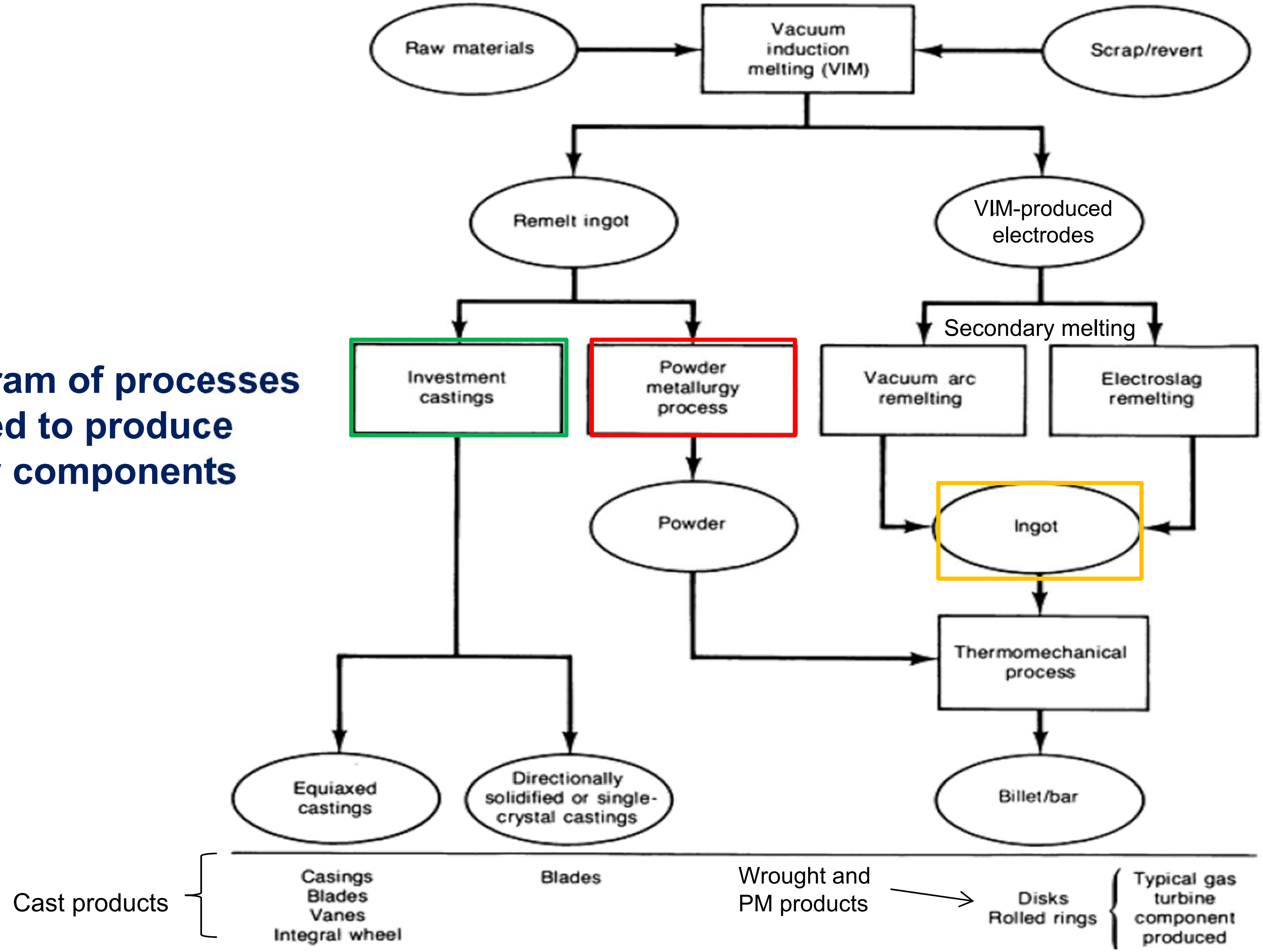
Nearly Lamellar



Near Gamma

Superalloys

Flow diagram of processes widely used to produce superalloy components



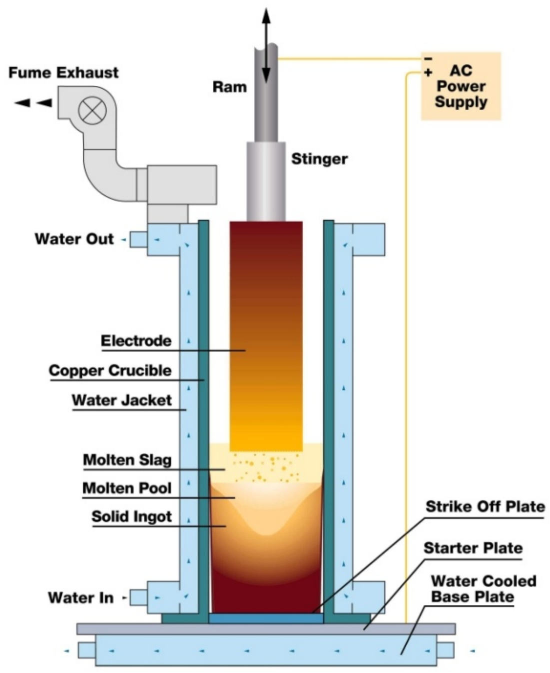
Superalloys and intermetallics

Vacuum induction melting consists of melting the required components of an alloy under high vacuum in an induction-heated crucible and pouring into an ingot (VIM-produced electrodes).

- Reduces interstitial gases to low levels.
- Enables higher and more reproducible levels of aluminum and titanium.
- Less contamination from slag formation than air melting.

•Secondary melting: converts VIM-processed electrodes into ingots with improved chemical and physical homogeneity.

- **Vacuum arc remelt (VAR) :** an arc is struck between the end of the electrode and the water-cooled copper crucible bottom. Maintaining the arc generates the heat required to melt the electrode, which drips into the crucible and can subsequently be poured into molds.
- **Elestroslag remelt (ESR)** : an ingot is built up in a water cooled mold by melting a consumable electrode that is immersed in a slag, which is superheated by means of resistance heating. Rather than operating in a vacuum, the process is conducted in air under the molten slag.

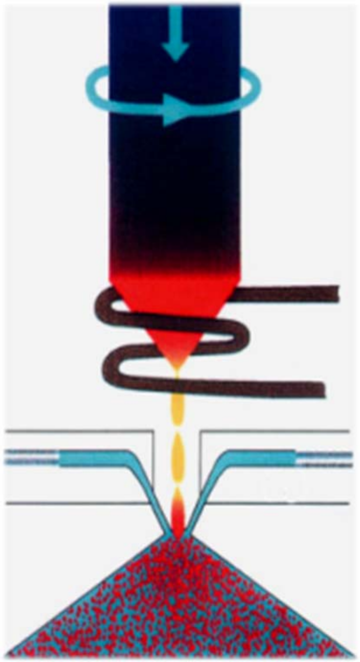


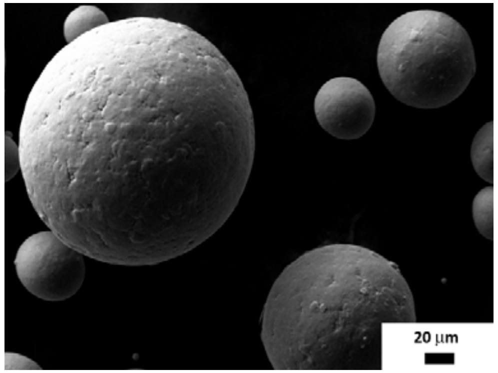
Elestroslag remelt (ESR)

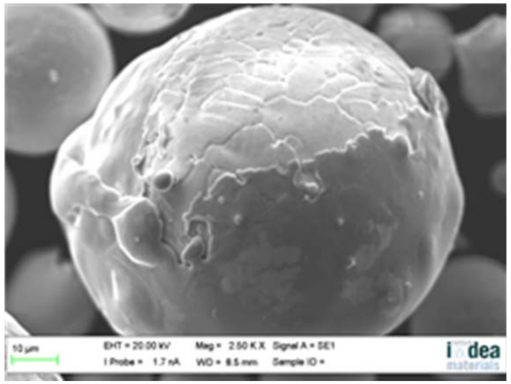
Superalloys and intermetallics

Powder production

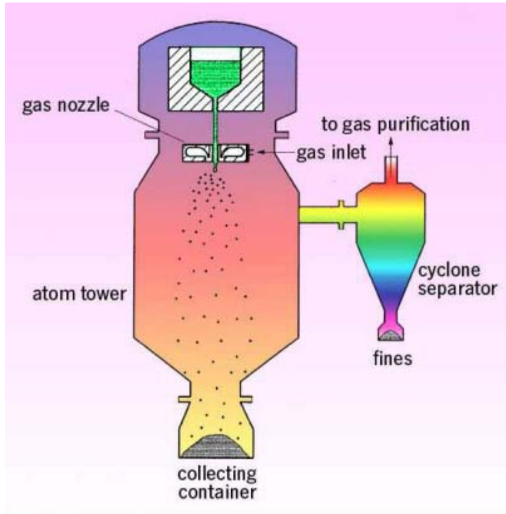
Electrode Induction Melting Gas Atomization







