COMPUSYSTEM srl

Stato dell'arte sui materiali per rotori di turbine a vapore e a gas nei cicli combinati

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Giornata di Studio AIM
Problematiche dei materiali nei cicli combinati tradizionali e innovativi
28 giugno 2018 - Milano Centro Congressi Fast

Rotori per turbine a vapore

- Acciai martensitici
- Superleghe a base nickel

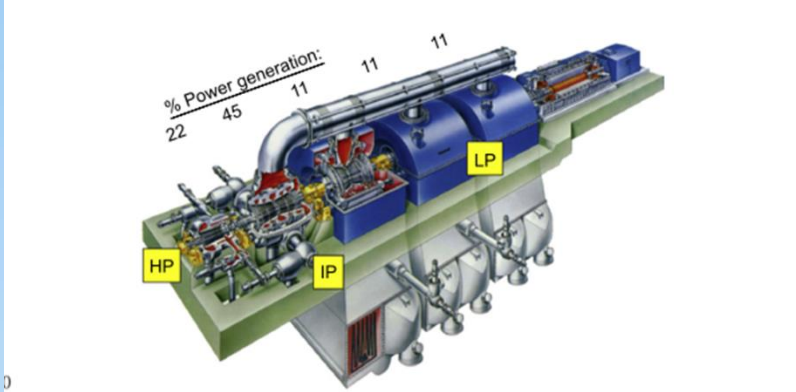


Figure 6.3 Typical Siemens steam turbine arrangement with high-pressure (*HP*), intermediate-pressure (*IP*), and low-pressure parts (*LP*).
Siemens AG, Power Generation.

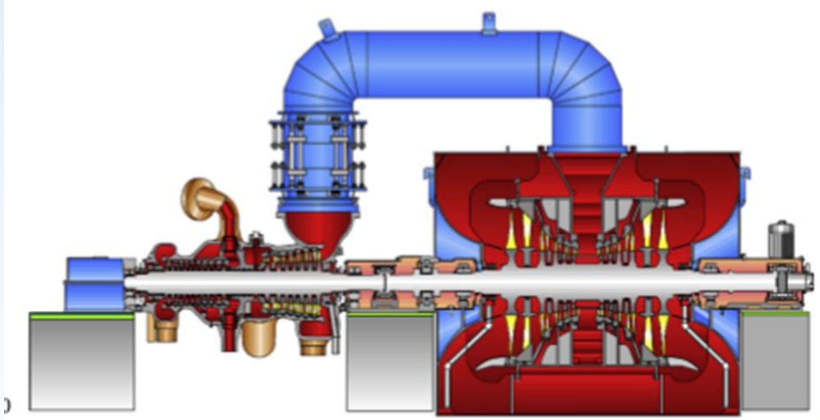


Figure 1.53 Toshiba's tandem-compound, double-flow, condensing steam turbines [37].

Figure 6.4 High-pressure turbine with combined intermediate-low pressure in welded design.
Siemens AG, Power Generation.

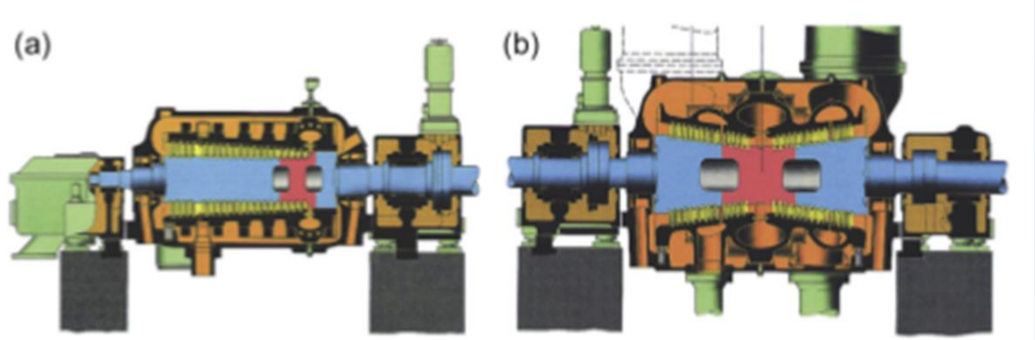


Figure 1.51 Alstom HP and IP turbines with welded rotors using 10% Cr steel in the hottest regions: (a) single flow, (b) double flux [34].

Materiali per turbine a vapore

Materiali per turbine di alta pressione

SUPERCRITICI - ULTRASUPERCRITICI - ADVANCED ULTRASUPERCRITICI

Component	566°C	620°C	700°C	760°C
Casings/Shells (valves; steam chests; nozzle box; cylinders)	CrMoV (cast) 10CrMoVNb	9-10%Cr(W) 12CrW(Co) CrMoWVNbN	CF8C+ CCA617 Inconel 625 IN 718 Nimonic 263	CCA617 Inconel 740
Bolting	422 9-12%CrMoV Nimonic 80A IN718	9-12%CrMoV A286 IN718	Nimonic 105 Nimonic 115 Waspaloy IN718	U700 U710 U720 Nimonic 105 Nimonic 115
Rotors/Discs	1CrMoV 12CrMoVNbN 26NiCrMoV11 5	9-12%CrWCo 12CrMoWVNbN	CCA617 Inconel 625 Haynes 230 IN740	CCA617 IN740
Vanes/Blades	422 10CrMoVNbN	9-12%CrWCo	Wrought Ni-base	Wrought Ni-base
Piping	P22	P92	CCA617	IN740

Materiali per turbine a vapore

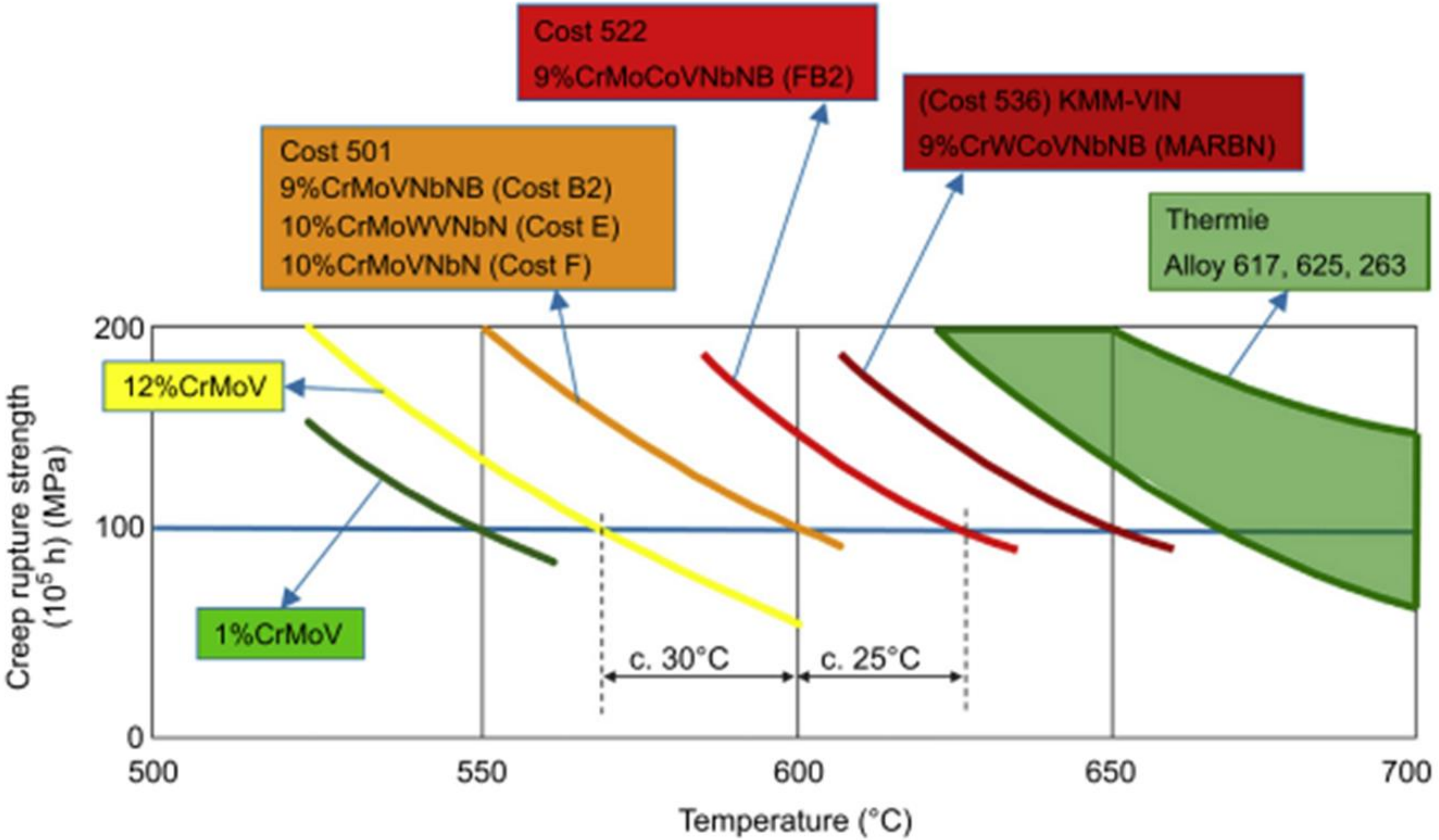


Figure 6.34 100,000 h creep rupture strength of the newly developed European steels.

Materiali per turbine a vapore

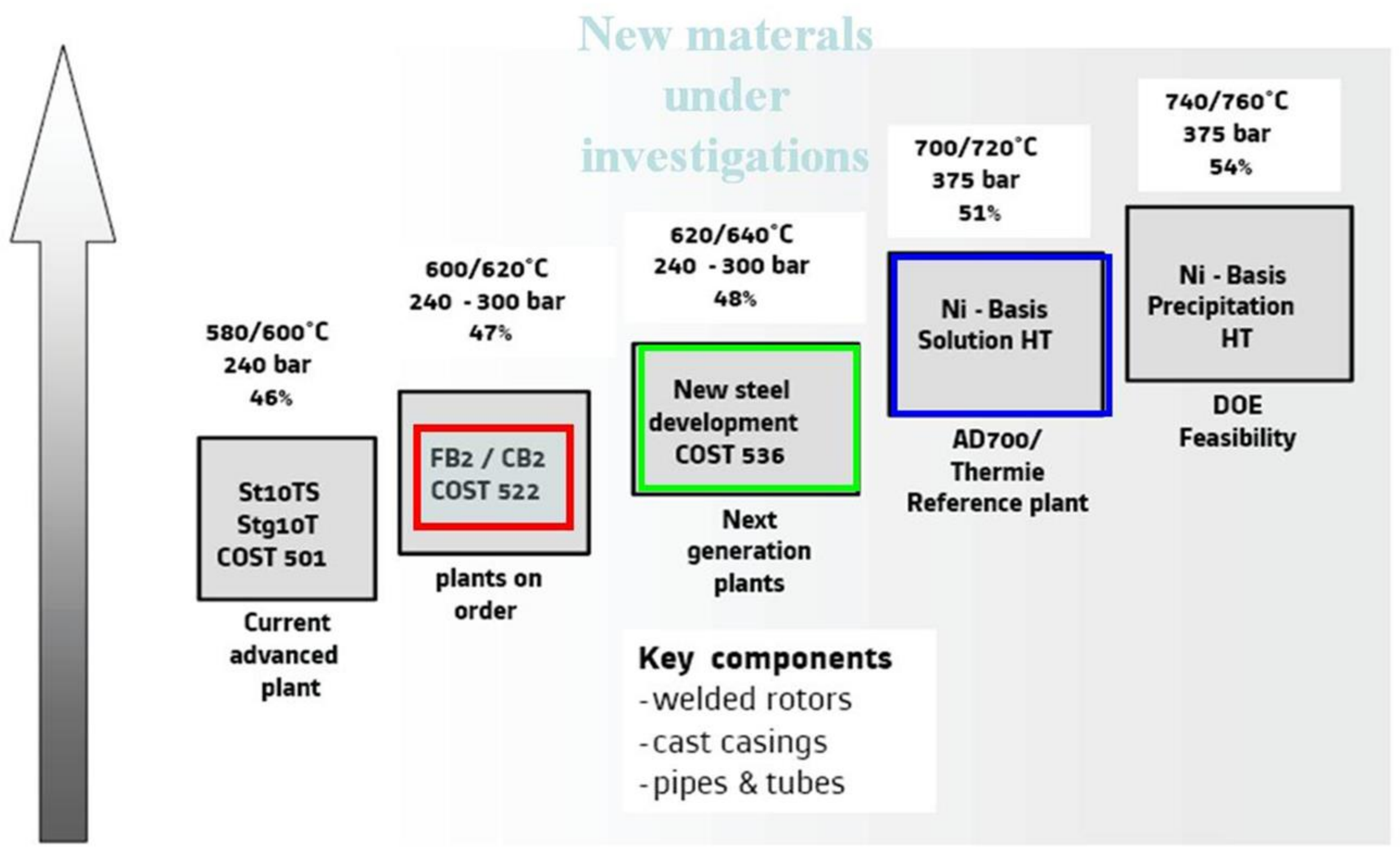
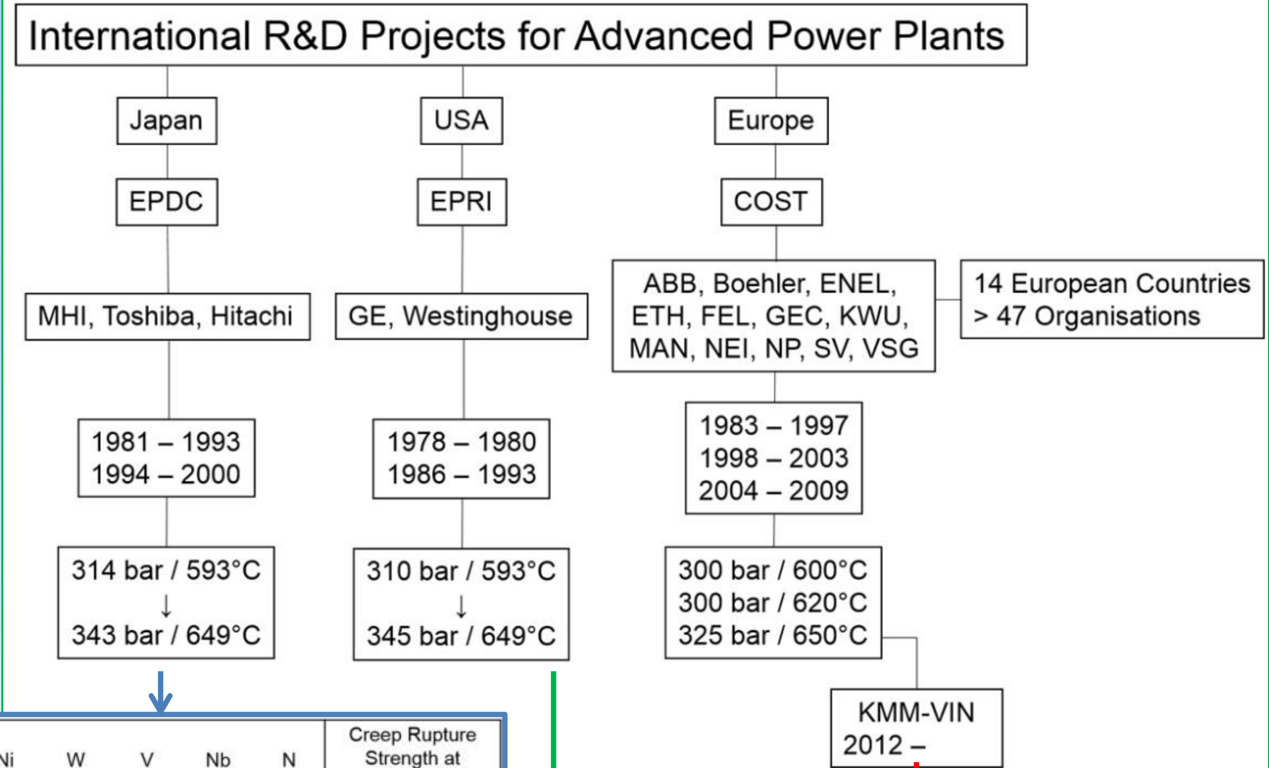


Figure 2: The role of materials development in increasing steam conditions and efficiency

Materiali per rotori di turbine a vapore



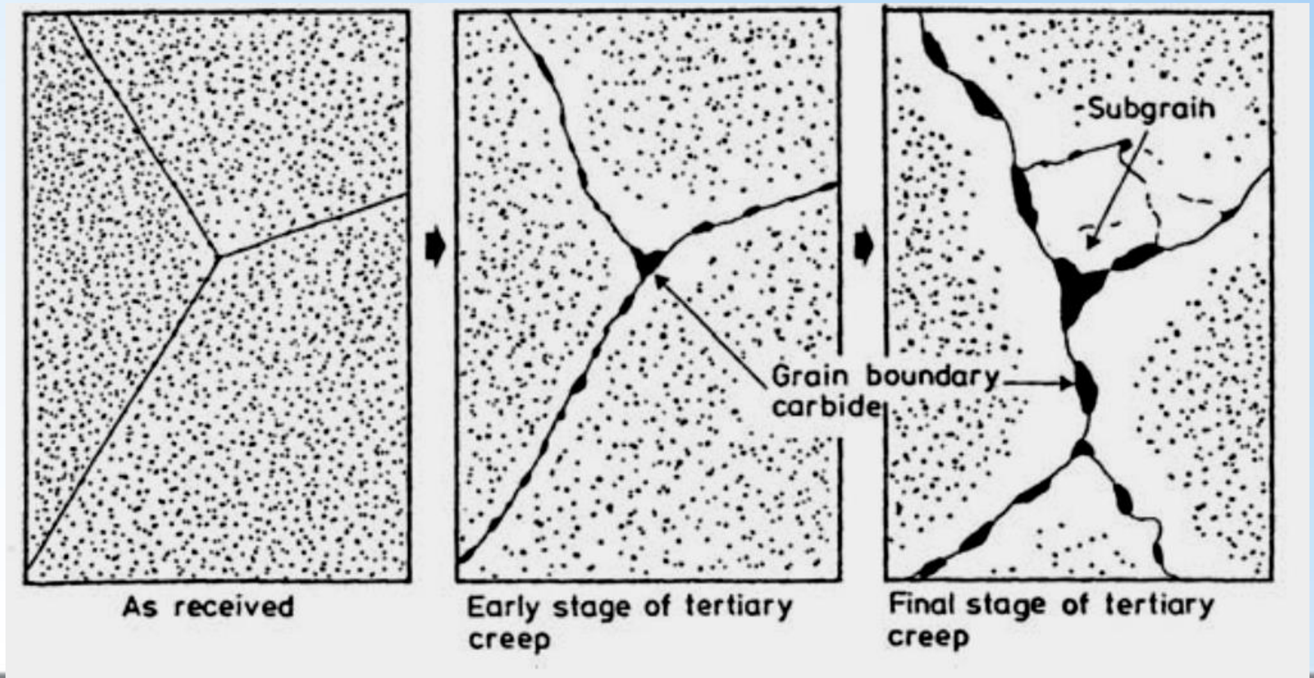
Steel	Source	C	Si	Mn	Cr	Mo [Weight %]	Ni	W	V	Nb	N	Creep Rupture Strength at 600°C/10^5 h [MPa]
TR1100 (TMK1)	Japan	0.14	0.05	0.50	10.3	1.50	0.60	-	0.17	0.05	0.04	90
TR1150 (TMK2)	Japan	0.14	0.05	0.50	10.3	0.50	0.70	1.80	0.17	0.05	0.04	90
TR1200	Japan	0.12	0.05	0.50	11.3	0.30	0.80	1.80	0.20	0.05	0.06	125

