Course goal: Compare the processing stages and properties of ***polycrystal superalloys for turbine disk*** applications, and ***single-crystal superalloys for turbine blade*** applications. Understand creep and fatigue processes, and the importance of defects, in single-crystal superalloys.

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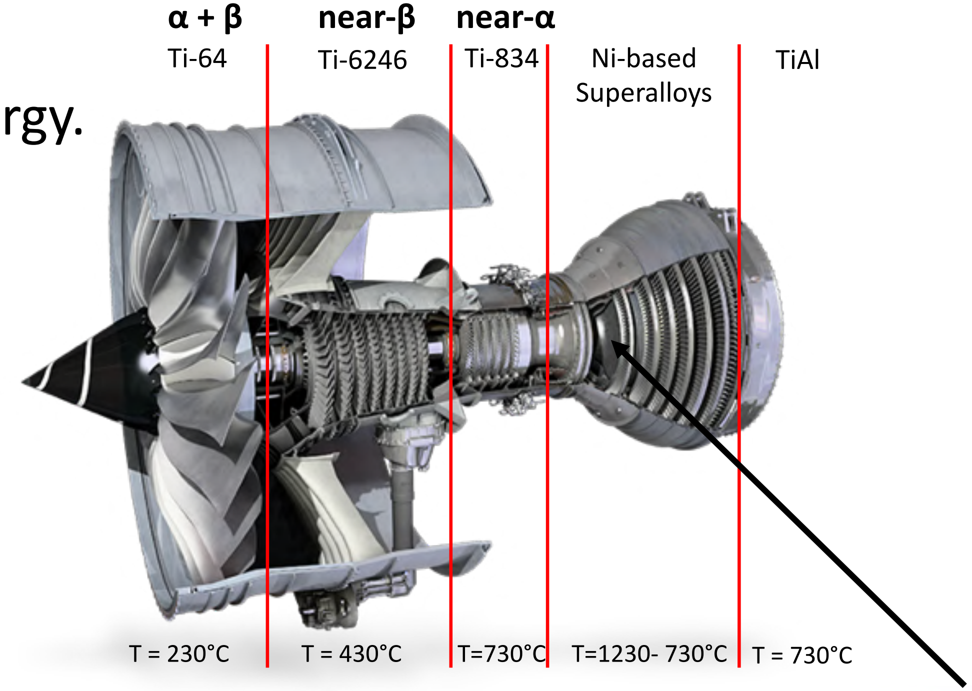
Turbine Disk – Hot Isostatically Pressed component, with polycrystalline superalloy microstructure.

Superalloys for Turbine Disk Applications

- Fixture for fan blades, extract mechanical energy.
- ***Critical component of jet engine!***
- Stresses ~ 1000 MPa at take-off.
- Working temperature ~ 650°C *(lower than operating temperature of the fan blades in the hot gas stream).*
- Tolerance to creep needed
- Tolerance to Low Cycle Fatigue (LCF) needed (*more so than HCF)*.



Turbine Disk – Hot Isostatically Pressed component, with polycrystalline superalloy microstructure.

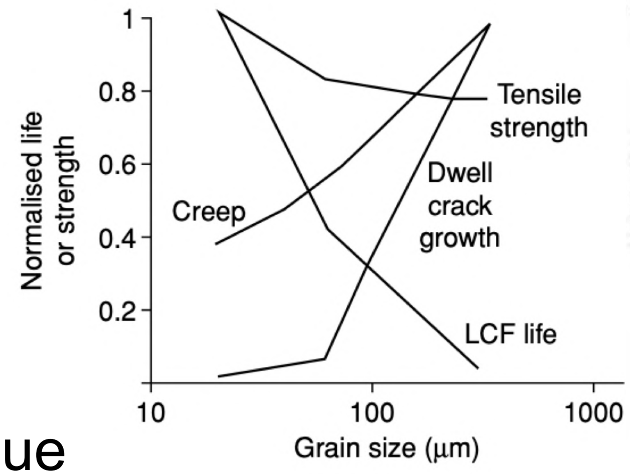
Superalloy Turbine Disk Properties

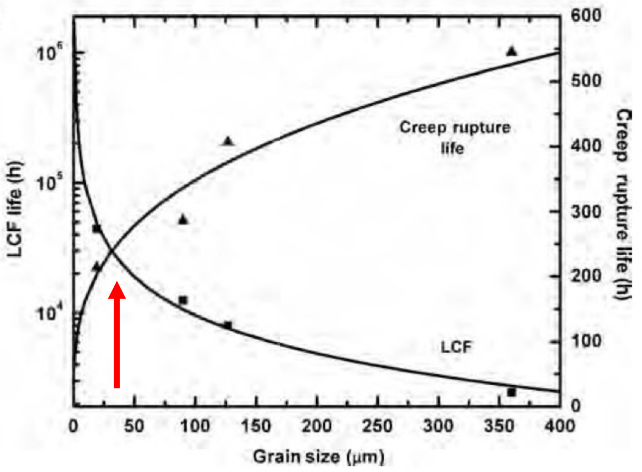
Aims for processing of polycrystalline superalloy turbine disk…

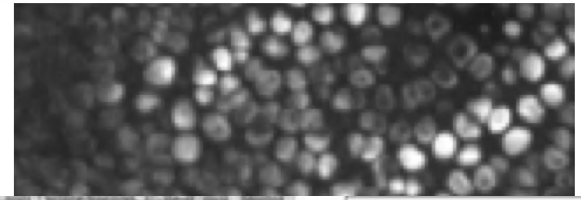
1. Grain size ~ 40 μm
   → strength, resistance to fatigue crack initiation *(↓ grain size)*
   + creep strength and resistance to fatigue crack growth *(↑ grain size).*

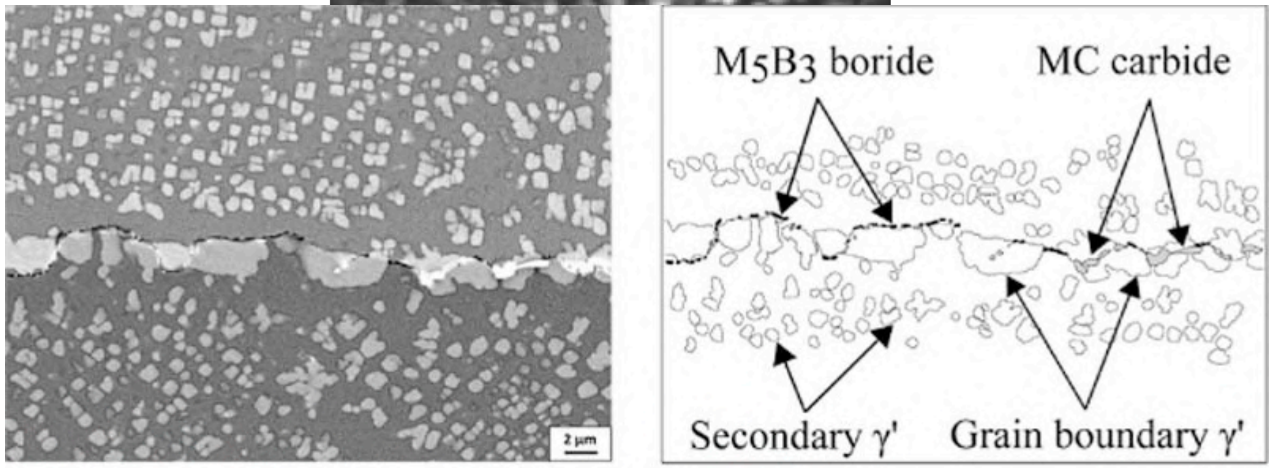
2. Uniform distribution of γ' phase
   40% – 50% volume fraction
   (Al, Ti, Ta additions and HT).
   → strength and fatigue resistance

3. Boride (B) and carbide (C) precipitation
   → grain boundary strengthening
   → reduce creep and LCF.

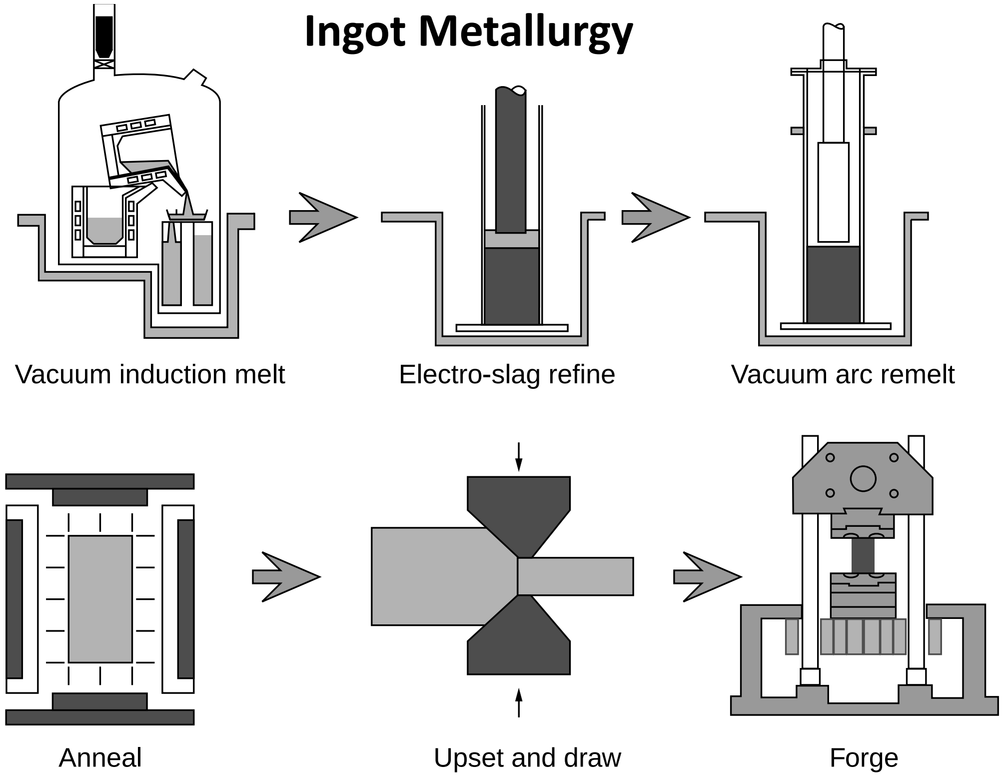








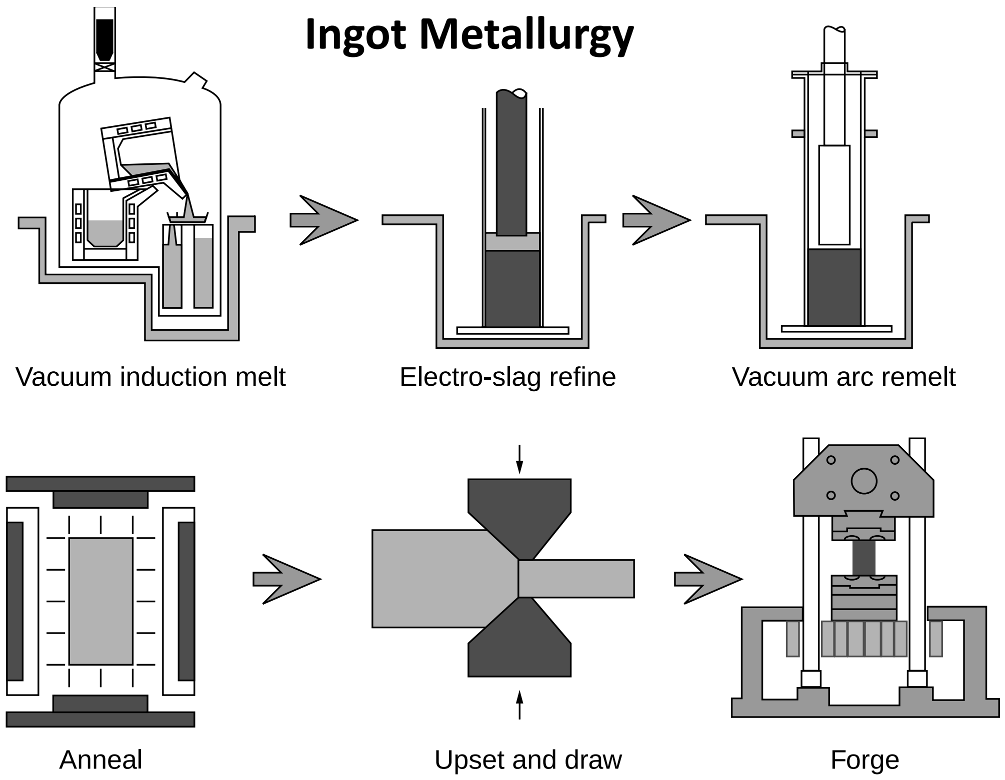
Processing of Superalloy Turbine Disks



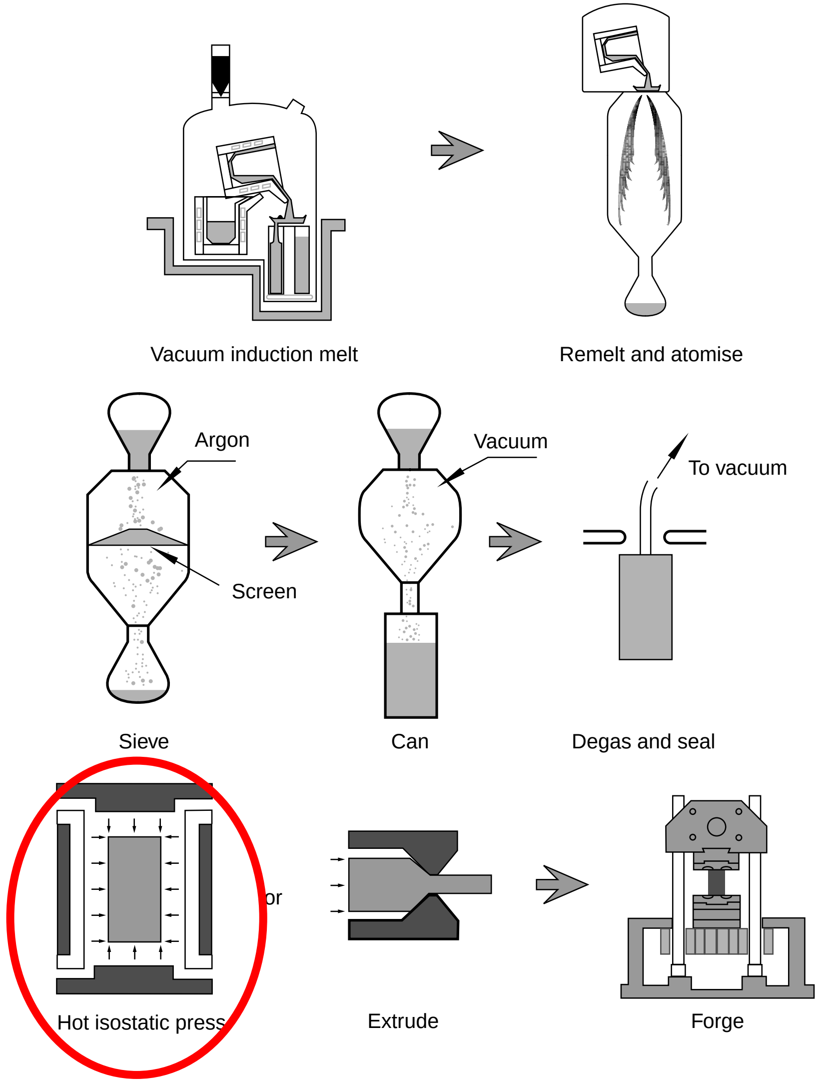
- Hot Working (Rolling, Forging) 1100-1200°C
- Solutionise: 4hrs at 1175°C (super-solvus) or 1100°C (sub-solvus)
  (Homogenize remnant cast structure, dissolve carbides, grain size development)
  – Cool
- Intragranular Strengthening Precipitation : 4hrs at ~ 1000°C (γ’ or γ”)
  – Air Cool
- Grain Boundary Carbide Precipitation : 16-40hrs at ~ 900°C *(Thermally treat)*

