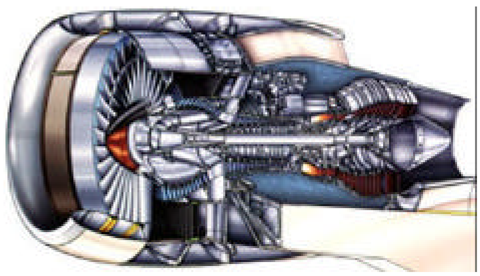
Lecture 22: Superalloys

MMat 380



Topics

Superalloys

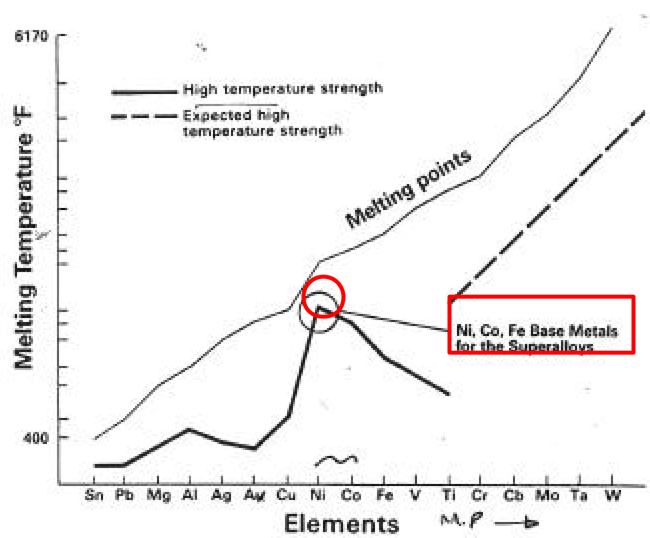
- Ni vs Co based
- History, uses
- Strengthening mechanisms

Single crystals

Superalloys

- Able to maintain high strengths at high temperatures
- Good corrosion and oxidation resistance at high temperatures (Cr, Al)
- Good resistance to creep and rupture at high temperatures
- 3 main classes of superalloys
  - Ni – Base
  - Ni-Fe – Base (cheaper than Ni-base)
  - Co – Base

High temperature strength



Ni-based superalloys

- Since 1950, these alloys have predominated in the range 750-980°C
- Due to the presence of very stable γ' ordered FCC precipitate (Ni_3Al,Ti) which provide high temperature strength
- The γ' phase in Co-based superalloys dissolves at 815-1050°C

Co-based superalloys

- Exhibit superior hot corrosion and strength characteristics at temperatures 980-1100°C
- Operating temperatures of the turbine and combustion section
- Co-based alloys sometimes used in the lower range of 750°C in preference to Ni-based superalloys
- Can be air or argon cast and are less expensive than the vacuum-processed Ni-alloys

Strengthening mechanisms in superalloys

Ni-based superalloys

a) solid solution strengthening (Mo and W)

b) addition of elements, e.g., Co which decrease the solubility of others to promote ppt of intermetallics

c) Al and Ti to form ordered FCC intermetallic precipitates of γ'-phase [Ni_3Al], [Ni_3Ti]

d) Carbides on grain boundaries (pin boundaries to stop shear) i.e. control grain boundary sliding

Strengthening mechanisms in superalloys

Ni-based superalloys

e) Small additions of B and Zr which segregate to the grain boundaries and retard sliding process and grain boundary diffusional process

f) Large grains; columnar grains; single crystal – to stop grain boundary shear

NB – Other phases (e.g. sigma) may form. They are not strengthening phases and their morphology is usually controlled so that they do not impair hot strength (e.g. by forming continuous GB ppts). In effect, they are undesirable, but may have to be tolerated

