FS 2025/26

MSE-422 – Advanced Metallurgy

5-Ni-based alloys

Christian Leinenbach

Ni alloys for high-T applications – introduction

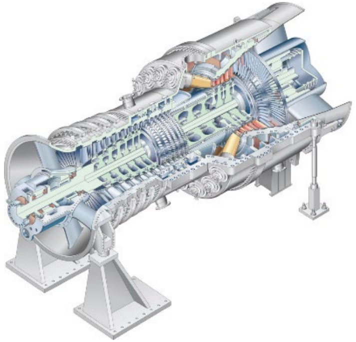
Gas turbines and jet engines

/www.powergeneration.siemens.de/

- Jet engines are designed to produce thrust from the direct impulse of exhaust gases
- Light-weight design to save fuel
  - Weight <3t
  - Maximum service T: 1’500°C
  - Thrust/weight ratio: 0.2-0.3
- Designed for frequent start/stop cycles

- Modern gas turbines for power generation are designed to power an electric generator
- Frames, bearings, and blading are of heavier construction than jet engines
  - Total length up to 30 m, weight >440 t
  - Maximum service T: 1’500 °C
  - Power: max 340 MW
- Designed for long-term operation (up to several years)

/www.airbus.com/

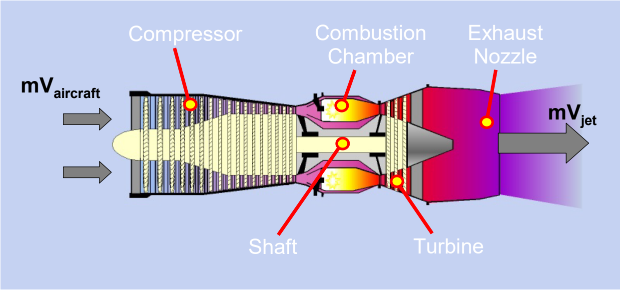


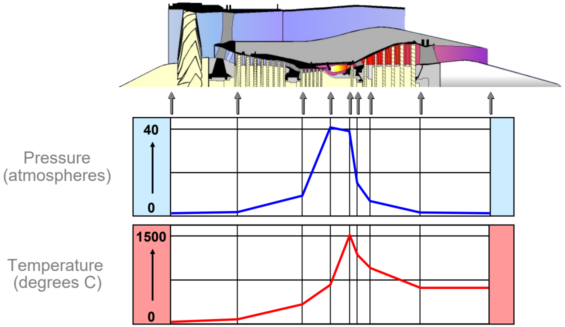
/www.volvo.com/

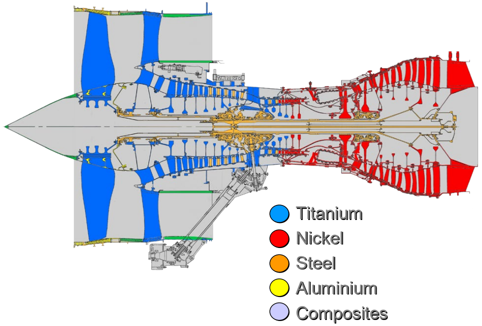
Ni alloys for high-T applications – introduction

Design and working principle of a jet engine

- Air is compressed by an arrangement of stator and compressor blades. The conical shape of the support of the compressor blades leads to an increase in pressure and temperature of the air
- The compressed air is then mixed with fuel and ignited in the combustion chamber and the gas is heated to high T (up to 1’500 °C)
- The hot gas flows out through the turbine, leading by the shape of the blades to the rotation of the axis (up to 25’000 rpm)
- The generated torque of the compressor blades is used to compress the air





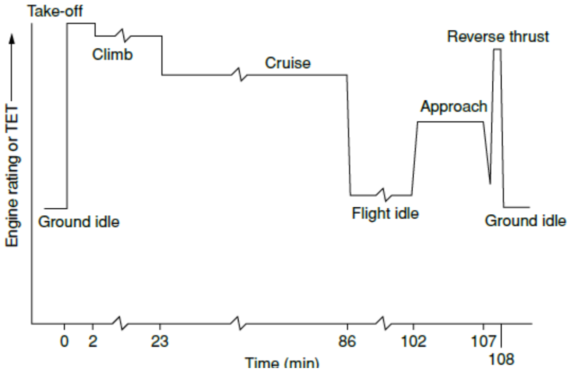


/Cervenka, Rolls Royce, 2000/

Ni alloys for high-T applications – introduction

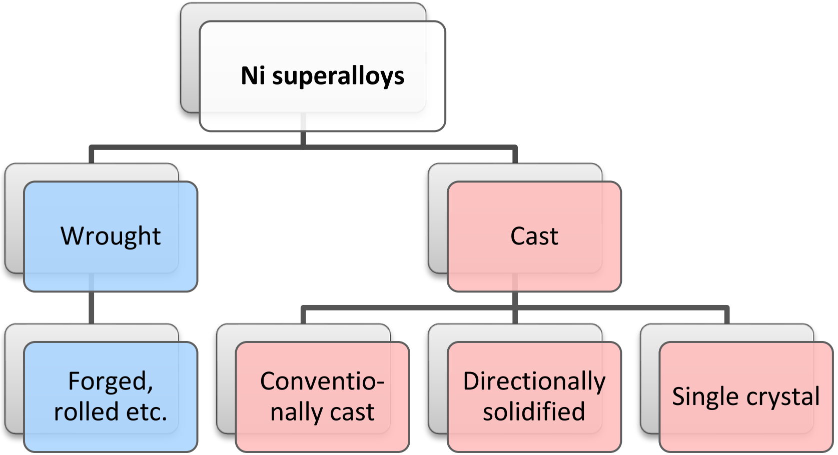
- Requirements for materials for gas turbines and jet engines
  - Long-term creep resistance at T>800°C (service intervals 10’000-20’000 h)
  - Resistant against thermo-fatigue (temperature cycles during flight, start-stop cycles)
  - Resistant against high temperature oxidation and gas corrosion
  - Sufficient ductility and fracture toughness even after long-term use

Variation of the turbine entry temperature (TET) during a typical flight cycle of a civil aircraft.



Classification of Ni alloys

- Ni alloys are primarily distinguished between wrought and cast alloys
- Ni alloys are mainly designated by their trade names and their manufacturers
- Alternative designation: Hastelloy X = NiCr22Fe18Mo → 22 wt.% Cr, 18 wt.%Fe, <1 wt.% Mo



Ni superalloys

Wrought

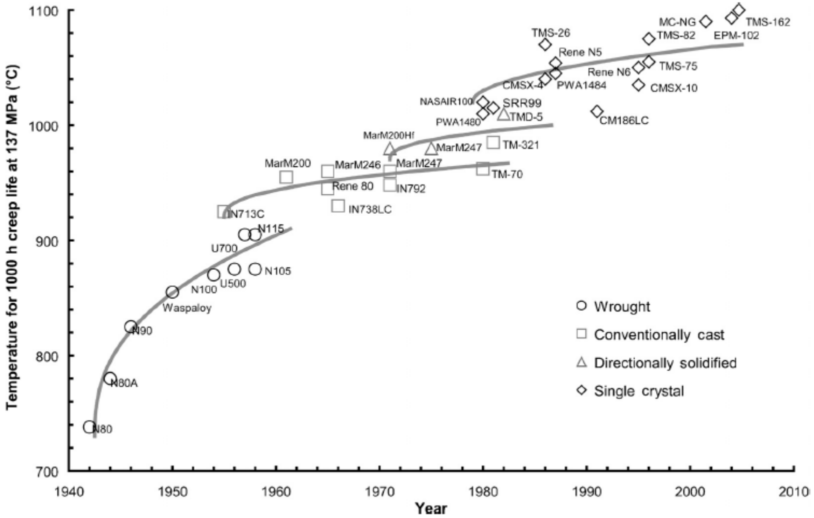
Cast

Forged, rolled etc.

Conventionally cast

Directionally solidified

Single crystal

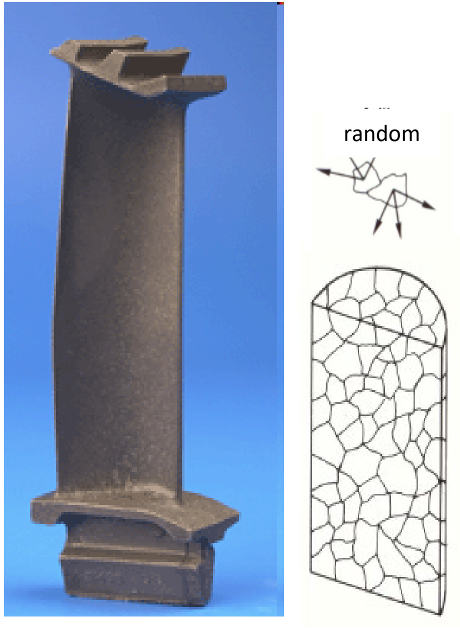


Evolution of the high-temperature capability of the superalloys over a 60 year period since their emergence in the 1940s.

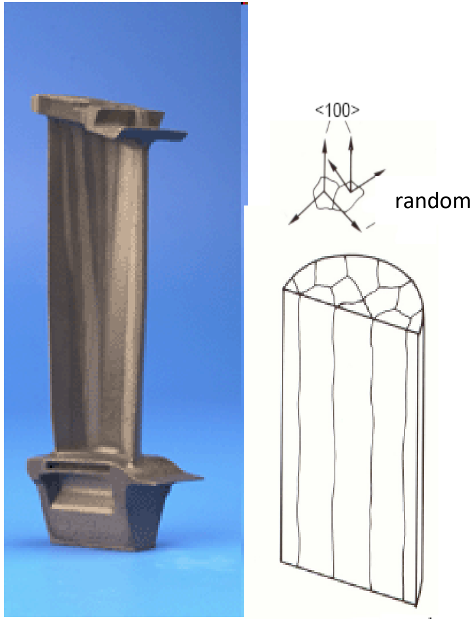
/R.C. Reed, The superalloys – fundamentals and applications, 2006/