Processing of Superalloy Turbine Disks

Ingot Metallurgy



Powder Metallurgy



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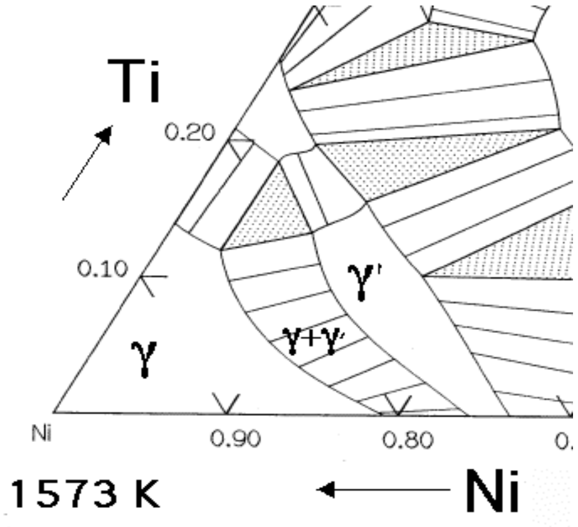
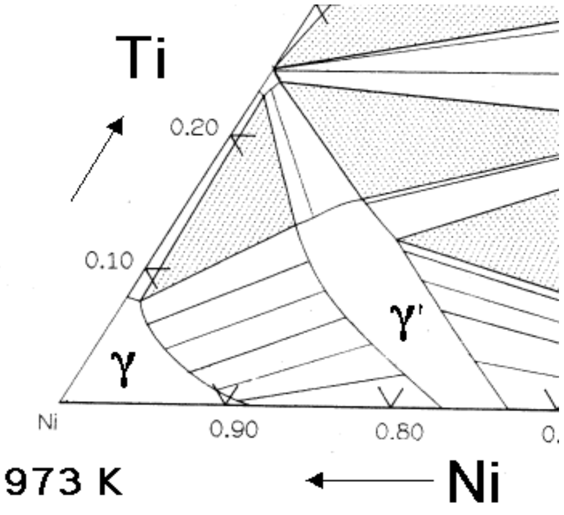
– Air Cool

- Grain Boundary Carbide Precipitation : 16-40hrs at ~ 900°C *(Thermally treat)*

Superalloy Turbine Disk Precipitation

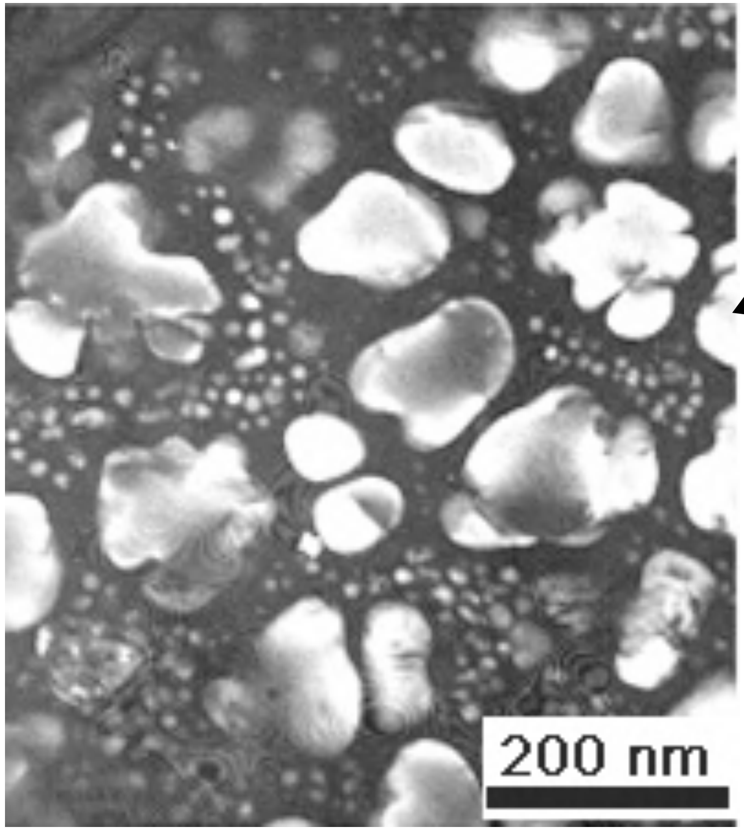
- Alloy contents are designed to be in the γ–γ’ phase field
- Chemical segregation must be reduced during solidification to optimise properties
- ***Solutionising*** → material is taken back up into the single phase γ (super-solvus), or two-phase γ–γ’ (sub-solvus)
- ***Intragranular precipitation*** occurs as solid solution is cooled into the more extensive two phase region.
- *Quench and step-wise heat treatments can be conducted to generate primary, duplex, and tertiary distributions of γ’*

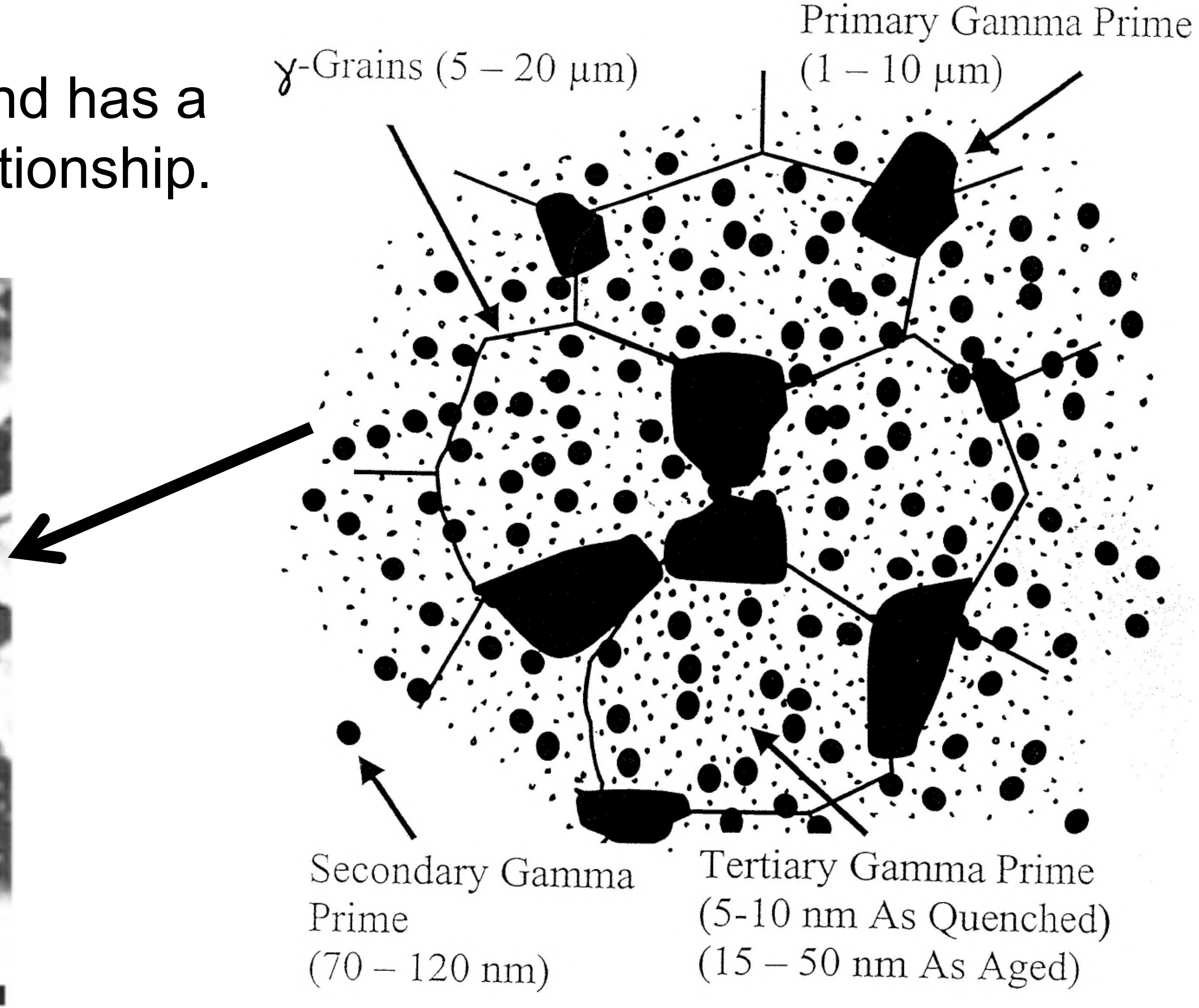




Typical Polycrystalline Superalloy Microstructure

- Intragranular γ′ is coherent with γ and has a simple cube-cube ([001]||[001]) relationship.

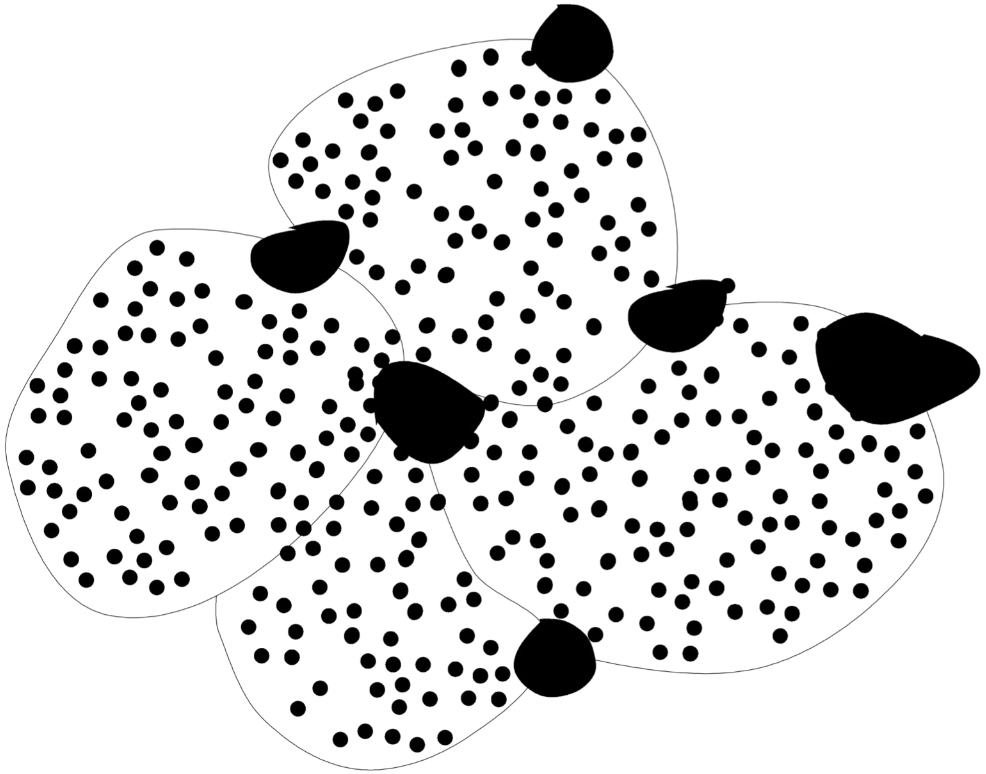




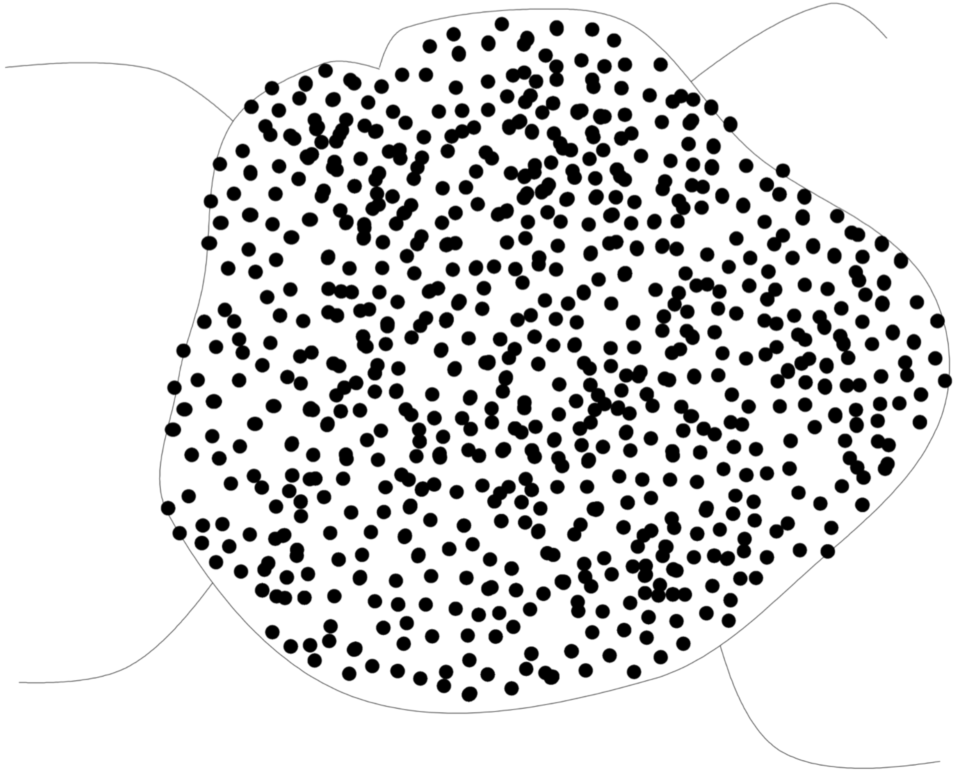
Sub-solvus and Super-solvus Heat-treatment