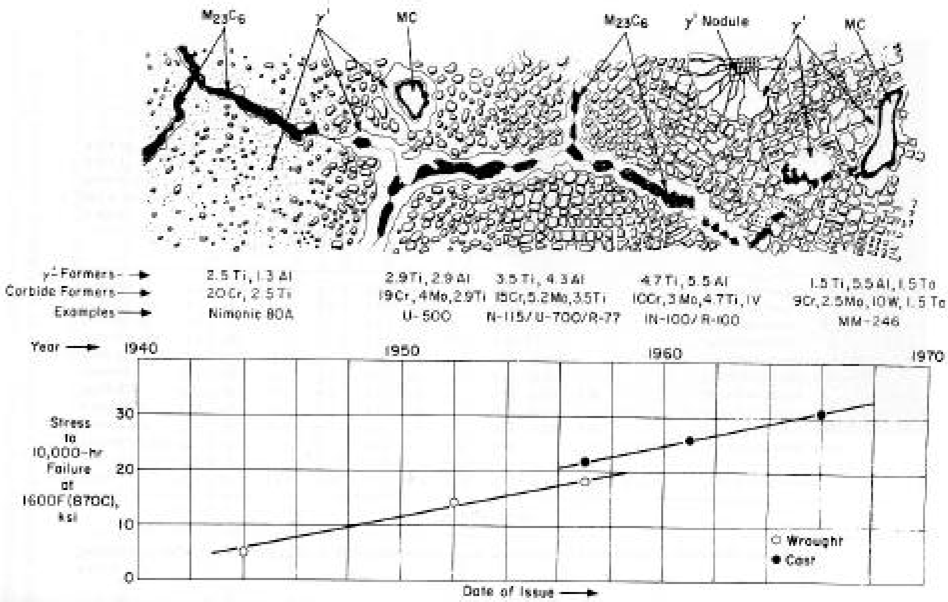
Uses of superalloys

- Largest application of superalloys:
  - aircraft and industrial gas turbines
- Also used in:
  - Space vehicles
  - Rocket engines
  - Submarines
  - Nuclear reactors

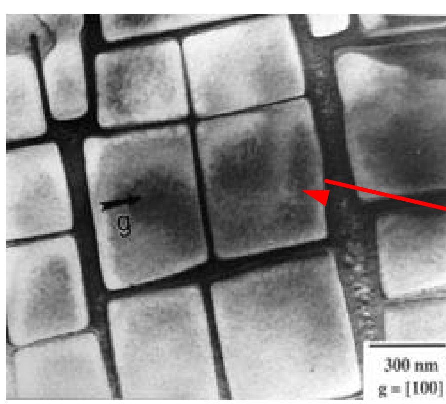
Major phases present

- γ (gamma) phase
  - continuous matrix of FCC austenite
- γ' (gamma prime) phase
  - major ppt phase
- carbides
  - various types, mainly $M_{23}C_6$ and MC

Historical changes in microstructure



Microstructure



Ni_3Al (γ^1)

Trends in microstructure design

- Volume fraction of γ' is increased
- The size of γ' first increased and then remained constant at ~1μm
- γ' became more "cubic"
- A secondary ppt of finely divided γ' appeared
- γ phase – strengthened by addition of solid-solution elements such as Cr, Mo, W, Co, Fe, Ti, Al

