Collation of Existing Knowledge of materials used in A-USC power plants

M.R. Ahmadi, B. Sonderegger

Institute of Materials Science, Joining and Forming

13/12/2017

Contents:

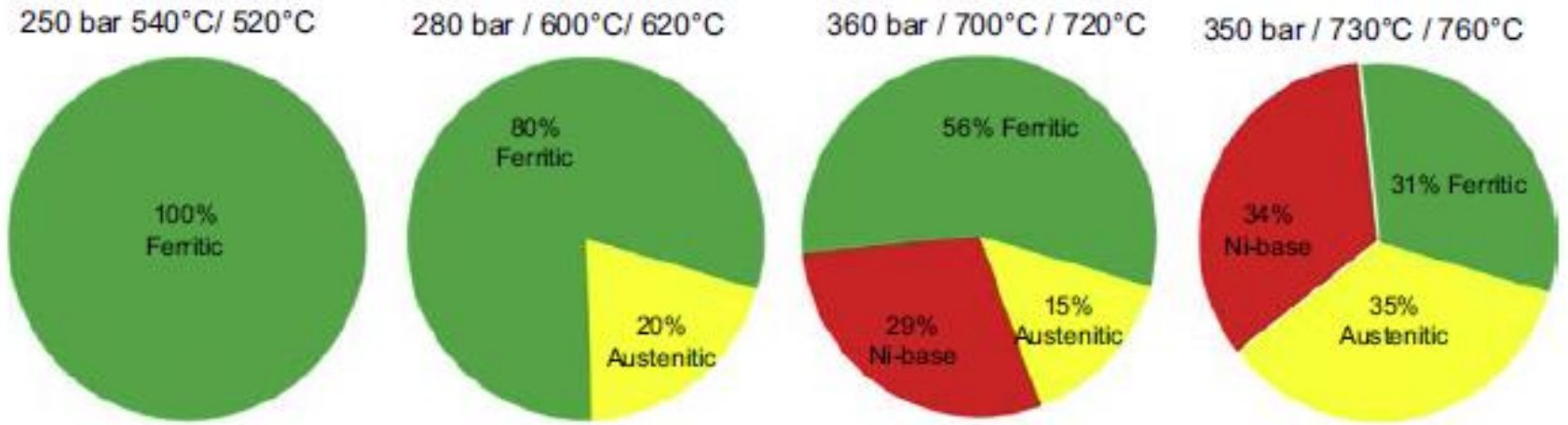
- Introduction
- Ferritic steels
  - History
  - Chemical composition
  - Creep strength
  - Microstructure
  - Corrosion
- Austenitic steels
  - Chemical composition
  - Phases
  - Mechanical properties
  - Creep strength
  - Corrosion
  - Welding
- Superalloys
  - History
  - Chemical composition
  - Creep strength
  - Corrosion
  - Deformation
  - Welding
  - Heat treatment
- Conclusion / outlook

Different generation of power plants:

Quantity	Sub-critical	Super-critical	600°C USC	700°C A-USC	760°C A-USC
Coal Cost, $/GJ	3.42	3.42	3.42	3.42	3.42
Main Steam Temperature, °C	541	582	604	680	732
Main Steam Pressure, bar	179	262	276	352	352
Net heat rate*, (Btu/kWh)**	9,430	8,860	8,700	7,990	7,633
Efficiency, %	35.5	38.5	39.2	42.7	44.7
Levelized Cost Of Electricity (LCOE), ($/MWh)	71.0	69.2	69.4	69.7	69.7
CO_2, kg/MWh from plant	900	851	836	763	729
Relative CO_2 Emissions vs Subcritical	100	94.5	92.9	84.8	81.0

[1]

*The **amount** of energy used by an electrical generator or power plant to generate one kilowatthour (**kWh**) of electricity.
**Btu=1.05506 kJ



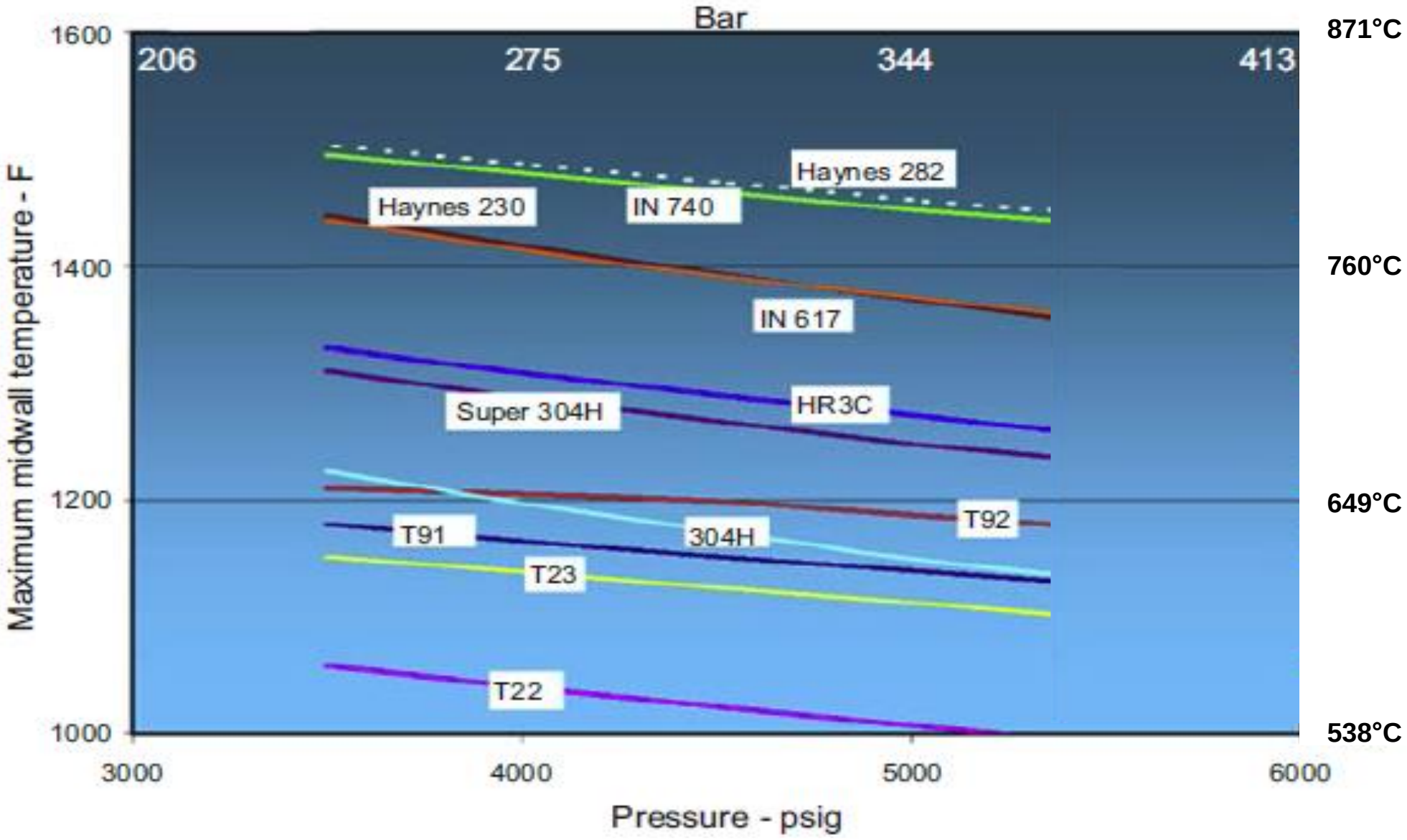
[2]

Materials used in SC, USC, and A-USC boiler

Materials used in the A-USC

- Low-alloyed steel
  a) Conventional low alloy steels: T1, T2, T12, T11, T22,
  b) Enhanced low alloy steels: T23, T24,
- High-alloyed martensitic steel
  - 9Cr1Mo (P9), X20, EM12, T5 , Gr. 91, Gr. 92, NF12, P122, VM12
- Austenitic steel
  - SAVE 12, A286, Esshete 1250, TP316, TP316H, TP316L, Super 304H, TP321, TP321H, TP347, TP347H, TP347HFG, TP304, TP304H, Alloy 800H, NF709, SANICRO 25, SAVE 25, HR3C, TP310NbN (HR3C), SANICRO28
- Superalloys
  - Alloy 617, Nimonic 263, INCONEL 740H, HAYNES 282, HR35, Alloy 141, HR6W

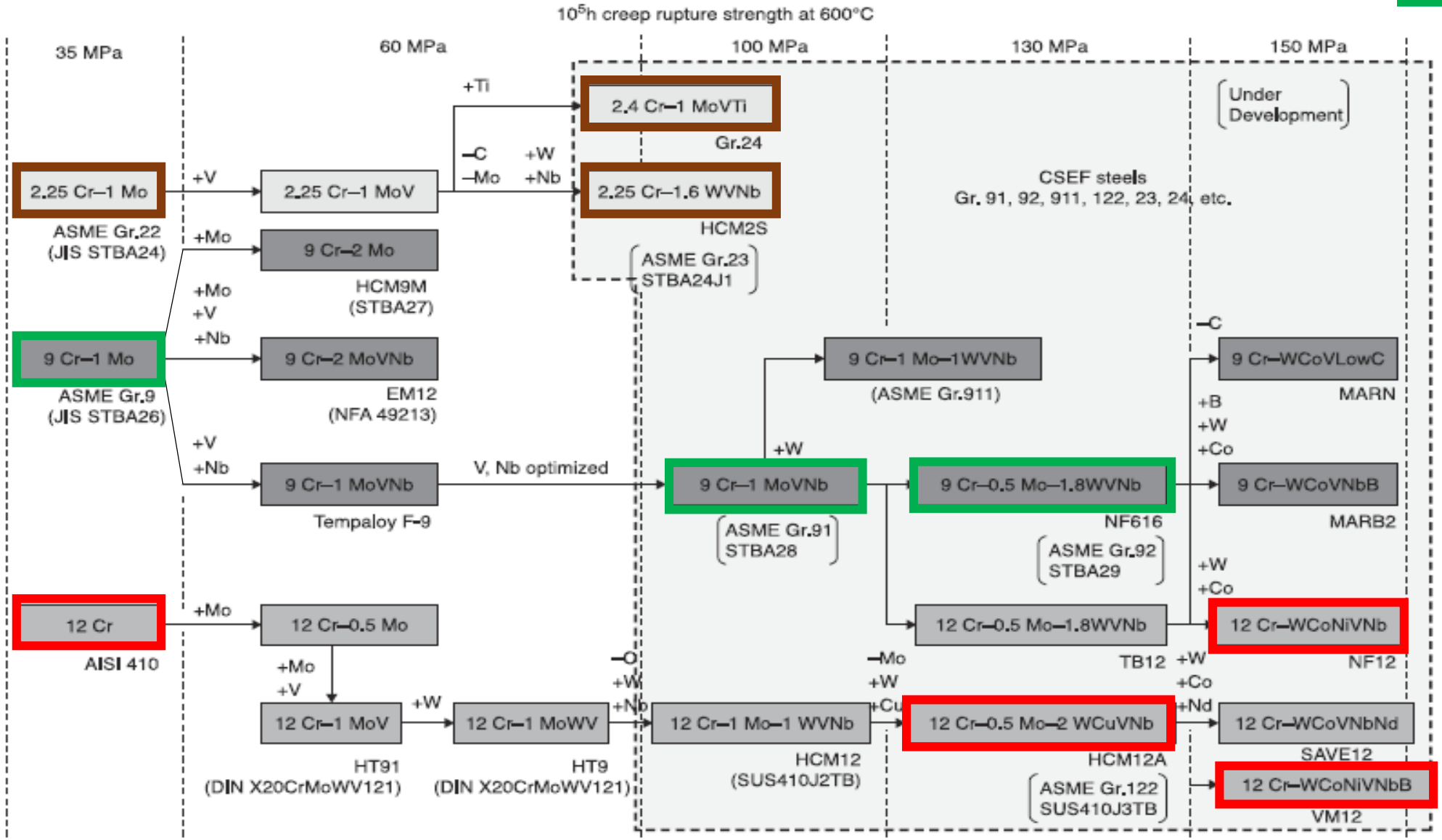
Allowed Service Temperature and Pressure



[2]

Ferritic stainless steels

Development in Ferritic steels (History):



3.1 Development of ferritic boiler steels.

[3]

Chemical composition of Ferritic steels:

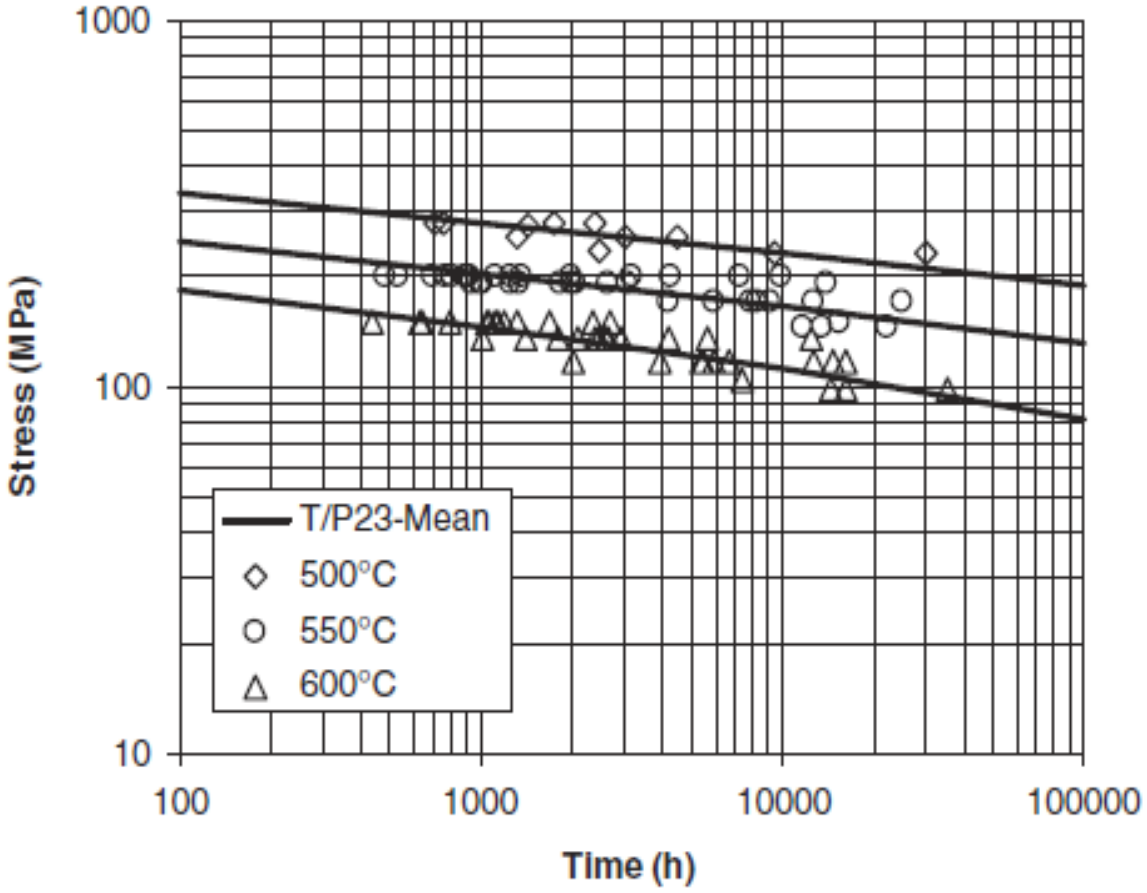
	T23	T24	P91	P92
C	0.04–0.10	0.05–0.10	0.1	0.1
Si	0.50 max	0.15–0.45	0.3	0.3
Mn	0.10–0.60	0.30–0.70	0.45	0.45
Cr	1.90–2.60	2.20–2.60	9	9
Ni	0.40 max	0.20 max	<0.2	<0.4
N	0.010 max	0.012 max	0.05	0.05
W	1.45–1.75			1.75
Nb	0.02–0.08		0.08	0.06
Ti		0.05–0.10		
B	0.0005–0.006	0.0015–0.007		0.003
Mo	0.05–0.30	0.90–1.10	1	0.45
V	0.20–0.30	0.20–0.30	0.2	0.2

- **Cr:** improves corrosion resistance, rupture ductility, and resistance against graphitization.
- **W, Mo**, **Nb :** improve solid solution strengthening
- **Nb, V, Ti:** beside C and N form carbides and carbonitrides contribute to the precipitation hardening.
- **B:** Addition of B and decrease of N can improve hardenability and creep strength during long-term.
- **Mo:** precipitation hardening due to formation of Laves phase and/or Mo_2C precipitates. (0.3-0.5% Mo with 0.15% C) → increase creep strength. At higher temperature, Mo_2C increases failure possibility in service. Instead of Mo-C composition, Mo-Cr is preferred for higher temperature.

