10. Cobalt and Cobalt Alloys

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This chapter comprises a survey on the properties, processing, performance and applications of cobalt alloys (Sect. 10.1). It includes essential information, including on alloys for specific environments or applications. Data tables covering the compositions (Sect. 10.2), specifications, applications and properties of the most commercially important heat, corrosion and wear-resistant cobalt alloys (Sect. 10.3), as well as those used in special-purpose applications, such as implants for the human body (Sect. 10.5) and cemented carbides (Sect. 10.6).

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Cobalt is applied as a base metal for a number of alloys, as an alloying element, and as a component of numerous inorganic compounds. Table 10.1 lists its major applications. Cobalt and cobalt-based materials are treated extensively in [10.1, 2].

Data on the electronic structure of Co and Co alloys may be found in [10.3]. Phase diagrams, crystal structures, and thermodynamic data of binary Co alloys may be found in [10.4].

Table 10.1 Applications of cobalt (after [10.1])

Application	Co consumption (%)	Form	Chapter
Co-based alloys, Co-based superalloys, steels	24.3	Base and alloying element	Chaps. 9, 10, 11
Hard facing and related materials	6.9	Base and alloying element	Sect. 10.2
Soft and hard magnetic materials, and controlled thermal expansion alloys	8.5	Base and alloying element, oxide	Chap. 22
Cemented carbides, diamond tooling	15.2	Metal, binder	Sect. 10.6
Catalysts	8.0	Metal, sulfates	–
Colorizer for glass, enamel, ceramics, plastics, fabrics	11.6	Oxides, salts	–
Batteries	9.5	Powder, hydroxide, $LiCoO_2$	–
Tire adhesives, soaps, driers	11.0	Soaps, complexes made from metal powder	–
Feedstuff, anodizing, electrolysis, copper winning	5.0	Sulphate, carbonate, hydroxide	–

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10.1 Co-Based Alloys

Cobalt-based alloys with a carbon content in the range of 1 to 3 wt% C are widely used as wear-resistant solid materials and weld overlays. Depending on the alloy composition and heat treatment, $M_{23}C_6$, M_6C, and MC carbides are formed. Materials with lower carbon content are mostly designed for corrosion and for heat resistance, sometimes combined with wear resistance. The metals W, Mo, and Ta are essentially added for solid solution strengthening. In a few alloys Ti and Al are added. They serve to form a coherent ordered $Co_3(Ti, Al)$ phase which precipitates and leads to strengthening by age hardening. The Cr content is generally rather high to provide oxidation and hot corrosion resistance. Table 10.2 presents a survey of Co-based alloys.