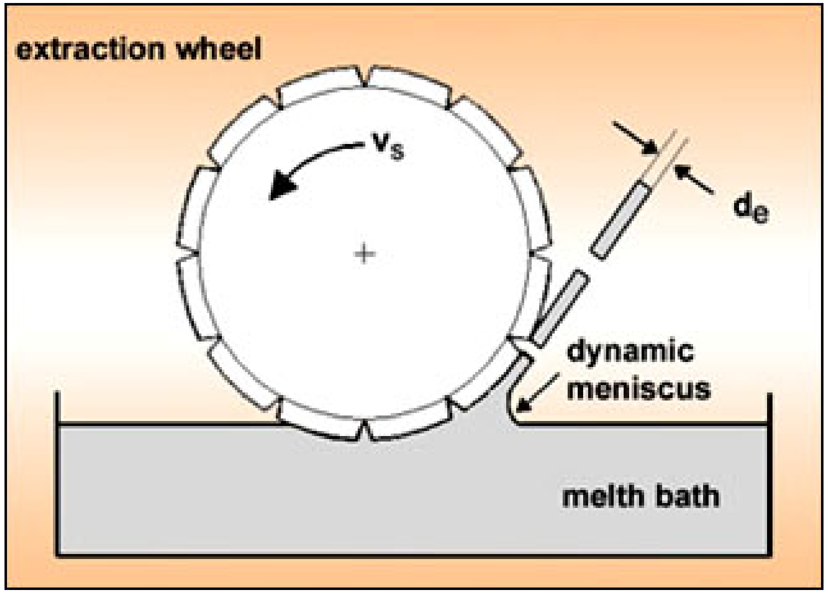
Gas Atomization

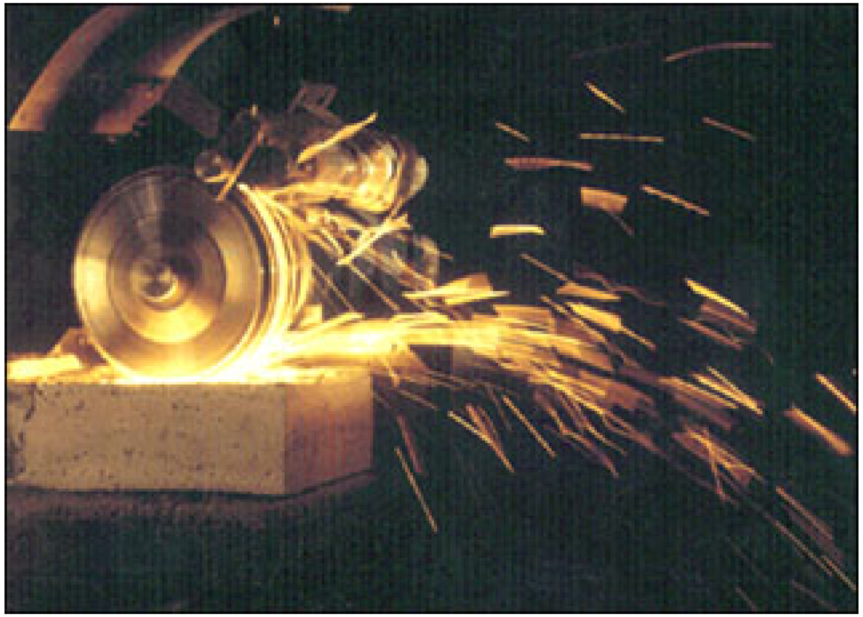


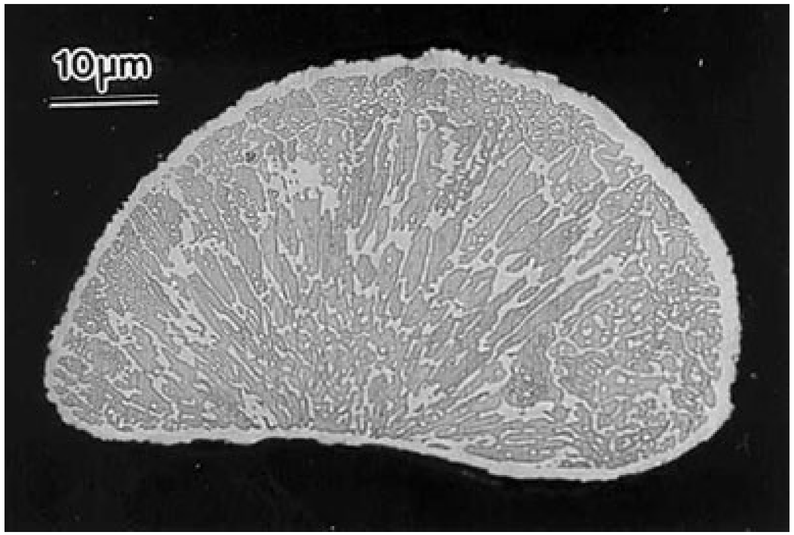
Superalloys and intermetallics

Powder production

Melt spinning





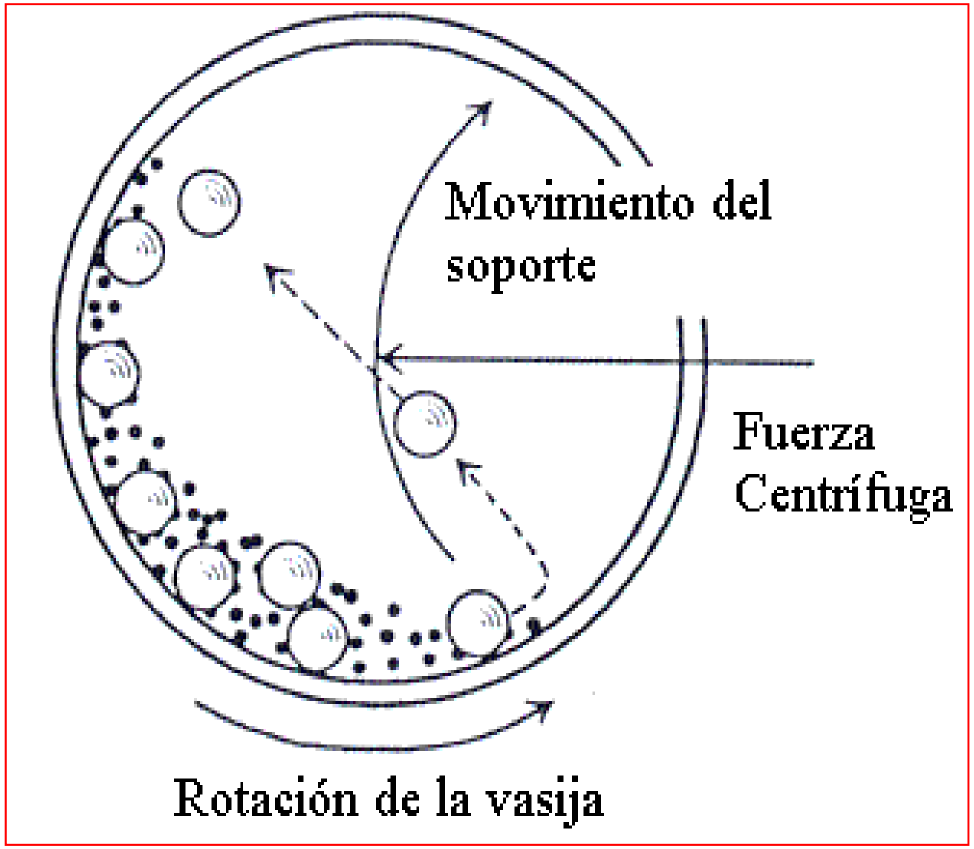


Materials: TiAl, NiAl, Fe-Al

Superalloys and intermetallics

Powder production

Mechanical alloying



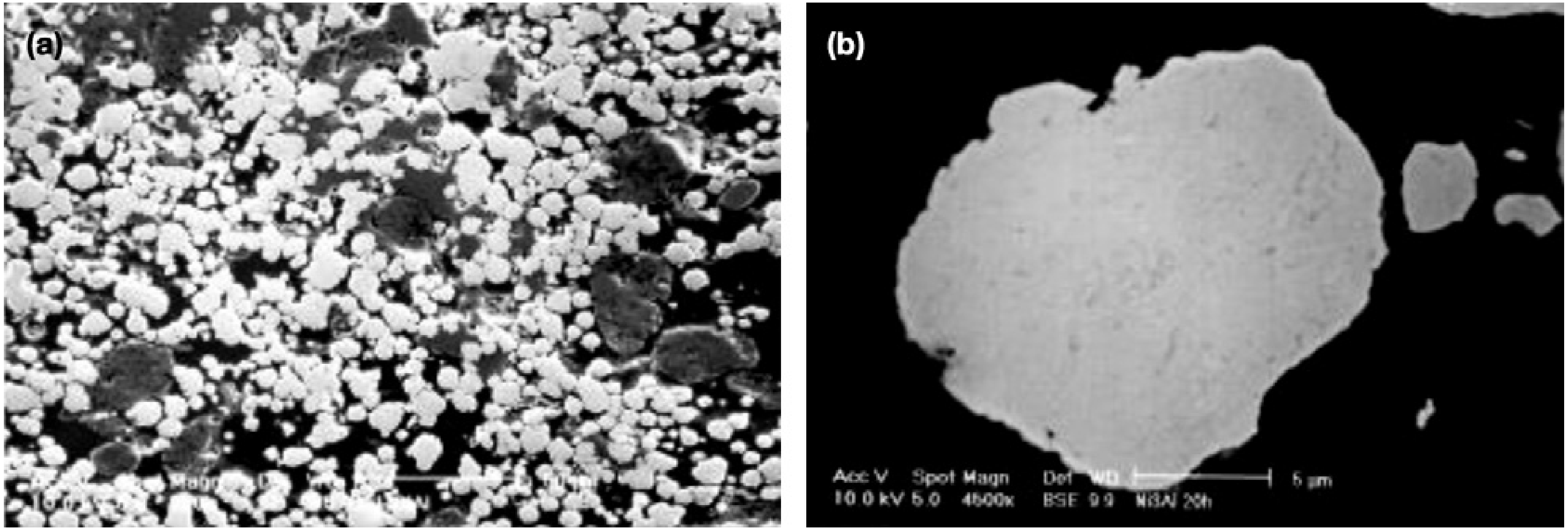
Superalloys and intermetallics

Powder production

Mechanical alloying

Ni+Al powders

Ni_3Al powders

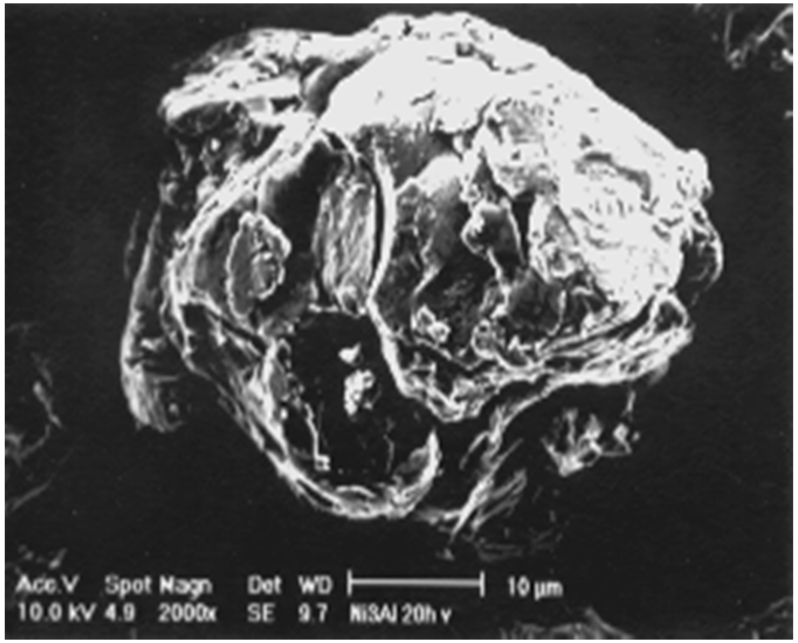


C.E. da Costa "Aluminium matrix composites reinforced with intermetallics obtained by poder metallurgy" PhD thesis, Technical University of Madrid, 1998.