Steel	Source	C
12%CrMoV	SEW 555	0.22
13%CrMoWV	USA	0.22
11%CrMoVNbN	USA	0.18

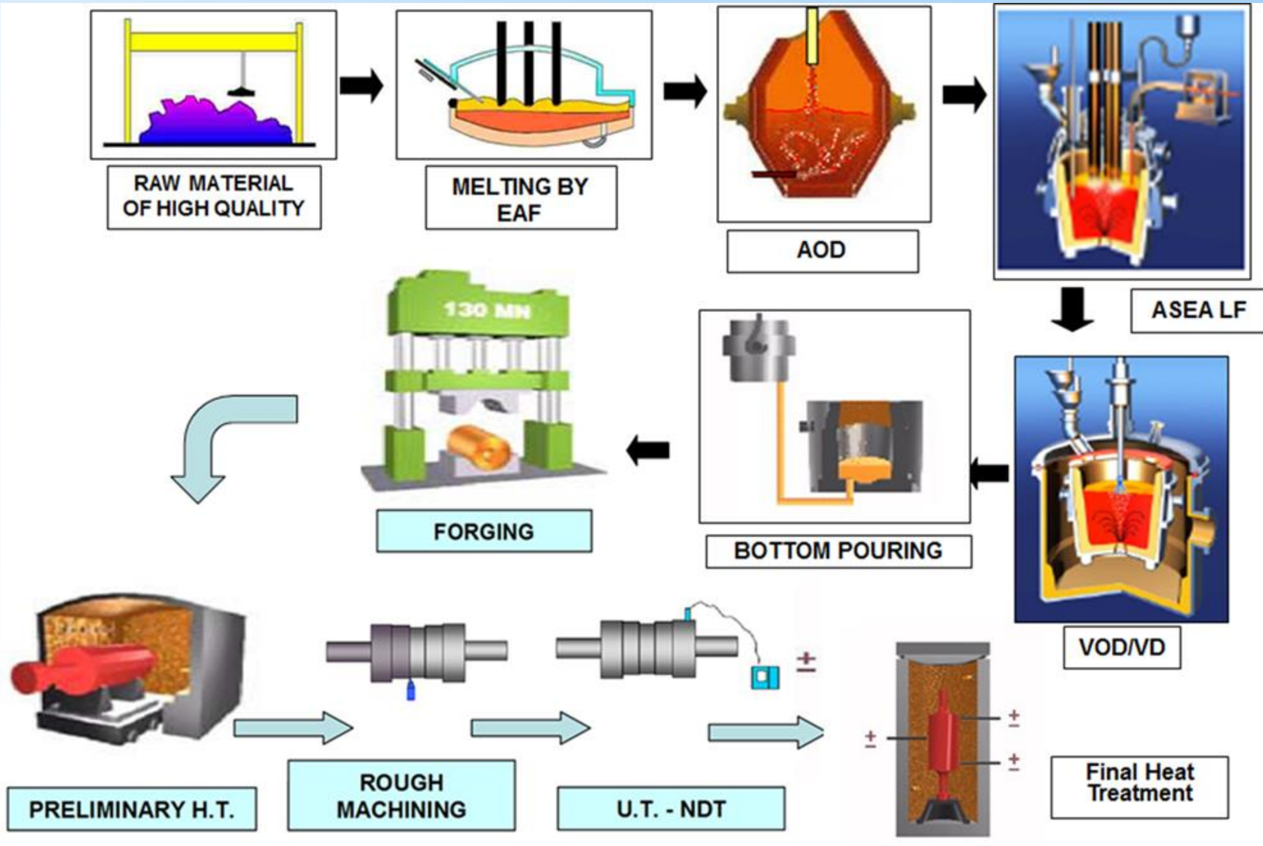
COST	Forged Steels	C	Cr	Mo	W	V	Ni	Nb	N	B	100MPa 100.000h	Status
	1CrMoV	0.25	1.0	1.0		0.25					550°C	Long term operating
	12CrMoV	0.23	11.5	1.0		0.25					570°C	Long term operating
501	Type F	0.1	10	1.0	1	0.2	0.7	0.05	0.05		597°C	Operating in plant
501	Type E	0.1	10	1.5		0.2	0.6	0.05	0.05		597°C	Operating in plant
501	Type B	0.2	9.0	1.5		0.2	0.1	0.05	0.02	0.01	620°C	
522 - 536	Type FB2 (SdF)	0.13	9.32	1.47		0.2	0.16	0.05	0.019	0.085	620°C	Trial rotors manufactured and in service

Materiali per turbine a vapore

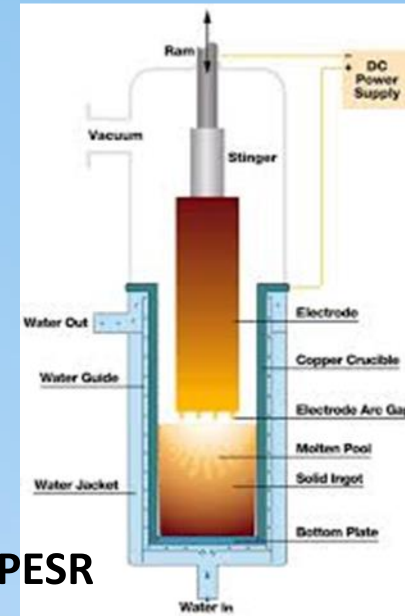
Steel	Steel	C	Si	Mn	P	S	Cr	Mo	Ni	V	W	Al	As	Cu	Sn	Sb	N
1%Cr	30CrMoNiV 5 11	0,27 - 0,31	< 0,1	0,3 – 0,8	< 0,007	< 0,007	1,1 - 1,4	1,0 - 1,2	0,5 - 0,75	0,25 – 0,35		< 0,01	< 0,02	< 0,12	< 0,0015	< 0,01	
2%Cr	22CrMoNiV 8 8	0,21 - 0,23	< 0,12	0,65 - 0,75	< 0,007	< 0,005	2,05 - 2,15	0,80 - 0,90	0,70 - 0,80	0,25 – 0,35	0,60 - 0,70	< 0,01	< 0,01	< 0,1	< 0,006	< 0,001	
9-12%Cr	COST501 – Rotor E	0,11 - 0,13	< 0,12	0,4 - 0,5	< 0,01	< 0,005	10,2 - 10,8	1,0 - 1,1	0,7 - 0,8	0,15 - 0,25	0,95 - 1,05	< 0,01	< 0,012	< 0,1	< 0,012	< 0,001	0,045 - 0,060



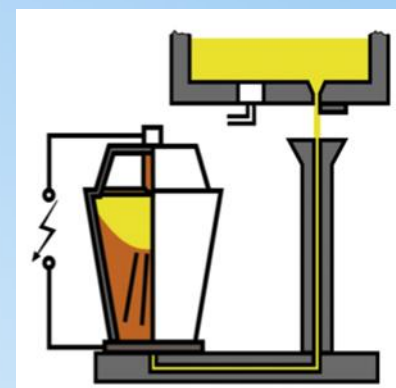
Materiali per turbine a vapore



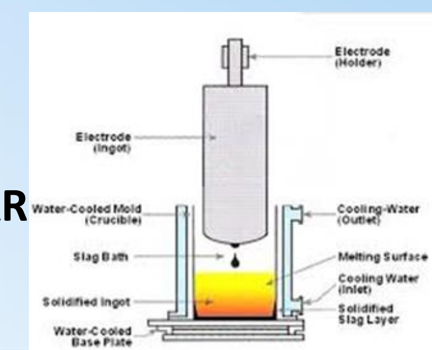
Convenzionale con colaggio bottom pouring



ESR/PESR



BEST

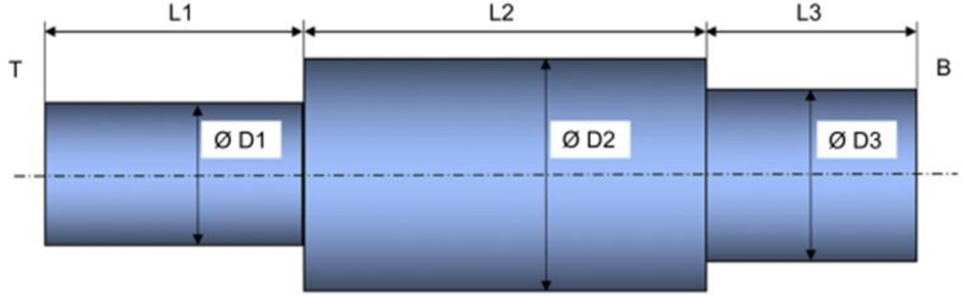


VAR

Materiali per turbine a vapore

Steel	C	Si	Mn	Cr	Mo	W	Ni	Co	V	Nb	N	B
FB2 test melt	0.13	0.05	0.82	9.32	1.47	–	0.16	0.96	0.20	0.050	0.019	0.0085
FB2 trial rotor	0.13	0.09	0.33	9.08	1.43	–	0.16	1.26	0.22	0.054	0.022	0.0076

Figure 6.9 Chemical compositions of steel FB2 [wt%].



Manufacturer	Melting process	D1 (mm)	D2 (mm)	D3 (mm)	L1 (mm)	L2 (mm)	L3 (mm)	MDDS (mm) D1/D2/D3
Bohler Kapfenberg (Austria)	BEST	770	1180	865	1350	930	1110	1.2/1.8/1.3
Societa delle Fucine Terni (Italy)	EAF/VCD	925	1110	790	800	2750	830	1.0/1.5/1.5
Saarschmiede Voelklingen (Germany)	ESR	800	1215	1050	1085	2130	800	1.5/2.0/1.7

MDDS, minimal detectable defect size

Figure 6.11 COST FB2 trial rotor forgings: dimensions and minimum detectable defect size (MDDS) results.

Materiali per turbine a vapore

Rotor	Manufacturer	Melting process	D_{max} (mm) / Ingot weight (kg)	Heat treatment	Test temp. (°C)	Periphery, tangential, body end							Core, radial, midsection body (* body end)						
						UTS (MPa)	0.2%YS (MPa)	EL (%)	RA (%)	Charpy (J)	FATT (°C)	Grain size (ASTM)	UTS (MPa)	0.2%YS (MPa)	EL (%)	RA (%)	Charpy (J)	FATT (°C)	Grain size (ASTM)
FB2	Boehler Kapfenberg (Austria)	BEST	1180	1100°C/spray Q + 570°C + 700°C	RT	824	702	16	56	37	+49	0–2	863	730	13	40	23	+67	0–1
			29,000		+625	378	332	21	82				368	308	29	79			
	Societa delle Fucine Terni (Italy)	EAF / VCD	1110	1100°C/oil + 570°C + 700°C	RT	776	656	20	62	14	+90	0–2	803	682	13	39	12	+94	
			53,000		+625	449	434	17	77				445	428	22	79			
	Saarschmiede Voelklingen (Germany)	ESR	1215	1100°C/oil + 570°C + 700°C	RT	846	720	15	56	36	+47	00–2	843 *	710	13	45	29	+58	< 00 = 70% > 00–2 = 30%
			56,000		+625	464	392	27	84				465 *	396	23	70			

Figure 6.12 Basic data and mechanical properties at RT of COST rotors FB2 (COST 522 Program).

La microstruttura nella condizione di trattamento termico di qualità in generale è costituita da martensite rinvenuta e precipitati, principalmente $M_{23}C_6$ che rappresentano il tipo di particelle dominanti. Durante il creep, si genera una diminuzione della densità di dislocazione, si formano e crescono i subgrani, gli $M_{23}C_6$ crescono di dimensioni, le lamelle di martensite diventano molto spesse, e si formano anche fasi nuove come la Laves o la fase Z.

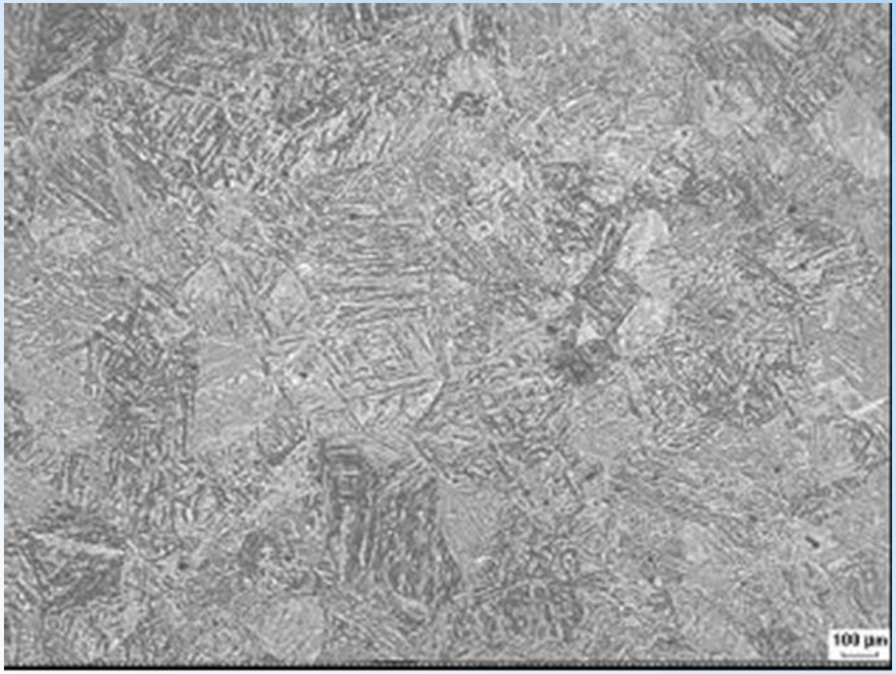
L'acciaio FB2 mostra comunque una buona stabilità ad alta temperatura dovuta a:

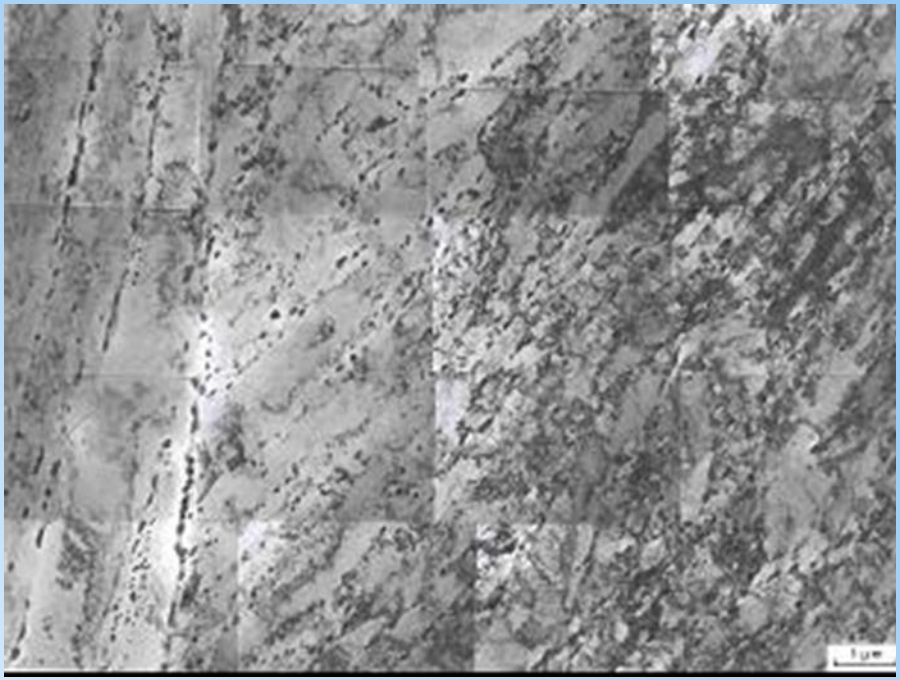
• una struttura martensitica con lamelle di martensite strette, decorate e quindi stabilizzate con carburi $M_{23}C_6$, a loro volta stabilizzati dal boro

.• una densità elevata di dislocazioni, che è mantenuta per tempi più lunghi,

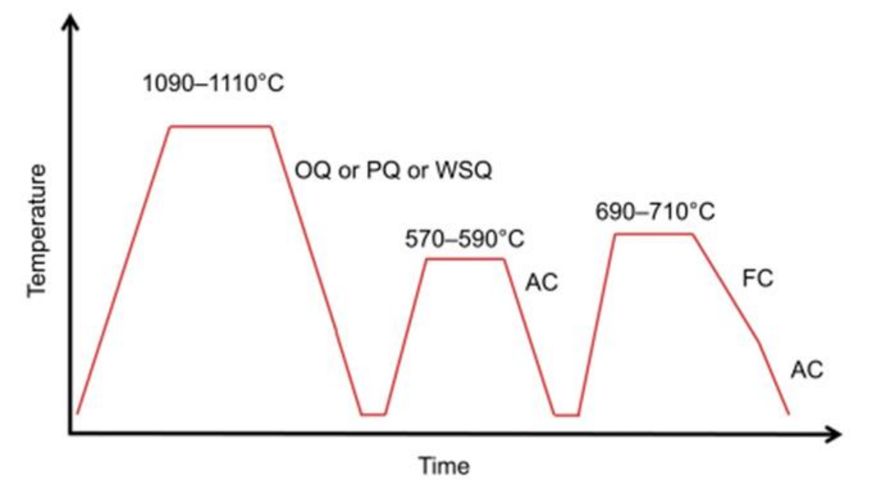
• (Nb,V)C (fino a circa 1 µm), che evitano la crescita del grano durante l'austenitizzazione e sono stabili durante la creep.

Materiali per turbine a vapore



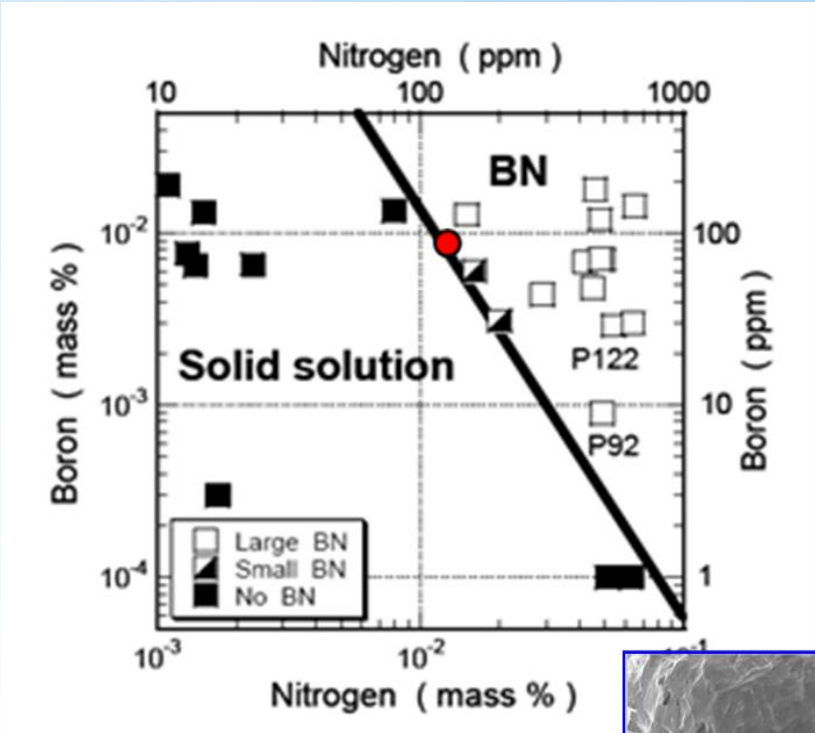


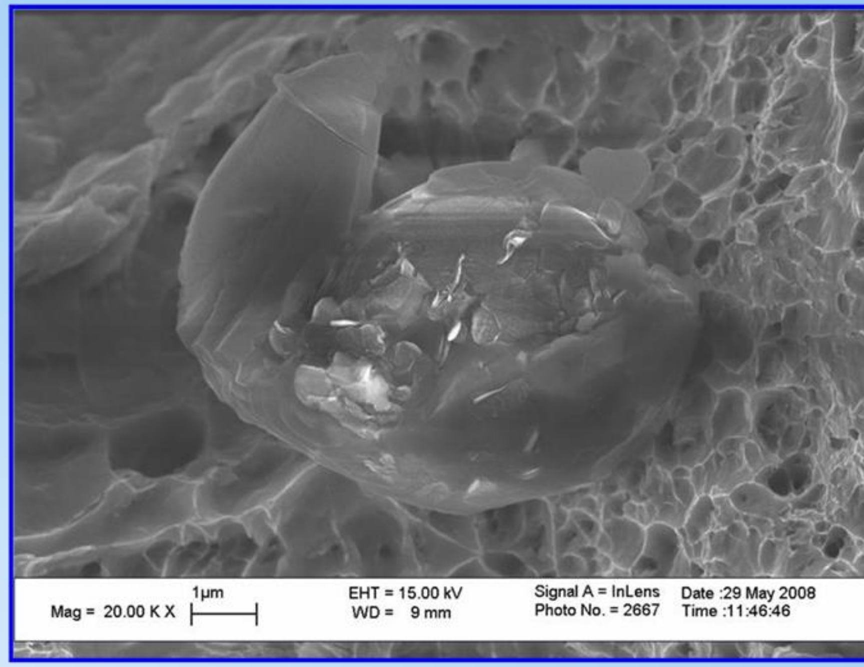
Microstruttura dell' Acciaio FB2: struttura martensite rinvenuta di un rotore dopo trattamento termico di qualità: microscopio ottico e TEM



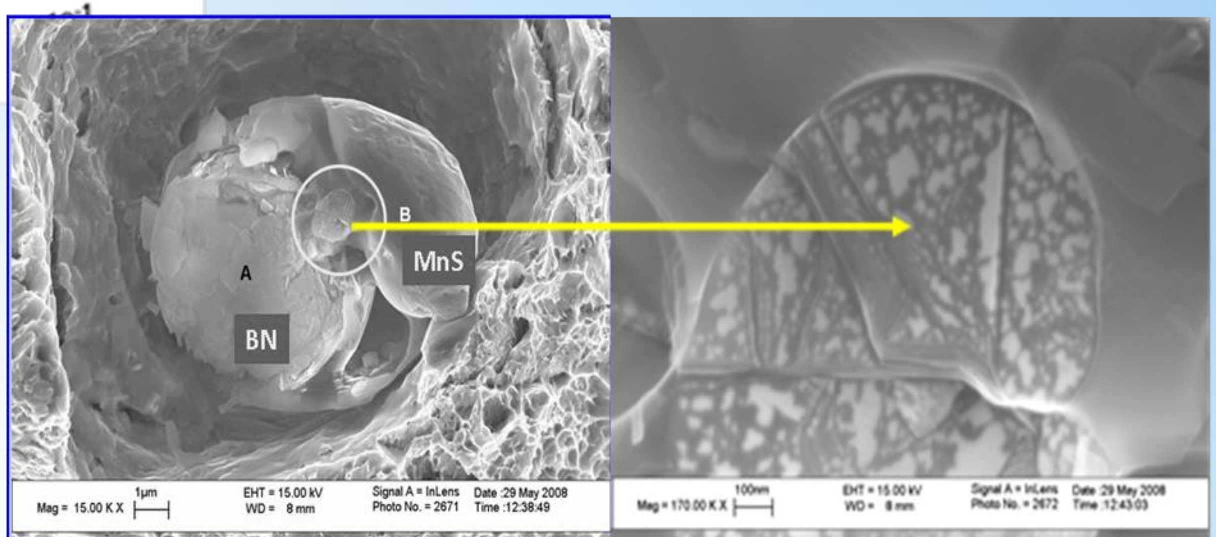
6.28 Quality HT cycle (schematic).

