Smithells Light Metals Handbook

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Contents

Preface

The light metals covered by this handbook are only those of industrial importance – aluminium, magnesium and titanium. The values given have been updated to the time of publication. They are intended for all those working with light metals; for research or design purposes Reference to source material may be found in *Smithells Metals Reference Book* (revised 7th edition). For design purpose values of mechanical properties must be obtained from the relevant specifications. Equilibrium diagrams are taken to be the most suitable for general work. For specialist work on any system, original sources should be consulted.

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1 Related specifications

Table 1.1 RELATED SPECIFICATIONS FOR WROUGHT ALUMINIUM ALLOYS

								Italy		
BS international	*Nominal composition old ISO No.* Al–	*UK former BS designation*	*France former NF*	*W. Germany Wk. No.*	*Canada*	*Sweden*	*USSR*	*Old UNI*	*New UNI*	*Japan*
1050A	99.5	1B	A5	3.0255	–	4 007	–	4 507	9001/2	A1050
1080A	99.8	1A	A8	3.0285	–	4 004	–	4 509	9001/4	A1080
1200	99	1C	A4	3.0205	990	4 010	–	3 567	9001/1	A1200
1350	99.5	1E	A5/6	3.0257	–	–	–	–	9001/5	–
2011	Cu6BiPb	FC1	A–U5 PbBi	3.1655	CB60	4 355	–	6 362	9002/5	A2011
2014A	Cu4SiMg	H15	A–U4SG	3.1255	CS41N	4 338	AK 8	3 581	9002/3	A2014
2017A	Cu4MgSi	–	A–U4G	3.1325	–	–	–	–	–	
2024	Cu4Mg1	2L97, 2L98, L109, L110, DTD5100A	A–U4G1	3.1355	CG42	–	D 16	3 583	9002/4	A2024
2031	Cu2NiMgFeSi	H12	A–U2N	–	–	–	–			
2117	Cu2Mg	3L86	A–U2G	3.1305	CG30	–	D 18	3 577	9002/1	A2217
2618A	Cu2Mg1.5 Fe1Ni1	H16	A–U2GN	–	–	–	AK 4-1	3 578	9002/6	–
3103	Mn1	N3	–	3.0515	–	4054	–	3 568	9003/3	–
3105	MnMg	N31	–	3.0505	–	–	–	–	9003/5	A3105
4043	Si5	N21	A–S5	–	–	–	–	–	–	A4043
4047	Si12	N2	A–S12	–	–	–	–	–	–	–
5005	Mg1	N41	A–G0.6	–	–	4106	–	5 764	9005/1	A5005
5056A	Mg5	N6	A–G5M	3.3555	–	–	–	–	–	–
5083	Mg4.5Mn	N8	A–G4.5MC	3.3547	GM41	4140	–	7 790	9005/5	A5083
5154A	Mg3.5	N5	–	–	GR40	–	AMG3	–	–	–
5251	Mg2	N4	A–G2M	3.3525	–	–	–	3 574	–	–
5454	Mg3.6	N51	A–G2.5MC	3.3537	GM31N	–	–	7 789	9005/3	A5454
5554	Mg3Mn	N52	–	–	GM31P	–	–	–	–	A5554
6061	Mg1SiCu	H20	A–GSUC	3.3211	GS11N	–	AD3	6 170	9006/2	A6061
6063	Mg0.5Si	H9	–	–	GS10	4104	AD31	–	–	A6063
6082	Si1MgMn	H30	A–SGM0.7	3.2315	–	4 212	–	3 571	9006/4	–
7020	Zn4.5Mg	H17	A–Z5G	3.4335	–	4 425	–	7 791	9007/1	–
7075	Zn6MgCu	2L95, L160, L161, L162	A–Z5GU	3.4365	ZG62	SM6958	V95	3 735	9007/2	A7075

Table 1.2 RELATED SPECIFICATIONS FOR MAGNESIUM ALLOYS

Nominal composition	*UK designation*	*UK BS2970 MAG*	*USA ASTM*	*USA AMS*	*France AFNOR*	*Standard AECMA*	*W. Germany aircraft*	*W. Germany DIN 1729*
Cast alloys								
RE3Zn2.5 Zr0.6	ZRE1	6-TE	EZ33A-T5	4442B	G-TR3Z2	MG-C-91	3.6204	3.5103
Zn4.2RE1.3 Zr0.7	RZ5	5-TE	ZE41A-T5	4439A	G-Z4TR	MG-C-43	3.6104	3.5101
Th3Zn2.2 Zr0.7	ZT1	8-TE	HZ32A-T5	4447B	G-Th3Z2	MG-C-81	3.6254	3.5105
Zn5.5Th1.8 Zr0.7	TZ6	9-TE	ZH62A-T5	4438B	–	MG-C-41	3.5114	3.5102
Al8Zn0.5 Mn0.3	A8	1-M	AZ81A-F	–	G-A9	MG-C-61	–	3.5812
Al9.5Zn0.5 Mn0.3	AZ91	3-7B	AZ91C-T4	–	G-A9Z1	–	3.5194	–
Al7.5/9.5 Zn0.3/1.5 Mn0.15min	C	7-M	–	–	–	–	–	3.5912
1.4.2 Wrought alloys								
Zn3Zr0.6	ZW3	E-151M	–	–	–	MG-P-43	–	–
Al6Zn1Mn0.3	AZM	E-121M	AZ61A-F	4350H	G-A6Z1	MG-P-63	W.3510	3.5612
Al8.5Zn0.5 Mn0.12min	AZ80	–	AZ80A	4360D	–	MG-P-61	W.3515	3.5812
Al3Zn1Mn0.3	AZ31	S-1110	AZ31B-0	4375F	G-A2Z1	MG-P-62	W.3504	3.5312

Table 1.3 TITANIUM AND TITANIUM ALLOYS. CORRESPONDING GRADES OR SPECIFICATIONS

IMI designation	*UK British Standards (Aerospace series) and Min. of Def.* DTD series*	*France* AIR-9182, 9183, 9184	*Germany BWB series*†	*AECMA recom-mendations*	*USA AMS series*‡	*USA ASTM series*
IMI 115	BS TA 1, DTD 5013	T-35	3.7024	Ti-POI		ASTM grade 1
IMI 125	BS TA 2,3,4,5	T-40	3.7034	Ti-PO2	AMS 4902, 4941, 4942, 4951	ASTM grade 2
IMI 130	DTD 5023, 5273, 5283, 5293	T-50			AMS 4900	ASTM grade 3
IMI 155	BS TA 6	T-60	3.7064	Ti-PO4	AMS 4901	ASTM grade 4
IMI 160	BS TA 7,8,9				AMS 4921	
IMI 230	BS TA 21, 22, 23, 24, BS TA 52–55, 58	T-U2.	3.7124	Ti-P11		
IMI 315	DTD 5043					
IMI 317	BS TA 14, 15, 16, 17	T-A5E		Ti-P65	AMS 4909, 4910, 4926, 4924, 4953, 4966	
IMI 318	BS TA 10, 11, 12, 13, 28, 56	T-A6V	3.7164	Ti-P63	AMS 4911, 4928, 4934, 4935, 4954, 4965, 4967	ASTM grade 5
IMI 318 ELI (extra low interstitial)	–	T-A6VELI			AMS 4907, 4930, 4931	ASTM grade 3, F. 136.

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Table 1.3 (*continued*)

IMI designation	*UK British Standards (Aerospace series) and Min. of Def.* DTD series*	*France* AIR-9182, 9183, 9184	*Germany BWB series*†	*AECMA recom-mendations*	*USA AMS series*‡	*USA ASTM series*
IMI 325	–	T-A3V2.5	3.7194		AMS 4943 4944	ASTM grade 9
IMI 550	BS TA 45–51, 57	T-A4DE	3.7184	Ti-P68		
IMI 551	BS TA 39–42					
IMI 624	–	T-A6Zr4 DE	3.7144		AMS 4919, 4975, 4976	
IMI 646	–	–	–	–	AMS 4981	
IMI 662	–	–	3.7174	–	AMS 4918, 4971, 4978, 4979	
IMI 679	BS TA 18–20, 25-27				AMS 4974	
IMI 680	DTD 5213	T-E11DA				
IMI 685	BS TA 43, 44	T-A6ZD	3.7154	Ti-P67		
IMI 811	–	T-A8DV			AMS 4915, 4916	
IMI 834	–	T-A6E Zr4Nb				

*UK BS 3531 Part 1 (Metal Implants in Bone Surgery), and Draft British Standard for Lining of Vessels and Equipment for Chemical Processes, Part 9, also refer.

†Germany DIN 17850, 17860, 17862, 17863, 17864 (3.7025/35/55/65), and TUV 230-1-68 Group I, II, III and IV also refer.

‡USA MIL-T-9011, 9046, 9047, 14577, 46038, 46077, 05-10737 and ASTM B265-69, B338-65, B348-59T, B367-61T. B381-61T, B382-61T also refer.

2 General physical properties of light metal alloys and pure light metals

2.1 General physical properties of pure light metals and their alloys

Table 2.1 PHYSICAL PROPERTIES OF ALUMINIUM, MAGNESIUM AND TITANIUM

Property		*Aluminium*	*Magnesium*	*Titanium*
Atomic weight C = 12		26.98154	24.305	47.88
Atomic number		13	12	22
Density (g cm^{-1})		2.70	1.74	4.5
liquid at 660 °C Al, 651 °C Mg, 1685 °C Ti		2.385	1.590	4.11
Melting point °C		660.323 (fixed pt ITS-90)	649	1667
Boiling point °C		2520	1090	3285
Thermal conductivity $Wm^{-1}K^{-1}$ at °C				
	0–100	238	155.5	16
	200	238	167	15
	400	238	130	14
	600	–	–	13
	800	–	–	(13)
Specific heat $Jkg^{-1}K^{-1}$ at °C				
	20	900	1022	519
	0–100	917	1038	528
	200	984	1110	569
	300	1030	–	–
	400	1076	1197	619
	600	–	–	636
	800	–	–	682
Coefficient of expansion $10^{-6}K^{-1}$ at °C				
	0–100	23.5	26.0	8.9
	100	23.9	26.1	8.8
	200	24.3	27.0	9.1
	300	25.3	–	–
	400	26.49	28.9	9.4
	600	–	–	9.7
	800	–	–	9.9
Electrical resistivity $\mu\Omega$ at °C				
	20	2.67	4.2	54
	100	3.55	5.6	70
	200	4.78	7.2	88
	300	5.99	–	–
	400	7.30	12.1	119
	600	–	–	152
	800	–	–	165
Temp. coefficient of resistivity 0–100 °C $10^{-3}K^{-1}$		4.5	4.25	3.8

Note: For surface tension and viscosity of liquid metals see *Metal Reference Book* 7th ed. pp. 14–7 to 14–8

2.2 The physical properties of aluminium and aluminium alloys

Table 2.2 THE PHYSICAL PROPERTIES OF ALUMINIUM AND ALUMINIUM ALLOYS AT NORMAL TEMPERATURES
sand cast

Material	*Nominal composition* %	*Density* g cm^{-3}	*Coefficient of expansion* 20–100 °C 10^{-6} K^{-1}	*Thermal conductivity* 100 °C W m^{-1} K^{-1}	*Resistivity* μΩ m	*Modulus of elasticity* MPa ×10^3
Al	Al 99.5	2.70	24.0	218	3.0	69
	Al 99.0	2.70	24.0	209	3.1	–
Al–Cu	Cu 4.5	2.75	22.5	180	3.6	71
	Cu 8	2.83	22.5	138	4.7	–
	Cu 12	2.93	22.5	130	4.9	–
Al–Mg	Mg 3.75	2.66	22.0	134	5.1	–
	Mg 5	2.65	23.0	130	5.6	–
	Mg 10	2.57	25.0	88	8.6	71
Al–Si	Si 5	2.67	21.0	159	4.1	71
	Si 11.5	2.65	20.0	142	4.6	–
Al–Si–Cu	Si 10 Cu 1.5	2.74	20.0	100	6.6	71
	Si 4.5 Cu 3	2.76	21.0	134	4.9	71
Al–Si–Cu–Mg*	Si 17 Cu 4.5 Mg 0.5	2.73	18.0	134	8.6	88
Al–Cu–Mg–Ni (Yalloy)	Cu 4 Mg 1.5 Ni 2	2.78	22.5	126	5.2	71
Al–Cu–Fe–Mg	Cu 10 Fe 1.25 Mg 0.25	2.88	22.0	138	4.7	71
Al–Si–Cu–Mg–Ni (Lo–Ex)	Si 12 Cu 1 Mg 1 Ni 2	2.71	19.0	121	5.3	71
	Si 23 Cu 1 Mg 1 Ni 1	2.65	16.5	107	–	88

*Die cast.

Table 2.3 THE PHYSICAL PROPERTIES OF ALUMINIUM AND ALUMINIUM ALLOYS AT NORMAL TEMPERATURES

wrought

Specification	*Nominal composition* %		*Condition**		*Density* g cm^{-3}	*Coefficient of expansion* 20–100 °C 10^{-6} K^{-1}	*Thermal conductivity* 100 °C W m^{-1} K^{-1}	*Resistivity* μΩ cm	*Temp. coeff. of resistance* 20–100 °C	*Modulus of elasticity* MPa ×10^3
1199	Al	99.992	Sheet	H111			239	2.68	0.0042	69
				H18	2.70	23.5	234	2.70	0.0042	69
			Extruded				239	2.68	0.0042	69
1080A	Al	99.8	Sheet	H111			234	2.74	0.0042	69
				H18	2.70	23.5	230	2.76	0.0042	69
			Extruded				230	2.79	0.0041	69
1050A	Al	99.5	Sheet	H111			230	2.80	0.0041	69
				H18	2.71	23.5	230	2.82	0.0041	69
			Extruded				226	2.85	0.0041	69
1200	Al	99	Sheet	H111			226	2.87	0.0040	69
				H18	2.71	23.5	226	2.89	0.0040	69
			Extruded				226	2.86	0.0040	69
2014A	Cu	4.4		T4	2.8	22	142	5.3		74
	Mg	0.7		T6	2.8	22	159	4.5		
	Si	0.8								
	Mn	0.75								
2024	Cu	4.5		T3	2.77	23		5.7		73
	Mg	1.5		T6	2.77	23	151	5.7		73
	Mn	0.6								
2090	Cu	2.7		T8	2.59	23.6	88.2	9.59		76
	Li	2.3								
	Zr	0.12								
2091	Cu	2.1		T8	2.58	23.9	84	9.59		75
	Li	2.0								
	Mg	1.50								
	Zr	0.1								
3103	Mn	1.25	Sheet	H111						
				H12						
				H14	2.74	23.0	180	3.9	0.0030	69
				H16						
				H18						
			Extruded				151	4.8	0.0024	–

continued overleaf

Table 2.3 *(continued)*

wrought

Specification	*Nominal composition* %		*Condition**		*Density* g cm^{-3}	*Coefficient of expansion* 20–100 °C 10^{-6} K^{-1}	*Thermal conductivity* 100 °C W m^{-1} K^{-1}	*Resistivity* μΩ cm	*Temp. coeff. of resistance* 20–100 °C	*Modulus of elasticity* MPa ×10^3
5083	Mg	4.5	Sheet	H111	2.67	24.5	109	6.1	0.0019	71
	Mn	0.7		H12						
	Cr	0.15		H14						
5251	Mg	2.0	Sheet	H111	2.69	24	155	4.7	0.0025	70
	Mn	0.3		H13						
				H16						
			Extruded				147	4.9	0.0023	–
5154A	Mg	3.5	Sheet	H111			142	5.3	0.0021	70
				H14	2.67	23.5	138	5.4	0.0021	–
			Extruded				134	5.7	0.0019	–
5454	Mg	2.7	Sheet	H111	2.68	24	147	5.1		70
	Mn	0.75		H22						
	Cr	0.12		H24						
Al–Li	Li	2.0	Sheet	T6	2.56	–	–	–	–	77
Al–Mg–Li	Mg	3.0	Sheet	T6	2.52	–	–	–	–	79
	Li	2.0								
Al–Li–Mg	Li	3.0	Sheet	T6	2.46	–	–	–	–	84
	Mg	2.0								
6061	Mg	1.0	Bar	H111	2.7	23.6	180			68.9
	Si	0.6		T4	2.7	23.6	154			68.9
	Cu	0.2		T6	2.7	23.6	167			68.9
	Cr	0.25								
6063	Mg	0.5	Extruded	T4	2.70	23.0	193	3.5	0.0033	71
	Si	0.5		T6			201	3.3	0.0035	–
6063A	Mg	0.5	Bar	T4	2.7	24	197	3.5		69
	Si	0.5		T5		24	209	3.2		69
				T6		24	201	3.3		69
6082	Mg	1.0	Bar/Extruded	T4	2.7	23	172	4.1	0.0031	69
	Si	1.0		T6	2.7	23	184	3.7	0.0031	69
	Mn	0.7								
6082	Mg	1.0	Sheet	T4			188	3.6	0.0033	69
	Si	1.0		T6	2.69	23.0	193	3.4	0.0035	–

6463	Mg	0.65	Bar	T5	2.71	23.4	209	3.1		69
	Si	0.4		T6	2.71	23.4	201	3.3		69
Al–Cu–Mg–Si	Cu	4.0	Sheet	T6	2.80	22.5	147	5.0	0.0023	73
(Duralumin)	Mg	0.6								
	Si	0.4								
	Mn	0.6								
	Cu	4.5	Sheet	T4	2.81	22.5	147	5.2	0.0022	73
	Mg	0.5		T6			159	4.5	0.0026	–
	Si	0.75								
	Mn	0.75								
Al–Cu–Mg–Ni	Cu	4.0	Forgings	T6	2.78	22.5	151	4.9	0.0023	72
(Yalloy)	Mg	1.5								
	Ni	2.0								
Al–Si–Cu–Mg	Si	12.0	Forgings	T6	2.66	19.5	151	4.9	0.0023	79
(Lo–Ex)	Cu	1.0								
	Mg	1.0								
	Ni	1.0								
Al–Zn–Mg	Zn	10.0	Forgings		2.91	23.5	151	4.9	0.0023	–
	Cu	1.0								
	Mn	0.7								
	Mg	0.4								
7075	Zn	5.7	Extrusion	T6	2.80	23.5	130	5.7	0.0020	72
	Mg	2.6								
	Cu	1.6								
	Cr	0.25								
8090	Li	2.5	Plate		2.55	21.4	93.5	9.59		77
	Cu	1.3								
	Mg	0.95								
	Zr	0.1								

H111 = Annealed.
H12,22 = Quarter hard.
H14,24 = Half hard.
H16,26 = Three-quarters hard.
H18,28 = Hard.

T4 = Solution treated and naturally aged.
T6 = Solution treated and artificially aged.

2.3 The physical properties of magnesium and magnesium alloys

Table 2.4 THE PHYSICAL PROPERTIES OF SOME MAGNESIUM AND MAGNESIUM ALLOYS AT NORMAL TEMPERATURE

Material	*Nominal composition*† %		*Condition*	*Density at* 20 °C g cm^{-3}	*Melting point* °C *Sol.*	*Liq.*	*Coeff. of thermal expansion* 20–200 °C 10^{-6} K^{-1}	*Thermal conductivity* W m^{-1} K^{-1}	*Electrical resistivity* μΩ cm	*Specific heat* 20–200 ° C J kg^{-1} K^{-1}	*Weldability by argon arc process*‡	*Relative damping capacity*§
Pure Mag	Mg	99.97	T1	1.74	650		27.0	167	3.9	1 050	A	
Mg–Mn	(MN70)Mn	0.75 approx.	T1	1.75	650	651	26.9	146	5	1 050	A	
	(AM503)Mn	1.5	T1	1.76	650	651	26.9	142	5.0	1 050	A	C
Mg–Al	AL80Al	0.75 approx.	T1	1.75	630	640	26.5	117	6	1 050	A	
	Be	0.005										
Mg–Al–Zn	(AZ31)Al	3	T1	1.78	575	630	26.0	(84)	10.0	1 050	A	
	Zn	1										
	(A8)Al	8	AC	1.81	475*	600	27.2	84	13.4	1 000	A	C
	Zn	0.5	AC T4	1.81			27.2	84	–	1 000		
	(AZ91)Al	9.5	AC	1.83	470*	595	27.0	84	14.1	1 000	A	C
	Zn	0.5	AC T4	1.83			27.0	84	–	1 000		
			AC T6	1.83			27.0	84	–	1 000		
	(AZM)Al	6	T1	1.80	510	610	27.3	79	14.3	14 000	A	
	Zn	1										
	(AZ855)Al	8	T1	1.80	475*	600	27.2	79	14.3	1 000	A	
	Zn	0.5										
Mg–Zn–Mn	(ZM21)Zn	2	T1	1.78			27.0			–	A	
	Mn	1										
Mg–Zn–Zr	(ZW1)Zn	1.3	T1	1.80	625	645	27.0	134	5.3	1 000	A	A
	Zr	0.6										
	(ZW3)Zn	3	T1	1.80	600	635	27.0	125	5.5	960	C	
	Zr	0.6										
	(Z5Z)Zn	4.5	AC T6	1.81	560	640	27.3	113	6.6	960	C	
	Zr	0.7										
	(ZW6)Zn	5.5	T5	1.83	530	630	26.0	117	6.0	1050	C	
	Zr	0.6										

Mg–Y–RE–Zr	(WE43)Y RE(Δ) Zr	4.0 3.4 0.6	AC T6	1.84	550	640	26.7	51	14.8	966	A	
	(WE54)Y RE(Δ) Zr	5.1 3.0 0.6	AC T6	1.85	550	640	24.6	52	17.3	960	A	
Mg–RE–Zn–Zr	(ZRE1)RE ZN Zr	2.7 2.2 0.7	AC T5	1.80	545	640	26.8	100	7.3	1 050	A	B
	(RZ5)Zn RE Zr	4.0 1.2 0.7	AC T5	1.84	510	640	27.1	113	6.8	960	B	
	(ZE63)Zn RE Zr	6 2.5 0.7	AC T6	1.87	515	630	27.0	109	5.6	960	A	
Mg–Th–Zn–Zr**	(ZTY)Th Zn Zr	0.8 0.5 0.6	T1	1.76	600	645	26.4	121	6.3	960	A	
	(ZT1)Th Zn Zr	3.0 2.2 0.7	AC T5	1.83	550	647	26.7	105	7.2	960	A	(B)
	(TZ6)Zn Th Zr	5.5 1.8 0.7	AC T5	1.87	500	630	27.6	113	6.6	960	B	
Mg–Ag–RE–Zr	(QE22)Ag RE(D) Zr	2.5 2.0 0.6	AC T6	1.82	550	640	26.7	113	6.85	1000	A	
	(EQ21)RE(D) Ag Cu Zr	2.2 1.5 0.07 0.7	AC T6	1.81	540	640	26.6	113	6.85	1000	A	

continued overleaf

Table 2.4 *(continued)*

Material	*Nominal composition*[†] *%*	*Condition*	*Density at 20 °C* $g\,cm^{-3}$	*Melting point °C* *Sol.*	*Liq.*	*Coeff. of thermal expansion 20–200 °C* $10^{-6}\ K^{-1}$	*Thermal conductivity* $W\,m^{-1}\,K^{-1}$	*Electrical resistivity* μΩ cm	*Specific heat 20–200 °C* $J\,kg^{-1}\,K^{-1}$	*Weldability by argon arc process*[‡]	*Relative damping capacity*[§]
Mg–Zn–Cu–Mn	(ZC63)Zn 6.0	AC T6	1.87	465	600	26.0	122	5.4	962	B	
	Cu 2.7										
	Mn 0.5										
	(ZC71)Zn 6.5	T6	1.87	465	600	26.0	122	5.4	62	B	
	Cu 1.3										
	Mn 0.8										
MG–Ag–RE–**											
Th–Zr	(QH21)Ag 2.5										
	RE(D) 1.0	AC T6	1.82	540	640	26.7	113	6.85	1005	A	–
	Th 1.0										
	Zr 0.7										
Mg–Zr	(ZA)Zr 0.6	AC	1.75	650	651	27.0	(146)	(4.5)	1050	A	A

AC Sand cast.

T4 Solution heat treated.

T5 Precipitation heat treated.

T6 Fully heat treated.

[†] Mg–Al type alloys normally contain 0.2–0.4% Mn to improve corrosion resistance.

** Thorium containing alloys are being replaced by alternative Mg alloys.

T1 Extruded, rolled or forged.

RE Cerium mischmetal containing approx. 50% Ce.

* Non-equilibrium solidus 420 °C.

() Estimated value.

RE(D) Mischmetal enriched in neodymium.

RE(Δ) Neodymium + Heavy Rare Earths.

[‡] Weldability rating:

A Fully weldable.

B Weldable.

C Not recommended where fusion welding is involved.

[§] Damping capacity rating:

A Outstanding.

B Equivalent to cast iron.

C Inferior to cast iron but better than Al-base cast alloys.

2.4 The physical properties of titanium and titanium alloys

Table 2.5 PHYSICAL PROPERTIES OF TITANIUM AND TITANIUM ALLOYS AT NORMAL TEMPERATURES

Material *IMI* *designation*	*Nominal* *composition* %	*Density* g cm^{-3}	*Coefficient of expansion* 20–100 °C 10^{-6} K^{-1}	*Thermal conductivity* 20–100 °C W m^{-1} K^{-1}	*Resistivity* 20 °C μΩ cm	*Temp. coefficient of resistivity* 20–100 °C μΩ cm K^{-1}	*Specific heat* 50 °C J kg^{-1} K^{-1}	*Magnetic suscept.* 10^{-6} cgs *units* g^{-1}
CP Titanium	Commercially pure	4.51	7.6	16	48.2	0.0022	528	+3.4
IMI 230	Cu 2.5	4.56	9.0	13	70	0.0026	–	–
IMI 260/261	Pd 0.2	4.52	7.6	16	48.2	0.0022	528	–
IMI 315	Al 2.0 Mn 2.0	4.51	6.7	8.4	101.5	0.0003	460	+4.1
IMI 317	Al 5.0 Sn 2.5	4.46	7.9	6.3	163	0.0006	470	+3.2
IMI 318	Al 6.0 V 4.0	4.42	8.0	5.8	168	0.0004	610	+3.3
IMI 550	Al 4.0 Mo 4.0 Sn 2.0 Si 0.5	4.60	8.8	7.9	159	0.0004	–	–
IMI 551	Al 4.0 Mo 4.0 Sn 4.0 Si 0.5	4.62	8.4	5.7	170	0.0003	400	+3.1
IMI 679	Sn 11.0 Zr 5.0 Al 2.25 Mo 1.0 Si 0.2	4.84	8.0	7.1	163	0.0004	–	–
IMI 680	Sn 11.0 Mo 4.0 Al 2.25 Si 0.2	4.86	8.9	7.5	165	0.0003	–	–
IMI 685	Al 6.0 Zr 5.0 Mo 0.5 Si 0.25	4.45	9.8	4.8	167	0.0004	–	–
IMI 829	Al 5.5 Sn 3.5 Zr 3.0 Nb 1.0 Mo 0.3 Si 0.3	4.53	9.45	7.8	–	–	530	–
IMI 834	Al 5.8 Sn 4.0 Zr 3.5 Nb 0.7 Mo 0.5 Si 0.35 C 0.06	4.55	10.6	–	–	–	–	–

3 Mechanical properties of light metals and alloys

The following tables summarize the mechanical properties of the more important industrial light metals and alloys.

In the tables of tensile properties at normal temperature the nominal composition of the alloys is given, followed by the appropriate British and other specification numbers. Most specifications permit considerable latitude in both composition and properties, but the data given in these tables represent typical average values which would be expected from materials of the nominal composition quoted, unless otherwise stated. For design purposes it is essential to consult the appropriate specifications to obtain minimum and maximum values and special conditions where these apply.

The data in the tables referring to properties at elevated and at sub-normal temperatures, and for creep, fatigue and impact strength have been obtained from a more limited number of tests and sometimes from a single example. In these cases the data refer to the particular specimens tested and cannot be relied upon as so generally applicable to other samples of material of the same nominal composition.

3.1 Mechanical properties of aluminium and aluminium alloys

The compositional specifications for wrought aluminium alloys are now internationally agreed throughout Europe, Australia, Japan and the USA. The system involves a four-digit description of the alloy and is now specified in the UK as BS EN 573, 1995. Registration of wrought alloys is administered by the Aluminum Association in Washington, DC. International agreement on temper designations has been achieved, and the standards agreed for the European Union, the Euro-Norms, are replacing the former British Standards. Thus BS EN 515. 1995 specifies in more detail the temper designations to be used for wrought alloys in the UK. At present, there is no Euro-Norm for cast alloys and the old temper designations are still used for cast alloys.

In the following tables the four-digit system is used, wherever possible, for wrought materials.

3.1.1 Alloy designation system for wrought aluminium

The first of the four digits in the designation indicates the alloy group according to the major alloying elements, as follow:

1XXX	aluminium of 99.0% minimum purity and higher
2XXX	copper
3XXX	manganese
4XXX	silicon
5XXX	magnesium
6XXX	magnesium and silicon
7XXX	zinc
8XXX	other element, incl. lithium
9XXX	unused

1XXX Group:	In this group the last two digits indicate the minimum aluminium percentage. Thus 1099 indicates aluminium with a minimum purity of 99.99%. The second digit indicates modifications in impurity or alloying element limits. 0 signifies unalloyed aluminium and integers 1 to 9 are allocated to specific additions.
2XXX-8XXX Groups:	In these groups the last two digits are simply used to identify the different alloys in the groups and have no special significance. The second digit indicates alloy modifications, zero being allotted to the original alloy.

National variations of existing compositions are indicated by a letter after the numerical designation, allotted in alphabetical sequence, starting with A for the first national variation registered.
The specifications and properties for Cast Aluminium Alloys are tabulated in Chapter 4.

3.1.2 Temper designation system for aluminium alloys

The following tables use the internationally agreed temper designations for wrought alloys, (BS EN 515. 1995) and the more frequently used ones are listed below. The old ones still used for existing BS specifications e.g. BS 1490. 1989 for castings are compared with the new ones at the end of this section.

U.K.	*Meaning*
F	As manufactured or fabricated
H111	Fully soft annealed condition
Strain-hardened alloys	
H	Strain hardened non-heat-treatable material
H1x	Strain hardened only
H2x	Strain hardened only and partially annealed to achieve required temper
H3x	Strain hardened only and stabilized by low temperature heat treatment to achieve required temper
H12,H22,H32	Quarter hard, equivalent to about 20–25% cold reduction
H14,H24,H34	Half hard, equivalent to about 35% cold reduction
H16,H26,H36	Three-quarter hard, equivalent to 50–55% cold reduction
H18,H28,H38	Fully hard, equivalent to about 75% cold reduction
Heat-treatable alloys	
T1	Cooled from an Elevated Temperature Shaping Process and aged naturally to a substantially stable condition
T2	Cooled from an Elevated Temperature Shaping Process, cold worked and aged naturally to a substantially stable condition
T3	Solution heat-treated, cold worked and aged naturally to a substantially stable condition
T4	Solution heat-treated and aged naturally to a substantially stable condition
T5	Cooled from an Elevated Temperature Shaping Process and then artificially aged
T6	Solution heat-treated and then artificially aged
T7	Solution heat-treated and then stabilized (over-aged)
T8	Solution heat-treated, cold worked and then artificially aged
T9	Solution heat-treated, artificially aged and then cold worked
T10	Cooled from an Elevated Temperature Shaping Process, artificially aged and then cold worked

A large number of variants in these tempers has been introduced by adding additional digits to the above designations. For example, the addition of the digit 5 after T1-9 signifies that a stress relieving treatment by stretching has been applied after solution heat-treatment.

A full list is given in BS EN 515. 1995 but some of the more common ones used in the following tables are given below.

T351	Solution heat-treated, stress-relieved by stretching a controlled amount (usually 1–3% permanent set) and then naturally aged. There is no further straightening after stretching. This applies to sheet, plate, rolled rod and bar and ring forging.
T3510	The same as T351 but applied to extruded rod, bar, shapes and tubes.
T3511	As T3510, except that minor straightening is allowed to meet tolerances.
T352	Solution heat-treated, stress-relieved by compressing (1–5% permanent set) and then naturally aged.
T651	Solution heat-treated, stress-relieved by stretching a controlled amount (usually 1–3% permanent set) and then artificially aged. There is no further straightening after stretching. This applies to sheet, plate, rolled rod and bar and ring forging.
T6510	The same as T651 but applied to extruded rod, bar, shapes and tubes.
T6511	As T6510, except that minor straightening is allowed to meet tolerances.
T73	Solution heat-treated and then artificially overaged to improve corrosion resistance.
T7651	Solution heat-treated, stress-relieved by stretching a controlled amount (Again about 1–3% permanent set) and then artificially over-aged in order to obtain a good resistance to exfoliation corrosion. There is no further straightening after stretching. This applies to sheet, plate, rolled rod and bar and to ring forging.
T76510	As T7651 but applied to extruded rod, bar, shapes and tubes.
T76511	As T7510, except that minor straightening is allowed to meet tolerances.

In some specifications, the old system is still being applied. The equivalents between old and new are as follows.

BS EN 515	BS1470/90	Pre-1969 BS
	F	M
H111	0	0
T3	TD	WD
T4	TB	W
T5	TE	P
T6	TF	WP
T8	TH	WDP

TH7 is as TH and then stabilised.

F/M is as manufactured or fabricated.