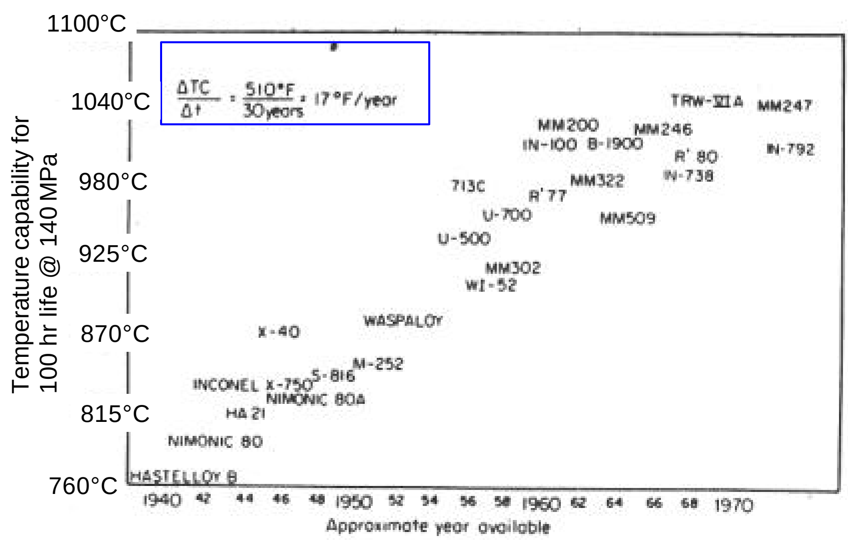
Trends in microstructure design

- γ' phase – precipitated in austenite nickel superalloys by precipitation hardening heat treatments
  - ppt in high-Ni matrices is of the FCC A_3B-type compound i.e. $Ni_3(Al,Ti)$ or $(Ni, Co)_3(Al,Ti)$
  - Degree of order in $Ni_3(Al,Ti)$ increases with temperature

Trends in microstructure design

- Carbides – C content 0.02-0.2%
  - Metallic carbides form in the grain boundaries and within the grains
  - Optimum distribution /amount of carbides along the grain boundaries
- No carbides – excess grain boundary sliding
- Continuous chain of carbides – continuous fracture paths will be formed (low-impact properties)
- Discontinuous chain of carbides along grain boundaries optimum

Historical development and typical temperature capability of superalloys



Microstructure: Astroloy forging

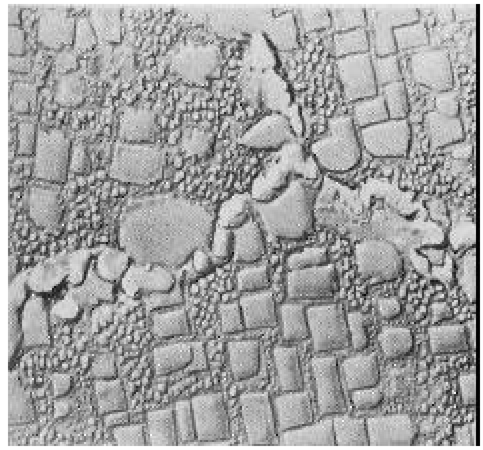
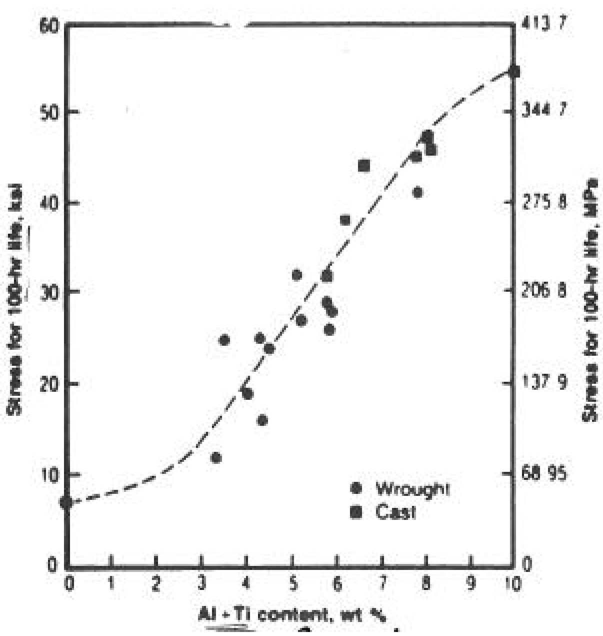


Fig 11-18: solution heat treated
1150ºC 4h, air cooled,
aged 1079ºC 4h, oil quenched, (intergranular γ' ppt)
aged 843ºC 4h, air-cooled, (Fine γ' ppt)
aged 760ºC 16h, air cooled, (Fine γ' ppt)