[2]

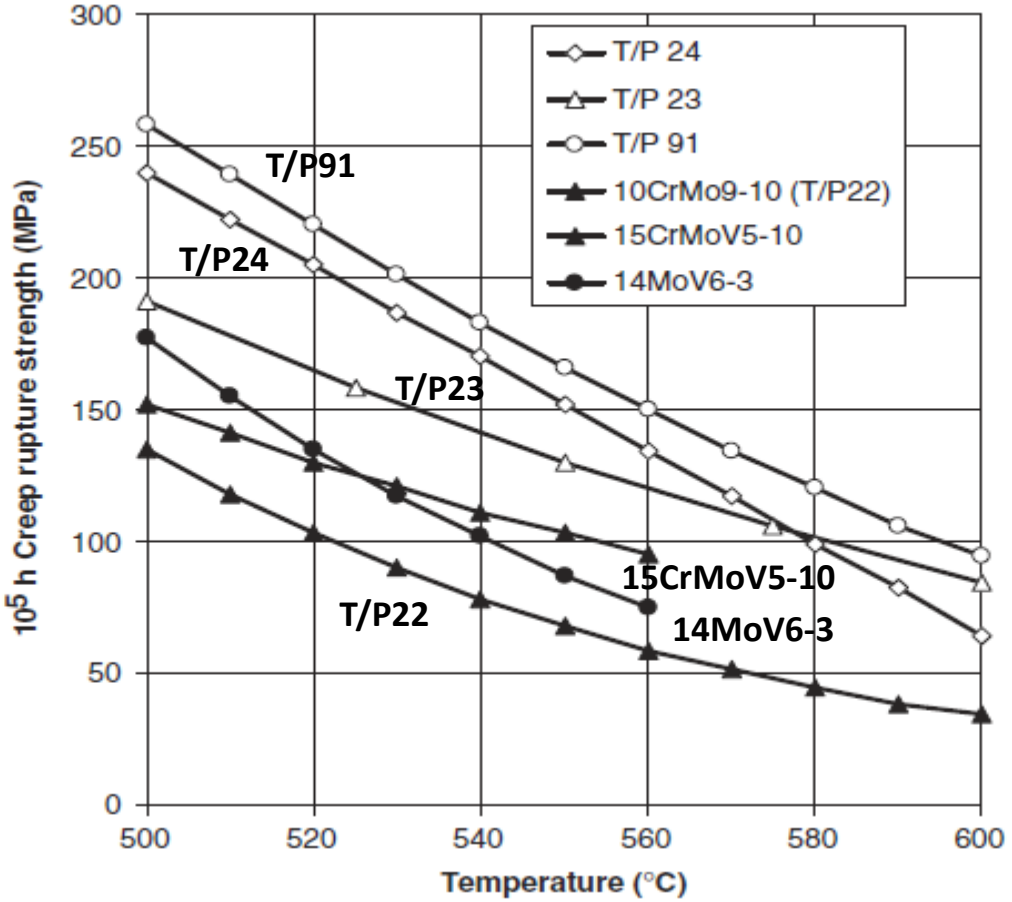
	Precipitate	Formula	Remark
P91	$M_{23}C_6$	$(Cr,Fe,Mo)_{23}C_6$	Precipitate during tempering
	MX	(Nb,V)(N,C)	Undissolved during austenitization
	MX	(V,Nb)(N,C)	Precipitate during tempering
	Laves phase	$(Fe,Cr)_2Mo$	Precipitate during creep (T < 650°C)
	Z-phase	[Cr(V,Nb)N]	Precipitate during creep

Creep rupture strength (Low alloy ferritic steels):



Vallourec & Mannesmann creep test results on T/P23

[4]



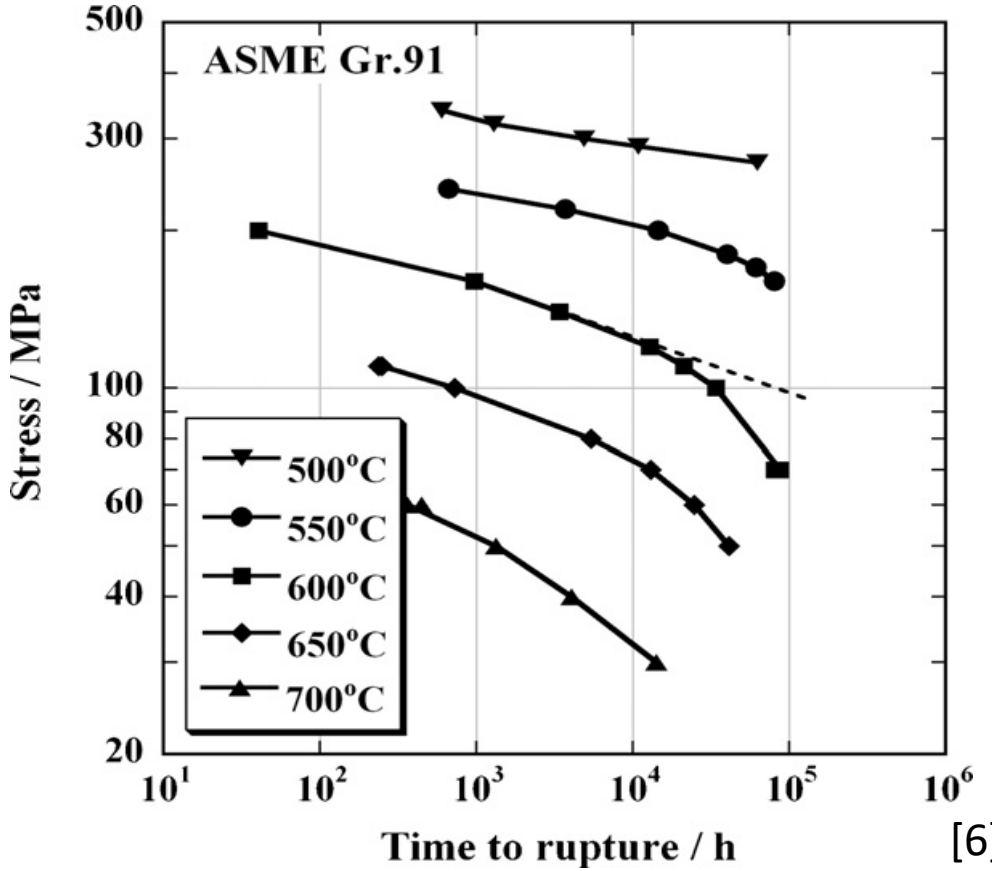
Creep rupture strength of heat resistant steel grades

[5]

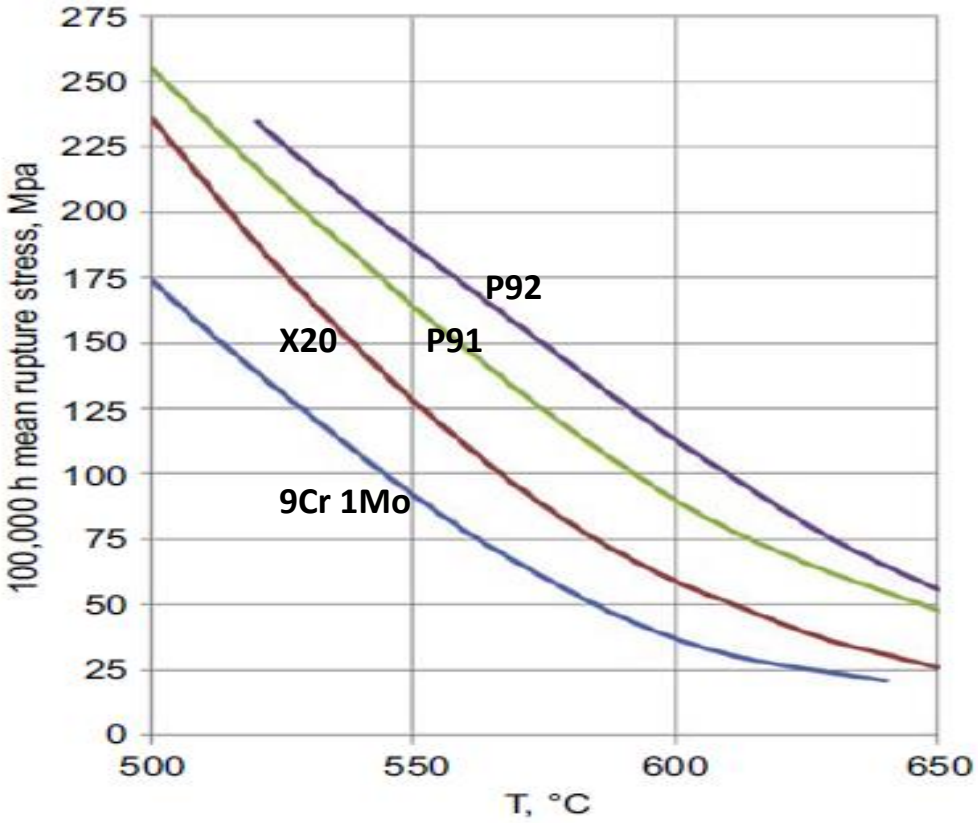
Creep rupture strength (Martensitic steels):

Ferritic Steels

At 500 °C and 550 °C, creep rupture time increases linearly with decrease of applied stress. Nevertheless, at higher temperature, the long-term creep life is shorter than the expected time due to the changes in microstructure indicated as premature failure.



[6]

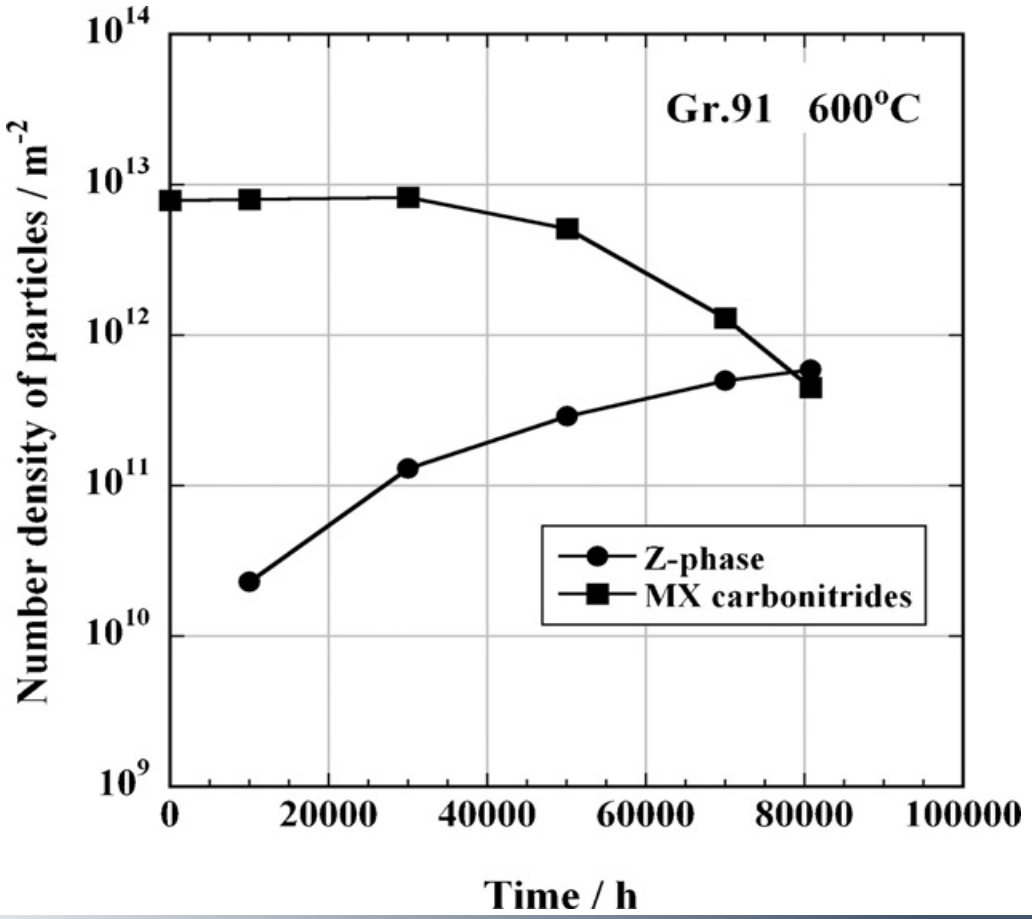


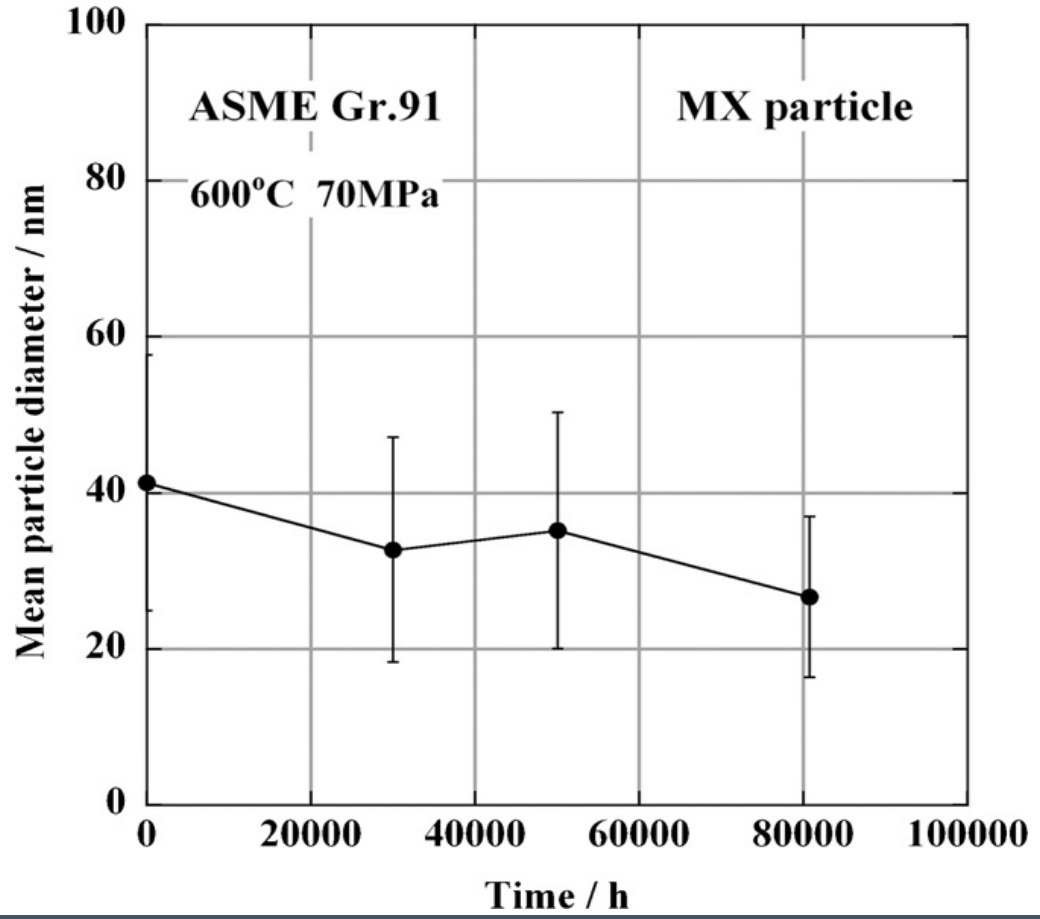
[2]

Currently, P92 is the best commercially steel used for USC power plants, which are operating up to 300 bar and 600°C

Microstructure:

The significant strengthening mechanism in P91 and P92 is precipitation hardening due to formation of precipitates after tempering or during creep. Sawada et al [6] reported formation of Z-phase after 30,000h service at 600°C under 70MPa. Z-phase and MX particles have similar constituent. Nevertheless, Z-phase is more stable than MX particles, thermodynamically. Consequently, MX particles dissolve during creep while Z-phases particles grow.



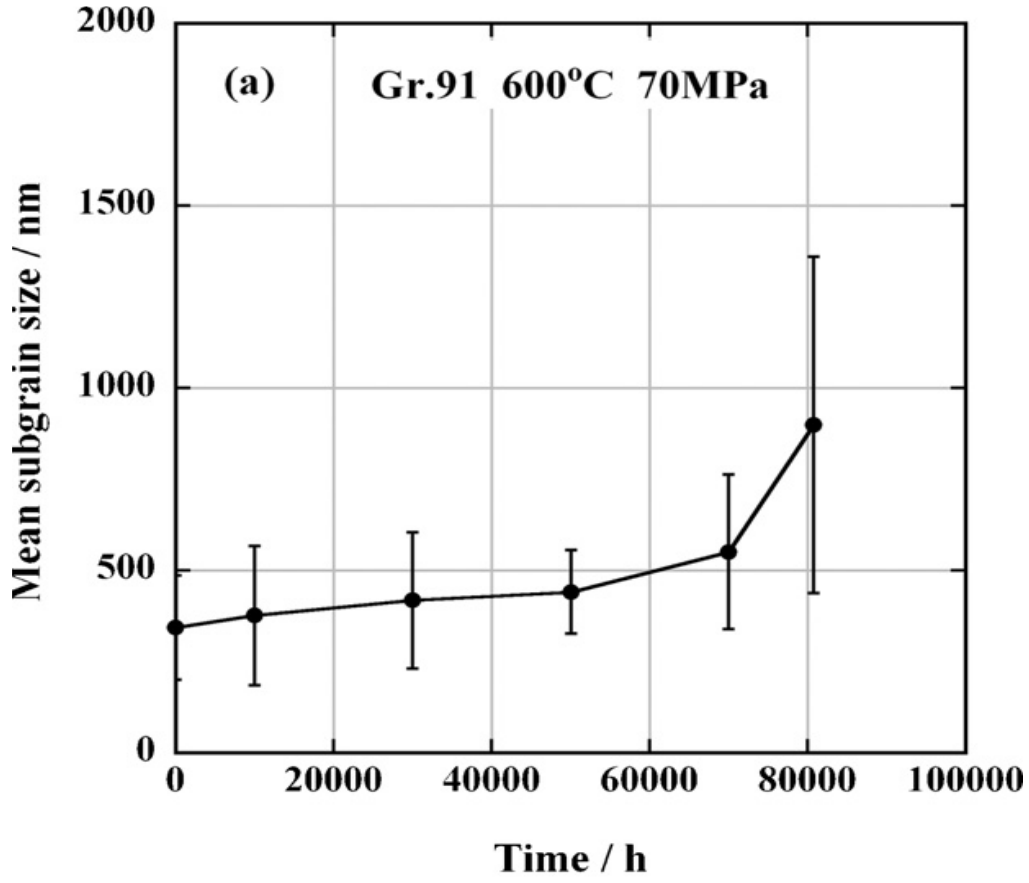


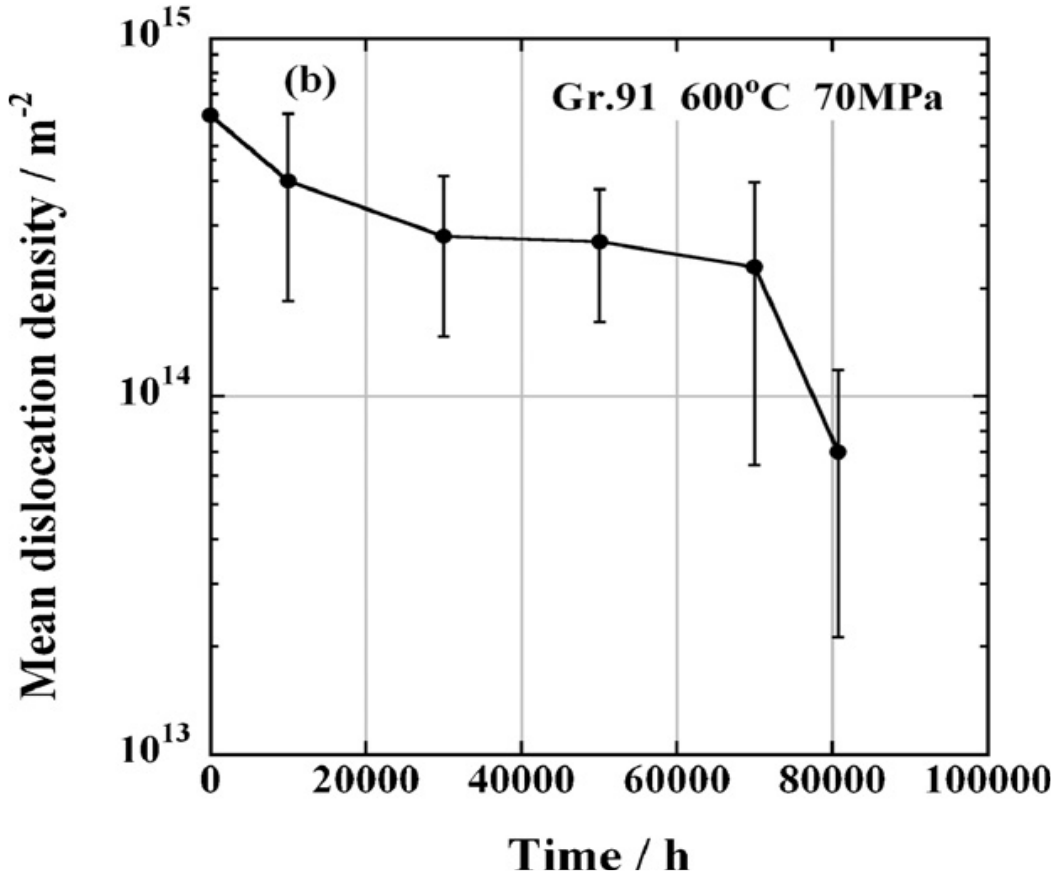
[6]

Microstructure:

Beside evolution and dissolution of different phases in the microstructure of Gr.91 steel, mean size of subgrains and dislocation density change during creep.