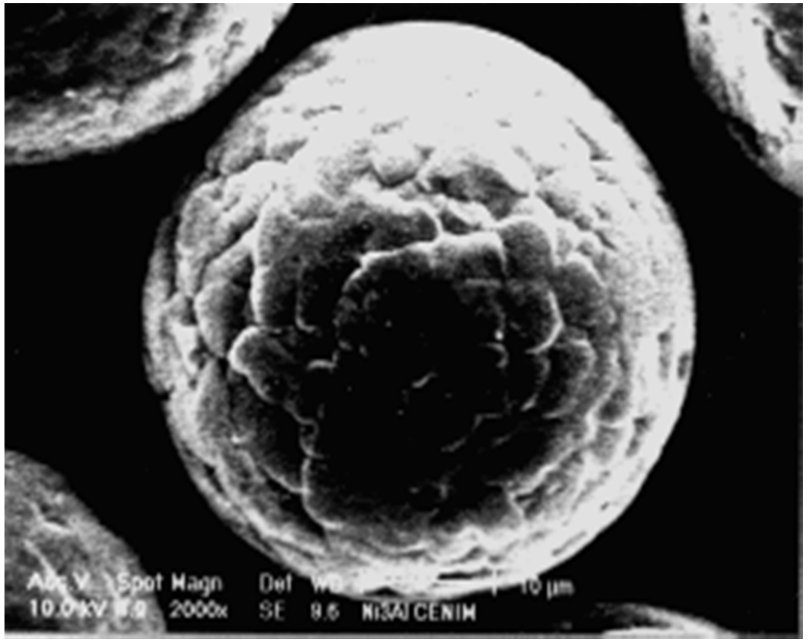
Superalloys and intermetallics

Powder production

Mechanical alloying



Ni_3Al MA



Ni_3Al Gas atomized

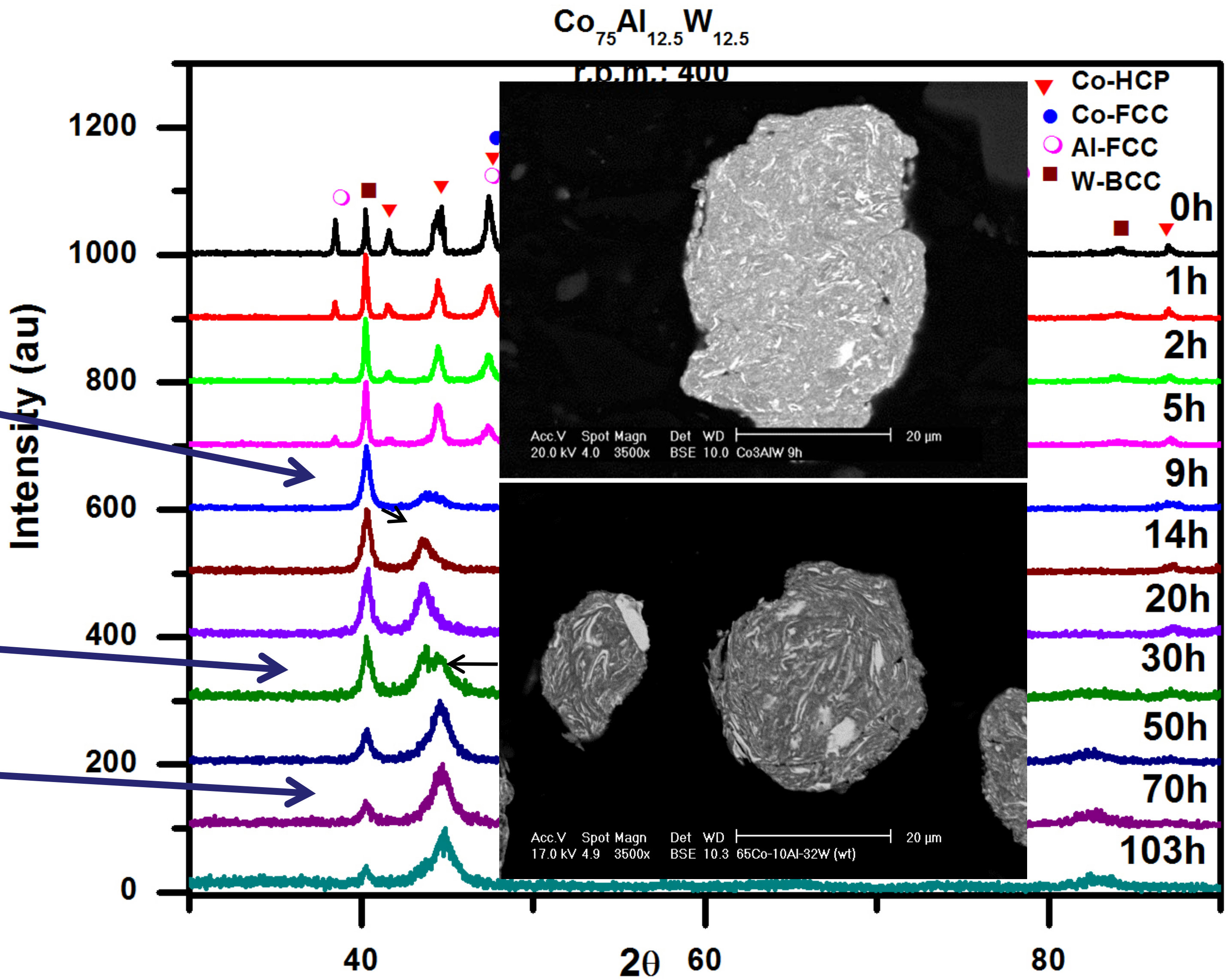
Superalloys and intermetallics

Powder production Mechanical alloying

Al peak disappeared & Co-FCC appears

Metastable AlCo BCC disordered phase

W dissolution

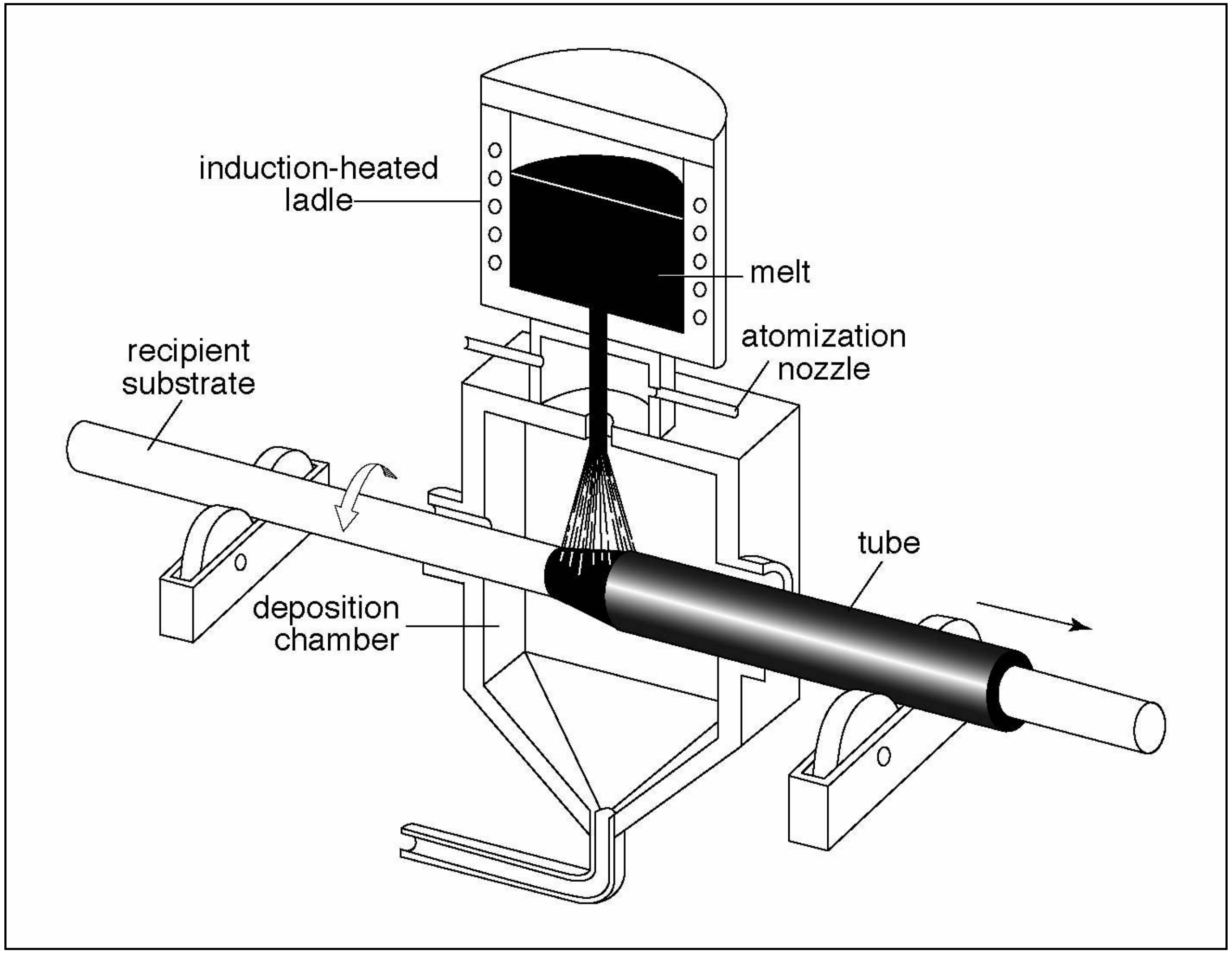


EPMA Powde

Superalloys

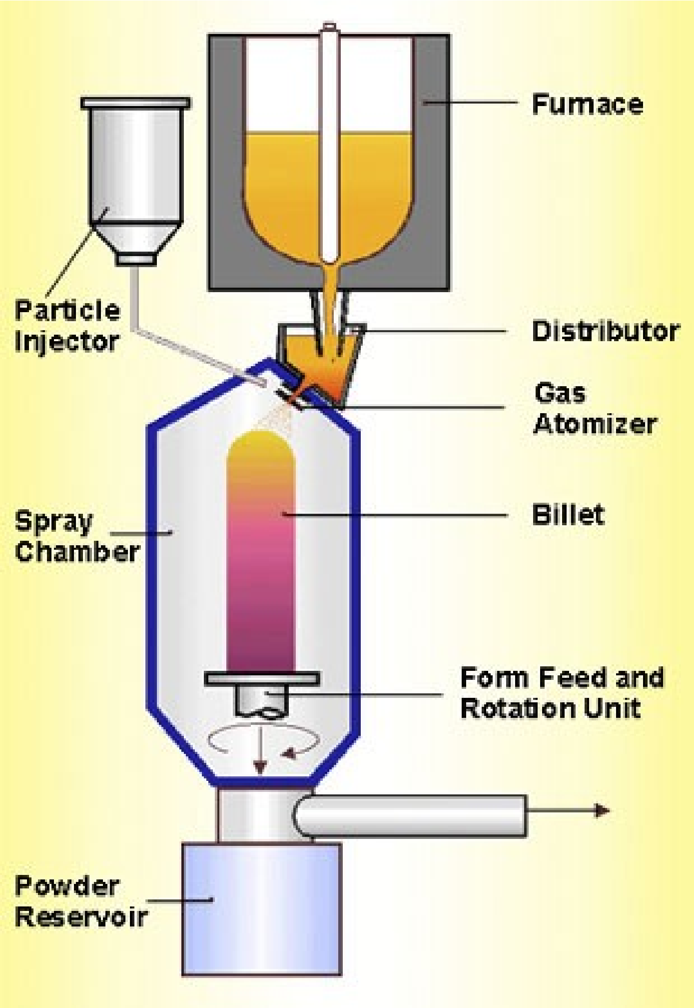
Consolidation

Spray Forming

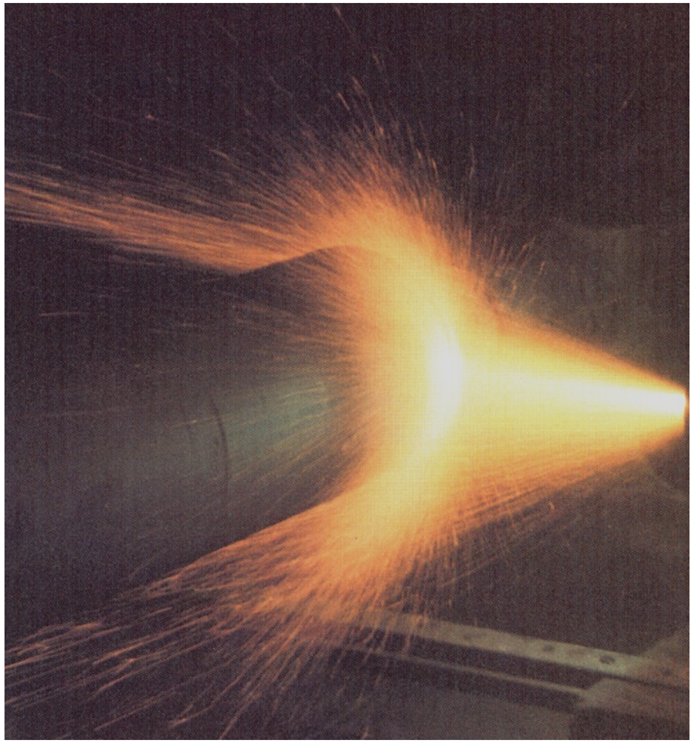


Superalloys

Consolidation



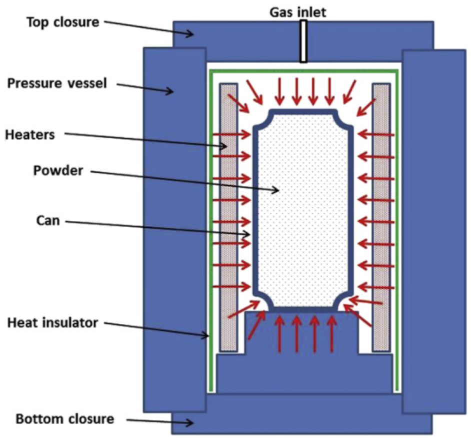
Spray Forming

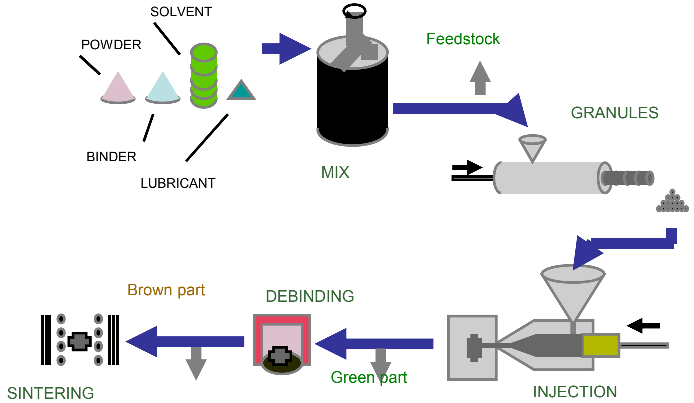


Superalloys and intermetallics

Consolidation

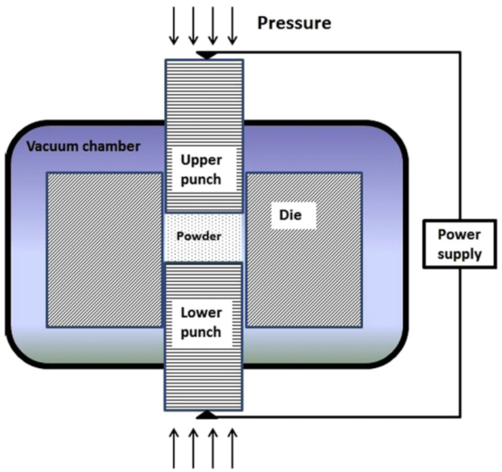
HIP

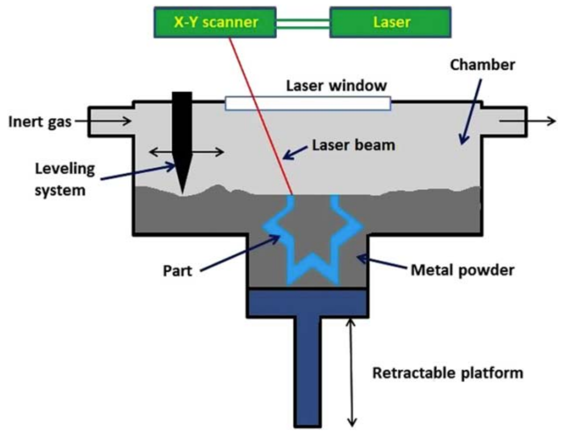




MIM

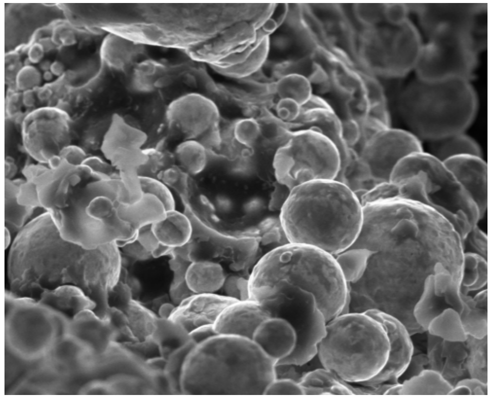
FAS





AM

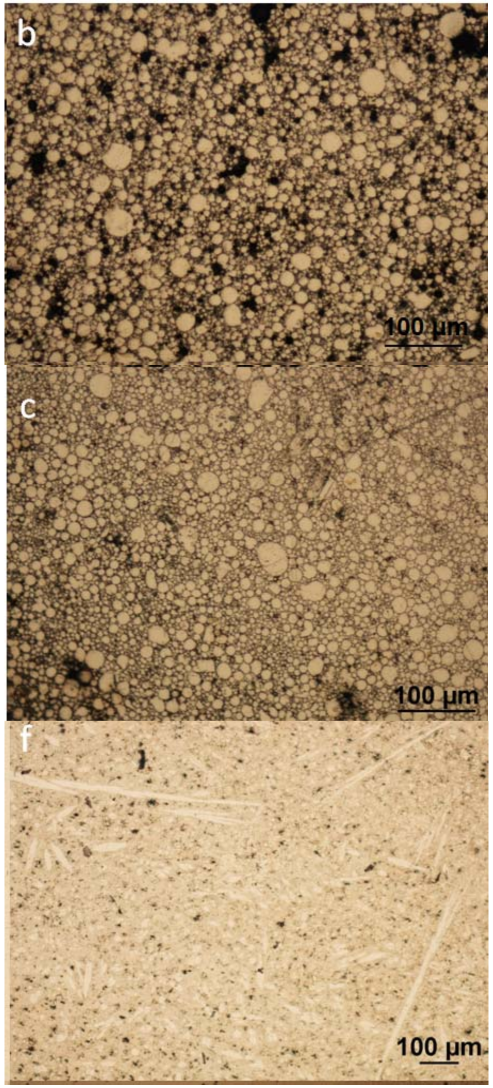
Inconel 718