Table 3.2 ALUMINIUM AND ALUMINIUM ALLOYS-MECHANICAL PROPERTIES AT ROOM TEMPERATURE

Wrought Alloys

Specification	*Nominal composition* %	*Form*	*Condition*	0.2% *Proof stress* MPa	*Tensile strength* MPa	*Elong.* % on 50 mm *($\geq$2.6 mm)* or $5.65\sqrt{S_0}$	*Shear strength* MPa	*Brinell hardness* $(P = 5D^2)$	*Fatigue strength (unnotched)* 500 MHz MPa	Impacy engery J	*Fracture toughness* (MPa m$^{1/2}$)	*Remarks*
1199	Al 99.99	Sheet	H111	20	55	55	50	15	–	–	–	Highest quality reflectors
			H14	60	85	20	60	23	–	–	–	
			H18	85	110	12	70	28	–	–	–	
1080A	Al 99.8	Sheet	H111	25	70	50	60	19	–	–	–	Domestic trim, chemical plant
			H14	95	100	17	70	29	–	–	–	
			H18	125	135	11	70	29	–	–	–	
		Wire	H111	–	70	–	60	19	–	–	–	
			H14	90	105	–	70	30	–	–	–	
			H18	110–140	130–160	–	–	35–41	–	–	–	
1050A	Al 99.5	Sheet	H111	35	80	47	65	21	–	–	–	General purpose formable alloy
			H14	105	110	15	75	30	–	–	–	
			H18	130	145	10	85	40	–	–	–	
		Bars and sections	as extruded	50	75	38	65	22	–	–	–	
		Rivet stock	H15	125	140	–	–	–	–	–	–	
		Tubes	H111	–	75	–	65	21	–	–	–	
			H18 $<$ 75 mm	120	125	–	75	–	–	–	–	
			H18 $>$ 75 mm	110	115	–	70	–	–	–	–	
		Wire	H111	42	75	–	65	21	–	–	–	
			H14	100	115	–	75	30	–	–	–	
			H18	115–170	140–195	–	–	38–48	–	–	–	
1350	Al 99.5	Wire	H111	28	83	–	55	–	–	–	–	Electrical conductors
			H14	97	110	–	69	–	–	–	–	
			H18	165	186	–	103	–	48	–	–	

continued overleaf

Table 3.2 (*continued*)

Wrought Alloys

Specification	*Nominal composition* %	*Form*	*Condition*	0.2% *Proof stress* MPa	*Tensile strength* MPa	*Elong.* % on 50 mm (≥ 2.6 mm) or $5.65\sqrt{S_0}$	*Shear strength* MPa	*Brinell hardness* $(P = 5D^2)$	*Fatigue strength (unnotched)* 500 MHz MPa	Impacy engery J	*Fracture toughness* (MPa m$^{1/2}$)	*Remarks*
1200	Al 99,0	Sheet	H111	35	90	43	70	22	35	27	–	
			H13	95	105	20	75	31	40	–	–	General purpose, slightly higher strength than 105A
			H14	115	120	12	80	35	50	31	–	
			H16	125	135	11	90	38	60	–	–	
			H18	145	160	9	95	42	60	26	–	
		Bars and sections	as extruded	40	85	38	70	23	45*	27		
		Tubes	H111	–	90	40	70	21	–	–	–	
			$H > 75$ mm	128	131	6	100	34	–	–	–	
			$H < 75$ mm	120	124	6	95	32	–	–	–	
2011	Cu 5.5	Extruded bar	T3 25 mm	295	340	14	240	95	–	–	–	Free machining alloy
	Bi 0.5		T6 50–75 mm	260	370	16	240	100	–	–	–	
	Pb 0.5	Wire	T3 ≤ 10 mm	350	365	–	–	–	–	–	–	
2014	Cu 4.4	Plate	T451	290	425	22	260	108	140	–	–	Heavy duty applications in transport and aerospace, e.g. large parts, wings
	Mg 0.7		T651	415	485	10	290	139	125	–	–	
	Si 0.8	Bar/tube	T6510	440	490	8	–	–	–	–	–	
	Mn 0.75											
2014A	Cu 4.4	Sheet	T4	270	450	20	260	115	130*	–	–	Aircraft applications (cladding when used 1070A)
	Mg 0.7		T6	430	480	10	295	135	130*	–	–	
	Si 0.8	Clad sheet	T4	250	425	22	250	–	95*	–	–	
	Mn 0.75		T6	385	440	10	260	–	95*	–	–	
		Bars and sections	T4	315	465	17	–	115	140	22	–	
			T6	465	500	10	–	135	124	8	–	
		Tubes	T4	310	425	12	–	115	–	–	–	
			T6	415	480	9	–	135	–	–	–	
		Wire	T4	340	445	15	–	115	–	–	–	
			T6	425	465	–	–	135	–	–	–	
		River stock	T4	340	450	–	–	–	–	–	–	
		Bolt and screw stock	T6	425	460	–	–	–	–	–	–	
2024	Cu 4.5	Plate	T3	345	485	18	285	120	140	–	–	Structural applications, especially transport and aerospace
	Mg 1.5		T351	325	470	19	285	120	140	–	–	
	Mn 0.6											

2024	Cu 4.5	Plate/sheet	H111	75	185	20	125	47	90	–	–	Aircraft
	Mg 1.5	extrusions	T4	325	470	20	285	120	140	–	–	structures
	Mn 0.6		T6	395	475	10	–	–	–	–	–	
2117	Cu 2.5	Sheet	T4	165	295	24	195	70	95	–	–	Vehicle body
	Si 0.6											sheet
	Mg 0.4											
2090	Cu 2.7	Plate	T81	517	550	8	–	–	–	–	71	High strength, low
	Li 2.7	Plate (12.5 mm)	T81	535	565	11	–	–	–	–	34	density aero-alloy
	Zr 0.12											
2091	Cu 2.1	Plate (12 mm)	T8 × 51	310	420	14	–	–	–	–	–	Medium strength, low
	Li 2.0	Plate (40 mm)	T8 × 51	310	430	6	–	–	–	–	–	density aero-alloy in
	Mg 1.50	Extrusion	T851	505	580	7	–	–	–	–	–	damage-tolerant
	Zr 0.1	(10 mm)										temper
		Extrusion	T851	465	520	11	–	–	–	–	35	
		(30 mm)										
		Plate (12 mm)	T851	460	525	10	–	–	–	–	43	Medium strength, low
		Plate (38 mm)	T851	430	495	8	–	–	–	–	38	density aero-alloy
		Sheet	T8	390	495	10	–	–	–	–	38	Medium strength, low
												density aero-alloy
2219	Cu 6	Plate/sheet/	H111	75	170	18	–	–	–	–	–	Weldable, creep
	Mn 0.3	forgings	T4	185	360	20	–	–	–	–	–	resistant, high-
	V 0.1		T6	290	415	10	–	–	105	–	–	temperature aerospace
												applications
2004	Cu 6	Sheet	H111	150	230	15	–	–	100*	–	–	Superplastically
	Zr 0.4		T6	300	420	12	–	–	150*	–	–	deformable sheet
2031	Cu 2.3	Forgings	T4	235	355	22	201	95	–	–	–	Aero-engines, missile
	Ni 1.0		T6	340	420	15	201	95	–	–	–	fins
Mg 0.9												
Si 0.9												
Fe 0.9												
2618A	Cu 2.0	Forgings	H111	70	170	20	–	45	85*	–	–	Aircraft engines
	Mg 1.5		T6	330	430	8	295	130	170*	–	–	
	Si 0.9											
	Fe 0.9											
	Ni 1.0											

continued overleaf

Table 3.2 (*continued*)

Wrought Alloys

Specification	*Nominal composition* %	*Form*	*Condition*	0.2% *Proof stress* MPa	*Tensile strength* Mpa	*Elong.%* on 50 mm ($\geq$2.6 mm) or $5.65\sqrt{S_0}$	*Shear strength* MPa	*Brinell hardness* ($P = 5D^2$)	*Fatigue strength (unnotched)* 500 MHz MPa	Impacy energy J	*Fracture toughness* (MPa m$^{1/2}$)	*Remarks*
3103	Mn 1.25	Sheet	H111	65	110	40	80	30	50	34	–	General purpose,
			H12	125	130	17	90	40	55	–	–	holloware, building
			H14	140	155	11	95	44	60	29	–	sheet
			H16	160	180	8	105	47	70	–	–	
			H18	185	200	7	110	51	70	20	–	
		Wire	H111	60	115	–	–	30	–	–	–	
			H14	135	155	–	–	45	–	–	–	
			H18	170–200	205–245	–	–	55–65	–	–	–	
3105	Mn 0.35	Sheet	H111	55	115	24	85	–	–	–	–	Building cladding sheet
	Mg 0.6		H14	150	170	5	105	–	–	–	–	
			H18	195	215	3	115	–	–	–	–	
3004	Mn 1.2	Sheet	H111	70	180	20	110	45	95	–	–	Sheet metal work,
	Mg 1.0		H14	200	240	9	125	63	105	–	–	storage tanks
			H18	250	285	5	145	77	110	–	–	
3008	Mn 1.6	Sheet	H111	50	120	23	–	–	–	–	–	Thermally reistant alloy.
	Fe 0.7		H18	270	280	4	–	–	–	–	–	Vitreous enamelling
	Zr 0.3											
3003	Mn 1.2	Sheet	H111	40	110	30	75	–	–	–	–	Flux brazing sheet
clad with 4343	Si 7.5		H12	125	130	10	85	–	–	–	–	
			H14	145	150	8	95	–	–	–	–	
			H16	170	175	5	105	–	–	–	–	
3003	Mn 1.2	Sheet	Physical properties		as for 3003 clad with 4343			–	–	–	–	Vacuum brazing
clad with 4004	Si 1.0											sheet
	Mg 1.5											

4032	Si 12.0 Cu 1.0 Mg 1.0 Ni 1.0	Forgings	T6	240	325	5	–	115	110	–	–	Pistons
4043A	Si 5.0	Rolled wire		75	130	20	–	–	–	–	–	Welding filler wire
4047A	Si 12.0	Wire	F	189	225	8	–	–	–	–	–	Brazing rod
5657	Mg 0.8	Sheet	H111	40	110	25	75	28	–	–	–	High base purity,
			H14	140	160	12	95	40	–	–	–	bright trim alloy
			H18	165	195	7	105	50	–	–	–	
5005	Mg 0.8	Sheet	H111	40	125	25	75	28	–	–	–	Architectural trim,
			H14	150	160	6	95	–	–	–	–	commercial vehicle
			H18	195	200	4	110	–	–	–	–	trim
5251	Mg 2.25	Sheet	H111	95	185	22	125	45	110	50	–	Sheet metal work
	Mn 0.25		H14	230	245	7	145	70	125	29	–	
			H18	275	285	2	175	80	140	–	–	
5251	Mg 2.0	Bar	F	60	170	16	–	–	–	–	–	Marine and transport
	Mn 0.3	Sheet	H111	60	180	20	125	47	92	–	–	applications; good
			H22	130	220	8	132	65	124	–	–	workability combined
			H24	175	250	5	139	74	–	–	–	with good corrosion
			H28	215	270	4	–	–	–	–	–	resistance and high
												fatigue resistance
		Bars and sections	as extruded (F)	95	185	20	125	45	95*	49	–	
		Tubes	H111	100	200	20	–	–	–	–	–	
			H14	230	250	6	–	–	–	–	–	
			H18	255	270	5	–	–	–	–	–	
		Wire	H111	95	200	–	–	48	–	–	–	
			H18	260–290	280–310	–	–	75–85	–	–	–	

continued overleaf

Table 3.2 (*continued*)

Wrought Alloys

Specification	*Nominal composition* %	*Form*	*Condition*	0.2% *Proof stress* MPa	*Tensile strength* MPa	*Elong.*% on 50 mm (≥2.6 mm) or 5.65$\sqrt{S_0}$	*Shear strength* MPa	*Brinell hardness* ($P = 5D^2$)	*Fatigue strength (unnotched)* 500 MHz MPa	Impacy energy J	*Fracture toughness* (MPa m$^{1/2}$)	*Remarks*
5154A	Mg 3.5 Mn 0.5	Sheet	H111	125	240	24	155	55	115	–	–	Welded structures, storage tanks, salt water service
			H22	245	295	10	175	80	125	–	–	
			H24	275	310	9	175	95	130	–	–	
		Bars and sections as extruded (F)		125	230	25	145	55	140*	48	–	
		Tubes	H111	125	225	20	–	55	–	–	–	
			H14	220	280	7	–	–	–	–	–	
		Wire	H111	125	240	–	–	55	–	–	–	
			H14	265	295	–	–	90	–	–	–	
			H18	310	355	–	–	100	–	–	–	
		Rivet stock	H111	125	250	–	–	–	–	–	–	
			H12	–	290	–	–	–	–	–	–	
5454	Mg 2.7 Mn 0.75 Cr 0.12	Sheet	H111	105	250	22	159	65	115	–	–	Higher strength alloy for marine and transport, pressure vessels and welded structures
			H22	200	277	7	165	77	125	–	–	
			H24	225	297	5	179	85	130	–	–	
5083	Mg 4.5 Mn 0.7 Cr 0.15	Sheet	H111	170	310	21	170	72	–	–	–	Marine applications, cryogenics, welded pressure vessels.
			H24	290	370	9	210	110	–	–	–	
		Bars and sections as extruded (F)		180	315	19	180	77	–	–	–	
5083	Mg 4.5 Mn 0.7 Cr 0.15	Tube	H111	180	320	20	–	77	–	–	–	
			H14	300	375	7	–	–	–	–	–	
5556A	Mg 5	Wire	H14	250	330	12	–	–	–	–	–	Weld filler wire
5056A	Mg 5.0 Mn 0.5	Wire	H111	140	300	–	–	65	–	–	–	Rivets, bolts, screws
			H14	300	340	–	–	95	–	–	–	
			H18	340–400	400–450	–	–	110–120	–	–	–	
		Rivet stock	H111	140	300	–	–	65	–	–	–	
			H12	–	350	–	–	–	–	–	–	
		Bolt and screw stock	H14	300	340	–	–	–	–	–	–	

6060	Mg 0.5	Bar	T4	90	150	20	–	–	–	–	–	Medium strength extrusion alloy for doors, windows, pipes, architectural use; weldable and corrosion-resistant
	Si 0.4		T5	130	175	13	–	–	–	–	–	
			T6	190	220	13	–	–	–	–	–	
6063	Mg 0.5	Bars, sections and forgings	F	85	155	30	100	35	–	–	–	Architectural extrusions (fast extruding)
	Si 0.5		T4	115	180	30	130	52	60	43	–	
			T6	210	245	20	160	75	70	31	–	
		Wire	H111	–	115	–	–	–	–	–	–	
			T4	115	180	–	–	50	–	–	–	
			T6	195	230	–	–	70	–	–	–	
6063A	Mg 1.0	Bar	T6510	280	310	22	129	50	79	–	–	Transport, windows, furniture, doors and architectural uses, pipes (irrigation)
	Si 0.5		T5	160	200	12	117	65	69	–	–	
			T6	210	240	12	152	78	85	–	–	
6061	Mg 1.0	Bars and sections	T4	145	230	20	160	60	–	34	–	Intermediate strength extrusion alloy
	Si 0.6		T6	280	310	13	200	90	–	27	–	
	Cr 0.25	Wire	T8 $\leq$ 6 mm	310–400	385–430	–	–	–	–	–	–	
	Cu 0.2		T8 (6–10 mm)	295–385	380–415	–	–	–	–	–	–	
		Bar	T6510	280	310	13	205	100	95	–	–	
		Bolt and screw stock	T8	290	340	–	–	–	–	–	–	
6082	Mg 1.0	Bar/extrusion	T5	260	300	15	185	85	–	–	–	
	Si 1.0		T6510	285	315	11	–	–	–	–	–	
	Mn 0.7	Plate	T451	150	240	19	–	68	–	–	–	
			T651	289	315	12	–	104	–	–	–	
			T6	285	315	12	205	100	–	–	–	
	Mg 1.0	Bars, sections and forgings	T4	160	240	25	180	65	–	41	–	
	Si 1.0		T6	285	310	13	215	100	–	34	–	
	Mn 0.5	Tubes	T4	160	245	20	–	65	–	–	–	
			T6	285	325	10	–	95	–	–	–	

continued overleaf

Table 3.2 (*continued*)

Wrought Alloys

Specification	*Nominal composition* %	*Form*	*Condition*	0.2% *Proof stress* MPa	*Tensile strength* Mpa	*Elong.%* on 50 mm ($\geq$2.6 mm) or $5.65\sqrt{S_0}$	*Shear strength* MPa	*Brinell hardness* ($P = 5D^2$)	*Fatigue strength (unnotched)* 500 MHz MPa	Impact energy J	*Fracture toughness* (MPa $m^{1/2}$)	*Remarks*
6463	Mg 0.55 Si 0.4	Bar	T4 T6	130 215	180 240	16 12	– 150	55 79	70 70	– –	– –	
6009	Si 0.8 Mg 0.6 Mn 0.5 Cu 0.4	Sheet	T4 T6	130 325	235 345	24 12	205 150	60 –	97 115	– –	– –	Vehicle body sheet
7020	Zn 4.5 Mg 1.2 Zr 0.15	Bars and sections	T4 T6	225 310	340 370	18 15	– –	100 126	– –	– –	– –	Transportable bridging
7075	Zn 5.6 Mg 2.5 Cu 1.6 Cr 0.25	Sheet/plate/ forgings/ extrusion	H111 T4 T73	105 505 435	230 570 505	17 11 13	150 330 –	60 150 –	– 160 –	– 7 –	– – –	Aircraft structures
7050	Zn 6.2 Mg 2.2 Cu 2.3 Zr 0.12	Thick section plate/ forgings	T736	455	515	11	–	–	220	–	–	Low quench sensitivity, high stress corrosion resistance. Aircraft structures
7475	Zn 5.7 Mg 2.2 Cu 1.5 Cr 0.2	Sheet/plate/ forgings	T61 T7351	525 –	460 –	12 –	– 270	– –	– 220	– –	– –	High base purity. High fracture toughness. Aircraft structures
7016	Zn 4.5 Mg 1.1 Cu 0.75	Extrusions	T6	315	360	12	–	–	–	–	–	Bright anodized vehicle bumpers
7021	Zn 5.5 Mg 1.5 Cu 0.25 Zr 0.12	Extrusion	H111 T6	115 395	235 435	16 13	– –	– –	– –	– –	– –	Bumper backing bars

8079	Fe 0.7	Foil	H111	35	95	26	–	–	–	–	–	Domestic foil
			H18	160	175	2	–	–	–	–	–	
8090	Li 2.5 Cu 1.3	Plate		483	518	4.3	–	–	–	–	42	As 2090 but lower density
	Mg 0.95 Zr 0.1	Plate (38/65 mm)	T8151	387	476	6.5	–	–	–	–	42.5	Under-aged, damage-tolerant condition
			T8771	483	518	4.3	–	–	–	–	42	Peak-aged, medium strength condition
		Sheet	T81	360	420	11	–	–	–	–	42	Under-aged, damage-tolerant condition with a recrystallized grain structure
			T6	373	472	5.7	–	–	–	–	–	
			T8	436	503	5	–	–	–	–	75	Peak-aged, medium strength condition
		Extrusion	T81551	440	510	4	–	–	–	–	45	Damage-tolerant condition
			T82551	460	515	4.2	–	–	–	–	39	Peak-aged, medium strength condition
		Extrusion (10 mm)	T851	515	580	5	–	–	–	–	30	
		Extrusion (30 mm)	T851	460	520	9	–	–	–	–	40	
		Plate (12 mm)	T851	455	500	7	–	–	–	–	33	
8090	Li 2.4 Cu 1.2	Forging	T651	468	517	7	–	–	–	–	28.1	Peak-aged (32 h at 170 °C. (Shrimpton)
	Mg 0.50 Zr 0.14		T651	400	453	7	–	–	–	–	36.7	Under-aged (20 h at 150 °C). (Shrimpton)
8090	Li 2.5 Cu 1.2 Mg 0.66 Zr 0.12	Forging		420	499	7.8	–	–	–	–	16.98	Soln. trt, 530 °C, WQ, aged 30 h at 170 °C
8091	Li 2.4 Cu 1.9 Mg 0.85 Zr 0.1		–	–	–	–	–	–	–	–	–	

continued overleaf

Table 3.2 (*continued*)

Wrought Alloys

Specification		*Nominal composition* %	*Form*	*Condition*	0.2% *Proof stress* MPa	*Tensile strength* MPa	*Elong.%* on 50 mm ($\geq$2.6 mm) or $5.65\sqrt{S_0}$	*Shear strength* MPa	*Brinell hardness* $(P = 5D^2)$	*Fatigue strength (unnotched)* 500 MHz MPa	Impact energy J	*Fracture toughness* (MPa m$^{1/2}$)	*Remarks*
8091		Li 2.4 Cu 2.0	Plate (40 mm)		460	–	–	–	164	–	–	–	Peak-aged (6% stretch, 32 h at 170 °C
		Mg 0.70 Zr 0.08			408	–	–	–	159	–	–	–	Peak aged (no stretch, 100 h at 170 °C)
					408	–	–	–	158	–	–	–	Duplex-aged (ditto, 24 h at RT, 48 h at 170 °C)
8091		Li 2.3 Cu 1.7 Mg 0.64 Zr 0.13	Forging	–	436	503	8.2	–	–	–	–	20.72	soln. trt. 530 °C, WQ, aged 20 h at 170 °C
							Cast alloys						
Al	(LMO)	Al 99.0	Sand cast	F	30	80	30	55	25	30*	19	–	High conductivity,
			Chill cast	F	30	80	40	55	25	30*	19	–	high ductility
Al–Mg	(LM5)	Mg 5.0	Sand cast	F	100	160	6	–	60	45	8	–	Very high corrosion
		Mn 0.5	Chill cast	F	100	215	10	–	65	95	12	–	resistance
	(LM10)	Mg 10.0	Sand cast	T4	180	295	12	230	85	55	15	–	Strength + corrosion
			Chill cast	T4	190	340	18	230	95	–	–	–	resistance
Al–Si	(LM18)	Si 5.0	Sand cast	F	60	125	5	90	40	55	1.5	–	Intricate castings
			Chill cast	F	70	155	6	120	50	85	2.5	–	
	(LM6) (LM20)	Si 11.5	Sand cast	F	65	170	8	110	55	45*	4	–	Very similar alloys, excellent casting
	(LM6)		Chill cast	F	75	215	10	130	60	60*	9.5	–	characteristics and corrosion resistance. LM6 has slightly supperior corrosion resistance
Al–Si–Mg		Si 7	Sand cast	T6	195	240	3	–	–	56	–	–	Good strength in fairly
	(2L99)	Mg 0.4	Chill cast	T6	210	290	6	–	90	90	–	–	difficult castings. Cast vehicle wheels

Al–Cu–Si	(L154)	Cu 4.2	Sand cast	T4	170	225	8	–	–	–	–	–	Aircraft castings
		Si 1.2	Chill cast	T4	175	280	15	–	–	–	–	–	
	(L155)		Sand cast	T6	215	295	5	–	85	–	–	–	
			Chill cast	T6	215	320	10	–	90	–	–	–	
Al–Cu–Si	(LM24)	Cu 3.5	Chill cast	F	110	200	3	–	85	–	–	–	Excellent die casting alloy
		Si 8.0	Die cast	F	150	320	2	–	85	–	–	–	
	(LM4)	Cu 3.0	Sand cast	F	90	155	3	–	70	70*	0.7	–	General engineering, particularly sand and permanent mould castings
		Si 5.0	Chill cast	F	100	170	3	–	80	75*	0.7	–	
			Sand cast	T6	230	260	1	–	105	–	–	–	
			Chill cast	T6	260	330	3	–	110	–	–	–	
	(LM22)	Cu 3.0 Si 5.0 Mn 0.5	Chill cast	T4	115	260	9	–	75	–	4.5	–	Good combination of impact resistance and strength
	(LM2)	Cu 1.5	Sand cast	F	85	140	1	–	70	55	–	–	General purpose die casting alloy
		Si 10.0	Chill cast	F	95	185	2	–	80	60	–	–	
Al–Cu–Mg	(LM12)	Cu 10.0	Chill cast	F	155	185	1	–	85	–	0.9	–	Castings to withstand high hydraulic pressure
		Mg 0.25	Chill cast	T6	285	310	–	–	130	60	–	–	
Al–Cu	(L119)	Cu 5.0 Ni 1.5	Sand cast	T6	200	225	2	–	90	–	–	–	Sand castings for elevated temperature service
Al–Zn–Mg	(DTT) 5008B	Zn 5.3 Mg 0.6 Cr 0.5	Sand cast	T4	–	220	5	–	–	–	–	–	Colour anodizing alloy
Al–Cu–Si–Zn	(LM27)	Cu 2.0 Si 7.0	Sand cast	F	85	155	2	–	75	–	–	–	Versatile general purpose alloy
			Chill cast	F	100	180	3	–	80	–	–	–	
Al–Si–Cu–Mg	(LM30)	Si 17.0	Chill cast	F	160	180	0.5	–	110	–	–	–	Die castings with high wear resistance, especially automobile cylinder blocks
		Cu 4.5	Die cast	F	240	275	1	–	120	–	–	–	
		Mg 0.6	Die cast	O	265	295	1	–	–	–	–	–	
	(LM16)	Si 5.0	Sand cast	T4	130	210	3	200	80	70	1.5	–	Water-cooled cylinder heads and applications requiring leak-proof castings
		Cu 1.0 Mg 0.5	Chill cast	T4	130	245	6	210	85	85	2.5	–	
			Sand cast	T6	245	255	1	215	100	60	1	–	
			Chill cast	T6	275	310	2	225	110	70	1.5	–	

continued overleaf

Table 3.2 *(continued)*

Cast Alloys

Specification		*Nominal composition* %	*Form*	*Condition*	0.2% *Proof stress* MPa	*Tensile strength* MPa	*Elong.*% on 50 mm ($\geq$2.6 mm) or $5.65\sqrt{S_0}$	*Shear strength* MPa	*Brinell hardness* ($P = 5D^2$)	*Fatigue strength (unnotched)* 500 MHz MPa	Impacy energy J	*Fracture toughness* (MPa $\mathrm{m}^{1/2}$)	*Remarks*
Al–Si–Mg–Mn	(LM9)	Si 12.0	Sand cast	T5	120	185	2	120	70	55*	1.5	–	Fluidity, corrosion resistance and high strength. Extensive use for low-pressure castings
		Mg 0.4	Chill cast	T5	160	255	2.5	160	80	70*	2.5	–	
		Mn 0.5											
			Sand cast	T6	235	255	1	200	100	70*	0.7	–	
			Chill cast	T6	275	310	1	230	110	85*	1.5	–	
	(LM25)	Si 7.0	Sand cast	F	90	140	2.5	–	60	–	–	–	The most widely used general purpose, high-strength casting alloy
		Mg 0.3	Chill cast	F	90	180	4	–	60	–	–	–	
			Sand cast	T5	135	165	1.5	–	75	55	–	–	
			Chill cast	T5	165	220	2.5	–	85	–	–	–	
			Sand cast	T7	95	170	3	–	65	–	–	–	
			Chill cast	T7	100	230	8	–	70	75	–	–	
			Sand cast	T6	225	255	1	–	105	60	–	–	
			Chill cast	T6	240	310	3	–	105	95	–	–	
Al–Cu–Mg–Ni (Y Alloy)	(L35)	Cu 4.0	Sand cast	T6	220	235	1	–	115	80*	1.5	–	Highly stressed components operating at elevated temperatures
		Mg 1.5	Chill cast	T6	240	290	2	–	115	110*	4.5	–	
		Ni 2.0											
Al–Si–Cu–Mg–Zn	(LM21)	Si 6.0	Sand cast	F	130	180	1	–	85	–	–	–	General engineering applications, particular crankcases
		Cu 4.0	Chill cast	F	130	200	2	–	90	–	–	–	
		Mg 0.2											
		Zn 1.0											
Al–Si–Cu–Mg–Ni		Si 23.0	Sand cast	T5	120	130	0.3	–	120	–	–	–	Pistons for high performance internal combustion engines
		Cu 1.0	Chill cast	T5	170	210	0.3	–	120	–	–	–	
	(LM29)	Mg 1.0	Sand cast	T6	120	130	0.3	–	120	–	–	–	High performance piston alloy
		Ni 1.0	Chill cast	T6	170	210	0.3	–	120	–	–	–	

	(LM28)	Si 19.0	Chill cast	T5	170	190	0.5	–	120	–	–	–	
		Cu 1.5											
		Mg 1.0	Sand cast	T6	120	130	0.5	–	120	–	–	–	
		Ni 1.0	Chill cast	T6	170	200	0.5	–	120	–	–	–	
		Si 11.0	Chill cast	T5	–	220	1	–	105	–	–	–	Low expansion piston alloy
		Cu 1.0											
	(LM13)	Mg 1.0	Sand cast	T6	190	200	0.5	–	115	85*	–	–	
		Ni 1.0	Chill cast	T6	280	290	1	190	125	100*	1.4	–	
	Lo–Ex		Sand cast	T7	140	150	1	–	75	–	–	–	
			Chill cast	T7	200	210	1	–	75	–	–	–	
	(LM26)	Si 9.0	Chill cast	T5	180	230	1	–	105	–	1.4	–	Piston alloy
		Cu 3.0											
		Mg 1.0											
		Ni 0.7											
Al–Cu–Si–Mg–Fe–Ni	(3L52)	Cu 2.0	Sand cast	T6	260	285	1	–	120	80	–	–	Aircraft engine castings for elevated temperature service
		Si 1.5	Chill cast	T6	305	335	1	–	125	–	–	–	
		Mg 1.0											
		Fe 1.0											
		Ni 1.25											
Al–Cu–Si–Fe–Ni–Mg	(3L51)	Cu 1.5	Sand cast	T5	135	170	2.5	–	70	–	–	–	Aircraft engine castings
		Si 2.0	Chill cast	T5	150	210	3.5	–	75	–	–	–	
		Fe 1.0											
		Ni 1.4											
		Mg 0.15											

*Fatigue Limit for 50×10^6 cycles.

M = as manufactured.

H111 = annealed.

H2, H4, H5, H6 } intermediate tempers.

H8 = fully hard temper.

(1) Special temper for maximum stress corrosion resistance (US designation T73).

(2) Special heat treatment for combination of properties (US designation T736).

(3) Special heat treatment for combination of properties (US designation T61).

(4) Special heat treatment for combination of properties (US designation T7351).