Cast Ni superalloys

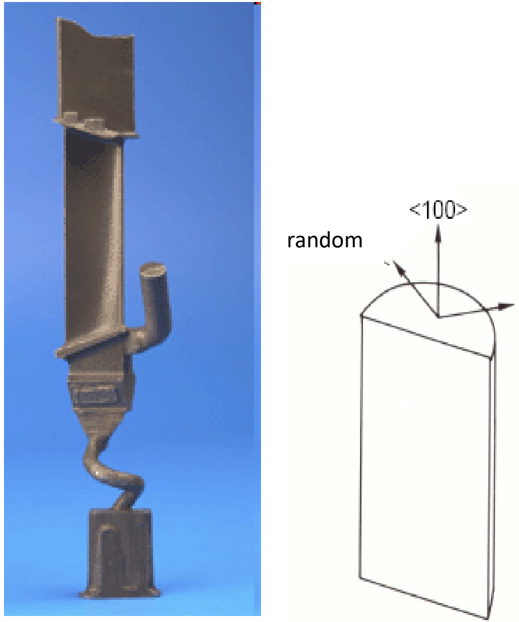
Conventionally cast



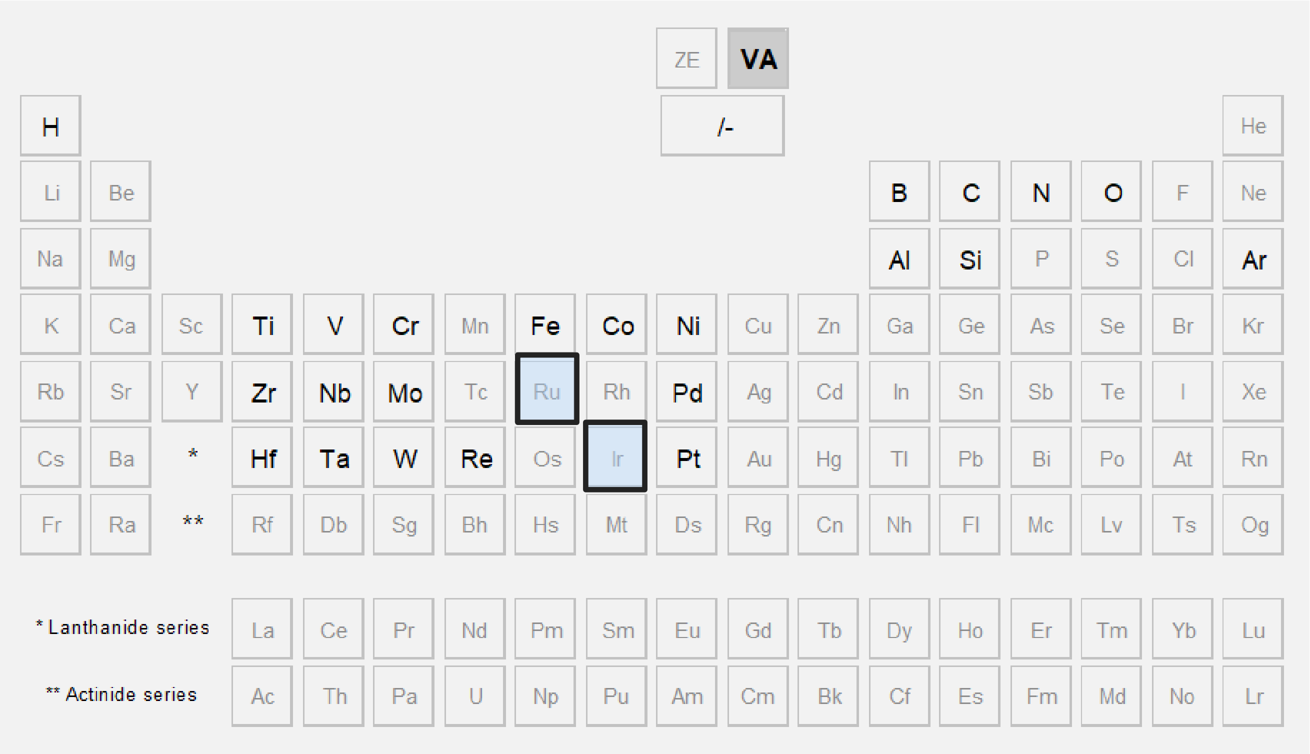
Directionally solidified



Single crystal (SX)



Main alloying elements in Ni



Role of main alloying elements in Ni

Element	Effect	Max. wt.%
Fe	+ cheap replacement for Ni - reduces high-T oxidation stability - supports detrimental IM phases	37
Cr	+ Forms Cr-rich protective layer + solid solution strengthener + carbide former - supports detrimental IM phases	30
Co	+ (mild) solid solution strengthener + reduces SFE + reduces solubility of Al and Ti - reduces high-T oxidation stability	20
Mo	+ solid solution strengthener + carbide former + increases E-modulus + reduces diffusion coefficient - supports detrimental IM phases	14

Element	Effect	Max. wt.%
W	Similar to Mo but - increase density - pronounced segregation tendency	4
Nb, Ta, Ti	+ solid solution strengthener + carbide former + increase γ’ amount (replace Al) + delay coarsening of γ’ (reduction of γ/γ’ lattice misfit) - reduces high-T oxidation stability - supports detrimental IM phases	5-12
Al	+ forms γ’-Ni_3Al + solid solution strengthener + reduces density + forms stable Al_2O_3 layer at HT	6

Role of main alloying elements in Ni

Element	Effect	Max. wt.%
Si	+ improves high-T oxidation stability - supports detrimental IM phases - reduces solidus temperature	1
C	+ carbide former - reduces solidus temperature	0.2
B	+ stabilizes grain boundaries + boride former - reduces solidus temperature	0.03
Hf, Zr	+ Scavenges S + carbide former +/- can reduce and increase hot cracking during casting + very reactive (mold reactions during casting possible)	0.2-1.5

Element	Effect	Max. wt.%
Re, Ru	+ solid solution strengthener + delay coarsening of γ’ (reduction of γ/γ’ lattice misfit) - support detrimental IM phases - increase density - very expensive	3-6

Strengthening mechanisms in Ni alloys

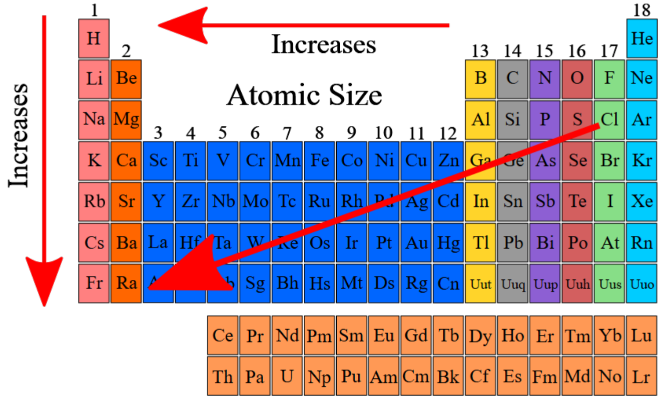
For high-T applications

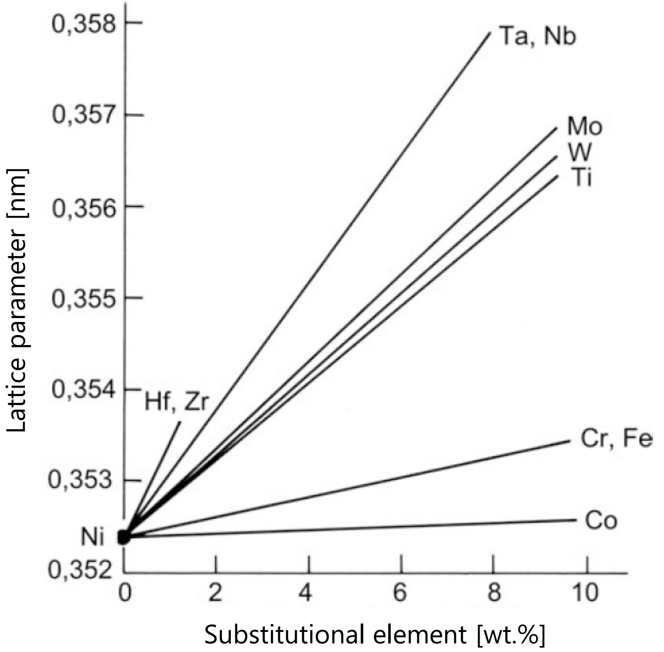
- Solid solution strengthening
- Particle strengthening
  - coherent γ‘-Ni_3Al precipitates with fcc superstructure
  - bct γ‘’-$Ni_3(Nb,Ti)$ in certain alloys containing Nb
  - carbides (with Cr, Mo, W, V, Nb, Ta, Hf, Ti) → MC, $M_{23}C_6$, M_6C, M_7Cr_3 (in wrought alloys)
  - in some alloys oxide dispersion strengthening (ODS) with nm-sized Y_2O_3

Effect of alloying elements in Ni alloys

Solid solution strengthening

- Solid solution strengthening effect depends on size of substitutional atom and solubility in Ni
- The effect of the elements can be ranked
  - weak effect: Fe, Co, Cr,
  - mild effect: V, Ti
  - strong effect: W, Mo, Al, Ta, Nb





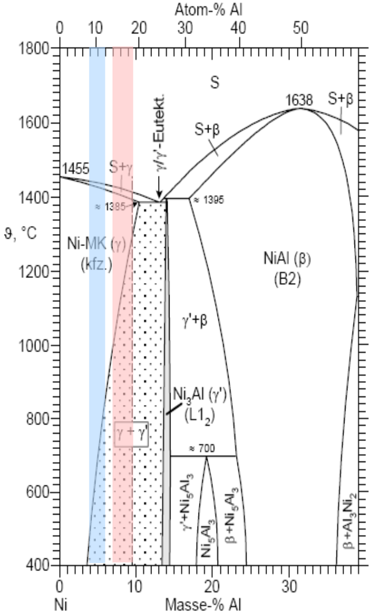
/Maier, Niendorf, Bürgel – Handbuch Hochtemperatur-Werkstofftechnik, 2015/

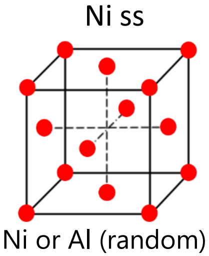
Effect of alloying elements in Ni alloys

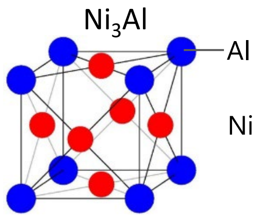
Precipitation strengthening - the γ’-Ni_3Al phase

- The γ’-Ni_3Al phase is an ordered IM phase with ordered fcc-superstructure
- Lattice parameter of Ni_3Al (0.357 nm) very similar to lattice parameter of Ni (0.352 nm)
  - → Ni_3Al forms coherent precipitates in Ni matrix
- Pronounced solubility of Al in Ni (max. 20 at.%)
  - → Large volume fractions of Ni_3Al in Ni possible (up to 70%)
- The Ni_3Al phase is stable up to the melting point
  - → No detrimental phase transformation or early dissolution

🟦: wrought 🟥: cast





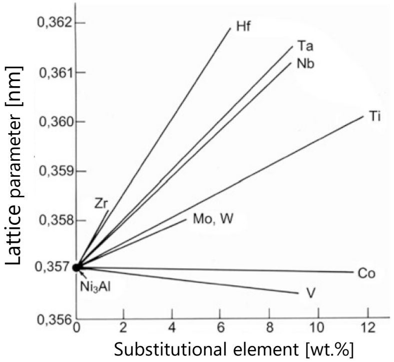


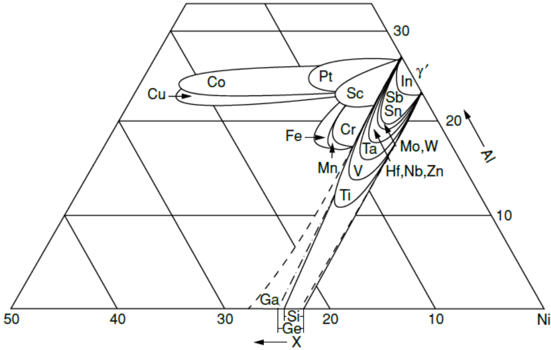
/Maier, Niendorf, Bürgel – Handbuch Hochtemperatur-Werkstofftechnik, 2015/

Effect of alloying elements in Ni alloys

Precipitation strengthening - the γ’-Ni_3Al phase

- Relatively small homogeneity range of Ni_3Al in binary Ni-Al
- Many possibilities for substitution with other elements
    - Main substitute for Ni: Co
    - Main substitutes for Al: Ti, Ta
- The alloying strategy of Ni-based superalloy development has to take into account changes in lattice parameter of both the matrix and the γ’ phase to provide coherency with the matrix.