Dislocation density decreased drastically up to rupture after 70,000 h while the mean size of subgrains increases.

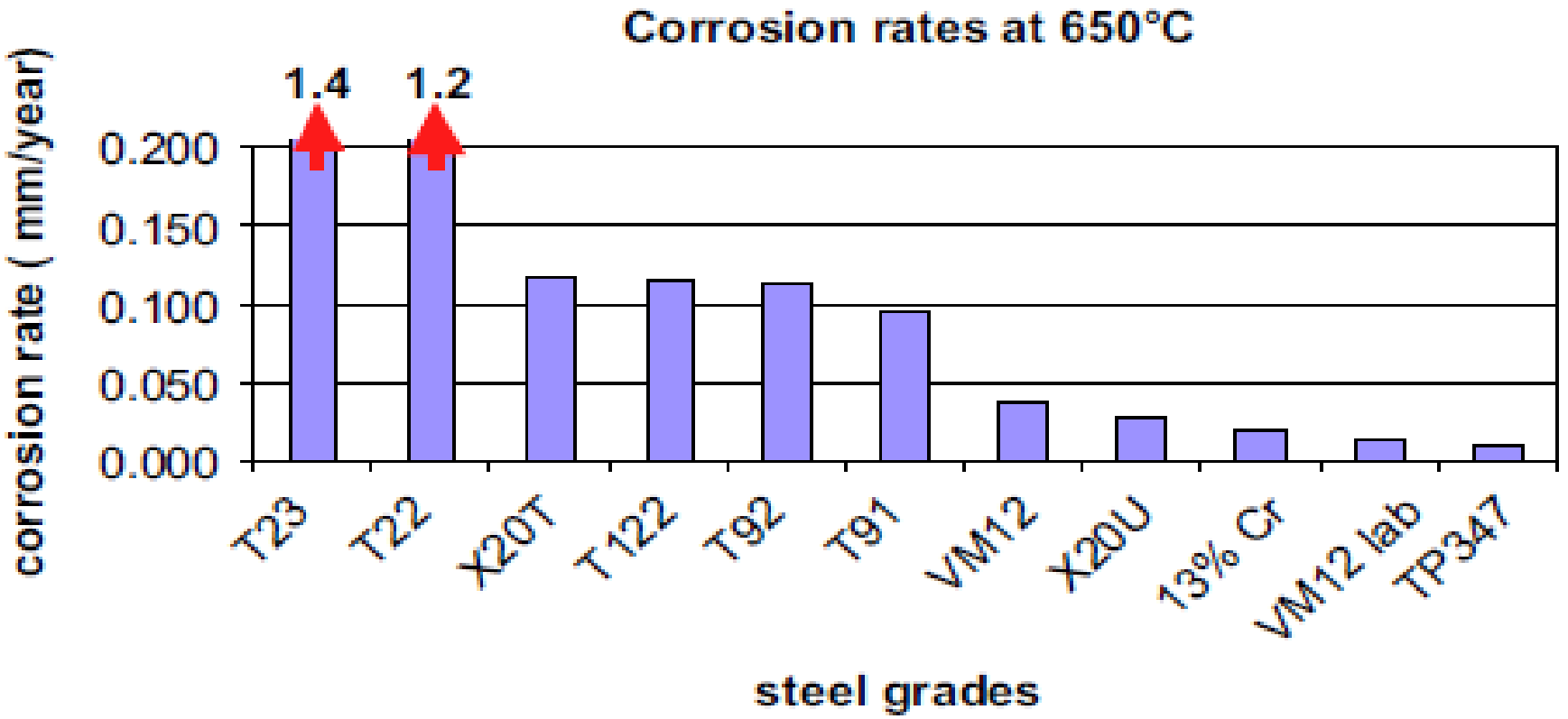




[6]

Corrosion:

Evolution of the corrosion rate in steam medium, extrapolated in mm per year, for various grades with different Cr content.



[4]

Austenitic stainless steels

Austenitic stainless steels:

- 300 austenitic stainless steels
- mainly contain (Fe–Cr–Ni alloys)
- low thermal conductivity and high thermal expansion coefficient
- used for superheater/reheater
- superior corrosion resistance and high temperature strength

Chemical composition of Austenitic steels:

	TP347HFG	Super 304H	TP310NbN (HR3C)	Sanicro 25
C	0.04-0.10	0.07-0.13	0.04-0.10	0.4-0.10
Si	0.75 max	0.3 max	0.75 max	0.4 max
Mn	2.00 max	1.0 max	2.0 max	0.6 max
P				0.03 max
S				0.015 max
Cr	17.0-20.0	17.0-19.0	24.0-26.0	21.5-23.5
Ni	9.0-13.0	7.5-10.5	17.0-23.0	23.5-26.6
N		0.05-0.12	0.15-0.30	0.15-0.3
W				2.0-4.0
Co				1.0-2.0
Cu		2.5-3.5		2.0-3.5
Nb	8× %C		0.20-0.60	0.30-0.60
Al		0.001-0.03		
B		0.001-0.01		

- **Nb:** Presence of Niobium in microstructure stabilize austenitic structure, inhibit intergranular corrosion by a strong carbide
- **Cu:** Copper can produce copper-rich nano particles improves creep resistance.
- **Ni, N:** Nickel and Nitrogen stabilise microstructure by suppressing formation of sigma phase facilitate fabricability.
- **Mn** and **N** can also persuade formation of austenite structure
- **Mn** degrade corrosion resistance
- **N** can improve high temperature creep resistance by formation of stable nitrides of transition metals
- **W, N, Co** and **Nb** improve solid solution strengthening
- **Nb, N, Cr**, and **Cu** are alloying elements contribute to the precipitation hardening.

[2]

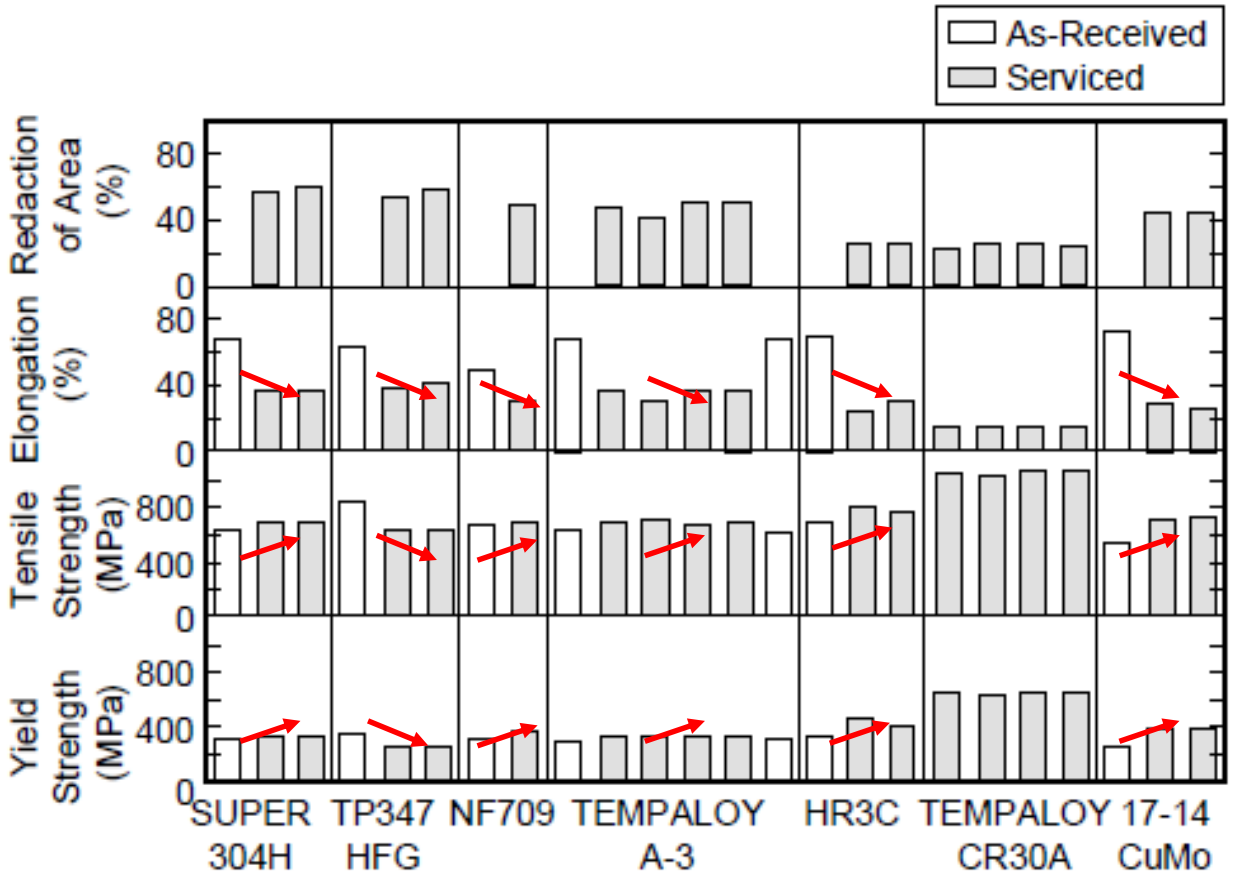
Phases:

High stability of microstructure is the main requirement for the steels working at high temperature for a long time.

- **Z-phases** (CrNbN) and **MX** (M = Nb; X = C, N) **$M_{23}C_6$ at grain** → improve creep strength
- **$M_{23}C_6$ at grain boundaries** → persuade intercrystalline corrosion
- **Cu-rich phases** leads to the high creep resistance at elevated temperatures
- **Laves phase** $(Fe, Cr)_2$ (Mo, W) , $(Fe, Cr)_2$ Nb. This phase cause creep instability in the steels because the solid solution strengthening effect from Mo and W will be lost, and the precipitation strengthening effect from Laves phase is not so significant.
- **Sigma phase** is intermetallic harmful phase containing Fe, Cr, Ni, Mo forming during creep condition. This phase can form within 1000 hours at 700 °C or within 50,000 hours at 650°C → This phase causes embrittlement of material at ambient temperature

Mechanical properties:

Tensile properties of TP347HFG with other austenitic steels before and after 75,075h service at 615°C under 35.1 MPa. As it is shown in this figure, yield and tensile strength of all the austenitic steels except TP347HFG increases while elongation in all cases decreases.

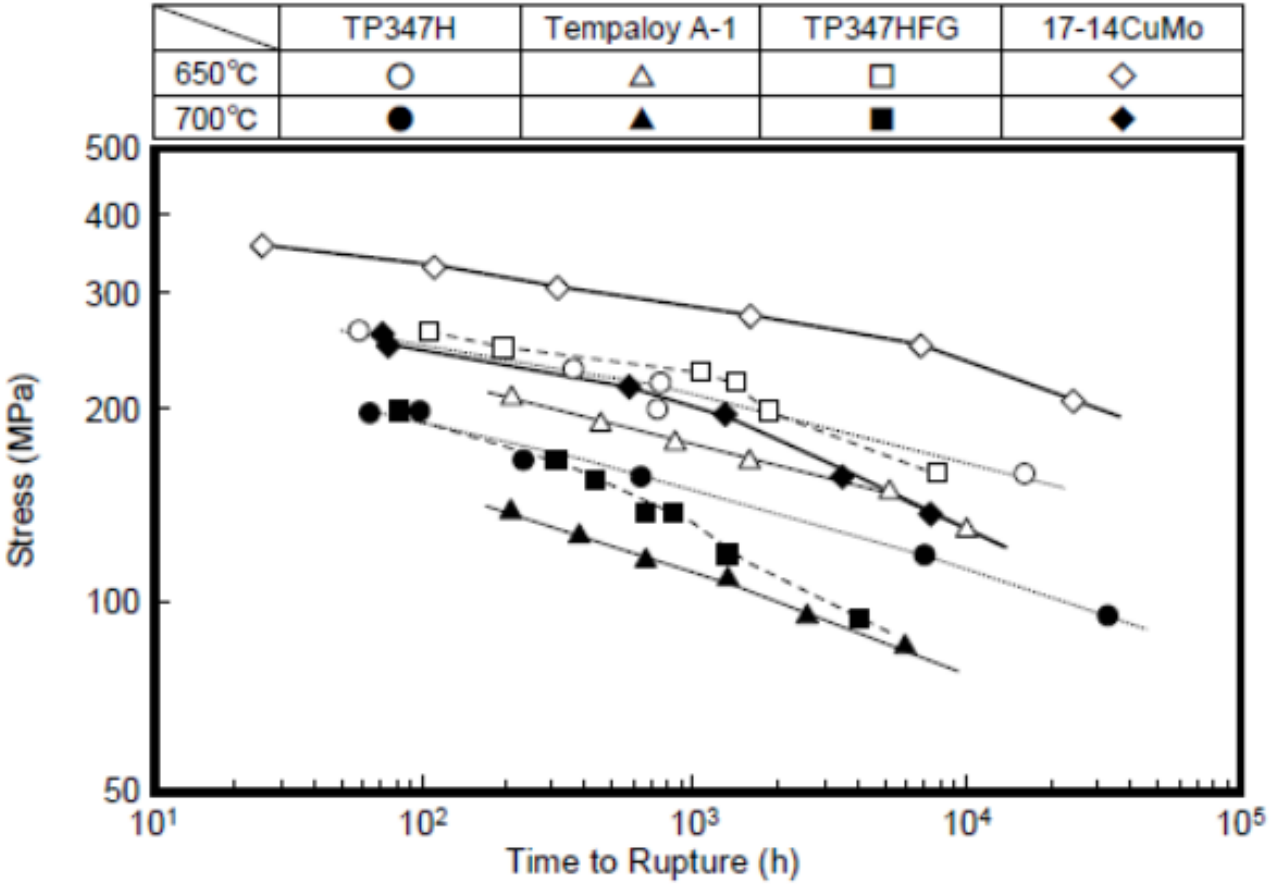


[7]

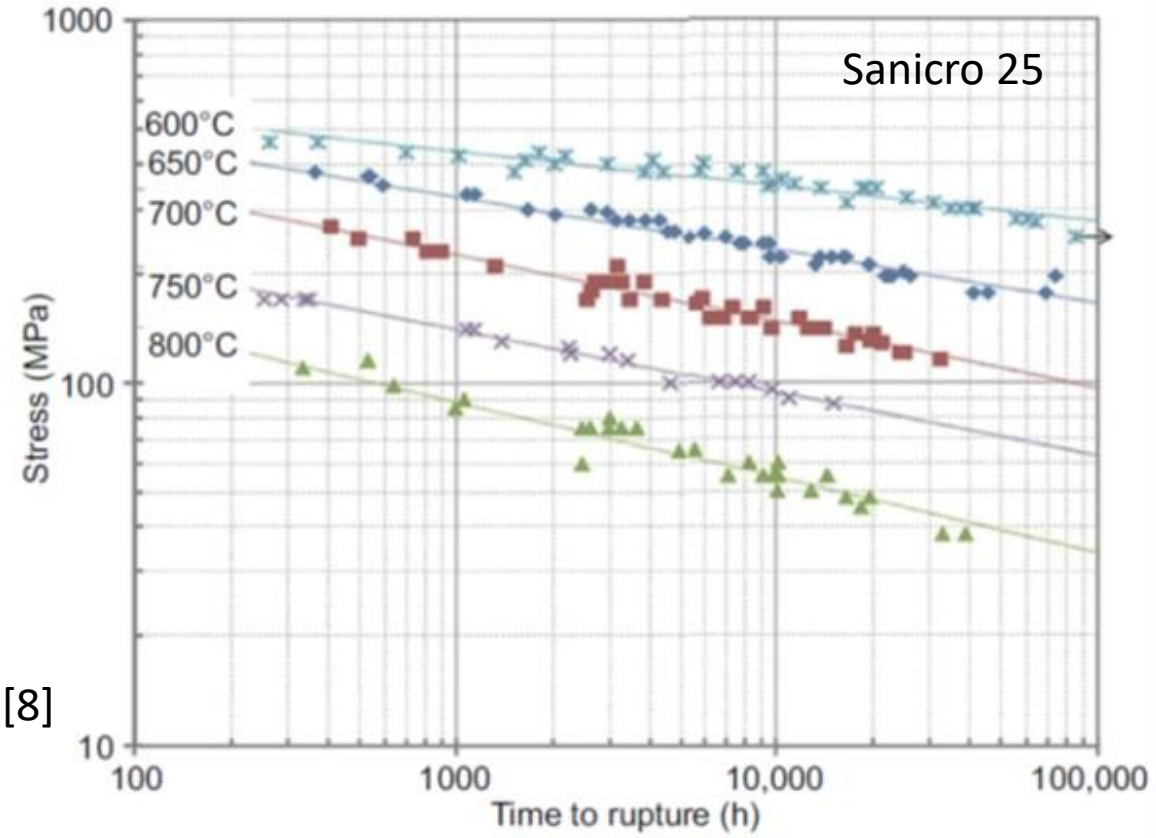
Creep rupture strength:

The applied stress of TP347HFG with TP347H, Tempaloy A-1 and 17-14CuMo in two different temperatures.