Table 3.3 ALUMINIUM AND ALUMINIUM ALLOYS – MECHANICAL PROPERTIES AT ELEVATED TEMPERATURES

Material (specification)	*Nominal composition* %	*Condition*		*Temp.* °C	*Time at temp.* h	0.2% *Proof stress* MPa	*Tensile strength* MPa	*Elong. % on* 50 mm *or* $5.65\sqrt{S_0}$
				Wrought Alloys				
Al (1095)	Al 99.95	Rolled rod	H111	24	–	–	55	61
				93	–	–	45	63
				203	–	–	25	80
				316	–	–	12	105
				427	–	–	5	131
(1200)	Al 99		H111	24	10 000	35	90	45
				100	10 000	35	75	45
				148	10 000	30	60	55
				203	10 000	25	40	65
				260	10 000	14	30	75
				316	10 000	11	17	80
				371	10 000	6	14	85
			H14	24	10 000	115	125	20
				100	10 000	105	110	20
				148	10 000	85	90	22
				203	10 000	50	65	25
				260	10 000	17	30	75
				316	10 000	11	17	80
				371	10 000	6	14	85
			H18	24	10 000	150	165	15
				100	10 000	125	150	15
				148	10 000	95	125	20
				203	10 000	30	40	65
				260	10 000	14	30	75
				316	10 000	11	17	80
				371	10 000	6	14	85
Al–Mn (3103)	Mn 1.25		H111	24	10 000	40	110	40
				100	10 000	37	90	43
				148	10 000	34	75	47
				203	10 000	30	60	60
				260	10 000	25	40	65
				316	10 000	17	30	70
				371	10 000	14	20	70
			H14	24	10 000	145	150	16
				100	10 000	130	145	16
				148	10 000	110	125	16
				203	10 000	60	95	20
				260	10 000	30	50	60
				316	10 000	17	30	70
				371	10 000	14	20	70
			H18	24	10 000	185	200	10
				148	10 000	110	155	11
				203	10 000	60	95	18
				260	10 000	30	50	60
				316	10 000	17	30	70
				371	10 000	14	20	70
Al–Mg (5050)	Mg 1.4		H111	24	10 000	55	145	–
				100	10 000	55	145	–
				148	10 000	55	130	–
				203	10 000	50	95	–
				260	10 000	40	60	–
				316	10 000	30	40	–
				371	10 000	20	30	–

Table 3.3 (*continued*)

Material (specification)	*Nominal composition* %	*Condition*	*Temp.* °C	*Time at temp.* h	0.2% *Proof stress* MPa	*Tensile strength* MPa	*Elong. % on* 50 mm *or* $5.65\sqrt{S_0}$
Al–Mg *(cont.)*		H14	24	10 000	165	195	–
			100	10 000	165	195	–
			148	10 000	150	165	–
			203	10 000	50	95	–
			260	10 000	40	60	–
			316	10 000	35	40	–
			371	10 000	20	30	–
		H18	24	10 000	200	220	–
			100	10 000	200	215	–
			148	10 000	175	180	–
			203	10 000	60	95	–
			260	10 000	40	60	–
			316	10 000	35	40	–
			371	10 000	20	30	–
Al–Mg–Cr (5052)	Mg 2.25 Cr 0.25	H111	24	10 000	90	195	30
			100	10 000	90	190	35
			148	10 000	90	165	50
			203	10 000	75	125	65
			260	10 000	50	80	80
			316	10 000	35	50	100
			371	10 000	20	35	130
		H14	24	10 000	215	260	14
			100	10 000	205	260	16
			148	10 000	185	215	25
			203	10 000	105	155	40
			260	10 000	50	80	80
			316	10 000	35	50	100
			317	10 000	20	35	130
		H18	24	10 000	255	290	8
			100	10 000	255	285	9
			148	10 000	200	235	20
			203	10 000	105	155	40
			260	10 000	50	80	80
			316	10 000	35	50	100
			371	10 000	20	35	130
(5154)	Mg 3.5 Cr 0.25	H111	24	10 000	125	240	25
			100	10 000	125	240	30
			148	10 000	125	195	40
			203	10 000	95	145	55
			260	10 000	60	110	70
			316	10 000	40	70	100
			371	10 000	30	40	130
		H14	24	10 000	225	290	12
			100	10 000	220	285	16
			148	10 000	195	235	25
			203	10 000	110	175	35
			260	10 000	60	110	70
			316	10 000	40	70	100
			371	10 000	30	40	130
		H18	24	10 000	270	330	8
			100	10 000	255	310	13
			148	10 000	220	270	20
			203	10 000	105	155	35
			260	10 000	60	110	70
			316	10 000	40	70	100
			371	10 000	30	40	130

continued overleaf

Table 3.3 (*continued*)

Material (specification)	*Nominal composition* %	*Condition*		*Temp.* °C	*Time at temp.* h	*0.2% Proof stress* MPa	*Tensile strength* MPa	*Elong. % on* 50 mm *or* $5.65\sqrt{S_0}$
Al–Mg–Mn	Mg 5.0	As extruded	F	20	1 000	145	300	25
(5056A)	Mn 0.3			50	1 000	145	300	27
				100	1 000	145	300	32
				150	1 000	135	245	45
				200	1 000	111	215	56
				250	1 000	75	130	77
				300	1 000	50	95	100
				350	1 000	20	60	140
Al–Mg–Si	Mg 0.7		T6	24	10 000	215	240	18
(6063)	Si 0.4			100	10 000	195	215	15
				148	10 000	135	145	20
				203	10 000	45	60	40
				260	10 000	25	30	75
				316	10 000	17	20	80
				371	10 000	14	17	105
(6082)	Mg 0.6		T6	24	10 000	230	330	17
	Si 1.0			100	10 000	270	290	19
	Cr 0.25			148	10 000	175	185	22
				203	10 000	65	80	40
				206	10 000	35	45	50
				316	10 000	30	35	50
				371	10 000	25	30	50
(6061)	Mg 1.0		T6	24	10 000	275	310	17
	Si 0.6			100	10 000	260	290	18
	Cu 0.25			148	10 000	213	235	20
	Cr 0.25			203	10 000	105	130	28
				260	10 000	35	50	60
				316	10 000	17	30	85
				371	10 000	14	20	95
Al–Cu–Mn	Cu 6.0	Forgings	T6	20	100	230	385	8
(2219)	Mn 0.25			100	100	–	365	–
				150	100	220	325	–
				200	100	185	280	–
				250	100	135	205	–
				300	100	110	145	–
				350	100	45	70	–
				400	100	20	30	–
Al–Cu–Pb–Bi	Cu 5.5		T4	24	10 000	295	375	15
(2011)	Pb 0.5			100	10 000	235	320	16
	Bi 0.5			148	10 000	130	195	25
				203	10 000	75	110	35
				260	10 000	30	45	45
				316	10 000	14	25	90
				371	10 000	11	17	125
Al–Cu–Mg–Mn	Cu 4.0		T4	24	10 000	275	430	22
(2017)	Mg 0.5			100	10 000	255	385	18
	Mn 0.5			148	10 000	205	274	16
				203	10 000	115	150	28
				260	10 000	65	80	45
				316	10 000	35	45	95
				371	10 000	25	30	100
(2024)	Cu 4.5		T4	24	10 000	340	470	19
	Mg 1.5			100	10 000	305	422	17
	Mn 0.6			148	10 000	245	295	17
				203	10 000	145	180	22
				260	10 000	65	95	45
				316	10 000	35	50	75
				371	10 000	25	35	100

Table 3.3 (*continued*)

Material (specification)	*Nominal composition* %	*Condition*		*Temp.* °C	*Time at temp.* h	0.2% *Proof stress* MPa	*Tensile strength* MPa	*Elong. % on* 50 mm *or* $5.65\sqrt{S_0}$
Wrought alloys								
Al–Cu–Mg–Si–Mn	Cu 4.4		T6	24	10 000	415	485	13
(2014)	Mg 0.4			100	10 000	385	455	14
	Si 0.8			148	10 000	275	325	15
	Mn 0.8			203	10 000	80	125	35
				260	10 000	60	75	45
				316	10 000	35	45	64
				371	10 000	25	30	20
		Forgings	T6	20	100	415*	480	10
				100	100	410	465	–
				150	100	400	430	–
				200	100	260	295	–
				250	100	85	110	–
				300	100	45	70	–
				350	100	35	50	–
Al–Cu–Mg–Ni	Cu 2.2	Forgings	T6	20	100	325*	430	8
(2618)	Mg 1.5			150	100	340	440	–
	Ni 1.2			200	100	260	300	–
	Fe 1.0			250	100	170	210	–
				300	100	70	115	–
				350	100	30	50	–
				400	100	20	30	–
(2031)	Cu 2.2	Forgings	T6	20	100	325*	430	13
	Mg 1.5			100	100	310	400	–
	Ni 1.2			200	100	255	310	–
	Fe 1.0			250	100	110	155	–
	Si 0.8			300	100	45	75	–
				350	100	30	40	–
Al–Si–Cu–Mg–Ni	Si 12.2	Forgings	T6	24	10 000	320	380	9
(4032)	Cu 0.9			100	10 000	305	345	9
	Mg 1.1			148	10 000	225	255	9
	Ni 0.9			203	10 000	60	90	30
(4032)				260	10 000	35	55	50
				316	10 000	20	35	70
				371	10 000	14	25	90
Al–Zn–Mg–Cu	Zn 5.6		T6	24	10 000	505	570	11
(7075)	Cu 1.6			100	10 000	430	455	15
	Mg 2.5			148	10 000	145	175	30
	Cr 0.3			203	10 000	80	95	60
				260	10 000	60	75	65
				316	10 000	45	60	80
				371	10 000	30	45	65
			Cast alloys					
Al–Mg	Mg 5.0	Sand cast	F	20	1 000	95	160	4
(LM 5)	Mn 0.5			100	1 000	100	160	3
				200	1 000	95	130	3
				300	1 000	55	95	4
				400	1 000	15	30	4
(LM 10)	Mg 10.0	Sand cast	T4	20	1 000	180	340	16
				100	1 000	205	350	10
				150	1 000	154	270	0
				200	1 000	105	185	42
				300	1 000	40	90	85
				400	1 000	11	45	100
Al–Si	Si 5.0	Pressure die cast	F	24	10 000	110	205	9
(LM 18)				100	10 000	110	175	9
				148	10 000	103	135	10
				203	10 000	80	110	17
				260	10 000	40	55	23

continued overleaf

Table 3.3 (*continued*)

Material (specification)	*Nominal composition* %	*Condition*		*Temp.* °C	*Time at temp.* h	*0.2% Proof stress* MPa	*Tensile strength* MPa	*Elong. % on* 50 mm *or* $5.65\sqrt{S_0}$
(LM 6)	Si 12.0	Pressure die	F	24	10 000	145	270	2
		cast		100	10 000	145	225	$2\frac{1}{2}$
				148	10 000	125	185	3
				206	10 000	105	150	7
				260	10 000	40	75	13
Al–Si–Cu	Si 5.0	Sand cast	F	20	1000	95*	155	2
(LM 4)	Cu 3.0			100	1000	140	180	2
	Mn 0.5			200	1000	110	135	2
				300	1000	40	60	12
				400	1000	20	30	27
Al–Si–Mg	Si 5.0	Chill cast	T6	20	1000	270*	325	2
(LM 25)	Mg 0.5			100	1000	255	290	2
				200	1000	60	90	25
				300	1000	25	40	65
				400	1000	12	25	65
Al–Cu–Mg–Ni	Cu 4.0	Sand cast	T6	20	1000	200*	275	$\frac{1}{2}$
(4L 35)	Mg 1.5			100	1000	255	325	$\frac{1}{2}$
	Ni 2.0			200	1000	150	135	$\frac{1}{2}$
				300	1000	30	55	32
				400	1000	15	40	60
Al–Si–Ni–Cu–Mg	Si 12.0	Chill cast	T6	20	1000	275*	285	$\frac{1}{2}$
(LM 13)	Ni 2.5			100	1000	280	320	$\frac{1}{2}$
	Cu 1.0			200	1000	110	165	$\frac{1}{2}$
	Mg 1.0			300	1000	30	60	15
				400	1000	15	35	25
		Chill cast	T6	20	1000	200*	275	1
		Special		100	1000	195	250	1
				200	1000	110	170	3
				300	1000	35	60	15
				400	1000	15	35	50

*0.1% Proof stress.

Table 3.4 ALUMINIUM AND ALUMINIUM ALLOYS – MECHANICAL PROPERTIES AT LOW TEMPERATURES

Material (specification)	*Nominal composition* %	*Condition*		*Temp.* °C	0.2% *Proof stress* MPa	*Tensile strength* MPa	*Elong.% on* 50 mm *or* 50 mm	*Reduction in area* %	*Fracture toughness* MPa $m^{1/2}$
Al	Al 9.0	Rolled and		24	34	90	42.5	76.4	–
(1200)		drawn rod	H111	−28	34	95	43.0	76.4	–
				−80	37	100	47.5	77.0	–
				−196	43	170	56	74.4	–
			H18	24	140	155	16	59.8	–
				−28	144	155	152	59.4	–
				−80	147	165	18.0	65.3	–
				−196	165	225	35.2	67.0	–
Al–Mn	Mn 1.25	Rolled and		24	40	110	43.0	80.6	–
(3103)		drawn rod	H111	−28	40	115	44.0	80.6	–
				−80	50	130	45.0	79.9	–
				−196	60	220	48.8	71.2	–

Table 3.4 (*continued*)

Material (specification)	*Nominal composition* %	*Condition*		*Temp.* °C	0.2% *Proof stress* MPa	*Tensile strength* MPa	*Elong.% on* 50 mm *or* 50 mm	*Reduction in area* %	*Fracture toughness* MPa $m^{1/2}$
		Rolled and drawn rod	H18	24	180	195	15.0	63.5	–
				28	185	205	15.0	64.4	–
				−80	195	215	16.5	66.5	–
				−196	220	290	32.0	62.3	–
Al–Mg (5052)	Mg 2.5 Cr 0.25	Rolled and drawn rod	H111	24	97	199	33.2	72.0	–
				−28	99	201	35.8	74.2	–
				−80	97	210	40.8	76.4	–
				−196	115	330	50.0	69.0	
			H18	24	235	275	16.6	59.1	–
				−28	230	280	18.3	63.2	–
				−80	236	290	20.6	64.5	–
				−196	275	400	30.9	57.4	–
(5154)	Mg 3.5 Cr 0.25	Sheet	H111	26	115	240	28	66	–
				−28	115	240	32	72	–
				−80	115	250	35	73	–
				−196	135	350	42	60	–
			H18	26	275	330	9	–	–
				−80	280	340	14	–	–
				−196	325	455	30	–	–
				−253	370	645	35	–	–
(5056A)	Mg 5.0 Mn 0.2	Plate	H111	20	130	290	30.5	32.0	–
				−75	130	290	38.2	48.2	–
				−196	145	420	50.0	36.2	–
Al–Mg–Si (6063)	Mg 0.7 Si 0.4	Extrusion	T4	26	90	175	32	78	–
				−28	105	190	33	75	–
				−80	115	200	36	75	–
				−196	115	260	42	73	–
		Extrusion	T6	26	215	240	16	36	–
				−28	220	250	16	36	–
				−80	225	260	17	38	–
				−196	250	330	21	40	–
Al–Mg–Si-Cr (6151)	Mg 0.7 Si 1.0 Cr 0.25	Forging	T6	24	300	320	15.2	38.8	–
				−28	310	352	12.0	34.0	–
				−80	305	330	14.9	38.7	–
				−196	330	385	18.3	34.7	–
Al–Mg–Si–Cu–Cr (6061)	Mg 1.0 Si 0.6 Cu 0.25 Cr 0.25	Rolled and drawn rod	T6	24	270	315	21.8	56.4	–
				−28	280	330	21.5	52.5	–
				−80	290	345	22.5	53.7	–
				−196	315	425	26.5	46.5	–
Al–Cu–Mg–Mn (2024)	Cu 4.5 Mg 1.5 Mn 0.6	Rolled and drawn rod	T4	24	300	480	23.3	31.8	–
				−28	305	500	24.4	33.1	–
				−80	320	510	25.3	30.8	–
				−196	400	615	26.7	26.3	–
		Rolled and drawn rod	T8	24	400	500	14.5	25.8	–
				−28	405	502	12.7	21.5	–
				−80	415	514	13.3	22.0	–
				−196	460	605	14.0	19.7	–
Al–Cu–Si–Mg–Mn (2014)	Cu 4.5 Si 0.8 Mg 0.5 Mn 0.8	Rod	T4	26	290	430	20	28	–
				−28	290	440	22	28	–
				−80	302	440	22	26	–
				−196	380	545	20	20	–
		Rod	T6	26	415	485	13	31	–
				−28	415	485	13	29	–
				−80	420	495	14	28	–
				−196	470	565	14	26	–

continued overleaf

Table 3.4 (*continued*)

Material (specification)	*Nominal composition* %	*Condition*		*Temp.* °C	0.2% *Proof stress* MPa	*Tensile strength* MPa	*Elong.% on* 50 mm *or* 50 mm	*Reduction in area* %	*Fracture toughness* MPa $m^{1/2}$
		Forging T6		26	410	465	12	24	–
				−80	460	510	14	24	–
				−196	530	610	11	22	–
				−253	590	715	7	22	–
(2090)	Cu 2.7	Plate		27	535	565	11	–	34
	Li 2.3	(12.5 mm)	T81	−196	600	715	13.5	–	57
	Zr 0.12			−269	615	820	17.5	–	72
(2091)	Cu 2.1	Plate		27	440	480	6	–	24
	Li 2.0	(38 mm)	T8	−73	460	495	7	–	32
	Mg 1.50			−196	495	565	10	–	32
	Zr 0.1			−269	550	630	7	–	32
Al–Zn–	Zn 5.6	Rolled and		24	485	560	15.0	29.1	–
Mg–Cu	Mg 2.5	drawn rod	T6	−28	490	570	15.3	26.2	–
(7075)	Cu 1.6			−80	505	590	15.3	23.6	–
				−196	570	670	16.0	20.1	–

H111 = Annealed. H18 = Fully hard temper. T4 = Solution treated and naturally aged. T6 = Solution treated and precipitation treated.

Table 3.5 ALUMINIUM ALLOYS – CREEP DATA

Material (specification)	*Nominal composition* %	*Condition*		*Temp.* °C	*Stress* MPa	*Minimum creep rate % per* 1000 h	*Total extension % in* 1000 h
Al	99.8	Sheet	H111	20	24.1	0.005	0.39
(1080)				20	27.6	0.045	1.28
				80	7.0	0.005	0.045
				80	8.3	0.01	0.065
				250	1.4	0.005	0.047
				250	2.1	0.01	0.047
				250	2.8	0.015	0.052
				250	4.1	0.055	0.152
Al–Mg	Mg	Sheet	H111	80	45	0.005	0.085
(5052)							
(LM 5)	Mg 5.6	Cast		100	110	0.055	0.33
				100	115	0.17	0.57
				100	125	0.21	1.19
				200	30	0.08	0.21
				200	45	0.20	0.39
				200	60	0.62	0.92
				300	3.90	0.045	0.10
				300	7.7	0.12	0.25
				300	15	0.35	0.60
(LM 10)	Mg 10	Cast		100	40	0.013	0.126
				100	55	0.022	0.107
				100	75	0.046	0.174
				150	7.5	0.126	0.413
				150	15	0.147	0.647
				200	7.5	0.107	0.341
				200	15	0.273	0.658
Al–Cu	Cu 4	Cast		205	17	0.04	–
				205	34	0.09	–
				205	51	0.14	–

Table 3.5 (*continued*)

Material (specification)	*Nominal composition %*	*Condition*	*Temp.* °C	*Stress* MPa	*Minimum creep rate % per* 1000 h	*Total extension % in* 1000 h
			205	70	0.69	–
			315	8.90	0.13	–
			315	13.1	0.29	–
	Cu 10	Cast	205	34	0.01	–
			205	68	0.11	–
			315	8.90	0.12	–
			315	13.1	0.43	–
			315	17	0.99	–
Al–Si	Si 13	Sandcast	100	45	0.016	0.190
(LM 13)	Ni 1.7	(modified)	100	60	0.06	0.675
	Mg 1.3		200	15	0.016	0.096
			200	23	0.054	0.179
			200	30	0.14	0.432
			300	3.8	0.013	0.026
			300	7.7	0.047	0.098
			300	15	0.223	0.428
Al–Mn	Mn 1.25	Extruded rod	200	15	0.001	–
(3103)			200	31	0.022	–
			200	34.8	0.040	–
			200	38.6	0.060	–
			200	42.5	0.13	–
			200	46	0.15	–
			200	54	0.73	–
			300	7.5	0.007	–
			300	15	0.39	–
Al–Cu–Si	Cu 4	Extruded T4	150	90	0.03	0.340
(2025)	Si 0.8		150	125	0.045	0.395
			150	155	0.325	0.722
			200	30	0.035	0.107
			200	45	0.1	0.204
			200	60	0.040	0.700
			250	15	0.02	0.156
			250	23	0.07	0.176
			250	30	2.36	–
Al–Cu–Mg–Mn	Cu 4.5	Clad sheet T4	35	415	10.0	–
(2024)	Mg 1.5		100	344	1.0	–
	Mn 0.6		100	385	10.0	–
			150	276	1.0	–
			150	327	10.0	–
			190	140	1.0	–
			190	200	10.0	–
		Clad sheet T6	35	424	1.0	–
			35	430	10.0	–
			100	347	1.0	–
			100	363	10.0	–
			150	242	1.0	–
			150	289	10.0	–
			190	117	1.0	–
			190	193	10.0	–
Al–Cu–Mg–Ni	Cu 4	Forged T4	100	193	0.01	0.394
(2218)	Mg 1.5		100	232	0.02	0.440
	Ni 2.2		100	270	0.04	0.835
			200	77	0.028	0.173
			200	108	0.16	0.345
			300	7	0.037	0.078
			300	15	0.5	0.640
			400	1.5	0.05	0.110

continued overleaf

Table 3.5 (*continued*)

Material (specification)	*Nominal composition %*	*Condition*	*Temp.* °C	*Stress* MPa	*Minimum creep rate % per* 1000 h	*Total extension % in* 1000 h
		Cast T4	200	77	0.01	0.153
			200	116	0.08	0.287
			300	7	0.018	0.072
			300	15	0.08	0.151
			400	1.50	0.06	0.132
Al–Cu–Mg–Zn	Zn 5.6	Clad sheet T6	35	430	0.1	–
(7075)	Cu 1.6		35	480	1.0	–
	Mg 2.5		35	495	10.0	–
			100	295	0.1	–
			100	355	1.0	–
			100	370	10.0	–
			150	70	0.1	–
			150	170	1.0	–
			150	245	10.0	–
			190	45	0.1	–
			190	75	1.0	–
			190	125	10.0	–
Al–Mg–Si–Mn	Mg 0.7	Extruded rod	100	193	0.007	–
(6351)	Si 1.0		100	201	0.010	–
	Mn 0.6		100	232	0.11	–
			100	255	1.6	–
			150	93	0.0087	–
			150	108	0.023	–
			150	154	0.22	–
			200	31	0.011	–
			200	46	0.040	–
			200	62	0.13	–
			200	77	0.28	–

H111 = Annealed.
T4 = Solution treated and naturally aged, will respond to precipitation treatment.
T6 = Solution treated and artificially aged.

Table 3.6 ALUMINIUM ALLOYS – FATIGUE STRENGTH AT VARIOUS TEMPERATURES

Material (specification)	*Nominal composition %*	*Condition*	*Temp.* °C	*Endurance (unnotched)* MPa	MHz	*Remarks*
Al–Mg	Mg 5.0	Extruded	−65	184	20	Rotating beam
(5056)			−35	164		
			+20	133		
	Mg 7.0	Extruded rod	−65	182	20	Rotating beam
			−35	178		
			+20	173		
(LM 10)	Mg 10.0	Sand cast (oil quenched)	20	93	30	Rotating beam
			150	77		
			200	40		
Al–Si	Si 12.0	Sand cast (modified)	20	51	50	Rotating beam, 24 h at temp.
(LM 6)			100	43		
			200	35		
			300	25		
Al–Cu	Cu 6.0	Forged T6	20	117	120	Reverse bending stresses
(2219)			150	65		
			200	62		
			250	46		
			300	39		
			350	23		

Table 3.6 (*continued*)

Material (specification)	*Nominal composition %*	*Temp. Condition*	*(unnotched) °C*	*Endurance* MPa	MHz	*Remarks*
Al–Si–Cu	Si 4.6	Sand cast	20	62	50	Rotating beam
(LM 22)	Cu 2.8		100	54		
			200	60		
			300	42		
Al–Cu–Si–Mn	Cu 4.5	Forgings T6	148	65	100	Rotating beam
(2014)	Si 0.8		203	45		
	Mn 0.8		260	25		
Al–Cu–Mn–Mg	Cu 4.0	Extruded T4	25	103	500	Rotating beam, 100
(2014)	Mn 0.5	rod	148	93		days at temp.
	Mg 0.5		203	65		
			260	31		
Al–Cu–Mg–Si–Mn	Cu 4.4	Forgings T4	20	119	120	Reversed bending
(2014)	Mg 0.7		150	90		
	Si 0.8		200	62		
	Mn 0.8		250	54		
			300	39		
		Forgings T6	20	130	120	Reversed bending
			150	79		
			200	57		
			250	39		
			300	39		
Al–Cu–Mg–Ni	Cu 4.0	Forged	20	117	500	Rotating beam after
(2218)	Mg 1.5		148	103	100	prolonged heating
	Ni 2.0		203	65	100	
			260	45	100	
		Chill cast T6	20	100	50	Rotating beam, 24 h
			100	105		at temp.
			200	108		
			300	80		
Al–Ni–Cu	Ni 2.5	Forged T6	20	113	120	Reversed bending
	Cu 2.2		150	82		
			200	70		
			250	59		
			300	39		
			350	39		
Al–Si–Cu–Mg–Ni	Si 12.0	Chill cast	20	97	50	Rotating beam,
(LM 13)	Cu 1.0	(Lo-Ex)	100	107		24 h at temp.
	Mg 1.0		200	97		
			300	54		
Al–Zn–Mg–Cu	Zn 5.6	Plate T6	24	151	500	Reversed bending
(7075)	Mg 2.5		149	83		
	Cu 1.6		204	59		
	Cr 0.2		260	48		

T4 = Solution treated and naturally aged, will respond to precipitation treatment.
T6 = Solution treated and artificially aged.

3.2 Mechanical properties of magnesium and magnesium alloys

Table 3.7 MAGNESIUM AND MAGNESIUM ALLOYS (WROUGHT) – TYPICAL MECHANICAL PROPERTIES AT ROOM TEMPERATURE

			Specifications				*Tension*			*Compression*	
Material	*Nominal* composition* %	*Form*	DTD or BS (Air)	BS (Gen. Eng.)	ASTM	*Elektron*	*Proof stress* 0.2% MPa	*UTS* MPa	*Elong.* %	*Proof stress* 0.2% MPa	*Hardness VPN* 30 kg
Mg	Mg 99.9	Sheet, annealed	–				69	185	4	–	30–35
		Bar, extruded	–				100	232	6	–	35–45
Mg–Mn	Mn 1.5	Sheet	118C	3370-MAG-S-101M	–	AM503	100	232	6	–	35–45
		Extruded bar (1 in diam.)	142B	3373-MAG-E-101M	M1A-F, B107		162	263	7	124	45–55
		Extruded tube	737A	3373-MAG-E-101M	M1A, B107		154	247	6	–	45–55
Mg–Al–Zn	Al 3.0	Sheet, annealed		3370-MAG-S-1110	AZ31, B90	AZ31	131	232	13	–	50–60
	Zn 1.0	half hard		3370-MAG-S-111M	AZ31, B90		170	263	10	100	55–70
	Mn 0.3	Extruded bar and sections		3373-MAG-E-111M	AZ31, B107		162	255	11	93	50–60
	Al 6.0	Forgings	2L513	3372-MAG-F-121M	AZ61, B91	AZM	183	293	8	147	60–70
	Zn 1.0	Extruded bar and sections	2L512	3373-MAG-E-121N	AZ61, B107		183	293	8	147	55–70
	Mn 0.3	Extruded tube	2L503	3373-MAG-E-121M	AZ61, B107		170	278	8	147	60–70
	Al 8.0	Forgings	88C	–	AZ80A, B91	AZ855	208	293	8	185	65–75
	Zn 0.5										
	Mn 0.3										
Mg–Zn–Mn	Zn 2.0	Sheet, annealed	5091	3370-MAG-S-1310		ZM21	131	232	13		
	Mn 1.0	half breed	5101	3370-MAG-S-131M			170	263	10		
		Extruded bar sections	–	3373-MAG-E-131M			162	255	11		
Mg–Zn–Zr	Zn 1.0	Sheet	2L514	3370-MAG-S-141M	–	ZW1	178	263	10	154	55–70
	Zr 0.6	Extruded bar and sections	2L508	3373-MAG-E-141M	–		208	293	13	177	60–75
		Extruded tube	2L509	3373-MAG-E-141M	–		193	278	7	–	60–75
	Zn 3.0	Sheet	2L504	3370-MAG-S-151M	–	ZW3	185	270	8	154	60–70

	Zr 0.6	Forgings	2L514	3372-NAG-F-151M	–		224	309	8	193	60–80
		Extruded bar and sections (1 in diam.)	2L505	3373-MAG-E-151M	–		239	309	18	213	65–75
	Zn 5.5 Zr 0.6	Bars and sections Heat treated	5041A	3373-MAG-E-161TE	ZK60A-T5, B107-70	ZW6	270	340	10	255	60–80
Mg–Zn–Cu–Mn	Zn 6.5 Cu 1.3 Mn 0.8	Bars and sections Heat treated	–	–	ZC71-T6, B107	ZC71	340	360	6	–	–
Mg–Th–Zn–Zr**	Th 0.8	Extruded bar and sections 5111	–	–	–	ZTy	147	263	18	–	50–70
(Creep resistant)	Zn 0.5 Zr 0.6	Forgings 5111	–	–	–		147	232	13	–	50–70
Mg–Th–Mn** (Creep resistant)	Th 2.0 Mn 0.75	Sheet	–	–	HM21-T8, B90	–	165	247	9	179	–
	Th 3.0 Mn 1.2	Extruded bar and sections	–	–	HM31-T5	–	227	287	8	185	–

Nuclear alloys: Two wrought magnesium alloys (Magnox AL80; Mg0.75Al-0.005 Be and MN70; Mg0.75 Mn) of interest only for their nuclear and high-temperature properties have room-temperature tensile properties similar to those of AM503.

*It is usual to add 0.2–0.4% Mn to alloys containing aluminium to improve corrosion resistance. M = As manufactured. O = Fully annealed. TE = Precipitation treated.

**Thorium-containing alloys are being replaced by alternative Mg alloys.

Table 3.8 MAGNESIUM AND MAGNESIUM ALLOYS (CAST) TYPICAL MECHANICAL PROPERTIES AT ROOM TEMPERATURE

			Specifications				*Tension*			*Compression*	
Material	*Nominal** *composition* %	*Condition*	DTD or BS (Air)	BS (Gen. Eng.)	ASTM	*Elektron*	*Proof stress* 0.2% MPa	*UTS* MPa	*Elong.* %	*Proof stress* 0.2% MPa	*Brinell hardnesst* *VPN* 30 kg
Mg–Zr	Zr 0.6	AC	–	–	KIA, B80	ZA	51	185	2.0	54	40–50
Mg–Al–Zn	Al 6.0	AC	–	–	AZ63A-F, B80	–	97	199	5	97	50
	Zn 3.0	TB	–	–	AZ63A-T4, B80		97	275	10	97	55
		TF	–	–	AZ63A-T6, B80		131	275	5	131	73
	Al 8.0	AC	–	2970 MAG 1-M		A8	86	158	4	86	50–60
	Zn 0.4	TB	3L122	2970 MAG 1-TB	AZ81A-T4, B80		82	247	11	82	50–60
	Al 9.5	AC	–	2970 MAG 3-M	AZ91C-F, B80	AZ91	93	154	2	93	55–65
	Zn 0.4	TB	3L124	2970 MAG 3-TB	AZ1C-T4, B80		90	232	6	90	55–65
		TF	3L125	2970 MAG 3-TF	AZ91C-T6, B80		127	239	2	124	75–85
		Die cast	–	–	AZ91B-F, B94		111	216	3	108	60–70
	Al 9.0	AC	–	–	AZ92A, B80	–	97	165	2	97	65
	Zn 2.0	TB	–	–	–		97	275	8	97	63
		TF	–	–	–		145	275	2	145	84
Mg–Zn–Zr	Zn 4.5	TE	2L127	2970 MAG 4-TE	ZK51A-T5, B80	Z5Z	161	263	6	162	65–75
	Zr 0.7										
Mg–Zn–RE–Zr	Zn 4.0	TE	2L128	2970 MAG 5-TE	ZE41A-T5, B80	RZ5	150	216	5	139	55–75
	RE 1.2										
	Zr 0.7										
	Zn 6.0	TF§	5045	–		ZE63	190	295	7	190	70–80
	RE 2.5										
	Zr 0.7										
Mg–RE–Zn–Zr (Creep resistant) to 250 °C)	RE 2.7	TE	2L126	2970 MAG 6-TE	EZ33A-T5, B80	ZRE1	95	162	4.5	93	50–60
	Zn 2.2										
	Zr 0.7										
Mg–Th–Zn–Zr** (Creep resistant to 350 °C)	Th 3.0	TE	5005A	2970 MAG 8-TE	HZ32A-T5, B80	ZT1	93	216	7	93	50–60
	Zn 2.2										
	Zr 0.7										
Mg–Zn–Th–Zr**	Zn 5.5	TE	5015A	2970 MAG 9-TE	ZH62A-T5, B80	TZ6	167	270	8	162	65–75
	Th 1.8										
	Zr 0.7										

Mg–Th–Zr[**]	Th 3.0 Zr 0.7	TF	–	–	HK31A-T6, B80	MTZ	93	208	5	93	50–60
Mg–Ag–RE[‡]-Zr	Ag 2.5 RE 2.0[‡] Zr 0.6	TF	5025A	–		MSR-A	187	247	5	178	65–80
			5035A	2970 MAG 12-TF		MSR-B	204	260	3	193	65–80
	Ag 2.5 RE 2.0[‡] Zr 0.6	TF	5055	–	QE22A-T6, B80	QE22	200	260	4	195	65–80
Mg–RE(D)–Ag–Zr-Cu	RE(D)2.2 Ag 1.5 Zr 0.6 Cu 0.07	TF	5055	2970 MAG 13-TF	EQ21A-T6, B80	EQ21	195	261	4	–	75–90
Mg–Ag–Th–RE[‡]Zr[**]	Ag 2.5 RE 1.0[‡] Th 1.0	TF	–	–	QH21A-T6, B80	QH21A	210	270	4	200	65–80
Mg–Y–RE(Δ)–Zr	Y 4.0 Zr 0.7 RE(Δ)3.4 Zr 0.6	TF	–	–	WE43-T6, B80	WE43	185	265	7	–	75–90
	Y 5.1 RE(Δ)3.0 Zr 0.6	TF	–	2970 MAG 14-TF	WE54-T6, B80	WE54	205	280	4	–	75–90
Mg–Zn–Cu–Mn	Zn 6.0 Cu 2.7 Mn 0.5	TF	–	–	ZC63-T6, B80	ZC63	158	242	4.5	–	55–65

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[*] It is usual to add 0.2–0.4% Mn to alloys containing aluminium to improve corrosion resistance. RE = Cerium mischmetal containing approx. 50% cerium.

RE(Δ) = Neodymium plus Heavy Rare Earth metals.

RE(D) = Neodymium enriched mischmetal.

[†] Brinell tests with 500 kg on 10 mm ball for 30 s.

[‡] Fractionated rare earth metals: MSR-A contains 1.7%; MSR-B contains 2.5%.

[§] Solution heat treated in an atmosphere of hydrogen.

AC = Sand cast. TE = Precipitation heat treated.

TB = Solution heat treated. TF = Fully heat treated.

[**] Thorium-containing alloys are being replaced by alternative Mg alloys.