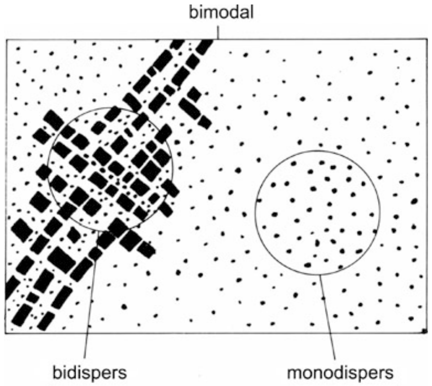


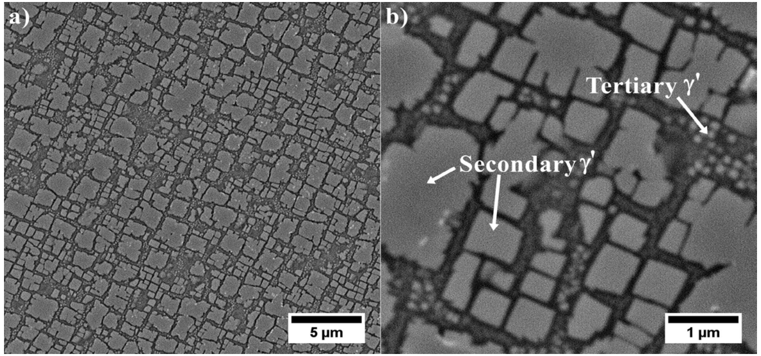
/R.C. Reed, The superalloys – fundamentals and applications, 2006/

Strengthening mechanisms in Ni alloys

Precipitation strengthening - the γ’-Ni_3Al phase

- In technical Ni alloys, a bimodal and bi-disperes γ’-Ni_3Al distribution is realized
  - Larger cuboidal γ’ grains with narrow, but connected γ channels inbetween
  - Smaller globular γ’ grains in the γ channels
- Dislocations in the narrow γ channels must shear or bypass the cuboids.
- A maximum amount of γ’-Ni_3Al of 60 vol.% is achieved; at higher fractions, the γ-channels are disconnected



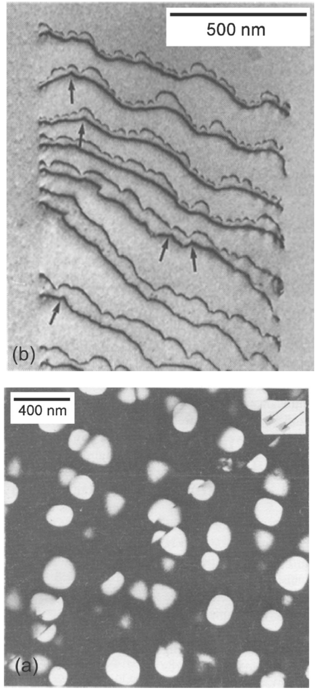


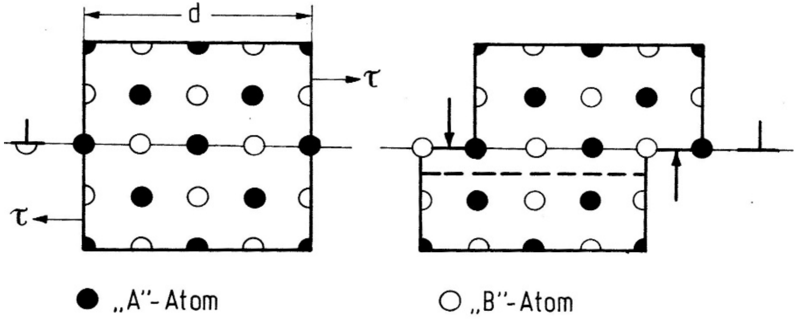
/© Lukas Karge, mlz-garching.de/

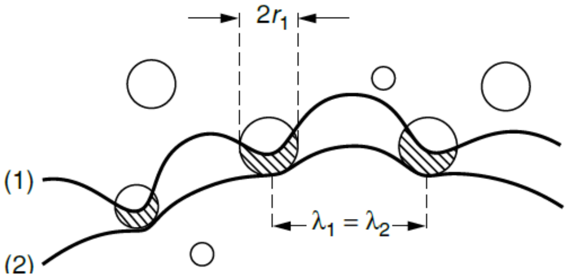
Strengthening mechanisms in Ni alloys

Precipitation strengthening - the γ’-Ni_3Al phase

- Because of the ordered nature of Ni_3Al, cutting by one single dislocation will create an anti-phase boundary (APB)
  → atoms are in an unfavored configuration
- Dislocations must travel through the *γ/γ’* structure in pairs, with a second dislocation removing the anti-phase boundary introduced by the first
- The associated anti-phase boundary energy, γ_{APB}, represents a barrier which must be overcome if particle cutting is to occur





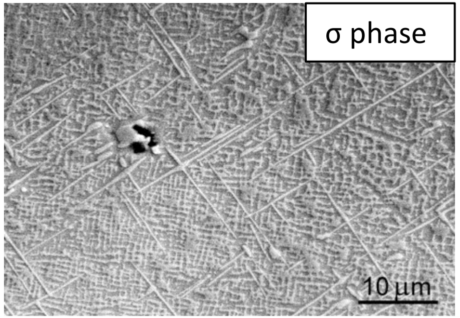


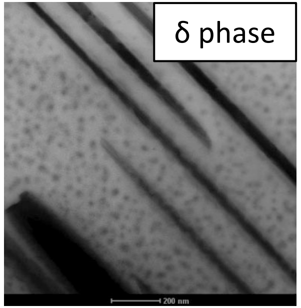
/R.C. Reed, The superalloys – fundamentals and applications, 2006/

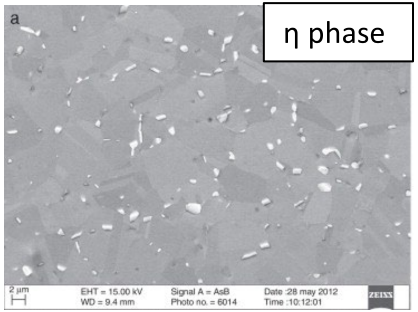
Effect of alloying elements in Ni alloys

Undesired IM phases

- TCP phases (σ, μ, χ, Laves)
  - They provide incoherent interfaces for rapid diffusion, leading to accelerated IM coarsening
  - They absorb Cr, Mo, and W from the matrix
    → negative effect on solid solution strengthening!
  - Precipitation on grain boundaries leads to brittleness at low T
- η-phase: Ni_3Ti (hcp) (semi-coherent)
  - Precipitates as platelets on the (111) planes of γ matrix.
  - Platelet shape indicates that growth is much easier in direction of high interface energy
- δ-phase: Ni_3Nb (incoherent orthorhombic)
  - The δ-phase is the incoherent, coarsened variant of the – for very small sizes – coherent γ’’ Ni_3Nb ($D0_{22}$).
  - The δ-phase is very similar to θ’’, θ’ and θ in Al-Cu alloys.



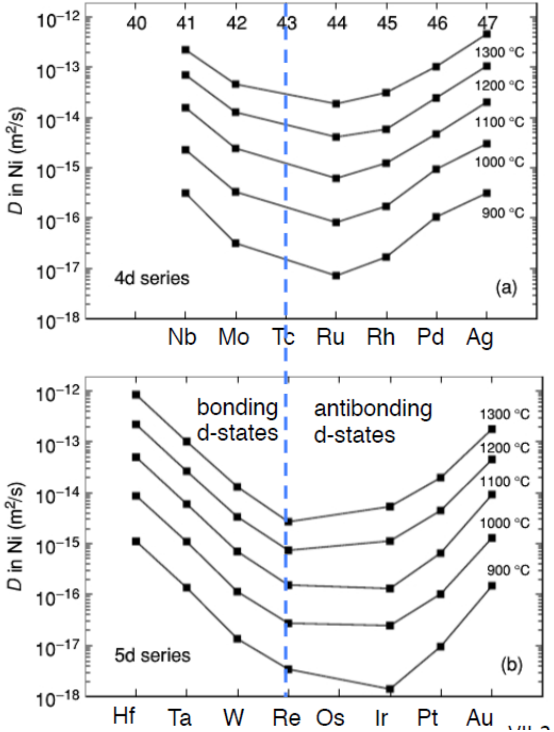




Effect of alloying elements in Ni alloys

Influence on diffusion properties

- Low diffusion rates crucial in Ni alloy design
  - Lower creep rates
  - Reduced γ’ coarsening and microstructural stability
  - Suppression of deleterious phase transformations
  - Maintaining compositional gradients and partitioning
- 4d and 5d transition metals strongly reduce the self-diffusion coefficient in Ni-based superalloys.
- These elements partition to the γ matrix and effectively slow γ’ coarsening.
- Modern superalloys commonly use Re, Ru, and Ir for this purpose, although they are extremely costly (Ru >25’000 CHF/kg, Ir>140’000 CHF/kg).
- Unlike Re and Ru, Ir does not promote TCP-phase formation.