Materiali per turbine a vapore

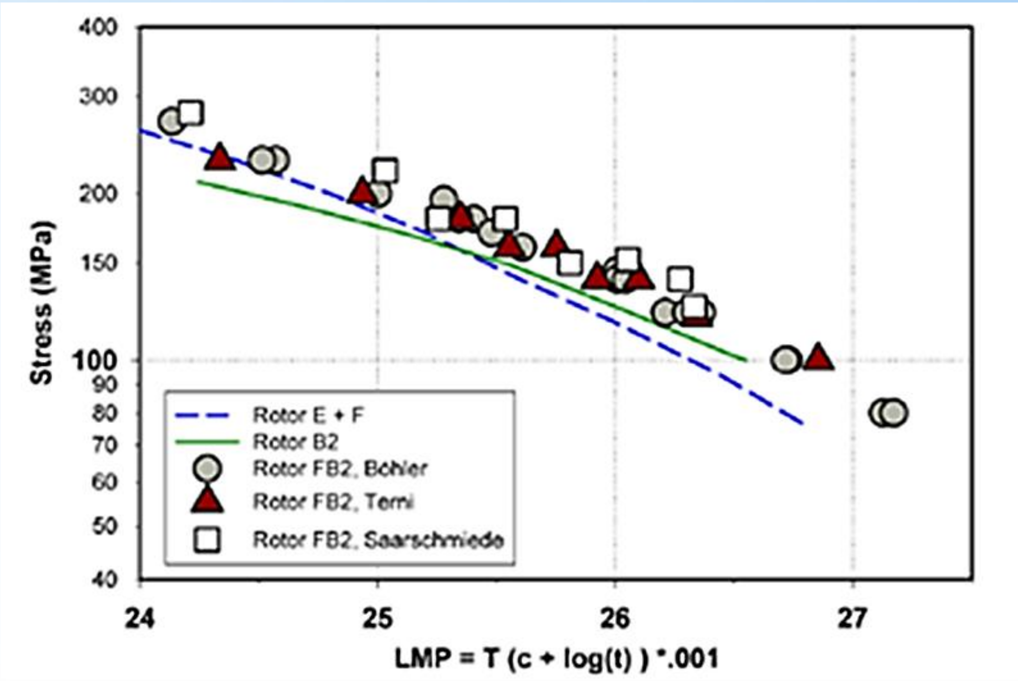


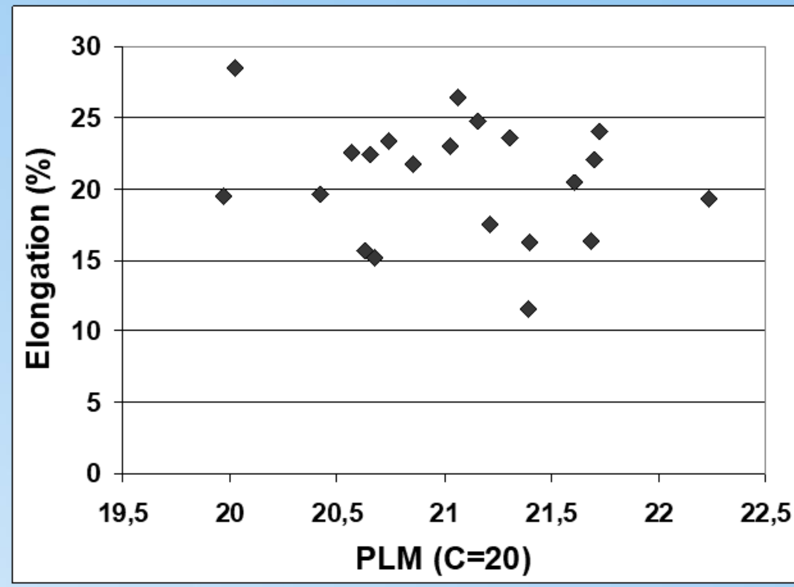


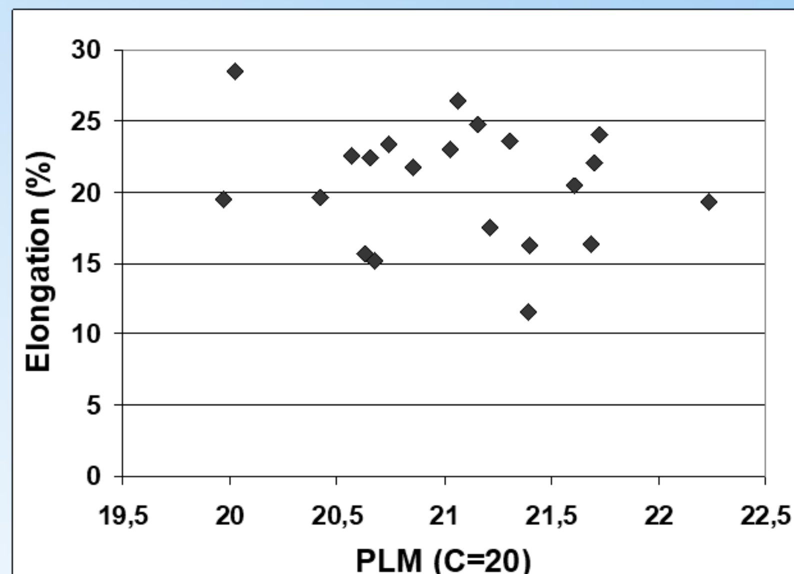
Superficie di frattura di provino di trazione di FB2: BN + MnO e una complessa particella di BN con MnS



Materiali per turbine a vapore







Proprietà di creep e duttilità

Materiali per turbine a vapore

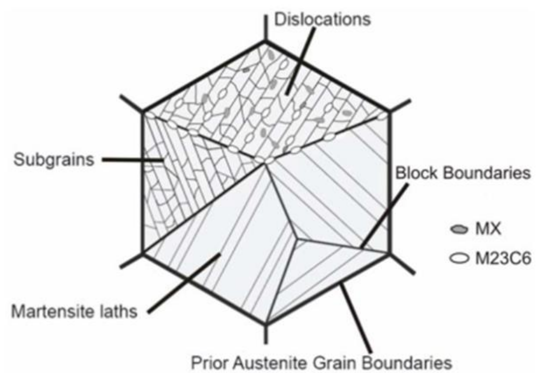


Fig. 3-4: Schematic illustration of microstructure of 9-12% Cr steel after tempering (Internal interfaces and precipitates) (adapted from [104]).

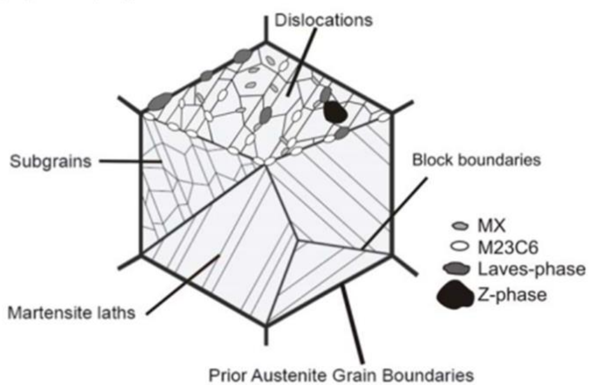
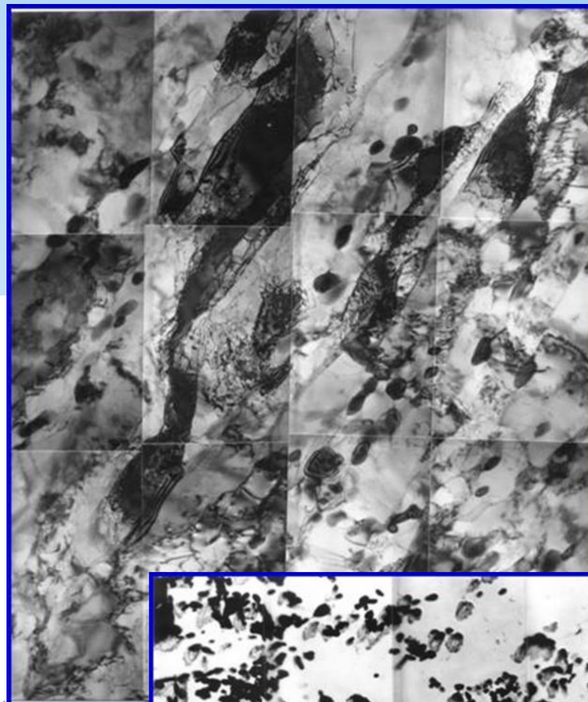
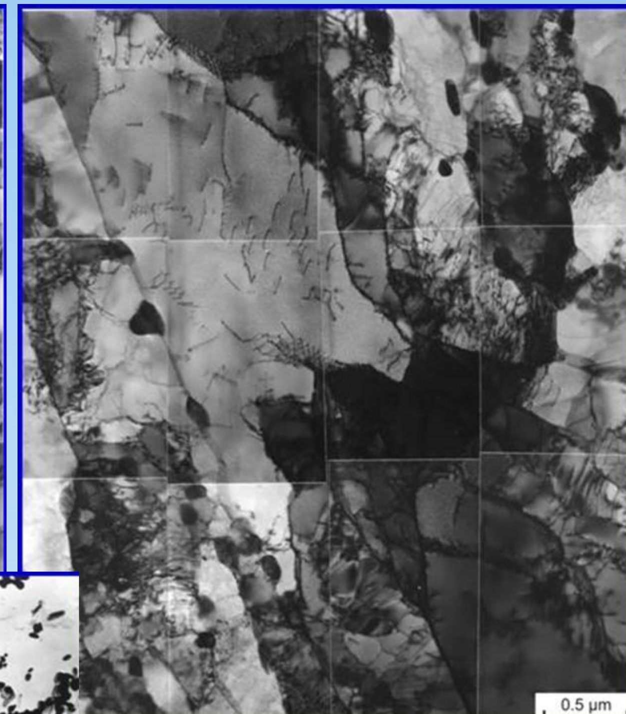
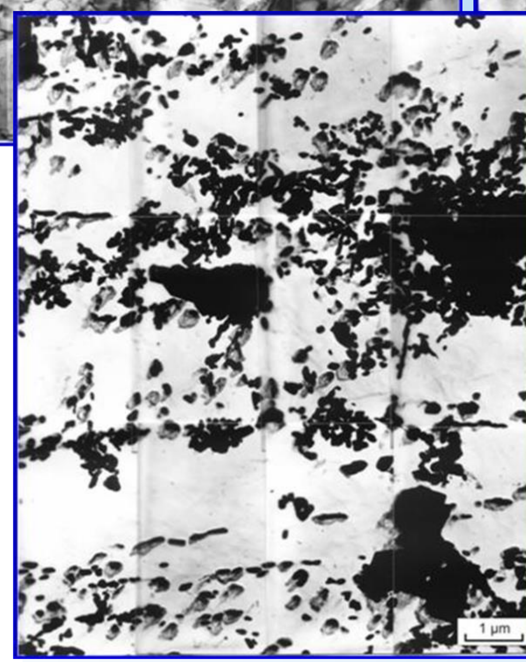
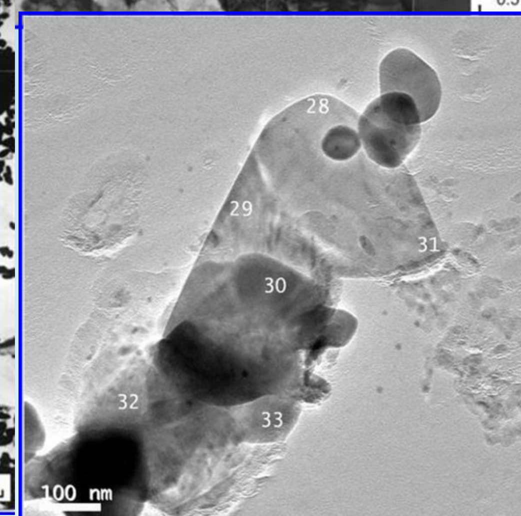


Fig. 3-5: Schematic illustration of microstructure evolution of 9-12% Cr steels after creep exposure (coarsening of internal interfaces and precipitation of more stables phases) (adapted from [104]).

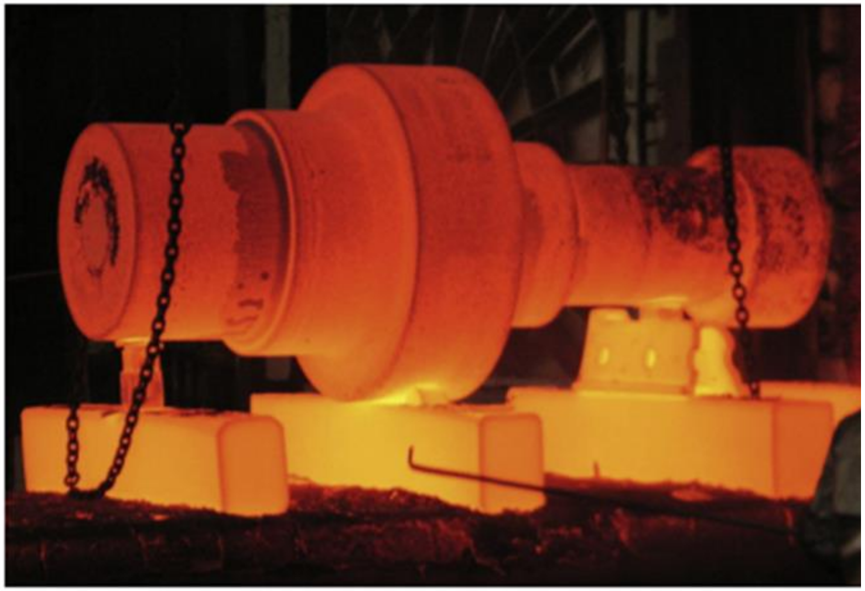








Materiali per turbine a vapore



Shaft component at QHT, COST steel F.

Shaft component machined, COST steel E.

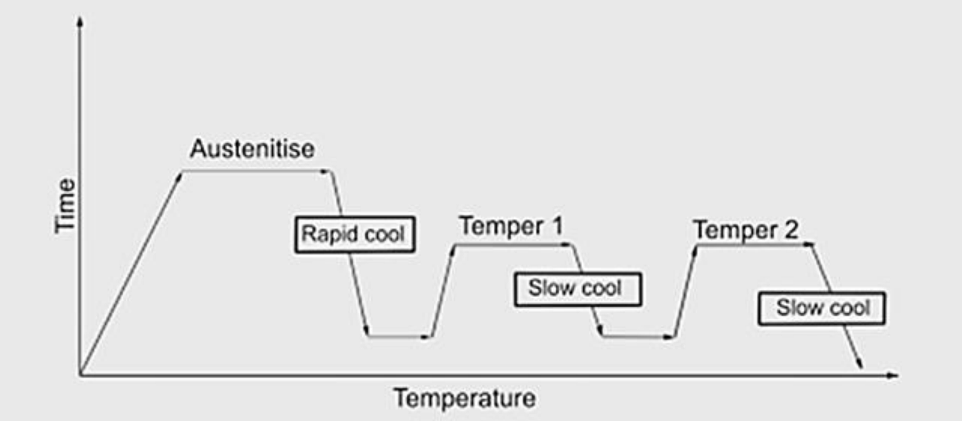
HP rotor at final forging, COST steel E.

Materiali per turbine a vapore

Table 5.1 **Typical valve and casing material grades**

Steel grade	C	Si	Mn	Ni	Cr	Mo	V	Nb	Other
Supercritical materials									
G17CrMo5-5 1¼Cr; ½Mo steel (Cr-Mo)	0.17	0.40	0.75	0.4x	1.25	0.55	–	–	
G17CrMoV5-10 1¼Cr; 1Mo; ¼V steel (Cr-Mo-V)	0.17	0.45	0.70	0.4x	1.35	1.0	0.25	–	Al <0.025
G17CrMo9-10 2¼Cr; 1Mo steel (Cr-Mo)	0.17	0.50	0.70	0.4x	2.25	1.0	0.02	–	Al <0.025
Ultra-supercritical materials									
G-X12CrMoVNbN9-1 P91/C12A type 9%Cr steel	0.12	0.30	0.60	0.4x	9.50	1.0	0.25	0.06	N:0.05
G-X12CrMoWVNb10-1-1 E911 type 9%Cr steel	0.12	0.25	0.75	0.60	10.0	1.0	0.25	0.06	W:1; N:0.05
GX-13CrMoCoVNbNB9 CB2 type 9%Cr steel with Boron	Nominal composition 9%Cr/1% Co/1.5% Mo, +V,Nb,B,N								
MarBN steel 9%Cr steel with Boron	Nominal composition 9%Cr/3% W/3% Co+V,Nb,B,N								

Materiali per turbine a vapore



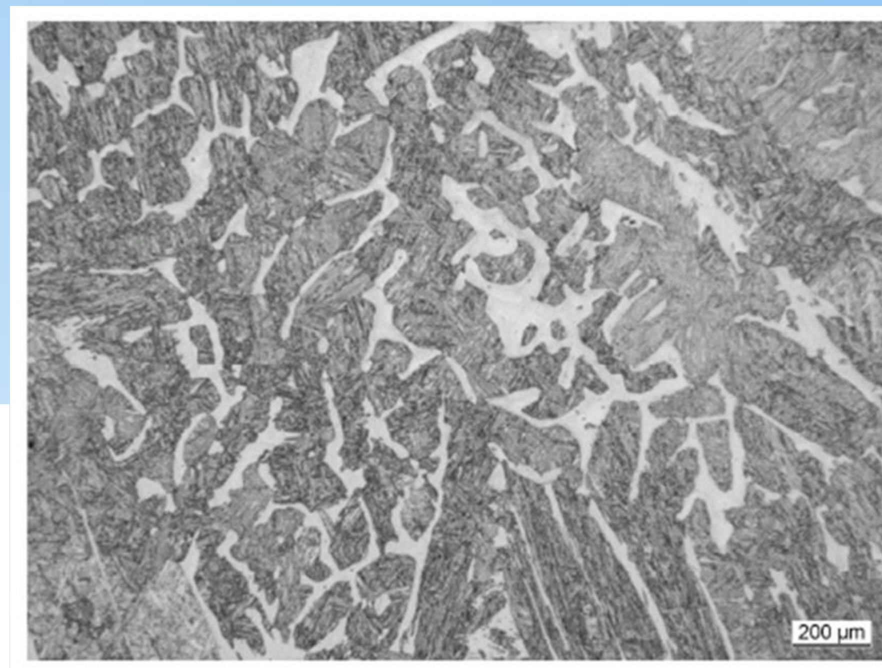
Schematic quality heat treatment for modified 9%Cr steels.