The applied stress versus rupture time of Sanicro 25 with no turn point. This means creep mechanism does not change with creep time and creep temperature between 600°C-800°C which shows structure stability of Sanicro 25.



[8]



[2]

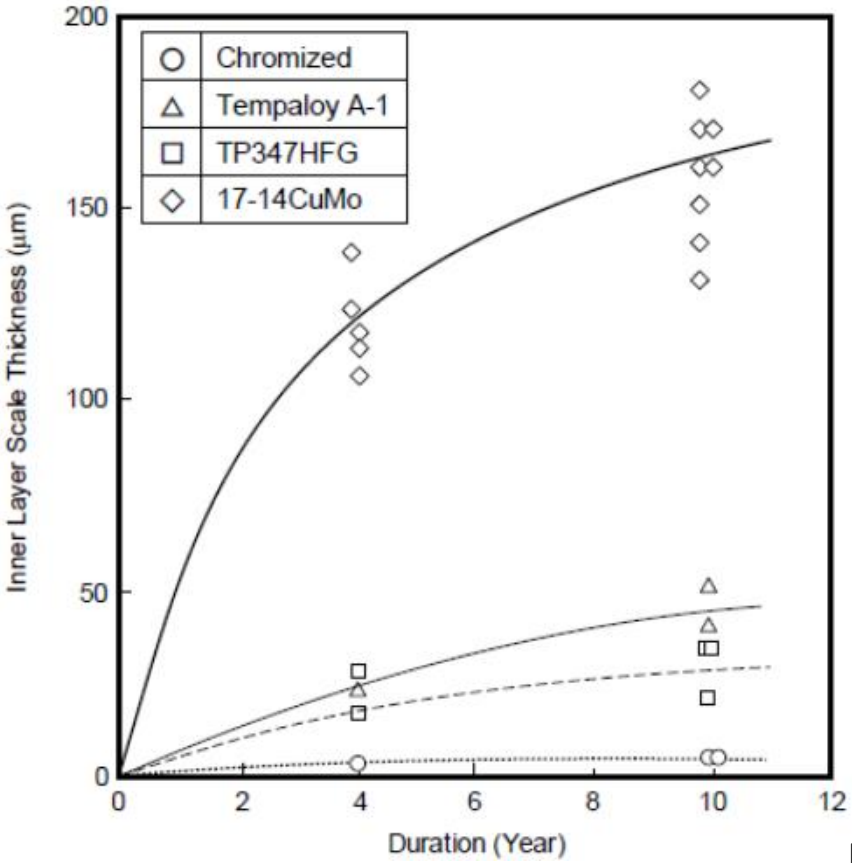
Corrosion/Oxidation behaviour:

Grain size effect:

Formation of a continuous oxide layer of Cr_2O_3 on the surface of the austenitic steels depends strongly on the diffusion of Cr at the grain boundaries. This means that in the fine grained TP347HFG, low concentration of Cr content (17.5 wt%) is enough to grow continuous Cr_2O_3 oxide scale. In contrary, in the coarse grains (~65 µm) austenitic steel, a higher amount of Cr (>17.5 wt%) is essential to form a continuous Cr_2O_3.

External stress:

Exertion of low stresses can accelerate migration of Cr to the surface which leads to formation of stable and dense Cr_2O_3 layer. The critical stress was reported 40 MPa. At higher stresses (> 40MPa) corrosion reactions become strong.



[8]

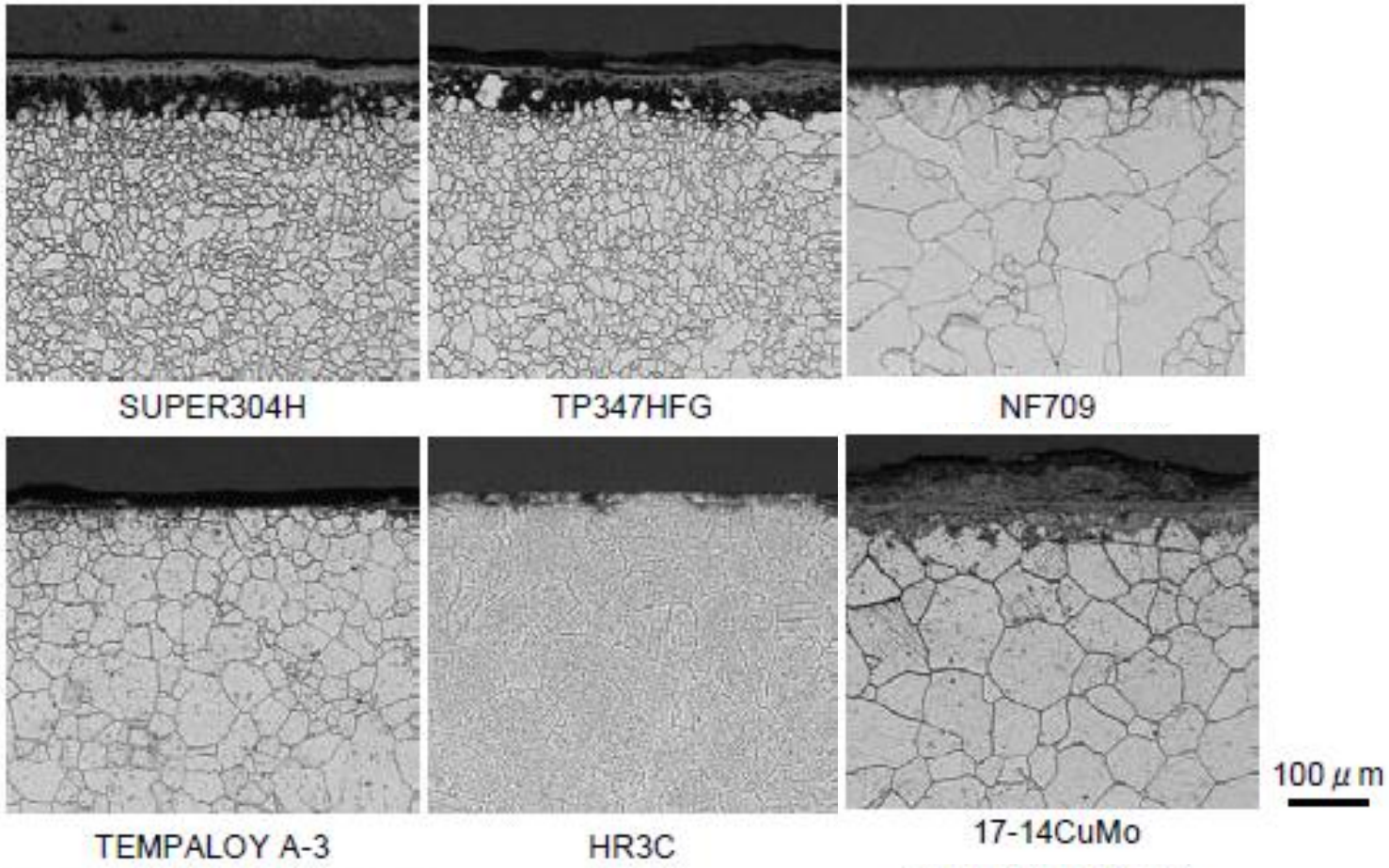
Growth of steam oxidation scale

growth of oxide scale of four austenitic steels at 632°C, by using parabolic law described in $d^2 = K_p t$

Chromized layer on TP347H:	2.00×10^{-15} cm^2 s^{-1}	Tempaloy A-1:	8.89×10^{-14} cm^2 s^{-1}
TP347HFG:	3.47×10^{-14} cm^2 s^{-1}	17-14CuMo:	1.42×10^{-12} cm^2 s^{-1}

Microstructure:

microstructures of the outer surfaces on the flame side of some austenitic steels



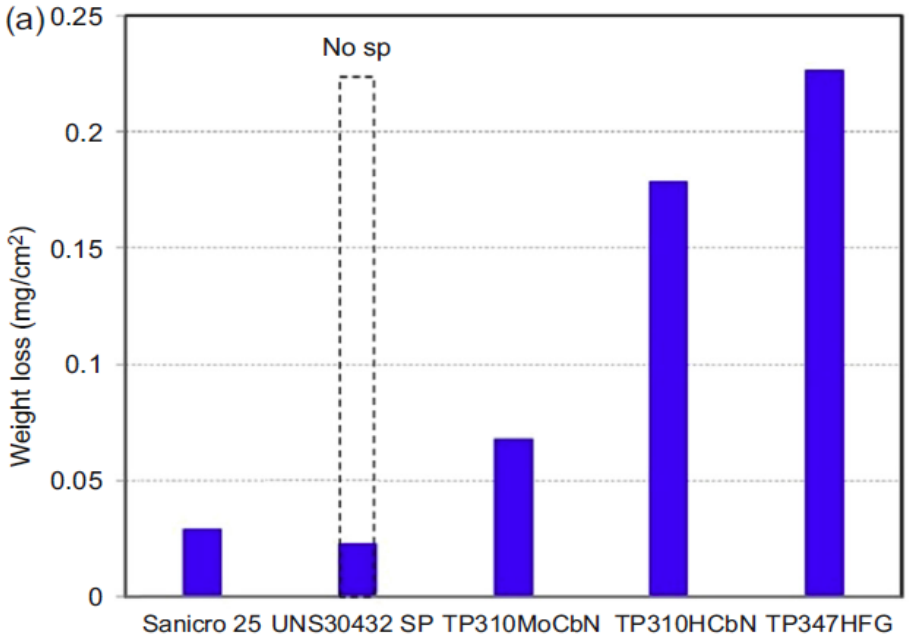
[7]

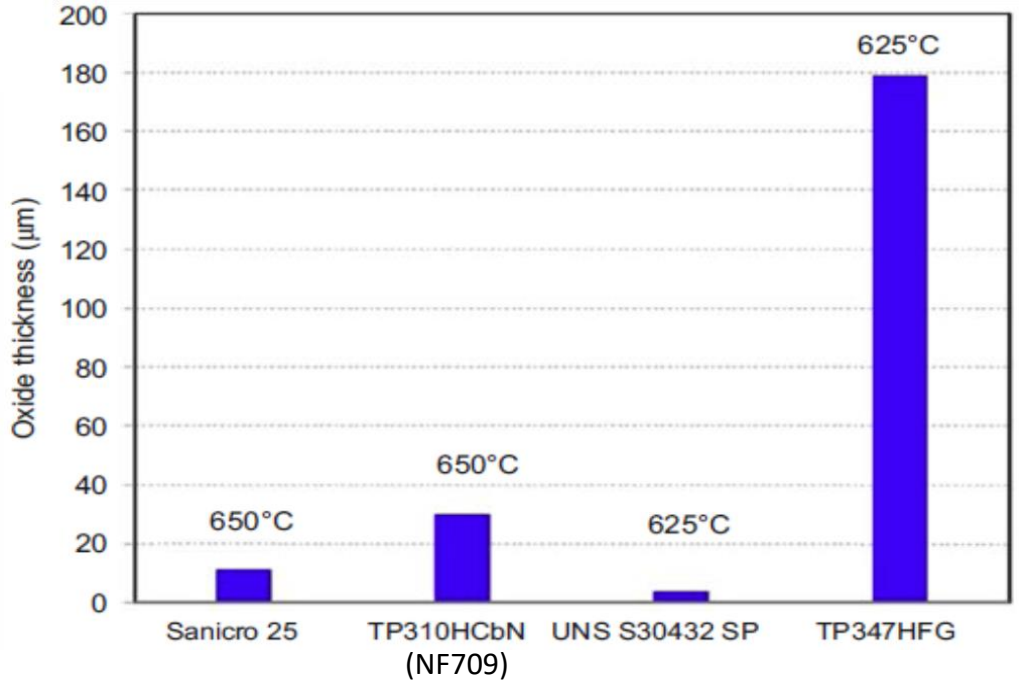
Corrosion/Oxidation behaviour

Austenitic Steels

Steam oxidation resistance of austenitic stainless steels after 1000 h at 700°C. Alloy Super304H has superior corrosion resistance among other austenitic steels. The corrosion resistance of Super304H can be enhanced after shot-peening.

Growth of oxide layer on the surface of some austenitic steels in steam at 650°C and 625°C after 10.000 h which confirms formation of the best protective oxide layer on the surface of Super304H



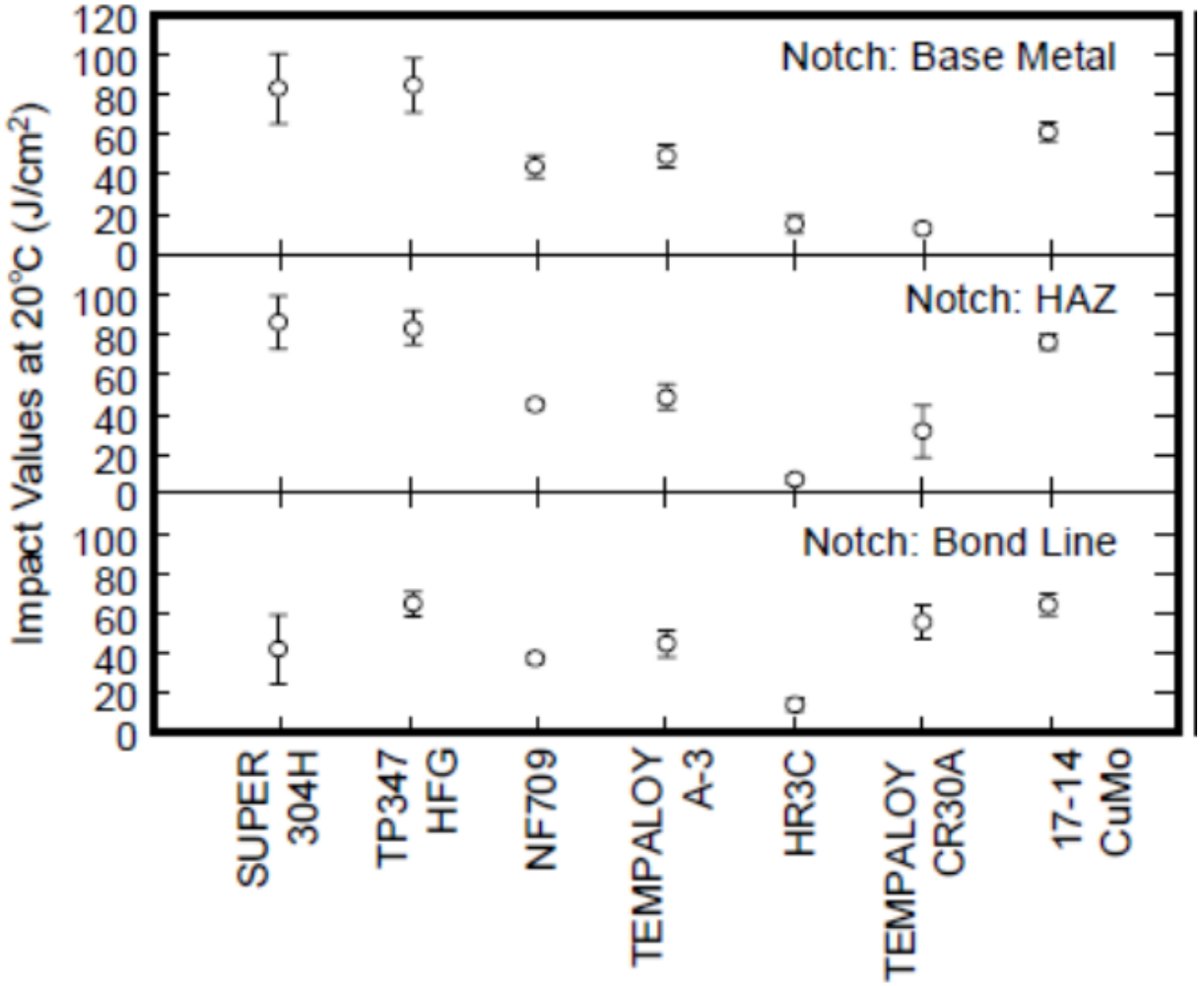


[2]

The Super304H is susceptible to the intergranular corrosion due to the unqualified match of **C** and **Nb** or the **inappropriate heat treatment**.

Welding:

The result of the Charpy impact tests with notches located in the base metal, HAZ and weld metal at 20°C. TP347HFG shows an acceptable impact values in different locations, although HR3C represent poor impact properties.



[7]

Superalloys

Alloy IN617B: (or 617mod), (N06617)

Alloys 617, which were introduced in the 1960s, were developed for aircraft engines but have found wide use in other applications requiring high-temperature strength and corrosion resistance. This alloy contains ≈ 55% nickel which shows good corrosion and creep resistance at high temperature.

Alloy Nimonic 263: (Nimonic 263 (UNS N07263/W.Nr. 2.4650/AMS5886)

For the first time, Nimonic 263 (UNS N07263/W.Nr. 2.4650/AMS5886) is developed by Rolls-Royce Ltd in 1971. This alloy is widely used in in several components of aircraft engines such as blades with operating temperature higher than 900°C, under 35 bar stress for a short time.

This alloy is also used in A-USC power plants at 750°C with applied stress of 350 bar (350 kg/cm^2) for a very long time. Alloy 263 has combination of

- very good strength at high-temperature, excellent weldability, formability, ductility.

Alloy Inconel 740H:

INCONEL 740H is suggested for use in Advanced Ultra-supercritical (A-USC) boiler tubes to provide boiler higher efficiency more than 50% at higher service temperature (700°C-760°C) and up to 35 MPa pressure.

The alloy was originally presented for use in the superheater sections of A-USC boiler tubes but it was then utilized for application as steam header components. Some of the Special properties of Inconel 740H are,

- High strength, Creep resistance at elevated temperature, Resistance to the ash corrosion, Good thermal stability

Alloy Haynes 282:

Haynes® Alloy 282 is an age-hardenable nickel based superalloy developed for high temperature applications, especially in aero and industrial gas turbine engines. This alloy has a unique

- Creep strength (excellent creep strength between 650-927°C higher than Waspaloy and close to R-41 alloy) ,
- Thermal stability, Forgeability, Fabricability , easier to weld than other γ’ alloys of similar strength.

Consequently, this alloy is preferred for A-USC applications which can operate below the γ’-solvus temperature of 997°C.