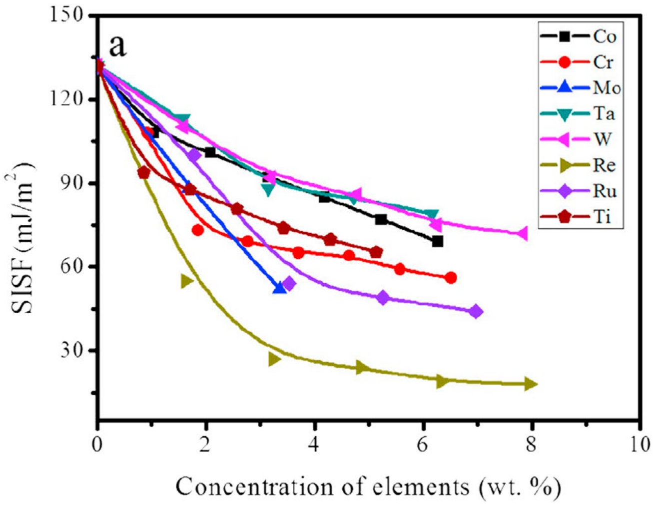


/R.C. Reed, The superalloys – fundamentals and applications, 2006/

Effect of alloying elements in Ni alloys

Influence on stacking fault energies

- SFE governs how dislocations behave during creep
  - High SFE → narrow dissociation of partials; easy cross-slip.
  - Low SFE → wide separation of partials; cross-slip is difficult.
- The creep rate in Ni decreases with decreasing SFE, approximately to the third power.
- Re, Mo, Ru, Cr have the strongest effect on the SFE, but they promote also the formation of unwanted TCP phases.
- The next best solution is the addition of Co



/W. Yang et al., Vacuum 181 (2020) 109682/

Selected Ni alloys – compositions

Wrought alloys

Alloy	Fe	Cr	Co	Mo	W	Nb	Al	Ti	C	B	Zr	others
Alloy/IN 600; 2.4816; NiCr15Fe	8	15.5					0.2	0.2	0.07	0.003		
Alloy/IN 601; 2.4851; NiCr23Fe	14	23					1.35	0 4	0 1	0.003		1 Mn; 0.5 Si
Hastelloy X NiCr22Fe18Mo	18.5	22	1.5	9	0.6				0.07	0.006		0.5 Mn; 0.5 Si
Haynes 230	1.5	22	2.5	2	1		0.3		0 1			0.5 Mn; 0.4 Si; 0.02 La
Haynes 282		20	10	8.5			1.5	2.1	0.06	0.005		
IN 617; 2.4663; NiCr23Co12Mo		22	12.5	9			1	0.3	0.07			
IN 625; 2.4856; NiCr22Mo9Nb	2.5	21.5		9		3.6	0.2	0.2	0.05			
IN 693	4	29				1	3	0.4	0.05			
IN 718; NiCr19NbMo	18.5	19		3		5.1	0.5	0.95	0.05	0.003		0.007 P
Nimonic 80A; 2.4952; NiCr20TiAl		19.5					1.4	2.3	0.07	0.003	0.06	
Udimet 500; 2.4666; NiCr18CoMo		18	19	4.2			3	3	0.07	0.007	0.05	
Udimet 720		18	14.5	3	1.3		2.5	5	0.03	0.03	0.03	
Waspaloy; 2.4654; NiCr20Co13Mo4Ti3Al		19.5	13.5	4.3			1.3	3	0.04	0.006		0.006 P

Selected Ni alloys – compositions

Conventionally cast alloys

Alloy	Cr	Co	Mo	W	Ta	Nb	Al	Ti	C	B	Zr	others
B 1914	10	10	3				5.5	5.2	0.01	0 1		
G NiCr50; 2 4678	50								0.05			
GTD 111	14	9.5	1.5	3.8	2.8		3	4.9	0.1	0.01		
GTD 222	22.5	19		2	1	0.8	1.2	2.3	0.1	0.008		
IN 100; 2 4674; G NiCo15Cr10AlTiMo	10	15	3				5.5	4.7	0.18	0.015	0.06	1 V
IN 713 LC; 2 4670; G NiCr13Al6MoNb	12		4.5			2	6	0.7	0.05	0.01	0.1	
IN 738 LC	16	8 5	1.7	2.6	1.7	0.9	3	3	0.11	0.01	0.05	
IN 792	12.5	9	1.9	4	4		3.5	3.9	0.08	0.02	0.1	1.4 Hf
IN 939	22.5	19		2	1	1	1.9	3.7	0.15	0.009	0.1	
MAR M 247	8.4	10	0.7	10	3		5.5	1	0.15	0.015	0.05	1.4 Hf
Rene 80	14	9.5	4	4			3	4.8	0.17	0.015	0.03	
Udimet 500; 2 4666	18	19	4				3	3	0.07	0.007	0.05	
Udimet 700	15	17	5.3				4.2	3.3	0.07	0.02		

Selected Ni alloys – compositions

Directionally solidified alloys

Alloy	Cr	Co	Mo	W	Ta	Nb	Al	Ti	C	B	Zr	others
ABB 16	13.2	4.1		1.9	5.1		3.7	5	0.07	0.015	0.016	
ABB 2 DS	12	9		9	5.5		3.5	2.3	0.07	0.015		
ExAl7	12	9	1.8	3.5	4		3.4	3.9	0.08			2.5 Re
GTD 111	14	9.5	1.5	3.8	2.8		3	4.9	0.10	0.01		
IN 6203	22	19		2	1.1	0.8	2.3	3.5	0.15	0.01	0.1	0.75 Hf
IN 792	12.5	9	1.9	4	4		3.5	3.9	0.08	0.02	0.1	1.4 Hf
Rene 80 H	14	9.5	4	4			3	4.8	0.08	0.015	0.02	0.75 Hf
CM 247 LC	8.1	9.2	0.5	9.5	3.2		5.6	0.7	0.07	0.01	0.01	1.4 Hf
MAR M 002	9	10		10	2.5		5.5	1.5	0.15	0.015	0.05	1.5 Hf
MAR M 200	9	10		12		1	5	2	0.1	0.015	0.08	2 Hf
MAR M 247	8.4	10	0.6	10	3		5.5	1	0.15	0.015	0.05	1.4 Hf
Rene 142	6.8	12	1.5	4.9	6.4		6.1		0.12	0.015	0.02	2.8 Re; 1.5 Hf

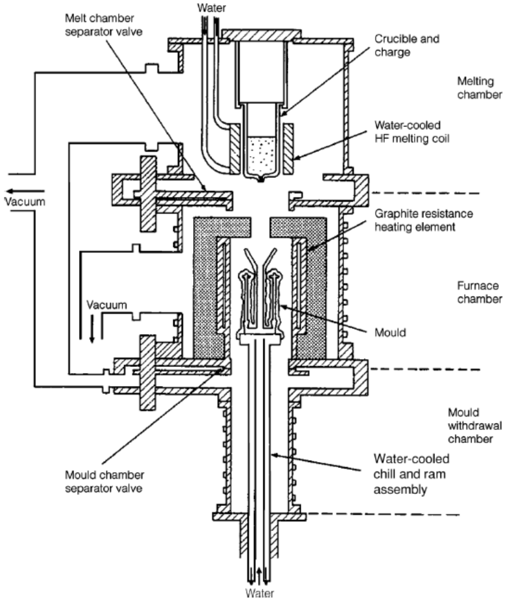
Selected Ni alloys – compositions

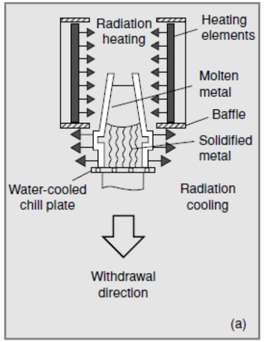
Single crystal alloys

Alloy	Cr	Co	Mo	W	Ta	Nb	Al	Ti	Re	C	B	Zr	Hf
CMSX 11B	12.5	7	0.5	5	5	0.1	3.6	4.2					0.04
CMSX 11C	14.9	3	0.4	4.5	5	0.1	3.4	4.2					0.04
PWA 1483	12.2	9	1.9	3.8	5		3.6	4.1		0.07			
CMSX 4	6.5	9	0.6	6	6.5		5.6	1	3				0.1
CMSX 6	10	5	3		2		4.8	4.7			0.03	0.08	
CMSX 10K	2.3	3.3	0.4	5.5	8.4	0.1	5.7	0.3	6.3				0.03
EPM 102	2	16.5	2	6	8.2		5.5		6	0.03	0 00	0.15	0.01 Y;3 Ru
NASAIR 100	8.5		1.1	10	3.3		5.8	1.2					
PWA 1480	10	5		4	12		5	1.5					
PWA 1484	5	10	2	6	8.7		5.6		3			0.1	
Rene N4	9.75	7.5	1.5	6	4.8	0.5	4.2	3.5		0.05	0.004	0.15	
Rene N5	7	7.5	1.5	5	6.5		6.2		3	0.05	0.004	0.15	0.01 Y
Rene N6	4.2	12.5	1.4	6	7.2		5.75		5.4	0.05	0.004	0.15	0.01 Y
SX 1	4.5	12.5		5.8	7		6		6.3			0.16	

Fabrication of single crystal parts

- Single crystalline Ni parts do not contain any grain boundaries and are oriented in <001> direction
  - No grain boundary sliding at high T
  - Direction with lowest E-modulus
- SX parts (e.g. blades) are produced by casting in vacuum (10^{-8} bar, Bridgman furnace)
  - Directional solidification conditions are ensured by putting the mold on a water-cooled chill plate
  - During casting, the mold is heated to ~1’500°C (above T_L) to prevent solidification at the walls
  - [001] grain selection occurs before the solidification front enters in the blade mold
  - The mold is slowly withdrawn from the heated zone
  - The standard technique to make the mold is lost wax investment casting

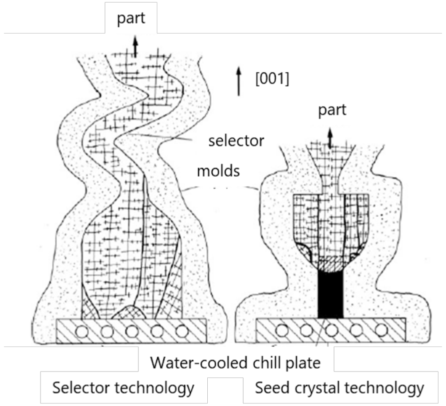


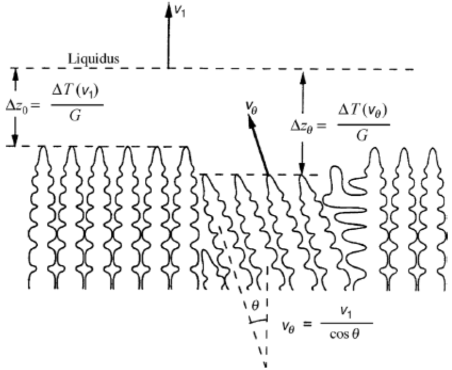


/R.C. Reed, The superalloys – fundamentals and applications, 2006/

Fabrication of single crystal parts

- On the chill plate formation of many randomly oriented grains
- The thermal gradient is set so that columnar dendritic growth occurs (~4000 K/m)
- The preferred growth direction of crystals during solidification of Ni is <001> → these grains grow fastest II to thermal gradient
- A single [001] is separated with a helical selector or with the seed crystal technology and enters the hot mold
- The dendrites grow at a rate which is controlled by solute diffusion, since the solid phase grows from the liquid with a very different composition from it
  - → the local dendrite tip undercooling, ΔT_{tip}, scales monotonically with the velocity, v, of the dendrite, measured along the temperature gradient
- Dendrites misaligned by an angle θ with respect to perfectly aligned ones must grow at a greater undercooling and hence at the rear of the growth front





/Maier, Niendorf, Bürgel – Handbuch Hochtemperatur-Werkstofftechnik, 2015/
/R.C. Reed, The superalloys – fundamentals and applications, 2006/

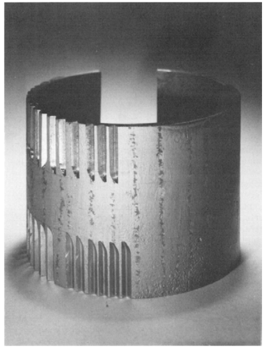
Fabrication of single crystal parts

Selected casting defects

Defect	Appearance	Origin
High-angle GBs	Large bi-/poly-crystals in the part	In the case of non-one-dimensional heat flow solidification front is curved and the dendrite stems do not grow parallel; with increasing misorientation, formation of high-angle GBs
Low-angle GBs	Slight angular deviation of dendrite cores	Like high-angle GBs but with small misorientation of dendrites; plastic deformation due to shrinkage constraints
Globular grains	Equiaxed microstructure	Temperature gradient too small and/or withdrawel speed too high
‘Freckles’	Small roundish grains parallel to the dendrite cores in the interdendritic areas; enriched in Al, Ti and Ta, depleted in W and Re	Flow of the melt in the interdendritic spaces due to segregation-related density differences; this causes dendrite tips or arms to break off, which lead to new equiaxed grains
‘Slivers’	Strip-shaped grains, mainly on the component surface	Reactions of certain alloying elements in the melt with the mold; formation of inclusions that act as nuclei for elongated grains.