- *Super-solvus heat treatment can improve high temperature properties, such as creep…*

Sub-solvus heat treatment



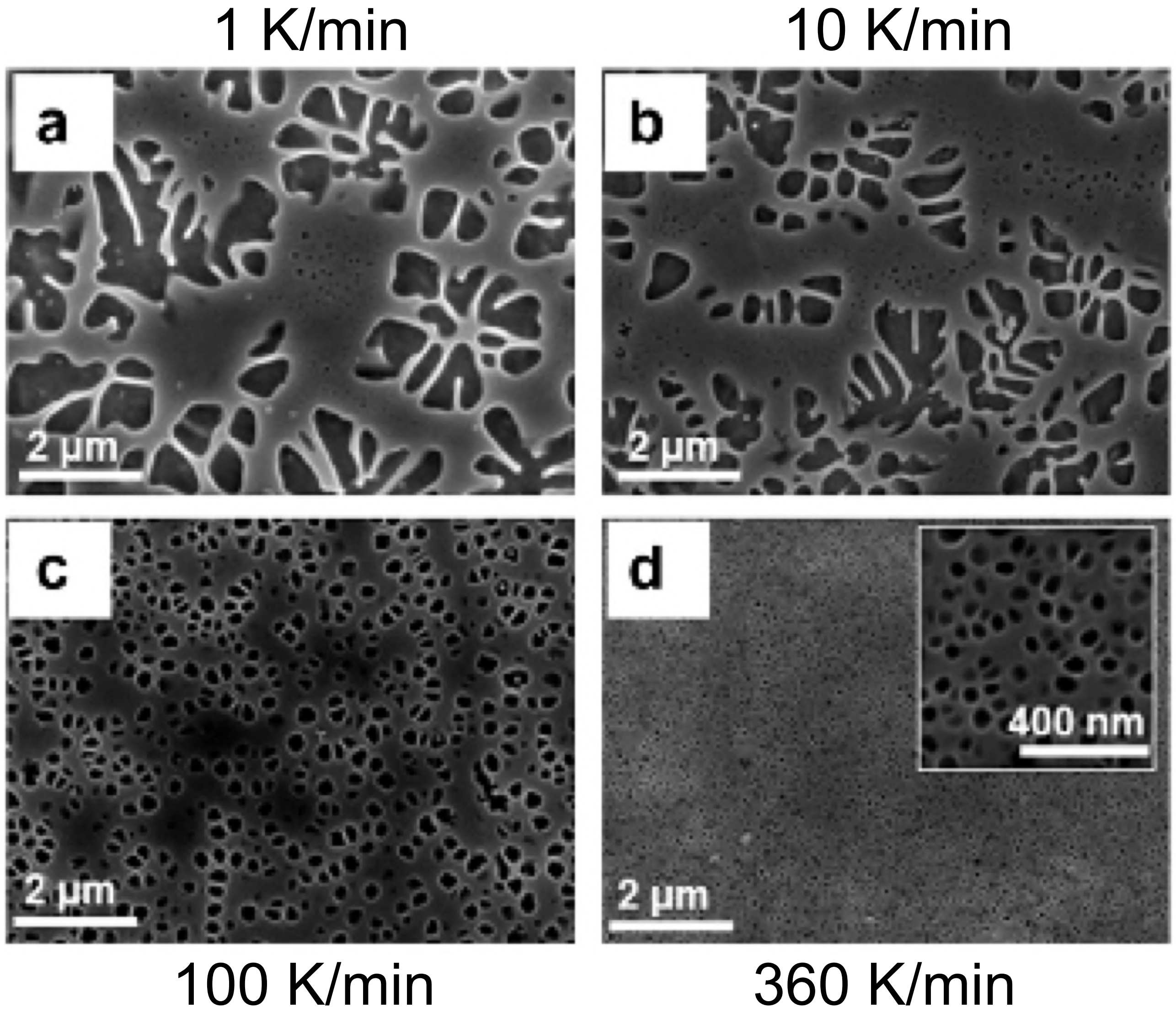
Super-solvus heat treatment



Effect of Cooling Rate on γ'

- Faster cooling rate
  → finer γ' phase distribution

  (diffusion kinetics)



Effect of Cooling Rate on γ’

Faster cooling rate

↓

Restrict elemental diffusion

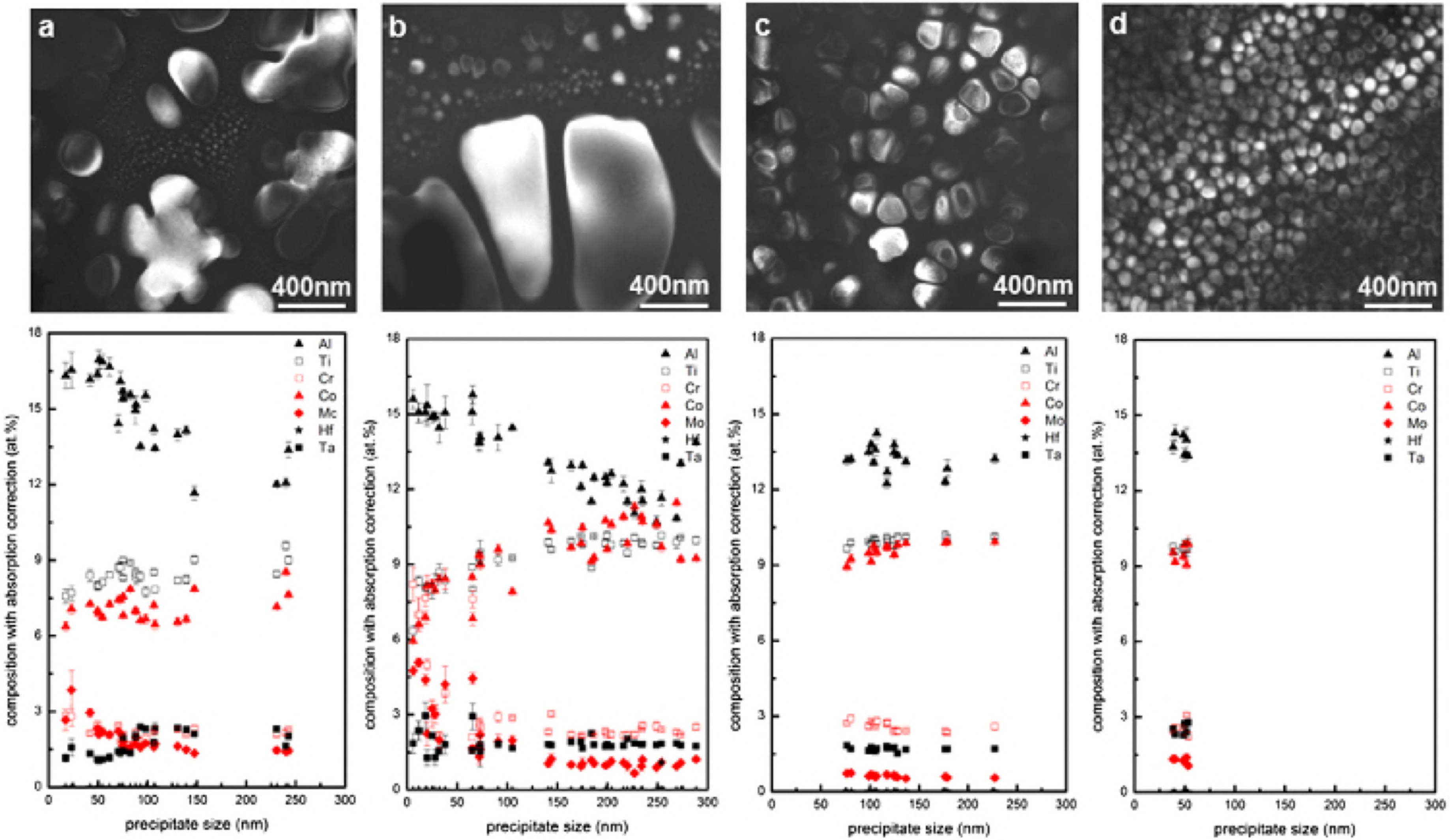
+

Minimise chemical partitioning

↓

Alter lattice misfit

1 K/min 10 K/min 100 K/min 360 K/min



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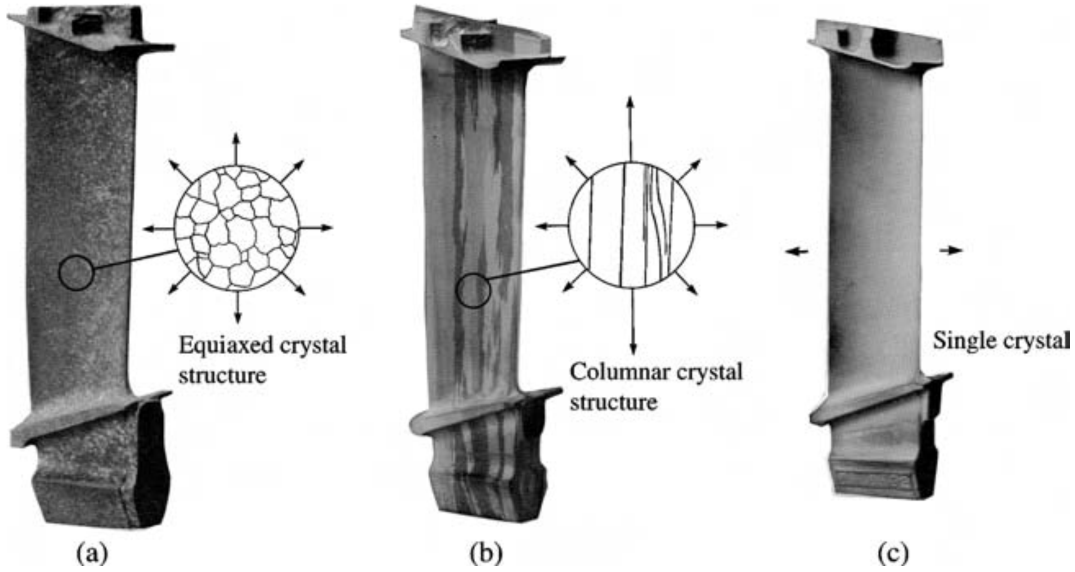
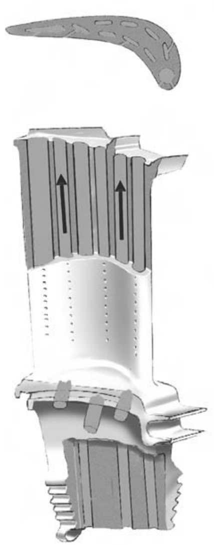


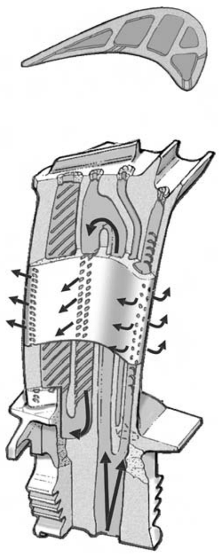
The move to using single-crystal superalloys for turbine blades has improved their high temperature creep properties, allowing them to withstand higher temperatures in the hot-gas stream of the jet engine.