Effect of Al & Ti content on strength of Ni-based superalloys at 870ºC

Nickel-Iron Base Superalloys

- Fe substituted in part for nickel (cheaper)
- However lower nickel contents mean they cannot be used at as high temperatures as the Ni-base superalloys (650-815°C)
  - 25-45 %Ni
  - 15-60 %Fe
  - 15-28 %Cr – oxidation resistance
  - 1-6 %Mo - solid solution strengthening

Nickel-Iron Base Superalloys

- Most Ni-Fe-based superalloys designed so that they have an austenitic FCC matrix
- Solid solution strengtheners:
  - Cr, Mo, Ti, Al, Nb
- Precipitation strengtheners:
  - Ti, Al, Nb
  - combine with Ni to form intermetallic phases

Some effect of elements on superalloys

Effect	Co-base	Ni-base
Solid-solution strengtheners	Nb, Cr, Mo, Ni, W, Ta	Co, Cr, Fe, Mo, W, Ta
Carbide forms:		
MC type	Ti	W, Ta, Ti, Mo, Nb
M_7C_3 type	Cr	Cr
$M_{23}C_6$ type	Cr	Cr, Mo, W
M_6C type	Mo,W	Mo, W
Forms γ' $Ni_3(Al,Ti)$		Al, Ti
Oxidation resistance	Al, Cr, Ta	Al, Cr, Ta
Sulfidation resistance	Cr	Cr
Changes gb morphology, enhances creep-rupture properties	B, Zr	B, Zr

*If B present in large amounts, borides are formed

Typical compositions of Ni base superalloys

Alloy	% Ni	% Cr	% Co	% Mo	% Al	% Ti	% Nb	% C	% B	% Zr	% Other
Wrought alloys											
Inconel X-750	73	15	. . .	. . .	0.8	2.5	0.9	0.04	. . .		6.8 Fe
Udimet 500	53.6	18	18.5	4.0	2.9	2.9		0.08	0.006	0.05	
Udimet 700	53.4	15	18.5	5.2	4.3	3.5		0.08	0.03	. . .	
Waspaloy	58.3	19.5	13.5	4.3	1.3	3.0		0.08	0.006	0.06	
Astroloy	55.1	15.0	17.0	5.2	4.0	3.5		0.06	0.03		
René 41	55.3	19.0	11.0	10.0	1.5	3.1		0.09	0.005		
Nimonic 80A	74.7	19.5	1.1	. . .	1.3	2.5		0.06	. . .		
Nimonic 90	57.4	19.5	18.0	. . .	1.4	2.4		0.07	. . .		
Nimonic 105	53.3	14.5	20.0	5.0	1.2	4.5		0.20	. . .		
Nimonic 115	57.3	15.0	15.0	3.5	5.0	4.0		0.15	. . .		
Cast alloys											
B-1900	64	8.0	10.0	6.0	6.0	1.0	. . .	0.10	0.015	0.1	4.0 Ta
MAR-M200	60	9.0	10.0	. . .	5.0	2.0	1.0	0.13	0.015	0.05	12 W
Inconel 738	61	16.0	8.5	1.7	3.4	3.4	0.9	0.12	0.01	0.10	1.7 Ta, 2.6 W
René 77	58	14.6	15.0	4.2	4.3	3.3	. . .	0.07	0.016	0.04	. . .
René 80	60	14.0	9.5	4.0	3.0	5.0	. . .	0.17	0.015	0.03	4.0 W