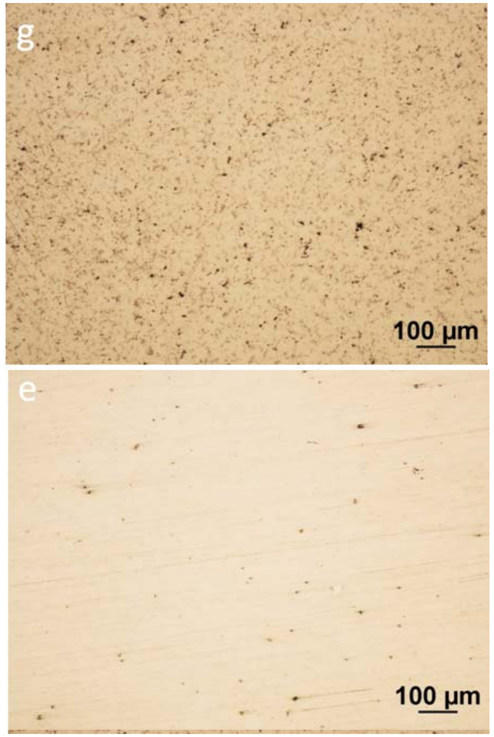


950ºC

1025ºC

1250ºC





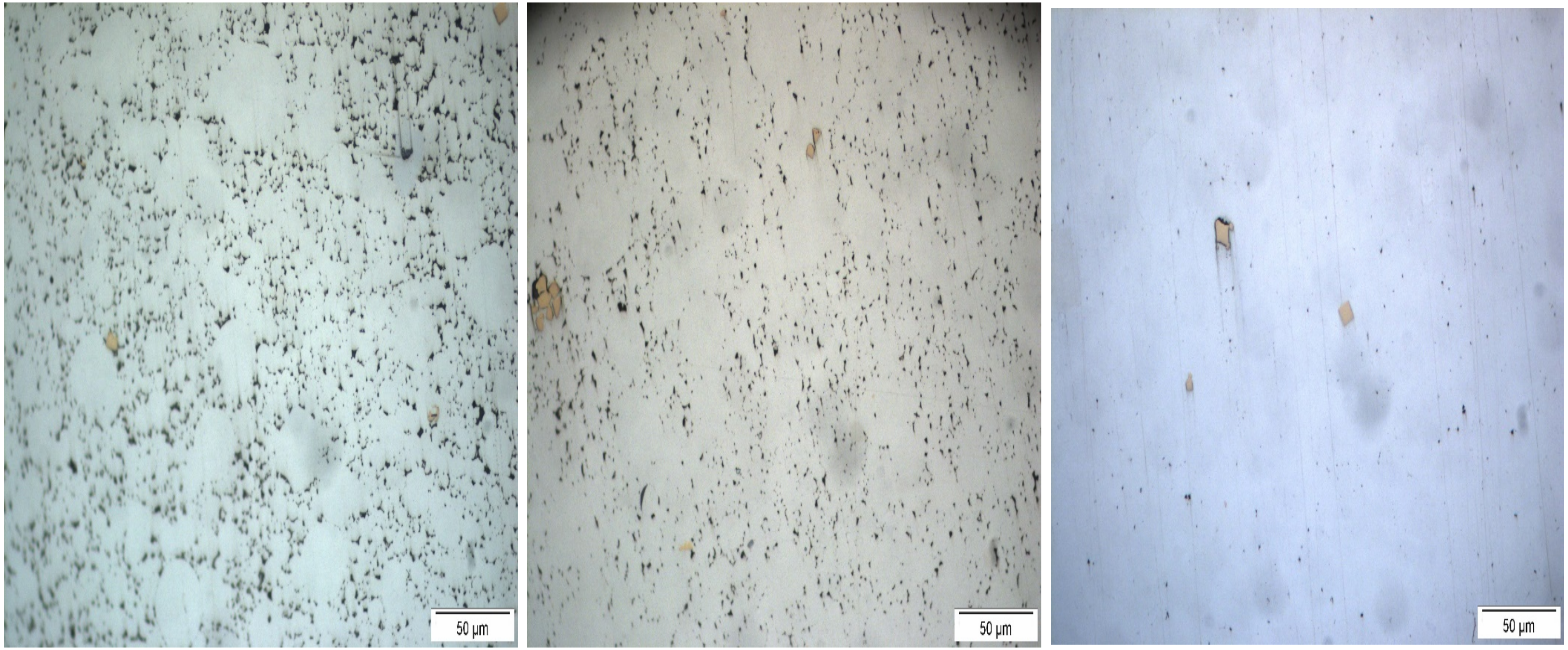
1000 ºC

1100 ºC

MIM

SPS

FAHP



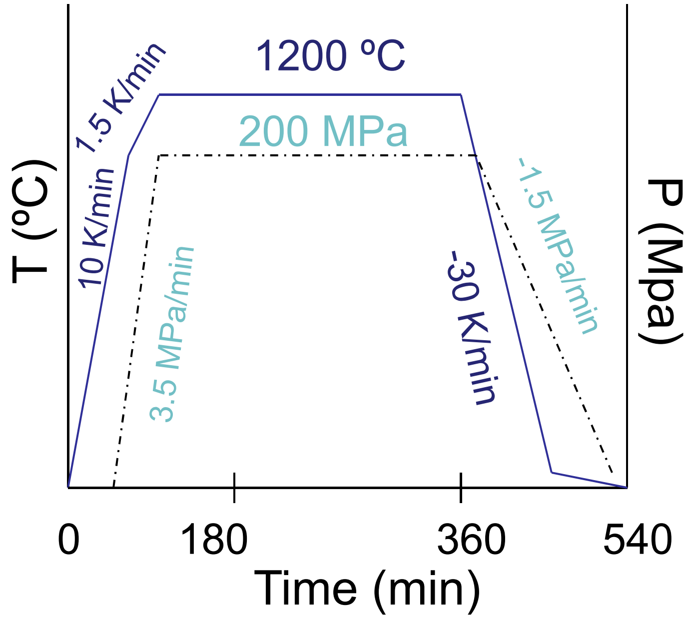
1100° C *1200° C* *1250° C*

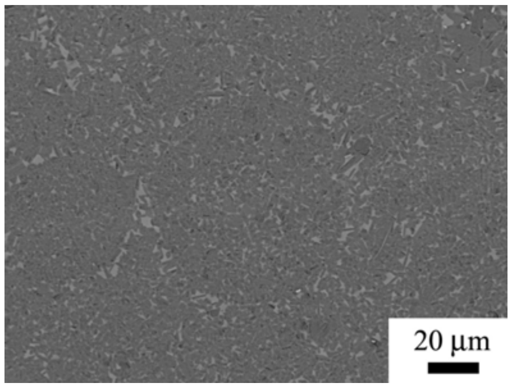
Inconel 718

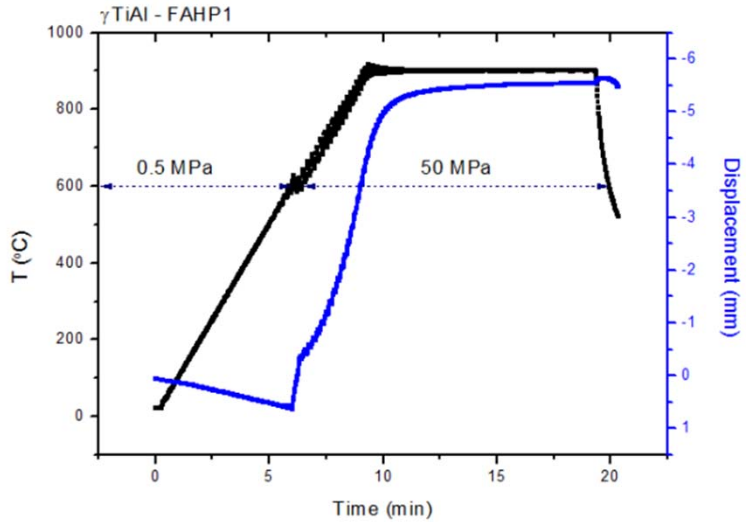
Superalloys and intermetallics

Consolidation

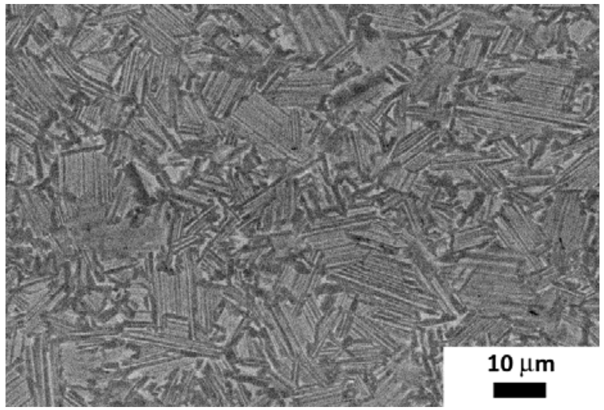
HIP





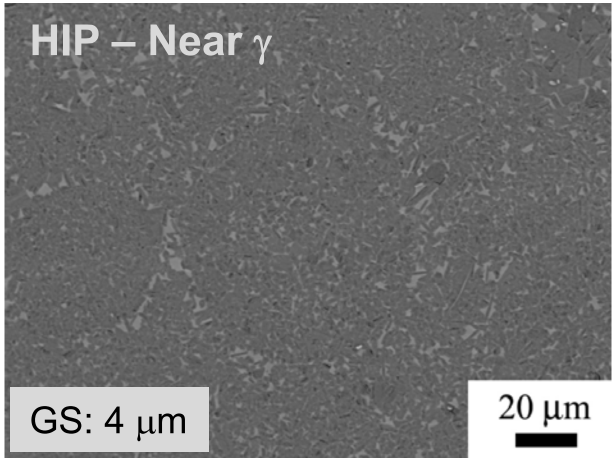


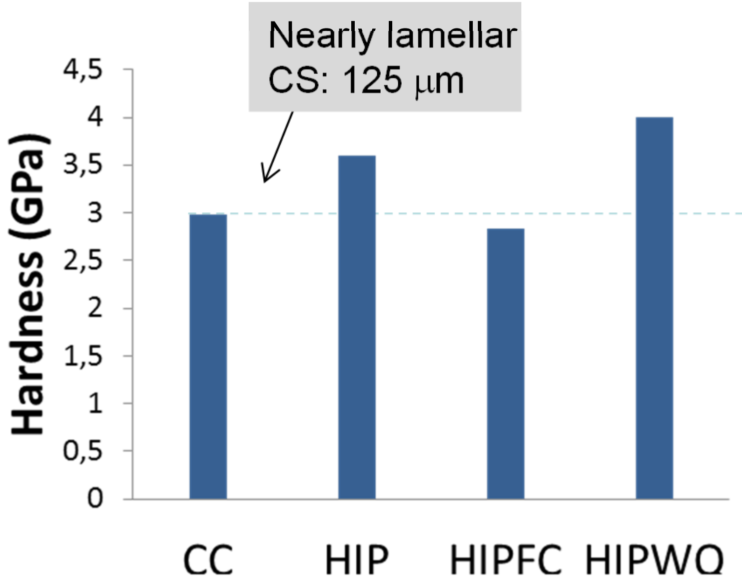
FAS

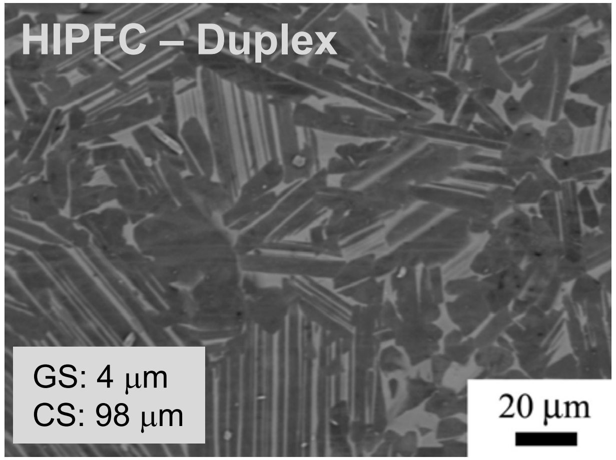


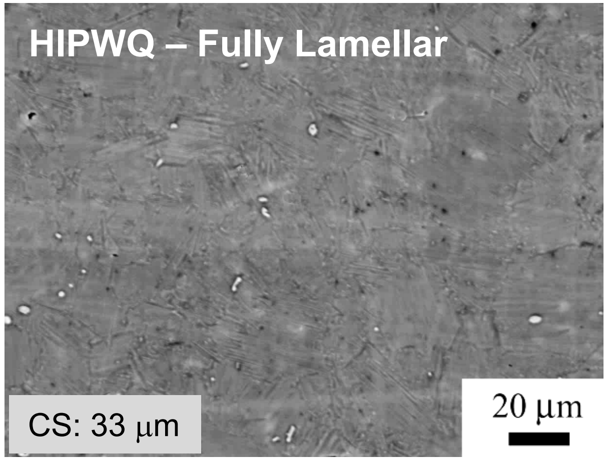
Superalloys and intermetallics

Heat treatments



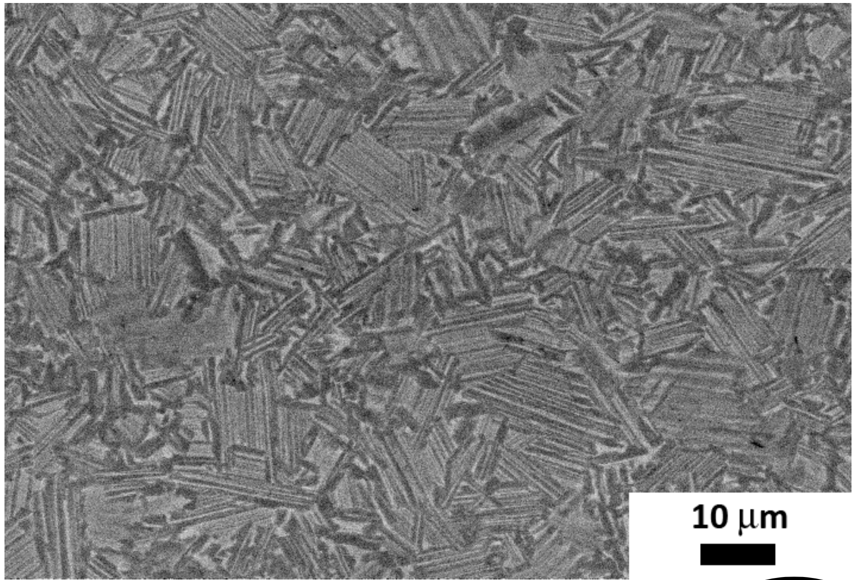


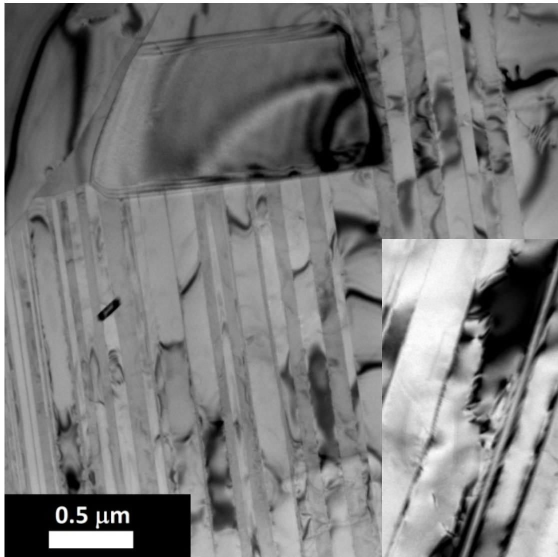


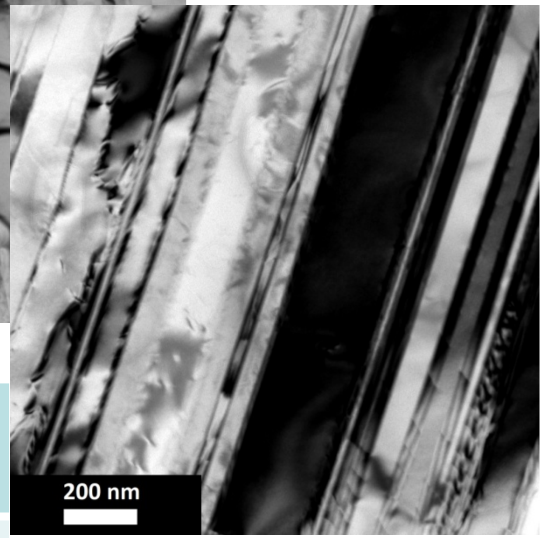


GS: Grain size,
CS: Colony size

Superalloys and intermetallics





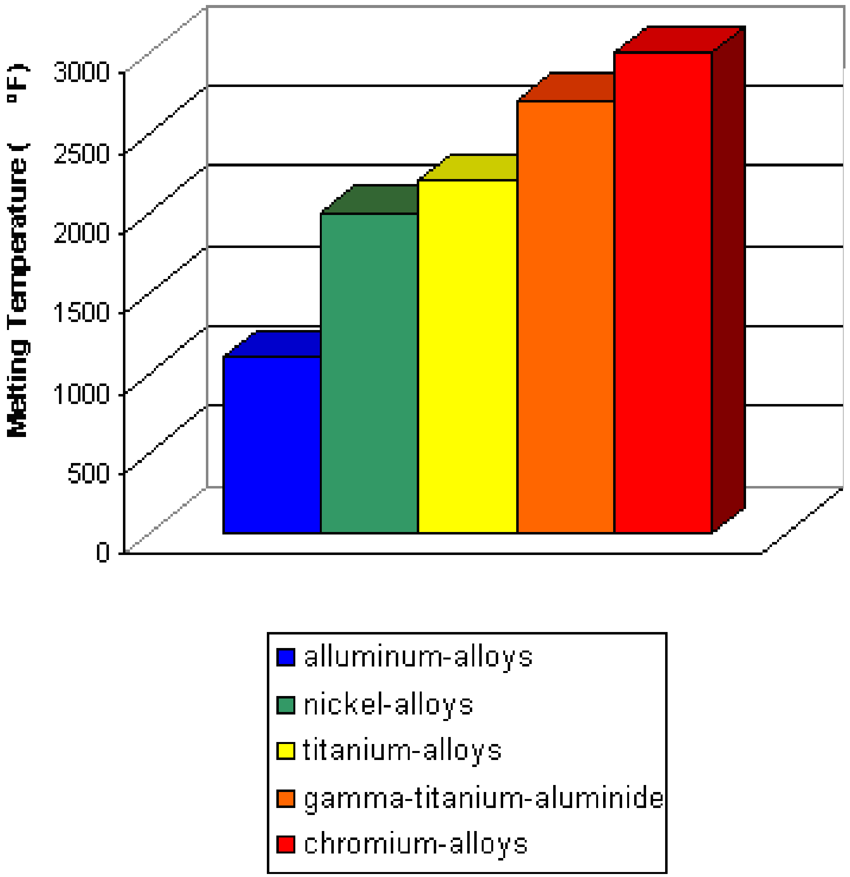


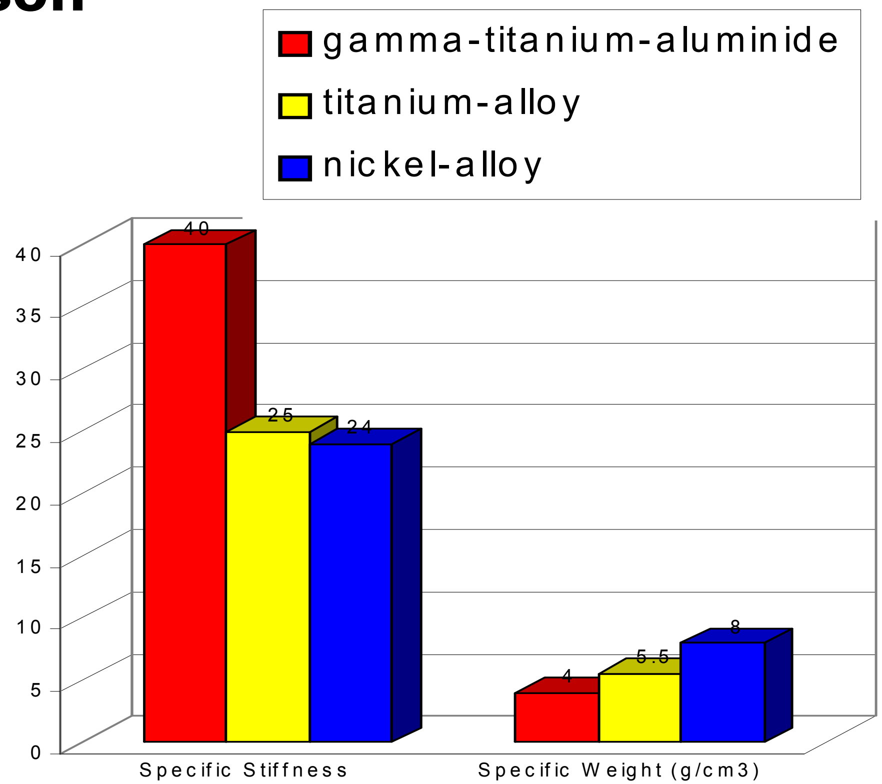
