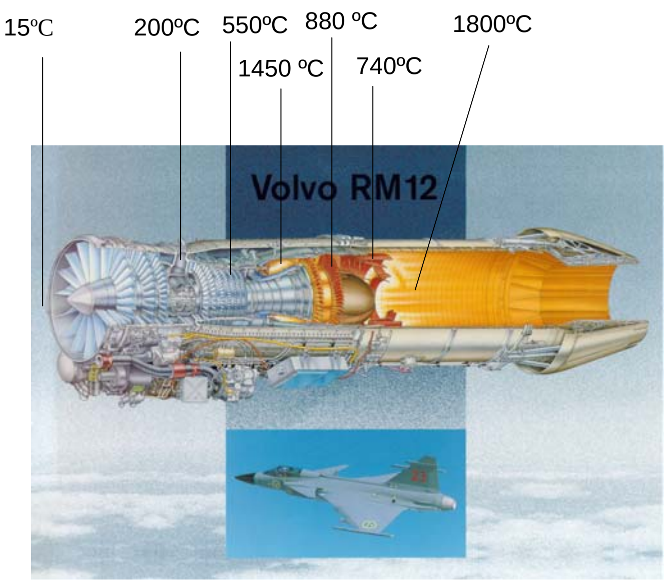
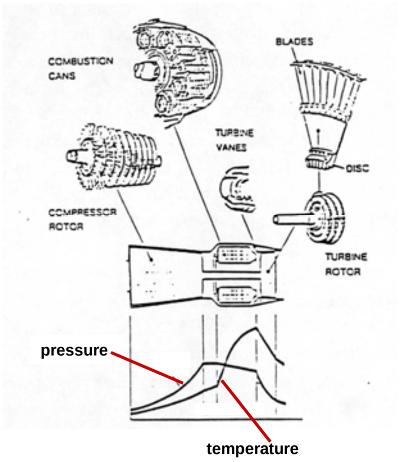
Ni-base superalloys

Superalloys: a broad class of metals with especially high strength at elevated temperatures

1. Ni-based
   used above 500ºC
   in oxidizing and corrosive environment
2. Cobalt- based
3. Iron-based



Air intake, fan, compressor, combustion chamber, turbine, exhaust system, control system



Principle components of aircraft gas turbine exposed to high loads and temperatures

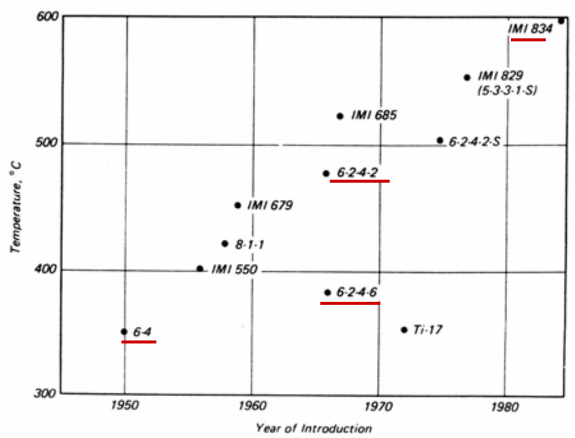
Aircraft engine

Compressor, Up to 550ºC and 550 MPa

Combustion chamber, Weak loaded; gas temp. 1700 ºC; under air cooling 1100-1300 ºC; main lifetime limiting factors: corrosion and thermal fatigue.

Turbine discs, up to 750 ºC, centrifugal force up to 500MPa; a high yield strength and high fatigue strength are required.

Turbine blade, withstand a combination of high stress and high temperature; high yield strength and high creep resistance are required in combination with thermal fatigue resistance and hot corrosion resistance



Year of introduction and operating temperature capability under optimum stress conditions. The suffix "S" indicates that a small amount of silicon (usually 0.25 wt %) has been added to the basic formulation.[142]

Fig. 54. High-temperature titanium-base alloys for aircraft engine applications

6242: Ti-6Al-2Sn-4Zr-2Mo; 6246: Ti-6Al-2Sn-4Zr-6Mo;

IMI834: Ti-5.5Al-4Sn-4Zr-1Nb-0.3Mo-0.5Si

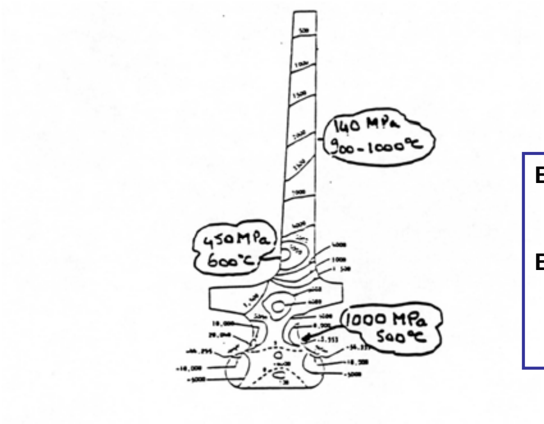


Figure 2. Temperature and stress distribution in a turbine blade.