Turbine Blades

- High temperatures ~ 1500°C in hot gas stream! Stress ~ 180 MPa.
- Blades expected to last ~ 3 years.
- Alloys optimised for ***high temp. creep strength*** and ***high cycle fatigue (HCF)***.
- *Alloys are not optimised for LCF.*

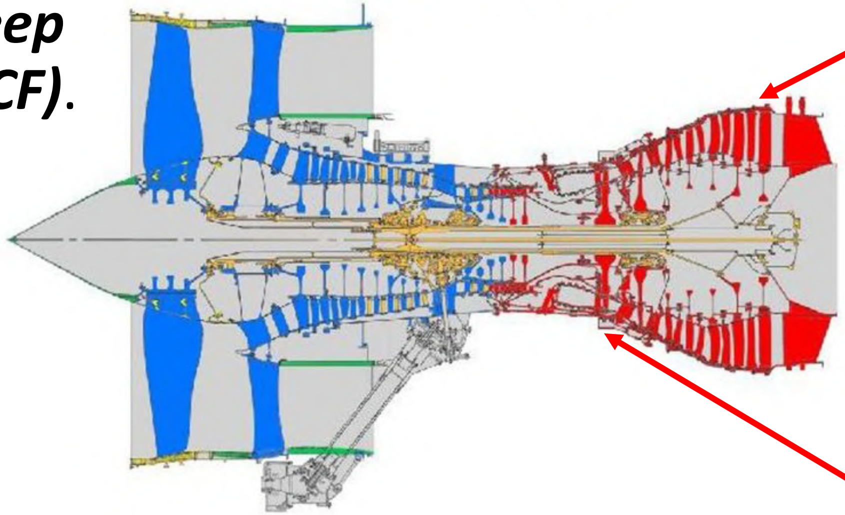


Single-pass cooling



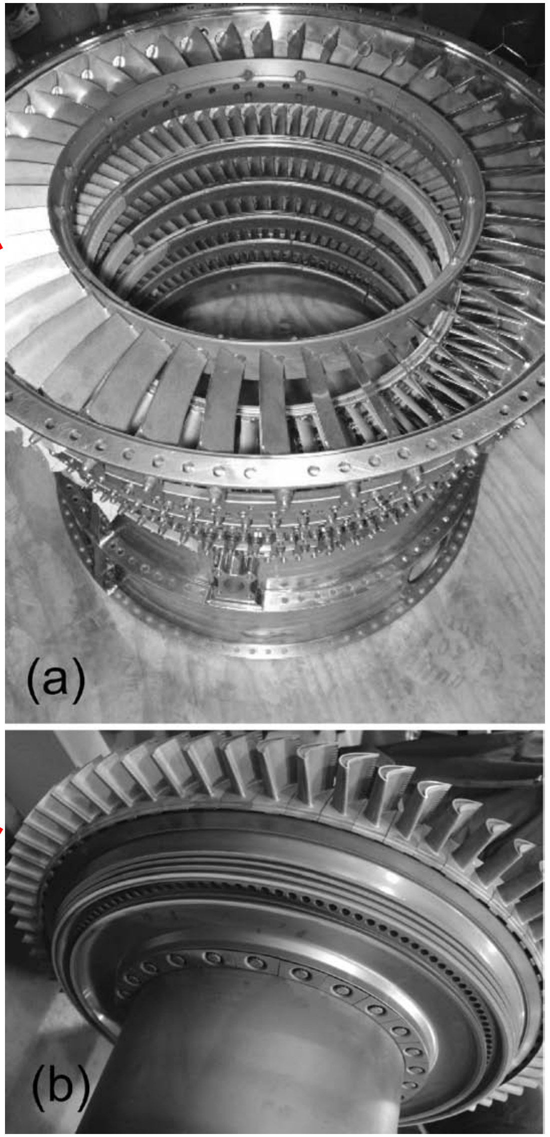
Multi-pass cooling

ENGINE MATERIALS



- Different materials used in Rolls-Royce jet engine
  - Blue: titanium is ideal for strength and density, but not at high temperatures
  - Red: nickel-based superalloys
  - Orange: steel used for the static parts of the compressor
  - Green: Composite

Low pressure turbine

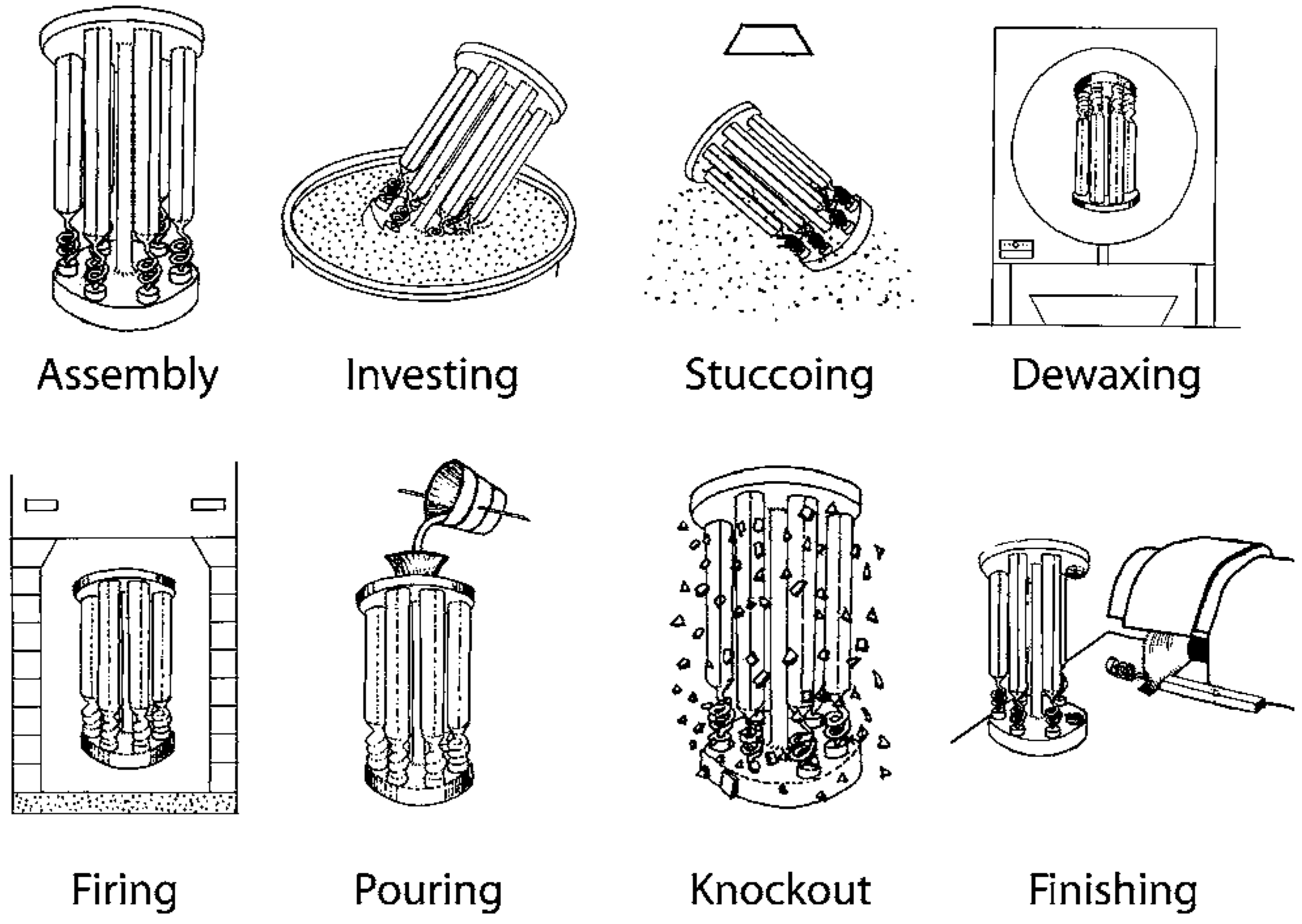


High pressure turbine

Processing of Turbine Blades

- Produced by investment casting, also called 'lost-wax' process

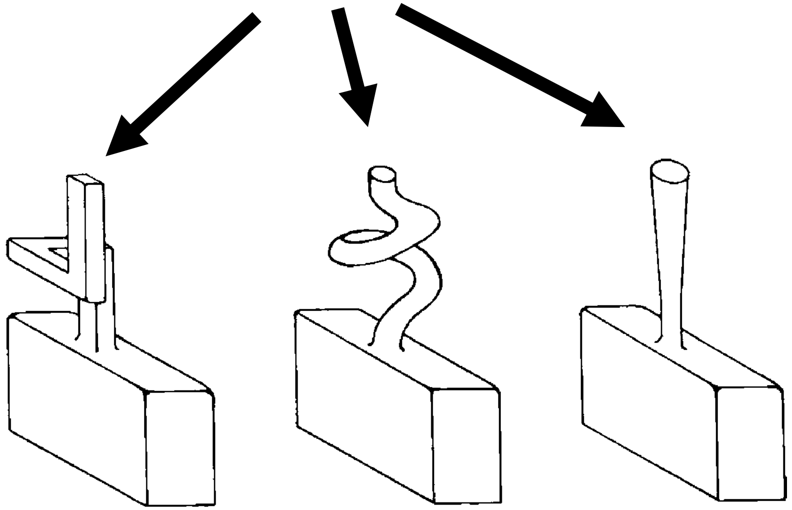
1. Production of wax model, wax will set around ceramic cores for cooling passages
2. Model is dipped into ceramics slurries consisting of binding agents and mixture of zircon ($ZrSiO_4$), alumina (Al_2O_3) and silica (SiO_2)
3. Mould is baked at low temperature to melt out the wax
4. High temperature to fire the ceramic mould
5. Pre-heating, degassing followed by vacuum pouring of molten superalloy



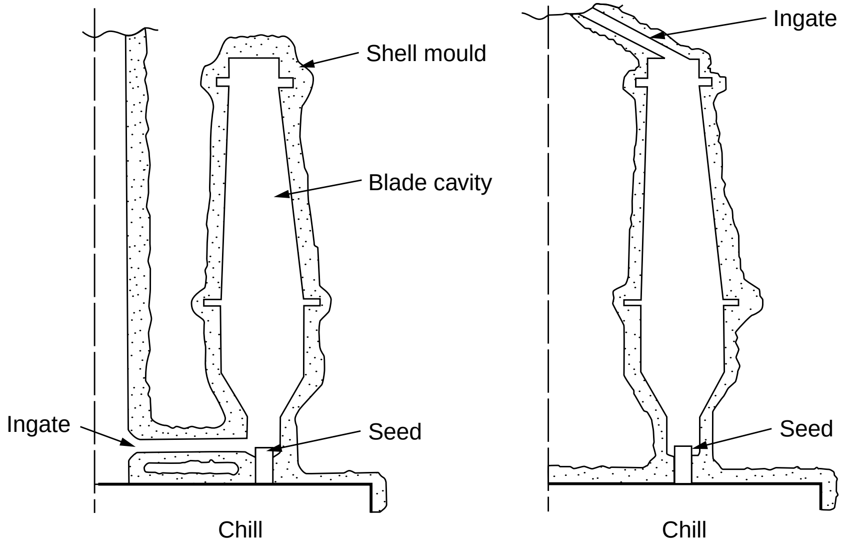
Directional Solidification

- Directional solidification by removing heat from one direction in a controlled manner *(crystal growth is 2-3 cm per hour)*

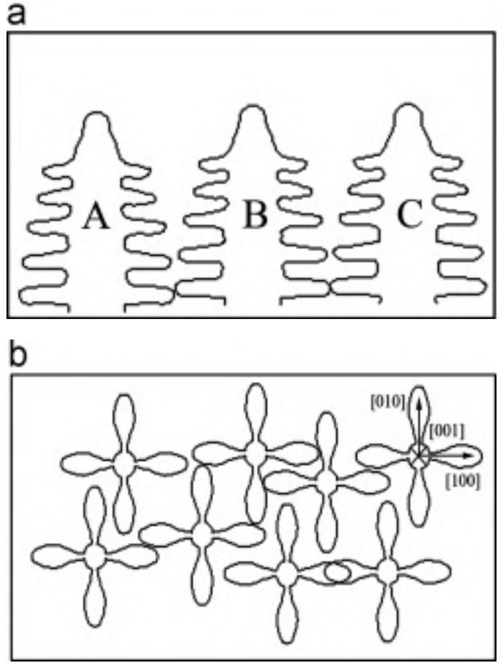
Pig-tail style grain selectors



Two configurations for growing single crystals



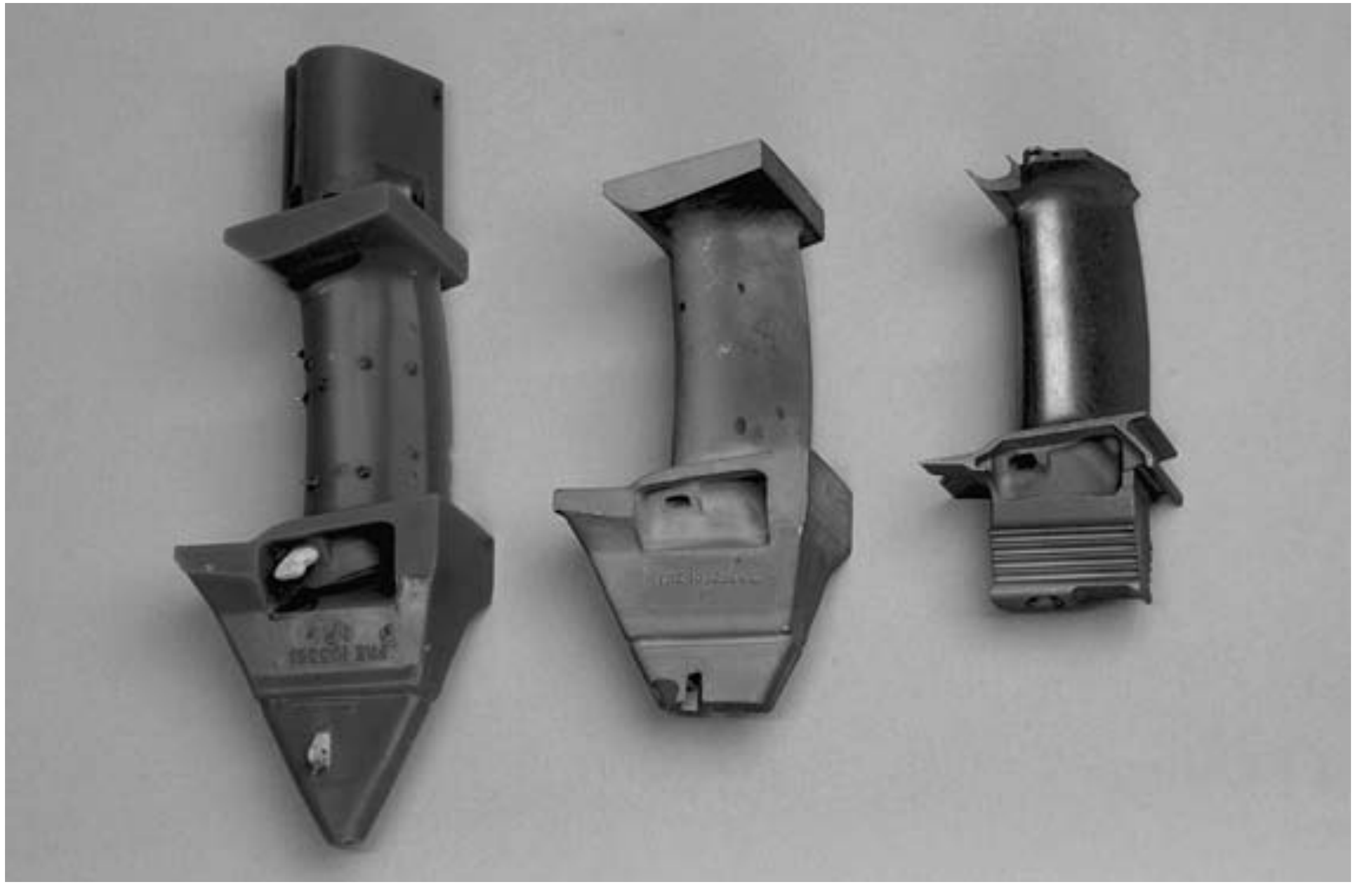
Dendrite growth from longitudinal and transverse sections



- When adding a 'grain selector' to the base of the wax mould, ***a single grain can be grown***
- <001> growth direction is chosen

Directionally Solidified Turbine Blade

- Final machining to achieve accurate shape tolerance.