Ti4522XD alloy	PM-HIP	PM-FAHP	Centrifugal Casting
Colony size	**33μm**	**10 μm**	120 μm
Lamellar spacing		**120 nm**	422 nm

Superalloys and intermetallics

Properties

γ-TiAl/Superalloys comparison

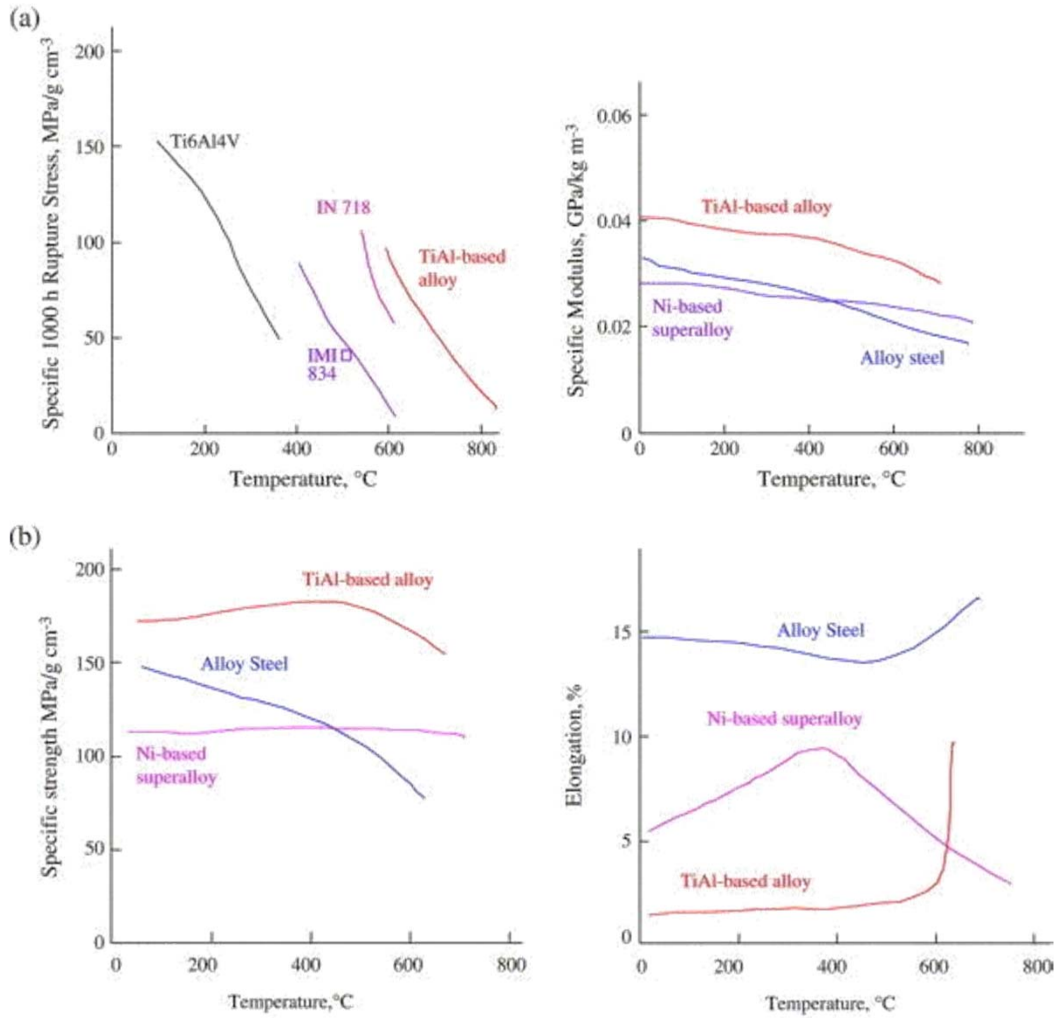




- 50% lighter
- Better creep, oxidation and strength than Ti alloys

Superalloys and intermetallics

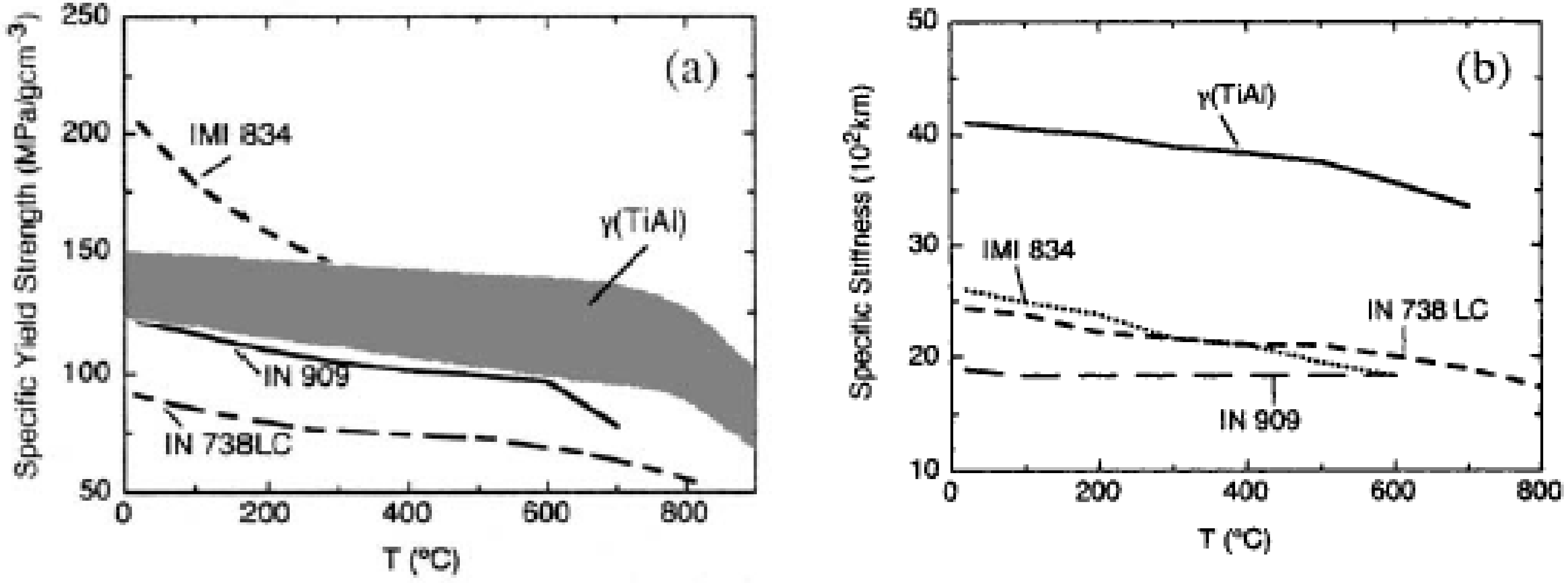
Properties



(a) 1000 h rupture strength as function of temperature for a TiAl-based alloy, for Ti834, IN 718 and Ti6Al4V and
(b) specific strength and ductility as function of temperature for an alloy steel, a Ni-based alloy and a TiAl-based alloy

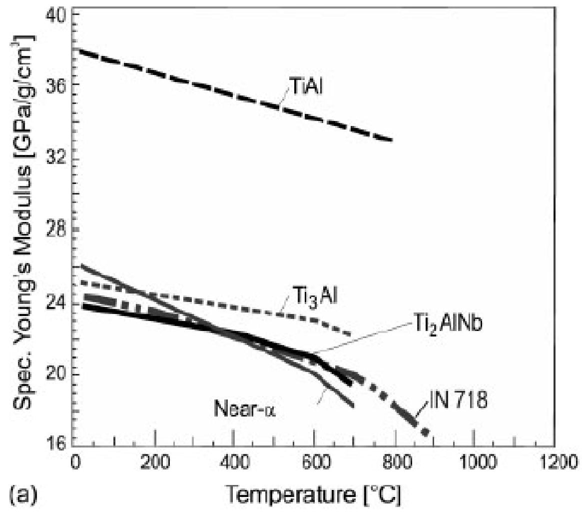
Superalloys and intermetallics

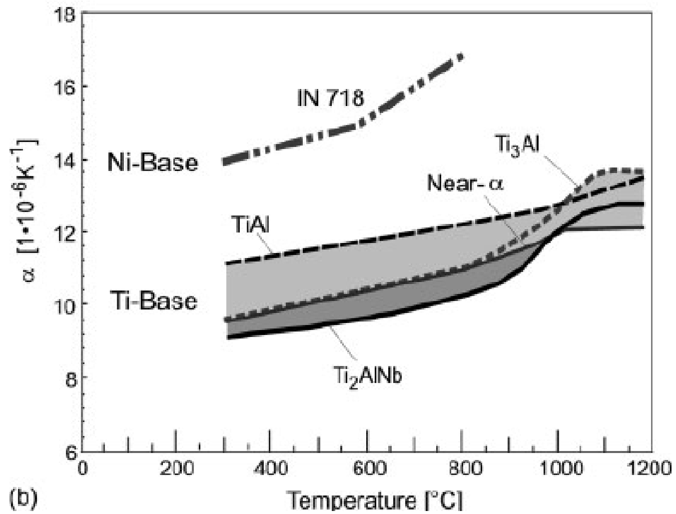
Properties



Properties of a near-α titanium alloy (IMIL 834), g TiAl alloy and and two nickel-based alloy (IN 738LC and IN 909; (a) specific Yiled Strength (b) Specific Stiffness