Blade edge,

150 MPa , 650-980ºC,

Blade root,

275-550 MPa, 750 ºC,

An Overview of the Ni-base superalloys

1. **Nickel matrix**,

   fcc, good ductility,

   without phase transformation up to T_m

2. **γ precipitates**

   up to 60 vol% (volume fraction), particle size < 0.5 μm

   Precipitation hardening

   Ni_3M, cubic structure, M: Al and/or Ti

3. **γ' precipitates**

   Precipitation hardening

   Ni_3 Nb, bct structure

4. ***Carbides**

5. **δ-phase,** Ni_3Nb, ordered orthorombic, transformed from γ' phase

6. **Undesirable phases, σ-phase containing Cr, Mo, W etc., formed after long term thermal exposure**

Carbides

MC carbides, M: Ti, Nb, Ta (tantalum)

- Coarse, inside in the Ni-matrix
- Stable up to higher temp. than γ and γ'
- Provide dispersion strengthening at high temp.

Complex carbides

- M_7C_3, M_6C and $M_{23}C_6$
- M: Mo, Cr, W, also Co, Fe and/or Ni
- Form at intermediate temp.
- $M_{23}C_6$, along GB, provides resistance to GB sliding but also a risk of brittleness

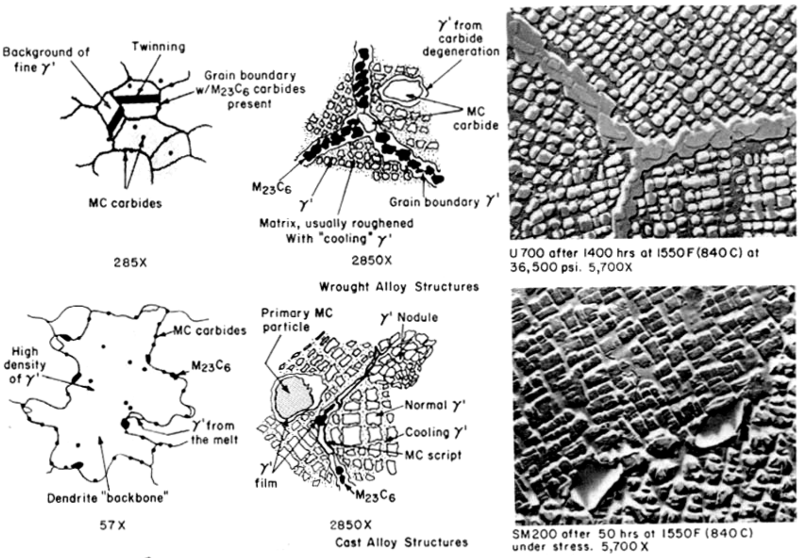
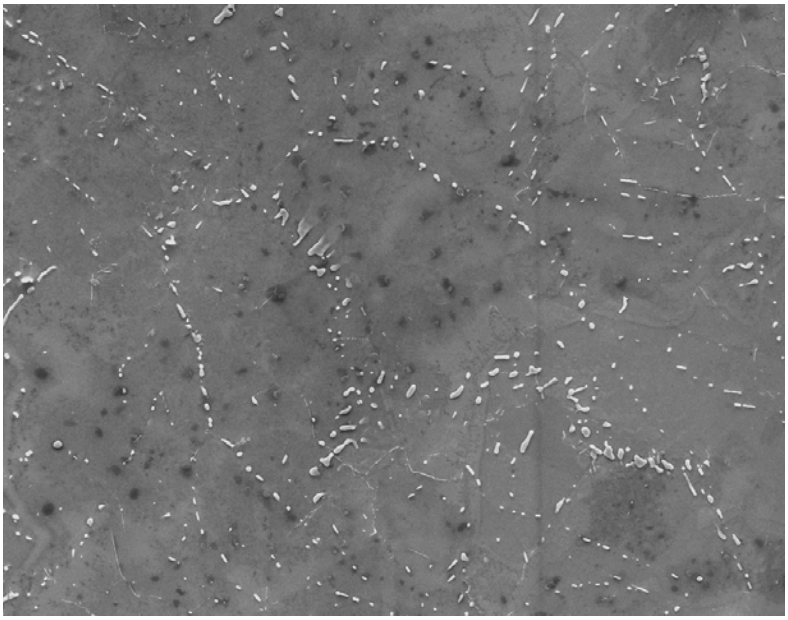
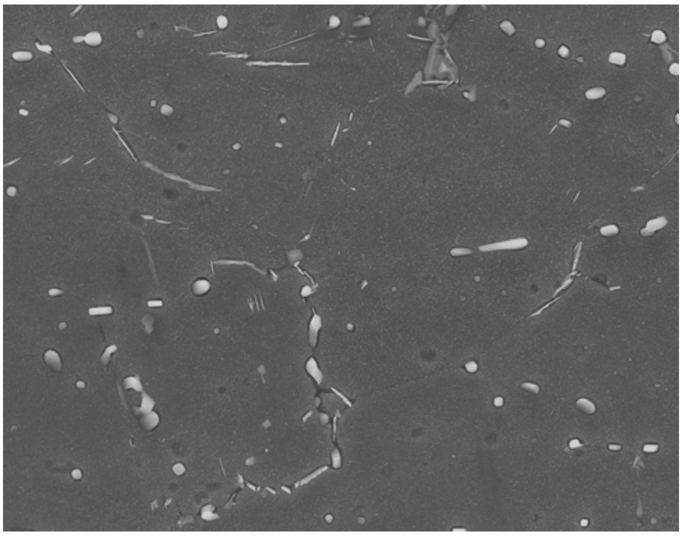