Wax model

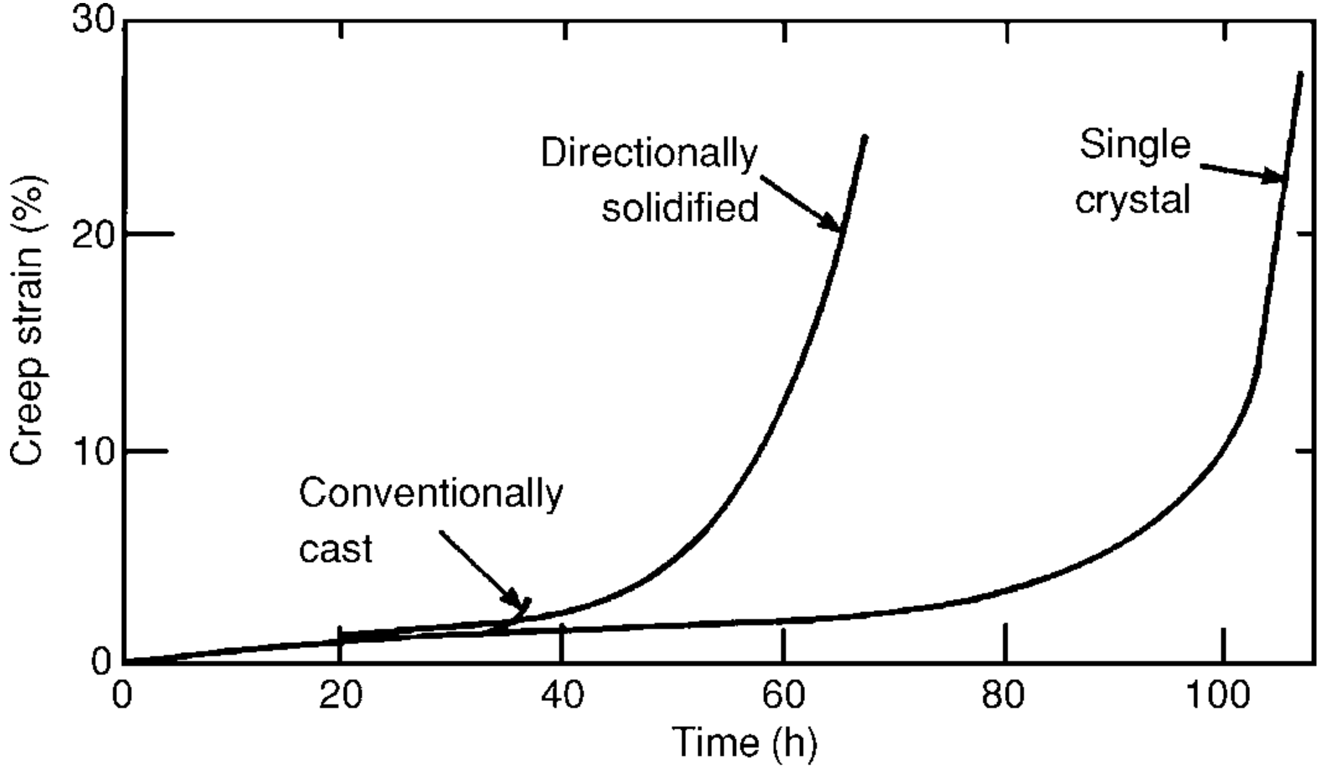
Finished casting with grain selector removed

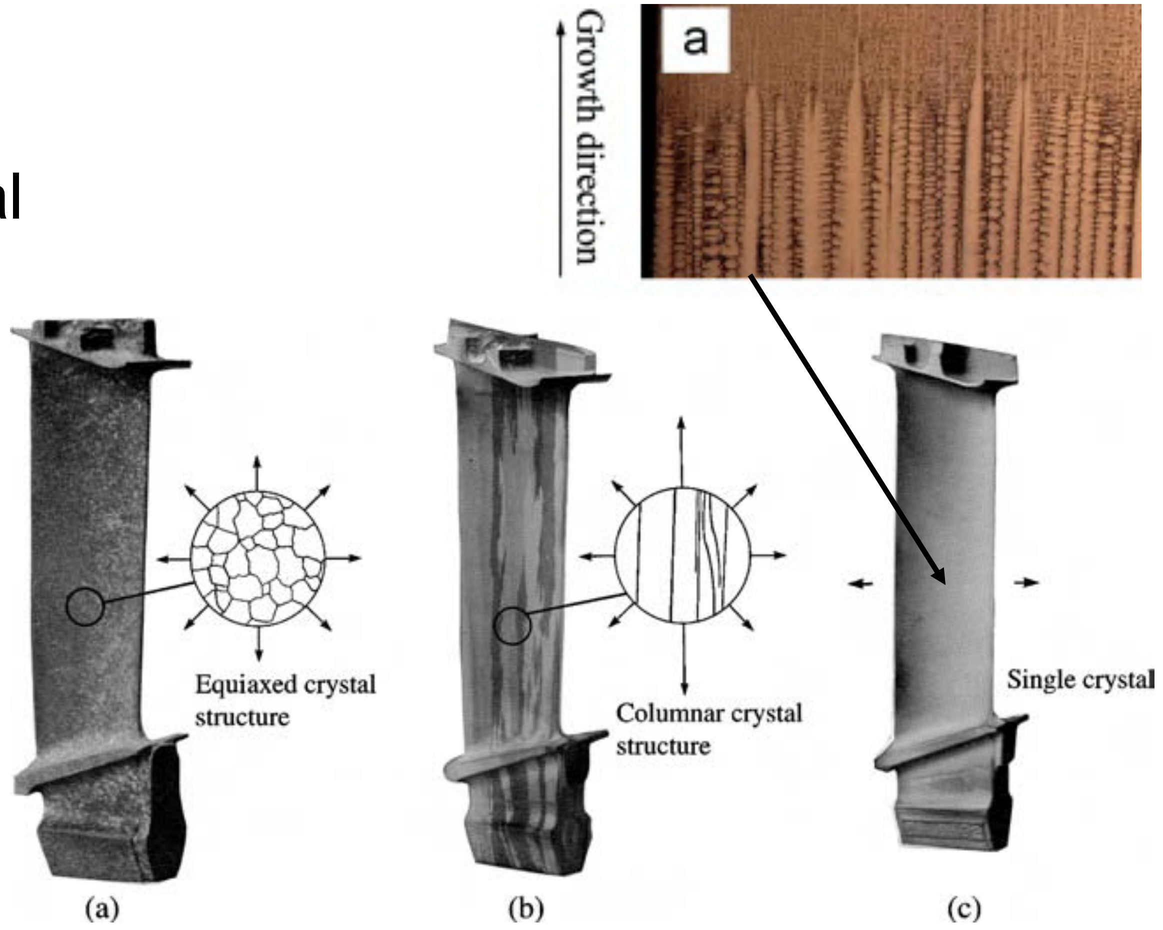
Finished blade after machining

Finished casting with grain selector

Creep Strain Comparison

- Superalloy Mar-M200 produced by conventional casting, directionally solidified (columnar grains) and single crystal
- ***Creep performance***
  cast < directionally solidified < single crystal





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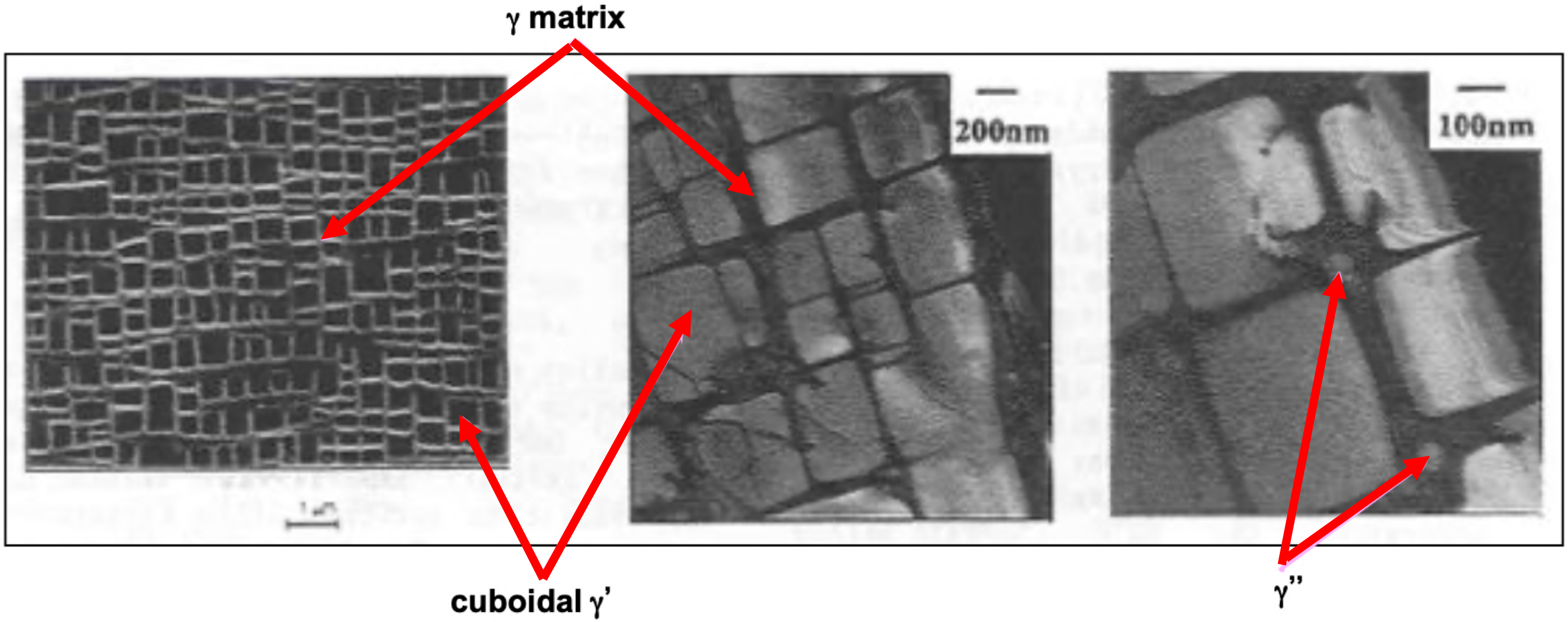
Freckling defect in single-crystal turbine blade, caused by chemical partitioning during solidification.