Superalloys and intermetallics



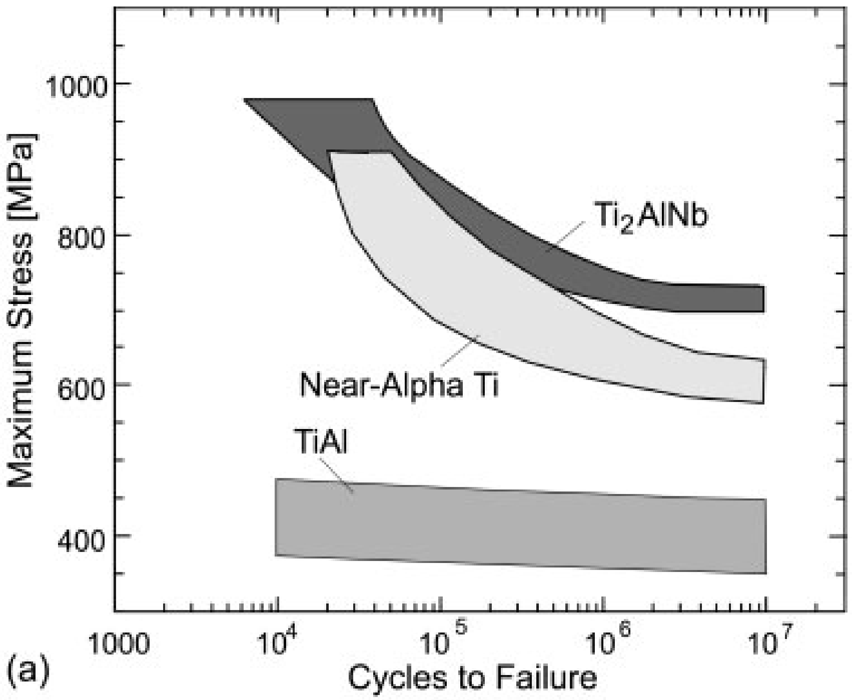


Properties

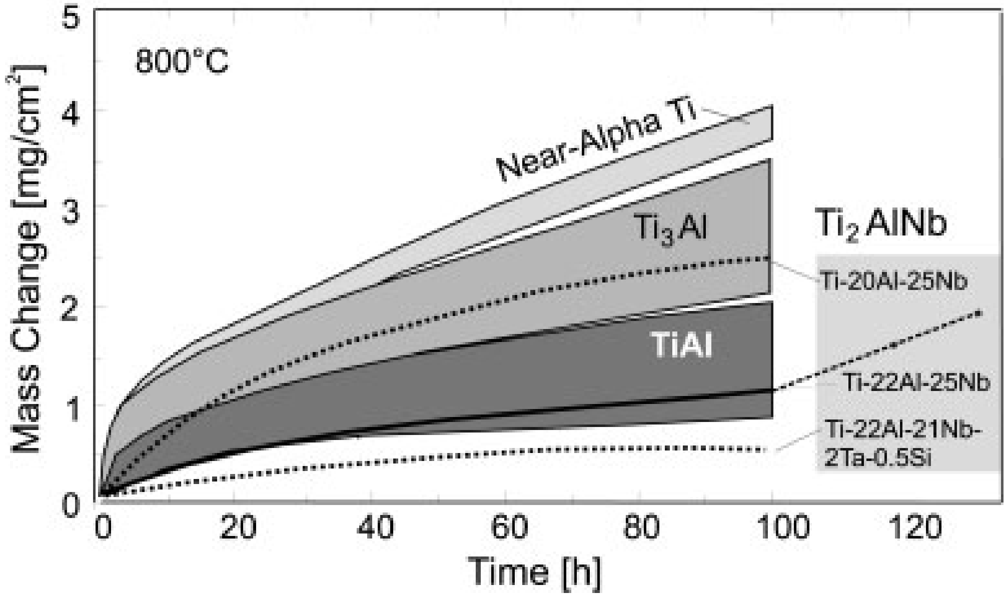
Physical properties of a Ti2AlNb-based alloy (Ti-22Al-25Nb), near-titanium alloy (TIMETAL 834), TiAl-based alloy (Ti-46.5Al-3.0Nb-2.1Cr-0.2W) and nickel-based alloy (IN 718); (a) specific Young's modulus, (b) coefficient of thermal expansion (CTE).

Superalloys and intermetallics

Properties



Fatigue behavior of Ti-22Al-23Nb (Ti_2AlNb), Ti-46.5Al-3.0Nb-2.1Cr-0.2W (γTiAl), and TIMETAL 834 (near-α) maximum stress vs. cycles,

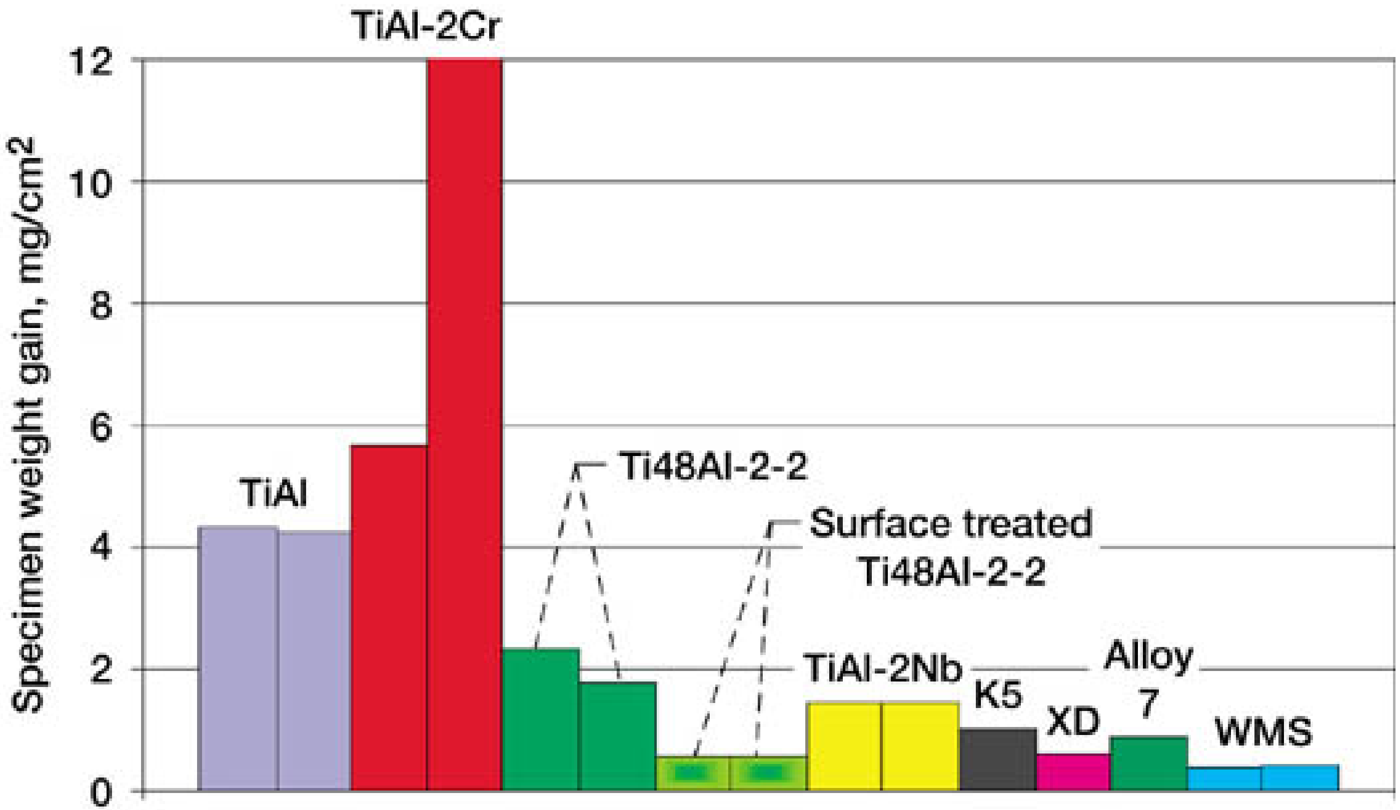


Isothermal oxidation resistance of different Ti_2AlNb-based alloys relative to γTiAl, Ti_3Al, and near-α titanium alloys

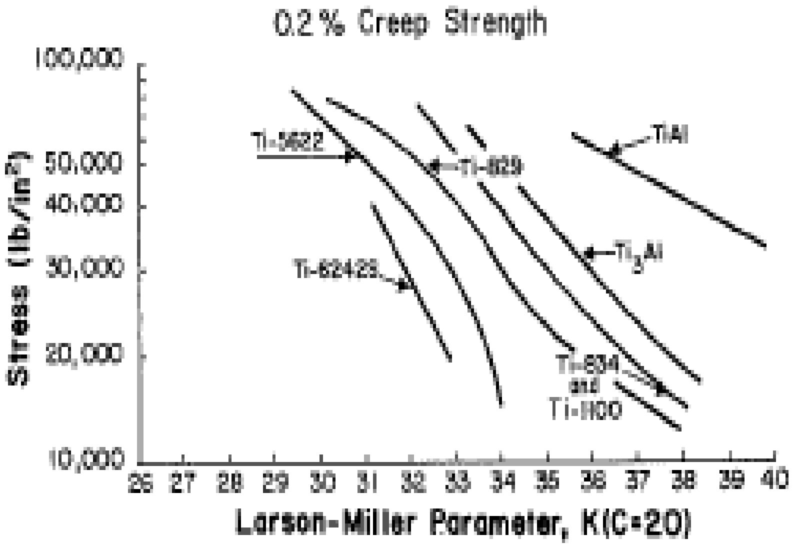
Superalloys and intermetallics

Properties

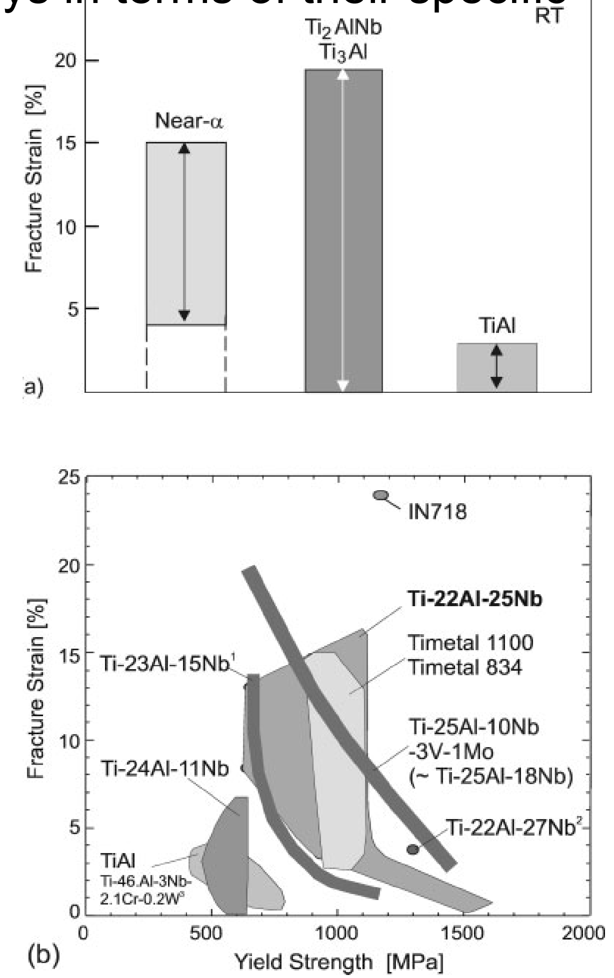
Oxidation behaviour



Specimen weight gain for model and advanced g-TiAl alloys after isothermal exposure to 704 ° C for 7000 hr in air. Duplicate tests were done for TiAl, TiAl-2Cr, Ti48Al-2-2, surface-treated Ti48Al-2-2, and TiAl-2Nb.



at temperatures between 600C and 800C (TiAl)-based alloys are superior to Ti-alloys in terms of their specific strength

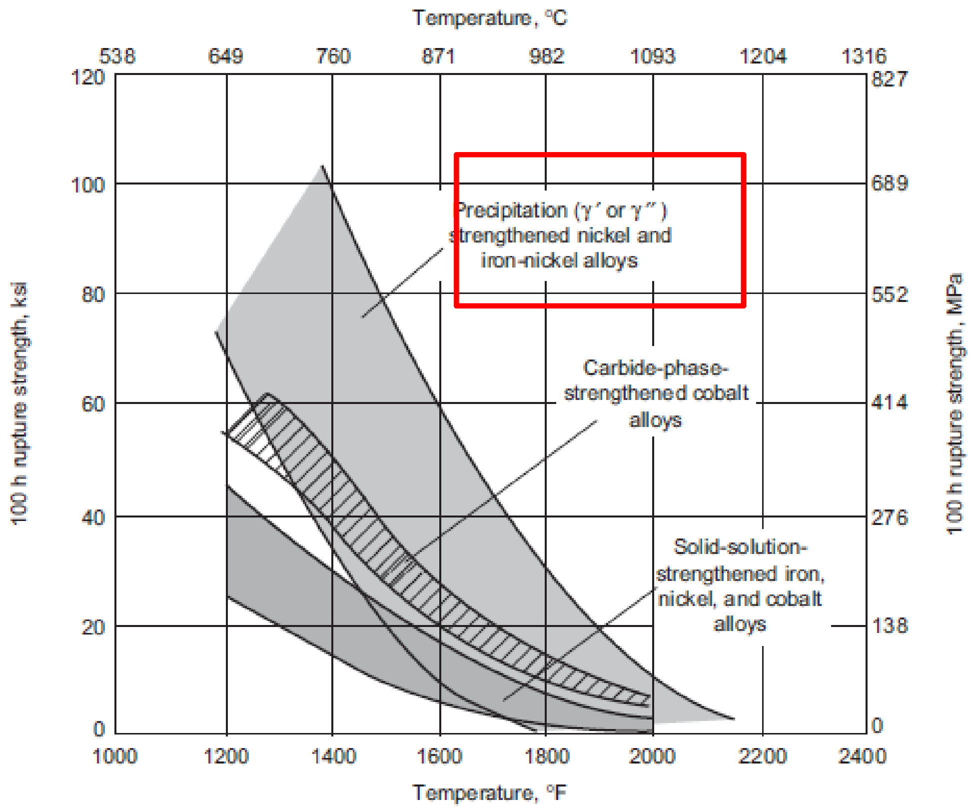


Room temperature tensile properties of orthorhombic titanium
aluminides (Ti2AlNb) in comparison to near- titanium, Ti3Albased,
and TiAl-based alloys, (a) typical range of ductility for different
microstructures, (b) fracture elongation vs. yield strength for different
compositions and microstructures.