Main steam valves (800-MW) and ancillary components material GX12CrMoVNbN9-1 (cast P91). (Courtesy of Goodwin)

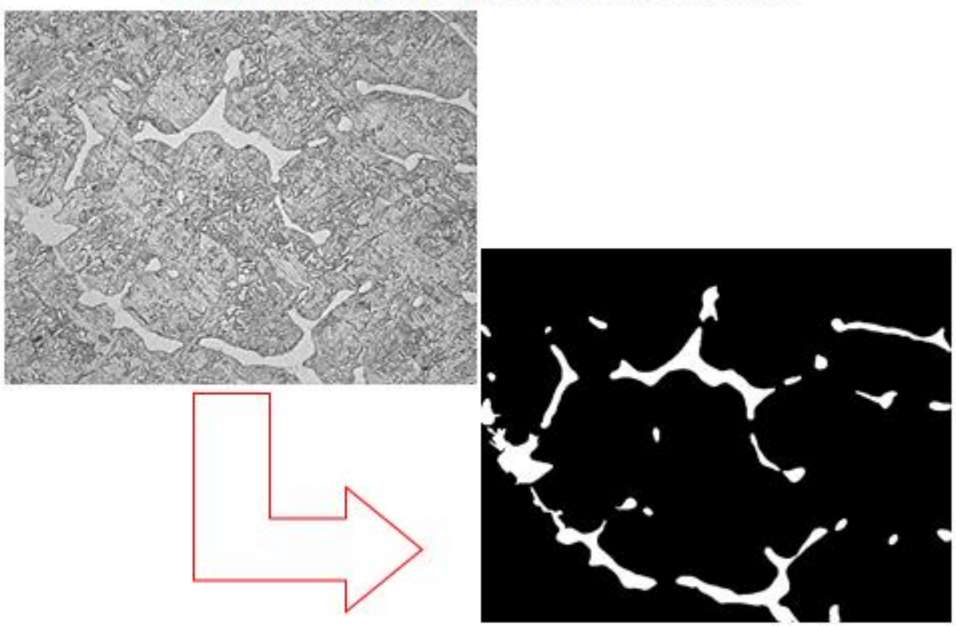
One thousand-MW unit comprised of eight castings (unit weight 49,000 kg); material: GX12CrMoWVNbN10-1-1 (cast E911). (Courtesy of Goodwin)

Materiali per turbine a vapore

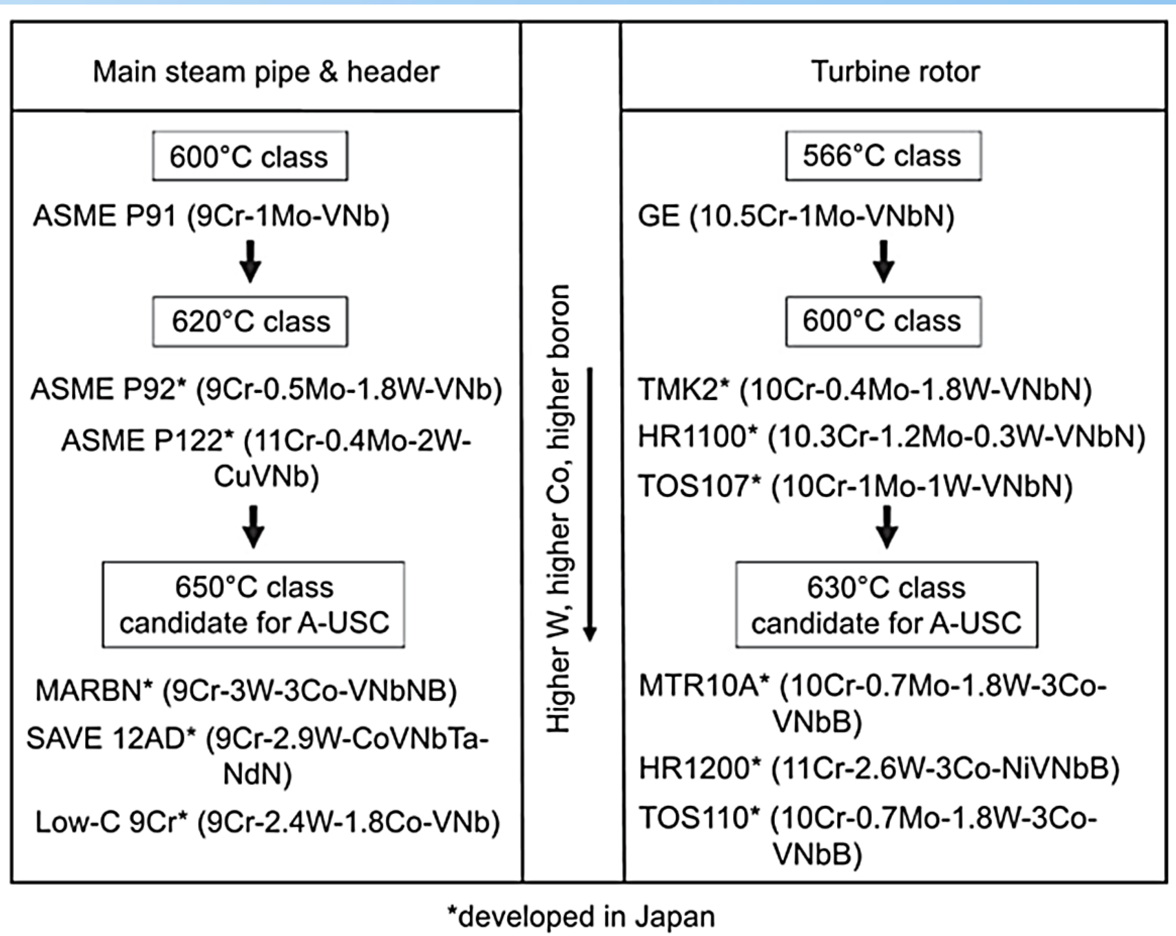
Nella fabbricazione di corpi fusi risulta fondamentale il controllo della velocità di solidificazione al fine evitare la formazione di ferrite



CONTEGGIO frazione volumetrica frazione ferrite



Materiali per turbine a vapore



Steel	C	Si	Mn	Cr	Mo	Ni	Co	W	V	Nb	N	B
MARBN	0.078	0.31	0.49	8.88	–	–	3.00	2.85	0.20	0.051	0.0079	0.0135
MARN	0.002	0.29	0.51	9.19	–	–	3.09	2.96	0.20	0.060	0.0490	0.0070

Figure 6.35 Chemical compositions of newly developed 9% Cr steels [wt%].

Materiali per turbine a vapore

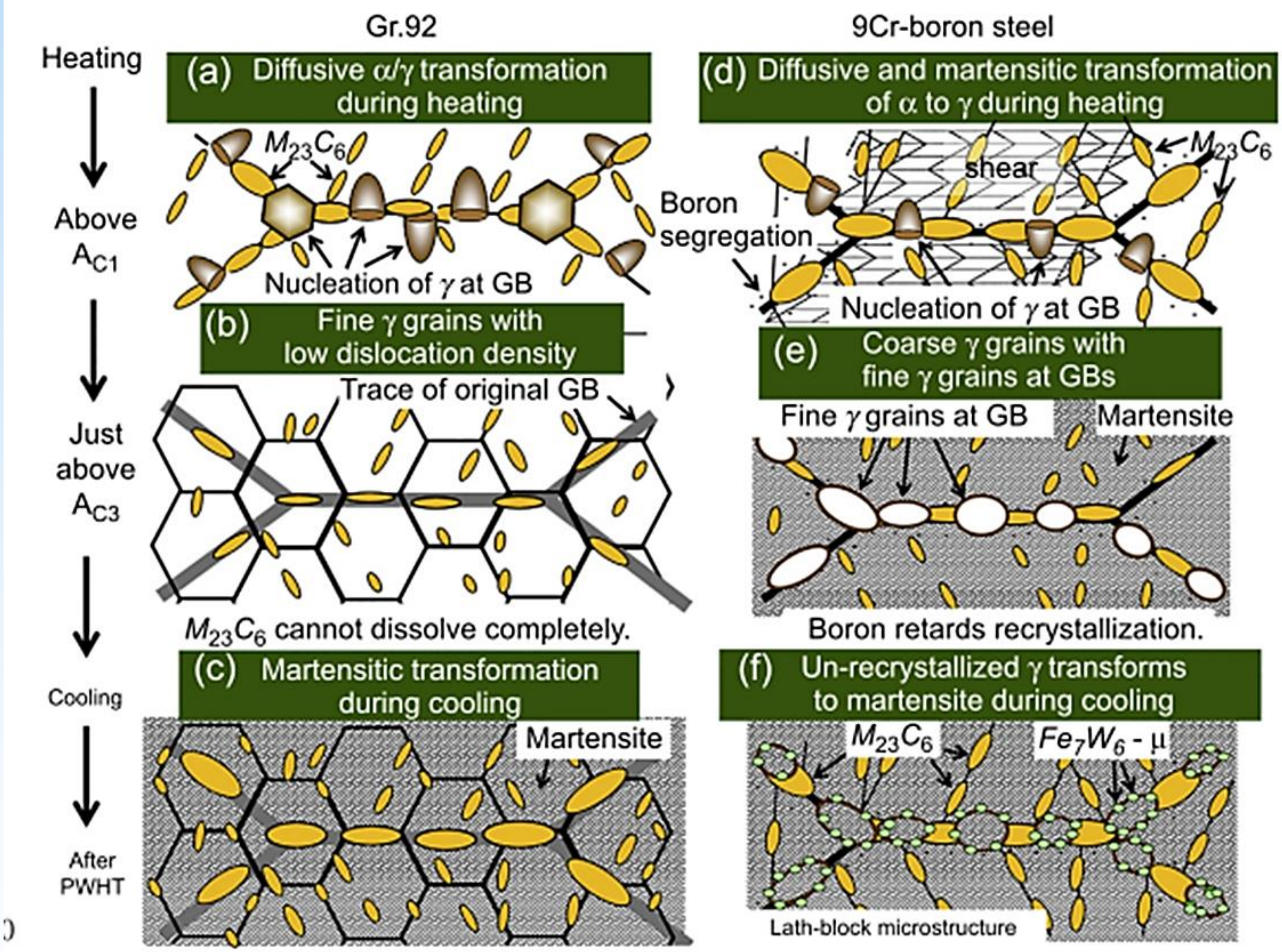
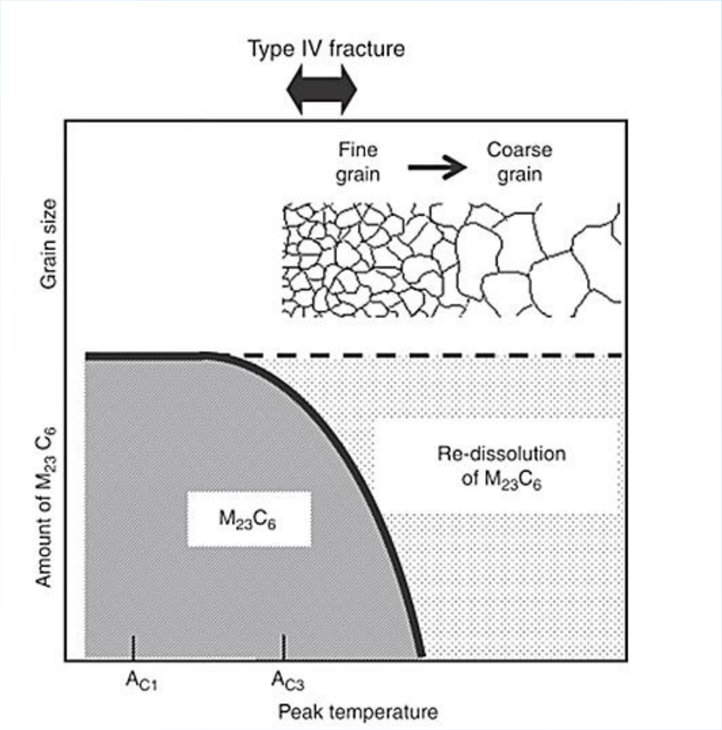
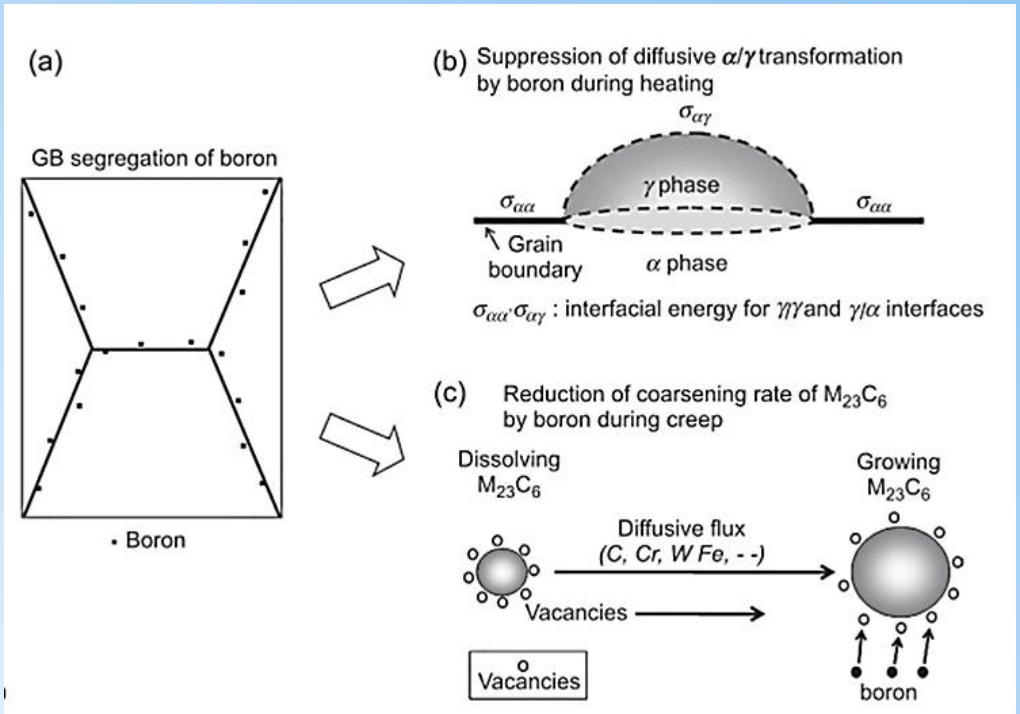


Figure 10.35 Schematics of microstructure evolution in Gr.92 and 9Cr-boron steel during simulated-HAZ thermal cycle.

Materiali per turbine a vapore





- Schematics of grain size and amount of M 23 C 6 carbides in Gr.92 during simulation heating

Schematics of (a) GB segregation of boron, (b) diffusive α / γ transformation at GB during heating and (c) reduction of coarsening rate of M23C6 carbides by boron during creep.

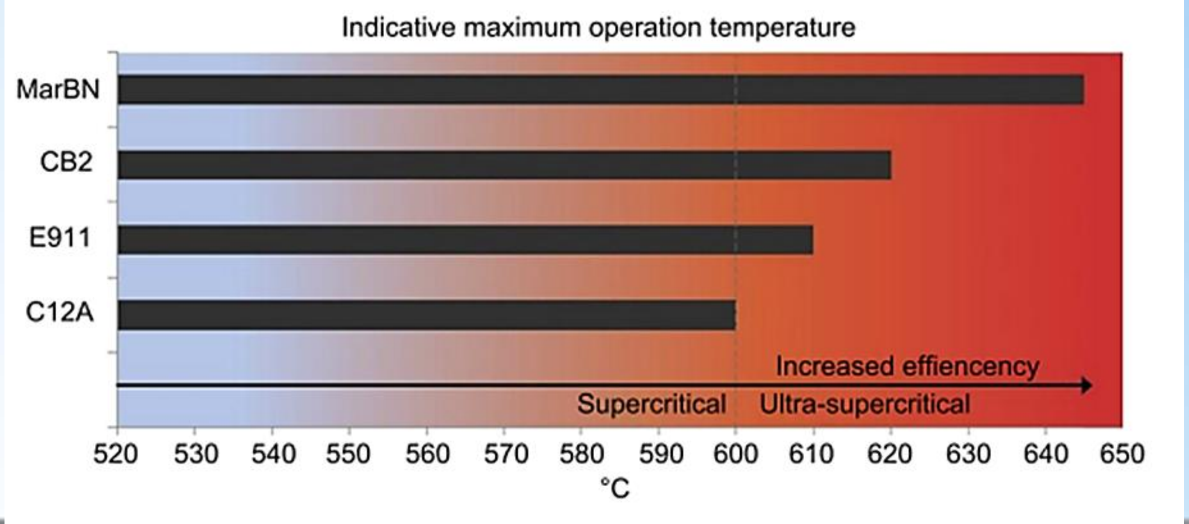
Materiali per turbine a vapore

Il nome MarBN deriva dal seguente: microstruttura martensitica e controllo del boro / azoto.

L'acciaio MarBN è stato originariamente proposto dal Prof. Fujio Abe del NIMS.

Lo sviluppo è basato su una nuova formulazione in lega: 9% Cr, 3% W, 3% Co.

Il MarBN si dimostra superiore ad altri acciai come il Grado 92 (9%Cr,1,5-2%W,0,5%Mo).



A graphical representation of the indicative maximum operating temperatures of common 9%Cr steel casting grades, state of the art grades and MarBN steel still underdevelopment. (Courtesy of Goodwin)

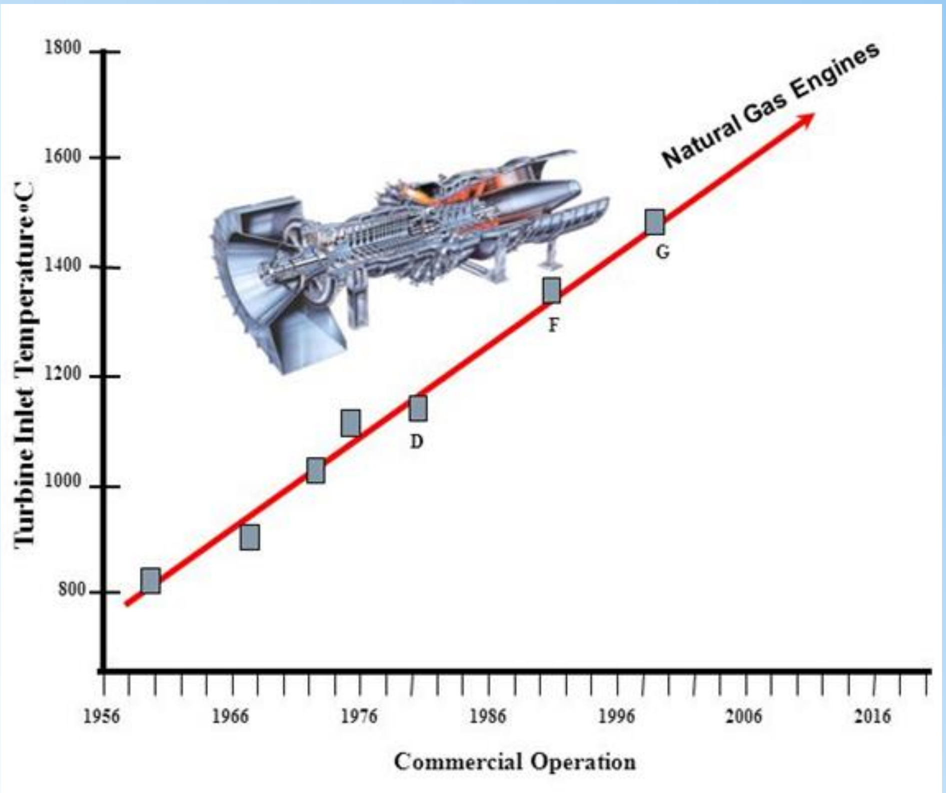
Rotture catastrofiche

Iranshahr Power Plant Explosion- Coupling Failure

Rotori per turbine a gas industriali:

- Superleghe base nickel

Rotori per turbine a gas industriali

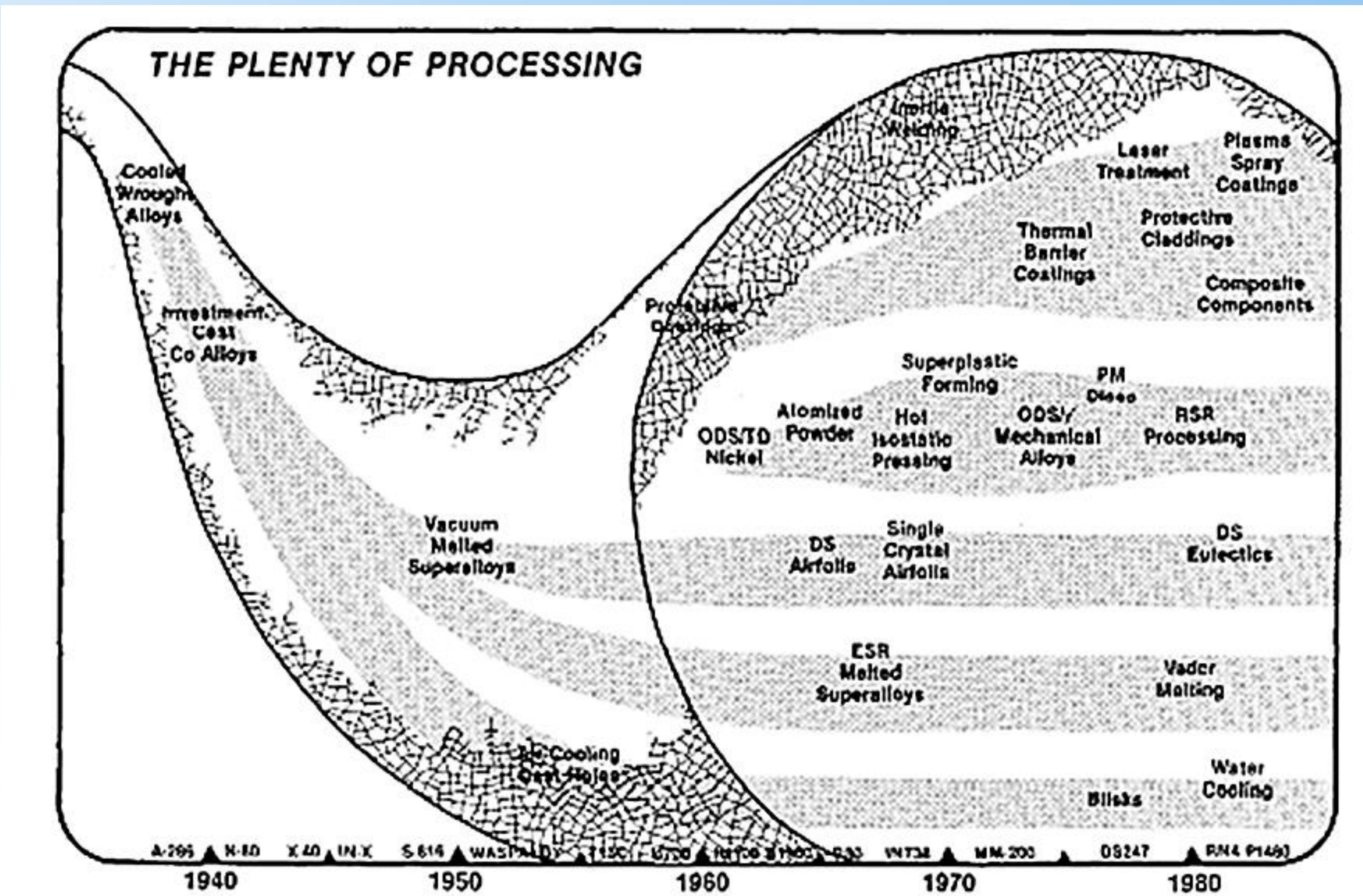


Engine	Rotor inlet temperature (°C)	Power output (MWe)	Predicted efficiency (%)
Westinghouse 501G	1426	240	58
Siemens V84/3a	1310	170	57
Alstom GT24/26	1240	188/281	57
General Electric 7FA	1290	150	55

Rotori per turbine a gas industriali

Component	Cr	Ni	Co	Fe	W	Mo	Ti	Al	Cb	V	C	B	Ta
Turbine Blades													
U500	18,5	**BAL**	18,5	_	_	4	3	3	_	_	0,07	0,006	_
RENE 77 (U700)	15	**BAL**	17	_	_	5,3	3,35	4,25	_	_	0,07	0,02	_
IN738	16	**BAL**	8,3	0,2	2,6	1,75	3,4	3,4	0,9	_	0,10	0,001	1,75
GTD111	14	**BAL**	9,5	_	3,8	1,5	4,9	3,0	_	_	0,10	0,01	2,8
Turbine Nozzles													
X40	25	10	**BAL**	1	8	_	_	_	_	_	0,50	0,01	_
X45	25	10	**BAL**	1	8	_	_	_	_	_	0,25	0,01	_
FSX414	28	10	**BAL**	1	7	_	_	_	_	_	0,25	0,01	_
N115	21	20	20	**BAL**	2,5	3	_	_	_	_	0,20	_	_
GTD-222	22,5	**BAL**	19	_	2,0	2,3	1,2	0,8	_	0,10	0,008	1,00	_
Combustors													
SS309	23	13	_	**BAL**	_	_	_	_	_	_	0,10	_	_
HAST X	22	**BAL**	1,5	1,9	0,7	9	_	_	_	_	0,07	0,005	_
N-263	20	**BAL**	20	0,4	_	6	2,1	0,4	_	_	0,06	_	_
HA-188	22	22	**BAL**	1,5	14,0						0,05	0,01	
Turbine Wheels													
Alloy 718	19	**BAL**	_	18,5	_	3,0	0,9	0,5	5,1	_	0,03	_	_
Alloy 706	16	**BAL**	_	37,0	_	_	1,8	_	2,9	_	0,03	_	_
Cr-Mo-V	1	0,5	_	**BAL**	_	1,25	_	_	_	0,25	0,30	_	_
A286	15	25	_	**BAL**	_	1,2	2	0,3	_	0,25	0,08	0,006	_
M152	12	2,5	_	**BAL**	_	1,7	_	_	_	0,3	0,12	_	_
Compressor Blades													
AISI 403	12	_	_	**BAL**	_	_	_	_	_	_	0,11	_	_
AISI 403 + Cb	12	_	_	**BAL**	_	_	_	_	0,2	_	0,15	_	_
GTD-450	15,5	6,3		**BAL**		0,8					0,03		

Rotori per turbine a gas industriali



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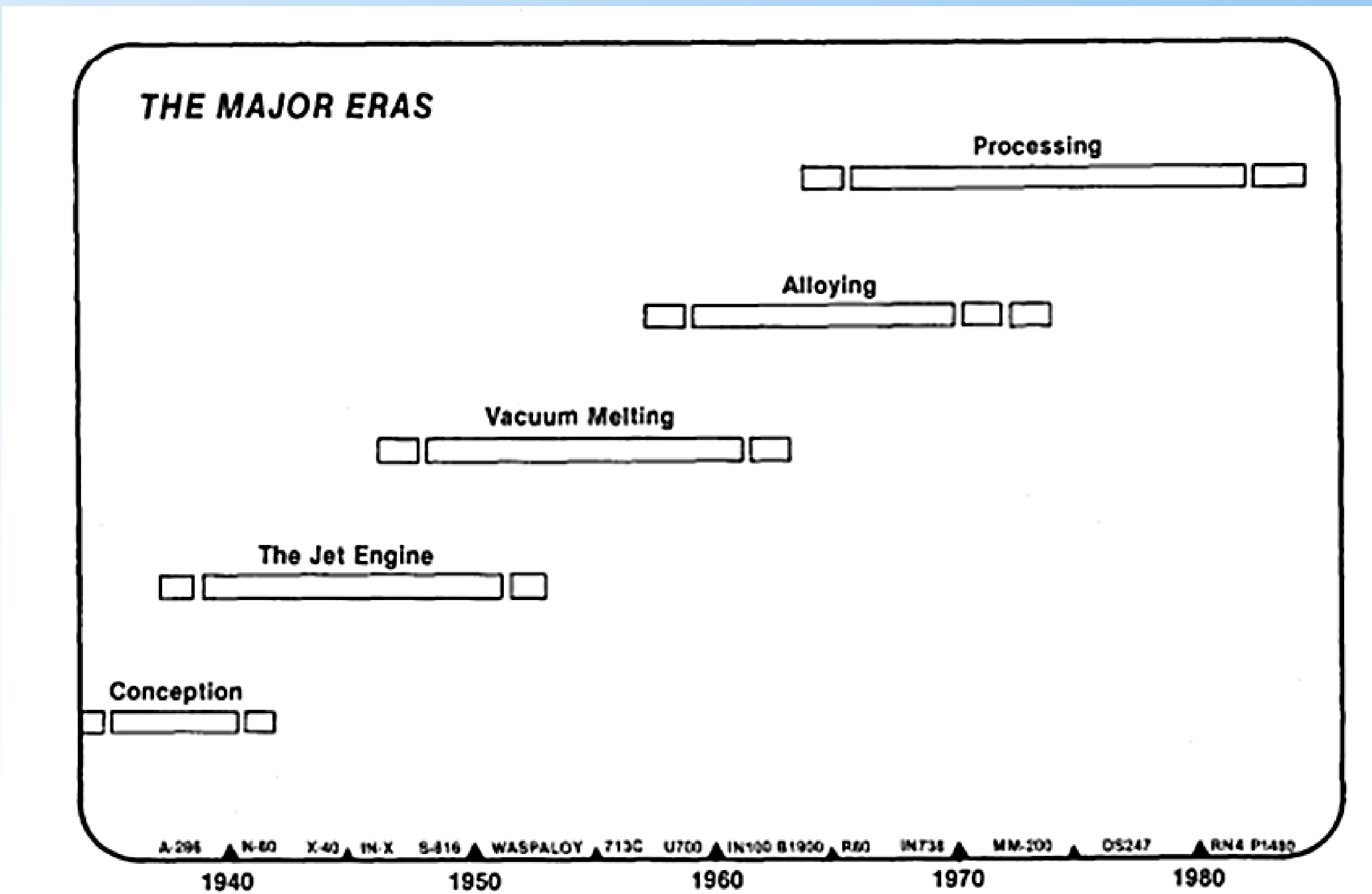
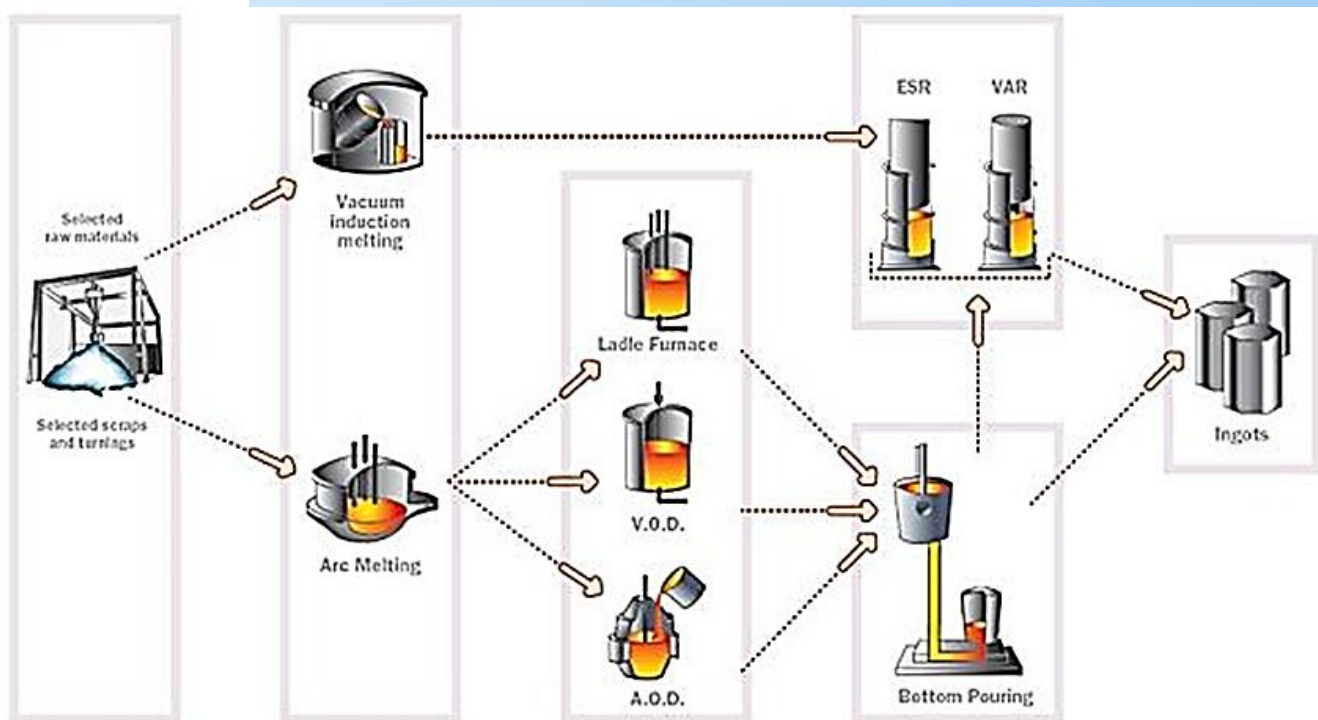


Rotori per turbine a gas industriali

Alloy	Melt method
600	EAF/AOD + ESR
625	EAF/AOD + ESR
	VIM + ESR
	VIM + VAR
706	VIM + ESR
	VIM + VAR
	VIM + ESR + VAR
718	VIM + ESR
	VIM + VAR
	VIM + ESR + VAR
925	EAF/AOD + ESR
A-286	EAF/AOD + ESR
	VIM + ESR
	VIM + VAR
C-276	EAF/AOD + ESR
Hast. X	EAF/AOD + ESR

Note: EAF, electric arc furnace; AOD, arg
rization; ESR, electroslag remelting; VIM
melting; VAR, vacuum arc remelting



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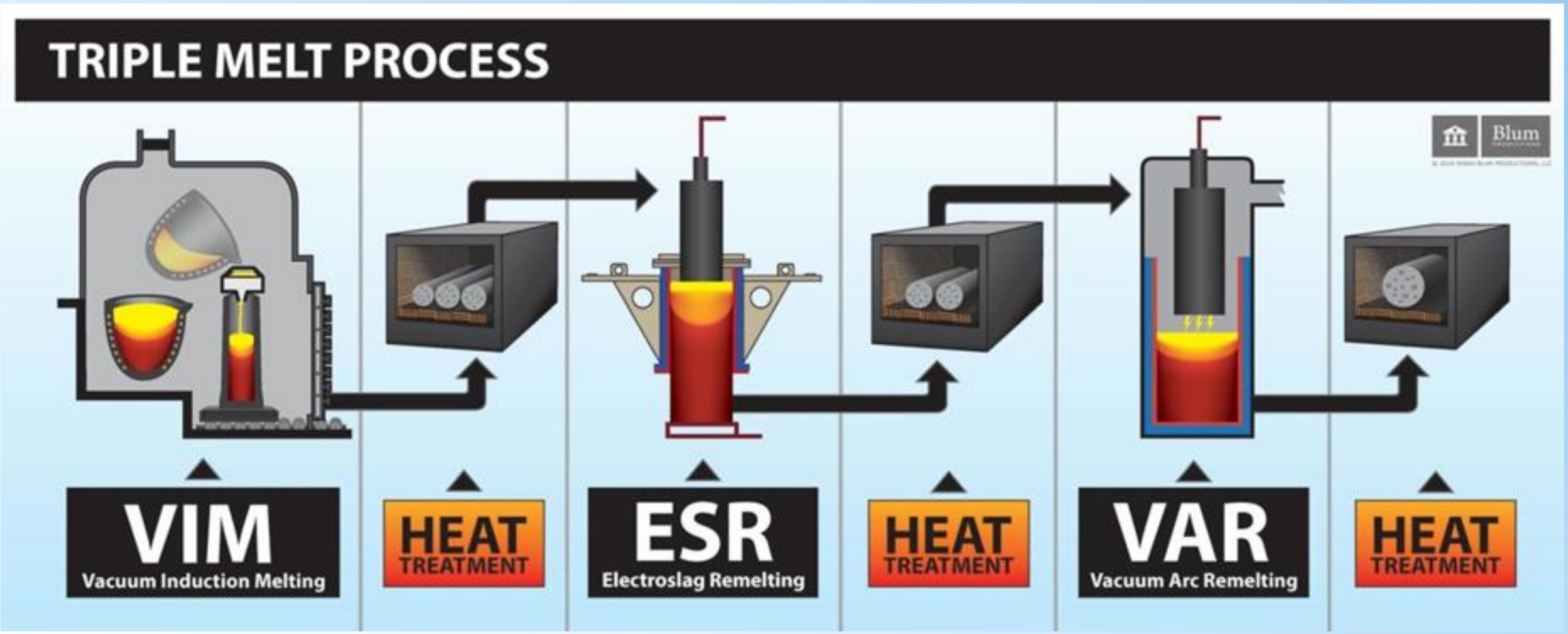

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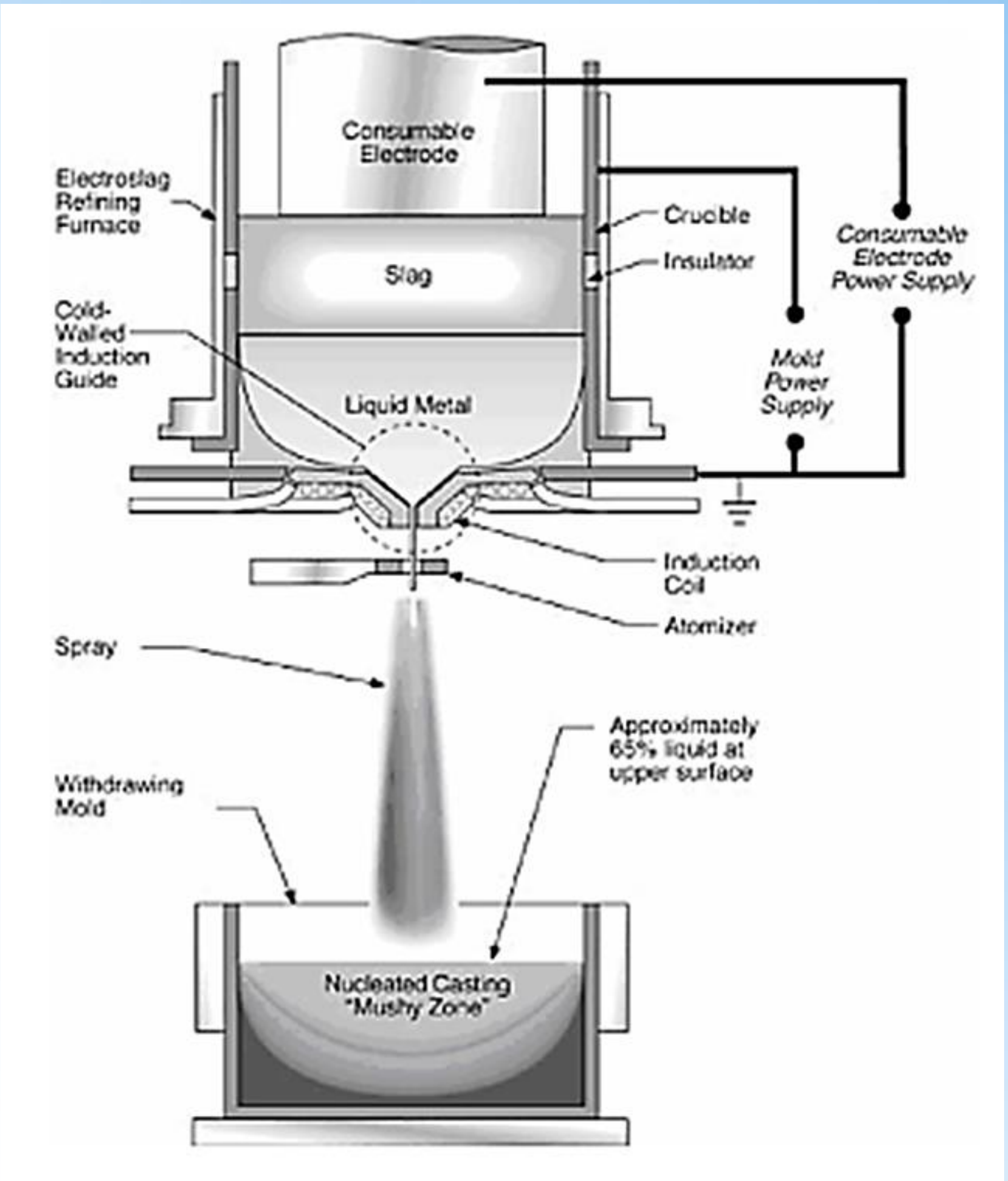
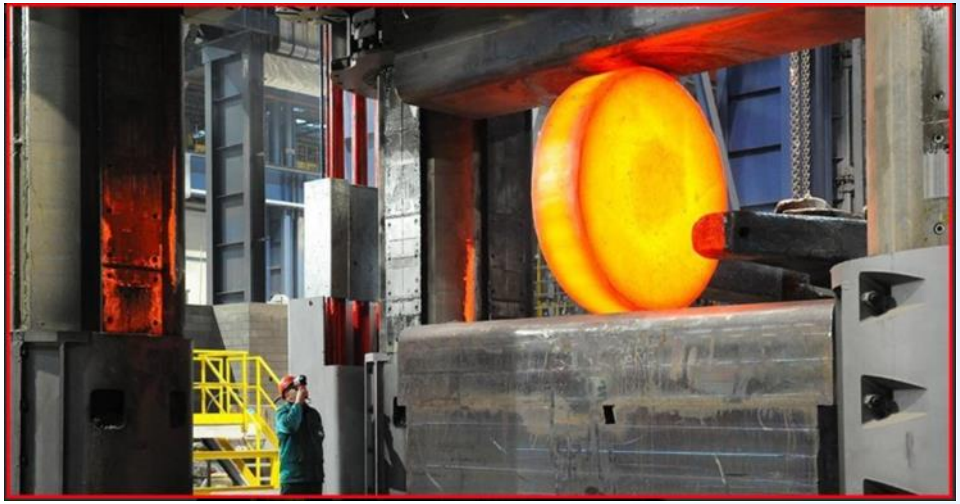