Good Single Crystal Properties

1. High proportions of γ' elements (Al, Ti, Ta)
   → ***γ' fraction ~ 70%***



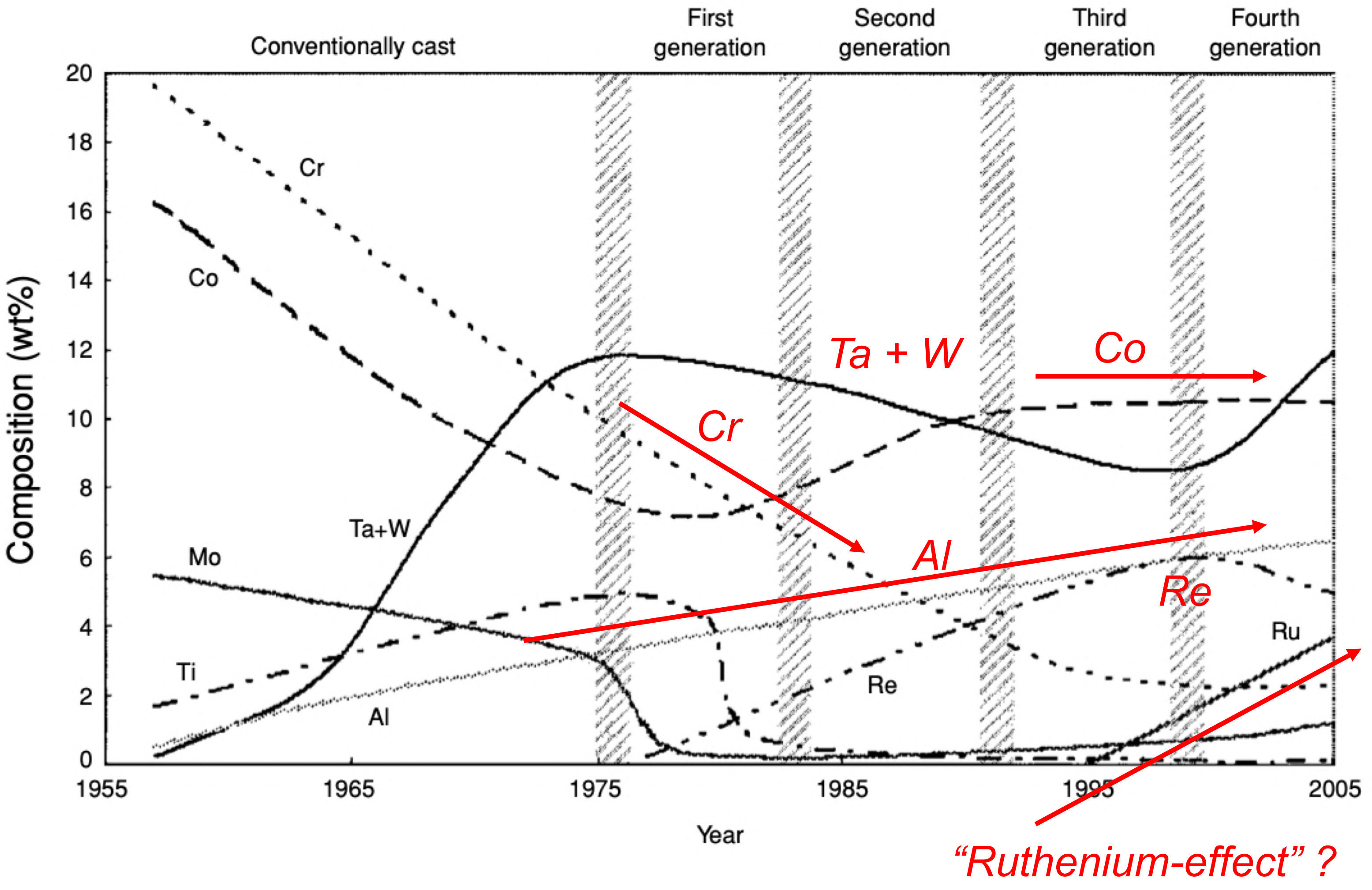
Good Single Crystal Properties

1. High proportions of γ' elements (Al, Ti, Ta)
→ ***γ' fraction ~ 70%***

2. Less importance to surface degradation → ***Coatings***

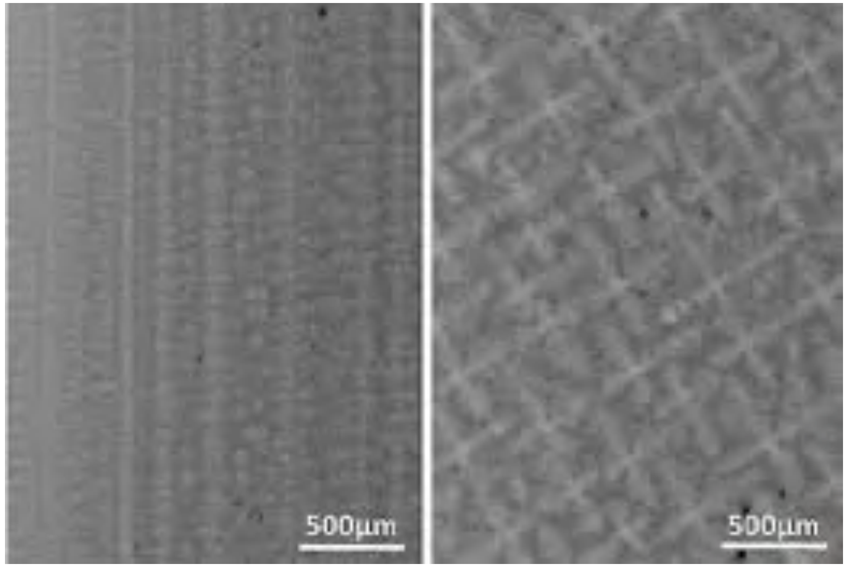
3. Small γ/γ' misfit to limit γ' coarsening
→ small particles *(vary composition, temperature)*

4. Re, W, Ta, Mo, Ru for ***creep strengthening and HCF***, *but limit TCP phases*

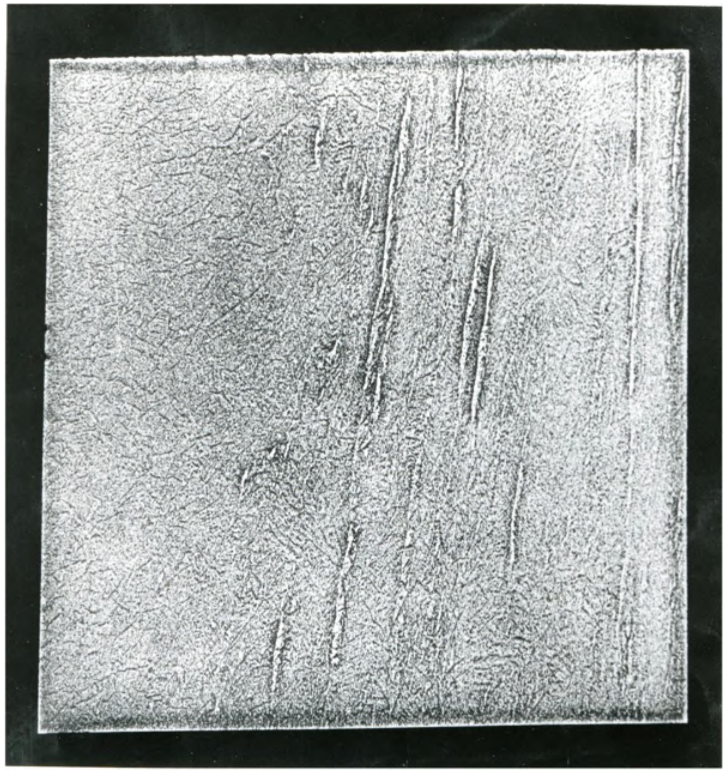


Single Crystal Defects – Freckling

- ‘Single crystal’ materials composed of dendrites.
- ***Freckling*** – thin chains of equiaxed grains from chemical composition heterogeneity *(Al, Ti, Ta, Nb partitioning)*
- *Any grain boundaries reduce creep tolerance of ‘single crystal’*

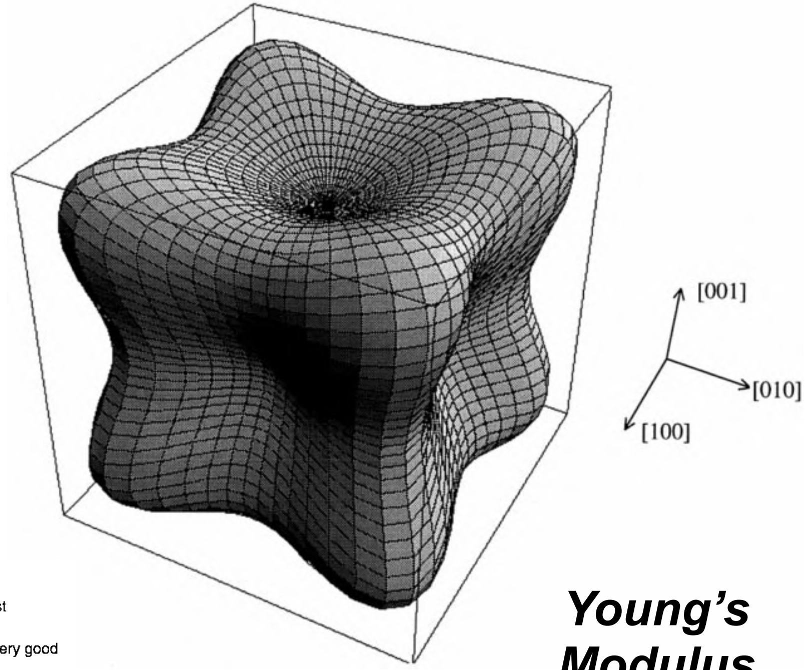


Dendrites from longitudinal and transverse direction

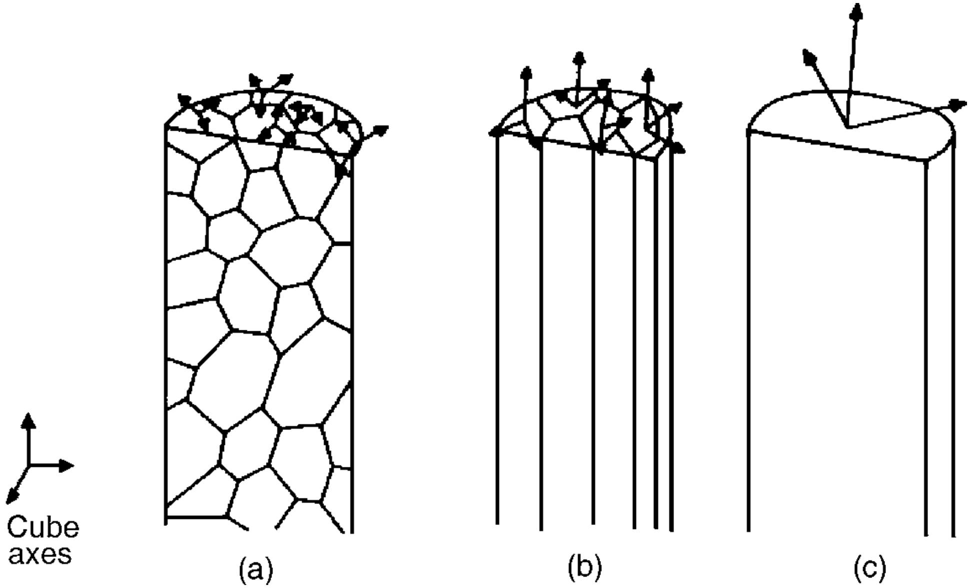


Single Crystal Defects – Orientation

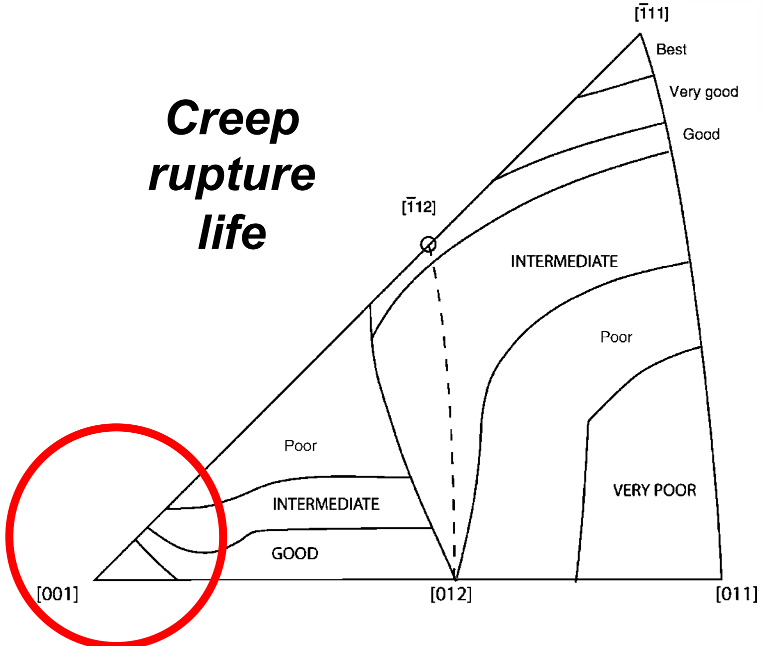
- Optimum yield stress, creep rupture life and fatigue strength for [001] along blade tensile axis.
- Small deviations from [001] can reduce creep life.

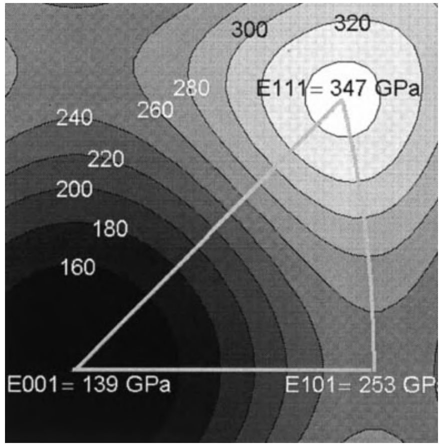


Young's Modulus



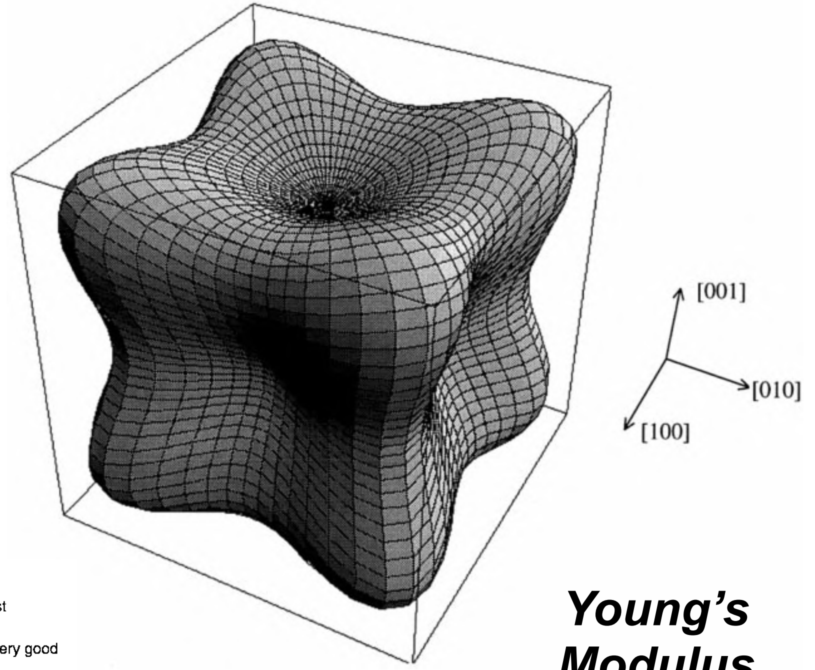
Creep rupture life





Single Crystal Defects – Grain Boundaries

- Optimum yield stress, creep rupture life and fatigue strength for [001] along blade tensile axis.
- Small deviations from [001] can reduce creep life.
- Any low angle grain boundaries could reduce creep rupture properties…