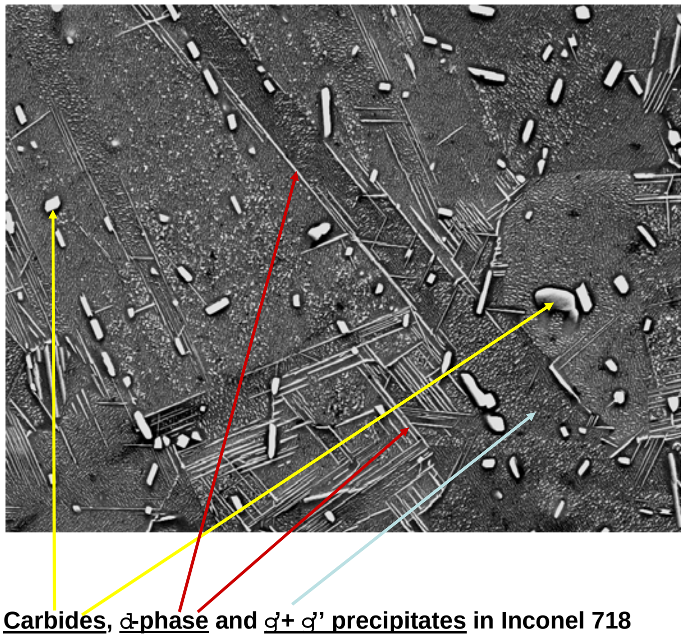
Fig. 11. Structures characteristic of wrought (top) and cast (bottom) nickel-base superalloys.



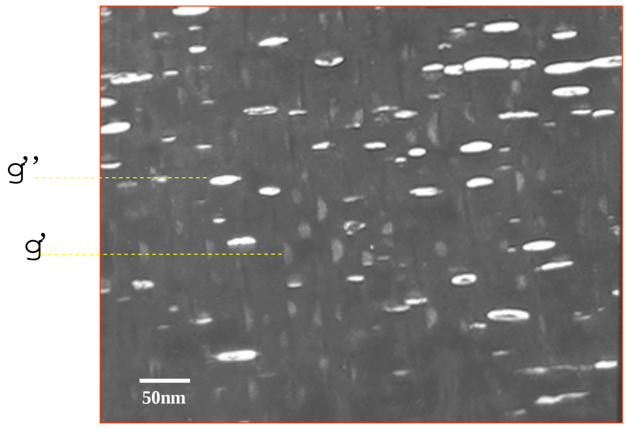
Carbides formed in a superalloy Inconel 718. SEM/SEI



Carbides formed in superalloy Inconel 718. SEM/SEI



Carbides, δ-phase and γ'+ γ'' precipitates in Inconel 718



Precipitation of both γ'' and γ' phases after aging 24h at 750 °C in a spray-formed IN 718. TEM, dark field, using a 100 diffraction beam.

Table 1. Alloying additions in Ni-base superalloys and their principle functions.

Addition	Function
Nickel	fcc matrix; forms γ'
Cobalt	solution strengthening; affects γ'; affects carbides
Iron	- " - - " - - " -
Chromium	oxidation resistance; solution strengthening; $M_{23}C_6$
Molybdenum	solution strengthening; affects γ'; affects carbides
Tungsten	- " - - " - - " -
Titanium	forms γ'; forms MC
Zirconium	forms MC; improves grain boundary strength
Niobium	forms γ"; forms MC
Tantalum	solution strengthening; forms MC; affects γ'
Aluminium	forms γ'; oxidation resistance
Carbon	carbide former

The main superalloys can be classified into four groups:

1 - only solution and carbide hardened
2 - γ' precipitation hardened
3 - γ" precipitation hardened
4 - oxide dispersion strengthened

solution treatment is utilised in all four groups

- **Wrought alloys**
- **Cast alloys – used in the as-cast condition**

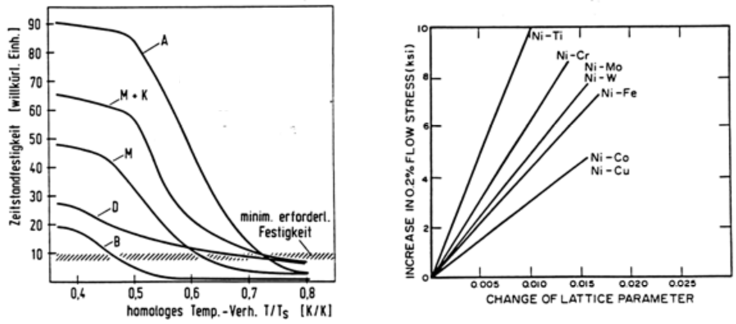


Figure 4. a) Relative effectiveness of various hardening mechanisms in Ni-base superalloys (2); b) solution hardening effect of various elements in Ni.