Table 3.9 MAGNESIUM AND MAGNESIUM ALLOYS (excluding high temperature alloys for which see table 3.10) – TYPICAL TENSILE PROPERTIES AT ELEVATED TEMPERATURES

				'Short-time' tension†			
Material	*Nominal composition** %	*Form and condition*	*Test temp.* °C	*Young's modulus* GPa	0.2% *proof stress* MPa	*UTS* MPa	*Elong.* %
Mg	Mg 99.95	Forged	20	45	–	170	5
			100	–	–	128	8
			150	–	–	93	16
			200	–	–	54	43
Mg–Al–Zn	Al 8.0 Zn 0.4 (A8)	Sand cast	20	45	86	158	4
			100	34	76	154	5
			150	32	65	145	11
			200	25	62	100	20
			250	–	–	75	27
		Sand cast and solution treated	20	45	82	247	11
			100	34	73	202	16
			150	33	65	154	21
			200	28	62	116	25
			250	–	–	85	21
	(AZ855)	Forged	20	45	221	309	8
			150	–	153	216	25
			200	–	102	154	28
	Al 9.5 Zn 0.4 (AZ91)	Sand cast	20	45	93	154	2
			100	–	–	131	2
			150	–	–	122	6
			200	–	–	108	25
			250	–	–	77	34
		Sand cast and solution treated	20	45	90	232	6
			100	–	–	222	12
			150	–	–	196	16
			200	–	–	139	20
		Sand cast and fully heat treated	20	45	127	239	2
			100	40	91	232	6
			150	37	77	185	25
			200	28	62	133	34
			250	19	46	103	30
Mg–Zn–Zr	Zn 4.5 Zr 0.7 (Z5Z)	Sand cast and heat treated	20	45	161	263	6
			100	34	124	185	14
			150	28	102	145	20
			200	22	79	113	23
			250	19	57	85	20
	Zn 3.0 Zr 0.6 (ZW3)	Extruded	20	45	255	309	18
			100	40	162	182	33
			200	22	46	127	56
			250	12	11	100	71
		Sheet	20	45	195	270	10
			100	40	120	165	33
			150	33	74	116	42
			200	–	–	76	51
			250	–	–	49	59
Mg–Zn–RE–Zr	Zn 4.0 Re 1.2 Zr 0.7 (RZ5)	Sand cast	20	45	150	216	4
		Sand cast treated	20	41	134	195	6
			150	40	120	167	19
			200	38	99	131	29
			250	33	74	99	35

Table 3.9 (*continued*)

				‘Short-time’ tension[†]			
Material	*Nominal composition*[*] %	*Form and condition*	*Test temp.* °C	*Young’s modulus* GPa	0.2% *proof stress* MPa	*UTS* MPa	*Elong.* %
Mg–Zn–Th–Zr[**]	Zn 5.5	Sand cast and heat treated	20	45	161	270	9
	Th 1.8		100	34	134	224	22
	Zr 0.7		150	31	110	178	26
	(TZ 6)		200	28	82	130	26
			250	26	52	91	25
Mg–Ag–RE–Zr (D)	Ag 2.5	Sand cast and fully heat treated	20	45	201	259	4
	RE(D)2.0		100	41	185	232	12
	Zr 0.6		150	40	171	210	16
	(QE22)		200	38	154	185	20
			250	34	102	142	27
			300	31	68	88	59
Mg–RE(D)–Ag–Zr–Cu	Re(D)2.2	Sand cast and fully heat treated	20	45	195	261	4
	Ag 1.5		100	43	189	230	10
	Zr 0.6		150	42	180	211	16
	Cu 0.07		200	41	170	191	16
	(EQ21)		250	39	152	169	15
			300	35	117	132	10
Mg–Ag–Re(D)[**] Th–Zr [‡]	Ag 2.6	Sand cast and fully heat treated	20	45	210	270	4
	RE(D)1.0		100	41	199	242	17
	Th 1.0		150	40	190	224	20
	Zr 0.6		200	38	183	205	18
	(OH21)		250	37	167	185	19
			300	33	120	131	20
Mg–Y–RE(Δ)–Zr	Y 4.0	Sand cast and fully heat treated	20	45	185	265	7
	RE(Δ)3.4		150	42	175	250	6
	Zr 0.6		200	39	170	245	11
	(WE43)		250	37	160	220	18
			300	35	120	160	40
	Y 5.1	Sand cast and fully heat treated	20	45	205	280	4
	RE(Δ)3.0		100	43	197	260	4.5
	Zr 0.6		150	42	195	255	5
	(WE54)		200	41	183	241	6.5
			250	39	175	230	9
			300	36	117	184	14.5
Mg–Zn–Cu–Mn	Zn 6.0	Sand cast and fully heat treated	20	45	158	242	4.5
	Cu 2.7		100	–	141	215	9
	Mn 0.5		150	–	134	179	14
	(Zc63)		200	–	118	142	11
	Zn 6.5	Extruded and fully heat treated	20	45	325	350	6
	Cu 1.3		100	40	206	259	16
	Mn 0.8		200	32	115	163	14
	(Zc71)						

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[*] It is usual to add 0.2–0.4% Mn to alloys containing aluminium to improve corrosion resistance.

[†] In accordance with BS1094: 1943; 1 h at temperature and strain rate 0.1–0.25 in in^{-1} min^{-1}.

[‡] Tested according to BS4A4. RE = Cerium mischmetal containing approx. 50% Ce. RE(D) = Neodymium enriched mischmetal. RE(Δ) = Neodymium plus Heavy Rare Earth metals.

[**] Thorium-containing alloys are being replaced by alternative Mg alloys.

Table 3.10 HIGH TEMPERATURE MAGNESIUM ALLOYS – TENSILE PROPERTIES AT ELEVATED TEMPERATURE

				'Short-time' tension†			
Material	*Nominal composition** %	*Form and condition*	*Test temp.* °C	*Young's modulus* GPa	0.2% *proof stress* MPa	*UTS* MPa	*Elong.* %
Mg–RE–Zn	RE 2.7	Sand cast	20	45	93	162	4.5
	Zn 2.2	and heat	100	40	79	150	11
	Zr 0.7	treated	150	38	76	139	19
	(ZRE1)		200	36	74	125	26
			250	33	65	107	35
			300	28	48	85	51
			350	21	26	56	90
Mg–Th–Zr**	Th 3.0	Sand cast	20	45	93	208	4
	Zr 0.7	and fully	100	40	88	188	10
	(HK31)	heat	150	38	86	174	13
	(MTZ)	treated	200	38	85	162	17
			250	36	83	150	20
			300	34	73	136	22
			350	29	56	103	23
Mg–Th–Zn–Zr**	Th 3.0	Sand cast	20	45	93	216	9
	Zn 2.2	and heat	100	36	88	159	23
	Zr 0.7	treated	150	34	79	131	27
	(ZT1)		200	33	65	108	33
			250	33	56	90	38
			300	31	49	76	41
			350	28	45	63	34
	Th 0.8	Sheet	20	45	181	266	10
	Zn 0.5		100	41	179	224	10
	Zr 0.6		150	41	176	201	11
	(ZTY)		200	40	165	171	15
			250	40	124	134	20
			300	34	73	96	27
			350	29	17	56	38
Mg–Ag–RE(D)–Zr	Ag 2.5 RE(D)2.0 Zr 0.6 (QE22)	Sand cast and fully heat treated	High strength cast alloys with good elevated temperature properties – for which *see* Table 3.9				
Mg–RE(D)–Ag–Zr–Cu	RE(D)2.2 Ag 1.5 Zr 0.6 Cu 0.07 (EQ21)	Sand cast and fully heat treated					
Mg–Ag–RE(D)–Th–Zr**	Ag 2.5 RE(D)1.0 Th 1.0 Zr 0.6 (QH21)	Sand cast and fully heat treated					
Mg–Y–RE(Δ)–Zr	Y 4.0 RE(Δ)3.4 (WE43)	Sand cast and fully treated					
	Y 5.1 RE(Δ)3.0 Zr 0.6 (WE54)	Sand cast and fully eat treated					

*It is usual to add 0.2–0.4% Mn to alloys containing aluminium to improve corrosion resistance.

†In accordance with BS 1094: 1943; 1 h at temperature; strain rate 0.1–0.25 in in^{-1} min^{-1}.

RE = Cerium mischmetal containing approx. 50% Ce. RE(D) = neodymium-enriched mischmetal.

RE(Δ) = Neodymium plus Heavy Rare Earths.

**Thorium containing alloys are being replaced by alternative Mg alloys.

Table 3.11 HIGH-TEMPERATURE MAGNESIUM ALLOYS – LONG-TERM CREEP RESISTANCE

					Stress to produce specified creep strains%				
Material	*Nominal composition* %	*Form and Condition*	*Temp.* °C	*Time*† h	0.05 MPa	0.1 MPa	0.2 MPa	0.5 MPa	1.0 MPa
Mg–RE–Zn–Zr	RE 2.7	Sand cast	200	100	52	66	71	–	–
	Zn 2.2	and heat		500	41	54	65	–	–
	Zr 0.7	treated		1 000	36	47	58	–	–
	(ZRE1)								
			250	100	23	28	32	36	–
				500	11	19	24	30	34
				1 000	–	14	20	26	30
			315	100	5.6	7.4	8	–	–
				500	–	5.2	6.5	–	–
				1 000	–	4.3	5.6	–	–
	Zn 4.0	Sand cast	100	100	–	97	111	117	–
	RE 1.2	and heat		500	–	–	106	117	–
	Zr 0.7	treated		1 000	–	–	103	116	–
	(RZ5)								
			150	100	77	86	97	101	107
				500	–	75	88	96	100
				1 000	–	70	83	91	97
			200	100	29	43	52	67	73
				500	22	28	37	52	64
				1 000	20	23	31	43	53
			250	100	6.2	12	19	32	39
				500	4.3	6.2	8.6	15	19
				1 000	3.9	5.4	6.9	12	15
Mg–Th–Zr**	Th 3.0	Sand cast	200	100	31*	45*	63*	97*	111*
	Zr 0.7	and fully		1 100	–	–	62*	100*	–
	(HK31)	heat							
	(MTZ)	treated	260	100	–	28*	43*	65*	–
				1 000	–	–	29*	45*	–
			315	100	9.3*	14*	19*	27*	32*
Mg–Th–Zn–Zr**	Th 0.8	Sheet	250	100	Stress of 46 MPa (3 tonf in^{-2}) produced 0.03% creep strain				
	Zn 0.5								
	Zr 0.6				Stress of 46 MPa (3 tonf in^{-2}) produced 0.03% creep strain				
	(ZTY)								
Mg–Th–Zn–Zr*	Th 3.0	Sand cast	250	100	42	50	56	63	66
	Zn 2.2	and heat		500	35	43	51	58	63
	Zr 0.7	treated		1 000	31	39	48	56	61
	(ZT1)								
			300	100	23	28	35	46	52
				500	19	21	25	36	41
				1 000	17	19	21	32	36
			325	100	14	19	24	29	36
				500	12	13	16	21	25
				1 000	10	12	13	15	20
			350	100	10	12	18	21	23
				500	–	9	10	12	14
				1 000	–	8	8	9	10
			375	100	–	8	11	12	13
				500	–	–	–	8	9
				1 000	–	–	–	–	8
	Zn 5.5	Sand cast	150	100	51	66	82	96	102
	Th 1.8	and heat		500	36	56	69	85	94
	Zr 0.7	treated		1 000	26	51	63	80	90
	(TZ6)								
			200	100	26	32	45	56	62
				500	15	22	26	40	49
				1 000	11	17	20	31	40

Table 3.11 (*continued*)

						Stress to produce specified creep strains%				
Material	*Nominal composition* %		*Form and Condition*	*Temp.* °C	*Time*[†] h	0.05 MPa	0.1 MPa	0.2 MPa	0.5 MPa	1.0 MPa
Mg–Ag–RE(D)–Zr	Ag	2.5	Sand cast	200	100	55	74	88	–	–
	RE(D)	2.0	and fully		500	–	54	65	82	89
	Zr	0.6	heat		1 000	–	46	56	73	79
	(QE22)		treated							
				250	100	18	26	33	–	–
					500	–	15	22	28	31
					1 000	–	10	16	22	26
Mg–RE(D)–Ag–Zr–Cu	RE(D)	2.2	Sand cast	200	100	–	78	95	116	–
	Ag	1.5	and fully		500	–	57	71	88	–
	Zr	0.6	heat		1 000	–	48	62	76	–
	Cu	0.07	treated							
	(EQ21)									
				250	100	–	29	36	42	–
					500	–	18	22	30	–
					1 000	–	14	19	24	–
Mg–Ag–RE(D)–Th–Zr[**]	Ag	2.5	Sand cast	250	100	22	32	39	–	–
	RE(D)	1.0	and fully		500	–	20	26	32	36
	Th	1.0	heat		1 000	–	–	21	26	30
	Zr	0.6	treated							
	(QH21)									
Mg–Y–RE(Δ)–Zr	Y	4.0	Sand cast	200	100	–	148	161	173	–
	RE(Δ)	3.4	and fully		500	–	–	115	148	–
	Zr	0.6	heat		1 000	–	–	96	139	–
	(WE43)		treated							
				250	100	–	44	61	–	–
					500	–	–	46	–	–
					1 000	–	–	39	–	–
	Y	5.1	Sand cast	200	100	–	160	165	–	–
	RE(Δ)	3.0	and fully		500	–	120	140	–	–
	Zr	0.6	heat		1 000	–	120	132	–	–
	(WE54)		treated							
				250	100	–	47	61	81	–
					500	–	43	40	58	–
					1 000	–	16	32	48	–
Mg–Zn–Cu–Mn	Zn	6.0	Sand cast	150	100	–	94	99	104	–
	Cu	2.7	and fully		500	–	82	92	98	–
	Mn	0.5	heat		1 000	–	74	89	95	–
	(ZC63)		treated							
				200	100	–	60	63	67	–
					500	–	51	55	61	–
					1 000	–	42	49	55	–

[*] Total strains.

[†] 4–6 h heating to test temperature followed by 16 h soaking at test temperature.

RE = Cerium mischmetal containing approx. 50% Ce.

RE(D) = Neodymium-enriched mischmetal.

RE(Δ) = Neodymium plus Heavy Rare Earth metals.

[**] Thorium-containing alloys are being replaced by alternative Mg alloys.

Table 3.12 HIGH-TEMPERATURE MAGNESIUM ALLOYS – SHORT-TERM CREEP RESISTANCE

Material	Nominal composition %	Form and condition	Temp. °C	Time† s	*Stress to produce specified creep strains%* 0.05 MPa	1.0 MPa	2.0 MPa	5.0 MPa	10.0 MPa	Stress to fracture MPa
Mg–RE–Zn–Zr	Re 2.7	Sand cast and heat treated	200	30	–	–	98	118	130	136
	Zn 2.2			60	–	–	97	117	128	134
	Zr 0.7 (ZRE1)			600	–	–	96	116	125	129
			250	30	76	84	92	111	123	130
				60	74	83	91	110	120	129
				600	73	82	89	108	114	125
			315	30	52	59	73	80	85	90
				60	51	58	69	76	83	88
				600	42	49	56	62	68	73
	Zn 4.0	Sand cast and heat treated	200	30	100	107	116	127	–	136
	RE 1.2			60	99	105	114	124	–	134
	Zr 0.7 (RZ5)			600	86	99	103	114	–	125
			250	30	86	90	94	99	–	116
				60	83	88	91	96	–	113
				600	71	76	81	86	–	93
			315	30	62	69	76	79	83	86
				60	59	66	73	76	79	82
				600	48	53	59	64	67	69
Mg–Th–Zr*	Th 3.0	Sand cast and fully heat treated	250	30	96	103	119	138	–	145
	Zr 0.7			60	95	103	118	137	–	145
	(HK31) (MTZ)			600	94	102	117	137	–	144
			315	30	80	88	103	117	–	128
				60	78	86	102	116	–	127
				600	74	82	96	107	–	120
Mg–Th–Zn–Zr*	Th 0.8	Sheet	250	30	–	–	110	159	163	165
	Zn 0.5			60	–	–	95	157	160	162
	Zr 0.6 (ZTY)			600	–	–	–	145	149	151
			350	30	20	32	48	80	93	102
				60	18	28	40	67	82	98
				600	–	15	20	31	42	66
Mg–Th–Zn–Zr*	Th 3.0	Sand cast and heat treated	200	30	–	–	–	100	118	125
	Zn 2.2			60	–	–	–	96	114	123
	Zr 0.7 (ZT1)			600	–	–	–	85	103	114
			250	30	58	65	71	84	102	111
				60	57	64	69	81	99	107
				600	56	63	68	74	86	98
			315	30	55	60	64	73	76	82
				60	53	59	63	72	76	80
				600	50	59	61	71	74	77
	Zn 5.5	Sand cast and heat treated	200	30	96	113	120	128	137	144
	Th 1.8			60	93	109	117	124	133	137
	Zr 0.7 (TZ6)			600	63	90	102	110	114	119
			250	30	70	77	85	96	99	107
				60	65	74	80	90	94	99
				600	56	60	66	74	77	82
			315	30	54	59	64	70	74	76
				60	52	57	62	66	70	73
				600	44	49	53	56	58	59

† 1 h heating to test temperature followed by 1 h soaking at test temperature.
RE = cerium mischmetal containing approx. 50% Ce.
*Therium-containing alloys are being replaced by alternative Mg alloys.

Table 3.13 MAGNESIUM AND MAGNESIUM ALLOYS – FATIGUE AND IMPACT STRENGTHS

					Fatigue strength† *at specified cycles*						*Impact strength*§ *for single blow fracture*		
Material	*Nominal* composition* %	*Condition*	‡ *State*	*temp.* °C	10^5 MPa	5×10^5 MPa	10^6 Mpa	5×10^6 MPa	10^7 MPa	5×10^7 MPa	*Test temp.* °C	*Unnotched* J	*Notched* J
Mg–Mn	Mn 1.5	Extruded	U	20	107	90	88	86	85	83	20	12–14	4–4.5
	(AM503)		N		76	90	54	51	50	48			
Mg–Al–Zn	Al 6.0	Extruded	U	20	161	139	133	125	124	120	20	34–43	7–9.5
	Zn 1.0		N		127	110	103	97	94	91			
	(AZM)												
	Al 8	Sand cast	U	20	108	93	90	88	88	86	20	3–5	1.5–2
	Zn 0.4		N		107	80	73	66	65	63			
	(A8)	Sand cast and solution treated	U	20	124	102	97	91	90	90	20	18–27	4.5–7
			N		108	86	82	74	73	69			
			U	150	93	69	66	59	57	57			
			U	200	71	52	48	38	36	31	−196	1.5	
	Al 9.5	Sand cast	U	20	114	91	89	88	86	85	20	1.5–2.0	1–1.5
	Zn 0.4		N		110	83	74	68	66	63			
	(AZ91)	Sand cast and solution treated	U	20	124	93	93	93	93	–	20	7–9.5	3–4
			N		103	82	80	79	79	77			
		Sand cast and fully heat treated	U	20	117	90	80	79	77	76	20	3–4	1–1.5
			N		93	66	66	65	65	65			
Mg–Zn–Zr	Zn 3.0	Extruded	U	20	151	137	134	128	127	124	20	23–31	9.5–12
	Zr 0.6		N		124	99	93	91	90	88			
	(ZW3)												
	Zn 4.5	Sand cast and heat treated	U	20	111	86	85	82	80	77	20	7–12	3–4
	Zr 0.7		N		90	86	85	82	80	77	−196	0.8	
	(Z5Z)												
Mg–Zn–RE–Zr	Zn 4.0	Sand cast and heat treated	U	20	124	99	97	97	96	94	20	4–5.5	1–2
	RE 1.2		N		108	93	91	88	86	83	−196	0.7	
	Zr 0.7		U	150	97	85	80	73	69	65			
	(RZ5)		U	200	93	74	69	62	59	54			
	Zn 2.2	Sand cast and heat treated	U	20	100	82	80	79	77	74	20	6–7.5	1–2
	RE 2.7		N		77	59	54	52	52	51			

	Zr	0.7		U	150	69	60	59	57	57	57			
	(ZRE1)			U	200	68	59	56	52	51	51			
				U	250	59	48	45	43	43	42	−196	0.5	
				U	300	49	39	37	37	36	34			
	Zn	6	Sand cast	U	20	144	131	127	121	119	117	20	12.9–17.6	2.3–2.7
	RE	2.5	and fully	N		99	83	79	73	72	71			
	Zr	0.6	heat treated**											
	(ZE63)													
Mg–Ag–RE(D)–Zr	Ag	2.5	Sand cast and	U	20	119	103	103	103	102	100			
	RE(D)	2.5	fully heat	N		77	65	63	62	62	62			
	Zr	0.6	treated	N	200	–	–	–	90	88	86			
	(MSR–B)			U	250	–	77	68	57	54	51			
Mg–Ag– RE(D)Th–Zr**	Ag	2.5	Sand cast and	U	20	135	114	111	109	108	108			
	Re(D)	1.0	fully heat	N		86	72	69	64	63	62			
	Th	1.0	treated	U	250	108	76	65	56	55	52			
	Zr	0.6												
	(QH21)													
Mg–Zn–Th–Zr**	Zn	5.5	Sand cast and	U	20	120	86	85	83	83	82	20	8–11	1.5–3
	Th	1.8	heat treated	N		100	86	80	77	76	76	−196	0.5	
	Zr	0.7												
	(TZ6)													
Mg–Th–Zr**	Th	3.0	Sand cast and	U	20	–	74	68	65	63	62			
	Zr	0.7	fully heat	N		–	48	40	36	34	32			
	(MTZ)		treated	U	200	–	74	68	60	59	58			
				U	250	80	63	59	54	52	51			

continued overleaf

Table 3.13 (*continued*)

						Fatigue strength[†] at specified cycles						*Impact strength[§] for single blow fracture*		
Material	*Nominal[*] composition* %		*Condition*	‡ *State*	*temp.* °C	10^5 MPa	5×10^5 MPa	10^6 Mpa	5×10^6 MPa	10^7 MPa	5×10^7 MPa	*Test temp.* °C	*Unnotched* J	*Notched* J
Mg–Th–Zn–Zr***	Th	0.7	Extruded	U	20	100	86	83	79	76	74			
	Zn	0.5		N		73	52	51	49	48	46			
	Zr	0.6		U	200	–	74	68	60	59	57			
	(ZTY)			U	250	80	63	59	54	52	51			
	Th	3.0	Sand cast and heat treated	U	20	97	82	79	74	71	68	20	7–8	1.5–3
	Zn	2.2		N		76	59	56	51	49	48			
	Zr	0.7		U	200	71	60	59	54	52	51			
	(ZT1)			U	250	66	51	46	43	42	39			
				U	325	–	–	43	37	34	29	−196	0.8	
Mg–RE(D)–As–Zr–Cu	RE(D)	2.2	Sand cast and fully heat treated	U	20	103	94	93	92	91	90			
	Ag	1.5												
	Zr	0.6												
	Cu	0.07												
Mg–Y–RE(Δ)–YZr	Y	4.0	Sand cast and fully heat treated	U	20	114	101	98	94	93	91			
	RE(Δ)	3.4		U	150	107	97	94	87	85	83			
	Zr	0.6		U	250	107	81	74	65	64	62			
	Y	5.9	Sand cast and fully heat treated	U	20	113	104	102	100	99	97			
	RE(Δ)	3.0		U	200	118	96	90	84	83	82			
	Zr	0.6		U	250	115	84	78	67	66	65			
Mg–Zn–Cu–Mn	Zn	6.0	Sand cast and fully heat treated	U	20	–	–	100	94	92	90			
	Cu	2.7		N		–	–	62	57	56	55			
	Mn	0.5												

[*] It is usual to add 0.2–0.4% Mn to alloys containing aluminium to improve corrosion resistance.

[**] Solution heat treated in an atmosphere of hydrogen.

[†] Wohler rotating beam tests at 2960 c.p.m.

[‡] U = Unnotched.

N = Notched. Semi-circular notch of 0.12 cm (0.047 in) radius. Stress concentration factor 1.8.

[§] Hounsfield balanced impact test, notched bar values are equivalent to Izod values.

RE(D) = Neodymium enriched mischmetal.

[***] Thorium-containing alloys are being replaced by alternative Mg alloys.

RE(Δ) = Neodymium plus Heavy Rare Earths.

Table 3.14 HEAT TREATMENT OF MAGNESIUM ALLOY CASTINGS

Heat treatment conditions for magnesium sand castings can be varied depending on the particular components and specific properties required. The following are examples of the conditions used for each alloy which will give properties meeting current national and international specifications.

Material		*Nominal* composition %*		*Condition*	*Time* h	*Temperature* °C
Mg–Al–Zn	(AZ80)	Al	8.0	TB	12–24	400–420
		Zn	0.4			
	(AZ91)	Al	9.5	TB	16–24	400–420
		Zn	0.4			
	(AZ91)			TF	16–24	400–420
						Air cool
					8–16	180–210
Mg–Zn–Zr	(Z5Z)	Zn	4.5	TE	10–20	170–200
		Zr	0.7			
Mg–Zn–RE–Zr	(RZ5)	Zn	4.0	TE	2–4	320–340
		RE	1.2			Air cool
		Zr	0.7		10–20	170–200
	(ZRE1)	RE	2.7	TE	10–20	170–200
		Zn	2.2			
		Zr	0.7			
Mg–Th–Zr†	(HK31)	Th	3.0	TF	2–4	560–570
		Zr	0.7			Air cool
					10–20	195–205
Mg–Zn–Th–Zr†	(TZ6)	Zn	5.5	TE	2–4	320–340
		Th	1.8			Air cool
		Zr	0.7		10–20	170–200
	(ZT1)	Th	3.0	TE	10–20	310–320
		Zn	2.2			
		Zr	0.7			
Mg–Ag–RE(D)Zr	(QE22)	Ag	2.5	TF	4–12	520–530
		RE(D)	2.0		Water/Oil Quench	
		Zr	0.6		8–16	195–205
Mg–RE(D)–Ag–Zr–Cu	(EQ21)	RE(D)	2.2	TF	4–12	515–525
		Ag	1.5		Water/Oil Quench	
		Zr	0.6		12–16	195–205
		Cu	0.07			
Mg–Ag–RE(D)–Th–Zr	(QH21)†	Ag	2.5	TF	4–12	520–530
		RE(D)	1.0		Water/Oil Quench	
		Th	1.0		12–20	195–205
		Zr	0.6			

Table 3.14 (*continued*)

Material		*Nominal* composition %*		*Condition*	*Time h*	*Temperature °C*
Mg–Y–RE(Δ)–Zr	(WE43)	Y	4.0	TF	4–12	520–530
		RE(Δ)	3.4		Water/Oil Quench	
		Zr	0.6		12–20	245–255
	(WE54)	Y	5.1	TF	4.12	520–530
		RE(Δ)	3.0		Water/Oil Quench/Air Cool	
		Zr	0.6		12–20	245–255
Mg–Zn–Cu–Mn	(ZC63)	Zn	6.0	TF	4–12	435–445
		Cu	2.7		Water Quench	
		Mn	0.5		16–24	180–200

Note:- Above 350 °C, furnace atmospheres must be inhibited to prevent oxidation of magnesium alloys. This can be achieved either by:

(i) adding 1/2–1%SO_1 gas to the furnace atmosphere; or

(ii) carrying out the heat treatment in an atmosphere of 100% dry CO_2.

*It is usual to add 0.2–0.4% Mn to alloys containing aluminium to improve corrosion resistance.

RE = Cerium mischmetal containing approximately 50% cerium.	TB = Solution heat treated.
RE(D) = Neodymium-enriched mischmetal.	TE = Precipitation heat treated.
RE(Δ) = Neodymium plus Heavy Rare Earth metals.	TF = Fully heat treated.

†Thorium-containing alloys are being replaced by alternative Mg alloys.

Mechanical properties at subnormal temperatures

At temperatures down to −200 °C tensile properties have approximately linear temperature coefficients: proof stress and UTS increase by 0.1–0.2% of the RT value per °C fall in temperature, and elongation falls at the same rate: modulus of elasticity rises approximately 19 MPa (2800 lbf in^{-2}) per °C over the range 0° to −100 °C. No brittle-ductile transitions have been found.

Tests at −70 °C have suggested that the magnesium-zinc-zirconium alloys show the best retention of ductility and notched impact resistance at this temperature.

3.3 Mechanical properties of titanium and titanium alloys

Table 3.15 PURE TITANIUM, TYPICAL MECHANICAL PROPERTIES AT ROOM TEMPERATURE

Designation[*]	*Grade*	*Condition*	0.2% *proof stress* MPa	*Tensile strength* MPa	*Elongation %* *on* 50 mm	*Elongation %* *on* 5D	*Red. in area* %	*Specification bend radius* 180° bend <1.83 mm	*Specification bend radius* 180° bend <3.25 mm	*Mod. of elasticity* GPa	*Mod. of rigidity* GPa
Iodide	Pure, 60 HV		103	241	55		80				
IMI 115	Commercially pure	Annealed sheet	255	370	33			1t	2t		
		Annealed rod	220	370		40	70				
		Annealed wire		390	38						
IMI 125	Commercially pure	[†]Annealed sheet	340	460	30			$1\frac{1}{2}$t	2t		
		Annealed rod	305	460		28	57				
		Annealed tube	325	480	35						
IMI 130	Commercially pure	Annealed sheet	420	540	25			2t^{+}	$2\frac{1}{2}$t		
		Annealed rod	360	540		24	48			105	38
		Annealed wire		550	24						
		Hard-drawn wire		700	11.5						
IMI 155	Commercially pure	Annealed sheet	540	640	24			$2\ \frac{1}{2}$t	3t		
IMI 160	Commercially pure	Annealed rod	500	670		23	46				
		Annealed wire		690	24						

[*] IMI Nomenclature. [†] Up to 16.3 mm.

Table 3.16 TITANIUM ALLOYS TYPICAL MECHANICAL PROPERTIES AT ROOM TEMPERATURE

*Designation**	*Nominal composition* %	*Condition*	0.2% *proof stress* MPa	*Tensile strength* MPa	*Elongation %* *on* 50 *mm*	*on* 5D	*Red. in area* %	*Specification bend radius* 180°	*Mod. of elasticity* GPa	*Mod. of rigidity* GPa
IMI 230	Cu 6.0	Annealed sheet	520	620	24			2t(0.5–3 mm)	125	
		Aged sheet	670	770	20			2t(typical)		
		Annealed rod	500	630		27	45			
		Aged rod	580	740		22	41		125	
IMI 260	Pd 0.2	Similiar to commercially Pure Titanium 115								
IMI 261	Pd 0.2	Similiar to commercially Pure Titanium 125								
IMI 315	Al 2.0 Mn 2.0	Annealed rod	590	720		21	50		120	
IMI 317	Al 5.0 Sn 2.5	Annealed sheet	820	860	16			4t(<2 mm) $4\frac{1}{2}$t(≤ 3 mm)		
		Annealed rod	930	1 000		15	37		120	
IMI 318	Al 6.0	Annealed sheet	1 110	1 160	10			5t(≤ 3.25 mm)		
	V 4.0	Annealed rod	990	1050		15	40		106	46
		Aged rod (fastener stock)	1 050	1 140		15	40			
		Hard-drawn wire		1 410	4					
IMI 550	Al 4.0 Mo 4.0 Sn 2.0 Si 0.5	F.h.t. rod	1 070	1 200		14	42		116	
IMI 551	Al 4.0 Mo 4.0 Sn 4.0 Si 0.5	F.h.t.rod	1 140	1 300		12	40		113	43

continued overleaf

IMI 679	Sn Al Mo Si	11.0 2.25 1.0 0.2	Quenched and aged rod	1 080	1230	11	40	108	46
			Air-cooled and aged rod	1 000	1120	13	45		
IMI 680	Sn Mo Al Si	11.0 4.0 2.25 0.2	Quenched and aged rod	1200	1350	12	37	115	
			Furnace-cooled and aged rod	1080	1160	14	47		
IMI 685	Al Zr Mo Si	6.0 5.0 0.5 0.25	F.h.t. rod	920	1020	11	22	124	47
IMI 829	Al Sn Zr Nb Mo Si	5.5 3.5 3.0 1.0 0.3 0.3	F.h.t. rod	848	965	12	22	120	
IMI 834	Al Sn Zr Nb Mo Si C	5.8 4.0 3.5 0.7 0.5 0.35 0.06	F.h.t. rod	931	1067	13	22	120	

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*IMI Nomenclature.

Table 3.17 COMMERCIALLY PURE TITANIUM SHEET, TYPICAL VARIATION OF PROPERTIES WITH TEMPERATURE

*Designation**	*Temperature* °C	0.2% *proof stress* MPa	*Tensile strength* MPa	*Elongation on* 50 mm %	*Mod. of elasticity* GPa	*Transformation temperature* °C
IMI 115	−196	442	641	34		$\alpha/\alpha+\beta$
	−100	306	444	34		865
	20	207	337	40		
	100	168	296	43		
	200	99	218	38		
	300	53	167	47		
	400	42	131	52		
	450	36	120	49		
IMI 125	20	334	479	31		
	100	250	397	32		
	200	184	300	40		
	300	142	232	45		
	400	127	190	38		
	450	119	175	35		
IMI 130	−196	730	855	28		
	−100	590	737	28		
	20	394	547	28	108	
	100	315	462	29	99	$\alpha+\beta/\beta$
	200	205	331	37	91	915
	300	139	247	40	83	
	400	102	199	34	65	
	450	93	182	28		
	500				46	
IMI 155	20	460	625	25		
	100	372	537	26		
	200	219	386	32		
	300	151	281	36		
	400	110	221	33		
	450	96	202	26		

*IMI nomenclature.