Superalloys and intermetallics

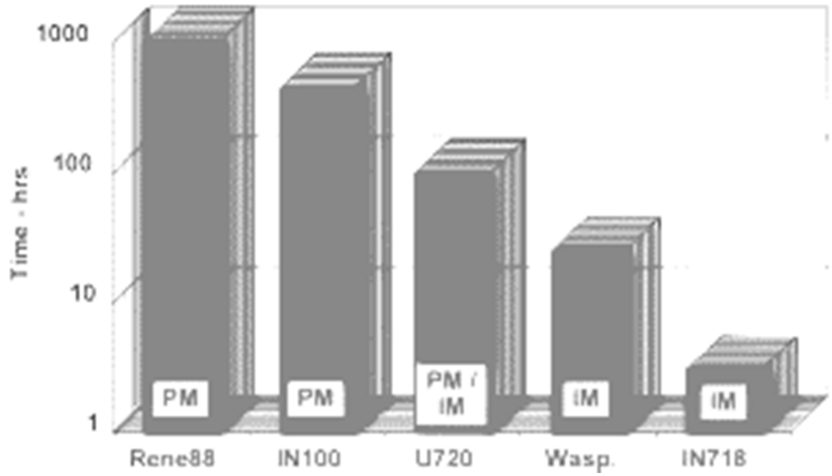
Properties

Displacement –limited or strain-limited design:



Stress-rupture strengths of superalloys

Evolutionary improvements in Ni alloys



Creep strength of 5 Ni-alloys. Time is for 0.2% strain at 650°C and 800 MPa

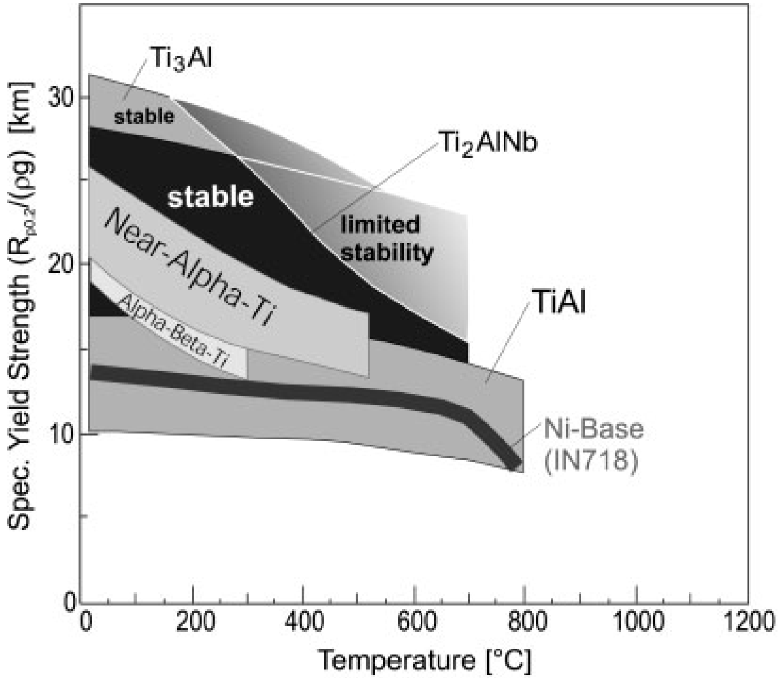
IN718 = 25 years old;

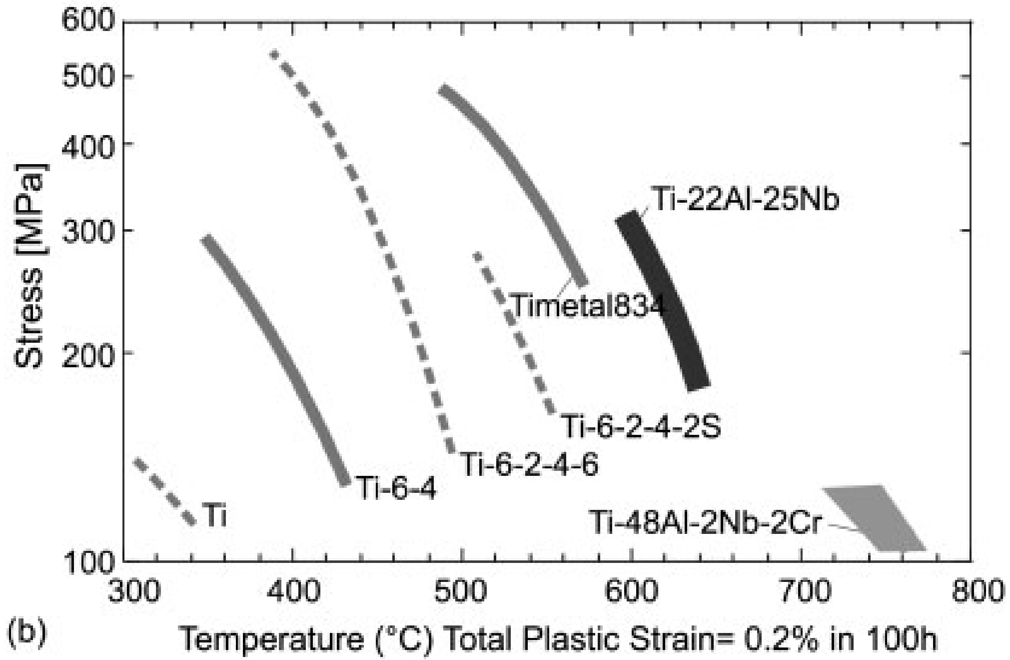
Rene88 the newest material

Superalloys and intermetallics

Properties

At temperatures between 600°C and 800°C (TiAl)-based alloys are superior to Ti-alloys





Specific yield strength ranges as a function of temperature and microstructure for an orthorhombic titanium aluminide alloy (Ti_2AlNb, Ti-22Al-25Nb) , near-α titanium alloys (TIMETAL 834/ 1100), a Ti_3Al-based alloy (Ti-25Al-10Nb-3V-1Mo), a TiAl-based alloy (Ti- 46.5Al-3.0Nb-2.1Cr-0.2W), and a nickel-based alloy (IN718).

Creep performance for total creep strain to 0.2% in 100 h in of the orthorhombic alloy Ti-22Al- 25Nb , the titanium base alloys and the γ-TiAl-based alloy Ti-48Al-2Nb-2Cr.

Superalloys and intermetallics

Applications

- Steam turbine power plant components:
  - Bolts, Blades, Stack-gas reheate,
- Automotive components:
  - Turbochargers, Exhaust valves
- Metal processing:
  - Hot work tools and dies, Casting dies
- Medical components:
  - Dentistry, Prosthetic devices
- Heat treating equipment:
  - Trays, Fixtures, Conveyor belts
- Nuclear power systems:
  - Control-rod drive mechanisms, Valve stems, Springs, Ducting
- Chemical and petrochemical industries:
  - Bolts, Valves, Reaction vessels, Piping, Pumps

Superalloys and intermetallics

Applications

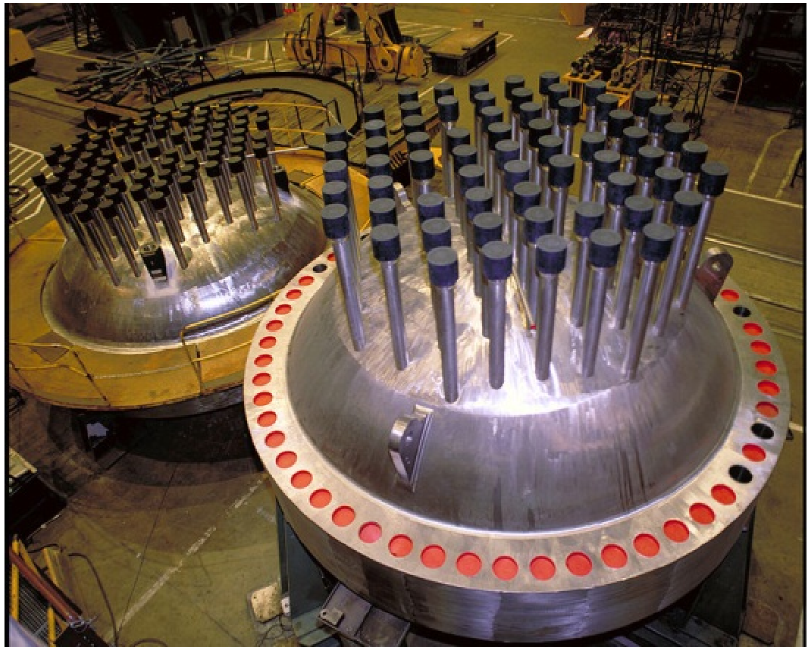
Aircraft gas turbines:

- Components in the power train :
  - Shafts (which are turned by)
  - Disks or wheels (attached to the shafts)
  - **Blades** or buckets (attached to the disks)
  - Vanes or stators (attached to the engine frame)
- Combustion systems for burning fuel in:
  - Burner cans or combusters (attached to the engine frame—may contain multiple parts),
  - Combustion chambers
- Other: bolts, casings, exhaust systems, cases, afterburners, thrust reversers

- **Space veihicles:** aerodynamically heated skins, rocket engine parts

Superalloys

Applications



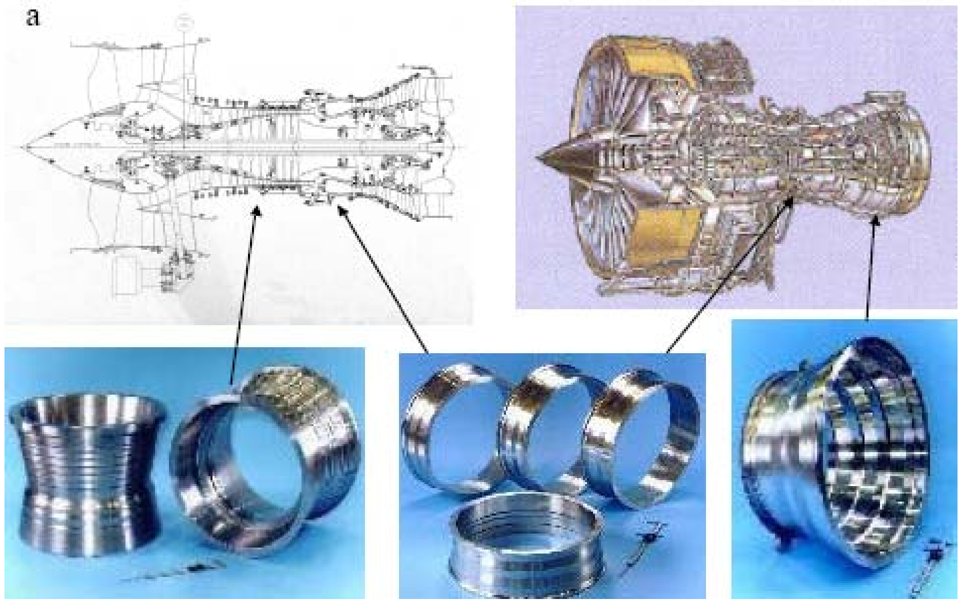
Pressurized water reactor vessel head

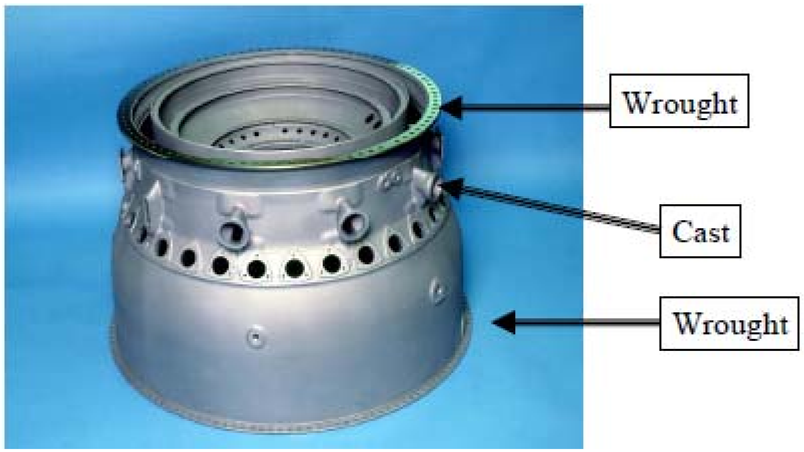
Rocket Motor Engine

Superalloys and intermetallics

Applications

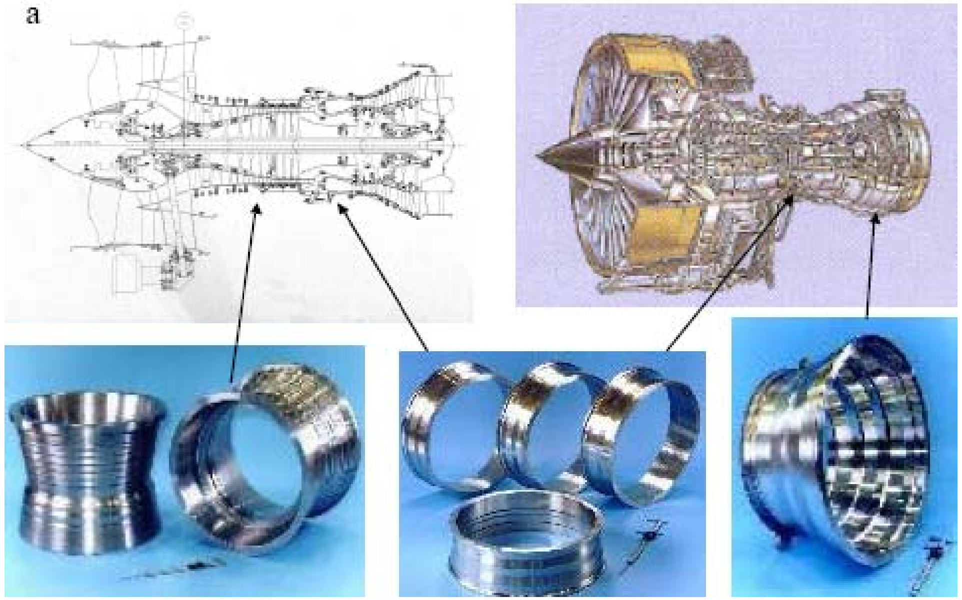
Discs for second stage for turbine aeroengines (HIP)

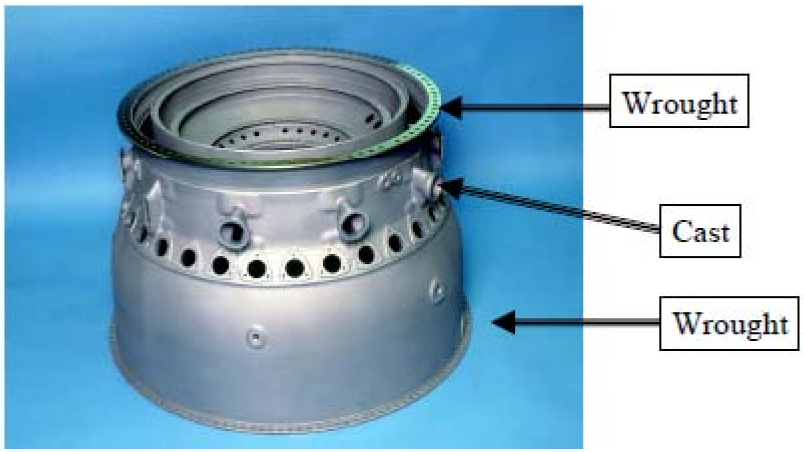




Ring preform Spraycast-X®
spray forming

Image courtesy University of Birmingha





HIP

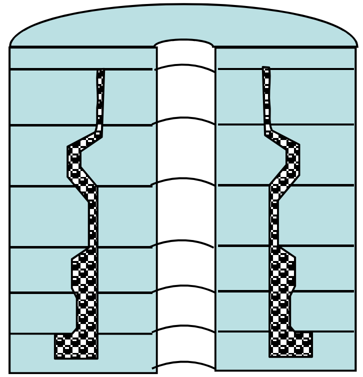


Image courtesy University of Birmingham

Intermetallics

Applications

Low-pressure turbines (LPT): *Airbus A320, Boeing 737*.

➔As the potential for weight reduction is highest in the low-pressure turbine, γ-TiAl will be introduced for the turbine's rear rotor blades.