Compusystem s.r.l

Rotori per turbine a gas industriali

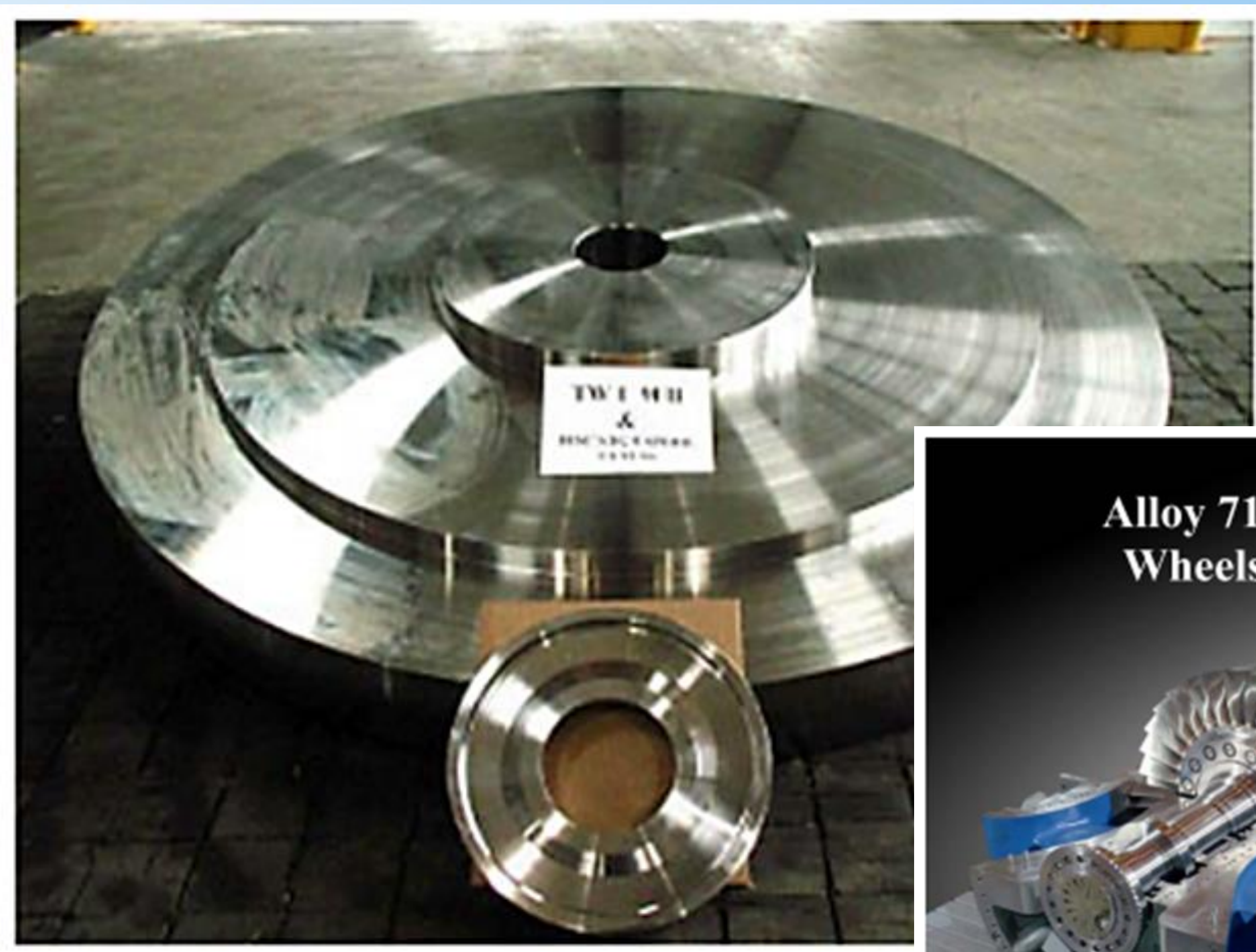
16Kton Press Courtesy of Forgiatura Morandini

IN706 turbine wheel (Courtesy of Aubert & Duval



IN718 Forging at Forgiatura Morandini

Rotori per turbine a gas industriali



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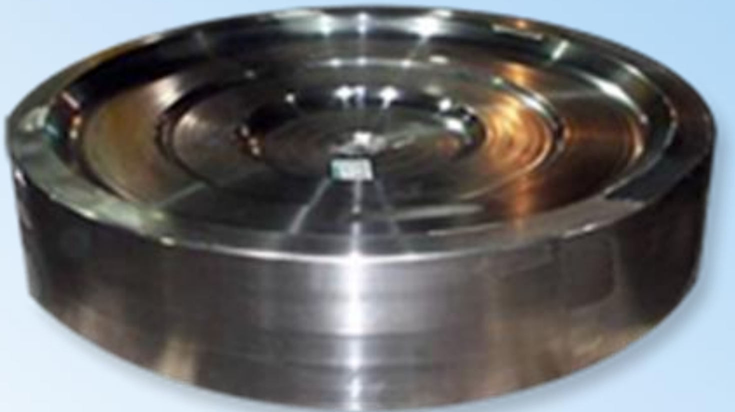

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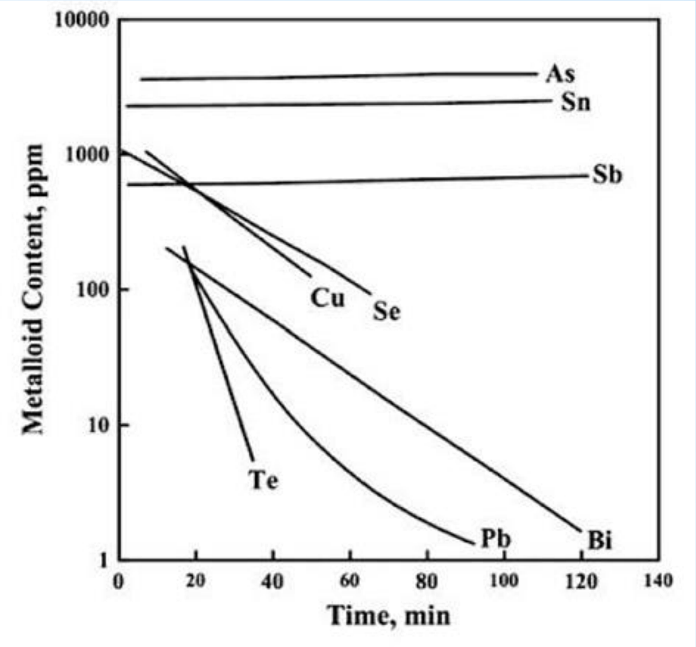


Removal of metalloid elements during refining

There are three classes of defects that are of concern in the remelting of Ni-base superalloys:

- White spots: which are local depletions in the strengthening elements;
- Freckles: which are enriched in primary strengthening elements;
- Ring pattern of equiaxed grains which occur due to the thermal fluctuations and restrict columnar grain growth.

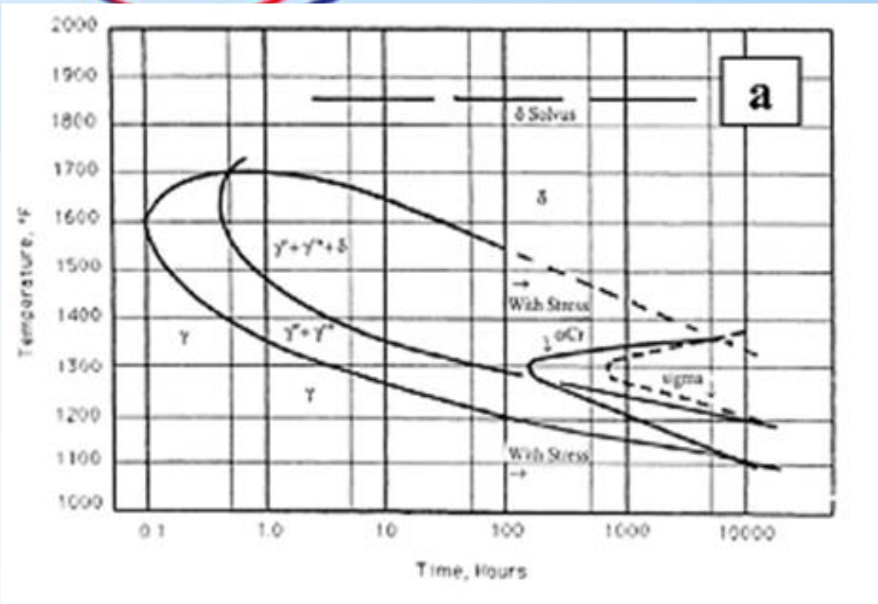
Materiali per rotori di turbine a vapore

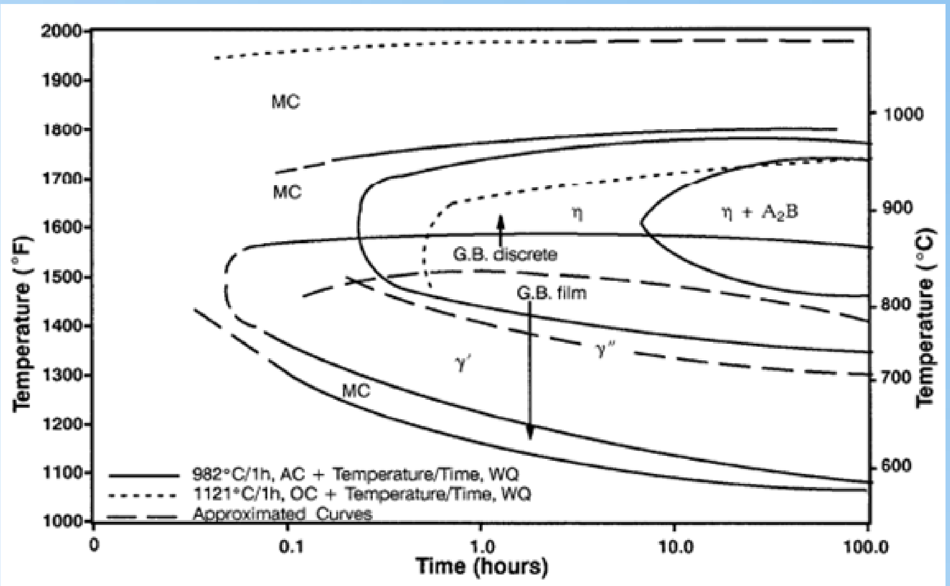
Alloy	Element	Ni + (Co)	Cr	Fe**	Nb + (Ta)	Mo	Al	Ti	C	Cu	Mn	Si	S	P	B	Co*
706	Min (%)	39	14.5		2.5			1.5								
	Max (%)	44	17.5	bal	3.3		0.4	2.0	0.06	0.3	0.35	0.35	0.015	0.02	0.006	1.0
718	Min (%)	50	17		4.75	2.8	0.2	0.65								
	Max (%)	55	21	bal	5.50	3.3	0.8	1.15	0.08	0.3	0.35	0.35	0.015	0.015	0.006	1.0

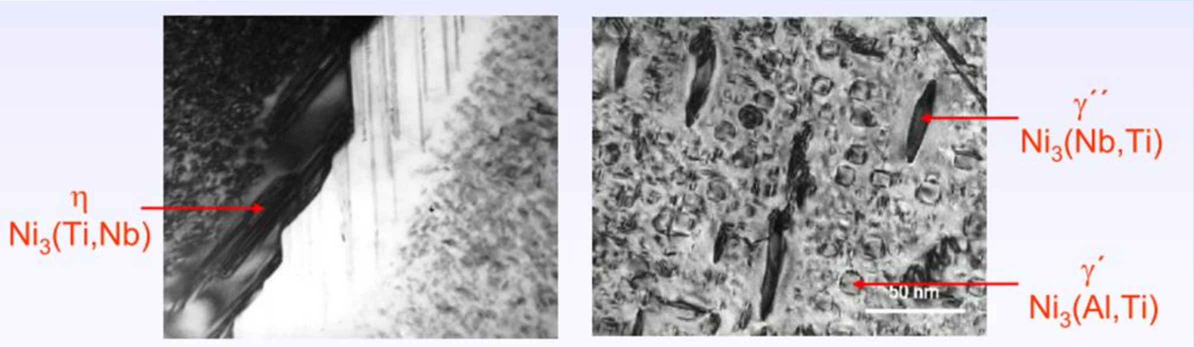
Traces: these elements have to be strictly recommended as low as possible:

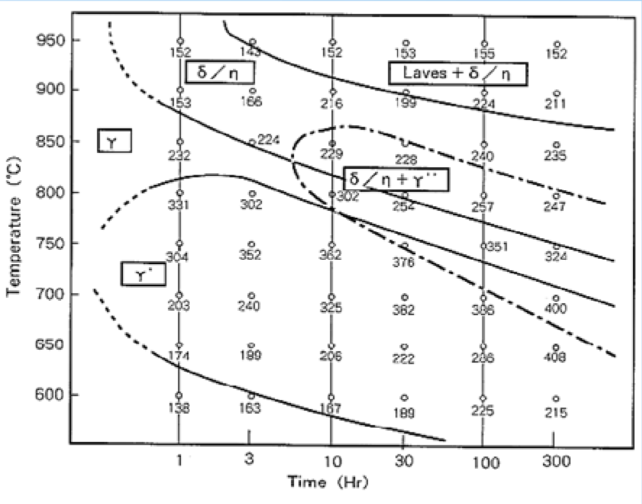
Ag < 5ppm
Pb < 20ppm
Bi < 1ppm
As < 30ppm
Sb < 30ppm
Sn < 30ppm
H < 3ppm
O < 20ppm

Rotori per turbine a gas industriali









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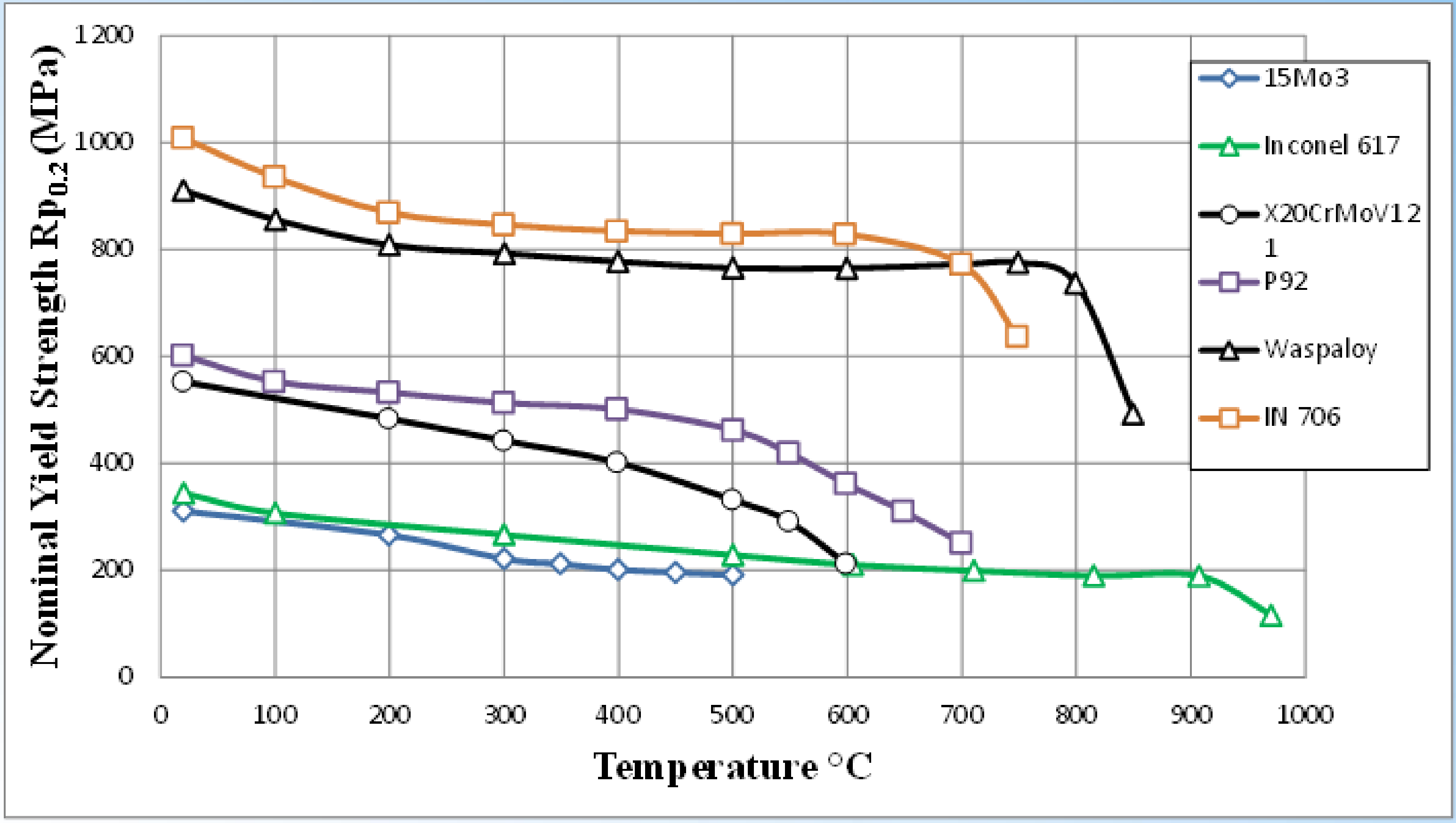
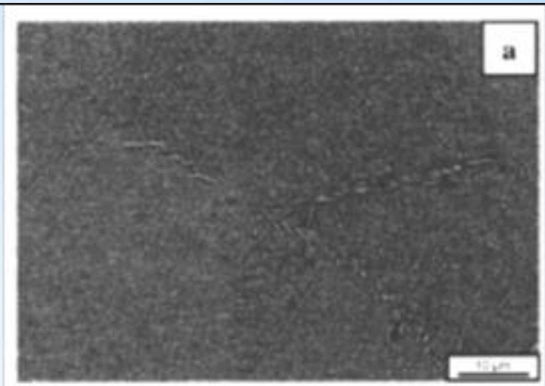
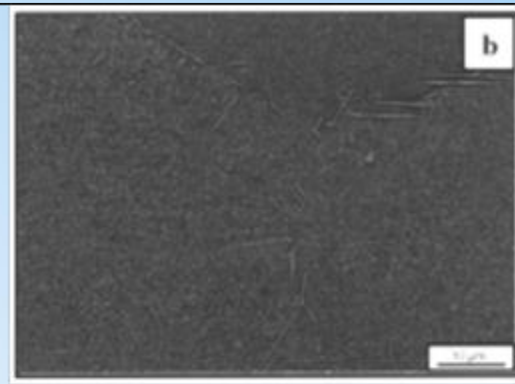
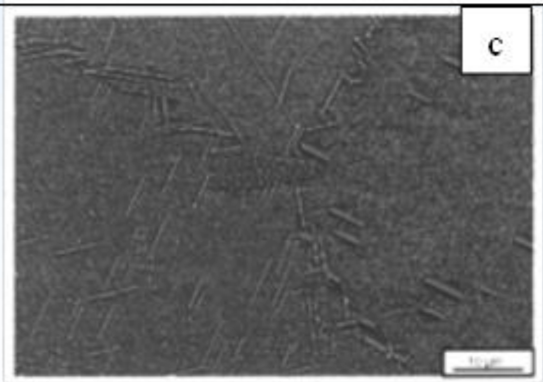