A = precipitation hardening

M+K = soln. + carbide hardening

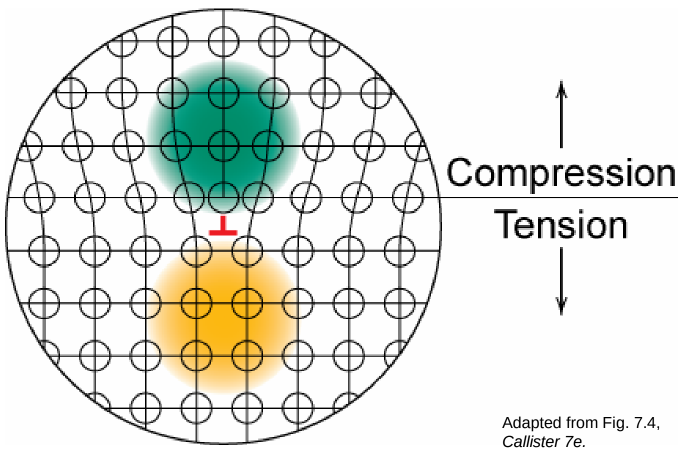
M = solution hardening

D = dispersion hardening

B = unhardened matrix

What is solution hardening? (p190)

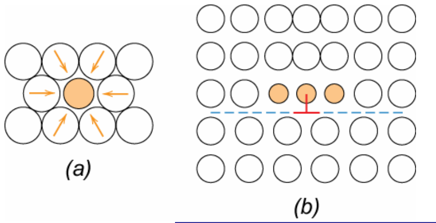
Stress Concentration at Dislocations



Adapted from Fig. 7.4, *Callister 7e.*

Strengthening by Alloying

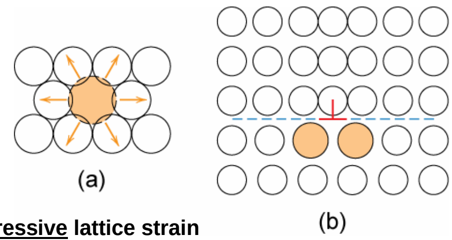
- small impurities tend to concentrate at dislocations
- reduce mobility of dislocation \ increase strength



Tensile lattice strain imposed on host atoms by a small substitutional impurity atom

Possible locations of small impurity atoms relative to an edge dislocation such that there is partial cancellation of impurity-dislocation lattice strains

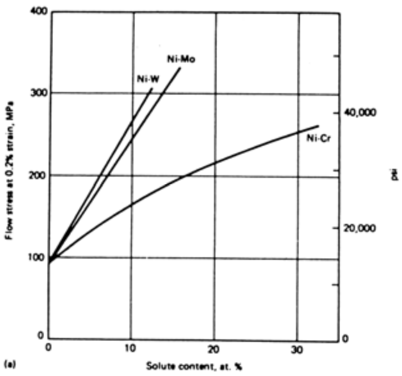
- large impurities concentrate at dislocations on low density side

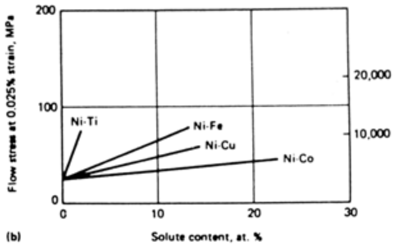


compressive lattice strain

Adapted from Fig. 7.17, *Callister 7e.*

Solution hardening





1. Effective elements: W, Mo, Cr
2. Fe, Cu, and Co are weaker
3. Solution hardening is retained until 0.6 T_m (Ni, Tm = 1455ºC)

Table 2. Examples of solution hardened Ni-base superalloys.

Alloy designation	C	Si	Mn	Cr	Fe	Ti	Al	Co	Mo	W	V
	Composition (wt.%)										
Inconel 600	0.1	0.5	0.5	15	8.5	-	-	-	-	-	-
Nimonic 75	0.12	1	1	19	5.0	0.4	-	-	-	-	-
Hastelloy C	0.01	0.1	1	16	7.0	-	-	2.5	-	-	0.35
Hastelloy W	0.12	1	1	5	5.5	-	-	-	24.5	-	0.6
Hastelloy N	0.08	1	1	8	17	Ti+Al	0.5	0.2	-	0.5	-
Hastelloy X	0.1	0.5	0.5	22	18	-	-	1.5	9.0	0.6	-
C 242	0.3	0.3	0.3	22	-	-	-	10	10	-	-
Inco 617	0.1	1	1	22	3	-	1.5	12.5	9	-	-

Carbide precipitation

1. **Strengthening effect at RT is slight**
2. **Significant influence on creep resistance at around 650ºC by reducing GB sliding**
3. **The strongest carbide formers in the order of strength:**

   Hf (hafnium), Zr, Ti, Nb, Ta (tantalum), V, Mo, W

4. **MC formed in the melt during casting, but decomposition could occur at temp. between 750-1000ºC**

   (Ti,Mo)C + (Ni, Cr, Al) → $Cr_{21}Mo_2C_6$ + $Ni_3(Al,Ti)$

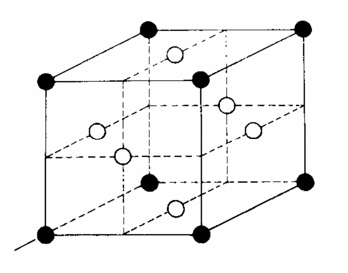
   MC   matrix   M23C6   γ',

5. **M_6C** [e.g. $(NI,Co)_3Mo_3C$, $(Ni,Co)_2W_4C$] **are stable at temp. up to 800-1000 ºC, formed through the decomposition of MC carbides.**
6. **M_7C_3 formed in alloys with relatively low Cr contents**