Table 3.18 TITANIUM ALLOYS, TYPICAL VARIATION OF PROPERTIES WITH TEMPERATURE

Designation	*Nominal composition* %	*Condition*	*Temperature* °C	0.2% *Proof stress* MPa	*Tensile strength* MPa	*Elongation %*		*Red in area* %	*Mod. of elasticity* GPa	*Transformation temperature* °C
						on 50 mm	*on* 5D			
IMI 230	Cu 2.5	S.h.t (trans.)	20	500	605	24				$\alpha/\alpha+\beta$
			100	410	540	29				790
			200	310	450	33				
			300	270	410	31				$\alpha+\beta/\beta$
			400	250	380	30				895 ± 10
			500	220	380	33				
		Aged sheet (trans.)	20	622	761	24				
			100	553	704	23				
			200	471	635	26				
			300	457	607	23				
			400	429	573	19				
			500	357	468	21				
		Aged	20	638	795		22	40	107	
			100	601	761		21	39	100	
			200	507	687		23	45	92	
			300	496	658		20	50	85	
			400	415	592		21	53	78	
			500	361	491		27	57	71	
IMI 260	Pd 0.2	Similar to IMI 115								
IMI 262	Pd 0.2	Similar to IMI 125								
IMI 315	Al 2.0	Annealed rod	20	618	757		18	41	110	$\alpha+\beta/\beta$
	Mn 2.0		100	510	649		21	46	107	915 ± 20
			200	386	525		22	48	97	
			300	293	432		19	50	86	
			400	278	417		18	56	76	
			500	201	340		22	72	62	
IMI 317	Al 5.0	Annealed rod	20	822	919		18	39	112	$\alpha/\alpha+\beta$
	Sn 2.5		100	692	798		19	40	109	950
			200	494	638		18	44	105	
			300	415	576		19	42	89	$\alpha+\beta/\beta$
			400	374	522		18	41	84	1025 ± 20
			500	346	485		21	57	81	

Table 3.18 (*continued*)

Designation	*Nominal composition* %	*Condition*	*Temperature* °C	0.2% *Proof stress* MPa	*Tensile strength* MPa	*Elongation %* *on* 50 mm	*Elongation %* *on* 5D	*Red in area* %	*Mod. of elasticity* GPa	*Transformation temperature* °C
IMI 318	Al 6.0	Annealed rod	−196	1560	1675		6	29		$\alpha + \beta/\beta$
	V 4.0		−100	1165	1265		12	33		1000 ± 15
			20	970	1040		15	38	106	
			100	825	920		17	43	102	
			200	710	815		18	49	96	
			300	645	750		18	56	90	
			400	580	700		18	63	85	
			500	450	605		26	72	79	
			600	125	265		58	85		
			700	40	135		127	94		
		Heat-treated rod (fastener stock)	20	1035	1145		14			
			100	925	1035		15			
			200	805	925		16			
			300	710	850		16			
			400	635	805		18			
			500	540	695		25			
IMI 550	Al 4.0	F.h.t. rod	20	1081	1220		15	49	116	$\alpha + \beta/\beta$
	Mo 4.0		100	965	1130		15	49	112	980 ± 10
	Sn 2.0		200	805	960		16	60	106	
	Si 0.5		300	700	900		16	55	101	
			400	655	835		17	60	95	
			500	585	780		19	68	90	
			600	310	585		26	83	85	
IMI 551	Al 4.0	F.h.t rod	20	1250	1390		10	27	113	$\alpha + \beta/\beta$
	Mo 4.0		100	1125	1300		11	29	108	1050 ± 15
	Sn 4.0		200	925	1145		14	38	103	
	Si 0.5		300	815	1045		15	38	98	
			400	745	970		14	41	93	
			500	670	920		18	55	88	
			600	460	755		27	65	81	
IMI 679	Sn 11.0	Quenched and aged rod	20	1050	1230		10	37		$\alpha + \beta/\beta$
	Zr 5.0		100	940	1145		11	43		950 ± 10
	Al 2.25		200	820	1020		12	45		
	Mo 1.0		300	740	990		11	46		
	Si 0.2		400	710	940		11	46		
			450	680	910		11	46		

			Air-cooled and aged rod	20	1 020	1 095		14	41	108	
				100	895	995		16	47	103	
				200	770	900		16	49	99	
				300	695	865		14	49	94	
				400	665	850		14	48	90	
				500	600	795		15	48	85	
IMI 680	Sn	11.0	Quenched and aged rod	20	1 180	1 330		12	43	106	$\alpha+\beta/\beta$
	Mo	4.0		100	1 020	1 190		14	49	100	945 ± 15
	Al	2.25		200	905	1 105		15	53	96	
	si	0.2		300	835	1 075		15	56	94	
				400	805	1 020		14	57	90	
				450	725	975		13	54	88	
			Furnace-cooled and aged rod	−196	1630	1730		$8\frac{1}{2}$	36		
				−100	1 280	1 380		10	43		
				20	1 030	1 130		15	49		
IMI 685	Al	6.0	F.h.t. rod	−196	1 480	1 560		6	13		$\alpha+\beta/\beta$
	Zr	5.0		−100	1 1 40	1270		10	18		1 020 ± 10
	Mn	0.5		20	890	1 030		12	22	124	
	Si	0.25		100	800	935		13	22	120	
				200	720	850		15	24	114	
				300	650	800		16	27	108	
				400	595	750		18	31	102	
				500	535	695		19	37	95	
IMI 829	Al	5.5	F.h.t. rod	20	895	1 028		$10\frac{1}{2}$	22	119	$\alpha+\beta\beta$
	Sm	3.5		200	622	792		$14\frac{1}{2}$	28	110	1 015 ± 15
	Zr	3.0		500	501	665		15	36	93	
	Nb	1.0		540	487	653		16	42	91	
	Mo	0.3		600	457	634		14	38	88	
	Si	0.3									
IMI 834	Al	5.8	F.h.t. rod	20	931	1 067		13	22	120	1045
	Sn	4.0		100	840	962		13	23	116	
	Zr	3.5		200	746	885		14	27	112	
	Nb	0.7		300	700	832		14	32	106	
	Mo	0.5		400	662	790		14	36	102	
	Si	0.35		500	609	764		15	42	96	
	C	0.06		600	505	656		16	50	92	

Table 3.19 COMMERCIALLY PURE TITANIUM – TYPICAL CREEP PROPERTIES

IMI designation	*Temperature* °C	*Stress* MPa *to produce* 0.1% *plastic strain in*		
		1000 h	10 000 h	100 000 h
IMI 130	20	288	270	207
	50	243	221	165
	100	179	165	119
	150	140	133	96
	200	113	116	77
	250	96	101	66
	300	87	83	55
IMI 155	20	309	278	260
	50	252	232	213
	100	188	170	157
	150	145	131	122
	200	116	108	104
	250	102	97	94
	300	93	90	86

Table 3.20 TITANIUM ALLOYS – TYPICAL CREEP PROPERTIES

IMI designation	*Nominal composition* %		*Condition*	*Temperature* °C	*Stress* MPa *to produce* 0.1% *total plastic strain in*			
					100 h	300 h	500 h	1000 h
IMI 230	Cu	2.5	Aged sheet	200	435	–	–	–
				300	375	–	–	–
				400	220	–	–	–
				450	109	–	–	–
			Annealed sheet	20	360	–	–	–
				100	279	–	–	–
				200	235	–	–	–
				300	202	–	–	–
				400	125	–	–	–
IMI 317	Al	5.0	Annealed rod	20	633	608	–	593
	Sn	2.5		100	474	463	–	458
				200	370	–	–	370
				300	359	–	–	359
				400	337	–	–	337
				500	162	119	–	88
IMI 318	Al	60	Annealed rod	20	832	818	–	788
	V	4.0		100	704	680	–	676
				200	638	636	–	635
				300	576	568	–	–
				400	287	144	–	102
				500	32	18	–	–
IMI 550	Al	4.0	Fully heat-treated bar	300	724	718	–	710
	Mo	4.0		400	551	516	–	471
	Sn	2.0		450	254	174	–	101
	Si	0.5		500	82	51	–	31
IMI 551	Al	4.0	Fully heat-treated rod	400	621	575	540	501
	Mo	4.0		450	307	217	–	–
	Sn	4.0						
IMI 679	Sn	11.0	Air-cooled and aged rod	20	896	880	–	880
	Zr	5.0		150	703	695	–	672
	Al	2.25		300	664	664	–	649
	Mo	1.0		400	579	571	–	526
	Si	0.2		450	448	386	–	247
				500	131	93	–	62

Table 3.20 (*continued*)

IMI designation	*Nominal composition %*	*Condition*	*Temperature* °C	*Stress* MPa *to produce* 0.1% *total plastic strain in*			
				100 h	300 h	500 h	1000 h
IMI 680	Sn 11.0	Quenched and aged rod	20	1127	1112	–	–
	Mo 4.0		150	945	942	–	–
	Al 2.25		200	862	856	–	–
	Si 0.2		300	804	788	–	–
			400	555	540	–	–
			450	298	209	–	–
			500	88	51	–	–
		Furnace-cooled and aged rod	300	570	–	–	–
			350	540	–	–	–
			400	490	–	–	–
IMI 685	Al 6.0	Heat-treated forgings	200	599	–	592	589
	Zr 5.0		300	551	–	541	535
	Mo 0.5		400	497	–	480	462
	Si 0.25		450	461	–	431	426
			500	408	–	340	–
IMI 829	Al 5.5	Fully heat treated rod	450	478	–	–	–
	Sn 3.5		500	420	–	–	–
	Zr 3.0		550	300	–	–	–
	Nb 1.0		600	130	–	–	–
	Mo 0.3						
	Si 0.3						
IMI 834	Al 5.8	Heat-treated forgings	500	461	–	–	–
	Sn 4.0		550	339	–	–	–
	Zr 3.5		600	205	–	–	–
	Nb 0.7						
	Mo 0.5						
	Si 0.35						
	C 0.06						

Table 3.21 TITANIUM AND TITANIUM ALLOYS – TYPICAL FATIGUE PROPERTIES

IMI designation	*Nominal composition %*	*Condition*	*Tempera-ture* °C	*Tensile strength* MPa	*Details of test*	*Endurance limit for* 10^7 cycles *stated)* MPa
					Rotating bend	
IMI 115	Commercial purity	Annealed rod	Room	354	Smooth $K_t = 1$	± 193
				354	Notched $K_t = 3$	± 123
					Rotating bend	
IMI 125	Commercial purity	Annealed rod	Room	417	Smooth $K_t = 1$	± 232
				417	Notched $K_t = 3$	± 154
					Rotating bend	
IMI 130	Commercial purity	Annealed rod	Room	550	Smooth $K_t = 1$	± 270
				550	Notched $K_t = 2$	± 170
				550	Notched $K_t = 3.3$	± 170
					Direct stress (Zero mean)	
				550	Smooth $K_t = 1$	± 263
				550	Notched $K_t = 1,5$	± 247
				550	Notched $K_t = 2$	± 170
				550	Notched $K_t = 3.3$	± 116
				589	Smooth $K_t = 1$	± 278
				589	Notched $K_t = 2$	± 147
				589	Notched $K_t = 3$	± 123
				589	Notched $K_t = 4$	± 116

continued overleaf

Table 3.21 (*continued*)

IMI designation	*Nominal composition %*		*Condition*	*Tempera-ture* °C	*Tensile strength* MPa	*Details of test*	*Endurance limit for 10^7 cycles stated)* MPa
						Direct stress (Zero mean)	
IMI 160	Commercial purity		Annealed rod	Room	674	Smooth K_t	± 376
IMI 230	Cu	2.5	Annealed sheet	Room	564	Reversed bend	± 390
			Aged sheet	room	772	Reversed bend	± 490
						Direct stress (Zero minimum)	
			Aged sheet	room	761	Smooth $K_t = 1$	0→560
						Rotating bend	
			Annealed rod	room	598	Smooth $K_t = 1$	± 370
				400		Smooth $K_t = 1$	± 150
						Direct stress (Zero mean)	
			Annealed	Room	638	Smooth $K_t = 1$	± 280
						Rotating bend	
			Aged rod	Room	700	Smooth $K_t = 1$	± 450
				400	–	Smooth $K_t = 1$	± 290
						Direct stress (Zero mean)	
			Aged rod	Room	792	Smooth $K_t = 1$	± 470
						Notched $K_t = 3.3$	± 200
IMI 260	Pd	0.2	Similar to IMI 115				
IMI 262	Pd	0.2	Similar to IMI 125				
						Rotating bend	Limits for this alloy 10^8 cycles
IMI 317	Al	5.0	Annealed rod	Room	–	Smooth $K_t = 1.0$	± 371
	Sn	2.5				Notched $K_t = 2.0$	± 263
						Notched $K_t = 3.3$	± 239
						Direct stress (Zero mean)	
						Smooth $K_t = 1.0$	± 433
						Notched $K_t = 1.5$	± 278
						Notched $K_t = 2.0$	± 201
						Notched $K_t = 3.3$	± 154
						Rotating bend	
IMI 318	Al	6.0	Annealed rod	Room	960	Smooth $K_t = 1$	± 470
	V	4.0			960	Notched $K_t = 2.7$	± 230
						Direct stress (Zero minimum)	
					1015	Smooth $K_t = 1$	0→750
					1015	Notched $K_t = 1$	0→325
						Direct stress (Zero minimum)	
IMI 550	Al	4.0	Fully heat-treated rod	Room	1180	Smooth $K_t = 1$	0→850
	Mo	4.0			1180	Notched $K_t = 3$	0→350
	Sn	2.0					
	Si	0.5					
						Rotating bend	
						Rotating bend	
						Smooth $K_t = 1$	± 587
						Notched $K_t = 2.4$	± 394
						Rotating bend	
IMI 551	Al	4.0	Fully heat-treated rod	Room	–	Smooth $K_t = 1$	± 750
	Mo	4.0			–	Notched $K_t = 3.2$	± 430
	Sn	4.0					
	Si	0.5					

Table 3.21 (*continued*)

IMI designation	*Nominal composition %*		*Condition*	*Temperature* °C	*Tensile strength* MPa	*Details of test*	*Endurance limit for* 10^7 cycles *stated)* MPa
						Rotating bend	
IMI 679	Sn	11.0	Air-cooled and aged rod	Room	–	Smooth $K_t = 1.0$	±641*
	Zr	5.0		200	–	Smooth $K_t = 1.0$	±510*
	Al	2.25		400	–	Smooth $K_t = 1.0$	±510*
	Mo	1.0		450	–	Smooth $K_t = 1.0$	± 556
	Si	0.2		500	–	Smooth $K_t = 1.0$	± 495
						Rotating bend	(Limits for 2×10^7 cycles)
IMI 680	Sn	11.0	Quenched and aged rod	Room	1272	Smooth $K_t = 1$	± 710
	Mo	4.0			1272	Notched $K_t = 2$	± 340
	Al	2.25			1272	Notched $K_t = 3.3$	± 293
	Si	0.2					
						Direct stress (Zero mean	(Limits for 2×10^7 cycles)
				Room	1272	Smooth $K_t = 1$	± 695
						Notched $K_t = 2$	± 371
						Notched $K_t = 3.3$	± 232
						Rotating bend	(Limits for 10^8 cycles)
				Room	–	Smooth $K_t = 1$	± 648
				200	–	Smooth $K_t = 1$	± 495
				400	–	Smooth $K_t = 1$	± 479
						Direct stress (Zero	
			Furnace-cooled rod	Room	1100	Smooth $K_t = 1$	± 680
						Direct stress (Zero mean)	
IMI 685	Al	6.0	Fully heat-treated rod	20	–	Smooth $K_t = 1$	± 440
	Zr	5.0		450	–	Smooth $K_t = 1$	± 300
	Mo	0.5		520	–	Smooth $K_t = 1$	± 260
	Si	0.25					
						Direct stress (Zero minimum)	
				450	–	Smooth $K_t = 1$	0→475
				520	–	Smooth $K_t = 1$	0→425
						Direct stress (Zero minimum)	
			Fully heat-treated forging	Room	–	Smooth $K_t = 1$	0→640
				Room	–	Notched $K_t = 3.5$	0→220
				475	–	Smooth $K_t = 1$	0→460
				475	–	Notched $K_t = 3.5$	0→210
						Direct stress (Zero minimum)	
IMI 829	Al	5.5	Fully heat-treated rod	Room	–	Smooth $K_t = 1$	0→550
	Sn	3.5				Notched $K_t = 3$	0→260
	Zr	3.0					
	Nb	1.0					
	Mo	0.3					
	Si	0.3					
						Direct stress (Zero minimum)	
IMI 834	Al	5.8	Fully heat-treated rod	Room	–	Smooth $K_t = 1$	0→577
	Sn	4.0			–	Notched $K_t = 2$	0→363
	Zr	3.5					
	Nb	0.7					
	Mo	0.5					
	Si	0.35					
	C	0.06					

*Limits for 10^8 cycles.

Table 3.22 IZOD IMPACT PROPERTIES OF TITANIUM AND TITANIUM ALLOYS

IMI designation	*Nominal composition %*	*Condition*	*Izod value* Joules (ft lbf)*							
			−196 °C	−78 °C	20 °C	100 °C	200 °C	300 °C	400 °C	500 °C
IMI 130[†]	Commer-	Annealed	–	62.4	61.0	62.4	72	82	84	82
	cially pure	rod		(46)	(45)	(46)	(53)	(60$\frac{1}{2}$)	(62)	(60$\frac{1}{2}$)
IMI 317	Sn 5.0	Annealed	17.6	20.3	27.1	35.2	52.8	63.7	70.5	71.8
	Al 2.5	rod	(13)	(15)	(20)	(26)	(39)	(47)	(52)	(53)
IMI 318	Al 6.0	Annealed	13.5	14.9	20.3	25.7	40.6	65.0	83.5	92.0
	V 4.0	rod	(10)	(11)	(15)	(19)	(30)	(48)	(63)	(68)
IMI 550	Al 4.0	Fully heat-	–	–	19.0	–	–	–	–	–
	Mo 4.0	treated rod			(14)					
	Sn 2.0									
	Si 0.5									

IMI designation	*Nominal composition %*	*Condition*	*Charpy value* Joules (ft lbf)							
			−196 °C	−78 °C	20 °C	100 °C	200 °C	300 °C	400 °C	500 °C
IMI 551	Al 4.0	Fully heat-	13.5	19	20.3	21.7	24.4	26.5	28.5	31.2
	Mo 4.0	treated rod	(10)	(14)	(15)	(16)	(18)	(19$\frac{1}{2}$)	(21)	(23)
	Sn 4.0									
	Si 0.5									
IMI 679	Sn 11.0	Air-cooled	10.8	13.5	14.9	16.3	19	25	30	33.9
	Zr 5.0	and aged	(8)	(10)	(11)	(12)	(14$\frac{1}{2}$)	(18$\frac{1}{2}$)	(22)	(25)
	Al 2.25									
	Mo 1.0									
	Si 0.2									
IMI 680	Sn 11.0	Quenched	8.1	8.8	10.8	12.2	14.9	17.6	20.3	25.7
	Mo 4.0	and aged	(6)	(6$\frac{1}{2}$)	(8)	(9)	(11)	(13)	(15)	(19)
	Al 2.25	rod								
	Si 0.2									
IMI 685	Al 6.0	Fully heat-	31.2	39.3	43.4	–	–	–	–	–
	Zr 5.0	treated rod	(23)	(29)	(32)					
	Mo 0.5									
	Si 0.25									

*BSS 131 (1) 0.45 in diameter straight notched test pieces. [†]Izod values of commercial purity titanium are appreciably affected by variation in hydrogen content within commercial limits (0.008% maximum) in Ti 130 rod.

4 Aluminium and magnesium casting alloys

4.1 Aluminium casting alloys

Table 4.1 ALUMINIUM-SILICON ALLOYS

Specification BS 1490: 1988	LM6M(Ge)							
Related British Specifications	BS L33	LM20M(Ge)	LM9M(SP)	LM9TE(SP)	LM9TE(SP)	LM13TE(SP)	LM13TF(SP)	LM13TF7(SP)
Composition (%) (single figure indicates maximum)								
Copper	0.1	0.4	0.1			0.7–1.5		
Magnesium	0.1	0.2–0.6	0.2			0.8–1.5		
Silicon	10.0–13.0	10.0–13.0	10.0–13.0			10.0–12.0		
Iron	0.6	1.0	0.6			1.0		
Manganese	0.5	0.5	0.3–0.7			0.5		
Nickel	0.1	0.1	0.1			1.5		
Zinc	0.1	0.2	0.1			0.5		
Lead	0.1	0.1	0.1			0.1		
Tin	0.05	0.1	0.05			0.1		
Titanium	0.2	0.2	0.2			0.2		
Other	–	–	–			–		
Properties of material								
Suitability for:								
Sand casting	E	E*	G			G		
Chill casting (gravity die)	E	E	E			G		
Die casting (press die)	G	G	G*			F*		
Strength at elevated temperature	P	P	G			E		
Corrosion resistance	E	G	E			G		
Pressure tightness	E	E	G			F		
Fluidity	E	E	G			G		
Resistance to hot shortness	E	E	E			E		
Machinability	F	F	F			F		
Melting range, C	565–575	565–575	550–575			525 560		
Casting temperature range, C	710–740	680–740	690–740			680–760		
Specific gravity	2.65	2.68	2.68			2.70		

Heat treatment								
Solution temperature, °C	–	–	–	–	520–535	–	515–525	515–525
Solution time, h	–	–	–	–	2–8	–	8 (minimum)	8 (minimum)
Quench	–	–	–	–	Cold water	–	Water, 70–80 °C	Water, 70–80 °C
Precipitation temperature, °C	–	–	–	150–170	150–170	160–180	160–180	For pistons:
Precipitation time, h	–	–	–	16 (minimum)	16 (minimum)	4–16	4–16	200–250
Stabilization temperature, °C	–	–	–	–	–	–	–	4–6**
Stabilization time, h	–	–	–	–	–	–	–	
Special properties	Suitable for thin and intricate castings, readily welded	Pressure casting alloy		Suitable for low-pressure cassting High strength and hardness			Low coefficient of expansion Good bearing properties Piston alloy	
Mechanical properties – sand cast – SI units (Imperial units in brackets)								
Tensile stress min., MPa (tonf in^{-2})	160(10.4)	–	–	170(11.0)	240(15.5)	–	170(11.0)	140(9.1)
Elongation min.%	5	–	–	1.5	0–1	–	0.5	1
Expected 0.2% proof stress,	60–70	–	–	110–130	220–250	–	160–190	130(8.4)
MPa (tonf in^{-2})	(3.9–4.5)			(7.1–8.4)	(14.2–16.2)		(10.4–12.3) HB 100–150	HB 65–85
Mechanical properties – chill cast – SI units (Imperial units in brackets)								
Tensile stress min., MPa (tonf in^{-2})	190(12.3)	190(12.3)	190(12.3)	230(14.9)	295(19.1)	210(13.6)	280(18.1)	200(12.9)
Elongation, min. %	7	5	3	2	0–1	1	1	1
Expected 0.2% proof stress,	70–80	70–80	75–85	150–170	270–280	–	270-300	190(12.3)
MPa (tonf in^{-2})	(4.5–5.2)	(4.5–5.2)	(4.9–5.5)	(9.7–11.0)	(17.5–18.1)	HB90-120	(17.5-19.4) HB 100–150	HB 65-85

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[*] Not normally used in this form.

[†] If Ti alone is used for grain refinement then Ti $\not<$ 0.05%.

[‡] Fully heat-treated.

[§] Refine with phosphorus – subject to examination under microscope.

[**] Or for such time to give required BHN.

Notes

Association of Light Alloy Refiners and Smelters Grading:
E – Excellent, F – Fair, G – Good, P – Poor, U – Unsuitable,
(Ge – General purpose alloy; SP – special purpose alloy as per BS 1490:1988).

Table 4.1 (*continued*)

Specification BS 1490: 1988 *Related British Specifications*	LM18M(SP)	LM25M(Ge)	LM25TE(Ge)	LM25TB7(Ge)	LM25TF(Ge)	LM29TE(SP)	LM29TF(SP)
Composition % (Single figure indicates maximum)							
Copper	0.1	0.20				0.8–1.3	
Magnesium	0.1	0.20–0.60				0.8–1.3	
Silicon	4.5–6.0	6.5–7.0				22–25	
Iron	0.6	0.5				0.7	
Manganese	0.5	0.3				0.6	
Nickel	0.1	0.1				0.8–1.3	
Zinc	0.1	0.1				0.2	
Lead	0.1	0.1				0.1	
Tin	0.05	0.05				0.1	
Titanium	0.2	0.2[†]				0.2	
Other	–	–				Cr 0.6; Co 0.5, P[§]	
Properties of material							
Suitability for:							
Sand casting	G	G				P	
Chill casting (gravity die)	G	E				F	
Die casting (press die)	G*	G*				U	
Strength at elevated temperature	P	G[‡]				G	
Corrosion resistance	E	E				G	
Pressure tightness	E	G				F	
Fluidity	G	G				F	
Resistance to hot shortness	E	G				E	
Machinability	F	F				P	
Melting range, C	565–625	550–615				520–770	
Casting temperature range, C	700–740	680–740				At least 830	
Specific gravity	2.69	2.68				2.65	

Heat treatment							
Solution temperature, °C	–	–	–	525–545	525–545	–	495–505
Solution time, h	–	–	–	4–12	4–12	–	4
Quench	–	–	–	Water, 70–80 °C	Water, 70–80 °C	–	Air blast
Precipitation temperature, °C	–	–	155–175	–	155–175	185	185
Precipitation time, h	–	–	8–12	–	8–12	To produce HB requirement	8
Stabilization temperature, °C	–	–	–	250	–	–	–
Stabilization time, h	–	–	–	2–4	–	–	–
Special properties	Readily welded		General purpose high-strength casting alloy			More suited to chill (grav, die) casting	Piston alloy
Mechanical properties – sand cast – SI units (Imperial units in brackets)							
Tensile stress min., MPa (tonf in^{-2})	120(7.8)	130(8.4)	150(9.7)	160(10.4)	230(149)	120(7.8)	120(7.8)
Elongation min. %	3	2	1	2.5	0–2	0.3	0.3
Expected 0.2% proof stress,	55–60(3.6–3.9)	80–100(5.2–6.5)	120–150 (7.8–9.7)	80–110 (5.2–6.5)	200–250 (12.9–16.2)	120(7.8)	120(7.8)
MPa (tonf in^{-2})						HB 100–140	HB 100–140
Mechanical properties – chill cast – SI units (Imperial units in brackets)							
Tensile stress min., MPa (tonf in^{-2})	140(9.1)	160(10.4)	190(12.3)	230(14.9)	280(18.1)	190(12.3)	190(12.3)
Elongation min. %	4	3	2	5	2	0.3	0.3
Expected 0.2% proof stress,	60–70(3.9–4.5)	80–100(5.2–6.5)	130-200(8.4–12.9)	90–110(5.8–7.1)	220–260 (14.2–16.8)	170(11.0)	170–190 (11.0–12.3)
MPa (tonf in^{-2})						HB 100–140	HB 100–140

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*Not normally used in this form.

†If Ti alone is used for grain refinement then Ti $\not<$ 0.05%.

‡Fully heat-treated.

§Refine with phosphorus-subject to examination under microscope.

**Or for such time to give required BHN.

Note

E – Excellent. F – Fair. G – Good. P – Poor. U – Unsuitable.

(Ge – General purpose alloy; SP – Special purpose alloy as per BS: 1490: 1988).

Table 4.2 ALUMINIUM-SILICON-COPPER ALLOYS

Specification BS 1490; 1988 *Related British Specifications*	LM2M(Ge)	LM4M(Ge)	LM4MTF (Ge)	LM16TB (SP)	LM16TF (SP) 3L78	LM21M(SP)
Composition % (Single figures indicate maximum)						
Copper	0.7–2.5	2.0–4.0		1.0–1.5		3.0–5.0
Magnesium	0.30	0.15		0.4–0.6		0.1–0.3
Silicon	9.0–11.5	4.0–6.0		4.5–5.5		5.0–7.0
Iron	1.0	0.8		0.6		1.0
Manganese	0.5	0.2–0.6		0.5		0.2–0.6
Nickel	0.5	0.3		0.25		0.3
Zinc	2.0	0.5		0.1		2.0
Lead	0.3	0.1		0.1		0.2
Tin	0.2	0.1		0.05		0.1
Titanium	0.2	0.2		0.2[*]		0.2
Properties of material						
Suitability for:						
Sand casting	G[†]	G		G		G
Chill casting (gravity die)	G[†]	G		G		G
Die casting (press die)	E	G		F[†]		G[†]
Strength at elevated temp.	G[‡]	G		G		G
Corrosion resistance	G	G		G		G
Pressure tightness	G	G		G		G
Fluidity	G	G		G		G
Resistance to hot shortness	E	G		G		G
Machinability	F	G		G		G
Melting range, °C	525–570	525–625		550–620		520–615
Casting temperature range, °C	–	700–760		690–760		680–760
Specific gravity	2.74	2.73		2.70		2.81
Heat treatment						
Solution temperature, °C	–	–	505–520	520–530	520–530	–
Solution time, h	–	–	6–16	12 (min)	12 (min)	–
Quench	–	–	Water at 70–80 °C	Water at 70–80 °C	Water at 70–80 °C	– –
Precipitation temperature, °C	–	–	150–170	–	160–170	–
Precipitation time, h	–	–	6–18	–	8–10	–
Special properties	Alloy for pressure die castings	General engineering alloy Can tolerate relatively high static loading in TF condition		Pressure tight. High strength alloy in TF condition		Equally suited to all casting processes
Mechanical properties – sand cast – SI units (Imperial units in brackets)						
Tensile stress min. MPa (tonf in $^{-2}$)	–	140(9.1)	230(14.9)	170(11.0)	230(14.9)	150(9.7)
Elongation min. %	–	2	–	2	–	1
Expected 0.2% proof stress, MPa (tonf in^{-2})	–	70–110 (4.5–7.1)	200–250 (12.9–16.2)	120–140 (7.8–9.1)	220–280 (14.2–18.1)	80–140 (5.2–9.1)
Mechanical properties – chill cast – SI units (Imperial units in brackets)						
Tensile strength min. MPa (tonf in^{-2})	150(9.7)	160(10.4)	280(18.1)	230(14.9)	280(18.1)	170(11.0)
Elongation min. %	1	2	1	3	–	1
Expected 0.2% proof stress, MPa (tonf in^{-2})	90–130 (5.8–8.4)	80–110 (5.2–7.1)	200–300 (12.9–19.4)	140–150 (9.1–9.7)	250–300 (16.2–19.4)	80–140 (5.2–9.1)

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[*] 0.05% min. if Ti alone used for grain refinement.

[†] Not normally used in this form.

[‡] The use of die castings is usually restricted to only moderately elevated temperatures.

Table 4.2 (*continued*)

Specification BS 1490: 1988 *Related British Specifications*	LM22TB (SP)	LM24M (Ge)	LM26TE (SP)	LM27M (Ge)	LM30M (SP)	LM30TS (SP)
Composition % (Single figures indicate maximum)						
Copper	2.8–3.8	3.0–4.0	2.0–4.0	1.5–2.5		4.0–5.0
Magnesium	0.05	0.1	0.5–1.5	0.3		0.4–0.7
Silicon	4.0–6.0	7.5–9.5	8.5–10.5	6.0–8.0		16–18
Iron	0.6	1.3	1.2	0.8		1.1
Manganese	0.2–0.6	0.5	0.5	0.2–0.6		0.3
Nickel	0.15	0.5	1.0	0.3		0.1
Zinc	0.15	3.0	1.0	1.0		0.2
Lead	0.1	0.3	0.2	0.2		0.1
Tin	0.05	0.2	0.1	0.1		0.1
Titanium	0.2	0.2	0.2	0.2		0.2
Properties of material Suitability for:						
Sand casting	G†	F†	G	G		U
Chill casting (gravity die)	G	F†	G	E		F
Die casting (press die)	G†	E	F†	G†		G
Strength at elevated temp.	G	G‡	E	G		G
Corrosion resistance	G	G	G	G		G
Pressure tightness	G	G	F	G		F
Fluidity	G	G	G	G		G
Resistance to hot shortness	G	G	F	G		F
Machinability	G	F	F	G		P
Melting range, °C	525–625	520–580	520–580	525–605		505–650
Casting temperature range, °C	700–740	–	670–740	680–740		Well above 650 °C
Specific gravity	2.77	2.79	2.76	2.75		2.73
Heat treatment						
Solution temperature, °C	515–530	–	–	–	–	
Solution time, h	6–9	–	–	–	–	
Quench	Water at 70–80 °C	–	–	–	–	*Stress relief*
Precipitation temperature, °C	–	–	200–210	–	–	175–225
Precipitation time, h	–	–	7–9	–	–	8(minimum)
Special properties	Chill casting alloy (grav. die)	Alloy for pressure die castings	Piston alloy, retains strength and hardness at elevated temps.	Excellent castability	Alloy for pressure die casting automobile engine cylinder blocks	
Mechanical properties – sand cast – SI units (Imperial units in brackets)						
Tensile stress min., MPa (tonf in^{-2})	–	–	–	140(9.1)	–	–
Elongation min. %	–	–	–	1	–	–
Expected 0.2% proof stress, MPa (tonf in^{-2})	–	–	–	80–90 (5.2–5.8)	–	–
Mechanical properties – chill cast – SI units (Imperial units in brackets)						
		HB = 90–120				
Tensile strength min., MPa (tonf in^{-2})	245(15.9)	180(11.7)	210(13.6)	160(10.4)	150(9.7)	160(10.4)
Elongation min. %	8	1.5	1	2	0.5	0.5
Expected 0.2% proof stress, MPa (tonf in^{-2})	110–120 (7.1–7.8)	100–120 (6.7–7.7)	160–190 (10.4–12.3)	90–110 (5.8–7.1)	150–200 (9.7–12.9)	160–200 (10.4–12.9)

Note:
E – Excellent. F – Fair. G – Good. P – Poor. U – Unsuitable.
(Ge – General purpose alloy; Sp-Special purpose alloy as per BS 1490;1988).

Table 4.3 ALUMINIUM-COPPER ALLOYS

Specification BS 1490; 1988	LM12M(SP)	LM12TF(SP)*	[LM14-WP]†	[LM11-W]	[LM11-WP]	–	–
Aerospace							
BSL series	–	–	4L35	2L91	2L92	–	–
DTD series	–	–	–	–	–	361B	741A
Composition % (Single figures indicate maximum)							
Copper	9.0–11.0		3.5–4.5	4.0–5.0		4.0–5.0	3.5–4.5
Magnesium	0.2–0.4		1.2–1.7	0.10		0.10	1.2–2.5
Silicon	2.5		0.6‡	0.25		0.25	0.5
Iron	1.0		0.6‡	0.25		0.25	0.5
Manganese	0.6		0.6	0.10		0.10	0.1
Nickel	0.5		1.8–2.3	0.10		0.10	0.1
Zinc	0.8		0.1	0.10		0.10	0.1
Lead	0.1		0.05	0.05		0.05	0.1
Tin	0.1		0.05	0.05		0.05	0.05
Titanium	0.2		0.25	0.25		Ti + Nb 0.05–0.30	–
Other	–		–	–		–	Co 0.5–1.0 Nb 0.05–0.3
Properties of material							
Suitability for:							
Sand casting	F		F	F		F	F
Chill casting (gravity die)	G		G	P		P	G
Die casting (press die)	U		U	U		U	–
Strength at elevated temperature	G		E	F		–	–
Corrosion resistance	P		F	F		F	F
Pressure tightness	G		E	P		P	F
Fluidity	F		G	F		F	G
Resistance to hot shortness	G		G	P		P	G
Machinability	E		G	G		G	G
Melting range, C	525–625		530–640	545–640		540–650	530–640
Casting temperature range, C	700–760		700–750	680–700		675–750	710–725
Specific gravity	2.94		2.82	2.80		2.80	2.80

Heat treatment							
Solution temp., °C	–	515–520	500–520	525–545	525–545	525–545	495–505
Solution time, h	–	6	6	12–16	12–16	16 (minimum)	10 (minimum)[††]
Quench	–	Water at 70–80 °C	Boiling water	Water at 70–80 °C	Water at 70–80 °C	Water or oil	Oil at 80–90 °C
Precipitation temperature, °C	–	175–180	95–103[§]	120–140	120–170	160–70	195–205
Precipitation time, h	–	2 (minimum)	2[**]	1–2	12–14	8–16	4–5
Special properties	Piston alloy, now superseded by LM13 and LM26. Excellent machinability		Excellent props. at elevated temperatures Grav. die alloy	Good shock resistance		High strength alloy	
Mechanical properties – sand cast – SI (Imperial units in brackets)							
Tensile stress min., MPa (tonf in^{-2})	–	–	220(14.2)	220(14.2)	280(18.1)	324(21.0)	263(17.0)
Elongation %	–	–	–	7	4	–	–
Expected 0.2% proof stress, min., MPa (tonf in^{-2})	–	–	210–240 (13.6–15.5)	165–200 (10.7–12.9)	200–240 (12.9–15.5)	310(20.1)	250(16.2)
Mechanical properties – chill cast – SI units (Imperial units in brackets)							
Tensile stress min., MPa (tonf in^{-2})	170	278(18.0)	280(18.1)	265(17.1)	310(20.1)	402(26.0)	340(22.0)
Elongation %	–	–	–	13	9	4	–
Expected 0.2% proof stress, min., MPa (tonf in^{-2})	140–170	139–170 (9.0–11.0) HB 100–150	230–260 (14.9–16.8) HB 100–130	165–200 (10.7–12.9)	200–240 (12.5–15.5)	360(23.3)	260(16.8)

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[*] Not included in BS 1490: 1988.