Chemical composition: [2]

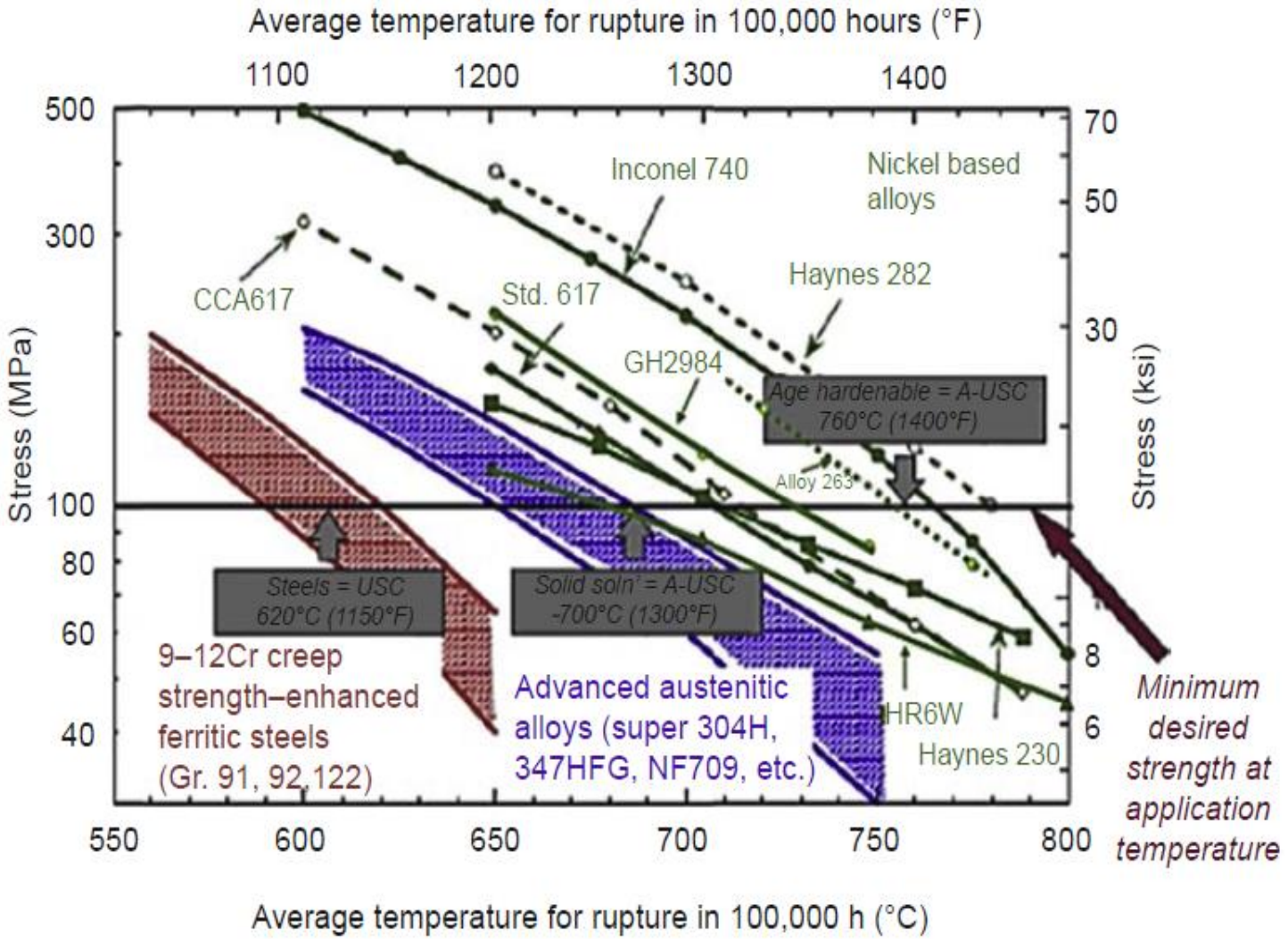
	Alloy 617B	Nimonic 263	Inconel 740H	HAYNES 282
Ni	Balance	Balance	Balance	57
Cr	21–23	19.0–21.0	24.5	20
Co	11–13	19.0–21.0	20	10
Mo	8–10	5.6–6.1	0.5	8.5
Ti	0.25–0.5	1.9–2.4 *	1.35	2.1
Al	0.8–1.3	<0.60 *	1.35	1.5
B	0.001–0.005	<0.005	0.002	0.005
Fe	≤ 1.5	<0.7	0.7	<1.5
Mn	< 0.5	<0.60	0.3	<0.3
Si	< 0.3	<0.40	0.15	<0.15
C	0.05–0.08	0.04–0.08	0.03	0.06
P	< 0.012		<0.002	
Cu	-	<0.20	<0.1	
S	< 0.008	<0.007	<0.002	
V	≤ 0.6			
Nb	≤ 0.6		1.5	
Ag	-	<0.0005		
Bi	-	<0.0001		
Pb		<0.0020		

*Al+Ti=(2.4–2.8)

- **Cr:** High amount of chromium content provides oxidation resistance by forming chromium oxide on the surface and form different carbides at grain boundaries, which prevent abnormal grain growth.
- **Co:** Addition of 10% Co helps to control the γ' solvus.
- **Mo:** Presence of higher amount of the Molybdenum can provide excellent creep strength, especially at higher temperature.
- **Nb, C, Mo, W, Ti, Cr, Al, Fe, Co:** Solid solution strengthening elements
- **Al, Ti:** The elements Al and Ti persuade formation of γ' phase.
- **V, Nb:** Addition of vanadium and/or niobium can persuade precipitation of fine carbides, which improves ductility. Additions of niobium and/or vanadium to the Alloy 617B is labelled Alloy 617occ (optimized chemical composition).
- **B:** Boron has a positive effect on the ductility of superalloys and decreases sensitivity to stress relaxation cracking. Recent research indicates segregation of boron at the matrix/carbide interface.
- **Mn, Si:** Mn and Si can enhance castability and oxidation resistance.

Creep strength

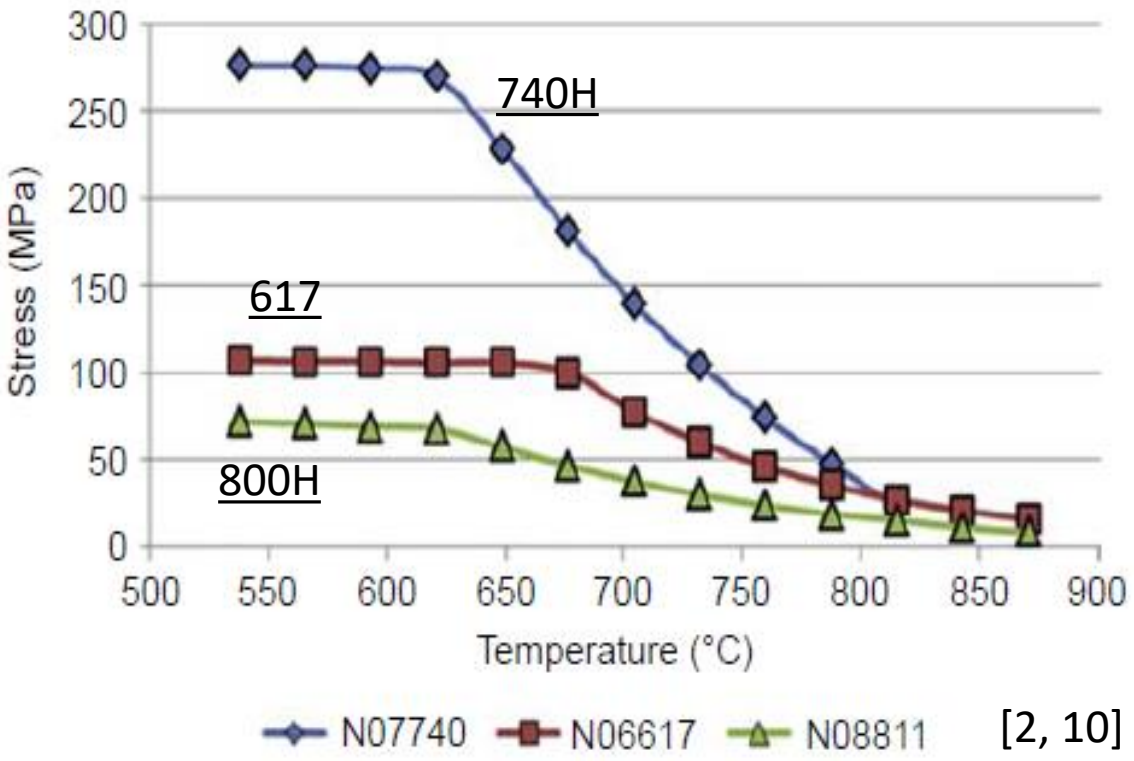
Rupture strength of some conventional alloys used in power plants after 100,000 hours service.



[9]

Creep strength

The maximum allowable stress values for alloys 740H, 617, and 800H is compared. INCONEL 740H demonstrates a significant strength advantage among the other alloy at temperatures below 800°C. Above this temperature, alloy 740H loses its strength due to the γ' coarsening and decreasing the volume fraction. The content of γ' at 800°C is less than 10%, although the expected γ' solvus is 973°C.



[2, 10]

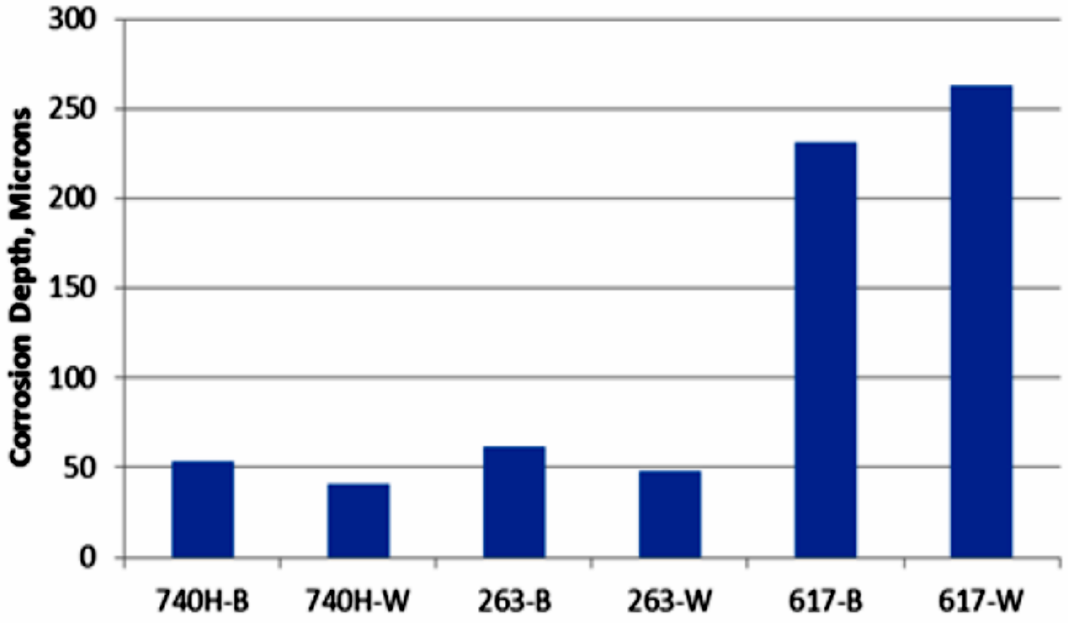
J. P. Shingledecker [11] suggested stress rupture fitting equation for 740H between 650°C-850°C as,

$$\log(t_r) = -C + \frac{A_1}{T} + \frac{A_2 \log(\sigma)}{T} + \frac{A_3 \log(\sigma)^2}{T} + \frac{A_4 \log(\sigma)^3}{T}$$

Where
C=19.392,
A1=23360,
A2=5532,
A3=-2065,
A4=-102.7

Corrosion / Fire side

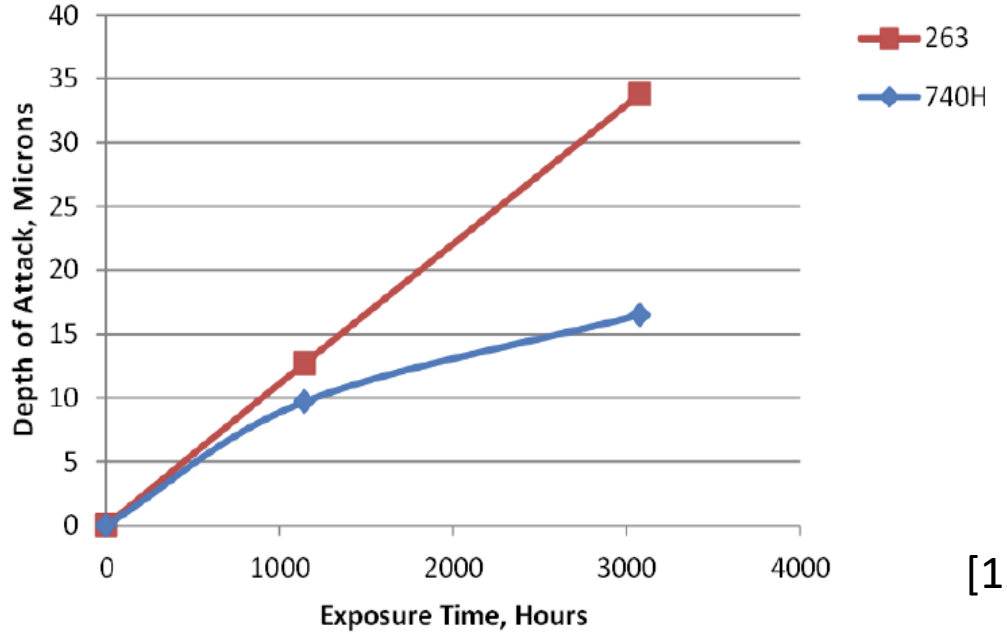
Depth of corrosion attack between INCONEL 740H, NIMONIC 263 and INCONEL 617 at 750°C after 1000 hours is compared where base metal is denoted with "B" and weld metal denoted with "W". In this experiment, the synthetic flue gas composition of 15 Vol. % CO_2 + 5.0% Vol. % H_2O -3.5 Vol. % O_2 + 0.1 Vol. % SO_2 + Bal. N_2 is used. The synthetic coal ash composition containing of 6% Fe_2O_3-29% $CaSO_4$-1.9% Na_2SO_4-1.9% K_2SO_4-39% SiO_2-22% Al_2O_3-0.05% KCl-0.05% NaCl.



Corrosion / Steam side

Superalloys

Oxidation depth result of INCONEL 740H and NIMONIC 263 in air +10% water vapour at 800°C after 3077 hours are compared. (Specimens were cooled down to the room temperature once per week).



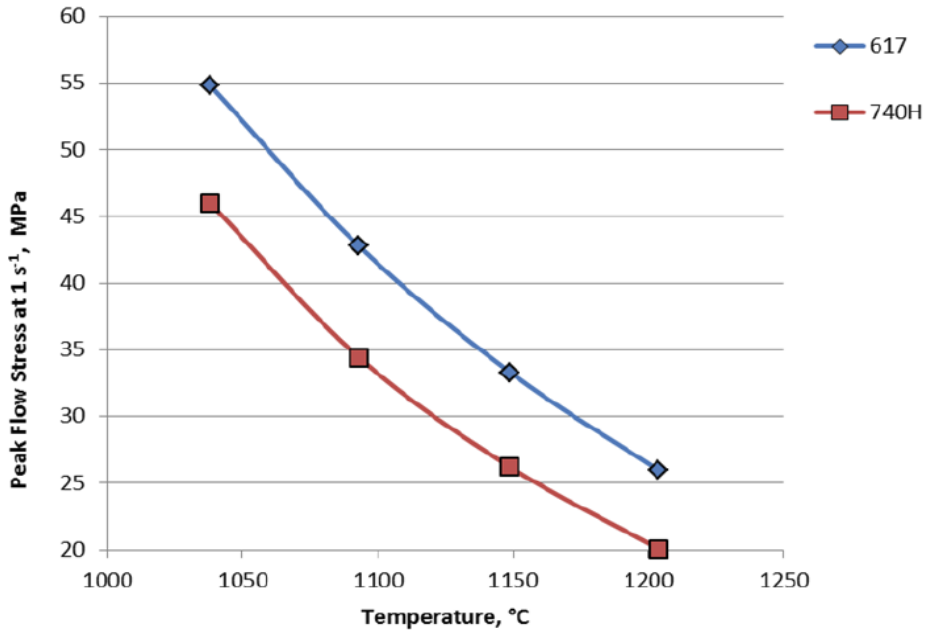
[12]

Alloy Inconel 740H:

Process/Deformation

The suggested temperature for hot forming (forging or hot rolling) is between 870°C-1190°C.

The required compressive flow stress of INCONEL 617 is approximately 30% higher than INCONEL 740H.



Ratio of peak compressive stress for INCONEL alloy 617 and INCONEL alloy 740H as a function of temperature.

[12]

Welding

High-strength γ’ alloys suffer from three different forms of weld cracking,

(a) strain-age cracking,

(b) weld solidification cracking, and

(c) heat-affected zone (HAZ) liquation cracking.