γ' precipitation hardening

● Al or Ti atoms

○ Ni aloms



Ordered atomic cell of γ' structure

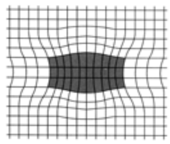
Cubic structure: ordered fcc

Coherent with the matrix, misfit: ±1%

Misfit = $(a_p - a_m)/a_p$,

a_p: lattice parameter of the precipitation

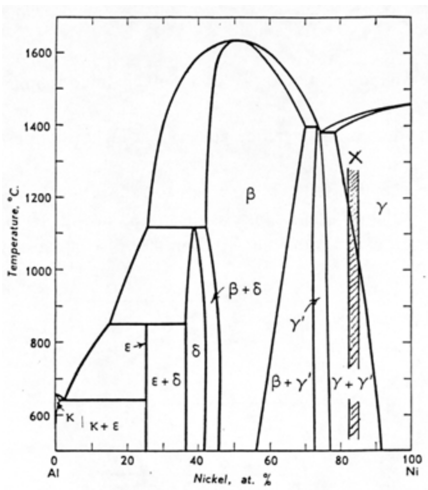
a_m: lattice parameter of the matrix



Coherent interface

Ni_3Al e.g. $(Ni_{0.98}Cr0._{016}Mo_{0.04})_3(Al_{0.71}Nb_{0.1}Ti_{0.05}Cr_{0.1})$ in 713C (Ni-12.5Cr-4.1Mo-2Nb-6Al-1Ti)

Precipitation processes

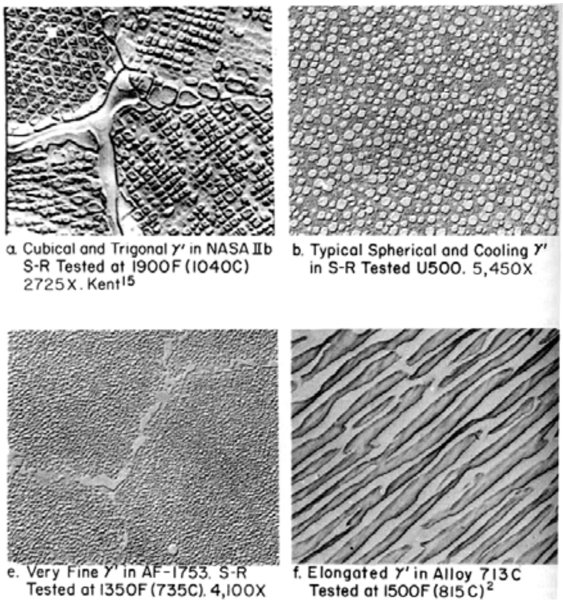


Solution treatment: ~ 1000-1100°C

Around X composition, giving ~ 50 vol % γ'

Aging temperature, 650-850°C

The Ni-Al phase diagram indicating alloy compositions suitable for γ' precipitation



illustrations of γ' morphology in Ni-base alloys

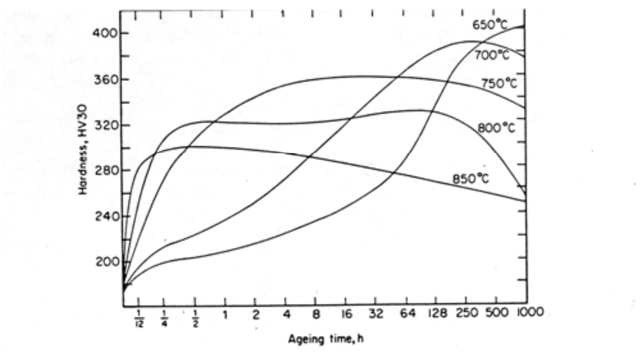


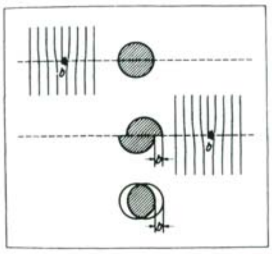
Figure 13. Effect of ageing temperature and time on the hardness of Nimonic 80A solution treated at 1080°C for 8h and then water quenched (5).

***Precipitation strengthening mechanisms*:**

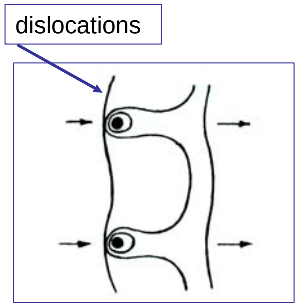
Particle cutting

Orowan looping

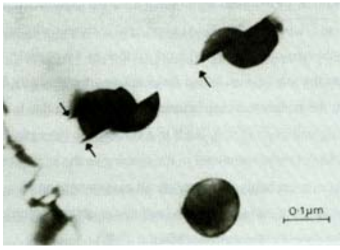
precipitation-hardening mechanisms



Particle cutting



Orowan looping



Sheared γ' particles in Ni-19Cr-6Al aged 540h at 750℃ and deformed 2%

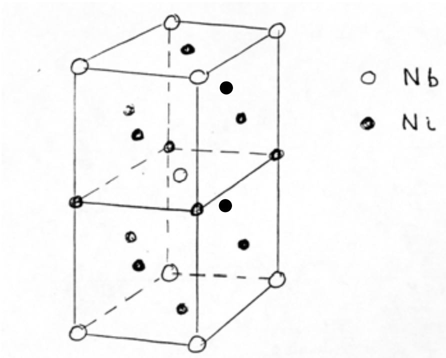
Table 3. Selected examples of commercial γ'-hardened Ni-based superalloys.