Table 10.2 Compositions of Co-based alloys

Alloy tradename	UNS No.	Nominal composition (wt%)									
		Co	Cr	W	Mo	C	Fe	Ni	Si	Mn	Others
Cast, P/M and weld overlay wear-resistant alloys											
Stellite 1	R30001	bal	30	13	0.5	2.5	3	1.5	1.3	0.5	–
Stellite 3 (P/M)	R30103	bal	30.5	12.5	–	2.4	5 (max)	3.5 (max)	2 (max)	2 (max)	1 B (max)
Stellite 4	R30404	bal	30	14	1 (max)	0.57	3 (max)	3 (max)	2 (max)	1 (max)	–
Stellite 6	R30006	bal	29	4.5	1.5 (max)	1.2	3 (max)	3 (max)	1.5 (max)	1 (max)	–
Stellite 6 (P/M)	R30106	bal	28.5	4.5	1.5 (max)	1	5 (max)	3 (max)	2 (max)	2 (max)	1 B (max)
Stellite 12	R30012	bal	30	8.3	–	1.4	3 (min)	1.5	0.7	2.5	–
Stellite 21	R30021	bal	27	–	5.5	0.25	3 (max)	2.75	1 (max)	1 (max)	0.007 B (max)
Stellite 98M2 (P/M)	–	bal	30	18.5	0.8 (max)	2	5 (max)	3.5	1 (max)	1 (max)	4.2 V, 1 B (max)
Stellite 703	–	bal	32	–	12	2.4	3 (max)	3 (max)	1.5 (max)	1.5 (max)	–
Stellite 706	–	bal	29	–	5	1.2	3 (max)	3 (max)	1.5 (max)	1.5 (max)	–
Stellite 712	–	bal	29	–	8.5	2	3 (max)	3 (max)	1.5 (max)	1.5 (max)	–
Stellite 720	–	bal	33	–	18	2.5	3 (max)	3 (max)	1.5 (max)	1.5 (max)	0.3 B
Stellite F	R30002	bal	25	12.3	1 (max)	1.75	3 (max)	22	2 (max)	1 (max)	–
Stellite Star J (P/M)	R30102	bal	32.5	17.5	–	2.5	3 (max)	2.5 (max)	2 (max)	2 (max)	1 B (max)
Stellite Star J	R31001	bal	32.5	17.5	–	2.5	3 (max)	2.5 (max)	2 (max)	2 (max)	–
Tantung G	–	bal	29.5	16.5	–	3	3.5	7 (max)	–	2 (max)	4.5 Ta/Nb
Tantung 144	–	bal	27.5	18.5	–	3	3.5	7 (max)	–		5.5 Ta/Nb
Laves-phase wear-resistant alloys											
Tribaloy T-400	R30400	bal	9	–	29	–	–	–	2.5	–	–
Tribaloy T-800	–	bal	18	–	29	–	–	–	3.5	–	–
Wrought wear-resistant alloys											
Stellite 6B	R30016	bal	30	4	1.5 (max)	1	3 (max)	2.5	0.7	1.4	–
Stellite 6K	–	bal	30	4.5	1.5 (max)	1.6	3 (max)	3 (max)	2 (max)	2 (max)	–
Wrought heat-resistant alloys (see Table 10.4 for cast alloy compositions)											
Haynes 25 (L605)	R30605	bal	20	15	–	0.1	3 (max)	10	0.4 (max)	1.5	–
Haynes 188	R30188	bal	22	14	–	0.1	3 (max)	22	0.35	1.25	0.03 La
Inconel 783	R30783	bal	3	–	–	0.03 (max)	25.5	28	0.5 (max)	0.5 (max)	5.5 Al, 3 Nb, 3.4 Ti (max)
UMCo-50	–	bal	28	–	–	0.02 (max)	21	–	0.75	0.75	–
S-816	R30816	40 (min)	20	4	4	0.37	5 (max)	20	1 (max)	1.5	4 Nb

Table 10.2 (continued)

Corrosion-resistant alloys											
Ultimet (1233)	R31233	bal	26	2	5	0.06	3	9	0.3	0.8	0.08 N
MP 159	R30159	bal	19	–	7	–	9	25.5	–	–	3 Ti, 0.6 Nb, 0.2 Al
MP35N	R30035	35	20	–	10	–	–	35	–	–	–
Duratherm 600	R30600	41.5	12	3.9	4	0.05 (max)	8.7	bal	0.4	0.75	2 Ti, 0.7 Al, 0.05 Be
Elgiloy	R30003	40	20	–	7	0.15 (max)	bal	15.5	–	2	1 Be (max)
Havar	R30004	42.5	20	2.8	2.4	0.2	bal	13	–	1.6	0.06 Be (max)

P/M: powder metallurgy; bal: balance

10.2 Co-Based Hard-Facing Alloys and Related Materials

The behavior of Co-based wear resistant alloys is based on a coarse dispersion of hard carbide phases embedded in a tough Co-rich metallic matrix. The volume fraction of the hard carbide phase is comparatively high: e.g., at 2.4 wt% C the carbide content is 30 wt%. The carbide phases are M_7C_3 (Cr_7C_3 type) and M_6C (W_6C type). Table 10.3 lists characteristic properties of Co-based hard facing alloys the compositions of which are listed Table 10.1.

Table 10.3 Properties of selected Co-based hard-facing alloys

Property	Stellite 21	Stellite 6	Stellite 12	Stellite 1	Tribaloy T-800
Density ($g\,cm^{-3}$)	8.3	8.3	8.6	8.6	8.6
Ultimate compressive strength, (MPa)	1295	1515	1765	1930	1780
Ultimate tensile strength, (MPa)	710	834	827	620	690
Elongation (%)	8	1.2	1	1	< 1
Coefficient of thermal expansion, $°C^{-1}$	14.8×10^{-6}	15.7×10^{-6}	14×10^{-6}	13.1×10^{-6}	12.3×10^{-6}
Hot hardness, HV, at:					
445 °C	150	300	345	510	659
540 °C	145	275	325	465	622
650 °C	135	260	285	390	490
760 °C	115	185	245	230	308
Unlubricated sliding wear[a], (mm^3) at:					
670 N	5.2	2.6	2.4	0.6	1.7
1330 N	14.5	18.8	18.4	0.8	2.1
Abrasive wear[b], mm^3 ($in^3 \times 10^{-3}$)					
OAW	–	29	12	8	–
GTAW	86 (5.33)	64	57 (3.52)	52 (3.22)	24 (1.49)
Unnotched Charpy impact strength (J)	37	23	5	5	1.4
Corrosion resistance[c]:					
65% nitric acid at 65 °C	U	U	U	U	S
5% sulfuric acid at 65 °C	E	E	E	E	–
50% phosphoric acid at 400 °C	E	E	E	E	E