Bicrystalline turbine blade

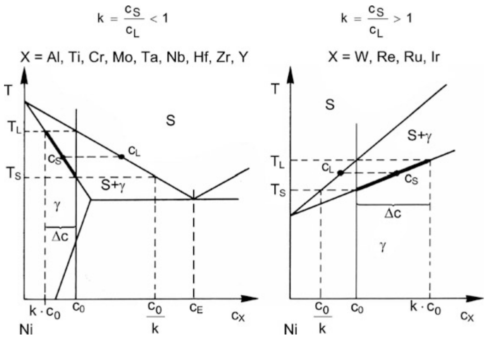
Freckles

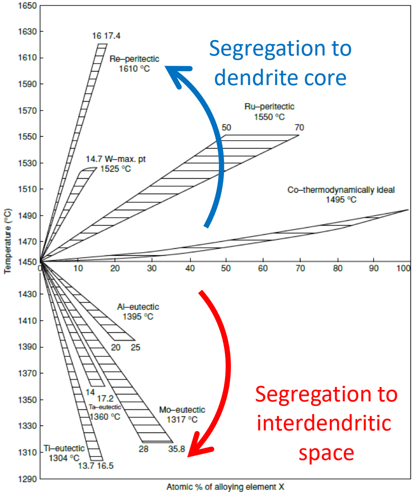


/A.F. Giamei, Metall. Trans. 1 (1970) 2183/

Microsegregation in SX alloys

- Microsegregation occurs because elements have different solubilities in solid and liquid phase, c_S and c_L ; partitioning coefficient is $k = c_S/c_L$
- Since k≠1 → the composition of the melt changes during solidification
  - k<1: enrichment of element X in the liquid
    - → X cannot diffuse quickly enough from the liquid into the solid
    - → Large solidifcation ranges; remaining melt can reach eutectic composition
  - k>1: enrichment of element X in the solid
    - → X cannot diffuse quickly enough out of the solid into the liquid
    - → The interdendritic regions are depleted of these elements
- The microsegregation depends mainly on
  - The solidification rate
  - The diffusion velocities of the alloying elements
  - The concentration difference Δc of the solid material in the solidification interval



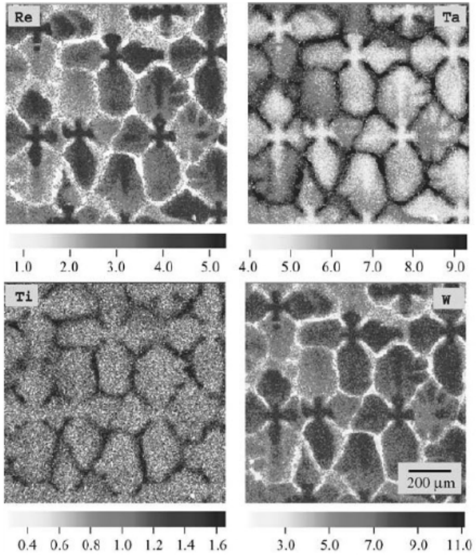


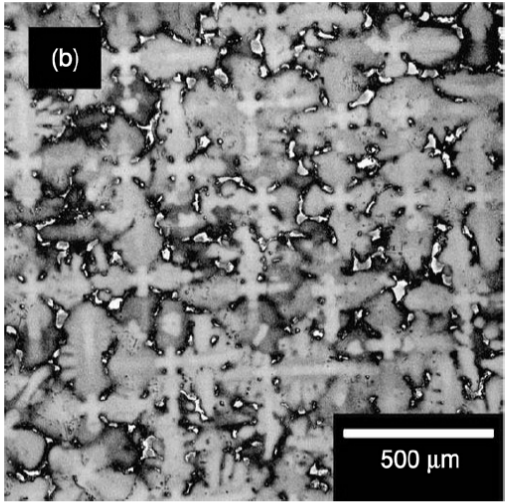
Segregation to dendrite core

Segregation to interdendritic space

Microsegregation in SX alloys

Partitioning of W and Re to the dendrite core, and Ti and Ta to the interdendritic regions in as-cast CMSX-4 superalloy



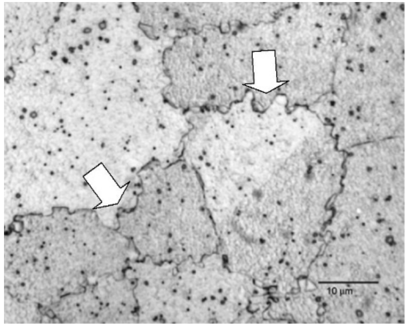


Dendritic microstructure of a single-crystal superalloy in the as-cast state

/R.C. Reed, The superalloys – fundamentals and applications, 2006/

Heat treatment of γ’-strengthened Ni alloys

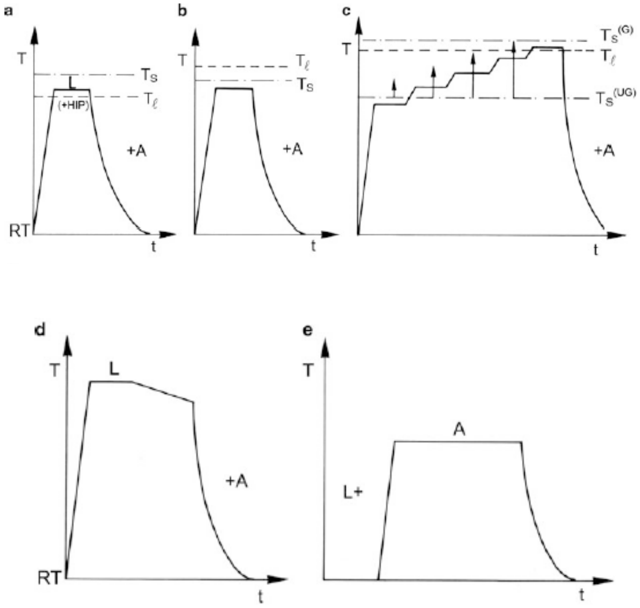
- The heat treatment of Ni alloys has different functions:
  - to reduce casting segregation and to distribute the alloying elements as homogeneously as possible; thus to raise the melting temperature towards the equilibrium solidus temperature
  - to reduce or completely dissolve γ/γ' residual eutectic
  - to adjust the optimum γ‘ size, shape and distribution
  - to precipitate hard particles (mostly carbides) on grain boundaries
  - to relieve residual stresses from manufacturing and fabrication
  - to adjust the grain size of wrought materials by recrystallization
  - to selectively change the grain boundary morphology (jagged grain boundaries)
  - to restore the optimum microstructural condition after operation and to eliminate any undesired precipitated phases



Heat treatment of γ’-strengthened Ni alloys

Typical temperature-time profiles

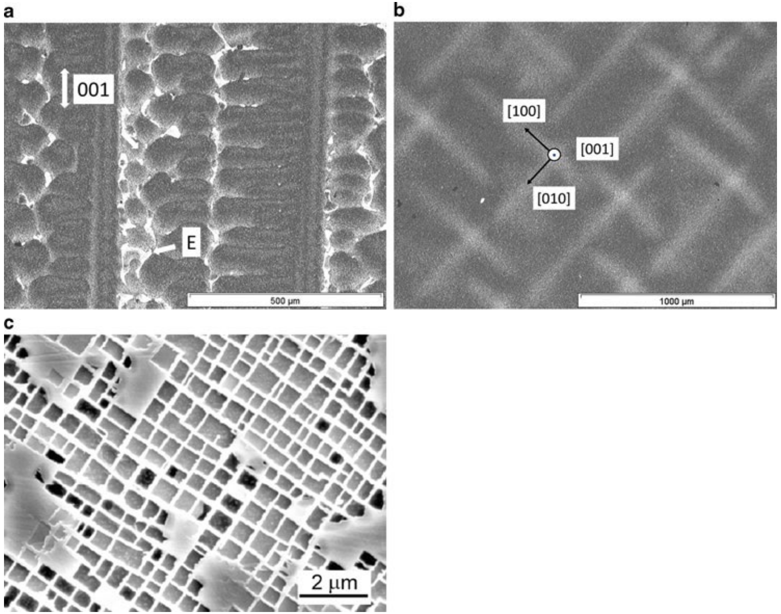
- Schematic temperature/time curves for heat treatments of precipitation hardening alloys (L: solution heat treatment; A: curing; T_l: solution temperature of the precipitates; T_S: solidus temperature).
  a) Complete solution annealing, possibly simultaneously as a HIP treatment
  b) Partial solution annealing (in which $T_l > T_S$),
  c) Multi-stage solution annealing.(T_S^{UG}: out-of-equilibrium solidus temperature; T_S^{G}: equilibrium solidus temperature),
  d) Solution annealing with slow cooling to form jagged grain boundaries
  e) one-step ageing heat treatment



/Maier, Niendorf, Bürgel – Handbuch Hochtemperatur-Werkstofftechnik, 2015/

Heat treatment of γ’-strengthened Ni alloys

- Microstructure of the single crystal alloy CMSX-4
  - a) As-cast state with dendritic structure and large γ/γ’ eutectic islands (E); longitudinal section with [001] orientation
  - b) After multi-stage solutionizing between 1200 and 1320°C s (transverse section); The dendrite structure is due to not completely removed segregations, mainly of W and Re. The γ/γ’ eutectic has disappeared.
  - c) After solutionizing and ageing at 870°C, γ’ precipitates (volume fraction approx. 63%)