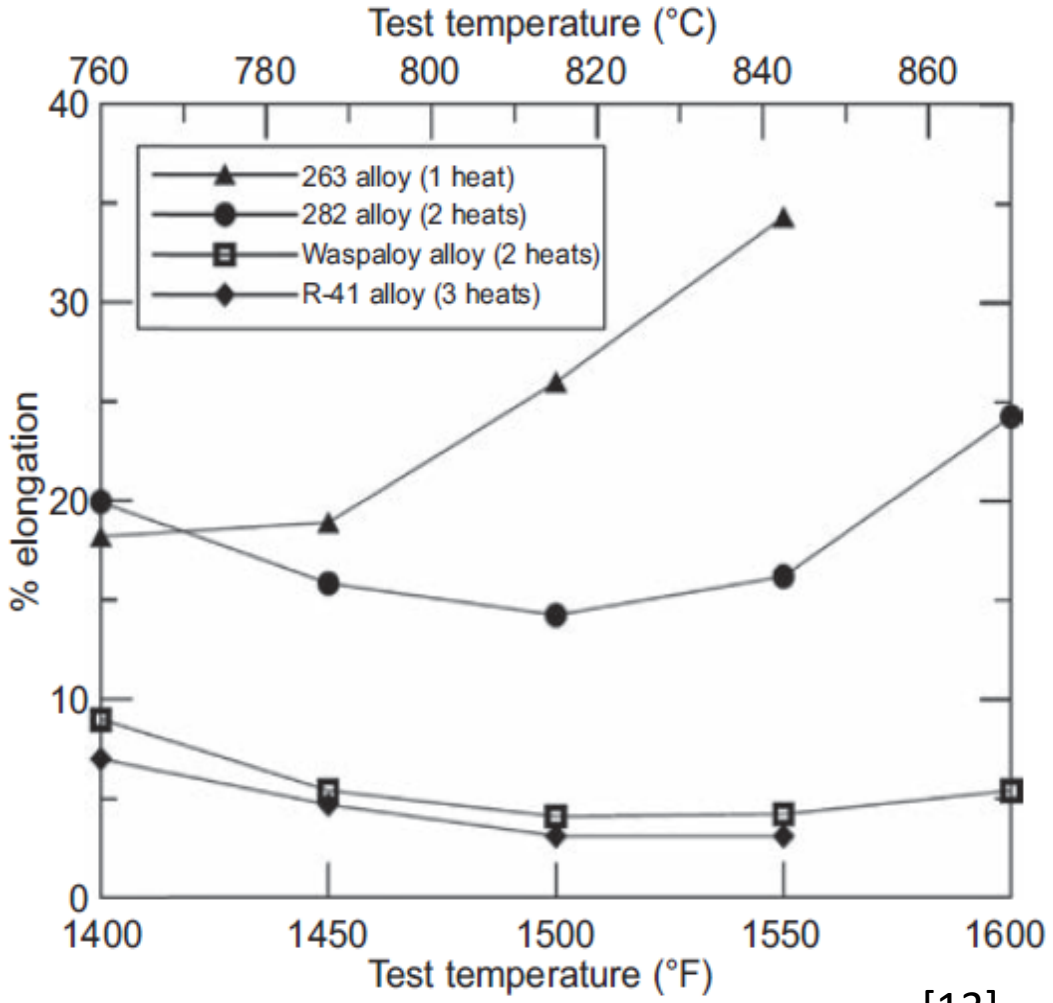
These properties define weldability of alloys.

Welding:

(a) Strain-age cracking

Strain-age cracking forms during heat treatment of industrial components tolerate residual stresses. In the case of Superalloys, formation of γ′ precipitates coupled with solidification shrinkage can stimulate formation of these cracks. Formation of these cracks typically occurs during heat up in the first post-weld heat treatment (e.g. post-weld solution annealing). Consequently, alloys with delay in precipitation kinetics (such as NIMONIC 263 and HAYNES 282) shows higher resistance to strain-age cracking.

The controlled heating rate tests (CHRT) is an effective method applied for evaluations of strain-age cracking of superalloys. Result of CHRT performed by Gleeble on the NIMONIC 263, HAYNES 282, Waspaloy and R-41 are demonstrated. This figure expresses lower susceptibility of HAYNES 282 to strain-age cracking than Waspaloy or R-41 alloys, while NIMONIC 263 shows even higher ductility.

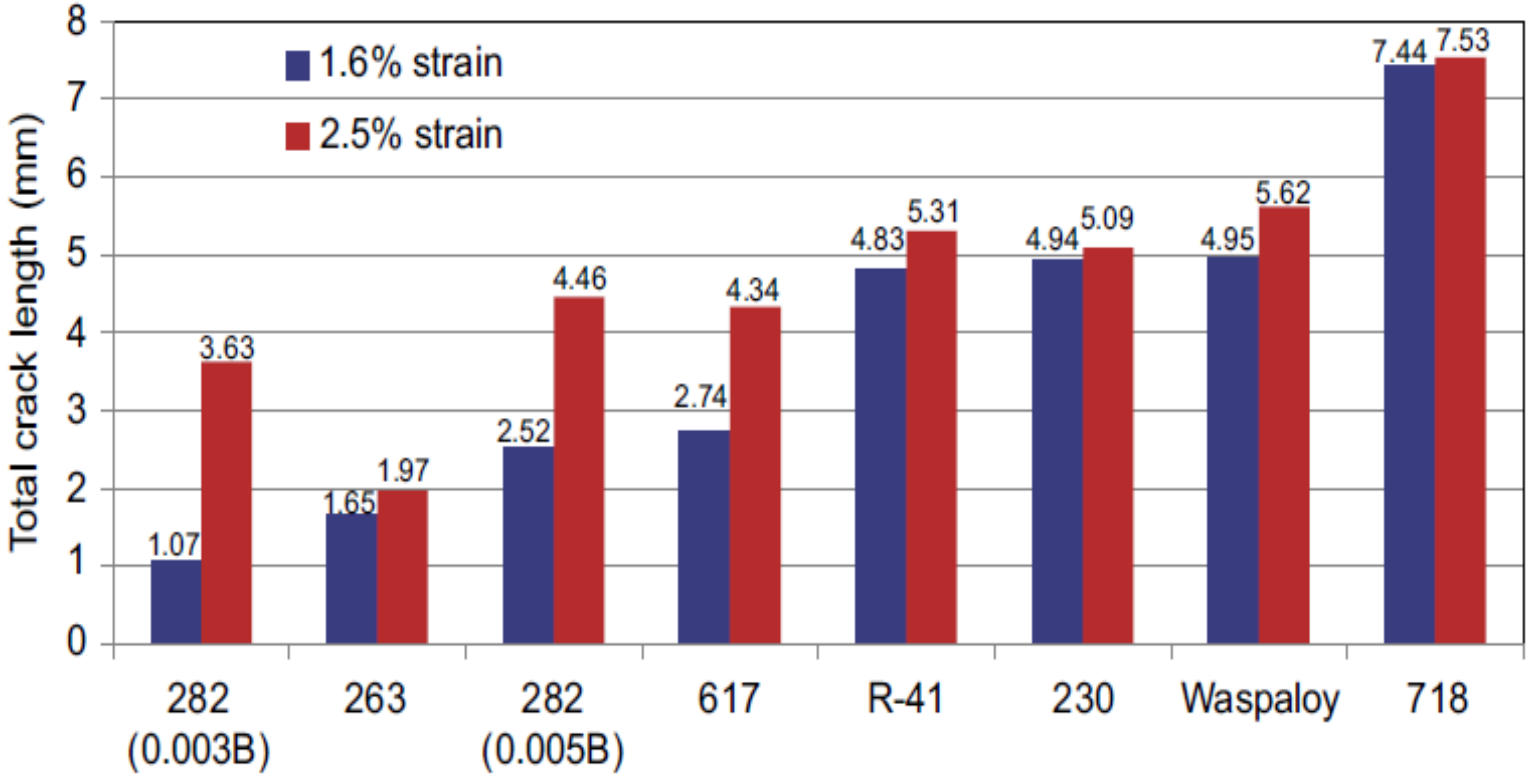


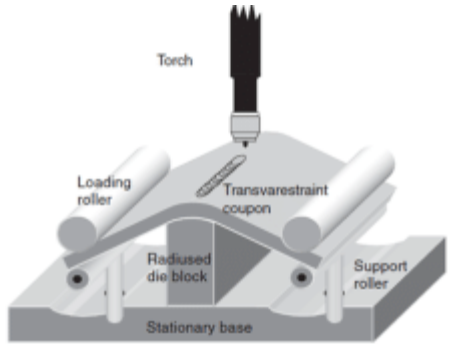
[13]

Welding:

(b) Weld solidification cracking

For evaluation of weld solidification cracking, the Variable Restraint (Varestraint) weldability test is applied by Caron. In this test, an autogenous GTAW weld bead is performed on a sample while a bending strain persuades cracking in the partially solidified metal at the rearward edge of the weld pool. The result of Varestraint tests between HAYNES 282 and other superalloys (regardless of boron content HAYNES 282) exhibits excellent resistance to the solidification cracking.





[14]

Welding:

(c) Heat-affected zone (HAZ) liquation cracking

Andersson et al. introduced “brittle temperature range” (BTR) term which is difference between the nil strength temperature (NST) due to the liquation on heating and ductility recovery temperature. Caron performed NST evaluations test by Gleeble to define “liquation cracking temperature range” (LCTR) and NST of HAYNES 282. Afterwards, he reported LCTR ~ 90°C and an NST ~ 1321°C (from an average of three samples). He reported similar data for Waspaloy (LCTR ~ 209°C) and 718 (LCTR ~ 103°C). Consequently, 282 alloy has better HAZ liquation cracking resistance than these alloys [2].

Heat Treatment : (Alloy Haynes 282)

The two-step age heat treatment contains three stages,

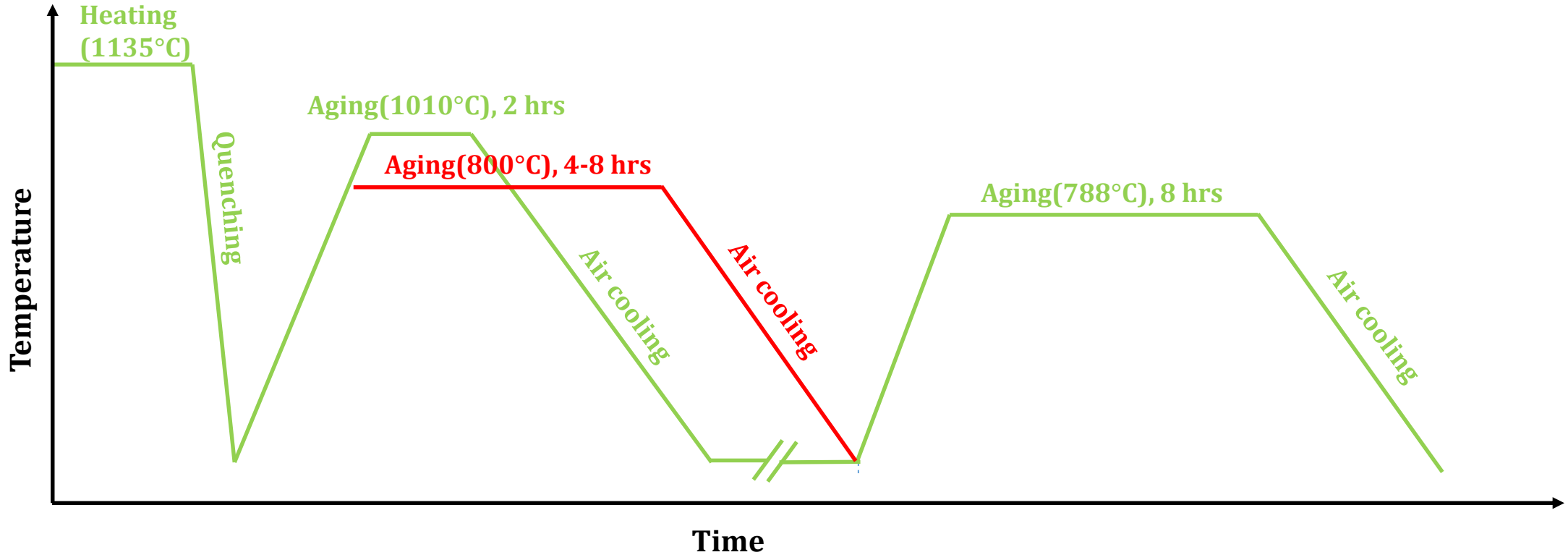
a) solution annealing at 1135°C continued by WQ
b) aging at 1010°C for 2 hours then continued by AC
c) aging at 788°C for 8 hours followed by AC.

Benefit of the Two-step aging is high-temperature ductility.

The single-step age suggested by Tortorelli et al. [15] in 2013. This heat treatment contains two stages

a) S. A. at 1135°C, continued by WQ
b) ageing at 800°C for 4-8 h continued by air cooling AC

The single-step age can generate an adequate γ' precipitate to strengthen the alloy.



Heat Treatment : (Alloy Haynes 282)

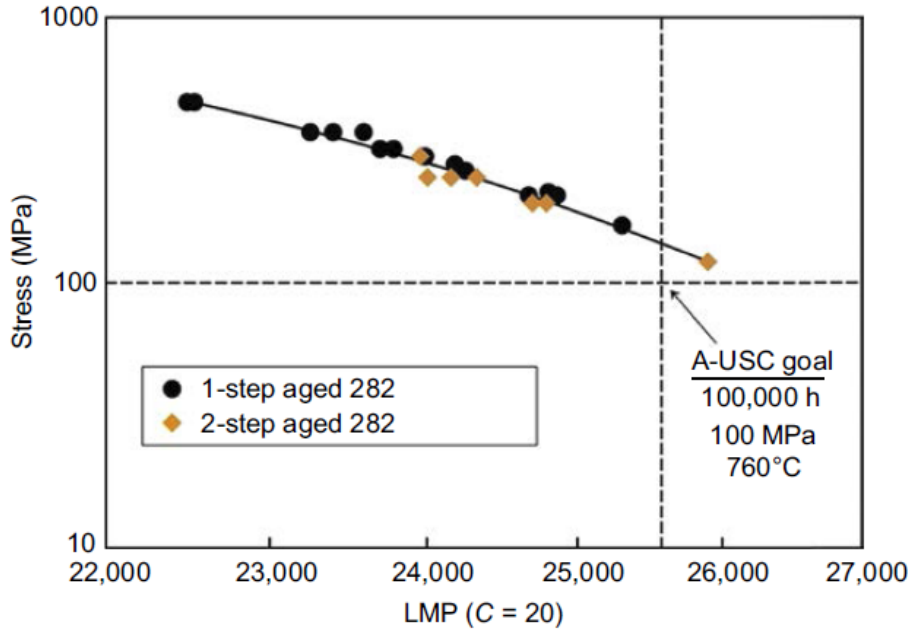
Comparison of tensile strength of single-step aged tensile properties for HAYNES 282 alloy with two-step aged values

Test temperature	Age-hardening treatment	0.2% YS MPa	UTS MPa	Elong %	R.A. %
Room temperature	Two-step age*	706	1152	29.9	33.1
	Single-step age**	741	1183	31.3	35.4
760°C	Two-step age	632	866	21.1	22.6
	Single-step age	658	857	18.3	18.3

*Two-step age = 1010°C /2 h/Air Cool (AC) + 788°C (1450°F)/8 h/AC.
**Single-step age = 800°C /8 h/AC

The similar creep strength of the single-step versus two-step aged treatment of HAYNES 282 after 100,000 h creep at the service temperatures of A-USC is demonstrated

[15]

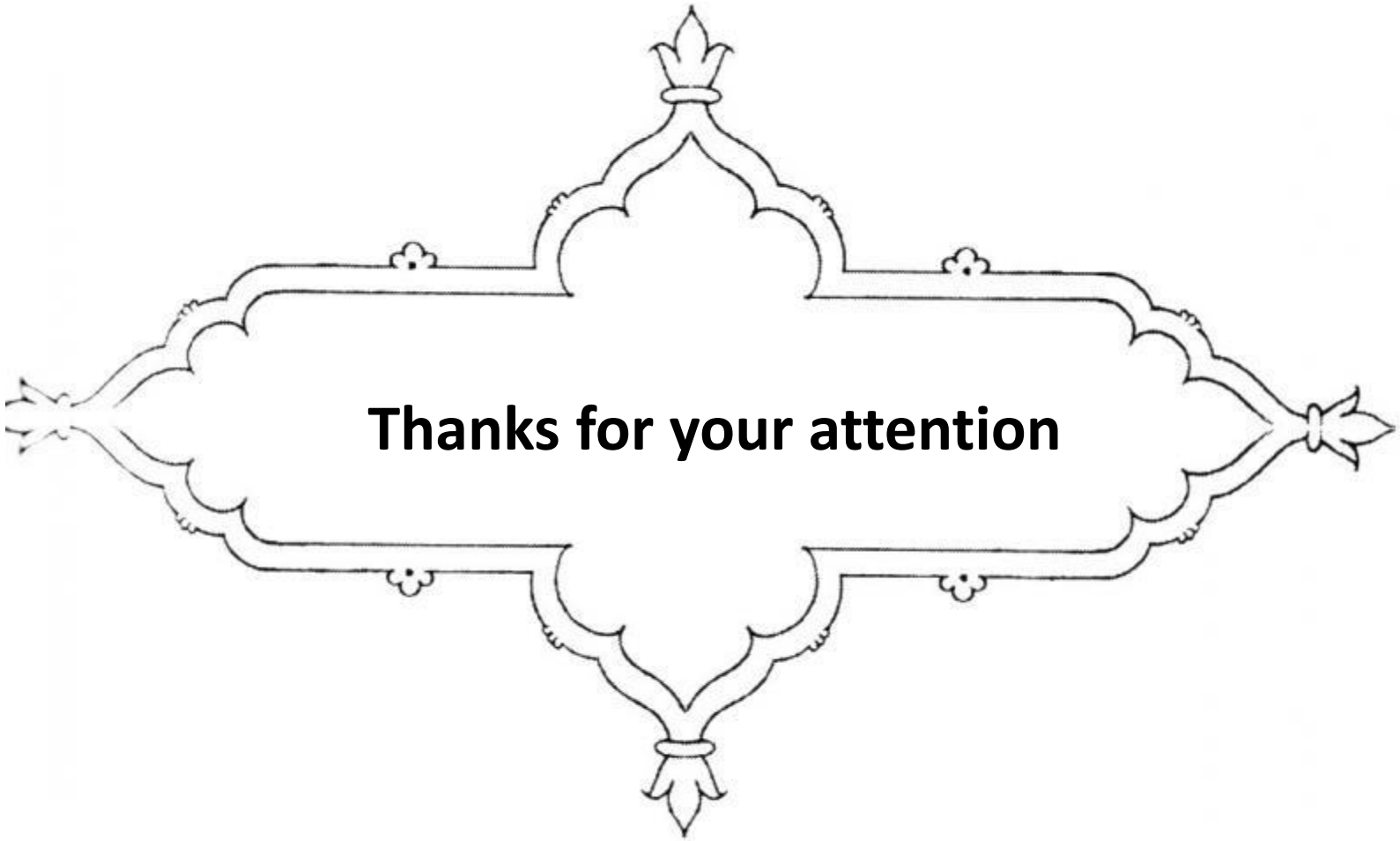


Conclusion:

- Austenitic steels and Superalloys play significant role in A-USC Power plants
- In Overall, Alloys Grade 92, Sanicro25 and Inconel 740H have superior properties in Ferritic steels, austenitic steels and superalloys, respectively.

Outlook:

- Evaluation of material properties used in A-USC power plants (such as strength, toughness, corrosion resistance, fatigue…) needs a long-time and expensive experiments. However, modelling and simulation can decrease expenditures.
- Design of new heat treatments can change microstructure and improve some properties.


Thanks for your attention

References:

[1] Engineering and Economic Evaluation of 1300F Series Ultra-Supercritical Pulverized Coal Power Plants: Phase 1.EPRI Report 1015699, Palo Alto, CA: September 2008.