➔This will achieve LPTs having increased revolutions and entry temperature that are capable of operating at higher efficiency compared with conventional LPTs.

- **1995 General Electric Aircraft Engines**: LPT blades-**Ti-48Al-2Cr-2Nb** (Ti-4822)

NASA -Aerospace Industry Technology Program funding was awarded to a GEAE-led team

→40% weight reduction from currently used Ni-base superalloys (70 kg per stage)

→Maintaining the current system cost.

Rolls-Royce : Titanium Aluminide (TiAl) is an inter-metallic material offering a significant weight benefit for LPT blades.

F-22 : γ-TiAl blades in LPT

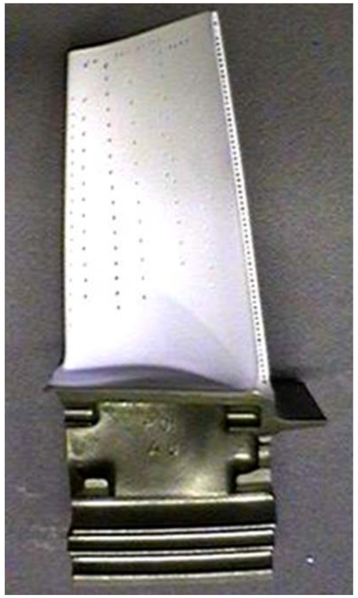
Rolls-Royce

NASA

The **Low Pressure Turbine (LPT**) makes up approximately 20 per cent of the overall engine weight and its aerodynamic efficiency is an important driver on fuel consumption. The 50 per cent reduction in material density enables additional weight savings in discs and casings.

GE Aviation

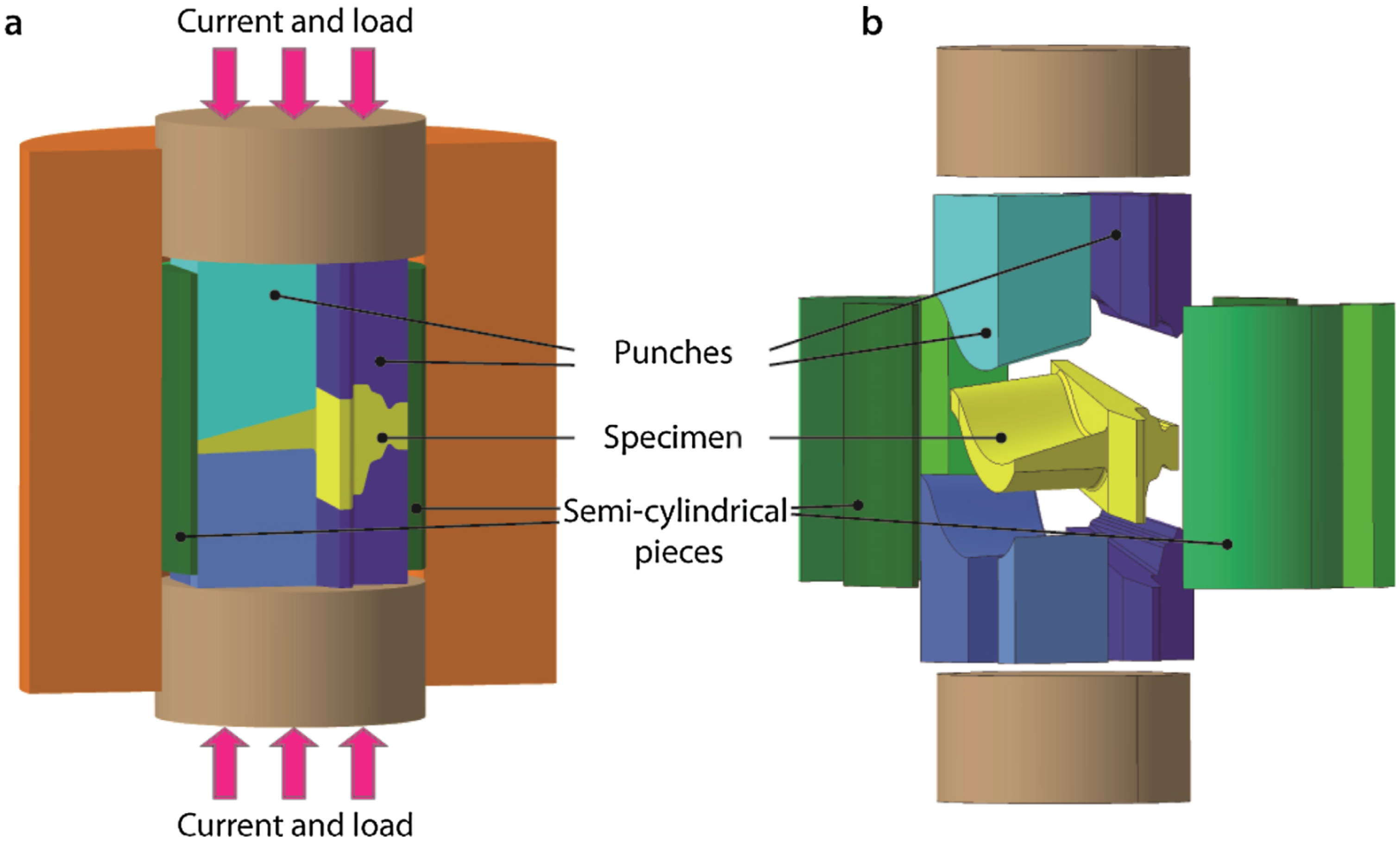
The GEnx™ Engine Family



Turbine Blades (Jet Engine)

An Innovative Way to Produce γ-TiAl Blades: Spark Plasma Sintering

Thomas Voisin, Jean-Philippe Monchoux, Lise Durand, Nikhil Karnatak, Marc Thomas and Alain Couret, University of Tolouse
ADVANCED ENGINEERINGMATERIALS, 2015


a
Current and load
Current and load
b
Punches
Specimen
Semi-cylindrical
pieces

Intermetallics

Applications

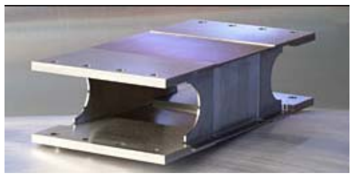
γTiAl sheet is being considered as a material candidate in current major ***American Aerospace Programs***

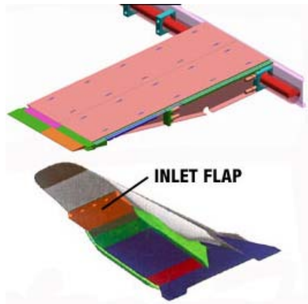
1) The Reusable Launch Vehicle
2) The NASA Future X Plane
3) The Joint Strike Fighter
4) The X-38 Crew Rescue Vehicle
5) Supersonic transport aircraft

TiAl Scramjet Inlet Flap Subelement

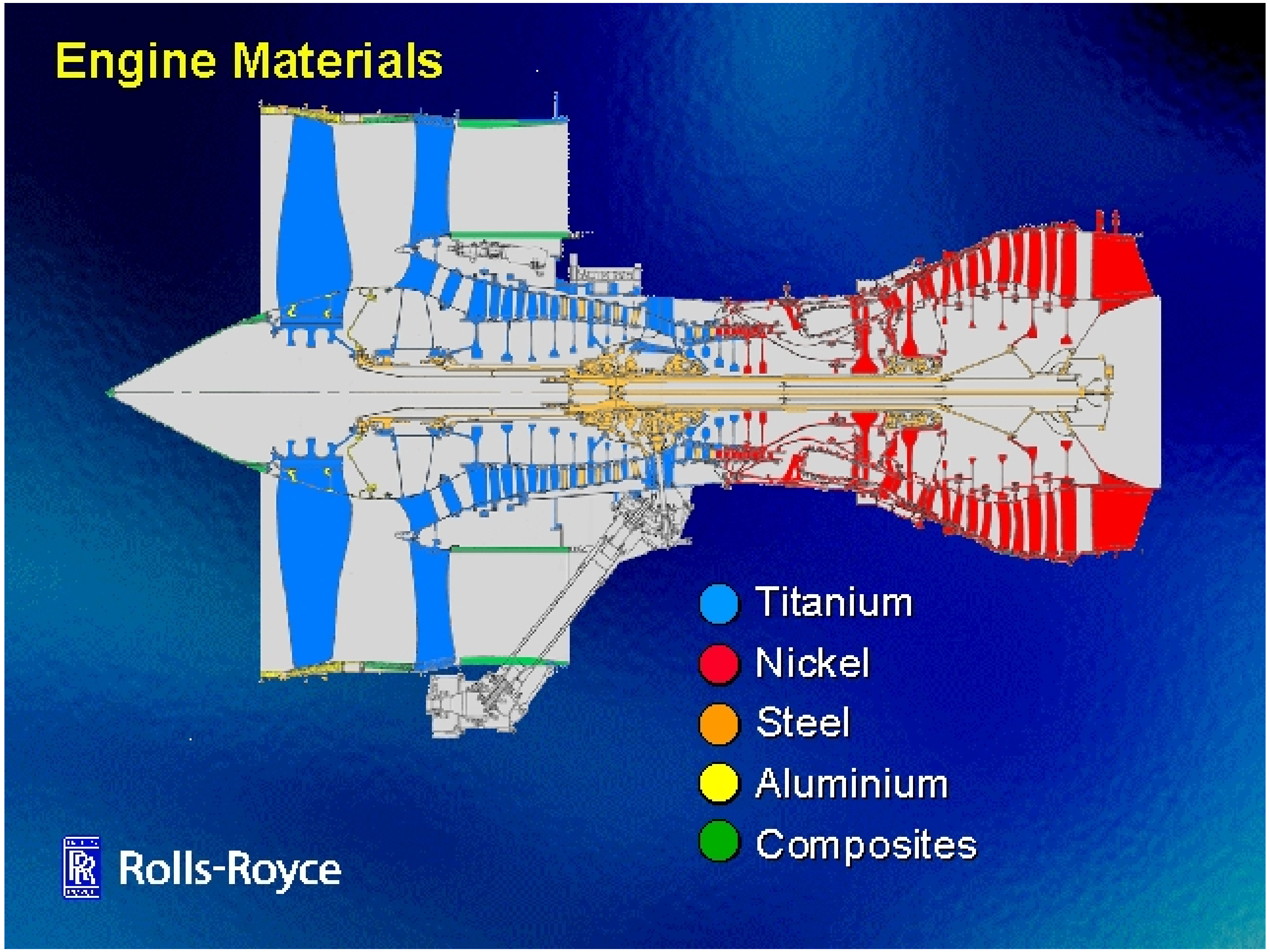
Future hypersonic vehicles will be powered by scramjets.

The use of TiAl scramjet inlet flap subelement will allow for major weight savings and temperature capability improvements.

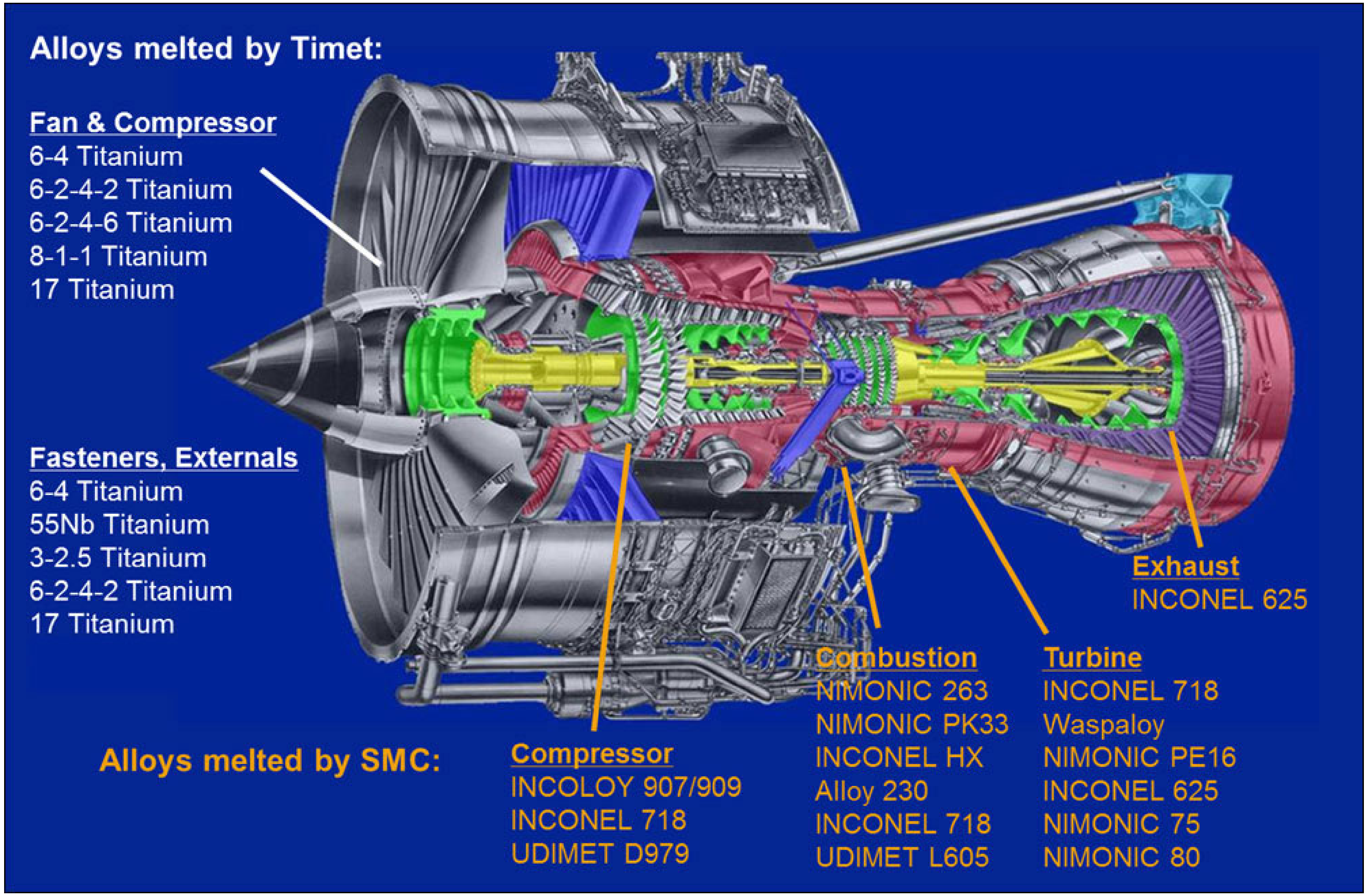




Who win the competition???



Who win the competition???



Thank you?

Questions?