[a] Wear measured from tests conducted on Dow-Corning LFW-1 against 4620 steel ring at 80 rev/min for 2000 rev varying the applied load
[b] Wear measured from dry sand rubber wheel abrasion tests. Tested for 2000 rev at a load of 135 N using a 230 mm diam rubber wheel and American Foundrymen's Society test sand. OAW, oxyacetylene welding; GTAW, gas-tungsten arc welding
[c] E, less than 0.05 mm/yr; S, 0.5 to less than 1.25 mm/yr; U, more than 1.25 mm/yr

10.3 Co-Based Heat-Resistant Alloys, Superalloys

Both wrought and cast Co-based heat resistant alloys, listed in Tables 10.2 and 10.4, respectively, are also referred to as Co superalloys. They are based on the face-centered cubic high-temperature phase of Co which is stabilized between room temperature and the solidus temperature by alloying with ≥ 10 wt% Ni. They are solid-solution strengthened by alloying with W, Ta and Mo. Furthermore, they are dispersion strengthened by carbides.

Differences of the high-temperature mechanical behavior of these materials are shown in terms of stress-rupture curves in Fig. 10.1.

Investment-cast Co alloys are generally used for parts of complex shape such as first- and second-stage vanes and nozzles in gas turbine engines.

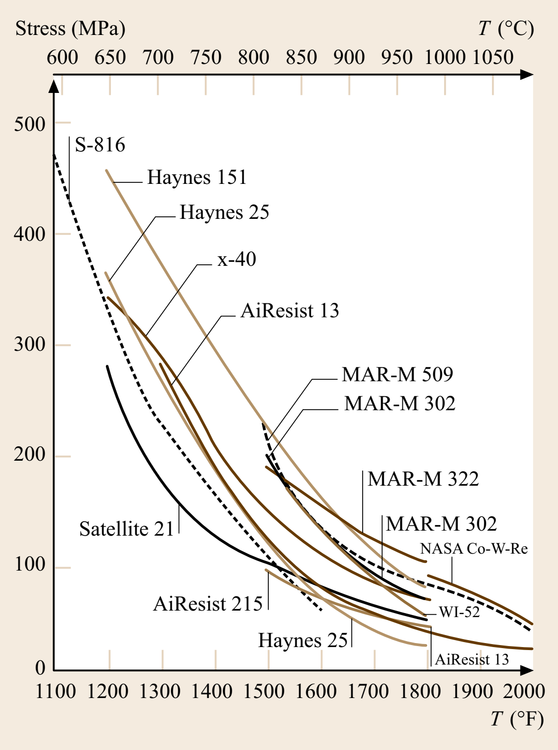

Fig. 10.1 Stress–rupture curves for 1000 h life of cast Co-based superalloys

Table 10.4 Nominal compositions of cast cobalt-based heat-resistant alloys

Alloy designation	Nominal composition (wt%)												
	C	Ni	Cr	Co	Mo	Fe	Al	B	Ti	Ta	W	Zr	Other
AiResist 13	0.45	–	21	62	–	–	3.4	–	–	2	11	–	0.1 Y
AiResist 213	0.20	0.5	20	64	–	0.5	3.5	–	–	6.5	4.5	0.1	0.1 Y
AiResist 215	0.35	0.5	19	63	–	0.5	4.3	–	–	7.5	4.5	0.1	0.1 Y
FSX-414	0.25	10	29	52.5	–	1	–	0.010	–	–	7.5	–	–
Haynes 25 (L-605)	0.1	10	20	54	–	1	–	–	–	–	15	–	–
J-1650	0.20	27	19	36	–	–	–	0.02	3.8	2	12	–	–
MAR-M 302	0.85	–	21.5	58	–	0.5	–	0.005	–	9	10	0.2	–
MAR-M 322	1.0	–	21.5	60.5	–	0.5	–	–	0.75	4.5	9	2	–
MAR-M 509	0.6	10	23.5	54.5	–	–	–	–	0.2	3.5	7.5	0.5	–
NASA (Co−W−Re)	0.40	–	3	67.5	–	–	–	–	1	–	25	1	2 Re
S-816	0.4	20	20	42	–	4	–	–	–	–	4	–	4 Mo, 4 Nb, 1.2 Mn, 0.4 Si
V-36	0.27	20	25	42	–	3	–	–	–	–	2	–	4 Mo, 2 Nb, 1 Mn, 0.4 Si
WI-52	0.45	–	21	63.5	–	2	–	–	–	–	11	–	2 Nb + Ta
Stellite 23	0.40	2	24	65.5	–	1	–	–	–	–	5	–	0.3 Mn, 0.6 Si
Stellite 27	0.40	32	25	35	5.5	1	–	–	–	–	–	–	0.3 Mn, 0.6 Si
Stellite 30	0.45	15	26	50.5	6	1	–	–	–	–	–	–	0.6 Mn, 0.6 Si
Stellite 31 (X-40)	0.50	10	22	57.5	–	1.5	–	–	–	–	7.5	–	0.5 Mn, 0.5 Si