Alloy designation	Composition (wt.%) C	Si	Mn	Cr	Fe	Ti	Al	Co	Mo	Other
Wrought:										
X-750	0.04	0.5	1	15	7	2.5	0.7	-	-	1Nb
Nimonic 80A	0.06	0.8	0.4	20	1.5	2.3	1.4	2	-	-
Nimonic 90	0.1	1	1	20	1.5	2.5	1.5	18	-	-
René 41	0.1	0.5	0.1	20	5	3.1	1.5	11	10	-
U 500	0.1	0.3	0.2	18	2	2.9	2.9	18	2	-
René 95	0.15	0.2	3.5	13	0.4	2.5	3.5	8	3.5	3.5Nb
Waspaloy	0.07	0.7	0.7	0	-	3.0	1.4	13.5	4.3	-
Cast:										
C 263	0.06	0.2	0.4	20	20	2.2	0.4	20	5.9	-
713	0.12	1	1	14	-	1	6	-	4.5	-
René 80	0.17	0.1	-	14	0.3	5	3	9.5	7.7	4W
MAR-M200	0.15	-	-	9	-	2	5	10	-	-

The influence of γ' on creep strength

1. **To inhibit the grain boundary sliding process**
2. **To provide barriers to dislocation climb**

γ'' precipitation hardening



The bct unit cell of γ''

Lattice parameters of phases in IN 718

γ'' (Ni_3Nb)
a = 0.3626 nm
c = 0.7416 nm

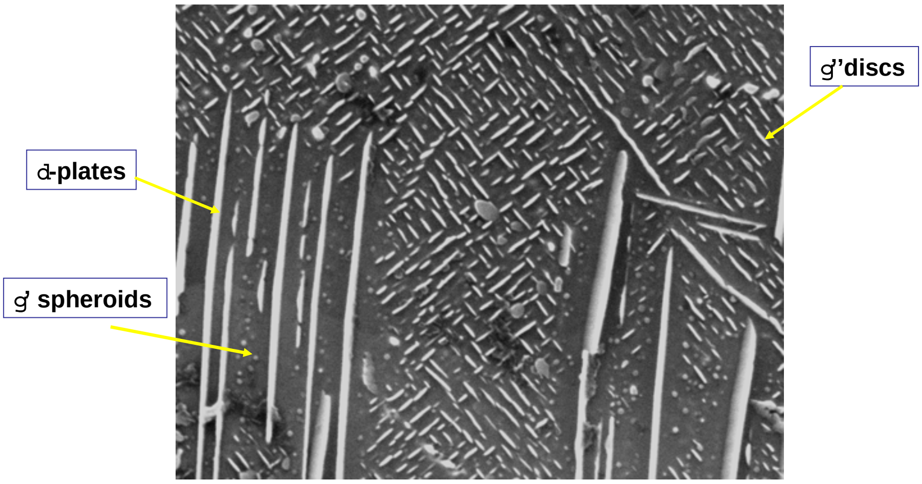
γ,
a = 0.3607 nm

Ni matrix,
a = 0.3616 nm

Table 4. Selected γ''-hardened superalloys.

Alloy designation	C	Si	Mn	Cr	Fe	Ti	Al	Co	Nb
Inconel 706	0.03	0.2	0.2	16	40	1.8	-	-	2.9
Inconel 718	0.04	0.2	0.2	19	19	0.9	0.5	-	5.1
Incoloy 903	0	0	-	-	41	1.4	0.7	-	3.0
Incoloy 909	0.01	0.4	-	-	42	1.5	0	-	4.7

1. Inconel 718 may contain 15 vol % γ'' + 5 vol % γ'
2. Provide high strength at low and moderate temperatures
3. Rapid softening above about 700°C
4. γ'' phase could transform to δ-phase at temp. above about 700°C
5. δ-phase: (Ni_3Nb), orthorhombic structure, a brittle intermetallic phase



SEM micrograph showing δ-plates, γ’’discs and γ’ spheroids in 718 treated isothermally at 825C/150h.

Heat treatment and thermomechanical treatment

<u>The main purposes of heat treatment are</u>:

1. **To give precipitation hardening**
2. **To achieve desired precipitation of carbide**
3. **To relieve the embrittling efects of mechanical working pocesses in wrought alloys through recrystallization and grain growth**
4. **To creat optimum grain size through grain growth (in cast and wrought alloys), and through recrystallization and grain growth in conjunction with mechanical deformation – so called thermomechanical processing (TMP).**

Large grain size gives:

1. **improved creep strength**
2. **reduced creep extension to failure**
3. **reduced short-term strength and failure strength**

Mechanical working of wrought superalloys:

1. To shape the component, (forging, rolling and extrution etc.)
2. To homogenise the microstructures, e.g. eliminating segregation of alloying additions after casting , and distributing MC carbides

The superalloys are seldom used in the as-work state, why?