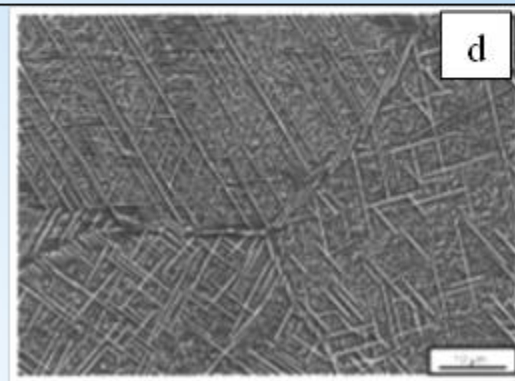
Rotori per turbine a gas industriali

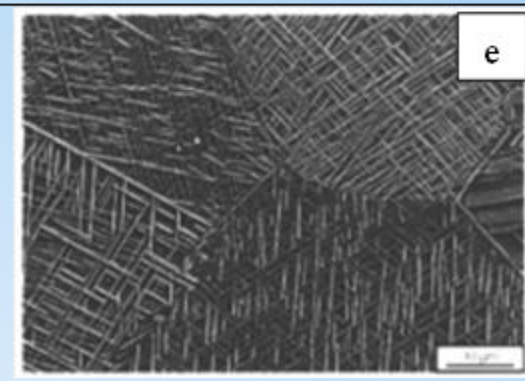




IN706B aged:
a) at 700°C for 427h,
b) at 700°C for 1065h,
c) at 750°C for 297h
d) at 750°C for 955h
e) at 750°C for 2330h







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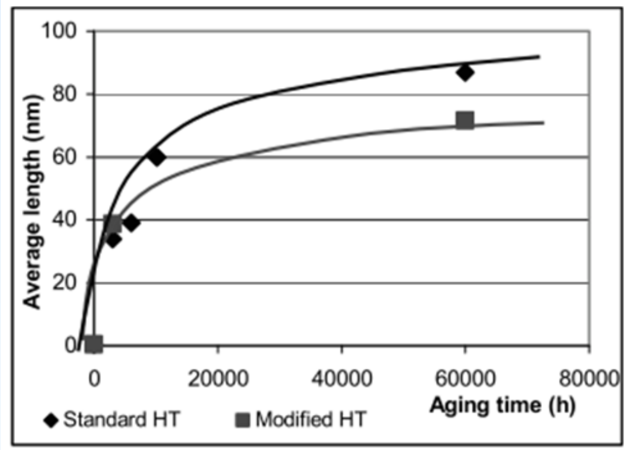
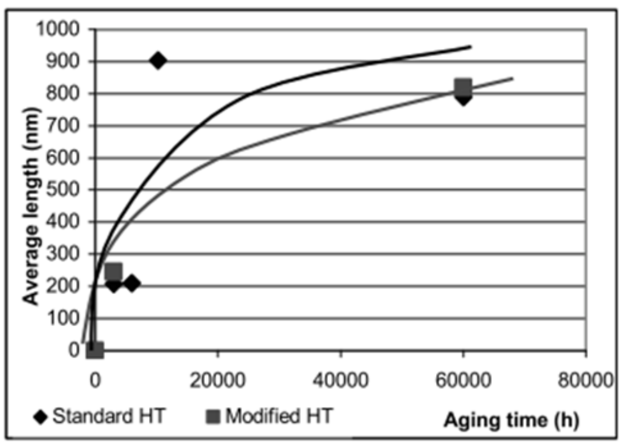
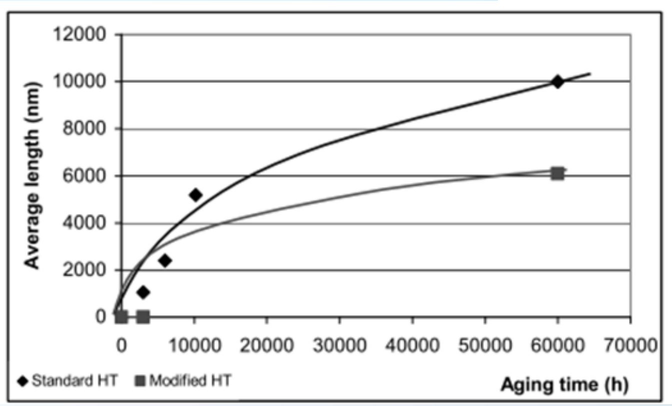
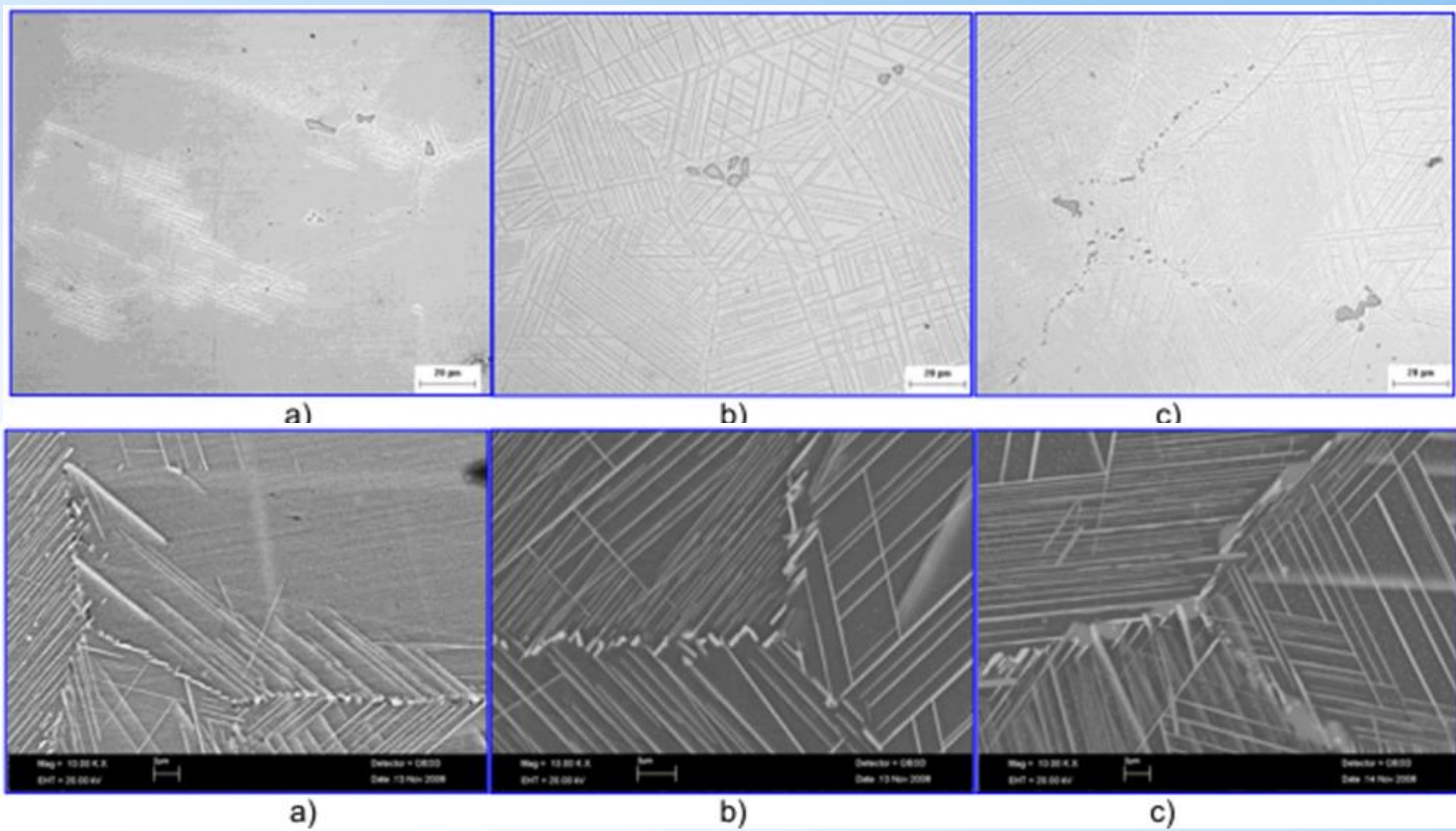






γ’ (left), γ’’ (right) and δ (bottom) phases coarsening in aging tests

Rotori per turbine a gas industriali



IN718 mod microstructures of aged specimens by LOM and SEM: a) 650°C – 25355h; b) 700°C – 25860h; c) 750°C – 33206h

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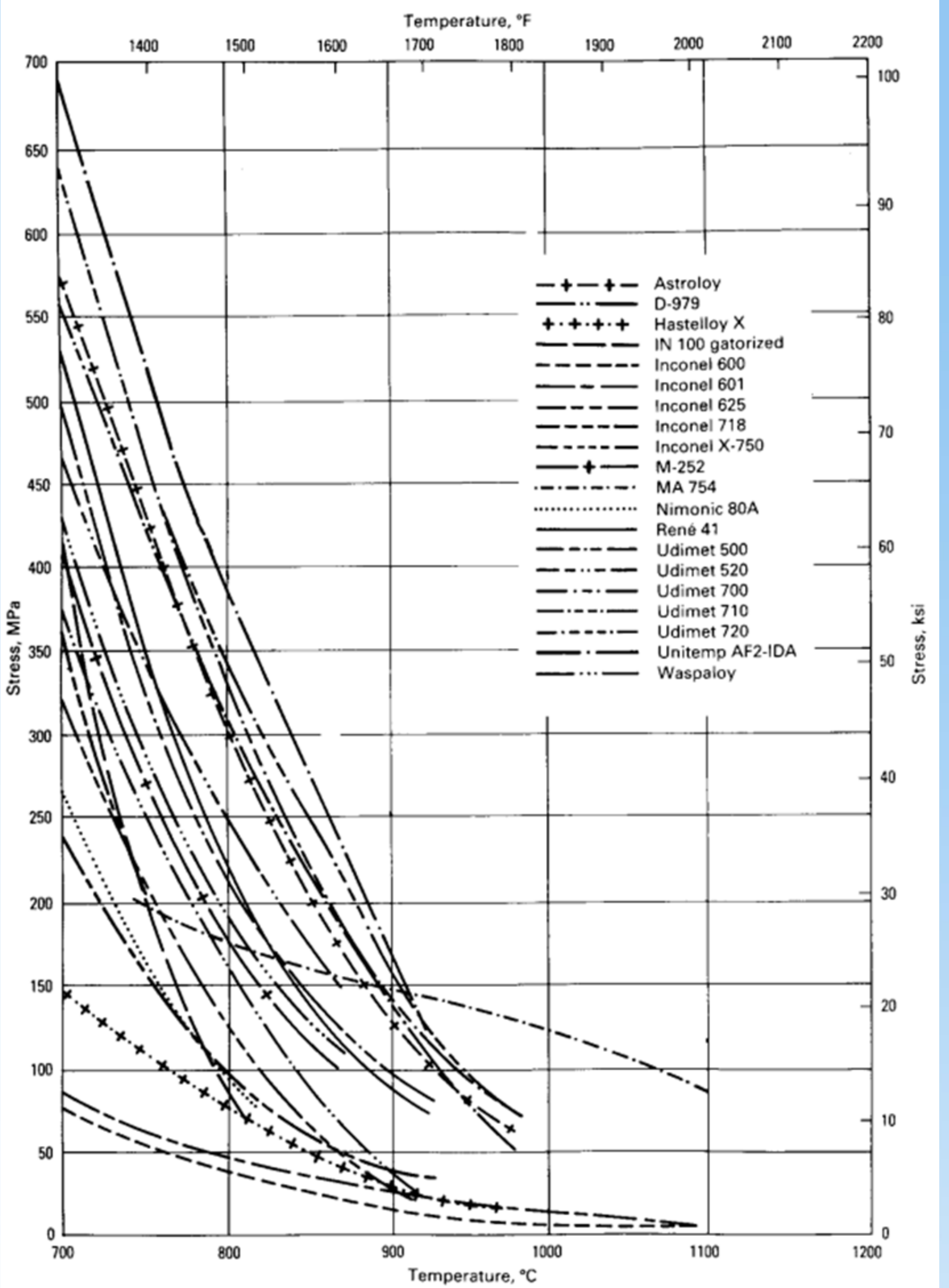

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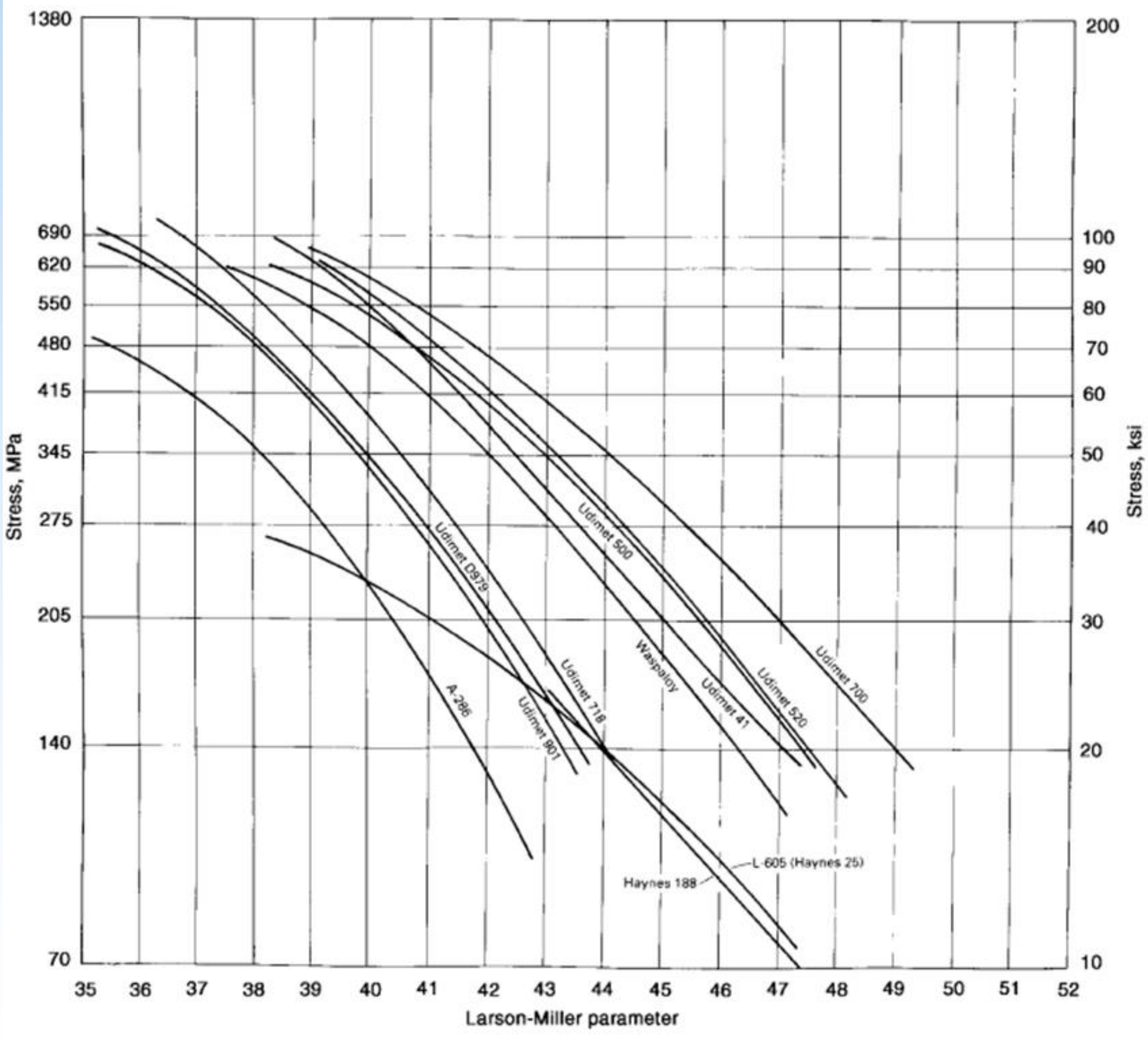

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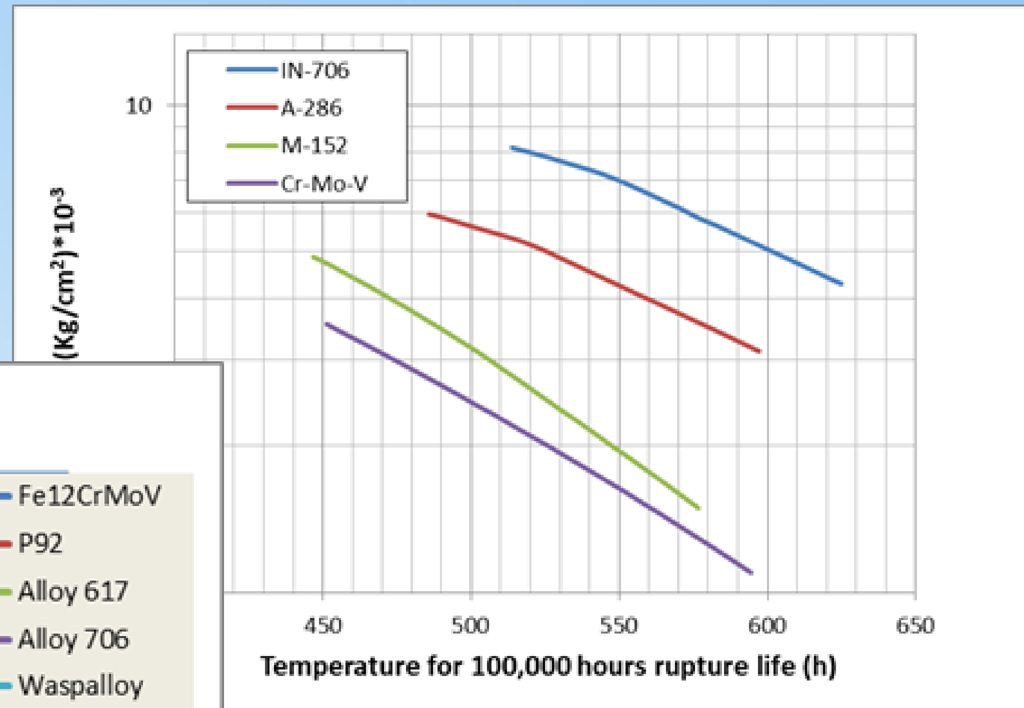