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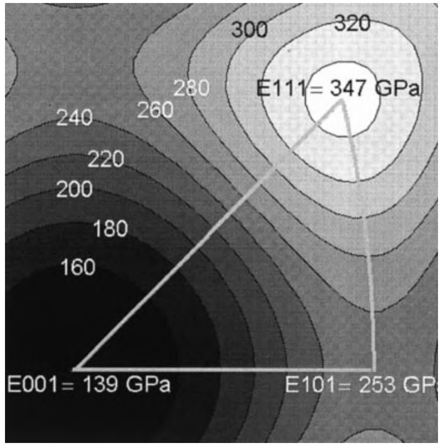
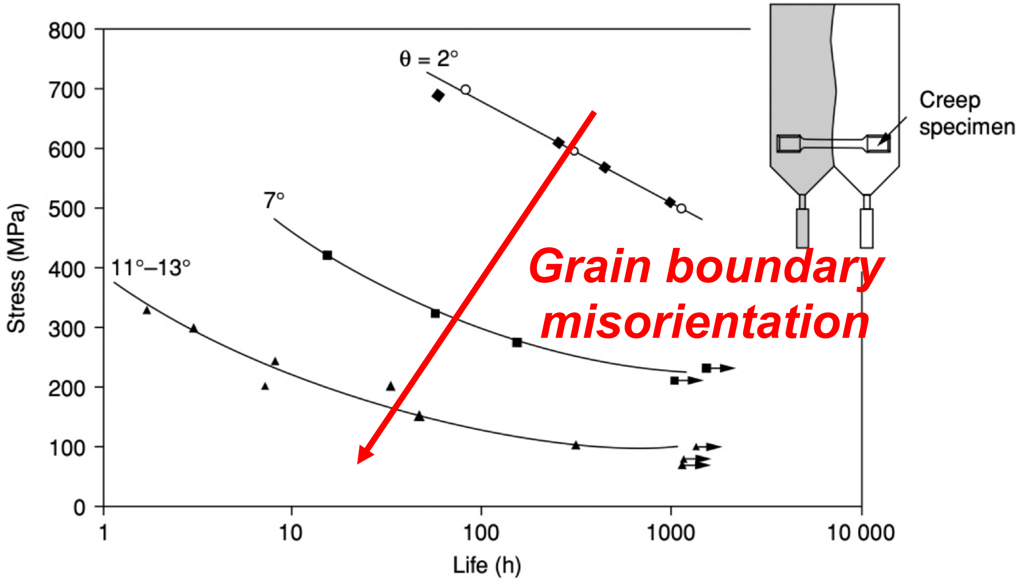
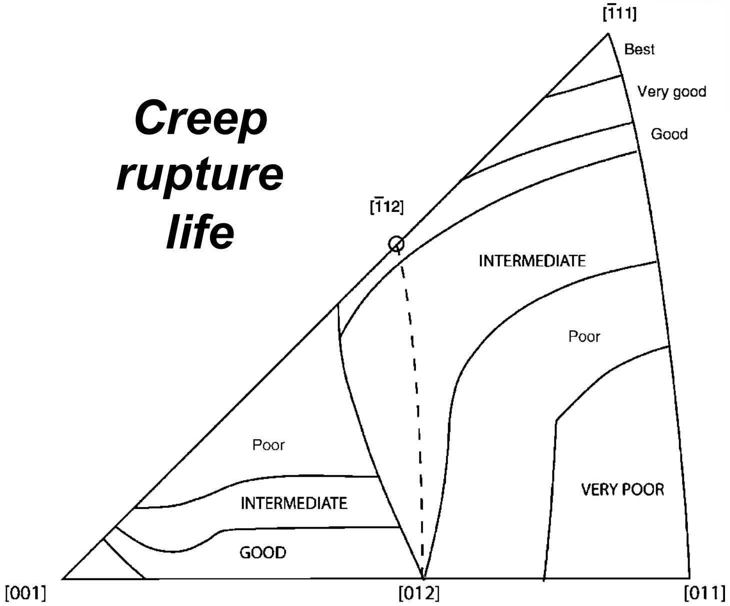




Creep rupture life



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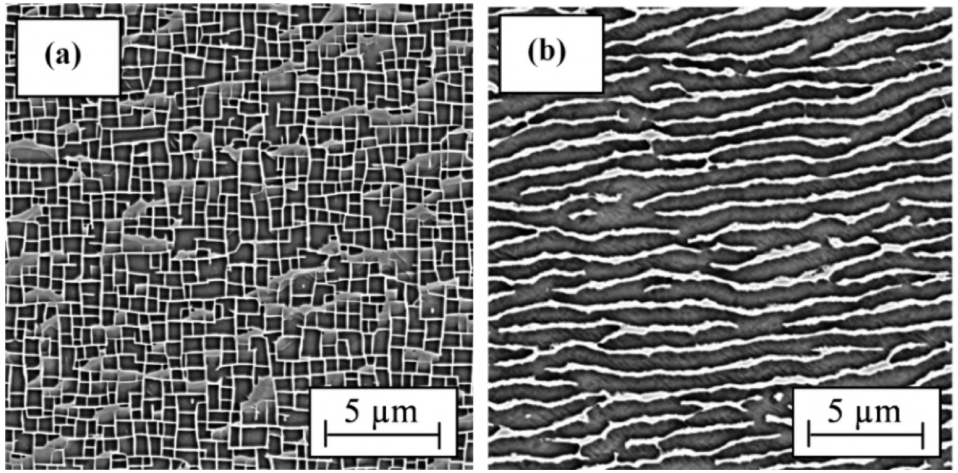
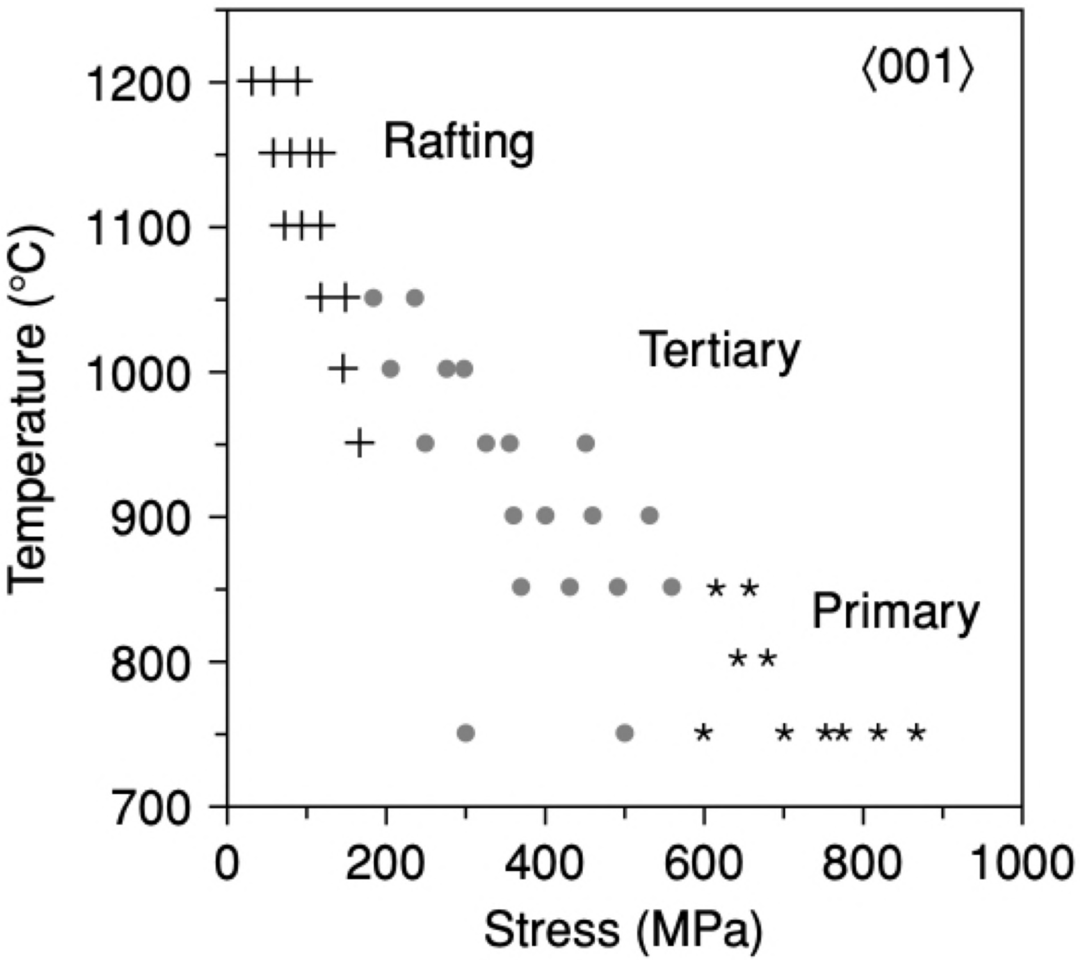


Single crystal microstructure with initial γ/γ' microstructure (a), and fully rafted microstructure after applied loading at high temperature (b).

Creep Performance

- Creep is a life-limiting factor, eventually blades lengthen and must be removed.
- Different creep regimes depending on operating temperature and stress
- Primary → non-uniform shape change of anisotropic single-crystal, γ' shearing.
- Tertiary → cross-slip in γ channels *(thermally activated)*.
- Rafting → γ' preferential directional coarsening

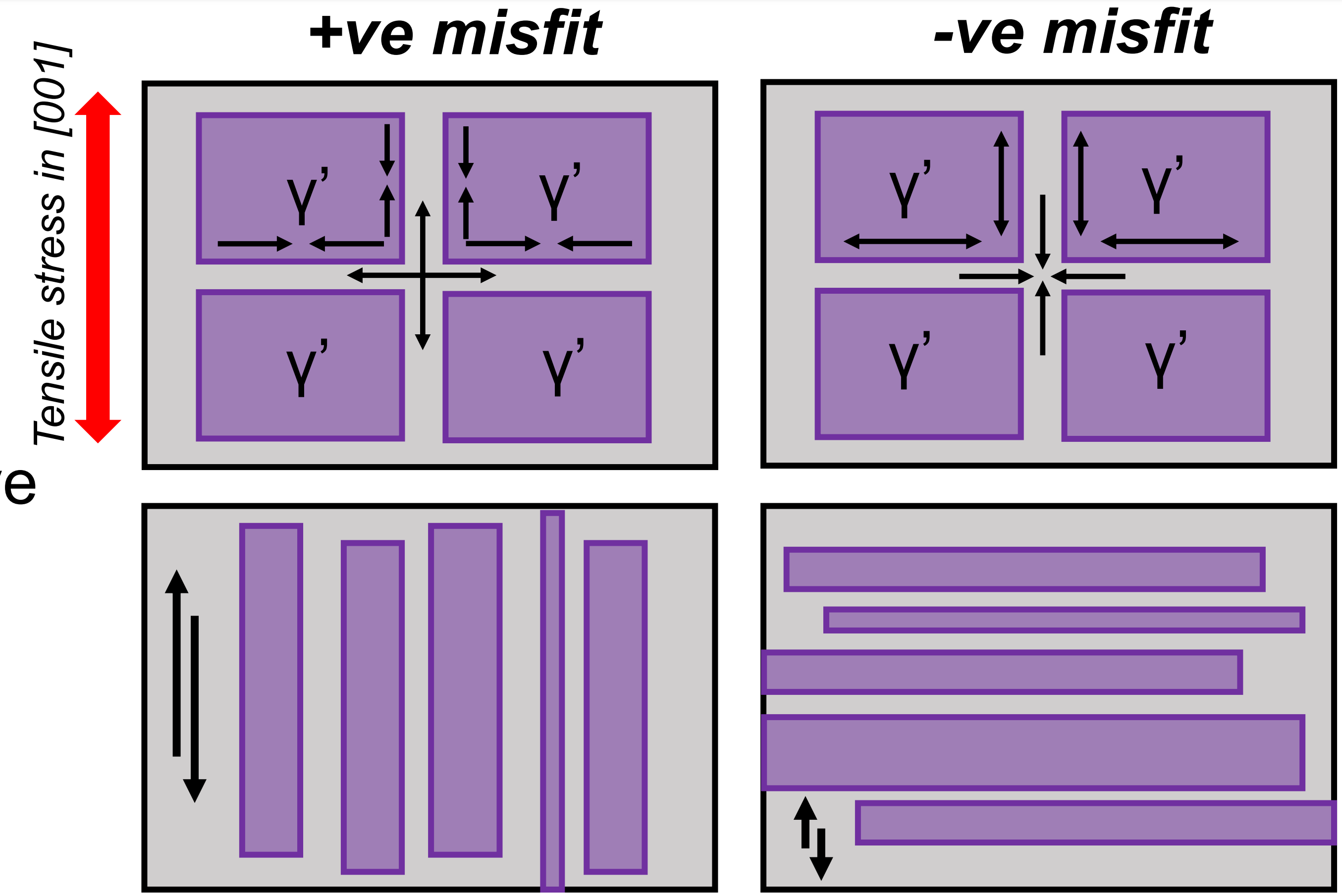


Rafting

- At high temperatures γ’ coarsen, γ-γ’ lattice misfit gives a directional dependence to coarsening.

- Lattice misfit can either be +ve or –ve
- *dependent on alloy content and chemical partitioning*
- $a_{\gamma'} > a_{\gamma}$ → +ve misfit → γ’ in compression and γ (near interface) in tension
- $a_{\gamma'} < a_{\gamma}$ → -ve misfit → γ’ in tension and γ (near interface) in compression

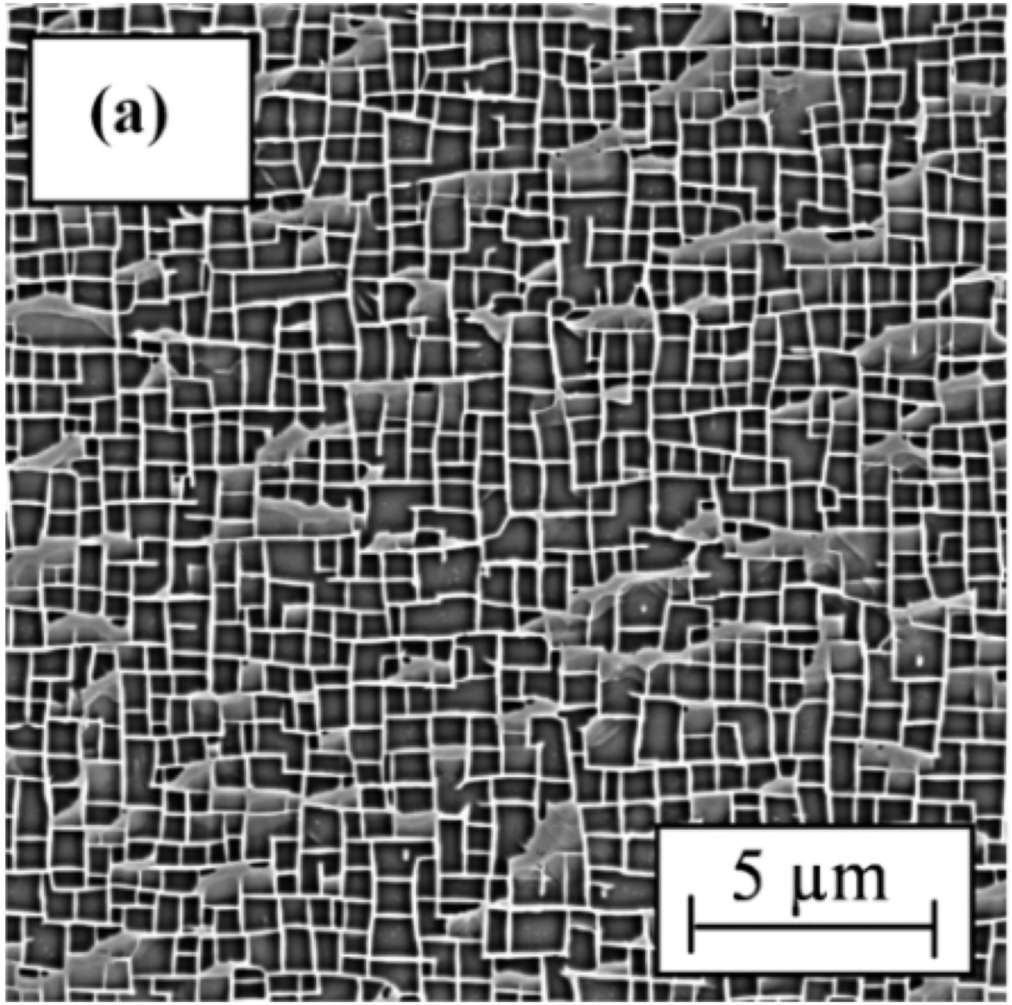
- Material diffuses from compressive to tensile locations.