- the reduced ductility (residual stress)
- the worked structure is always unstable in high-temperature situations

How to perform precipitation-hardening treatment

1. Solution treatment

   Heated to the single-phase region, e.g. the g region. Precipitation of grain boundary carbides with suitable morphology often requires a higher temperature (1100-1200ºC)

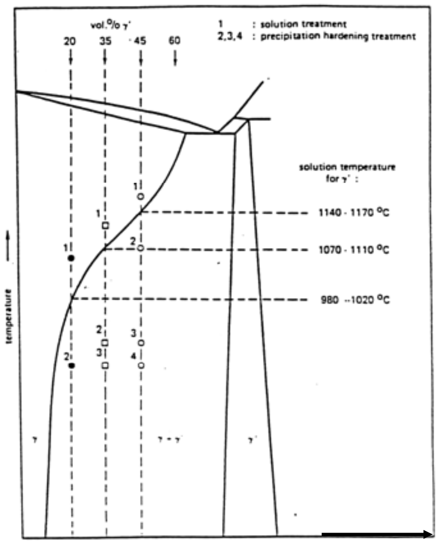
2. Quenching

   rapid cooling to room temperature to form a supersaturated solid solution (SSSS*)

3. Aging

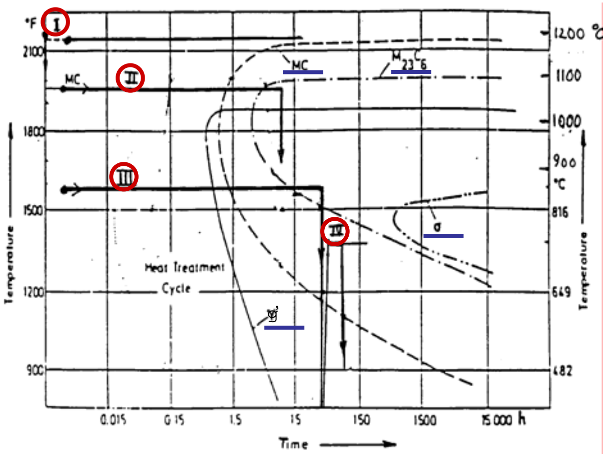
   Decomposition of the SSSS in the two-phase field - to form the fine precipitates

SSSS - an unstable condition and easy to form metastable phases to lower the energy of the system



Schematic phase diagram for Ni-M system where M represents combined g' forming elements

Precipitation processes in the alloy U700



- I. 1175°C/4h, air cool
- II. 1080°C/4h, AC
- III. 845°C/24h, AC
- IV. 760°C/16h, AC

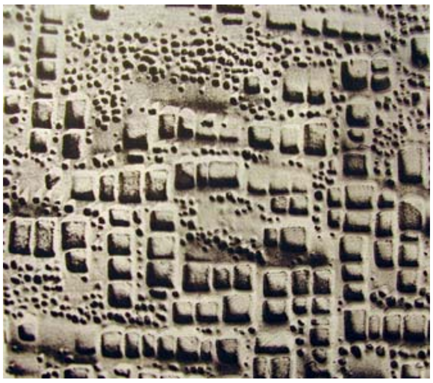
Precipitation processes in the alloy U700

I. **Solution treatment dissolving all γ' and most carbides, air cooling to RT is sufficient to prevent significant precipitation**

II. **Ageing at 1080ºC causes grain boundary precipitation of $M_{23}C_6$.**

III. **24h at 845ºC yields a rapid precipitation of significant amount of moderately sized γ'**

IV. **At 760ºC a background of finer γ' is achieved.**

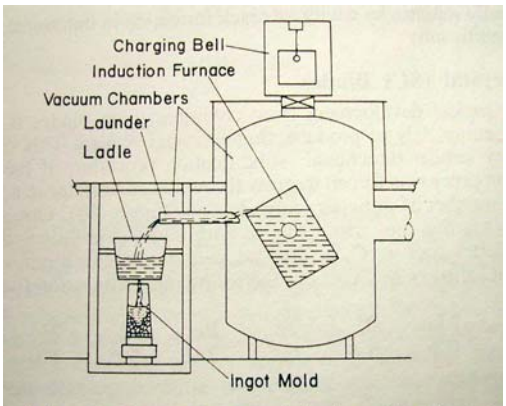


Melting and casting of superalloys

Melting

Induction melting in vacuum (VIM)

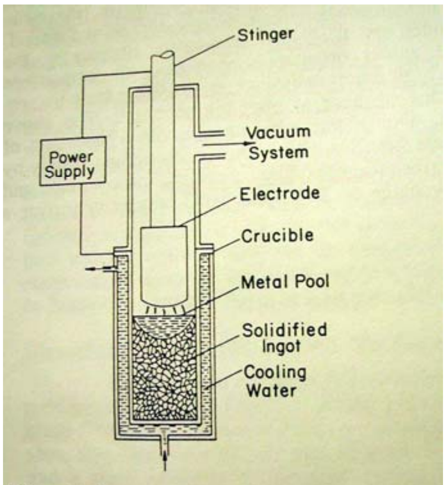
Cast into ingot in vacuum



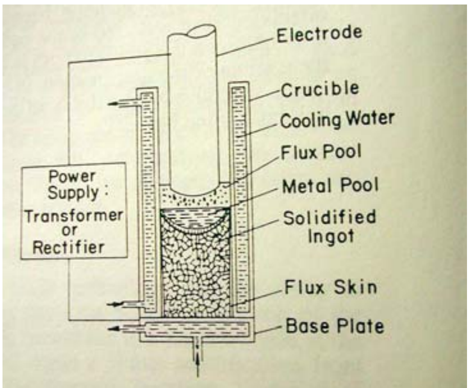
Schematic diagram of vacuum induction melting furnace.