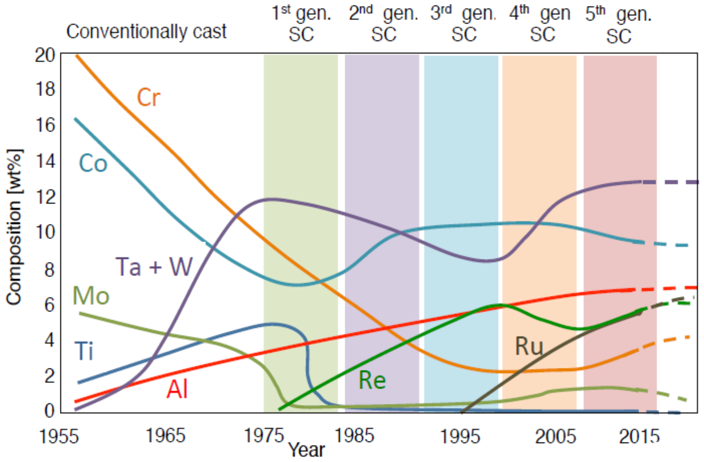
/Maier, Niendorf, Bürgel – Handbuch Hochtemperatur-Werkstofftechnik, 2015/

Main challenges in design of Ni superalloys

- Target γ′ fraction of ≈ 60-70 vol.%.
- Stabilize γ′ by reducing lattice mismatch (and interface energy) between γ and γ′; requires knowledge of partitioning coefficients k of alloying elements and their effect on lattice parameters, which vary with temperature.
- Slow coarsening by lowering diffusion in the matrix; Re, Ru, and Ir are especially effective, but extremely expensive.
- Avoid unwanted phases, again dependent on element partitioning between γ and γ′.
- Control microsegregation and solidification rate to prevent convection in interdendritic liquid and freckles.
- Lower stacking fault energy to improve γ-matrix creep resistance.

Evolution of composition of Ni-based superalloys

- Cr has been reduced from over 20% to a few %; Al and Ta take over the role of forming protective oxide scales
- Ta+W have been increased first then reduced to compensate for increasing Re-contents
- Mo and Ti have virtually been eliminated from modern alloys
- Lately Re has been again reduced (and Ta+W increased) as Ru has provided slow diffusion
- Co has been reduced and is now again introduced in order to lower the stacking fault energy.
- The latest developments include Ir additions (after 2005), but price development poses a challenge



/R.C. Reed, The superalloys – fundamentals and applications, 2006/

Mechanical properties of Ni alloys

0.2% yield strength of selected Ni alloys at different temperatures

wrought

Alloy	21°C	540°C	650°C	760°C	870°C
Inconel 600	285	220	205	180	40
Inconel 617	295	200	170	180	195
Inconel 718	1185	1065	1020	740	330
Nimonic 80A	620	530	550	505	260
Udimet 630	1310	1170	1105	860	---
Waspalloy	795	725	690	675	520
René 95	1310	1255	1220	1100	---

cast

Alloy	21°C	540°C	1100°C
IN-713 LC	740	705	---
IN-162	815	795	---
MAR-M-432	1070	910	---
Nimocast 90	520	420	---
CMSX2	1135	1245	1105
PWA-1480	895	905	495

Mechanical properties of Ni alloys

<001> texture/orientation strengthening

- In a heated constrained part or in a locally heated volume element of a part under loading in z-direction, the strain is

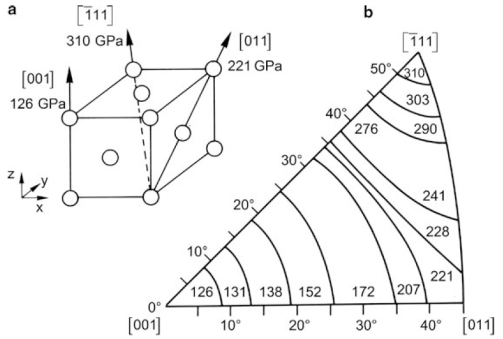
$$\varepsilon_z = \varepsilon_{therm} + \varepsilon_{mech} = \alpha_{CTE} \cdot \Delta T + \frac{\sigma_z}{E} = 0$$

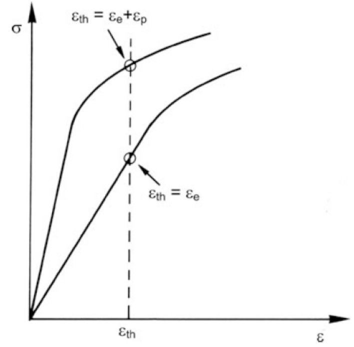
- The resulting stress can thus be calculated as

$$\sigma_z = -E \cdot \varepsilon_{therm} = -\mathrm{E} \cdot \alpha_{CTE} \cdot \Delta T$$

- For E ≈ 200 GPa and α ≈ 15x10^{-6} 1/K → $\Delta\sigma_z$= 3 MPa/K
- For isotropic (polycrstal) Ni, the resulting stresses can exceed the yield strength of the materials
- In a fcc single crystal, the E-modulus is anisotropic with the lowest value in <001> direction

→ the same load leads to significantly lower stresses



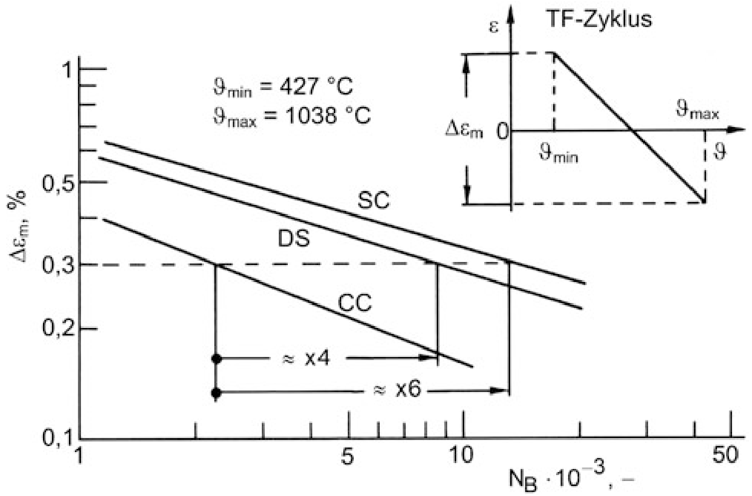


/Maier, Niendorf, Bürgel – Handbuch Hochtemperatur-Werkstofftechnik, 2015/

Mechanical properties of Ni alloys

Thermal fatigue behaviour

- Comparison of material properties under TMF loading between a conventionally cast (CC) superalloy, a directionally solidified superalloy (DS) with grains in <100>-orientation and a <100>-oriented single crystal (SC) superalloy.
- The stress direction for the DS and SC alloys is in the <100> direction of the grains
- <001>-oriented samples show a significantly longer lifetime at a give strain amplitude



/Maier, Niendorf, Bürgel – Handbuch Hochtemperatur-Werkstofftechnik, 2015/

Mechanical properties of Ni alloys

High-T performance of wrought Ni alloys

- Tensile strength:
  - wrought Ni alloys maintain high strength until approx 700-800°C, thereafter sharp drop.
- Creep:
  - Pronounced creep at T>600°C,
  - Sharp drop of stress-rupture strength up to 800°C

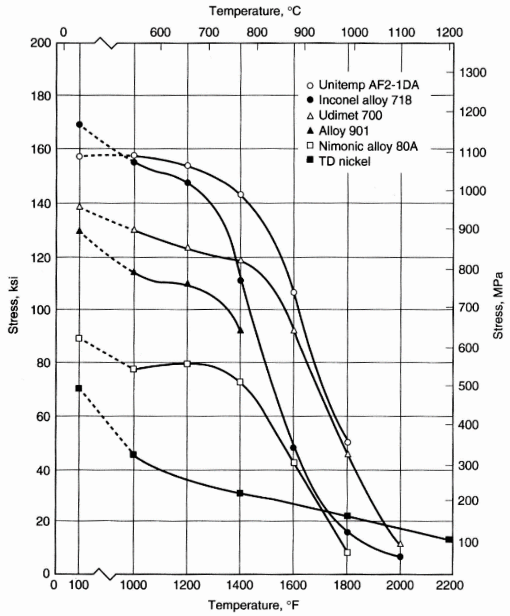


Fig. 15 Effect of temperature on the 0.2% offset yield strength of Inconel 718 and competing alloys. Product form: bar stock. Source: Ref 13

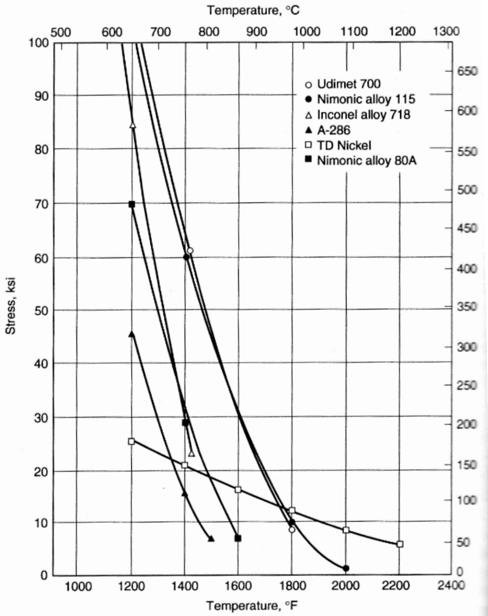


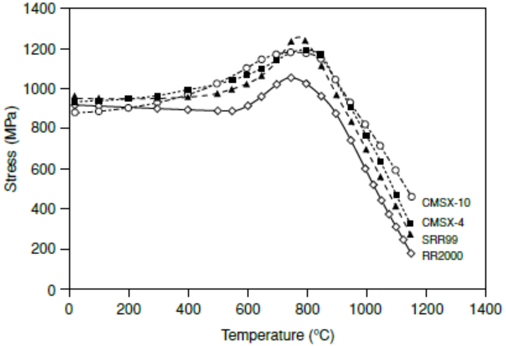
Fig. 16 1000 h stress-rupture strength of Inconel 718 and competing alloys. Product bar stock. Source: Ref 13

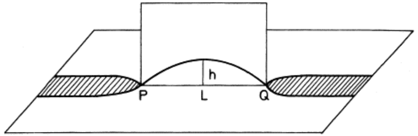
/ASM Metals Handbook, Ni and Ni alloys, 1998/

Mechanical properties of Ni alloys

Anomalous yielding effect in γ’-strengthened SX alloys

- Yield stress in SX Ni alloys increases with T up to ~800 °C
- Screw superdislocations in γ′ normally glide on {111} planes.
- With higher T, cross-slip onto {010}/{001} cube planes occurs.
- Glide on cube planes creates high-energy APBs
  → dislocation pinning.
- Result: higher yield stress until recovery/climb softening sets in above ~800 °C.
- Yield strength also depends on crystal orientation:
  - Slip occurs on {111}<110> systems → resolved shear stress (Schmid factor) depends on loading axis ([001], [011], [111]).
  - In [001] orientation, fewer slip systems are favorably oriented → dislocations cut γ′ less easily → higher strength.
  - In [111], more slip systems are active → easier glide → lower strength.