[2] Materials for Ultra-Supercritical and Advanced Ultra-Supercritical Power Plants, Edited by Augusto Di Gianfrancesco. 2017.

[3] Coal Power Plant Materials and Life Assessment, Chapter 3, T23 and T24 – new generation low alloyed steels, S. PADDEA, F. MASUYAMA, A. SHIBLI.

[4] J.C. Vaillant et al. / International Journal of Pressure Vessels and Piping 85 (2008) 38–46.

[5] W. Bendick et al. / International Journal of Pressure Vessels and Piping 84 (2007) 13–20.

[6] K. Sawada, H. Kushima, M. Tabuchi, K. Kimura, "Microstructural degradation of Gr.91 steel during creep under low stress", Materials Science and Engineering A 528 (2011) 5511–5518.

[7] N. Komai, M. Igarashi, Y. Minami, H. Mimura, F. Masuyama, M. Prager, P. R. Boyles, "FIELD TEST RESULTS OF NEWLY DEVELOPED AUSTENITIC STEELS IN THE EDDYSTONE UNIT NO.1 BOILER", Proceedings of CREEP8 Eighth International Conference on Creep and Fatigue at Elevated Temperatures July 22-26, 2007, San Antonio, Texas.

[8] Fujimitsu Masuyama, Peter R. Boyles, "EFFECT OF SERVICE EXPOSURE ON MATERIAL PROPERTIES OF AUSTENITIC BOILER STEELS", Proceedings of CREEP8 Eighth International Conference on Creep and Fatigue at Elevated Temperatures July 22-26, 2007, San Antonio, Texas.

[9] X.S. Xie, J.X. Dong, J. Wang, Structure Stability Analyses on Nimonic 263 After Long Time Stress Rupture Tests (internal report), High Temperature Materials Research laboratories, University of Science & Technology, Beijing, 2011.

[10] ASME, Case 2702 Seamless Ni-25Cr-20Co material, Section 1, cases of the ASME boilerand pressure Vessel code, BPV-Supp. 7, American Society of Mechanical Engineers, 2011.

[11] P. Shingledecker, "Metallurgical Effects of Long-Term Stress Rupture in a New Nickel-Base Alloy," Doctoral Dissertation, University of Tennessee, Knoxville, May, 2012.

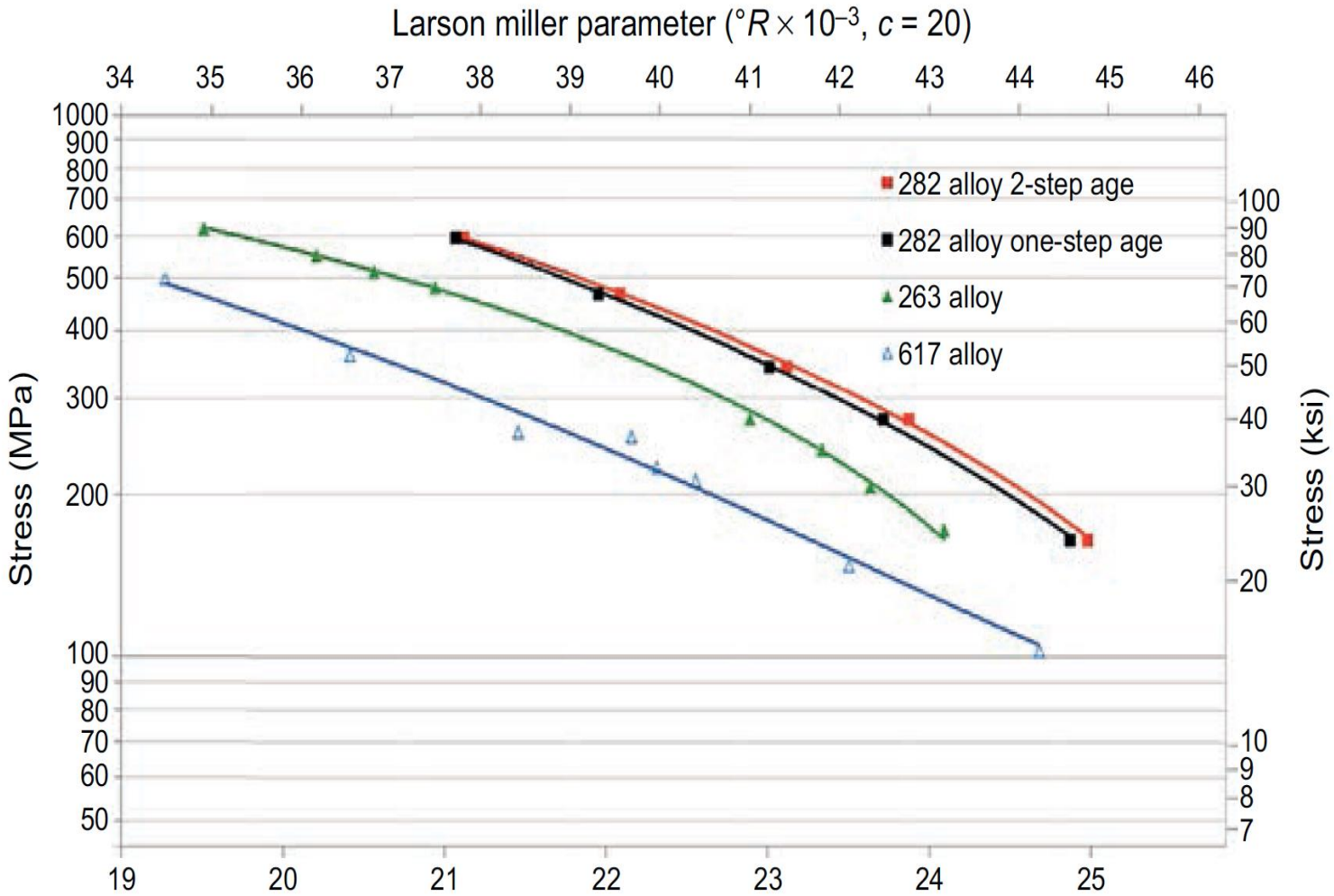
[12] INCONEL® ALLOY 740H® A Superalloy Specifically Designed For Advanced Ultra Supercritical Power Generation. www.specialmetals.com/…/PCC%20EG%20740H%.

[13] L. Pike, Development of a fabricable gamma-prime (γ') strengthened superalloy, in: R. Reed et al. (Ed.), Superalloys 2008, TMS, 2008, pp. 191–200.

[14] J. Caron, Weldability and welding metallurgy of HAYNES 282 alloy, in: 8th International Symposium on Superalloy 718 and Derivatives, John Wiley & Sons, 2014, pp. 273–286.

[15] P. Tortorelli, K. Unocic, H. Wang, M. Santella, J. Shingledecker, Ni-Based alloys for advanced ultrasupercritical steam boilers, in: Fossil Energy Crosscutting Research Program Review, May 22, 2014, Pittsburgh, Pennsylvania, 2014. http://www.netl.doe.gov/File%20Library/Events/2014/crosscutting/Crosscutting_20140522_1600B_ORNL.pdf.

Previous Next



2.1. Collation of Existing Knowledge

Under this task there are 3 sub-tasks namely

a) Material properties, including thermo-physical and mechanical data,

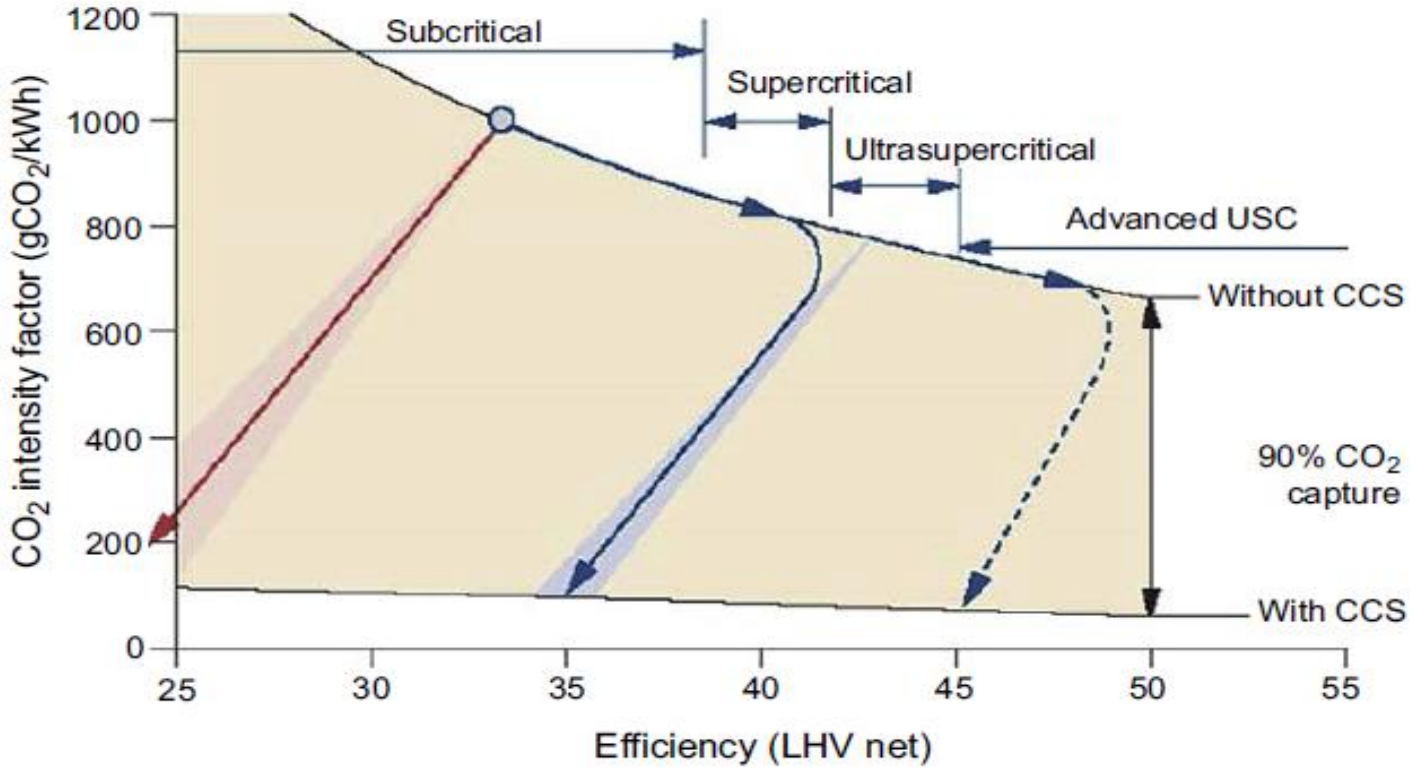
b) Data assessment methods for estimating typical and/or design data and

c) Plant feedback, including manufacturing, fabrication and erection.

TUG will be responsible for the collation of data from the literature and all partners. DOB will specify the material list, property required and data templates.
All partners will bring historic data, e.g. from NextGenPower, ComTes 700, etc.

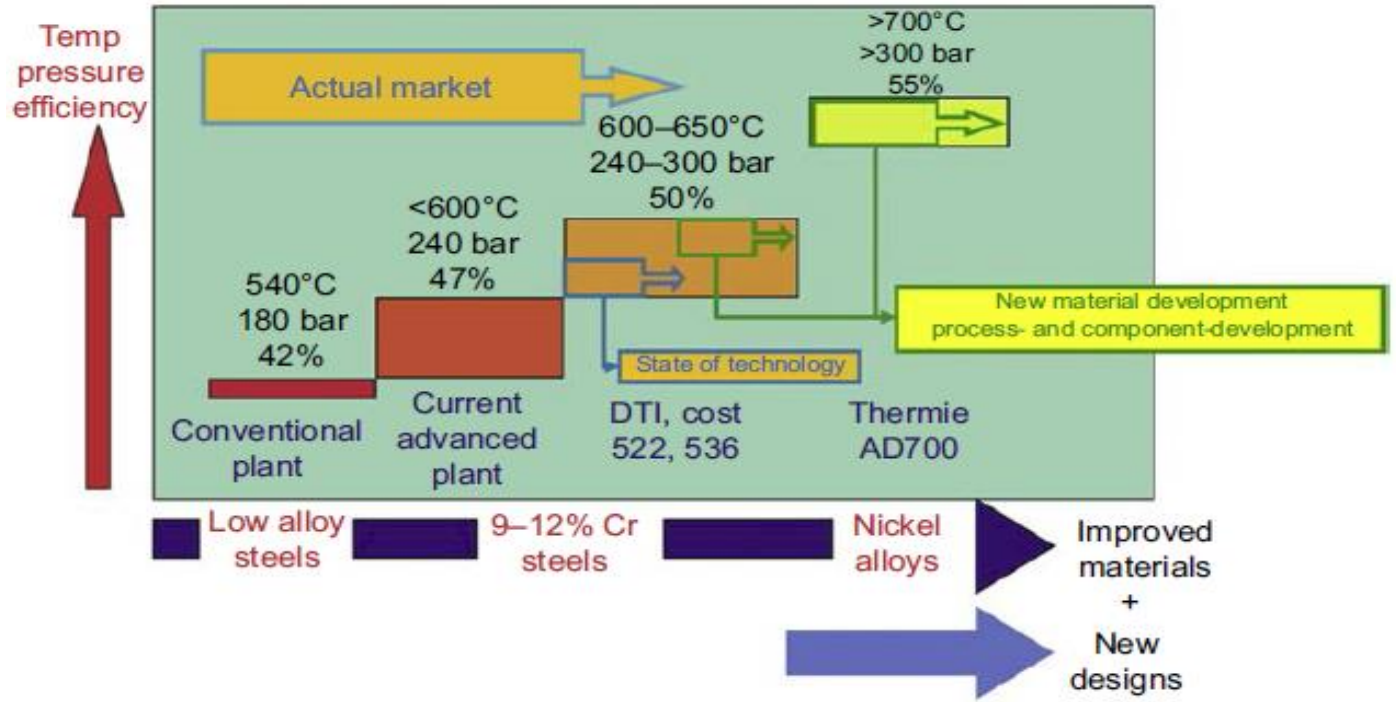
Depend on the steam pressure, Service temperature and efficiency, the power plant are classified to the three generations,

	steam pressure (bar)	Service temperature	efficiency
Subcritical power plants	140	560–580°C	37%
advanced power plants	280	600°C	40–45%
USC power plants	350	760°C	60%



Depend on the steam pressure, Service temperature and efficiency, the power plant are classified to the three generations,

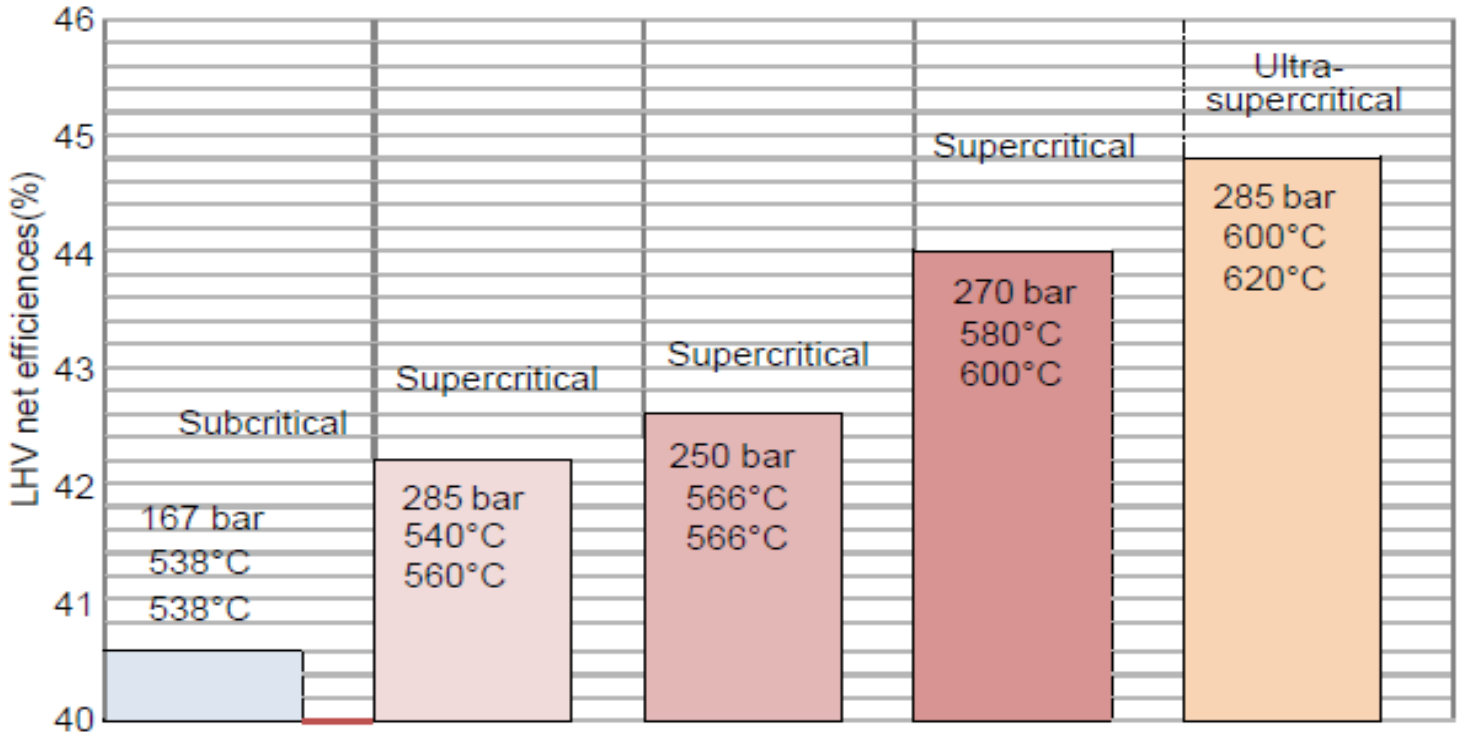
	steam pressure (bar)	Service temperature	efficiency
Subcritical power plants	140	560–580°C	37%
advanced power plants	280	600°C	40–45%
USC power plants	350	760°C	60%



Steps in the development of the materials for USCs. Voest Alpine AG, Foundry Linz, Know how and process development for components used in (A) USC power plants, 10th Liege cost Conference on materials for advanced power Engineering, September 14th–17th 2014, 2014