[†] [ ] signifies obsolete specification.

[‡] Si + Fe 1.0 max.

[§] Or 5 days ageing at room temp.

[**] Can substitute stabilizing treatment at 200–250 °C if used for pistons.

[††] Allow to cool to 480 °C before quench.

Note:

E – Excellent. F – Fair. G – Good. P – Poor. U – Unsuitable.

(Ge – General purpose alloy; SP – Special purpose alloy as per BS 1490: 1988).

Table 4.4 MISCELLANEOUS ALUMINIUM ALLOYS

Specification BS 1400; 1988	LM5M(SP)	–	LM10TB(SP)	–
Aerospace				
BSL series	–	–	4L53	L99
DTD series	–	5018A	–	–
Composition % (Single figures indicate maximum)				
Copper	0.1	0.2	0.1	0.1
Magnesium	3.0–6.0	7.4–7.9	9.5–11.0	0.20–0.45
Silicon	0.3	0.25	0.25	6.5–7.5
Iron	0.6	0.35	0.35	0.20
Manganese	0.3–0.7	0.1–0.3	0.10	0.10
Nickel	0.1	0.1	0.10	0.10
Zinc	0.1	0.9–1.4	0.10	0.10
Lead	0.05	0.05	0.05	0.05
Tin	0.1	0.05	0.05	0.05
Titanium	0.2	0.25	0.2[†]	0.20
Other	–	–	–	–
Properties of material				
Suitability for:				
Sand casting	F	F	F	G
Chill casting (gravity die)	F	F	F	E
Die casting (press die)	F[‡]	–	F[‡]	F[‡]
Strength at elevated temp.	F	F	F	–
Corrosion resistance	E	E	E	E
Pressure tightness	P	P	P	G
Fluidity	F	F	F	G
Resistance to hot shortness	F	G	G	G
Machinability	G	G	G	F
Melting range, °C	580–642	–	450–620	550–615
Casting temperature range, °C	680–740	680–720	680–720	680–740
Specific gravity	2.65	2.64	2.57	2.67
Heat treatment				
Solution temperature, °C	–	425–435[§]	425–435	535–545
Solution time, h	–	8	8	12
Quench	–	Oil at 160 °C[**] or boiling water	Oil at no more[††] than 160 °C	Water at 65 °C min
Precipitation temp., °C	–	–	–	150–160
Precipitation time, h	–	–	–	4
Special properties	Good corrosion resistance in marine atmospheres	–	Good shock resistance and high corrosion resistance ***	Excellent castability with good mech. props.
Mechanical properties – Sand cast – SI units (Imperial units in brackets)				
Tensile stress min, MPa (tonf in^{-2})	140(9.1)	278	280(18.0)	230(14.9)
Elongation %	3	3	8	2
Expected 0.2% proof stress, min MPa (tonf in^{-2})	90–110(5.8–7.1)	170(11.0)	170–190 (11.0-12.3)	185(12.0)
Mechanical properties – chill cast – SI units (Imperial units in brackets)				
Tensile stress min, MPa (tonf in^{-2})	170(11.0)	309(20.0)	310(20.1)	280(18.1)
Elongation %	5	10	12	5
Expected 0.2% proof stress, min MPa (tonf in^{-2})	90–120(5.8–7.8)	170(11.0)	170–200 (11.0–12.9)	200(12.9)

[*] [ ] obsolete.

[†] 0.05% min. if Ti alone used for grain refinement.

[††] Not normally used in this form.

[§] Or 8 h at 435–445 C then raise to 490–500 C for further 8 h and quench as in table.

[**] Do not retain castings in oil for more than 1 h.

[***] Not generally recommended since occasional brittleness can develop over long periods.

Table 4.4 (*continued*)

Specification BS 1400: 1988	LM28TE(SP)	LM28TF(SP)	[LM23P]*	[LM15WP]*	–
Aerospace					
BSL series	–	–	3L51	3L52	–
DTD series	–	–	–	–	5008B
Composition % (Single figures indicate maximum)					
Copper		1.3–1.8	0.8–2.0	1.3–3.0	0.1
Magnesium		0.8–1.5	0.05–0.2	0.5–1.7	0.5–0.75
Silicon		17–20	1.5–2.8	0.6–2.0	0.25
Iron		0.7	0.8–1.4	0.8–1.4	0.5
Manganese		0.6	0.1	0.1	0.1
Nickel		0.8–1.5	0.8–1.7	0.5–2.0	0.1
Zinc		0.2	0.1	0.1	4.8–5.7
Lead		0.1	0.05	0.05	0.1
Tin		0.1	0.05	0.05	0.05
Titanium		0.2	0.25	0.25	0.15–0.25
Other		Cr 0.6 Co 0.5	–	–	Cr 0.4–0.6
Properties of material					
Suitability for:					
Sand casting		P	G	F	F
Chill casting (gravity die)		F	G	G	P
Die casting (press die)		–	G[‡]	U	U[‡]
Strength at elevated temp.		F	G	E	F
Corrosion resistance		G	G	G	E
Pressure tightness		F	G	F	F
Fluidity		F	F	F	F
Resistance to hot shortness		G	G	G	P
Machinability		P	G	G	G
Melting range, °C		520–675	545–635	600–645	572–615
Casting temp. range, °C		≮735	680–750	685–755	730–770
Specific gravity		2.68	2.77	2.75	2.81
Heat treatment					
Solution temperature, °C	–	495–505	–	520–540	–
Solution time, h	–	4	–	4	–
Quench	–	Air blast	–	Water at 80–100 °C Oil or air blast	–
Precipitation temp, °C	185	185	150–175	150–180 (195–205)	175–185[‡‡] (at least 24 h after cast)
Precipitation time, h	To produce required HB	8	8–24	8–24(2–5)	10(at least 24 h after cast)
Special properties	Piston alloy		Aircraft engine castings	High mechanical props. at elevated temps.	Good strength without heat treatment. *See*[‡‡]
Mechanical properties – sand cast – SI units (Imperial units in brackets)					
Tensile stress min, MPa (tonf in^{-2})	–	120(7.8)	160(10.4)	280(18.1)	216(14.0)
Elongation %	–	–	2	–	4
Expected 0.2% proof stress, min MPa (tonf in^{-2})	–	– HB100–140	125(8.1)	245(15.9)	150(9.7)
Mechanical properties – chill cast – SI units (Imperial units in brackets)					
Tensile stress min, MPa (tonf in^{-2})	170(11.0)	190(12.3)	200(13.0)	325(21.0)	232(15.0)
Elongation %	–	–	3	–	5
Expected 0.2% proof stress min, MPa (tonf in^{-2})	– HB 90–130	160–190 (10.4–12.3) HB 100–140	140(19.1)	295(19.1)	180(11.7)

[††] Can be furnace cooled to 385–395 °C before quench. Do not retain in oil for more than 1 h. Further quench in water or air.

[‡‡] Alternative-room temp. age-harden for 3 weeks.

Note:
E – Excellent. F – Fair. G – Good. P – Poor. U – Unsuitable.
(Ge – General purpose alloy; SP – Special purpose alloy as per BS 1490: 1988).

Table 4.5 HIGH STRENGTH CAST AL ALLOYS BASED ON AL-4.5 CU

European Designation	*KO1*				*A-U5GT*					
Al Assoc (USA) designation	201.0	201.2	A201.0	A201.2	204.0	204.2	206.0	206.2	A206.0	A206.2
Cu	4.0–5.2	4.0–5.2	4.0–5.0	4.0–5.0	4.2–5.0	4.2–4.9	4.2–5.0	4.2–5.0	4.2–5.0	4.2–5.0
Mg	0.15–0.55	0.20–0.55	0.15–0.35	0.20–0.35	0.15–0.35	0.20–0.35	0.15–0.35	0.20–0.35	0.15–0.35	0.20–0.35
Si	0.10	0.10	0.05	0.05	0.20	0.15	0.10	0.10	0.05	0.05
Fe	0.15	0.10	0.10	0.07	0.35	0.10–0.20	0.15	0.10	0.10	0.07
Mn	0.20–0.50	0.20–0.50	0.20–0.40	0.20–0.40	0.10	0.05	0.20–0.50	0.20–0.50	0.20–0.50	0.20–0.50
Ni	–	–	–	–	0.05	0.03	0.05	0.03	0.05	0.03
Zn	–	–	–	–	0.10	0.05	0.10	0.05	0.10	0.05
Sn	–	–	–	–	0.05	0.05	0.05	0.05	0.05	0.05
Ti	0.15–0.35	0.15–0.35	0.15–0.35	0.15–0.35	0.15–0.30	0.15–0.25	0.15–0.3	0.15–0.25	0.15–0.30	0.15–0.25
Ag	0.40–1.0	0.40–1.0	0.40–1.0	0.40–1.0	–	–	–	–	–	–
Others each	0.05	0.05	0.03	0.03	0.05	0.05	0.05	0.05	0.05	0.05
Others total	0.10	0.10	0.10	0.10	0.15	0.15	0.15	0.15	0.15	0.15

Table 4.6 MINIMUM REQUIREMENTS FOR SEPARATELY CAST TEST BARS

Alloy	*Sand/Die*	*Treatment**	*UTS* MPa	0.2 *PS* MPa	*EI%* *in* 50 mm *or* 4 × diam	*Typical HB* 500 kgf 10 mm
201.0	Sand	T6	414	345	5.0	110–140
	Sand	T7	414	345	3.0	130
204.0	Sand	T4	311	194	6.0	95
	Die	T4	331	220	8.0	

*For temper designations see Table 7.3.

Table 4.7 TYPICAL PROPERTIES OF SEPARATELY CAST TEST BARS

Alloy	*Sand/Die*	*Treatment**			*UTS* MPa	0.2 *PS* MPa	*EI%* *in* 50 mm *or* 4 × diam	*Typical HB* 500 kgf 10 mm
201.0	Sand	T4			365	215	20	95
		T43			414	255	17	
	Sand	T6			448–485	380–435	7–8	135
	Sand	T7	Room	Temp.	460–469	415	4.5–5.5	130
		T7	150C*	0.5–100 h	380	360	6–8.5	
				1 000 h	360	345	8	
				10 000 h	315	275	7	
			205C	0.5 h	325	310	9	
				100 h	285	270	10	
				1 000 h	250	230	9	
				10 000 h	185	150	14	
			260C	0.5 h	195	185	14	
				100 h	150	140	17	
				1 000 h	125	110	18	
			315C	0.5 h	140	130	12	
				100 h	85	75	30	
				1 000 h	70	60	39	
				10 000 h	60	55	43	
A206.0	Sand	T4						118HV
		T7		20C	436	347	11.7	137HV
				120C	384	316	14.0	
				175C	333	302	17.7	

*Elevated temperature properties.

4.2 Magnesium alloys

Table 4.8 ZIRCONIUM-FREE MAGNESIUM ALLOYS

Grain refined (0.05–0.2 mm *chill cast) when superheated to* 850–900 °C *or suitably treated with carbon (as hexachlorethane)*

Elektron designation	A8		A8 *(High purity)*	
ASTM designation	AZ81		AZ81	
Specifications BS 2970: 1989	MAG1M* (GP)[†]	MAG1TB* (GP)	MAG2M(SP)[†]	MAG2TB(SP)
BSS L series	–	3L. 112	–	–
Equivalent DTD	–	–	684A	690A
Composition % (Single figures indicate maximum)				
Aluminium	7.5–9.0		7.5–9.0	
Zinc	0.3–1.0		0.3–1.0	
Manganese	0.15–0.4		0.15–0.7	
Copper	0.15		0.005	
Silicon	0.3		0.01	
Iron	0.05		0.003	
Nickel	0.01		0.001	
Cu+Si+Fe+4Ni	0.40		–	
Material properties				
Founding	Good		Good	
Characteristics	Sand and permanent[‡] mould		Special melting technique required	
Tendency to hot tearing	Little		Little	
Tendency to micro-porosity	Appreciable		Appreciable	
Castability[§]	A		A	
Weldability (Ar-Arc process)	Good		Good	
Relative damping capacity[¶]	C		C	
Strength at elevated temperature[**]	C		C	
Corrosion resistance	Moderate		Moderate	
Density, g cm^{-3}	1.81		1.81	
Liquids, °C	600		600	
Solidus, °C	475		475	
Non-equilibrium solidus, °C	420		420	
Casting temperature range, °C	680–800		680–800	

Heat treatment						
Solution:						
Time, h	–	12 (min)	–			12 (min)
Temperature, °C	–	435 (max)[‡‡]	–			435 (max)[‡‡]
Cooling	–	Air, oil or water	–			Air, oil or water
Elektron designation		AZ91				
ASTM designation		AZ91			C alloy	
Specifications BS 2970: 1989	MAG3M(GP)	MAG3TB(GP)	MAG3TF(GP)	MAG7M(GP)	MAG7TF(GP)	
BSS L series	–	3L.124	3L.125	–	–	–
Equivalent DTD	–	–	–	–	–	–
Composition % (Single figures indicate maximum)						
Aluminium		9.0–10.5			7.5–9.5	
Zinc		0.3–1.0			0.3–1.5	
Manganese		0.15–0.4			0.15–0.8	
Copper		0.15			0.35	
Silicon		0.3			0.40	
Iron		0.05			0.05	
Nickel		0.01			0.02	
Cu + Si + Fe + Ni		0.40			0.75	
Material properties						
Founding		Good			Good	
Characteristics		Sand, permanent mould and die (pressure)			Sand, permanent mould and die (pressure)	
Tencency to hot tearing		Little			Little	
Tendency to micro-porosity		Less than MAG1			Less than MAG1	
Castability[§]		A			A	
Weldability (Ar-Arc process)		Good, but some difficulty with die castings			Good, but some difficulty with die castings	
Relative damping capacity[¶]		C			C	
Strength at elevated temperature[**]		C			C	
Corrosion resistance		Moderate			Moderate	
Density, g cm^{-3}		1.83			1.82	
Liquidus, °C		595			600	
Solidus, °C		470			475	
Non-equilibrium solidus, °C		420			420	
Casting temperature range, °C		680–800			680–800	

continued overleaf

Table 4.8 (*continued*)

Heat treatment				
Solution:				
Time, h	–	16 (min)	–	16 (min)
Temperature, °C	–	435 (max)[‡‡]	–	435 (max)[‡‡]
Cooling	–	Air, oil or water	–	Air, oil or water

Elektron designation	AZ91 (HP)		ZC63
ASTM designation	AZ91E	AZ91D	ZC63
Specifications BS 2970: 1989	MAG11 (GP)		–
BSS L series	–		–
Equivalent DTD	–		–
Composition % (Single figures indicate maximum)			
Aluminium	8.5–9.5		–
Zinc	0.45–0.9		5.5–6.5
Manganese	0.15–0.40		0.25–0.75
Copper	0.015		2.4–3.0
Silicon	0.020		0.20
Iron	0.005		0.05
Nickel	0.0010		0.01
Cu + Si + Fe + Ni	–		–
Material properties			
Founding	Sand and permanent mould	High pressure die	Sand, permanent and high pressure die
Characteristics	Good	Good	Good
Tendency to hot tearing	Little	Little	Little
Tendency to micro-porosity	Less than MAG1	Little	Little
Castability[§]	A	A	B
Weldability (Ar-Arc process)	Good	Difficult	Good
Relative damping capacity[¶]	C	C	C
Strength at elevated temperature[**]	C	C	B
Corrosion resistance	Excellent	Excellent	Moderate
Density, g cm^{-3}	1.83	1.83	1.84
Liquidus, °C	595	595	635
Solidus, °C	470	470	465
Non-equilibrium solidus, °C	420	420	–
Casting temperature range, °C	680–800	620–680	700–810

Heat treatment			
Time, h	16 (min)	Not suitable	8
Temperature, °C	435 (max)		440 (max)
Cooling	Air, oil or water		oil or water

Elektron designation	A8		A8 *(High purity)*	
ASTM designation	AZ81		AZ81	
Specifications BS 2970: 1989	MAG1M* (GP)†	MAG1TB* (GP)	MAG2M(SP)†	MAG2TB(SP)
BSS L series	–	3L.122	–	–
Equivalent DTD	–	–	684A	690A
Heat treatment – continued				
Precipitation:				
Time, h	–	–	–	–
Temperature, °C	–	–	–	–
Stress relief:				
Time, h	2–4	–	2–4	–
Temperature, °C	250–330	–	250–330	–
Mechanical propefties – sand cast – (SI units first, Imperial units following in brackets)				
Tensile strength (min), MPa (tonf in^{-2})	140 (9.1)	200 (13.0)	140 (9.1)	200 (13.0)
0.2% proof stress (min), MPa (tonf in^{-2})	85 (5.5)	80 (5.2)	85 (5.5)	80 (5.2)
Elongation % (min) ($5.65\sqrt{S_0}$)	2	6	2	6
Mechanical properties – chill cast – (SI units first, Imperial units following in brackets)				
Tensile strength (min), MPa (tonf in^{-2})	185 (12.0)	230 (14.9)	185 (12.0)	230 (14.9)
0.2% proof stress (min), MPa (tonf in^{-2})	85 (5.5)	80 (5.2)	85 (5.5)	80 (5.2)
Elongation % (min) ($5.65\sqrt{S_0}$)	4	10	4	10
Applications	Automobile road wheels	Good ductility and shock resistance	High-purity alloy – offers good corrosion resistance	

continued overleaf

Table 4.8 (*continued*)

Elektron designation *ASTM designation*	AZ91			*C alloy*		
Specifications BS 2970: 1989	MAG3M(GP)	MAG3TB(GP)	MAG3TF(GP)	MAG7M(GP)	MAG7TB(GP)	MAG7TF(GP)
BSS L series	–	3L.124	3L.125	–	–	–
Equivalent DTD	–	–	–	–	–	–
Precipitation:						
Time, h	–	–	8(min)	–	–	8(min)
Temperature, °C	–	–	210(max)	–	–	210(max)
Stress relief:						
Time, h	2–4	–	–	2–4	–	–
Temperature, °C	250–330	–	–	250–330	–	–
Mechanical properties – sand cast – (SI units first, Imperial units following in brackets)						
Tensile strength (min), MPa (tonf in^{-2})††	125 (8.1)	200 (13.0)	200 (13.0)	125 (8.1)	185 (12.0)	185 (12.0)
0.2% proof stress (min), MPa (tonf in^{-2})	95 (6.2)	85 (5.5)	130 (8.4)	85 (5.5)	80 (5.2)	110 (7.1)
Elongation % (min) ($5.65\sqrt{S_0}$)	–	4	–	–	4	–
Mechanical properties – chill cast – (SI units first, Imperial units following in brackets)						
Tensile strength (min), MPa (tonf in^{-2})	170 (11.0)	215 (13.9)	215 (13.9)	170 (11.0)	215 (13.9)	215 (13.9)
0.2% proof stress (min), MPa (tonf in^{-2})	100 (6.5)	85 (5.5)	130 (8.4)	85 (5.5)	80 (5.2)	110 (7.1)
Elongation % (min) ($5.66\sqrt{S_0}$)	2	5	2	2	5	2
Applications	For pressure tight applications Increased proof stress after full heat treatment			Principal alloy for commercial usage		

Elektron designation	AZ91(HP)		ZC63
ASTM designation	AZ91E	AZ91D	ZC63
Specifications BS 2970: 1989	MAG11(GP)		–
BSS L series	–		–
Equivalent DTD	–		–
Precipitation:			
Time, h	8 (min)	Not suitable	16 (min)
Temperature, °C	210 (max)		200 (max)
Stress relief:			
Time, h	–	–	–
Temperature, °C	–	–	–
Mechanical properties – sand cast – (SI units first, Imperial units following in brackets)			
Tensile strength (min), MPa (tonf in^{-2})	200	Typical high	210
0.2% proof stress (min), MPa (tonf in^{-2})	130	pressure die-cast	125
Elongation % (min) ($5.65\sqrt{S_0}$)	2	properties	3
Mechanical properties – chill cast – (SI units first, Imperial units following in brackets)			
Tensile strength (min), MPa (tonf in^{-2})	215	200	210
0.2% proof stress (min), MPa (tonf in^{-2})	130	150	125
Elongation % (min) ($5.65\sqrt{S_0}$)	2	1	3
Applications	High purity alloy – offers excellent corrosion resistance. Max. temp. 120 °C		Better foundability than AZ91 with superior elevated temperature properties

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[*] M-as cast.
TS – Stress relieved only.
TE – Precipitation treated only.
TB – Solution treated only.
TF – Solution and precipitation treated.

[†] GP General purpose alloy.
SP Special purpose alloy.

[‡] Permanent mould=gravity die casting.

[§] Ability to fill mould easily. A, B, C, indicate decreasing castability.

[¶] Damping capacity ratings.
A=Outstanding; better than grey cast iron.
B=Equivalent to cast-iron.
C=Infersior to cast-iron but better Al-base cast alloys.

[**] A=Particularly recommended.
B=Suitable but not especially recommended.
C=Not recommended where strength at elev. temps is likely to be an important consideration.

[††] 1 MPa=1 H m^{-2} =0 064 75 tonf in^{-2}.

[‡‡] SO_2 or CO_2 atmosphere.

Table 4.9 MAGNESIUM-ZIRCONIUM ALLOYS
Inherently fine grained (0.015–0.035 mm *chill cast*)

Elektron designation *ASTM designation*	Z5Z ZK51	RZ5 ZE41	ZRE1 EZ33
Specifications BS 2970: 1989	MAG4TE[*] (GP)[†]	MAG5TE(SP)	MAG6TE(SP)
BSS L series	2L.127	2L.128	2L.126
Equivalent DTD	–	–	–
Composition % (Single figures indicate maximum)			
Zinc	3.5–5.5	3.5–5.5	0.8–3.0
Silver	–	–	–
Rare earth metals	–	0.75–1.75	2.5–4.0
Thorium	–	–	–
Zirconium	0.4–1.0	0.4–1.0	0.4–1.0
Copper	0.03	0.03	0.03
Nickel	0.005	0.005	0.005
Iron	–	–	–
Silicon	–	–	–
Manganese	–	–	–
Material properties			
Founding characteristics	Good in sand and permanent moulds[§]	Good in sand and permanent moulds	Excellent in sand and permanent moulds
Tendency to hot tearing	Marked	Some	Little
Tendency to micro-porosity	Very appreciable	Virtually none	None
Castability[¶]	B	A	A
Weldability (Ar-Arc Process)	Not recommended	Moderate	Very good
Relative damping capacity[**]	B/C	B/C	B
Strength at elevated temperature[††]	C	B	A
Resistance to creep at elevated temperature	Poor	Moderate	Good up to 250 °C
Corrosion resistance	Moderate	Moderate	Moderate
Density, g cm^{-3} (20 °C)	1.81	1.84	1.80
Liquidus, °C	640	640	640
Solidus, °C	560	510	545
Casting temperature range, °C	720–810	720–810	720–810

Heat treatment			
Solution:			
Time, h	–	–	–
Temperature, °C	–	–	–
Cooling	–	–	–
Precipitation:			
Time, h	16	2 followed by 16	8
Temperature, °C	180	330 180	200
	Air cool	Air cool after each	Air cool
Post – weld stress relief:			
Time, h	2	Precipitation treatment affords s/relief	10
	330		250 max
	to precede precipitation treatment		Air cool
Mechanical properties – sand cost – SI units (Imperial units in brackets)			
Tensile strength min, MPa (tonf in^{-2})	230 (14.9)	200 (13.0)	140 (9.1)
0.2% proof stress min, MPa (tonf in^{-2})	145 (9.4)	135 (8.7)	95 (6.2)
Elongation, % $(5.65\sqrt{S_0})$ min	5	3	3
Mechanical properties – chill cast – SI units (Imperial units in brackets)			
Tensile strength min, MPa (tonf in^{-2})	245 (15.9)	215 (13.9)	155 (10.0)
0.2% proof stress min, MPa (tonf in^{-2})	145 (9.4)	135 (8.7)	110 (7.1)
Elongation, % $(5.65\sqrt{S_0})$ min	7	4	3
Applications	High strength plus good ductility. Not suitable for spidery complex shapes	For high-strength pressure-tight applications	High degree of pressure tightness at room and elevated temperatures

continued overleaf

Table 4.9 (*continued*)

Elektron designation *ASTM designation*	ZT1[‡‡‡] HZ32	TZ6[‡‡‡] ZH62	ZE63 ZE63
Specifications BS 2970: 1989	MAG8TE(SP)	MAG9TE(SP)	–
BSS L series			
Equivalent DTD	5005A	5015A	5045
Composition % (Single figures indicate maximum)			
Zinc	1.7–2.5	5.0–6.0	5.5–6.0
Silver	–	–	–
Rare earth metals	0.10	0.20	2.0–3.0
Thorium	2.5–4.0	1.5–2.3	–
Zirconium	0.4–1.0	0.4–1.0	0.4–1.0
Copper	0.03	0.03	0.03
Nickel	0.005	0.005	0.005
Iron	0.01	0.01	0.01
Silicon	0.01	0.01	0.01
Manganese	0.15	0.15	0.15
Material properties			
Founding characteristics	As per MAG7 but more sluggish	Similar to MAG5	Good
Tendency to hot tearing	Little	Very little	Negligible
Tendency to micro-porosity	None	Low	Virtually none
Castability[¶]	C	B	A
Weldability (Ar-Arc process)	Very good	Fair	Very good[***]
Relative damping capacity[**]	B	C	B/C
Strength at elevated temperature[††]	A	B	C
Resistance to creep at elevated temperature	Good up to 350 °C	Fair	Poor
Corrosion resistance	Moderate	Moderate	Moderate
Density, g cm^{-3} (20 °)	1.85	1.87	1.87
Liquidus, °C	645	630	625
Solidus, °C	550	520	516
Casting temperature range, °C	720 – 810	720 – 810	720 – 810

Heat treatment			
Solution:			
Time, h	–	–	30 for 12 mm sctn. 70 for 25 mm sctn.
Temperature, °C	–	–	480[†††]
Cooling	–	–	Air blast or water spray
Precipitation:			
Time, h	16	2 followed 16	48 or 72
Temperature, °C	315	330 by 180	138 127
	Air cool	Air cool after each	Air cool
Post weld stress relief:			
Time, h	2	Pptn. treatment affords stress relief	–
Temperature, °C	350		–
	Air cool		
Mechanical properties – sand cast – SI units (Imperial units in brackets)			
Tensile strength min, MPa (tonf in^{-2})	185 (12.0)	255 (16.5)	275 (17.8)
0.2% proof stress min, MPa (tonf in^{-2})	85 (5.5)	155 (10.0)	170 (11.0)
Elongation, % $(5.65\sqrt{S_0})$ min	5	5	5
Mechanical properties – chill cast – SI units (Imperial units in brackets)			
Tensile strength min, MPa (tonf in^{-2})	185 (12.0)	255 (16.5)	Sand
0.2% proof stress min, MPa	85 (5.5)	155 (10.0)	Cast
Elongation, % $(5.65\sqrt{S_0})$ min	5	5	Alloy
Applications	Creep resistant alloy	For heavy duty structural usage	High strength with good ductility and excellent fatigue resistance. Structural parts aircraft, etc.

continued overleaf

Table 4.9 (*continued*)

Elektron designation *ASTM*	MSR-A	MSR-B	MSR QE22	MTZ[‡‡‡] HK31	EQ21 EQ21	WE54 WE54	WE43 WE43
Specifications BS 2970: 1972	–	MAG12TF(SP)	–	–	MAG13TF(SP)	MAG14TF(SP)	–
BSS L series	–	–	–	–	–	–	–
Equivalent DTD	5025A	5035A	5055	–	–	–	–
Composition % (Single figures indicate maximum)							
Zinc	0.2	0.2	0.2	0.3	0.2	0.2	0.2
Silver	2.0–3.0	2.0–3.0	2.0–3.0	–	1.3–1.7	–	–
Rare earth metals	1.2–2.0[‡]	2.0–3.0[‡]	1.8–2.5[‡]	0.1	1.5–3.0[‡]	2.0–4.0[¶¶¶]	2.4–4.4[¶¶¶]
Thorium	–	–	–	2.5–4.0	–	–	–
Zirconium	0.4–1.0	0.4–1.0	0.4–1.0	0.4–1.0	0.4–1.0	0.4–1.0	0.4–1.0
Copper	0.03	0.03	0.03	0.03	0.05–0.10	0.03	0.03
Nickel	0.005	0.005	0.005	0.005	0.005	0.005	0.005
Iron	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Silicon	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Manganese	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Yttrium	–	–	–	–	–	4.75–5.5	3.7–4.3

Elektron designation *ASTM designation*	MSR-A –	MSR-B –	MSR QE22	MTZ[‡‡‡] MK31	EQ21 EQ21	WE54 WE54	WE43 WE43
Specifications BS 2970: 1989	–	MAG12TF (SP)	–	–	MAG13TF(SP)	MAG14TF(SP)	–
BSS L series	–	–	–	–	–	–	–
Equipment DTD	5025A	5035A	5055	–	–	–	–
Material properties							
Founding characteristics	Good	Good	Good	Less easy to found than MSR types	Good	Good	Good
Tendency to hot tearing	Little	Little	Little	Very little	Little	Very little	Very little
Tendency to micro-porosity	Slight	Slight	Slight	Negligible	Slight	Slight	Slight
Cqstability[¶]	B	B	B	C	B	B	B
Weldability (Ar-Arc process)	Very good	Very good	Very good	Very good	Very good	Very good	Very good
Relative damping capacity[**]	B/C	B/C	B/C	B/C	B/C	B/C	B/C
Strength at elevated temperature[††]	A	A	A	A	A	A	A
Resistance to creep at elevated temperature	Good up to 200 °C	Good up to 200 °C	Good up to 200 °C	Good up to 350 °C for short time applications	Good up to 200 °C	Very good up to 250 °C	Very good up to 250 °C
Corrosion resistance	Moderate	Moderate	Moderate	Moderate	Moderate	Excellent	Excellent
Density, g cm^{-3} (20 °C)	1.81	1.82	1.81	1.84	1.81	1.85	1.85
Liquidus, °C	640	640	640	645	640	640	640
Solidus, °C	550	550	550	590	545	550	550
Casting temperature range, °C	720–810	720–810	720–810	720–810	720–810	720–810	720–810
Heat treatment							
Solution:							
Time, h	8	8	8	2	8	8	8
Temperature, °C	525[‡‡]	525[‡‡]	525[‡‡]	565[‡‡,¶¶]	520[‡‡]	525[‡‡]	525[‡‡]
Cooling	Water or oil	Water or oil	Water or oil	Air cool	Water or oil	Air cool	Water or oil
Precipitation:							
Time, h	16	16	16	16	16	16	16
Temperature, °C	200	200	200	200	200	250	250
	Air cool	Air cool	Air cool	Air cool	Air cool	Air cool	Air cool

continued overleaf

Table 4.9 (*continued*)

Elektron designation *ASTM designation*	MSR-A –	MSR-B –	MSR QE22	MTZ[‡‡‡] MK31	EQ21 EQ21	WE54 WE54	WE43 WE43
Specifications BS 2970: 1989	–	MAG12TF(SP)	–	–	MAG13TF(SP)	MAG14TF(SP)	–
BSS L series	–	–	–	–	–	–	–
Equipment DTD	5025A	5035A	5055	–	–	–	–
Post-weld stress relief:							
Time, h	1			Repeat above	1	1	1
Temperature, °C	510 followed by above quench and age			cycle	505 followed by above quench and age	510 followed by above aircool and age	510 followed by above quench and age
Mechanical properties – sand cast – SI units (Imperial units in brackets)							
Tensile strength min, MPa (tonf in^{-2})	240 (15.5)	240 (15.5)	240 (15.5)	200 (13.0)	240	250	250
0.2% proof stress min, MPa (tonf in^{-2})	170 (11.0)	185 (12.0)	175 (11.3)	93 (6.0)	170	175	165
Elongation, % $(5.65\sqrt{S_0})$ min	4	2	2	5	2	2	2
Mechanical properties – chill cast – SI units (Imperial units in brackets)							
Tensile strength min, MPa (tonf in^{-2})	240 (15.5)	240 (15.5)	240 (15.5)		240	250	250
0.2% proof stress min, MPa (tonf in^{-2})	170 (11.0)	185 (12.1)	175 (11.3)	Usually sand	170	175	165
Elongation, % $(5.65\sqrt{S_0})$ min	4	2	2	2	cast	2	2
Applications	High strength in thick and thin section castings. Good elevated temperature (up to 250 °C) short time tensile and fatigue props.		Similar to MSRA-B	Superior short time tensile and creep resistance at temperatures around 300 °C	Similar to MSR alloys but less but less	Excellent strength up to 300 °C for short time applications. Excellent corrosion resistance	Excellent strength up to 250 °C for long time applications. Excellent corrosion resistance

[*] *See* footnote to Table 4.1.

[†] *See* footnote to Table 4.1.

[‡] Neodymium-rich rare rearths (others Ce-rich).

[¶] *See* footnote to Table 4.1.

[**] *See* footnote to Table 4.1.

[§] *See* footnote to Table 4.1.

[††] *See* footnote to Table 4.1.

[‡‡] SO_2 or CO_2 atmosphere.

[¶¶] Castings to be loaded into furnace at operating temperature.

[***] But only before hydriding treatment.

[†††] In hydrogen at atmospheric pressure.