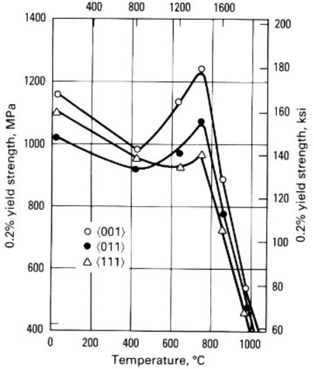


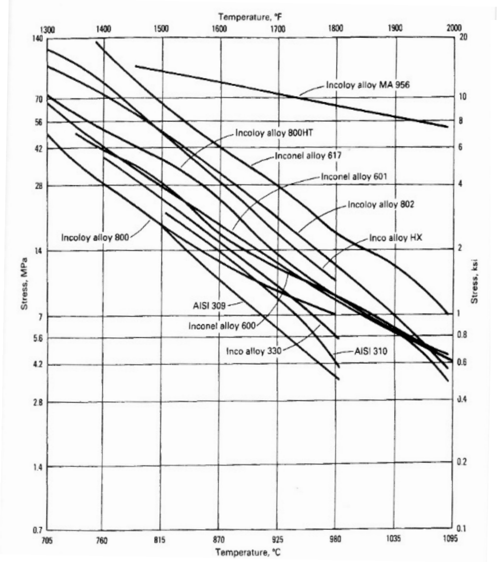
Fig. 8 Yield strength of single-crystal PWA 1480 alloy as a function of temperature and orientation. Source: Ref 15

/ASM Metals Handbook, Ni and Ni alloys, 1998/

Mechanical properties of Ni alloys

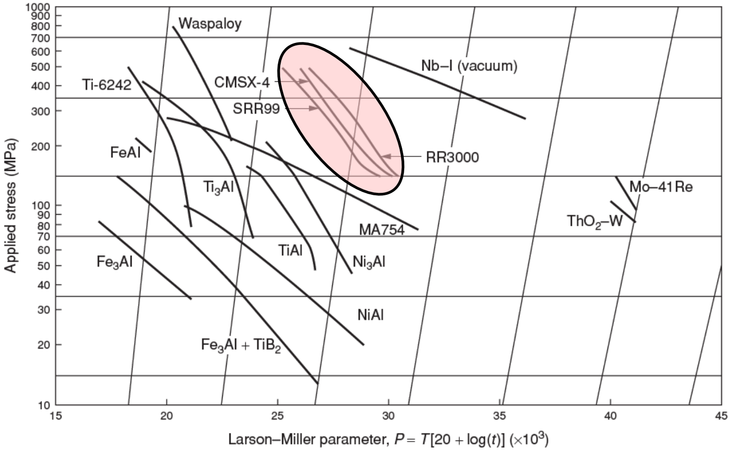
Creep performance of γ’-strengthened alloys

10’000h rupture strength of wrought Ni alloys and stainless steels



/ASM Metals Handbook, Ni and Ni alloys, 1998/

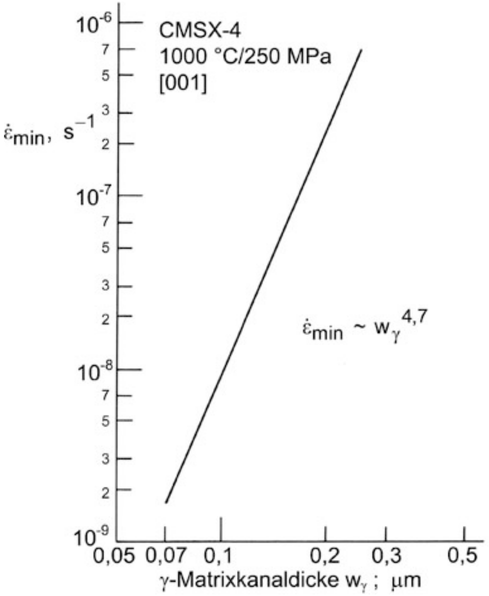
Larson–Miller parameter, P, for a number of high-temperature materials



- The horizontal and near-vertical lines have spacings equivalent to a factor of 2 change in creep life and 200°C temperature capability
- the materials with the best high-temperature performance lie towards the top right of the diagram.

/R.C. Reed, The superalloys – fundamentals and applications, 2006/

Minimum creep rate as function of matrix channel thickness



/Maier, Niendorf, Bürgel – Handbuch Hochtemperatur-Werkstofftechnik, 2015/

Mechanical properties of Ni alloys

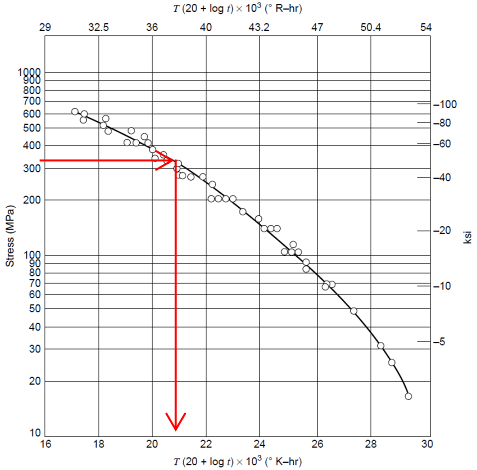
Accelerated creep testing – Larson-Miller approach

- Creep rupture tests at higher temperatures, comparable stress

- Shorter time periods
- Data extrapolation

  Larson-Miller parameter $\mathrm{LMP} = T(C + log(t))$:

  For a specific stress the time to rupture is defined (depending on the temperature)



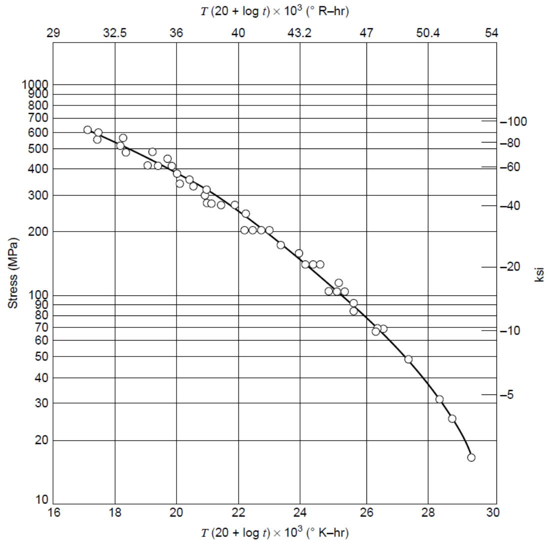
Mechanical properties of Ni alloys

Accelerated creep testing – Larson-Miller approach

- The service life of turbine blade is on the order of years. A commonly used extrapolation procedure employs the Larson–Miller parameter, defined as: $LMP = T(C + log(t))$
- **Derive the Larson-Miller relation:**

- $\dot{\varepsilon} = Ae^{-\frac{\Delta H}{RT}} \rightarrow \frac{\Delta H}{R} = T(ln(A) - ln(\dot{\varepsilon}))$
- $\frac{1}{t} = A'e^{-\frac{\Delta H}{RT}}$
- $\frac{\Delta H}{RT} = (ln(A') + ln(\mathrm{t})) = (2.303\log(A') + 2.303log(t))$
- $\frac{\Delta H}{R*2.303} = T(\log(A') + log(t))$

$$\underbrace{\frac{\Delta H}{R*2.303}}_{\text{LMP}} = T(\underbrace{\log(A')}_{\text{C} \sim 20} + log(t))$$



Mechanical properties of Ni alloys

Creep performance of SX Ni alloys

- The creep performance could be significantly improved with the optimization of the SX Ni alloys

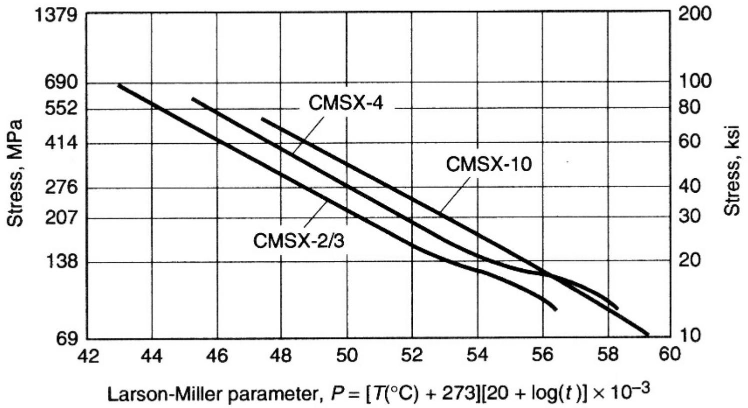


Fig. 19 Average Larson-Miller stress rupture of CMSX-10 vs. that of CMSX-4 and CMSX-2/3. Source: Ref 34

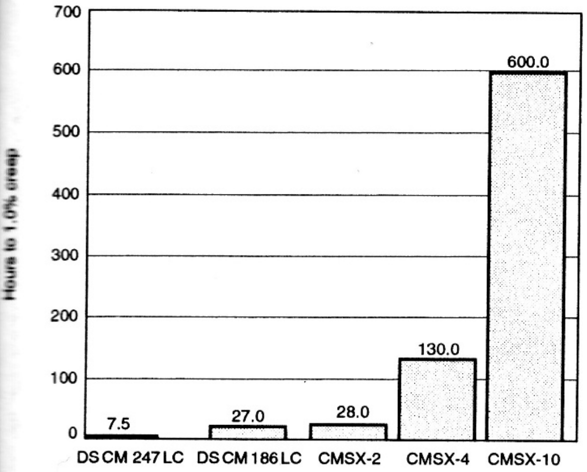


Fig. 21 Average 1.0% creep strengths at 982 °C/248 MPa (1800 °F/36 ksi) test condition for CMSX-10, CMSX-4, CMSX-2, DS CM 186 LC, and DS CM 247 LC. Source: Ref 34