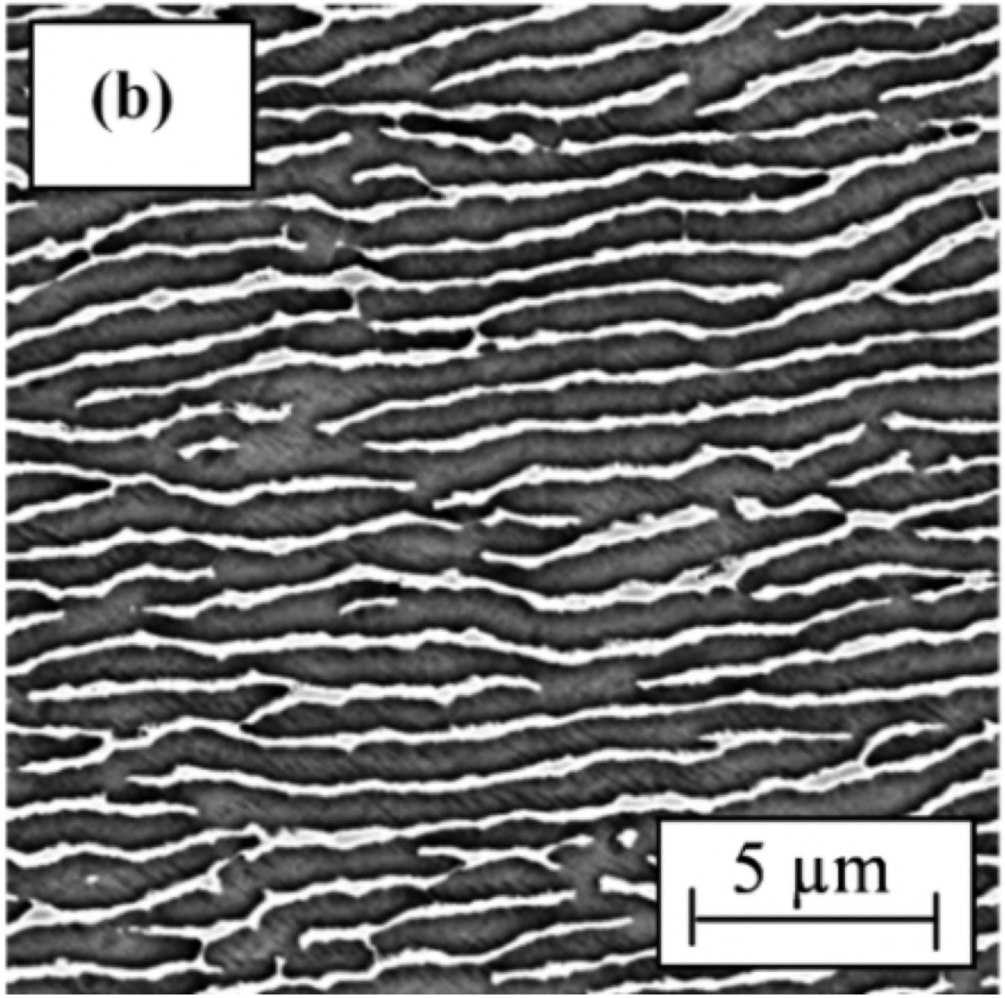


Formation of γ’ rods accelerate creep rate

Formation of γ’ rafts reduce creep rate

Rafting





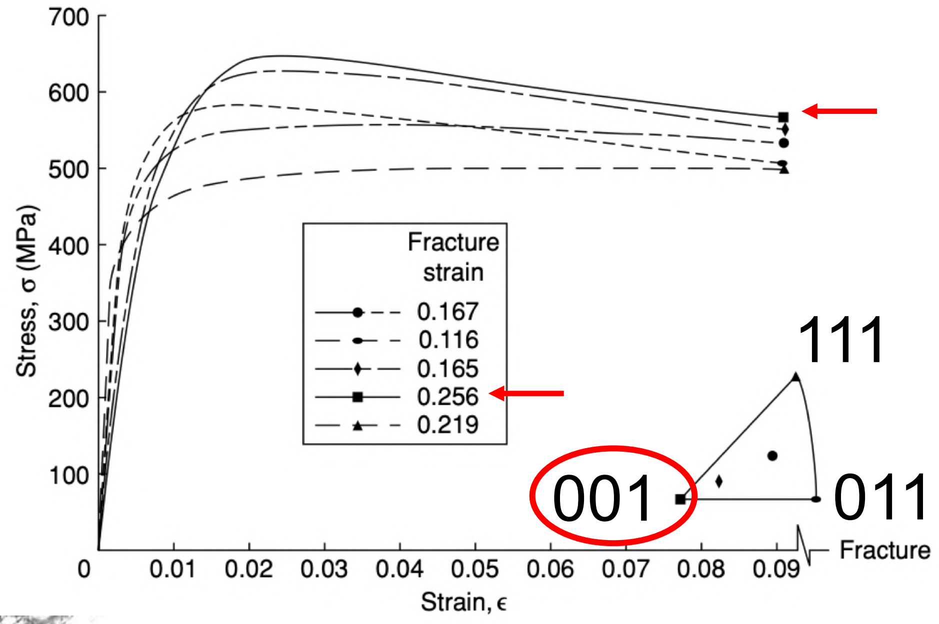
→ ***fully rafted state (with -ve misfit)***

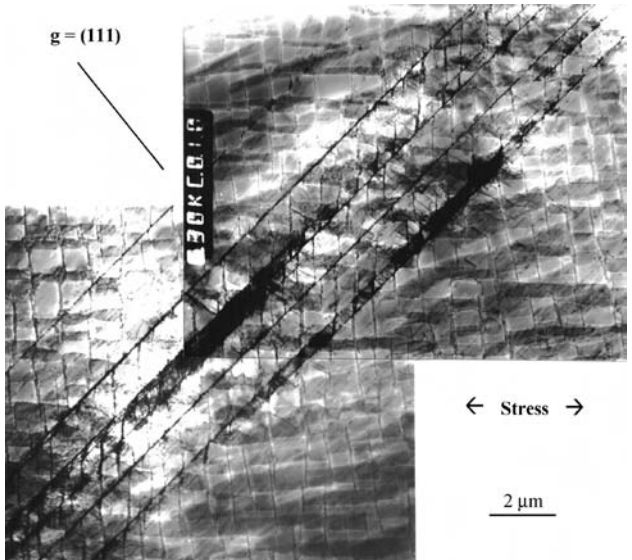
Fatigue Performance

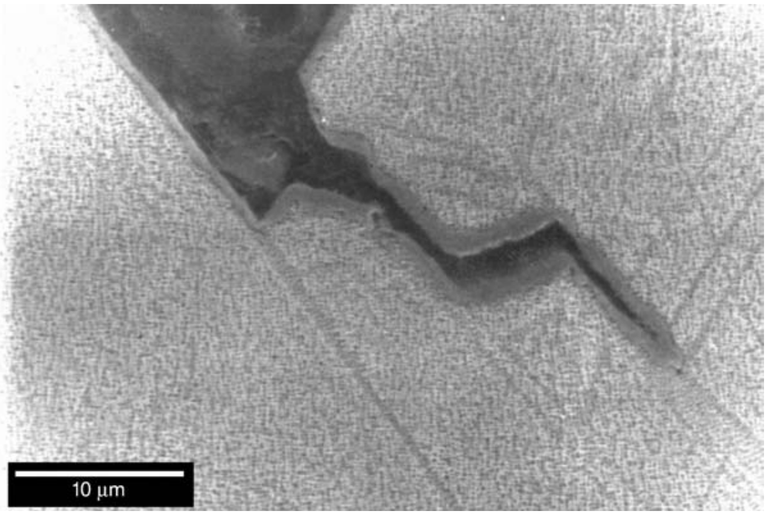
- Fan blades susceptible to HCF
  → initiation sites for localised plastic deformation.
  (Note, LCF is propagation rather than initiation)

- Fatigue initiates in *surface pits, oxide cracks, carbides, eutectic γ', …*
  → slip bands
  → shearing of γ' particles.

- Fatigue strength of <001> is highest, *elastically softer with higher yield stress*







The Need for Coatings

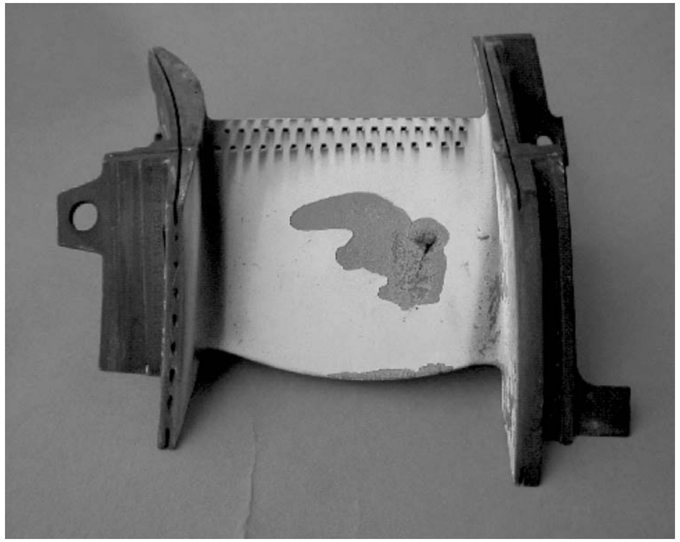
→ ***reduce oxidation and corrosion***

→ ***increase hot gas entry temperature beyond Ni melting point.***

- Diffusion coatings → overlay coatings → thermal barrier coatings

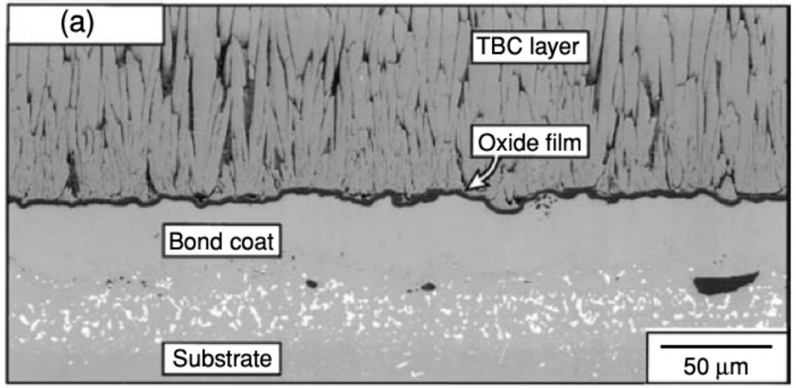
  (Can be used in combination)

Coating life, temperature enhancement



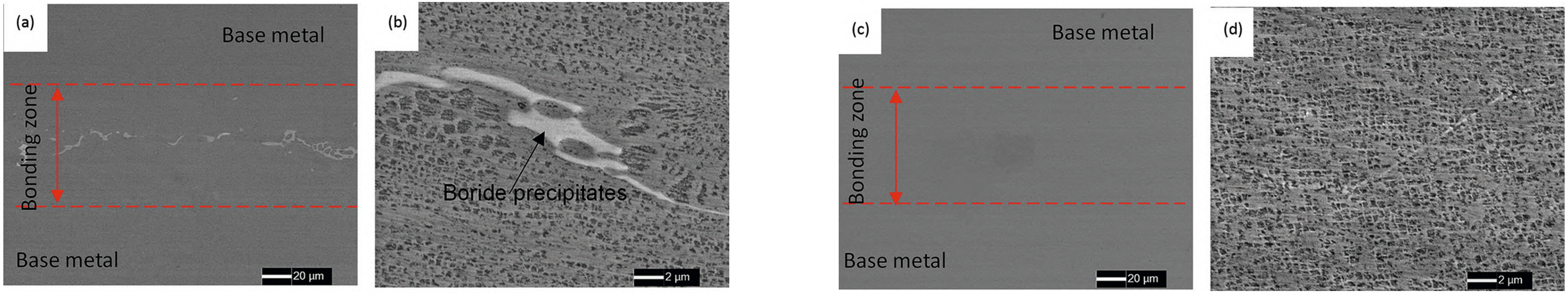
- Applied by electron beam physical vapour deposition (EB-PVD), plasma spraying (PS), chemical vapour deposition (CVD)

- Spallation in-service is an issue. Possible to combine thermal barrier coatings with bond coating for higher temperature coating…?



Joining Superalloys

- Due to creep accumulation and fatigue cracking it is necessary to completely remove or repair components.
- Repair easier for wrought polycrystalline alloys *(welded zones could easily be solutionised and heat treated to restore γ' properties of the original material).*
- With single crystal this is more problematic, any GBs will destroy properties.



- Transient liquid phase (TLP) bonding → epitaxial regrowth of solid state across melted zone ***(requires good crystallographic alignment!).***