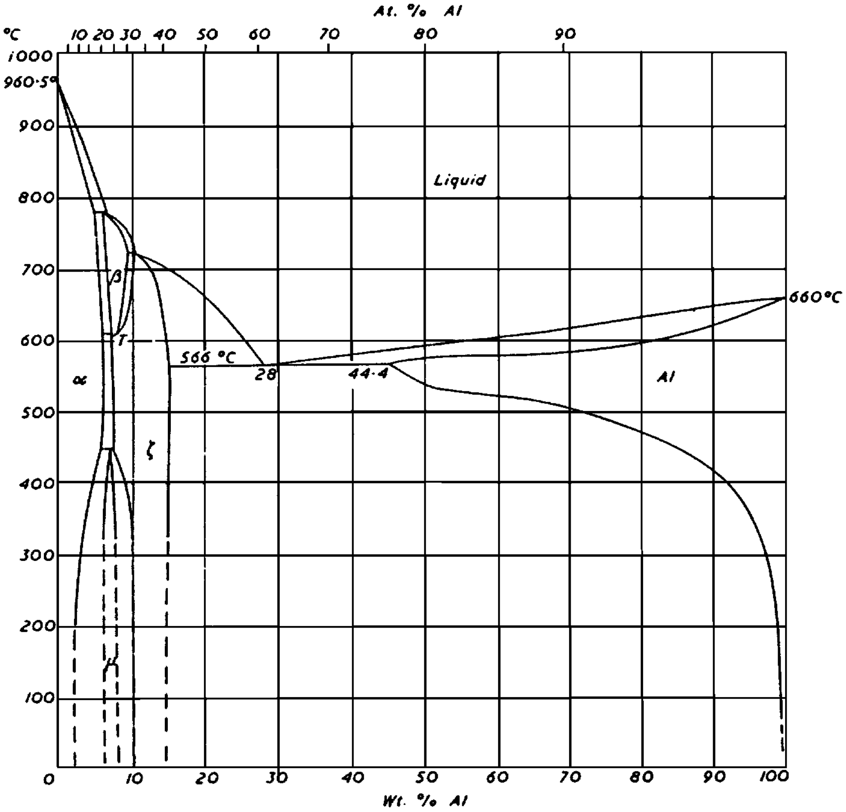
[‡‡‡] Thorium containing alloys are being replaced by alternative magnesium based alloys.

[¶¶¶] Neodymium and heavy rare earths.

5 Equilibrium diagrams

5.1 Index of binary diagrams

Ag–Al


At. % Al
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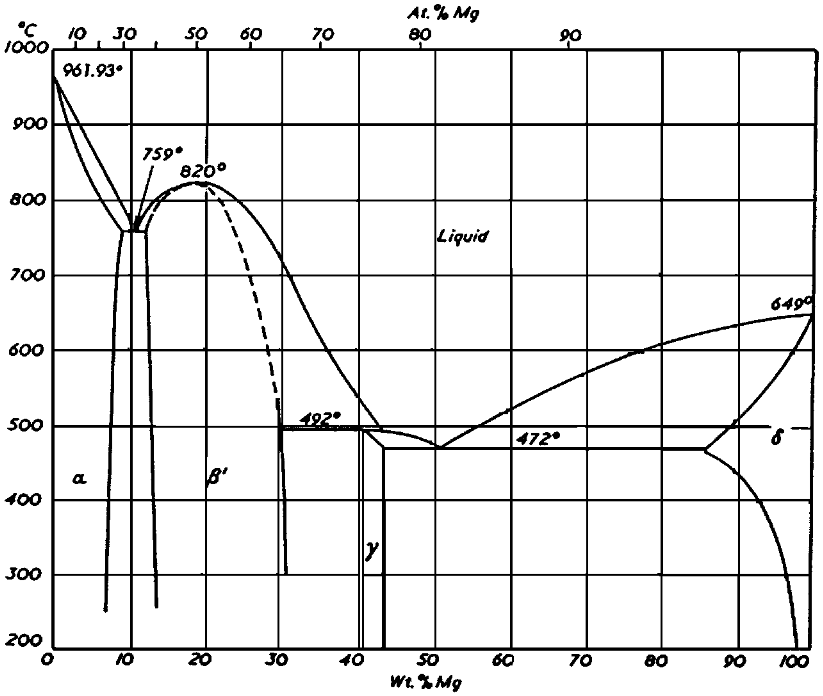
50
60
70
80
90
1000
960·5°
900
800
700
600
500
400
300
200
100
Liquid
660°C
β
T
566 °C
28
44·4
α
Al
ζ
μ
0
10
20
30
40
50
60
70
80
90
100
Wt. % Al

Ag–Mg


At.% Mg
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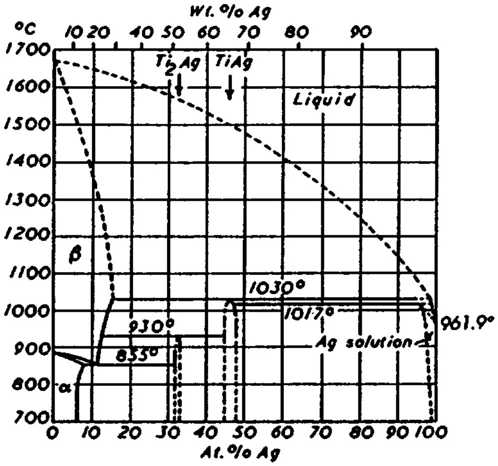
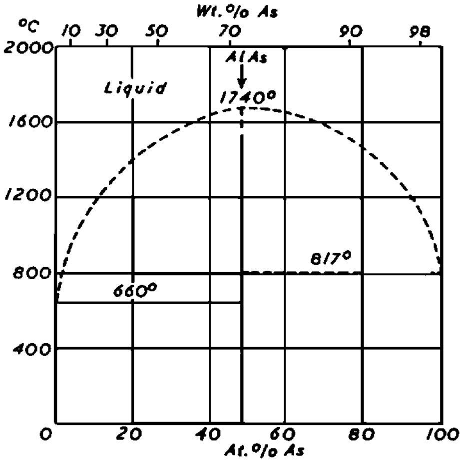
30
50
60
70
80
90
°C
1000
900
800
700
600
500
400
300
200
961.93°
759°
820°
Liquid
649°
492°
472°
δ
α
β'
γ
0
10
20
30
40
50
60
70
80
90
100
Wt.% Mg

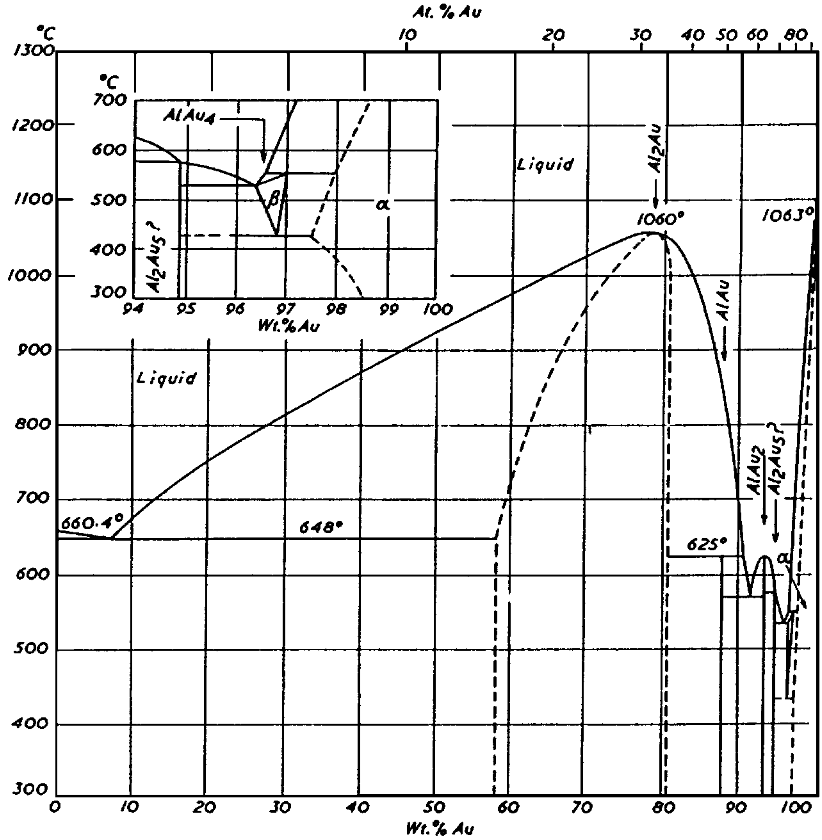
Ag–Ti

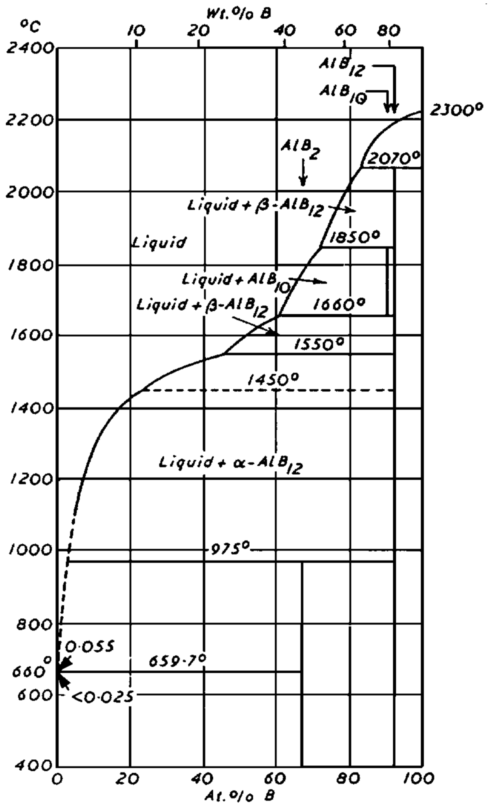

Wt. % Ag
10
20
40
50
60
70
80
90
°C
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
Ti_2Ag
TiAg
Liquid
β
1030°
1017°
930°
855°
961.9°
Ag solution
α
0
10
20
30
40
50
60
70
80
90
100
At. % Ag

Al–As

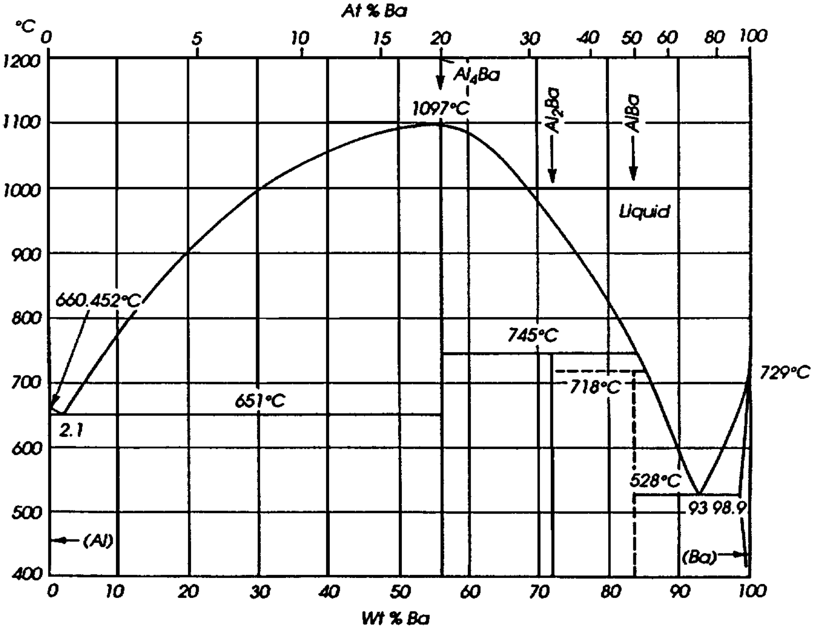

Wt.% As
°C
10
30
50
70
90
98
2000
1600
1200
800
400
0
20
40
60
80
100
At.% As
AlAs
1740°
Liquid
817°
660°

Al–Au


At.% Au
°C
1300
1200
1100
1000
900
800
700
600
500
400
300
10
20
30
40
50
60
80
Liquid
Al2Au
1060°
1063°
AlAu
AlAu2
Al2Au5?
625°
α
660.4°
648°
Liquid
0
10
20
30
40
50
60
70
80
90
100
Wt.% Au
°C
700
600
500
400
300
AlAu4
β
α
Al2Au5?
94
95
96
97
98
99
100
Wt.% Au

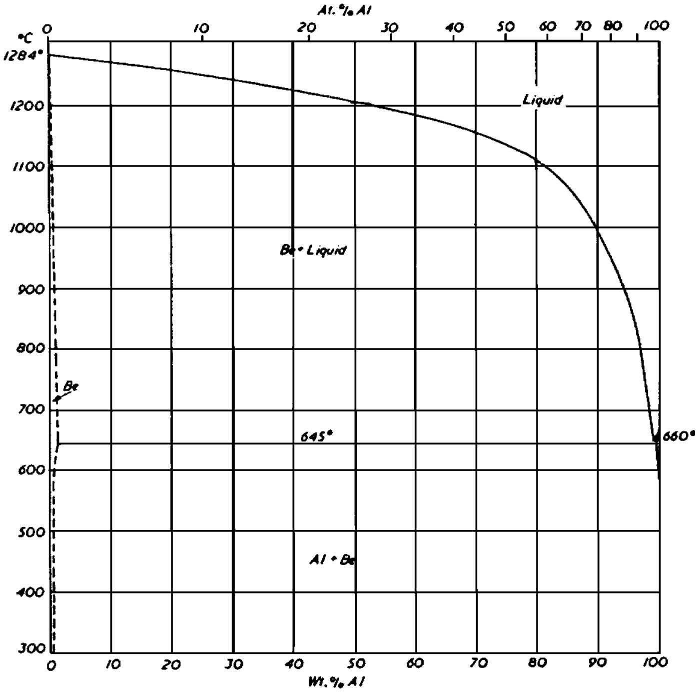

Wt.% B
°C
10
20
40
60
80
2400
AlB12
AlB10
2300°
2200
2070°
AlB2
2000
Liquid + β-AlB12
1850°
Liquid
1800
Liquid + AlB10
Liquid + β-AlB12
1660°
1600
1550°
1450°
1400
Liquid + α-AlB12
1200
1000
975°
800
0·055
660°
659·7°
600
<0·025
400
0
20
40
60
80
100
At.% B

Al–B

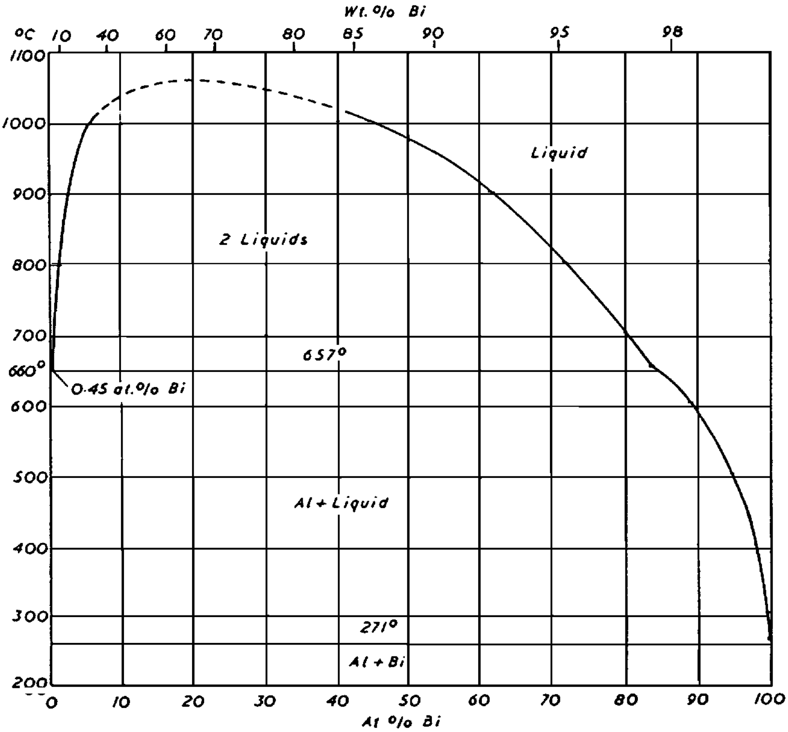

At % Ba
°C
0
5
10
15
20
30
40
50
60
80
100
1200
Al4Ba
1097°C
Al2Ba
AlBa
1100
1000
Liquid
900
660.452°C
800
745°C
700
718°C
729°C
651°C
2.1
600
528°C
500
93 98.9
(Al)
(Ba)
400
0
10
20
30
40
50
60
70
80
90
100
Wt % Ba

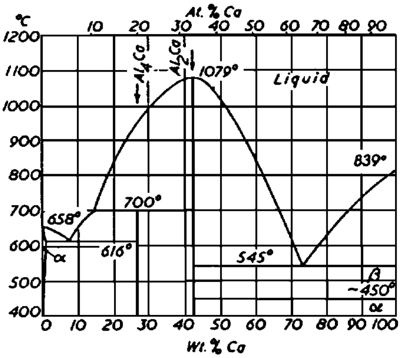
Al–Ba

Al–Be

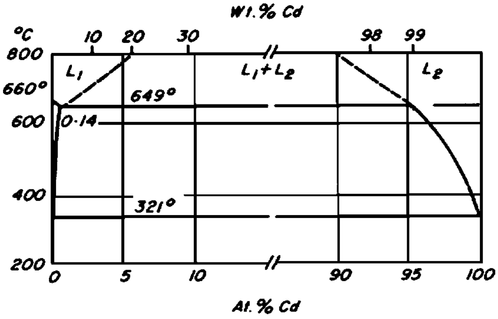

At.% Al
0
10
20
30
40
50
60
70
80
100
°C
1284°
1200
1100
1000
900
800
700
600
500
400
300
Liquid
Be + Liquid
Be
645°
660°
Al + Be
0
10
20
30
40
50
60
70
80
90
100
Wt.% Al

Al–Bi

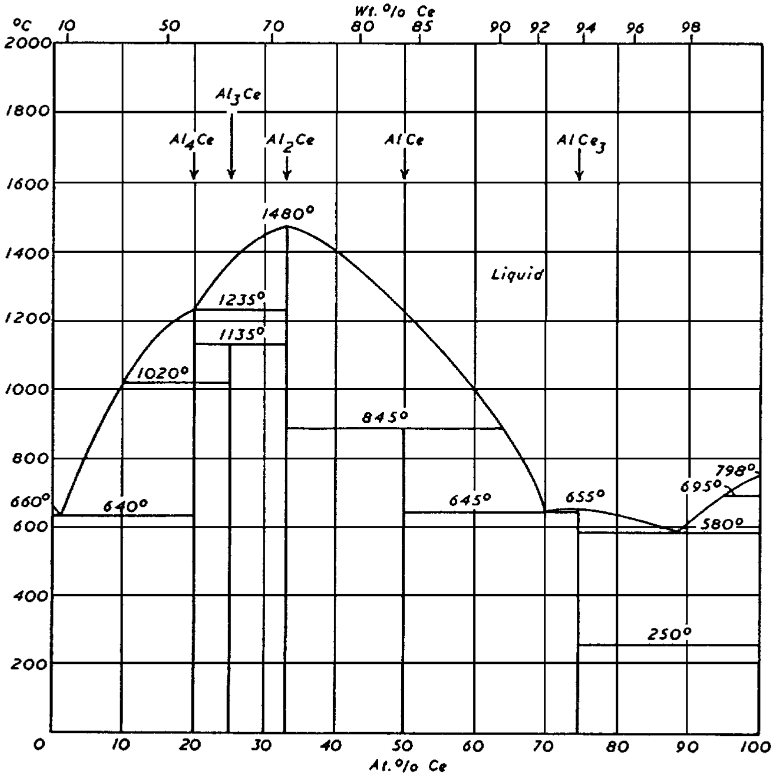

Wt.% Bi
10
40
60
70
80
85
90
95
98
°C
1100
1000
900
800
700
660°
600
500
400
300
200
Liquid
2 Liquids
657°
0.45 at.% Bi
Al + Liquid
271°
Al + Bi
0
10
20
30
40
50
60
70
80
90
100
At % Bi



Al–Ca

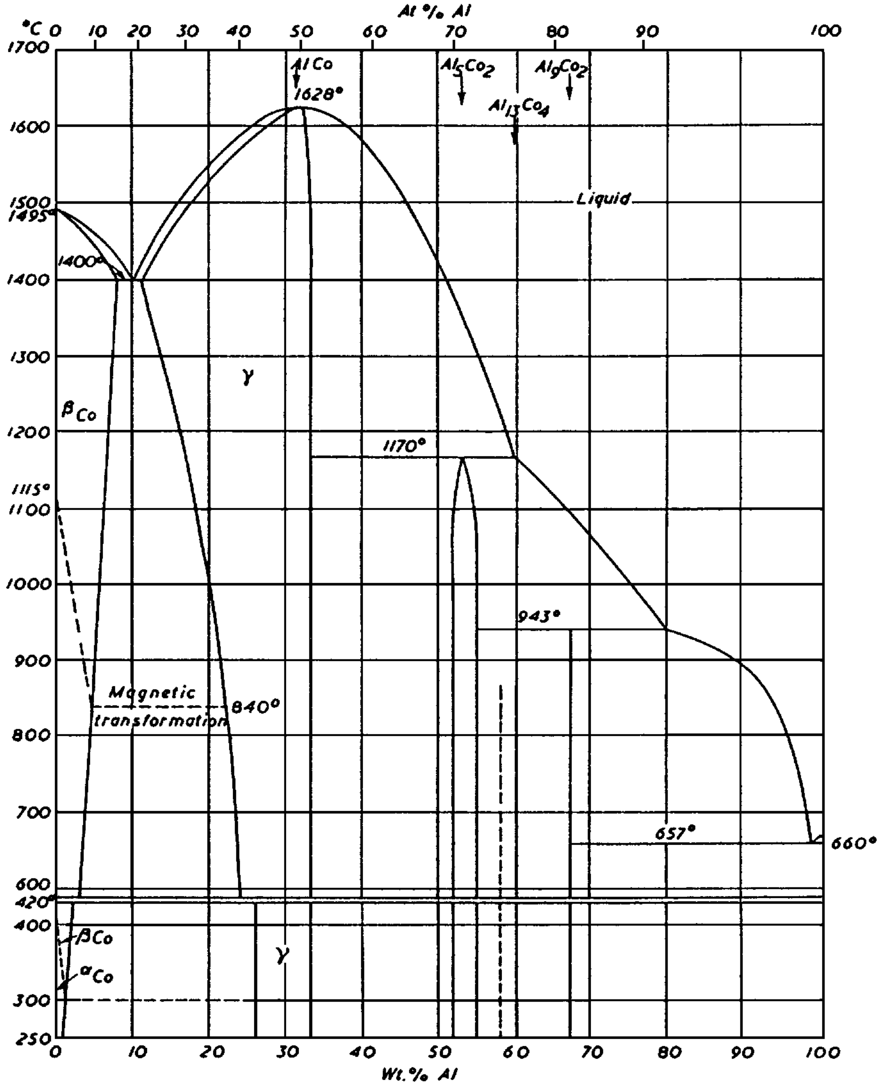


Al–Cd

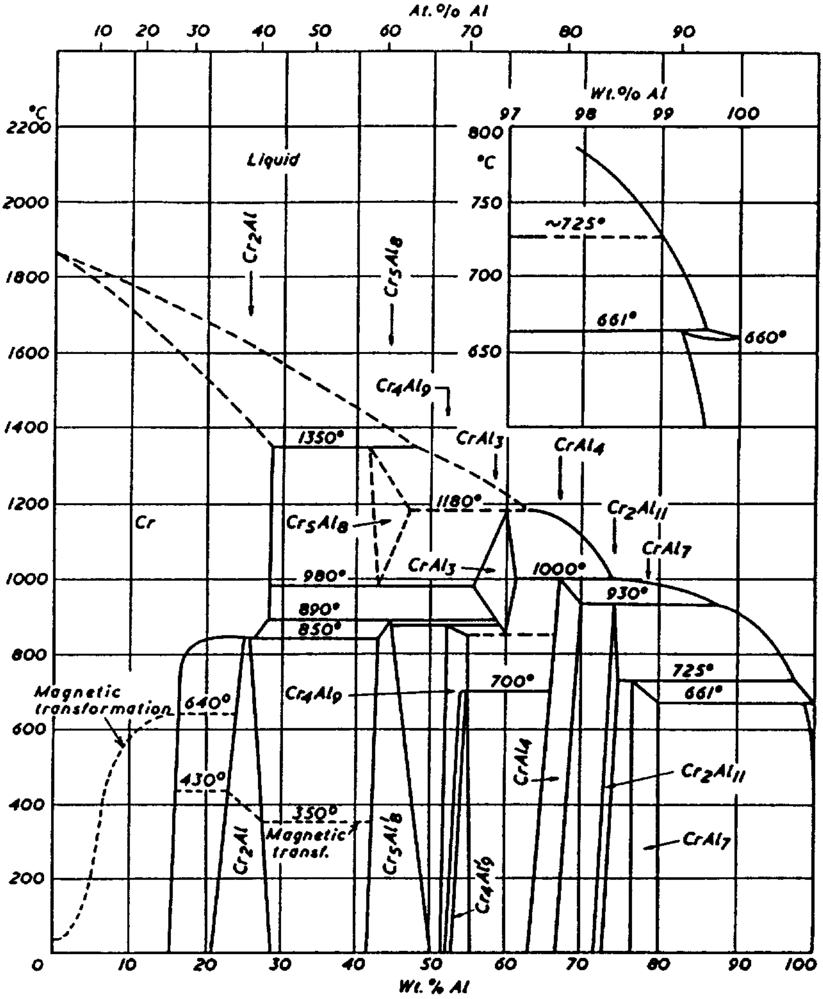


Al–Ce

Al–Co

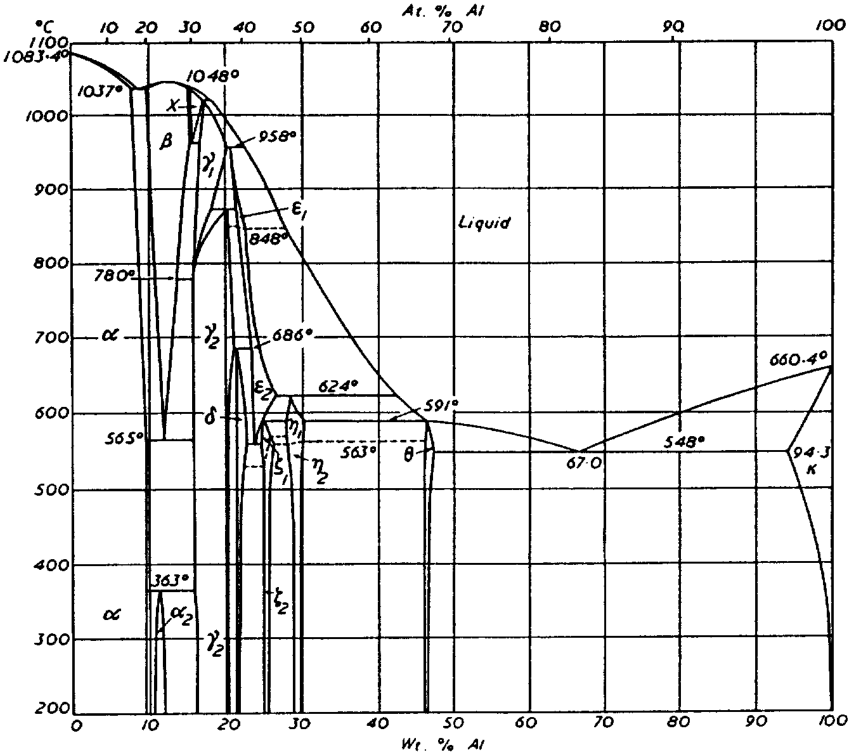

At.% Al
°C
0
10
20
30
40
50
60
70
80
90
100
1700
1600
1500
1495°
1400
1300
1200
1115°
1100
1000
900
800
700
600
420°
400
300
250
AlCo
1628°
Al5Co2
Al9Co2
Al13Co4
Liquid
1400°
γ
βCo
1170°
943°
Magnetic transformation
840°
657°
660°
βCo
αCo
γ
0
10
20
30
40
50
60
70
80
90
100
Wt.% Al

Al−Cr

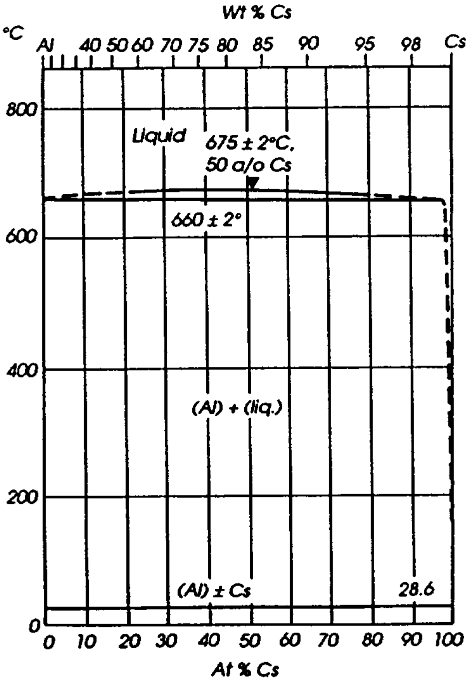


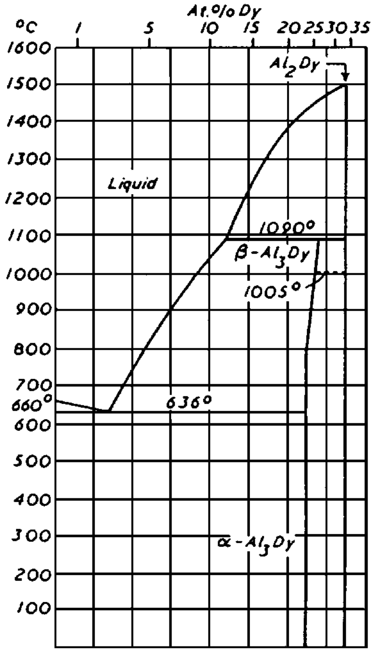
At.% Al
10
20
30
40
50
60
70
80
90
Wt.% Al
97
98
99
100
800
°C
750
700
650
~725°
661°
660°
°C
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
Liquid
Cr2Al
Cr5Al8
Cr4Al9
CrAl3
CrAl4
Cr2Al11
CrAl7
1350°
1180°
Cr
Cr5Al8
CrAl3
980°
1000°
930°
890°
850°
Cr4Al9
700°
725°
661°
Magnetic transformation
640°
430°
350°
Magnetic transf.
Cr2Al
Cr5Al8
Cr4Al9
CrAl4
Cr2Al11
CrAl7
10
20
30
40
50
60
70
80
90
100
Wt.% Al

Al–Cu

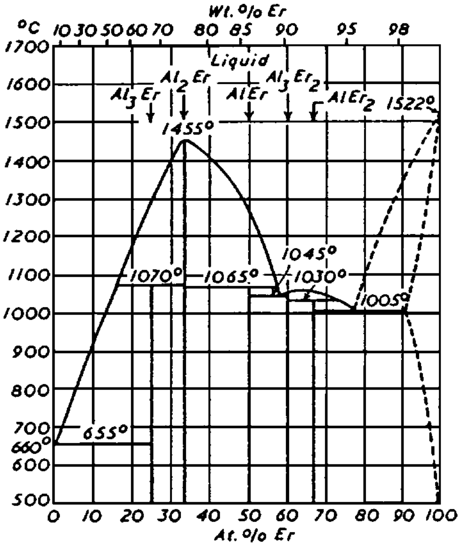

At. % Al
°C
10
20
30
40
50
60
70
80
90
100
1100
1083·4°
1037°
1048°
X
1000
β
958°
γ_1
900
ε_1
Liquid
848°
800
780°
700
α
γ_2
686°
660·4°
624°
ε_2
600
591°
δ
η_1
565°
563°
θ
548°
94·3
67·0
κ
ζ_1
η_2
500
400
363°
ζ_2
α
α_2
300
γ_2
200
0
10
20
30
40
50
60
70
80
90
100
Wt. % Al

Al–Cs


Wt % Cs
°C
Al
40
50
60
70
75
80
85
90
95
98
Cs
800
Liquid
675 ± 2°C,
50 a/o Cs
660 ± 2°
600
400
(Al) + (liq.)
200
(Al) ± Cs
28.6
0
0
10
20
30
40
50
60
70
80
90
100
At % Cs

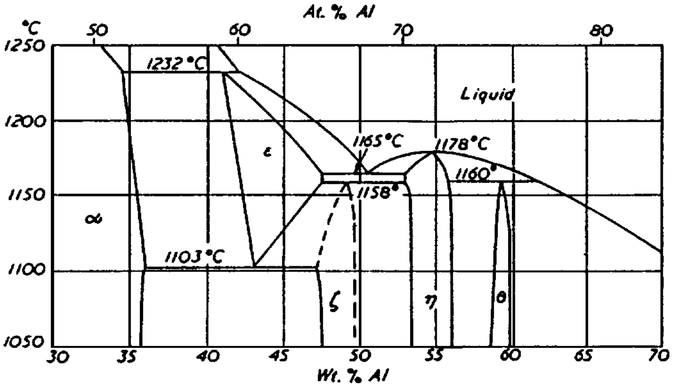

At.% Dy
°C
1
5
10
15
20
25
30
35
1600
1500
1400
1300
1200
1100
1000
900
800
700
660°
600
500
400
300
200
100
Al_2Dy
Liquid
1090°
β-Al_3Dy
1005°
636°
α-Al_3Dy