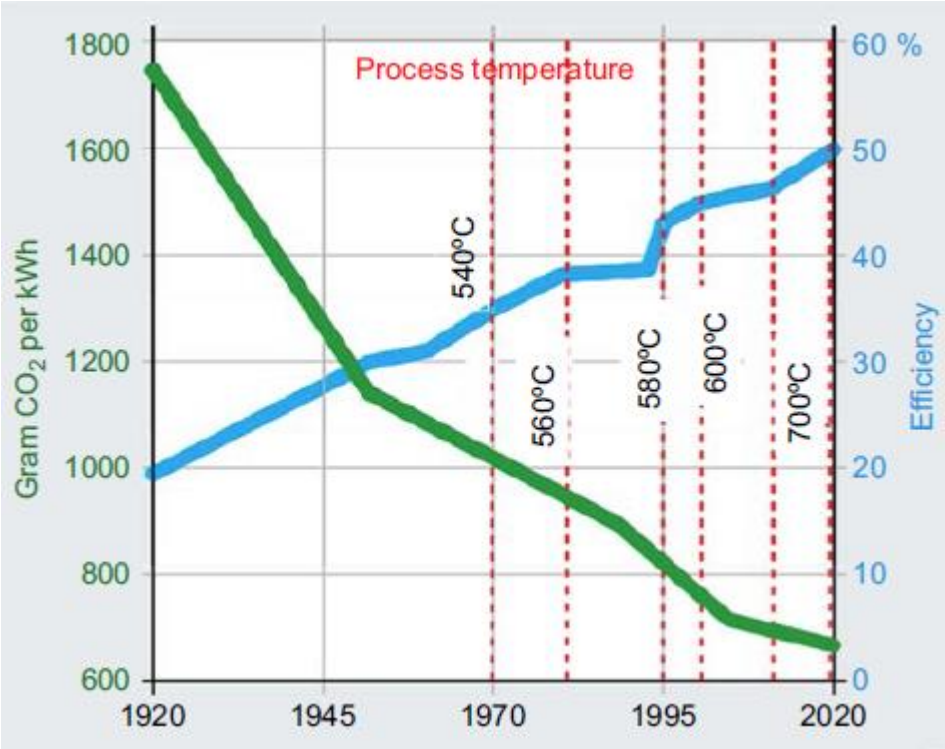
Depend on the steam pressure, Service temperature and efficiency, the power plant are classified to the three generations,

	steam pressure (bar)	Service temperature	efficiency
Subcritical power plants	140	560–580°C	37%
advanced power plants	280	600°C	40–45%
USC power plants	350	760°C	60%

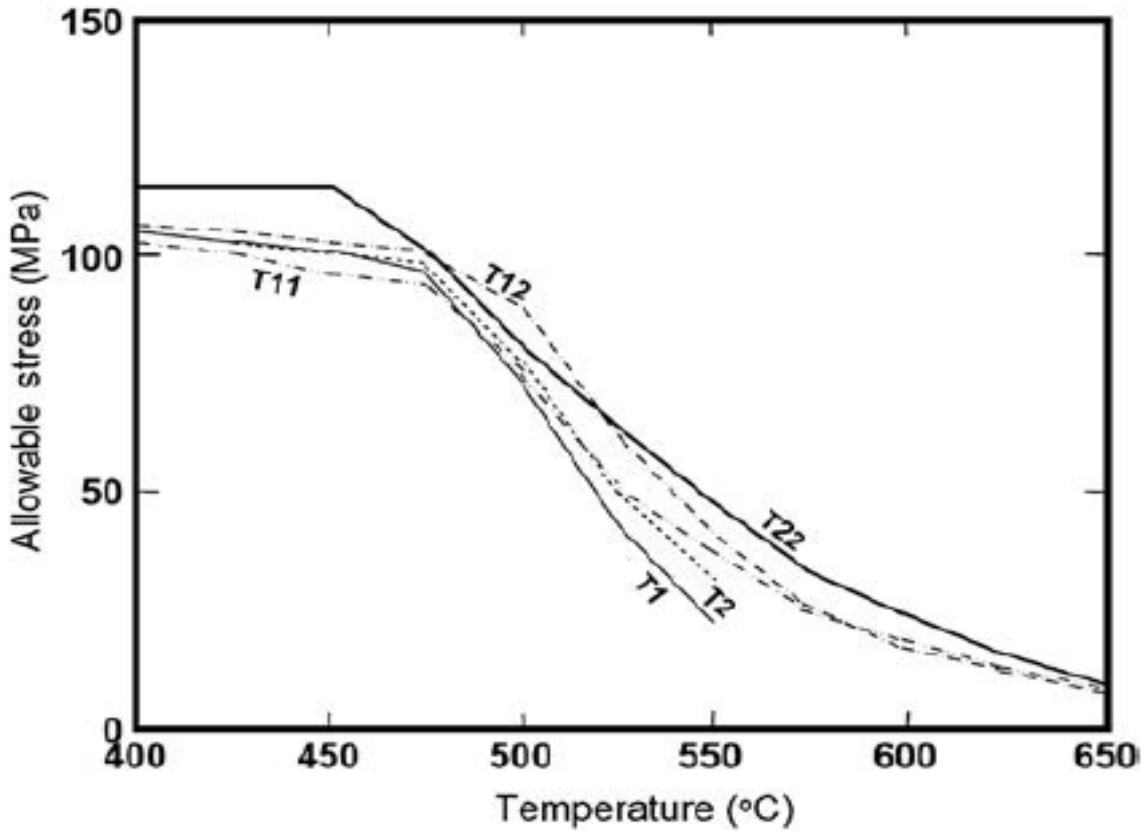


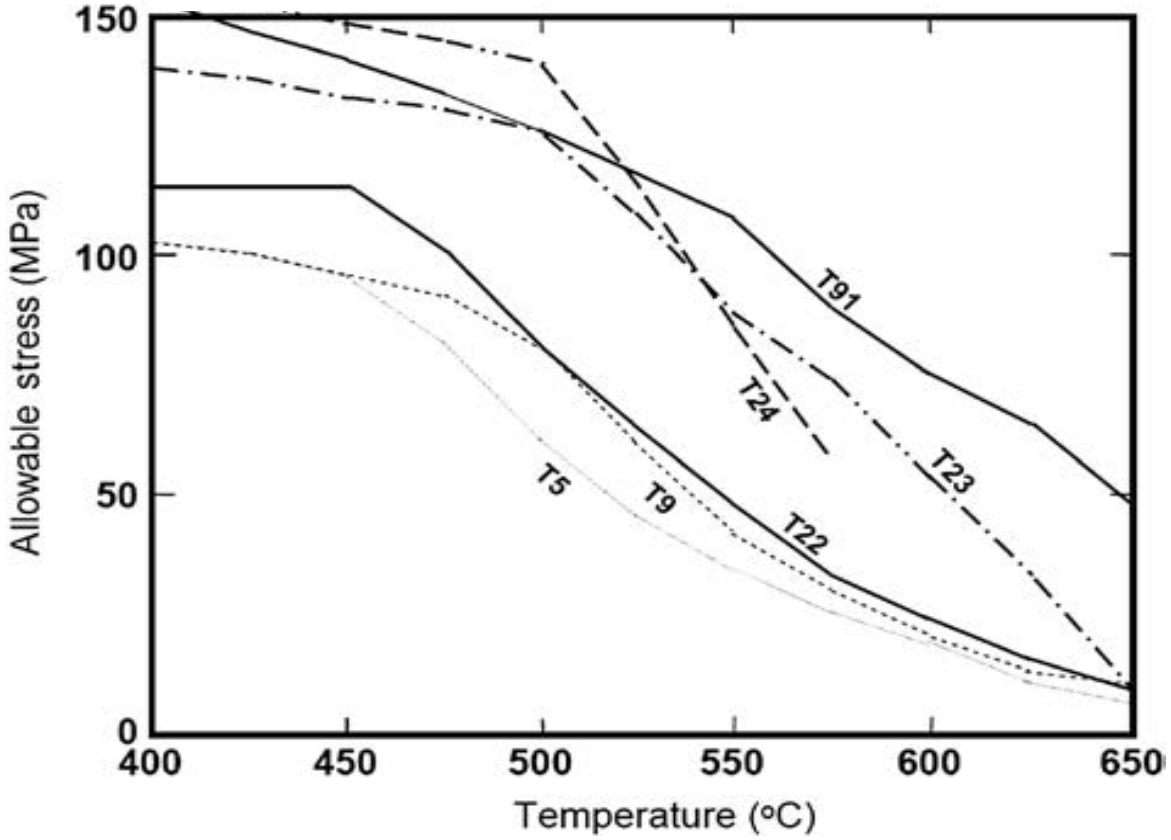
Depend on the steam pressure, Service temperature and efficiency, the power plant are classified to the three generations,

	steam pressure (bar)	Service temperature	efficiency
Subcritical power plants	140	560–580°C	37%
advanced power plants	280	600°C	40–45%
USC power plants	350	760°C	60%



Mechanical properties (allowable stress):





Materials for Ultra-Supercritical and Advanced Ultra-Supercritical Power Plants, Edited by Augusto Di Gianfrancesco, 2017

Mechanical properties (allowable stress):

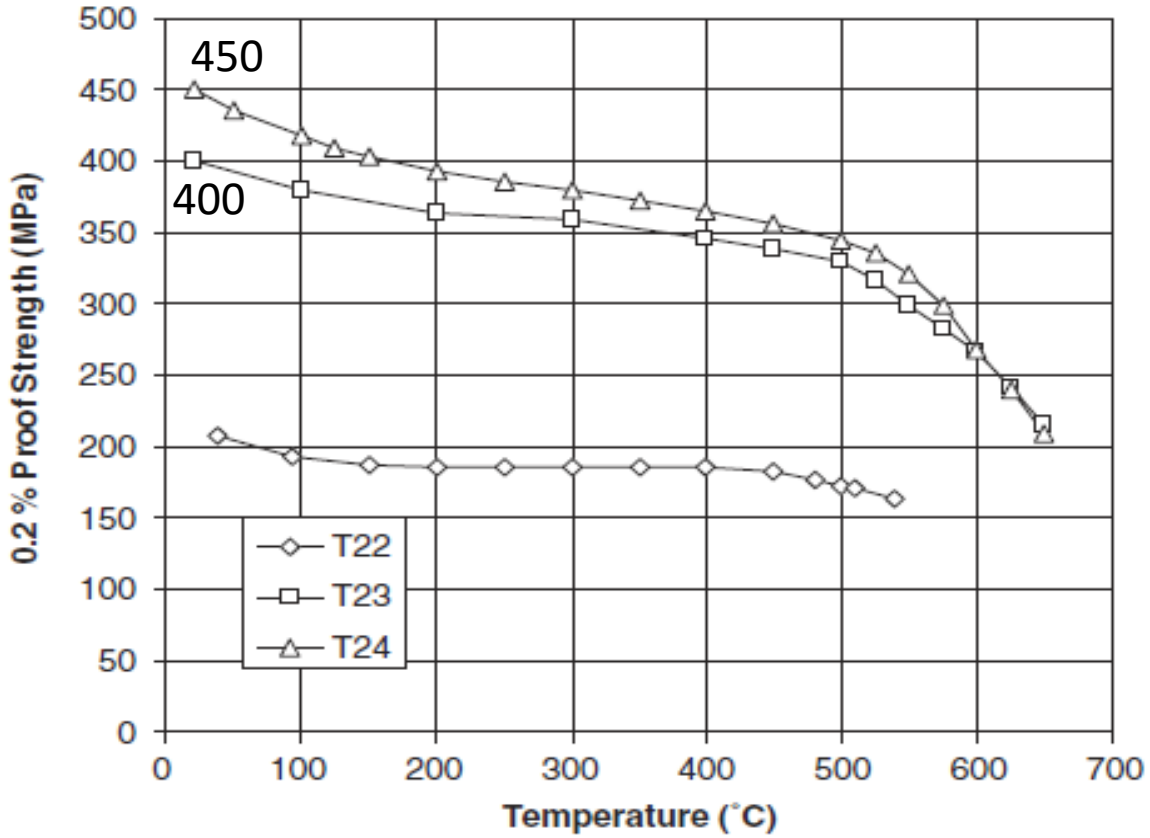


Fig. 3. Minimum 0.2% proof strength of T22, T23 and T24.

W. Bendick et al. / International Journal of Pressure Vessels and Piping 84 (2007) 13–20

J.C. Vaillant et al. / International Journal of Pressure Vessels and Piping 85 (2008) 38–46

Effect of alloying elements:

- **Cr:** improves corrosion resistance, rupture ductility, and resistance against graphitization.
- **W, Mo**, **Nb :** improve solid solution strengthening
- **Nb, V, Ti:** beside C and N form carbides and carbonitrides contribute to the precipitation hardening.
- **B:** Addition of B and decrease of N can improve hardenability and creep strength during long-term.
- **Mo:**
  - solution hardening in metal matrix
  - precipitation hardening due to formation of Mo_2C precipitates.
  - 0.3-0.5% Mo with 0.15% C can increase creep strength
  - At higher temperature, graphitization increases failure possibility in service. Instead of Mo-C composition, Mo-

	Precipitate	Formula	Remark
P91	$M_{23}C_6$	$(Cr,Fe,Mo)_{23}C_6$	Precipitate during tempering
	MX	(Nb,V)(N,C)	Undissolved during austenitization
	MX	(V,Nb)(N,C)	Precipitate during tempering
	Laves phase	$(Fe,Cr)_2Mo$	Precipitate during creep (T < 650°C)
	Z-phase	[Cr(V,Nb)N]	Precipitate during creep

Effect of alloying elements:

- **Nb:** Presence of Niobium in microstructure → stabilize austenitic structure.
- **Cu:** Copper can produce copper-rich nano particles → improves creep resistance.
- **Ni, N:** Nickel and Nitrogen stabilise microstructure by suppressing formation of sigma phase → facilitate fabricability.
- **W, N, Co** and **Nb** improve solid solution strengthening
- **Nb, N, Cr**, and **Cu** are alloying elements contribute to the precipitation hardening.
- **Mn** and **N** can also persuade formation of austenite structure
- **Mn** degrade corrosion resistance
- **N** can improve high temperature creep resistance by formation of stable nitrides of transition metals

Effect of alloying elements:

- **Cr:** High amount of chromium content in IN617 provides oxidation resistance by forming chromium *oxide* on the surface and form different carbides at grain boundaries, which prevent abnormal grain growth.
- **Co:** Addition of 10% Co helps to control the γ’ solvus.
- **Mo:** Presence of higher amount of the Molybdenum can provide excellent creep strength, especially at higher temperature.
- **Nb, C, Mo, W, Ti, Cr, Al, Fe, Co:** Solid solution strengthening elements
- **Al, Ti:** The elements Al and Ti persuade formation of γ’ phase.
- **V, Nb:** Addition of vanadium and/or niobium can persuade precipitation of fine carbides, which improves ductility. Additions of niobium and/or vanadium to the Alloy 617B is labelled Alloy 617occ (optimized chemical composition).
- **B:** Boron has a positive effect on the ductility of superalloys and decreases sensitivity to stress relaxation cracking. Recent research indicates segregation of boron at the matrix/carbide interface.
- **Mn, Si:** Mn and Si can enhance castability and oxidation resistance.

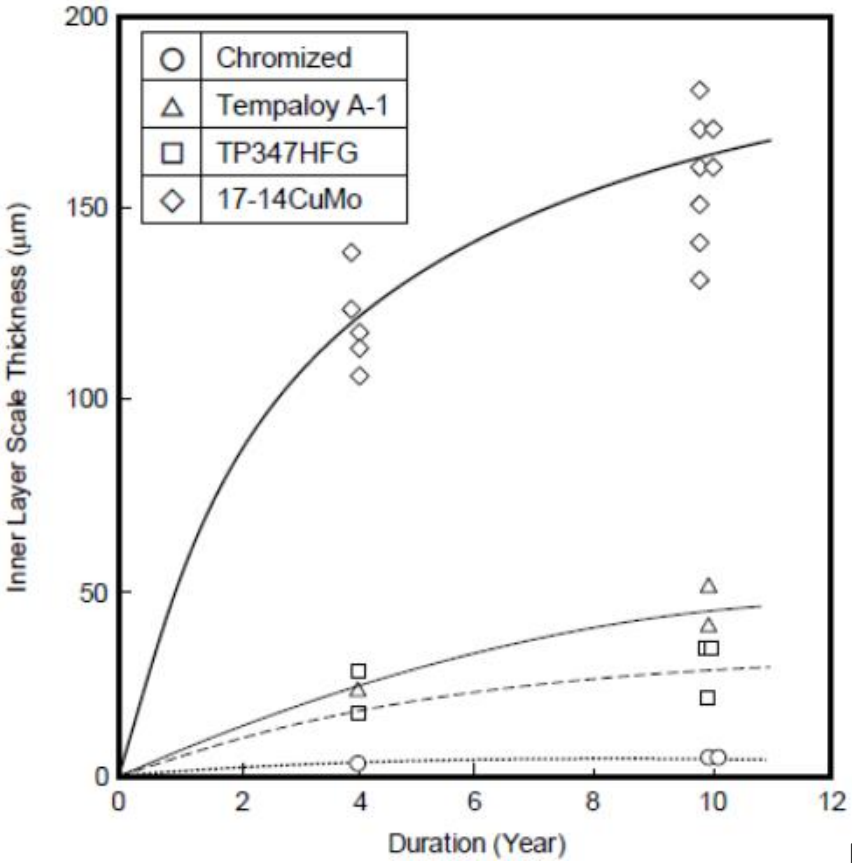
Corrosion/Oxidation behaviour:

Grain size effect:

Formation of a continuous oxide layer of Cr_2O_3 on the surface of the austenitic steels depends strongly on the diffusion of Cr at the grain boundaries. This means that in the fine grained TP347HFG, low concentration of Cr content (17.5 wt%) is enough to grow continuous Cr_2O_3 oxide scale. In contrary, in the coarse grains (~65 µm) austenitic steel, a higher amount of Cr (>17.5 wt%) is essential to form a continuous Cr_2O_3.

External stress:

Exertion of low stresses can cause many micro cracks and defects, which accelerate migration of Cr through cracks and defects to the surface which leads to formation of stable and dense Cr_2O_3 layer. The critical stress was reported 40 MPa. At higher stresses (> 40MPa) corrosion reactions become strong.



[8]

Growth of steam oxidation scale

growth of oxide scale of four austenitic steels at 632°C, by using parabolic law described in $d^2 = K_p t$

Chromized layer on TP347H:	2.00×10^{-15} $cm^2 s^{-1}$	Tempaloy A-1:	8.89×10^{-14} $cm^2 s^{-1}$
TP347HFG:	3.47×10^{-14} $cm^2 s^{-1}$	17-14CuMo:	1.42×10^{-12} $cm^2 s^{-1}$