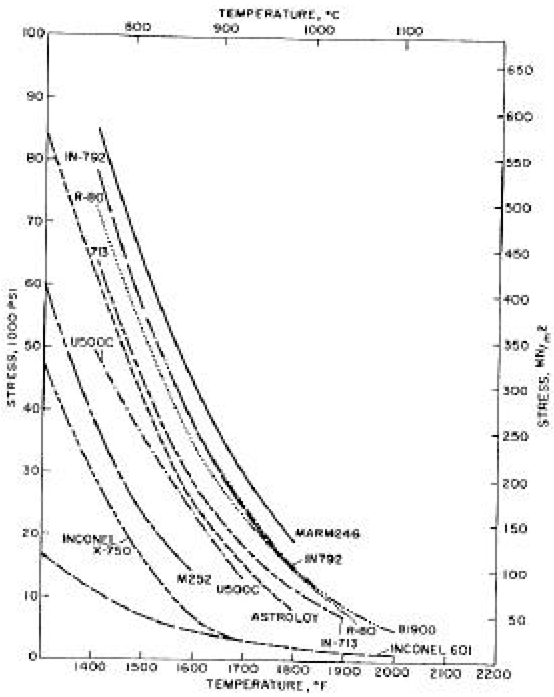
† After "ASM Databook," published in *Met. Prog.*, vol. 114, no. 1, mid-June 1978.

Co-based superalloys

- At room temperature Co: HCP crystal structure
- At 417°C Co undergoes an allotropic transformation and changes to an FCC structure
- Typical composition
  - 50-60 %Co
  - 20-30 %Cr
  - 5-10 %W
  - 0.1-1 %C
- Strengthening:
  - solid solution strengthening
  - carbide precipitation
- Lower strength of cobalt alloys at intermediate temperatures due to a lack of γ'

Stress rupture properties

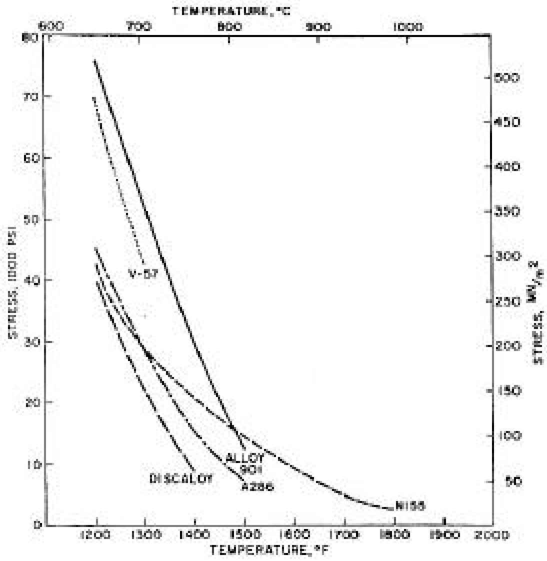
- Ni-based superalloys used in the 760-980 C temperature range
- Cast alloys maintain highest strength at the higher temperatures
  - i.e., MAR-M246 – casting alloy has a rupture strength of 18 ksi after 1000 h at 982 C
- Nickel-iron based superalloys used up to 650-815 C (depending on Ni level)
  - Note – These alloys rupture at considerably lower strengths than the Ni-based superalloys



Stress vs T curves for Rupture in 1000h for Ni-base alloys

Rupture strengths of wrought and cast Ni-base superalloys at 3 T's

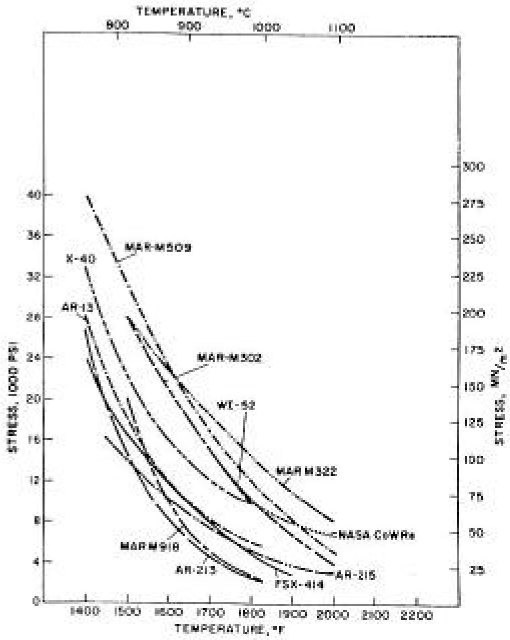
	Characteristic rupture strengths, MPa					
	650°C		815°C		982°C	
Alloy	**100h**	**1000h**	**100h**	**1000h**	**100h**	**1000h**
Wrought						
Inconel X-750	**552**	**469**	179	110	**24**	
Udimet 700		703	400	296	117	**55**
Astroloy		772	407	290	103	55
Cast						
IN-100			503	379	172	**103**
MAR-M246			565	448	186	**124**