/ASM Metals Handbook, Ni and Ni alloys, 1998/

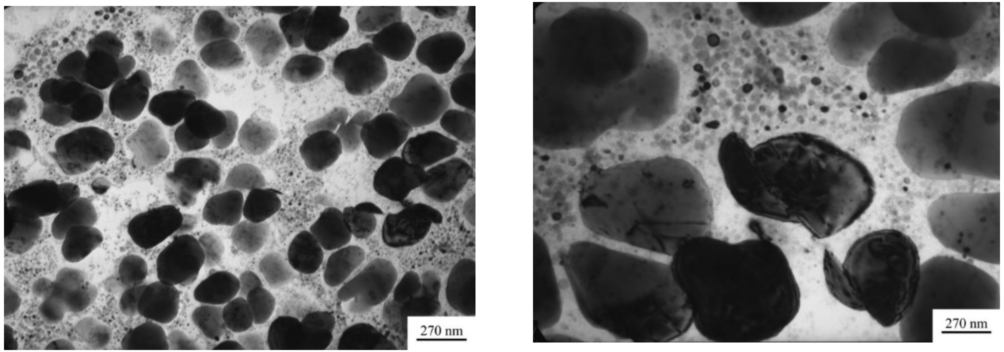
Microstructural changes in Ni alloys

Coarsing of γ'-Ni_3Al

- During service at elevated temperatures for long durations coarsening of the γ' phase
- This can have detrimental effects on the strength of the alloy
- In Ni alloys with lower γ' fractions the growth follows the Wagner-Lifshitz-Slyozov model:

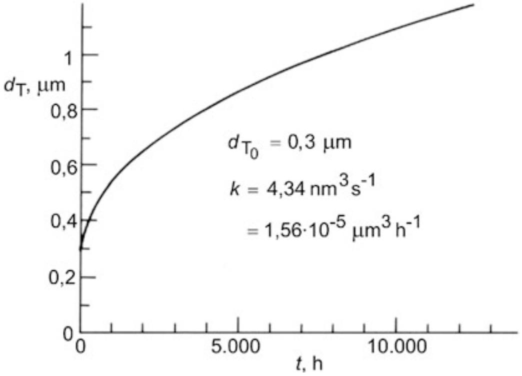
$$d_T^3 - d_{T0}^3 = k \cdot t \text{ with } k = \alpha \cdot \frac{8D \cdot \gamma_{Ph} \cdot c_0 \cdot V_m^2}{R \cdot T}$$

α: constant
D: Diffusion constant of the slowest species
γ_{Ph}: specific interfacial enthalpy matrix/particle
c_0: saturation conc. of particle-forming element
V_m : molar volume of particles



/www.phase-trans.msm.cam.ac.uk/

γ' coarsening in IN738 LC at 920 °C



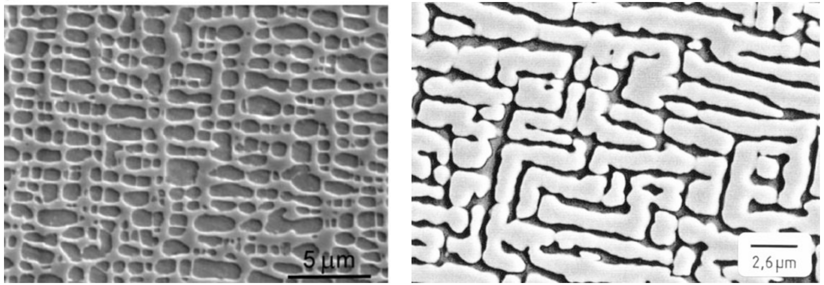
/Maier, Niendorf, Bürgel – Handbuch Hochtemperatur-Werkstofftechnik, 2015/

Microstructural changes in Ni alloys

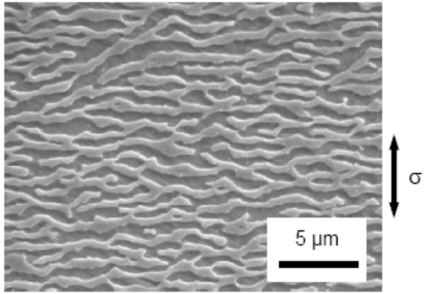
Coarsening of γ’ grains in SX alloys under creep load

- In SX alloys with high fractions of γ’ and at high T (> 900°C), the coboidal precipitates grow to elongated structures
- At low external stresses, the γ’ grains grow in different directions and finally become meander-shaped
- Under external stresses, directional growth of the γ’ phase (‘rafting’)
  - Type N: elongated grains perpendicular to external loading direction
  - Type P: elongated grains parallel to external loading direction

Without or at low external load



175 MPa – type N

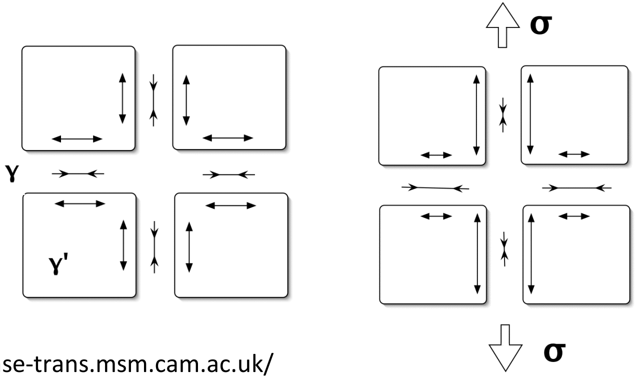


/Maier, Niendorf, Bürgel – Handbuch Hochtemperatur-Werkstofftechnik, 2015/

Microstructural changes in Ni alloys

Coarsening of γ’ grains in SX alloys under creep load

- Directional coarsening is caused by the superposition of external load stresses and internal coherence stresses
  - If the γ’/γ lattice mismatch is positive ($a_\gamma < a_{\gamma'}$) → type P
  - If the γ’/γ lattice mismatch is negative ($a_\gamma > a_{\gamma'}$) → type N (most frequent case)
- This results in different local stress fields in the γ channels perpendicular and parallel to the loading direction
- These stress differences are the driving force for a directional diffusion; the γ’ particles grow in the direction of the lower lattice distortion in the γ channels



/www.phase-trans.msm.cam.ac.uk/

- Type N rafting with $a_\gamma > a_\gamma$; The γ phase is in compression in the vicinity of the interface with γ‘ → compensating tensile stresses in the γ'.
- The application of a uniaxial tensile stress exaggerates any tensile stress in the vertical direction and reduces those in the horizontal orientation.
- The applied tensile stress reduces the compressive stress in the vertical γ channels and via the Poisson effect, increases those in the horizontal channels.

High-temperature corrosion resistance

- High-temperature corrosion describes the reaction of an alloy with constituents of a gaseous atmosphere (e.g. C, S) at elevated temperatures
- High temperature corrosion properties are characterized by exposing the material to a corrosive atmosphere (e.g. in a combustion chamber) and measuring the weight gain or the depth of attack in the sample as a function of temperature and time

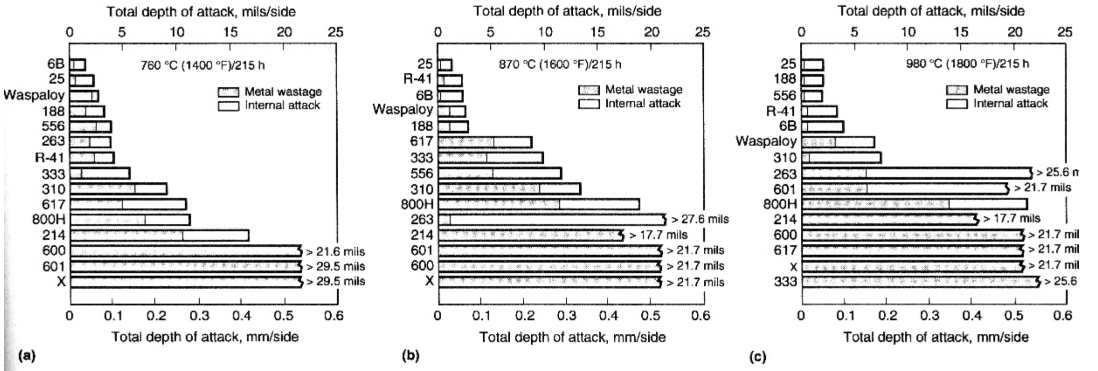
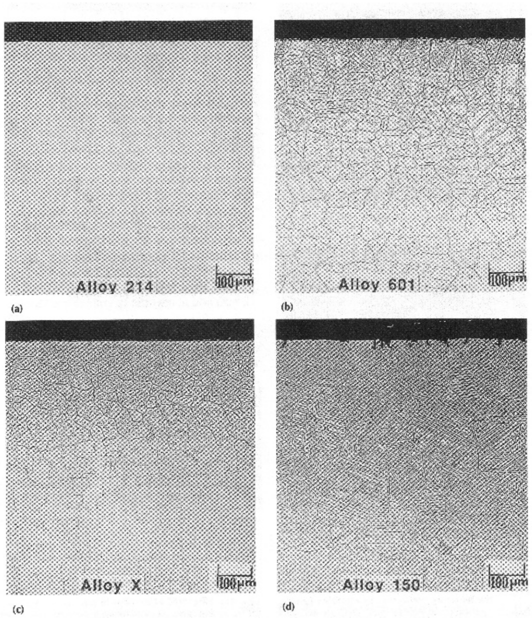


Fig. 18 Corrosion of iron-, nickel-, and cobalt-base alloys after 215 h at (a) 760 °C (1400 °F), (b) 870 °C (1600 °F), and (c) 980 °C (1800 °F) in Ar-5H$_2$-5CO-1CO$_2$-0.15H$_2$S. Source: Ref 38



/ASM Metals Handbook, Ni and Ni alloys, 1998/

The need for further alloy optimization

Southwest Airline Flight 1380
March 2018

Fatigue failure of turbine blade
1 person killed

Qantas Flight B734
November 2009

Excessive creep extension of blade, tip shroud/seal interference and blade rupture

Learning objectives

- Difference between wrought and cast Ni alloys (conventional, directional, single crystal)
- Main alloying elements in Al alloys and their effect on
  - Solid solution strengthening
  - Precipitation strengthening
  - Diffusion properties
  - Stacking fault energies
- The γ'-Ni_3Al phase (structure, composition) and its role for HT-strengthening of Ni alloys
- Fabrication of directionally solidified/single crystal alloys incl. main casting defects
- Role of heat treatments for Ni alloys
- Explain microstructural changes after high-T exposure/heat treatments
- High-T mechanical performance of Ni alloys
  - High-T tensile
  - Creep – Larson-Miller approach
  - Thermo-mechanical

Abbreviations and manufacturers

ABB – Asea Brown Boveri Ltd.
Allvac – ATI Allvac, Allegheny Technologies Comp.
Cabot – Cabot Corp.
CM, CMSX – Cannon-Muskegon Corp.
GTD – General Electric Comp.
Hastelloy – Cabot Corp.
Haynes – Haynes International
Incoloy – International Nickel Comp. (jetzt Special Metals Corp.)
Inconel (IN) – International Nickel Comp. (jetzt Special Metals Corp.)
MAR-M – Martin Marietta Corp.
Nicrofer – Krupp VDM GmbH
Nimonic – International Nickel Comp. (jetzt Special Metals Corp.)
PM – Metallwerk Plansee GmbH
PWA – Pratt & Whitney Aircraft (United Technologies Corp.)
René – General Electric Comp.
RJM – Johnson Matthey & Co Ltd.
SRR – Rolls-Royce Ltd.
Udimet – Special Metals Corp.
Waspaloy – United Technologies Corp.