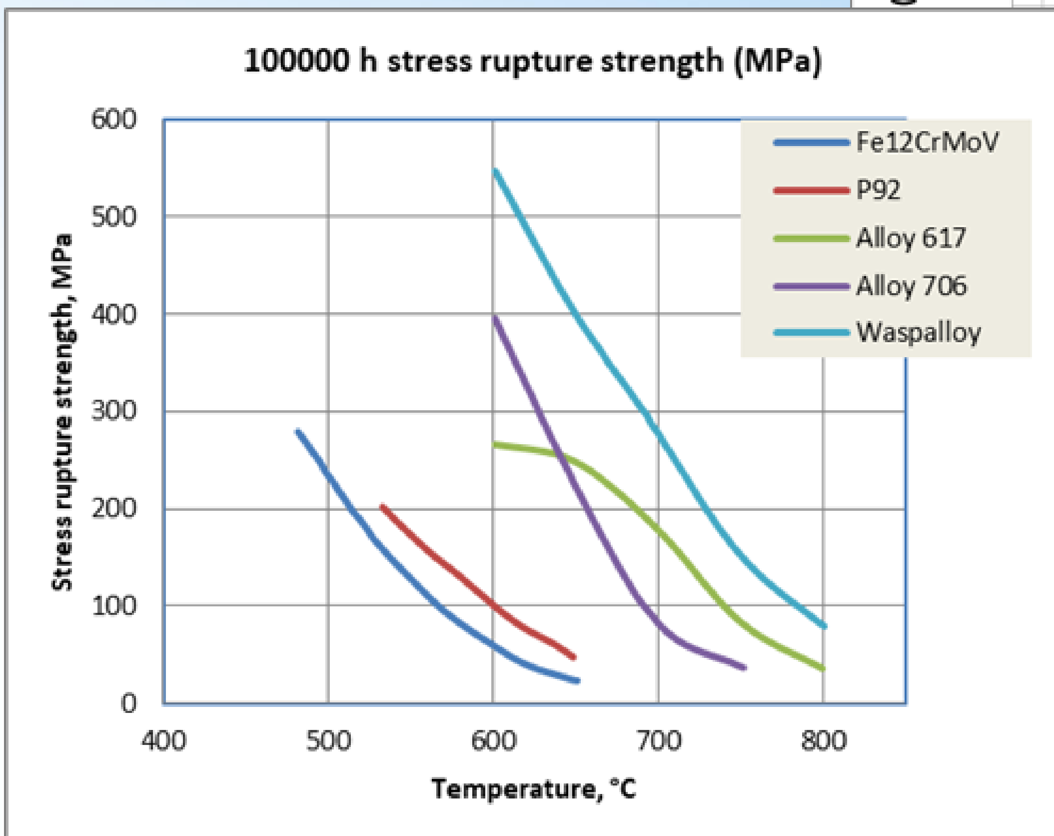

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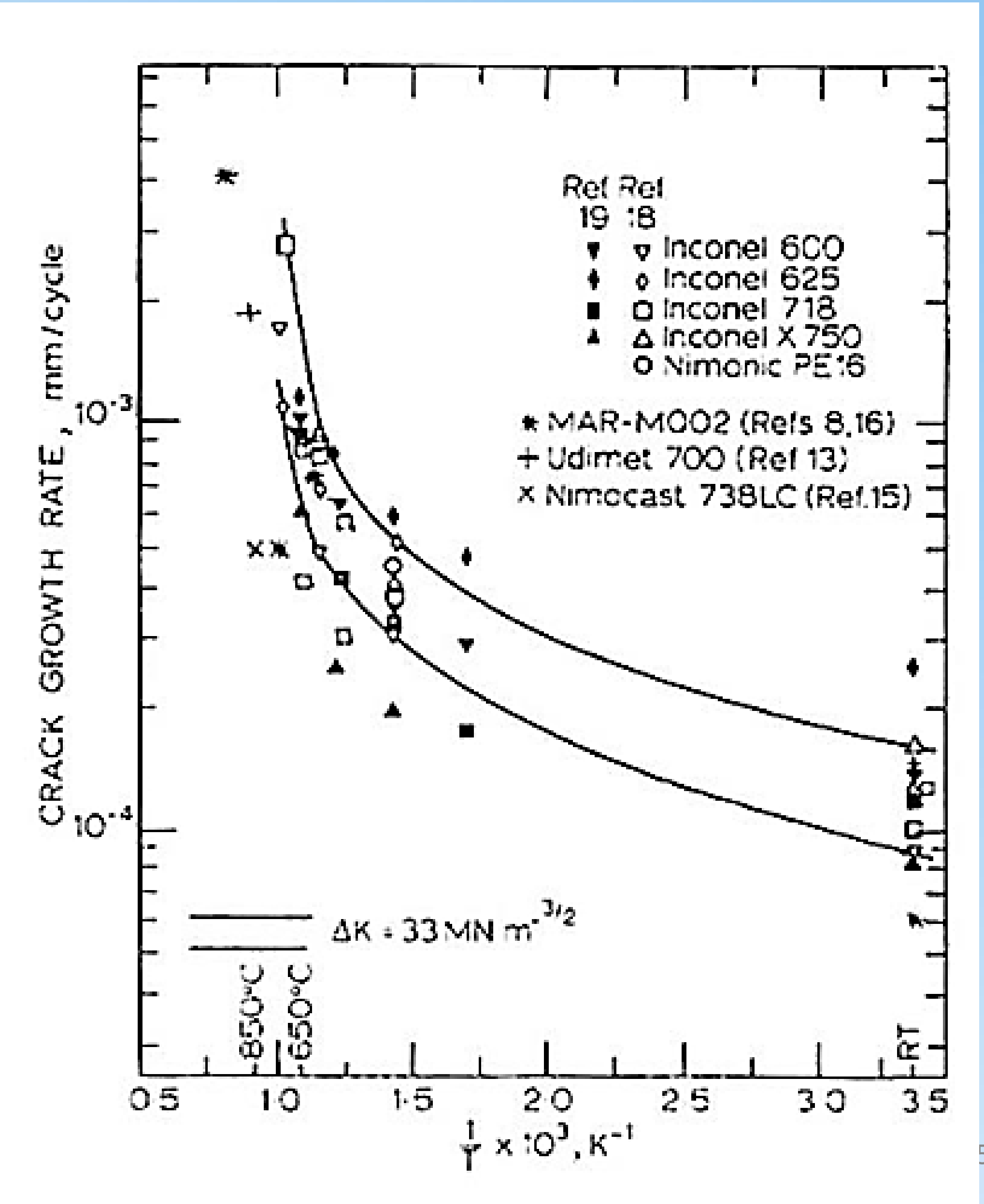

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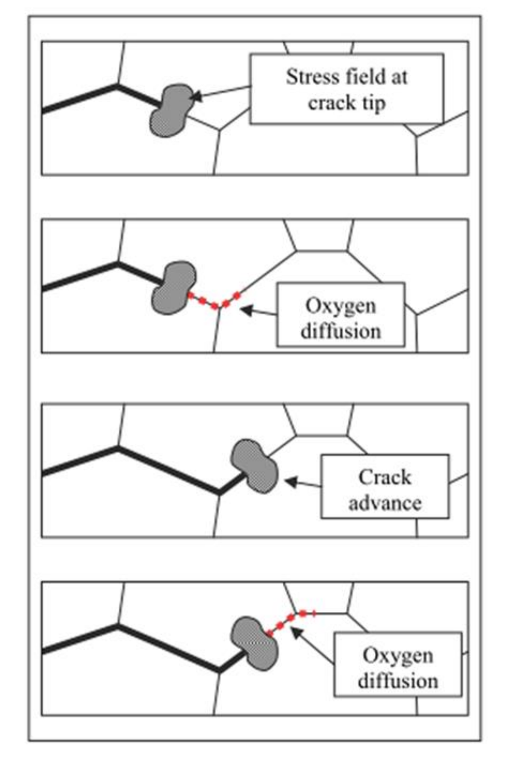
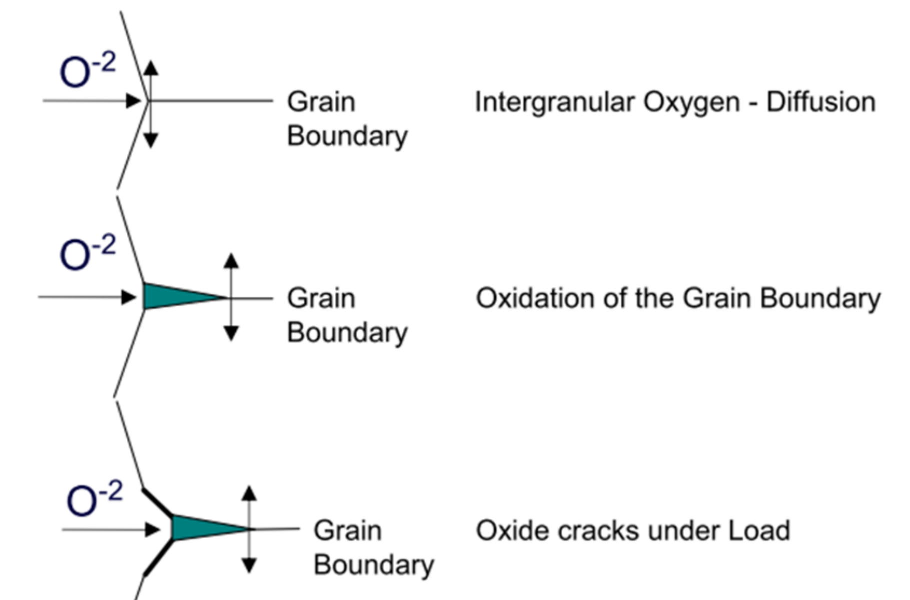
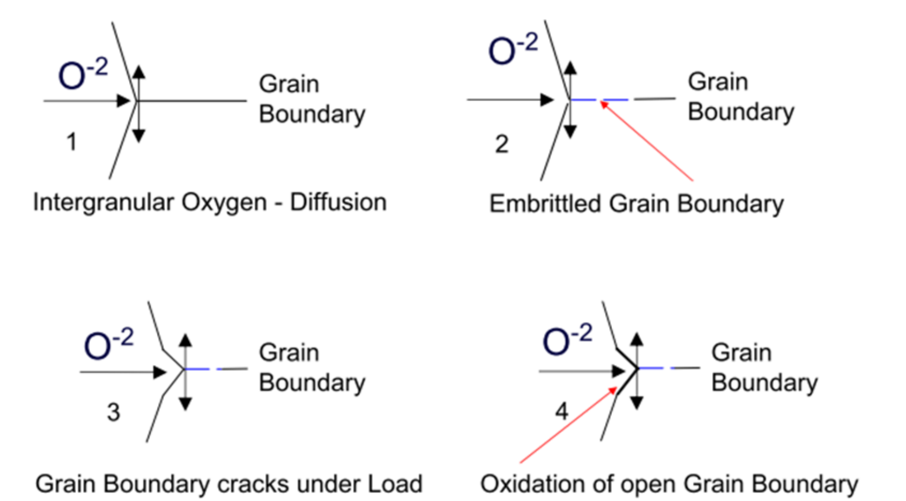




McMahon and Collin: Mechanisms of Damage and Fracture in High-Temperature, Low –Cycle Fatigue of a Cast-Based Superalloy, Metallurgical Transactions, Vol.1,3443 (1970)



Bricknell and Woodford: Grain Boundary Embrittlement of the Iron-Base Superalloy IN903A, Metallurgical Transactions12A,1673, (1981)

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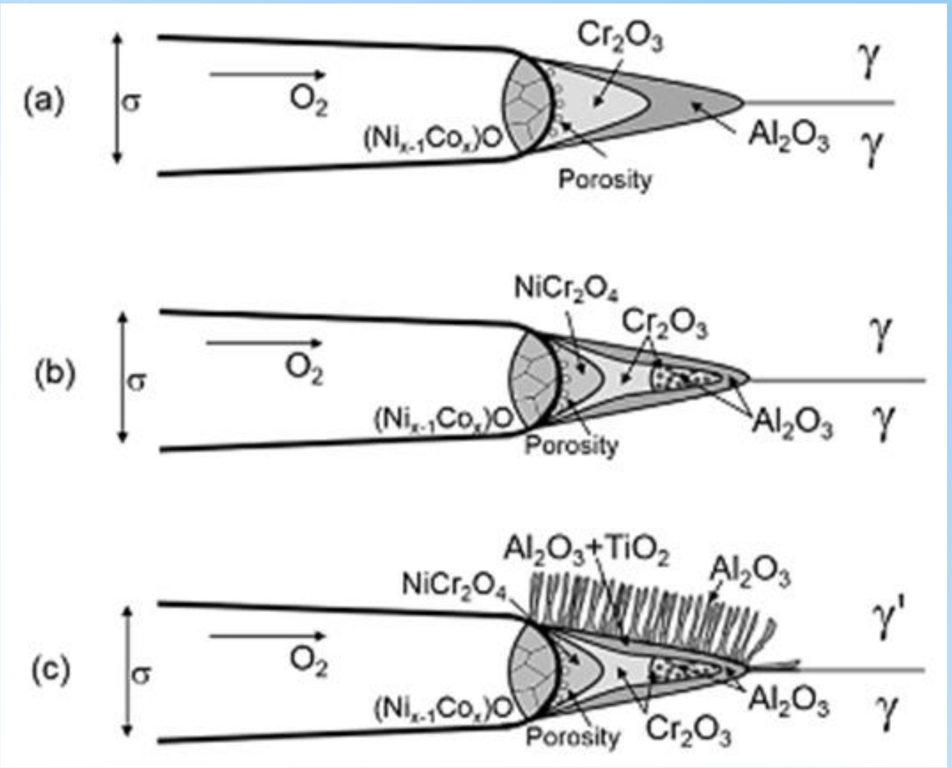

In conclusion, INCONEL Alloy 706 is a precipitation-hardenable alloy with excellent mechanical strength, good fabricability and resistance against oxidation and corrosion.
Stress Accelerated Grain Boundary Oxidation (SAGBO) in Alloy 706 has been reported as the cause of cracking in the gas turbine discs.

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Figure 2. View of the left side of the No. 1 engine showing the engine split in two.

Figure 3. View of the exhaust of No. 2 engine showing piece of HPT stage 1 disk protruding from the right side of the engine exhaust duct.

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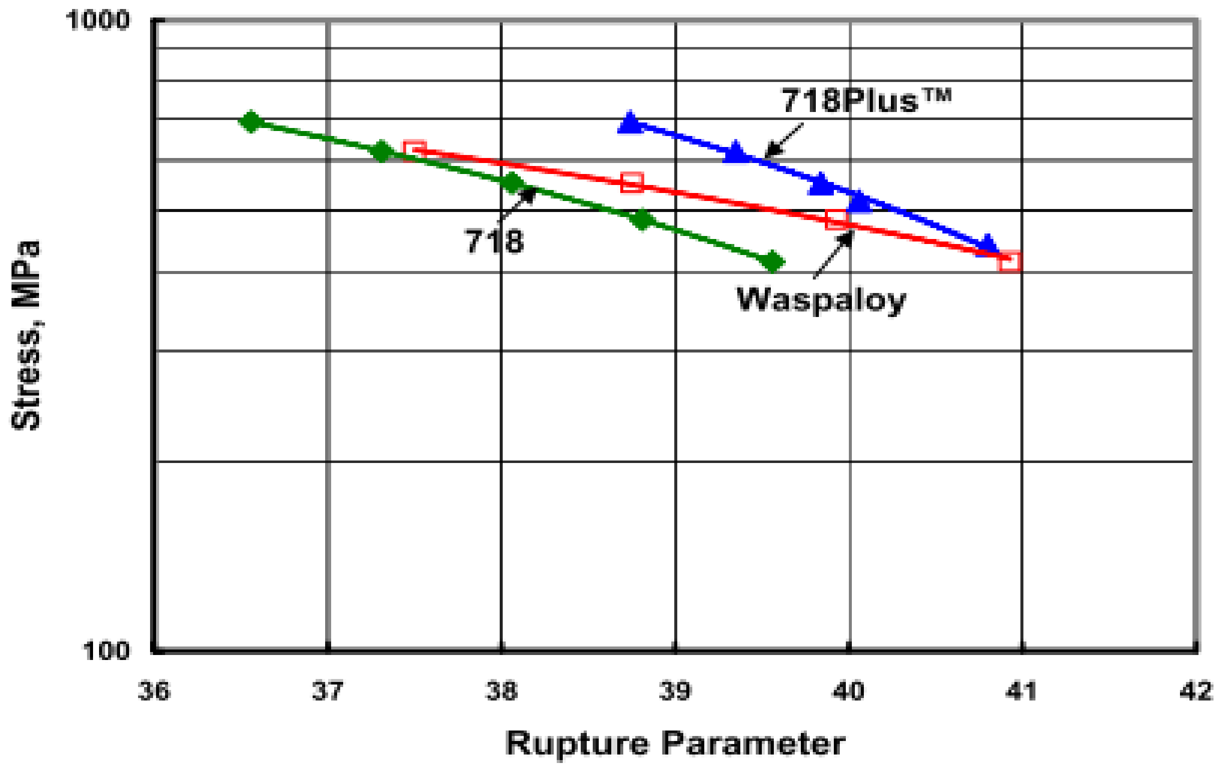

Figure 7. Larson-Miller Plot of Stress Rupture Life of Alloy 718Plus™.

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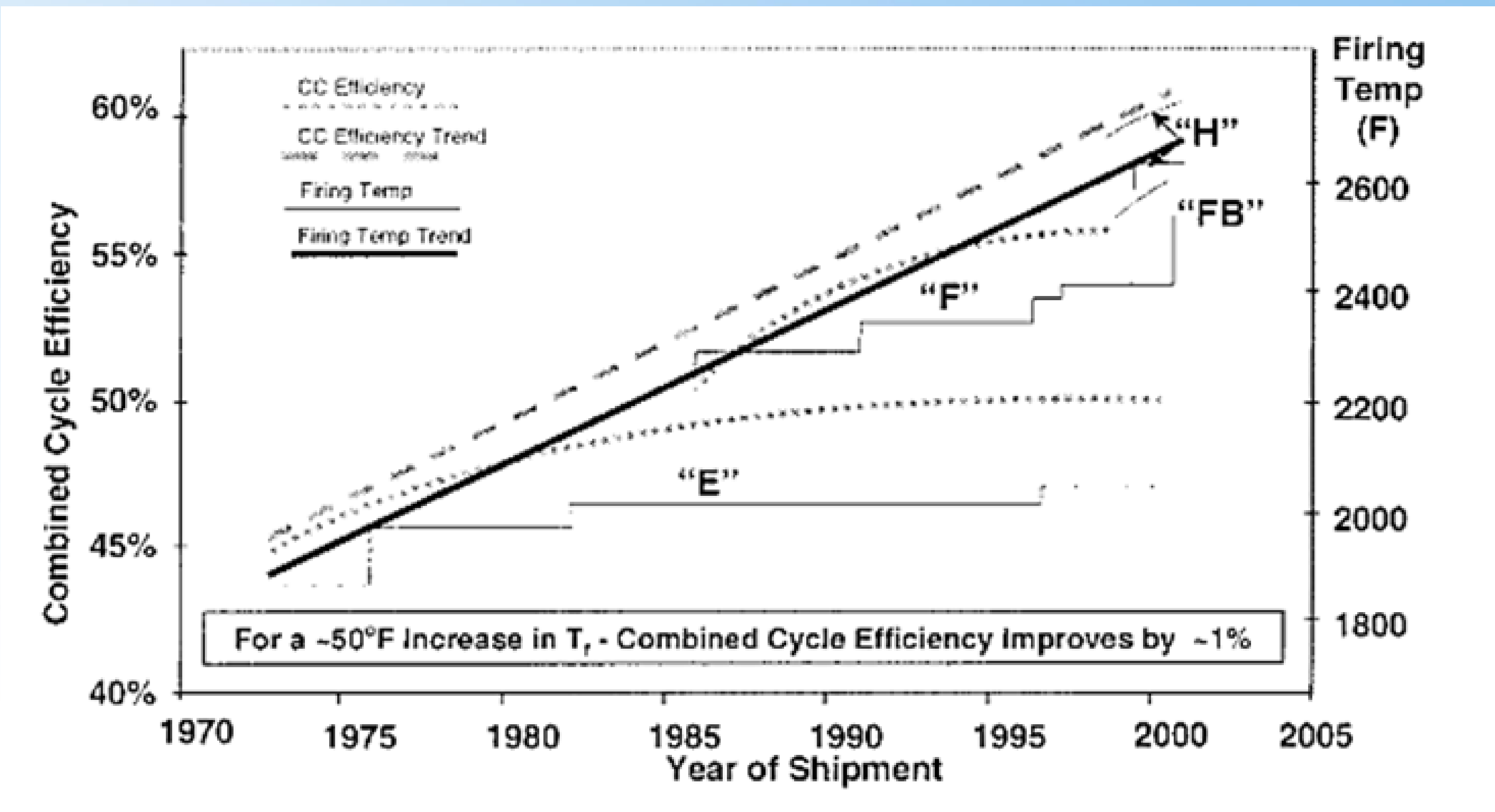

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Grazie per la vostra attenzione

Compusystem srl

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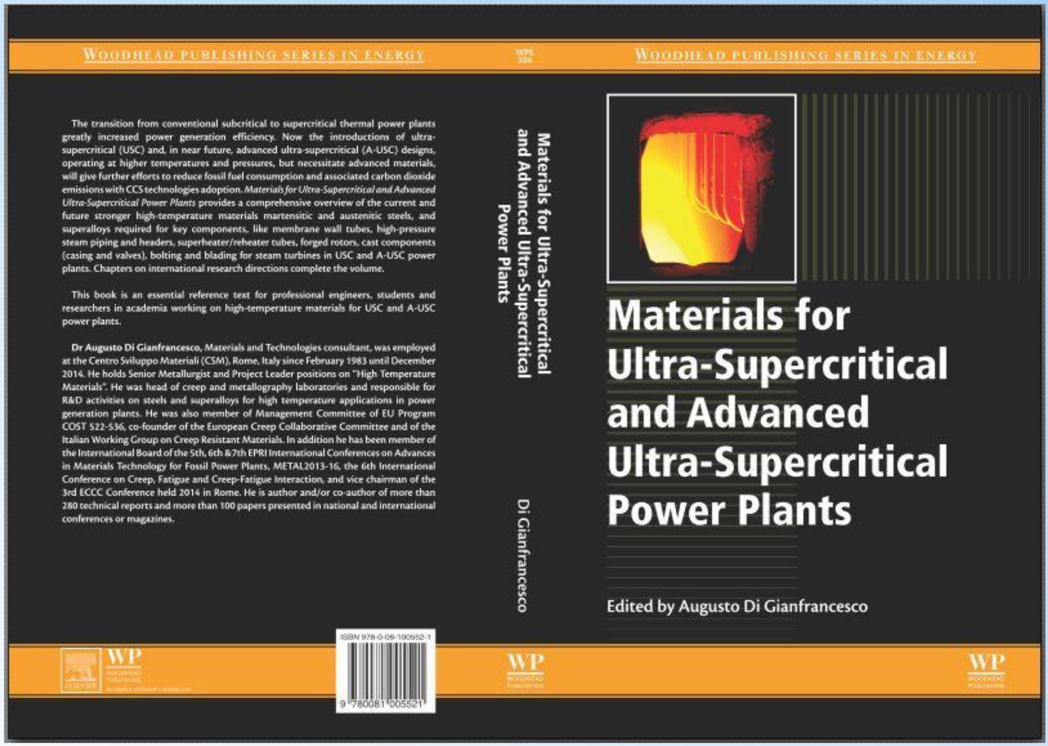

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