10.4 Co-Based Corrosion-Resistant Alloys

Compared to the heat resistant Co-based alloys, the corrosion-resistant alloys have low C concentrations and are alloyed with higher Mo contents rather than with W since Mo contributes to their corrosion and oxidation resistance. Table 10.5 shows the compositions of various Co-based corrosion-resistant alloys.

The multiphase (MP) alloys MP35N and MP159 combine ultra-high strength, high ductility, and corrosion resistance, including resistance to stress-corrosion cracking in the work-hardened state. The prime strengthening is based on the deformation-induced martensitic transformation of the fcc matrix phase into the hcp phase which has been termed a multiphase reaction. The multiphase microstructure provides an increased density of barriers for slip dislocations. Subsequent annealing leads to a stabilization of the two-phase structure by solute partitioning. Figures 10.2 and 10.3 show the increase in strength and decrease in ductility for alloys MP35N and Duratherm 600 with work hardening and aging.

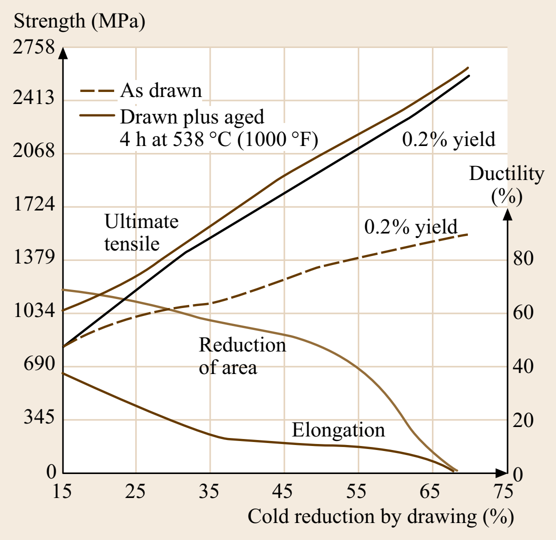

Fig. 10.2 Tensile properties of cold-drawn and aged MP35N

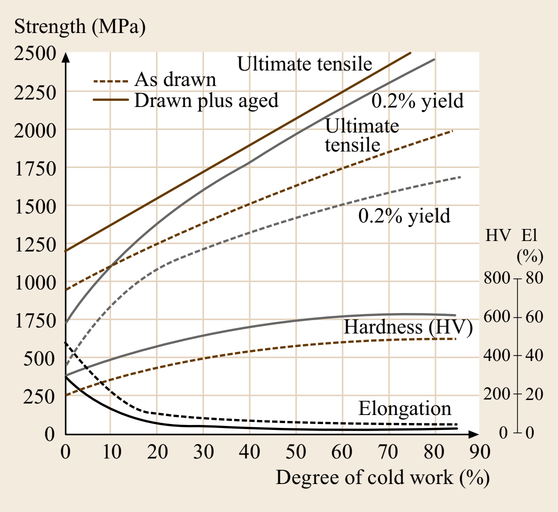

Fig. 10.3 Tensile properties of cold-drawn and aged Duratherm 600

Table 10.5 Co-based corrosion resistant alloys

Alloy tradename	UNS No.	Nominal Composition (wt%)									
		Co	Cr	W	Mo	C	Fe	Ni	Si	Mn	Others
Ultimet (1233)	R31233	bal	26	2	5	0.06	3	9	0.3	0.8	0.08 N
MP 159	R30159	bal	19	–	7	–	9	25.5	–	–	3 Ti, 0.6 Nb, 0.2 Al
MP35N	R30035	35	20	–	10	–	–	35	–	–	–
Duratherm 600	R30600	41.5	12	3.9	4	0.05 (max)	8.7	bal	0.4	0.75	2 Ti, 0.7 Al, 0.05 Be
Elgiloy	R30003	40	20	–	7	0.15 (max)	bal	15.5	–	2	1 Be (max)
Havar	R30004	42.5	20	2.8	2.4	0.2	bal	13	–	1.6	0.06 Be (max)