Remelting, to reduce the degree of segregation

Vacuum arc remelting
Electroslag remelting



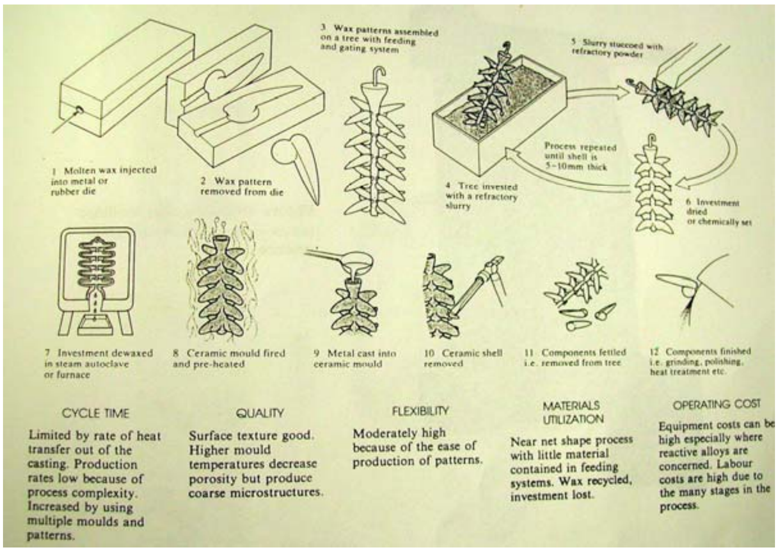
Schematic diagram of vacuum arc remelting furnace.



Schematic diagram of electroslag remelting furnace

Precision investment casting

Complex shape
Near net shape
Lost wax process

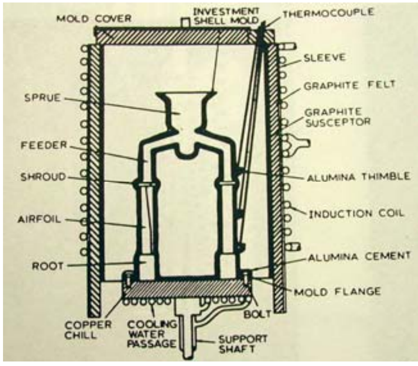


Directionally solidified (DS) turbine blades

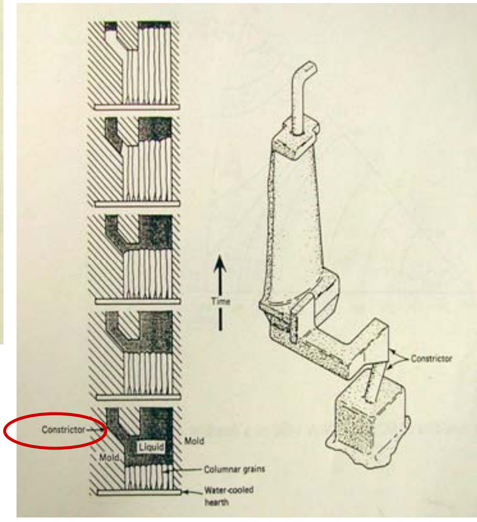
- Columnar grains stretching from the bottom to the top
- Keep the mould hot
- Water cooling its base at the same time, to create a planar solidification front and a steep temperature gradient

Single crystal (SC) blades

- To eliminate grain boundaries completely, by using a similar directional solidification procedure
- Groeth through a constrictor (a zig-zag pipe) – reduce the number of growing grains to one.



Furnace for directional solidification



Constrictor principle for creating crystal component.

Assignment, Ni-base superalloys

Precipitation and Heat Treatment

a) Fig 15.1 shows a part of the phase diagram for the Ni-Al system.

(i) Considering precipitation strengthening, what is a suitable solution temperature for an alloy of Ni-8wt% Al?
(ii) What amount of precipitates can be expected in an alloy aged at about 700°C?

b) Figure 15.2 shows a precipitation-time-temperature diagram for the kinetics of precipitation while Figure 15.3 indicates the time and temperature dependence of precipitate particle growth. Use these figures to predict the microstucture of a Ni-8wt% Al alloy subject to the following heat treatment:

1160°C 4h + fast cool to RT
1085°C 4h + fast cool to RT
925°C 24h + fast cool to RT
760°C 16h + fast cool to RT

The heating process can also be assumed to be fast

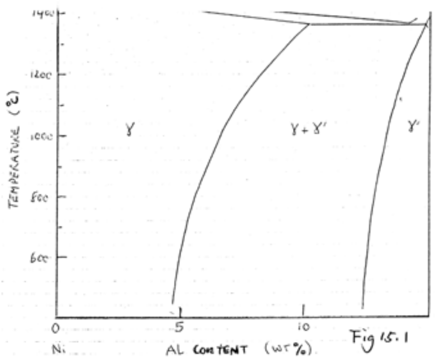


Fig 15.1

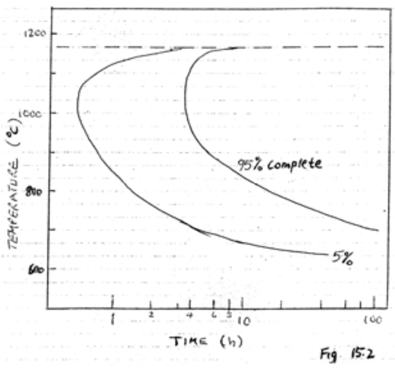


Fig 15.2