Stress vs T curves for Rupture in 1000h for Ni-Fe base alloys

Co-based superalloys

- High temperature stress rupture strengths
- At lower and intermediate temperatures cobalt alloys are not as strong as Ni-based superalloys
- Reason: lack of coherent γ' precipitate $Ni_3(Al,Ti)(Ni_3Ti)$
- Co alloys used for low-stress high-temperature long life parts such as vanes in industrial turbines



Stress-T curves for rupture in 1000h for selected Co-based alloys

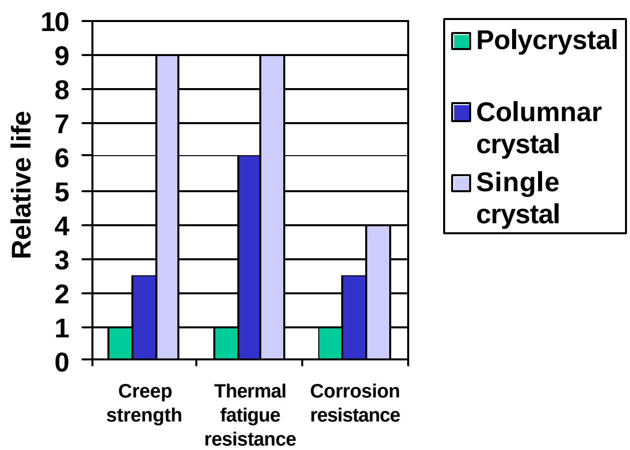
Rupture strengths of wrought and cast Co-base superalloys at 3 T's

	Characteristic rupture strengths, MPa					
	650ºC		815ºC		982ºC	
Alloy	**100h**	**1000h**	**100h**	**1000h**	**100h**	**1000h**
Wrought						
S-816	172	124				
HS-188	152	110	41	25	**15**	
Cast						
X-40	179	138	76	55	**28**	
MAR-M509	**269**	**228**	117	90	55	**38**

Single crystal's

- 1970's and 1980's – introduction of columnar-grained and single-grained castings to replace polycrystal castings of Ni-based superalloys for gas turbine airfoils
- Major increase in the strength and Temp. capability of superalloy castings
  - able to operate 50ºC higher with 100 h/ 140 MPa stress rupture capability

Ni-base superalloys



Chemical composition of **directionally solidified** Ni-base superalloys

Alloy	Composition, %											
	Cr	Co	W	Mo	Ta	Nb	Ti	Al	Hf	B	Zr	C
Columnar grain alloys												
MAR-M200 + Hf	9	10	12			1.0	2.0	5.0	2.0	0.015	0.08	0.14
MAR-M246 + Hf	9	10	10	2.5	1.5		1.5	5.5	1.5	0.015	0.05	0.15
MAR-M247	8.4	10	10	0.6	3.0		1.0	5.5	1.4	0.015	0.05	0.15
Rene 80H	14	9.5	4	4			4.8	3.0	0.75	0.015	0.02	0.08
Single Crystal alloys												
PWA 1480	10	5	4		12		1.5	5				
PWA 1484 (3% Re)	5	10	6	2	8.7			5.6	0.1			
CMSX-2	8	5	8	0.6	6		1.0	5.5				
CMSX-3	8	5	8	0.6	6		1.0	5.5	0.15			
SRR99	8.5	5	9.5		2.8		2.2	5.5				

Comparison of creep strengths of:

single-crystal alloy PWA 1480 and Mar-M200