bal: balance

10.5 Co-Based Surgical Implant Alloys

Co-based surgical implant alloys (Table 10.6 for compositions) are used to fabricate a variety of implant parts and devices. These are predominantly implants for hip and knee joint replacements, implants that fix bone fractures such as bone screws, staples, plates, support structures for heart valves, and dental implants. The mechanical properties (shown in Table 10.7) depend sensitively on the thermal and thermomechanical treatments of the materials.

Table 10.6 Compositions of Co-based surgical implant alloys

ASTM specification	Composition (wt%)								
	Co	Cr	Ni	Mo	Fe	C	Mn	Si	Other
F75	bal	27.0–30.0	1.0	5.0–7.0	0.75	0.35	1.0	1.0	–
F90	bal	19.0–21.0	9.0–11.0	–	3 (max)	0.05–0.15	1.0–2.0	0.4	14.0–16.0 W
F562	bal	19.0–21.0	33.0–37.0	9.0–10.5	1 (max)	0.025 (max)	0.15 (max)	0.15 (max)	1.0 Ti (max)

bal: balance

Table 10.7 Mechanical properties of Co-based surgical implant alloys

ASTM specification	Alloy system	Condition	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Elastic modulus (GPa)
F75	Co-Cr-Mo	Cast	450	655	8	248
F799	Co-Cr-Mo	Thermomechanically processed	827	1172	12	–
F90	Co-Cr-WN-i	Wrought	379	896	–	242
F562	Co-Ni-Cr-Mo	Annealed, cold-worked and aged	241–448 1586	793–1000 1793	50 8	228 –

10.6 Cemented Carbides

The term cemented carbides, also called hardmetals, refers to powder-composite materials consisting of carbide particles bonded with metals or alloys. Extensive treatments are given in [10.5, 6]. The most common cemented carbide is WC bonded with Co. Cobalt is used as a binder since it wets the angular WC particles particularly well. Nickel is added to increase corrosion and oxidation resistance of the Co binder phase. The metals Ta, Nb, and Ti may be added to form a (W, Ta, Nb, or Ti) C solid solution carbide phase which is an additional microstructural constituent in the form of rounded particles in the so-called complex grade, multigrade, or steel-cutting grade cemented carbides. Table 10.8 lists representative materials.

Table 10.8 Compositions, microstructures and properties of representative Co-bonded cemented carbides

Nominal composition	Grain size	Hardness (HRA)[a]	Density ($g\,cm^{-3}$)	Transverse strength (MPa)	Compressive strength (MPa)	Modulus of elasticity (GPa)	Relative abrasion resistance[b]	Coefficient of thermal expansion (μm/m K) at 200 °C (390 °F)	Coefficient of thermal expansion (μm/m K) at 1000 °C (1830 °F)	Thermal conductivity (W/m K)
97WC–3Co	Medium	92.5–93.2	15.3	1590	5860	641	100	4.0	–	121
94WC–6Co	Fine	92.5–93.1	15.0	1790	5930	614	100	4.3	5.9	–
	Medium	91.7–92.2	15.0	2000	5450	648	58	4.3	5.4	100
	Coarse	90.5–91.5	15.0	2210	5170	641	25	4.3	5.6	121
90WC–10Co	Fine	90.7–91.3	14.6	3100	5170	620	22	–	–	–
	Coarse	87.4–88.2	14.5	2760	4000	552	7	5.2	–	112
84WC–16Co	Fine	89	13.9	3380	4070	524	5	–	–	–
	Coarse	86.0–87.5	13.9	2900	3860	524	5	5.8	7.0	88
75WC–25Co	Medium	83–85	13.0	2550	3100	483	3	6.3	–	71
71WC–12.5TiC –12TaC–4.5Co	Medium	92.1–92.8	12.0	1380	5790	565	11	5.2	6.5	35
72WC–8TiC –11.5TaC–8.5Co	Medium	90.7–91.5	12.6	1720	5170	558	13	5.8	6.8	50

[a] According to Rockwell Hardness A Scale
[b] Based on a value of 100 for the most abrasion-resistant material

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