Al–Dy

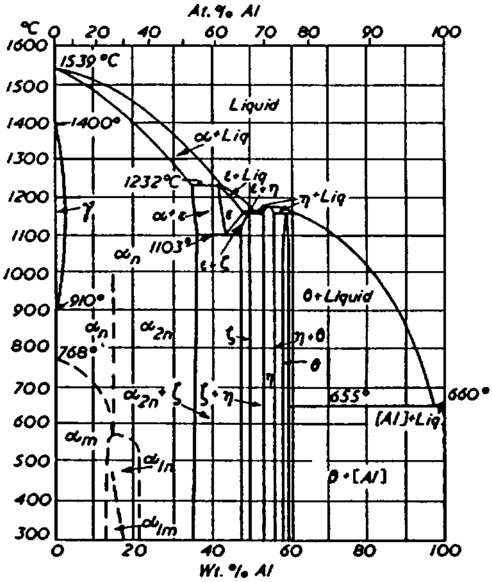

Wt.% Er
°C
10
30
50
60
70
80
85
90
95
98
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
660°
600
500
Liquid
Al_2Er
Al_3Er
$AlEr$
Al_3Er_2
$AlEr_2$
1522°
1455°
1045°
1070°
1065°
1030°
1005°
655°
0
10
20
30
40
50
60
70
80
90
100
At.% Er

Al–Er

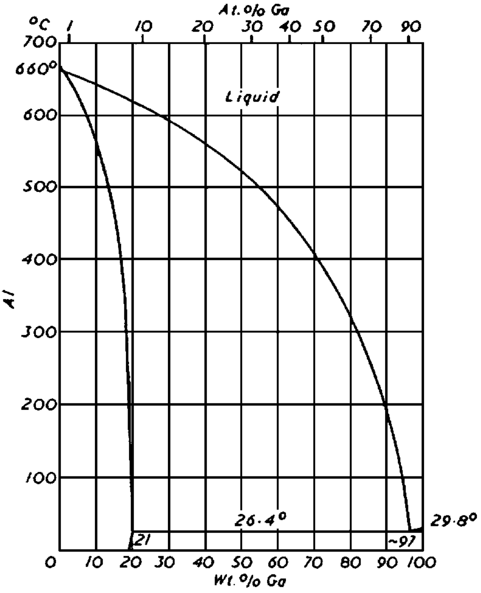
Al–Fe


At. % Al
°C
50
60
70
80
1250
1200
1150
1100
1050
1232 °C
Liquid
ε
1165 °C
1178 °C
1160°
1158°
α
1103 °C
ζ
η
θ
30
35
40
45
50
55
60
65
70
Wt. % Al

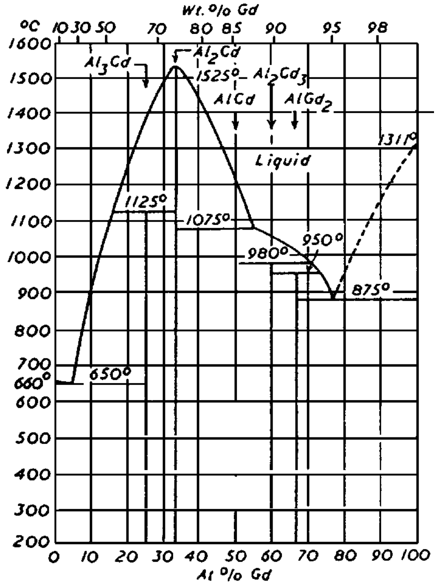
Al–Fe


At. % Al
°C
0
20
40
60
70
80
90
100
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
1539 °C
Liquid
1400°
α+Liq
1232°C
ε+Liq
ε+η
η+Liq
γ
α+ε
ε
1103°
αn
ε+ζ
910°
θ+Liquid
αn
α2n
ζ
η+θ
768°
θ
η
α2n+ζ
ζ+η
655°
660°
[Al]+Liq
αm
α1n
θ+[Al]
α1m
0
20
40
60
80
100
Wt. % Al

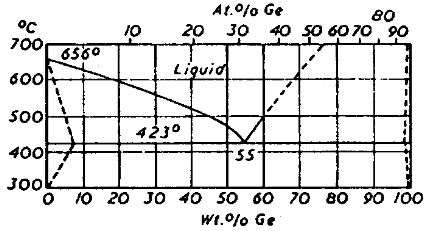
Al–Ga



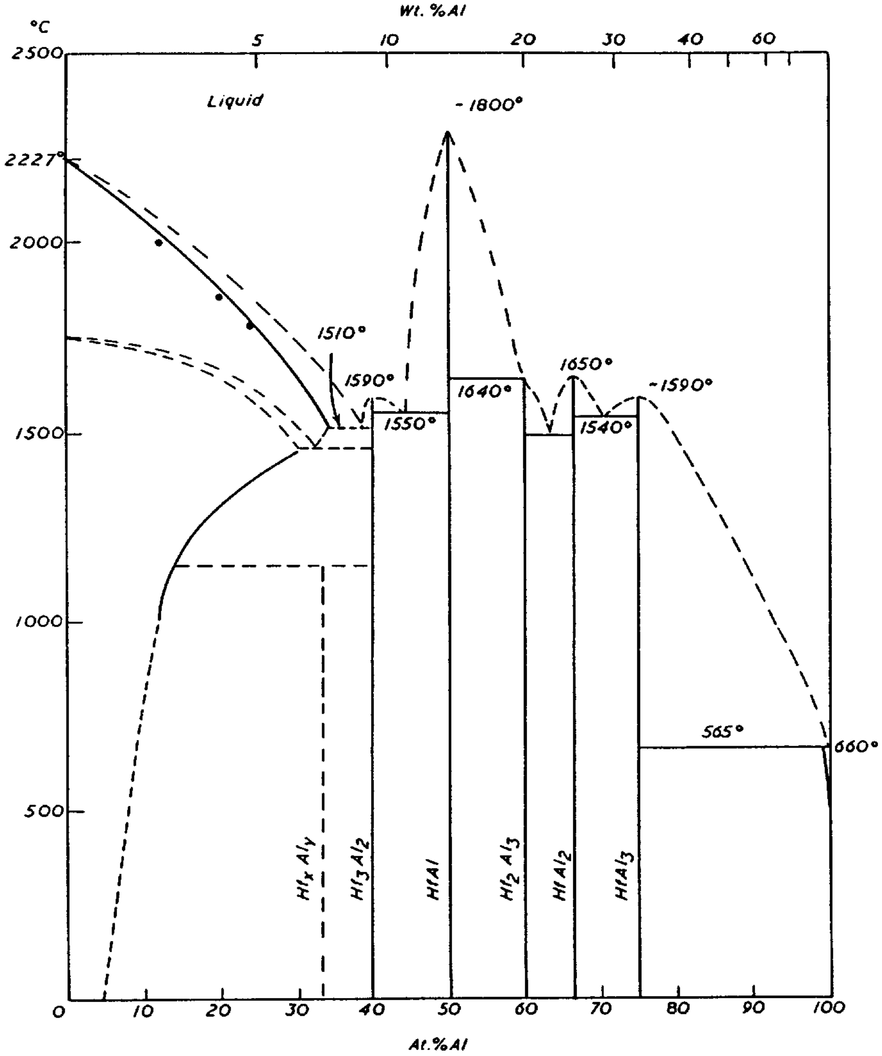
Al–Gd



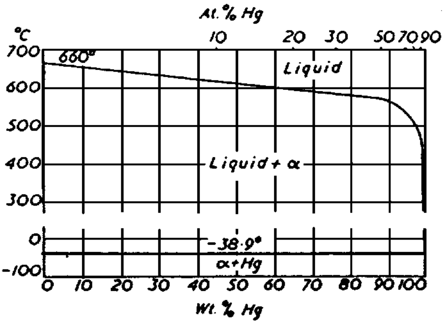
Al–Ge



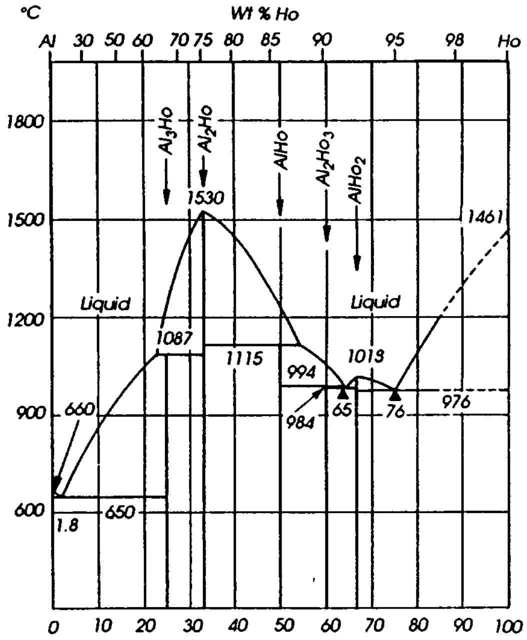
Al–Hf


Wt. % Al
°C
5
10
20
30
40
60
2500
Liquid
~1800°
2227°
2000
1510°
1590°
1650°
~1590°
1640°
1550°
1540°
1500
1000
565°
660°
500
Hf_xAl_y
Hf_3Al_2
HfAl
Hf_2Al_3
$HfAl_2$
$HfAl_3$
0
10
20
30
40
50
60
70
80
90
100
At. % Al

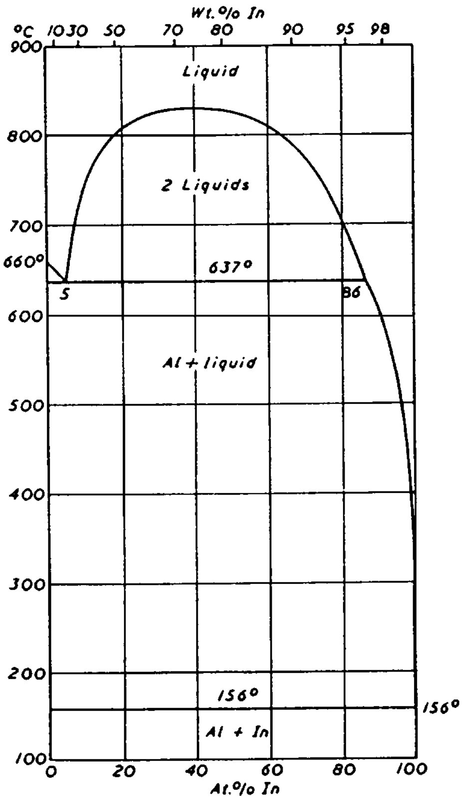
Al–Hg


At. % Hg
°C
10
20
30
50 70 90
700
660°
Liquid
600
500
400
Liquid + α
300
0
−38·9°
α+Hg
−100
0
10
20
30
40
50
60
70
80
90
100
Wt. % Hg

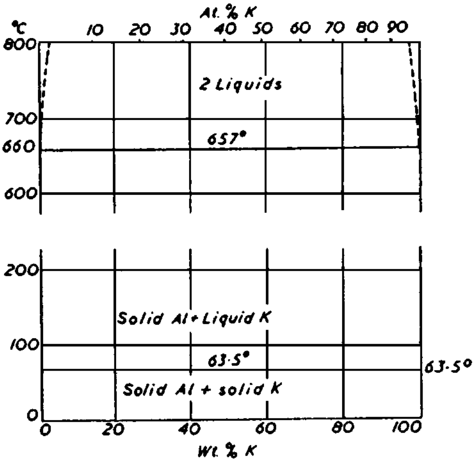
Al–Ho


°C
Wt % Ho
Al
30
50
60
70
75
80
85
90
95
98
Ho
1800
1500
1200
900
600
Al_3Ho
Al_2Ho
AlHo
Al_2Ho_3
$AlHo_2$
1530
1461
Liquid
Liquid
1087
1115
994
1013
660
984
65
76
976
650
1.8
0
10
20
30
40
50
60
70
80
90
100

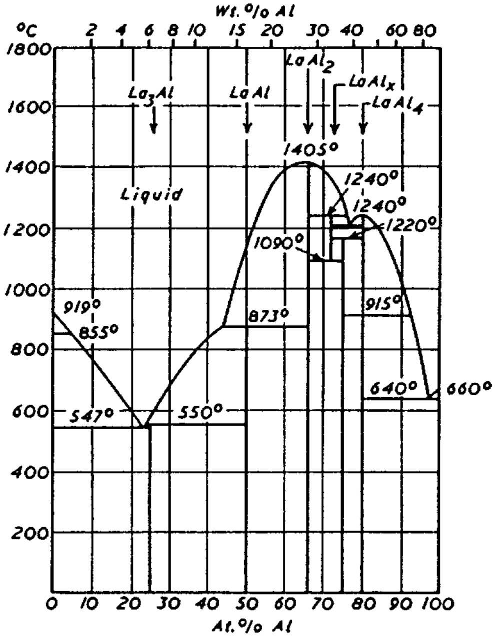
Al–In


Wt.% In
°C
10
30
50
70
80
90
95
98
900
800
700
660°
600
500
400
300
200
100
Liquid
2 Liquids
637°
5
86
Al + liquid
156°
156°
Al + In
0
20
40
60
80
100
At.% In

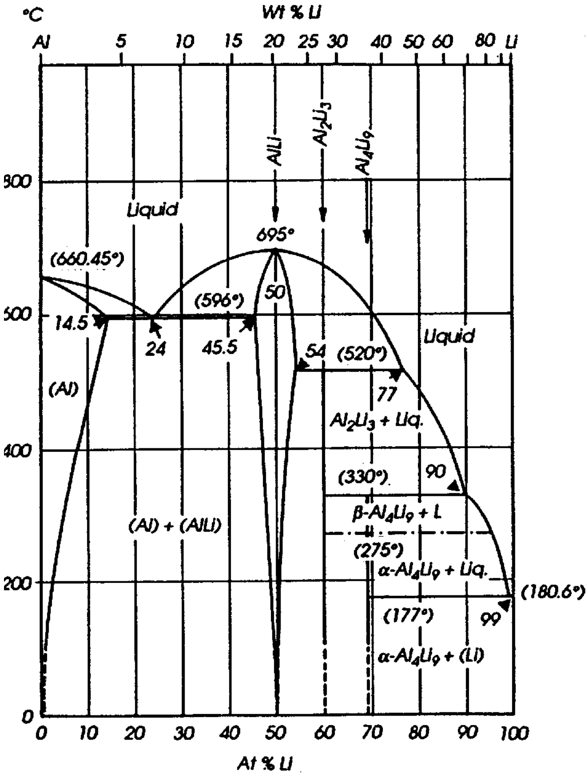
Al–K


At.% K
°C
10
20
30
40
50
60
70
80
90
800
700
660
600
2 Liquids
657°
200
100
0
Solid Al + Liquid K
63·5°
63·5°
Solid Al + solid K
0
20
40
60
80
100
Wt.% K

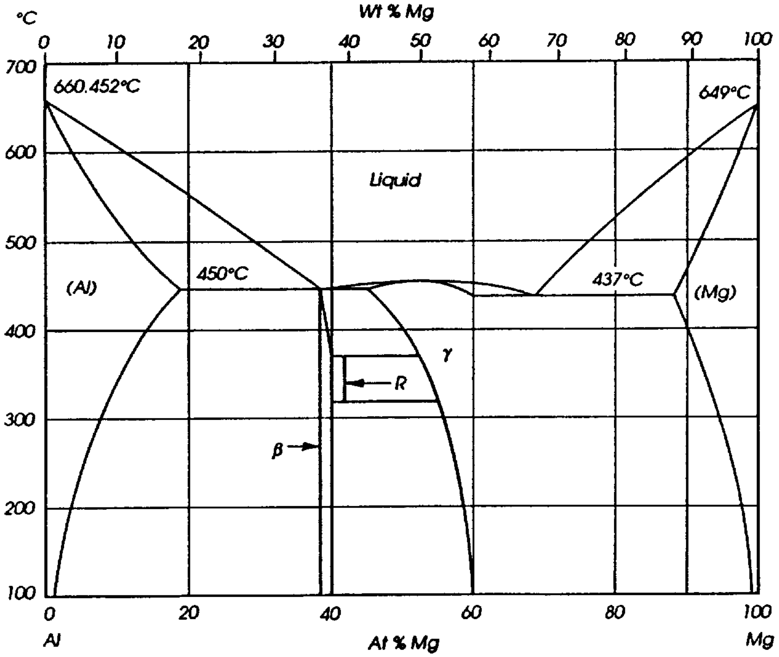
Al–La


Wt.% Al
°C
2
4
6
8
10
15
20
30
40
60
80
1800
1600
1400
1200
1000
800
600
400
200
La_3Al
LaAl
$LaAl_2$
$LaAl_x$
$LaAl_4$
1405°
Liquid
1240°
1240°
1220°
1090°
919°
855°
873°
915°
640°
660°
547°
550°
0
10
20
30
40
50
60
70
80
90
100
At.% Al

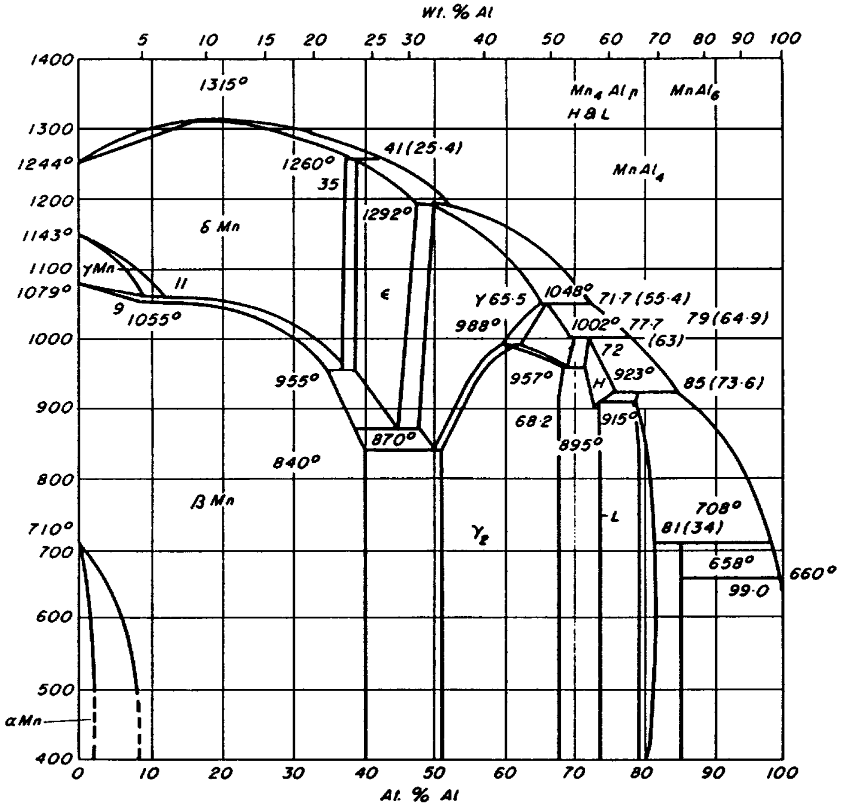
Al–Li


°C
Wt % Li
Al
5
10
15
20
25
30
40
50
60
80
Li
AlLi
Al2Li3
Al4Li9
800
600
400
200
0
Liquid
695°
(660.45°)
(596°)
50
14.5
24
45.5
54
(520°)
Liquid
77
(Al)
Al2Li3 + Liq.
(330°)
90
β-Al4Li9 + L
(Al) + (AlLi)
(275°)
α-Al4Li9 + Liq.
(180.6°)
(177°)
99
α-Al4Li9 + (Li)
0
10
20
30
40
50
60
70
80
90
100
At % Li

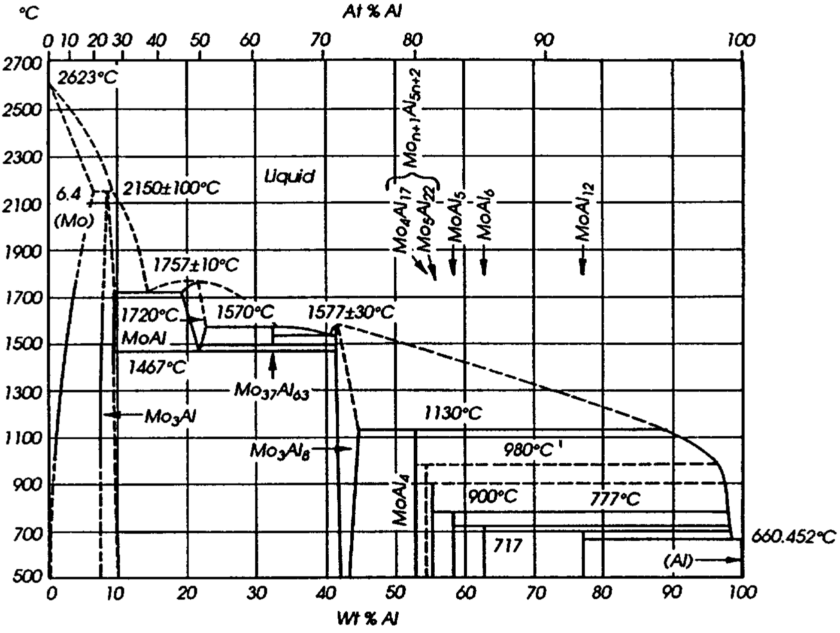
Al–Mg


°C
Wt % Mg
0
10
20
30
40
50
60
70
80
90
100
700
600
500
400
300
200
100
660.452°C
649°C
Liquid
450°C
437°C
(Al)
(Mg)
γ
R
β
0
20
40
60
80
100
Al
At % Mg
Mg

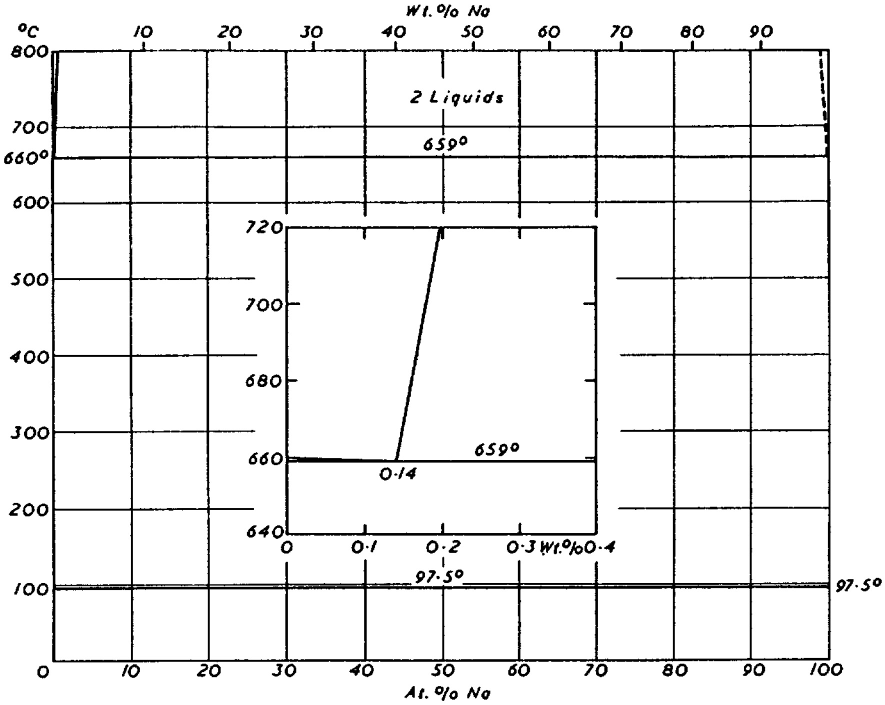
Al–Mn


Wt. % Al
5
10
15
20
25
30
40
50
60
70
80
90
100
1400
1300
1244°
1200
1143°
1100
1079°
1000
900
800
710°
700
600
500
400
1315°
Mn4 Al 11
H & L
MnAl6
41 (25·4)
1260°
35
MnAl4
1292°
δ Mn
γ Mn
11
9
1055°
ε
γ 65·5
1048°
71·7 (55·4)
988°
1002°
77·7
79 (64·9)
(63)
72
957°
923°
85 (73·6)
955°
H
68·2
915°
870°
895°
840°
β Mn
L
708°
81 (34)
γ2
658°
660°
99·0
α Mn
0
10
20
30
40
50
60
70
80
90
100
At. % Al

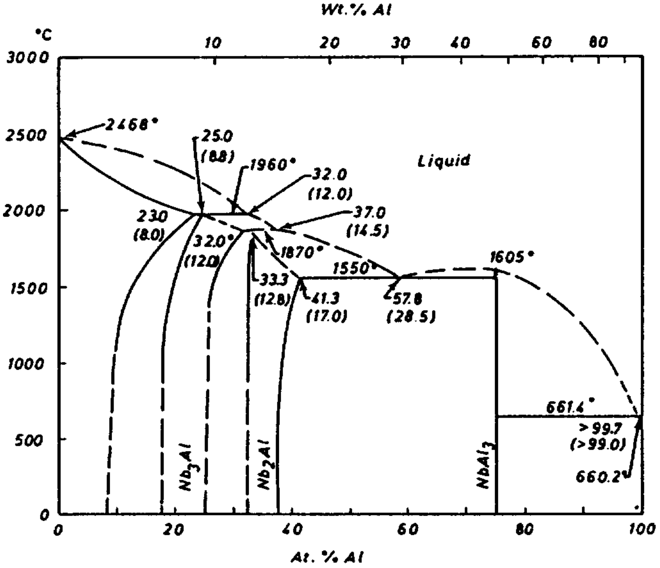
Al–Mo


°C
At % Al
0
10
20
30
40
50
60
70
80
90
100
2700
2500
2300
2100
1900
1700
1500
1300
1100
900
700
500
2623°C
6.4
(Mo)
2150±100°C
Liquid
Mon+1Al5n+2
Mo4Al17
Mo5Al22
MoAl5
MoAl6
MoAl12
1757±10°C
1720°C
1570°C
1577±30°C
MoAl
1467°C
Mo37Al63
Mo3Al
1130°C
Mo3Al8
980°C
MoAl4
900°C
777°C
717
660.452°C
(Al)
0
10
20
30
40
50
60
70
80
90
100
Wt % Al

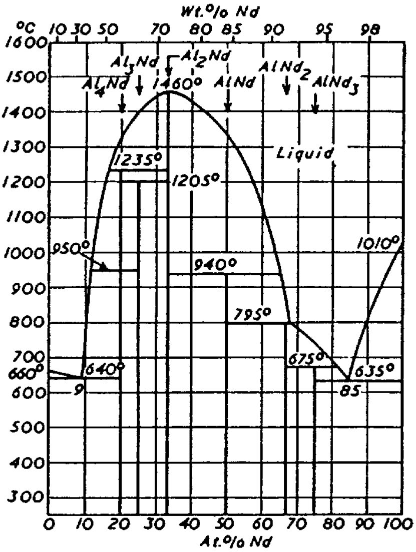
Al–Na


Wt.% Na
°C
10
20
30
40
50
60
70
80
90
800
700
660°
600
500
400
300
200
100
0
2 Liquids
659°
720
700
680
660
640
0
0·1
0·2
0·3 Wt.%
0·4
659°
0·14
97·5°
97·5°
0
10
20
30
40
50
60
70
80
90
100
At.% Na

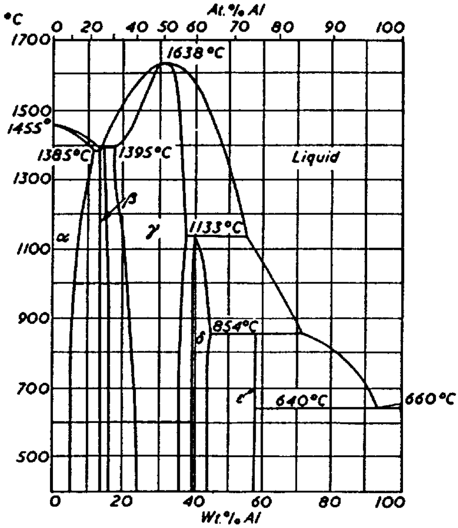
Al–Nb


Wt.% Al
°C
10
20
30
40
60
80
3000
2500
2000
1500
1000
500
0
2468°
25.0
(8.8)
1960°
32.0
(12.0)
37.0
(14.5)
Liquid
23.0
(8.0)
32.0°
(12.0)
1870°
1550°
1605°
33.3
(12.8)
41.3
(17.0)
57.8
(28.5)
661.4°
>99.7
(>99.0)
660.2°
Nb_3Al
Nb_2Al
$NbAl_3$
0
20
40
60
80
100
At.% Al

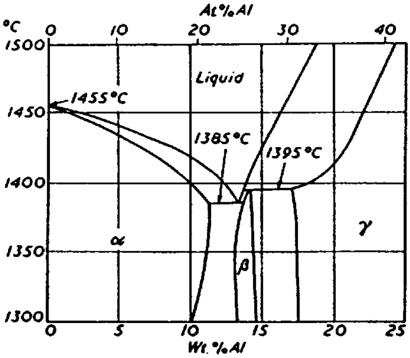
Al–Nd



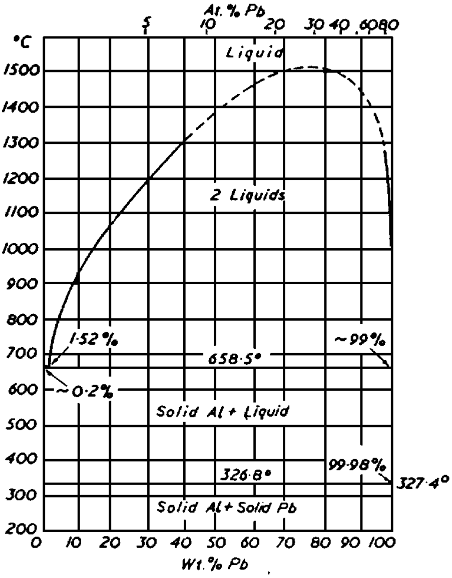
Al–Ni

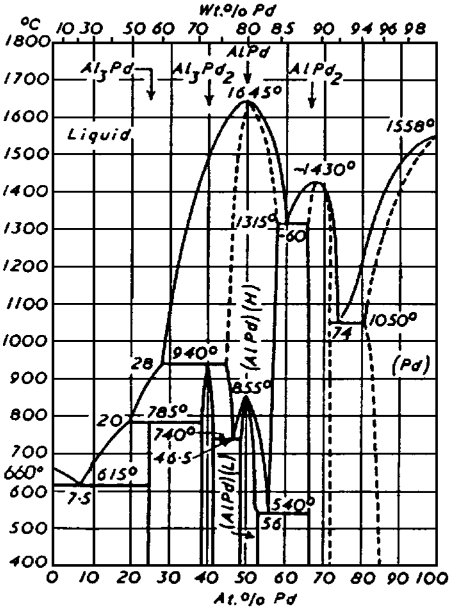


Al–Ni

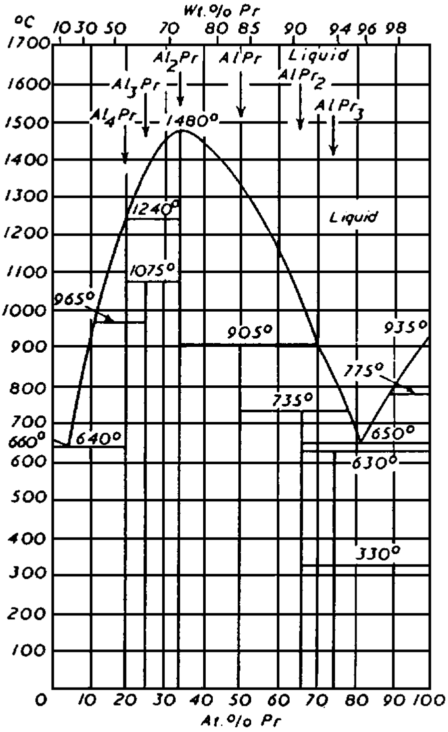


Al–Pb



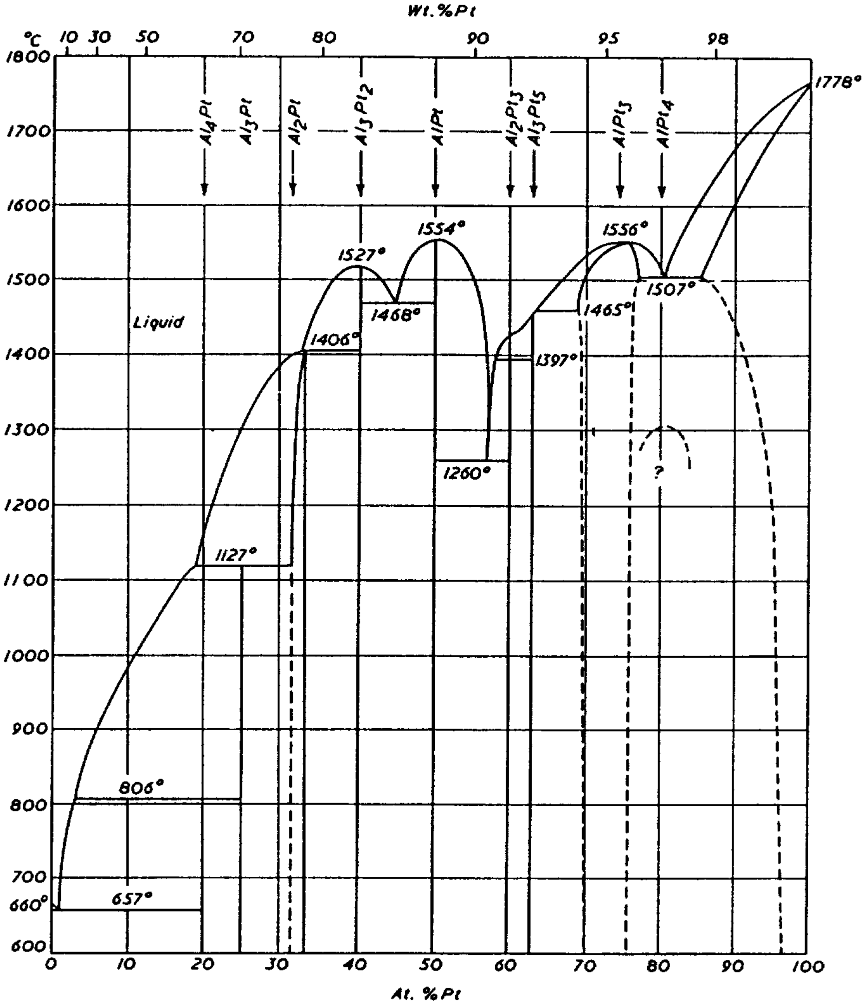

Wt.% Pd
°C
10 30 50 60 70 80 85 90 94 96 98
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
660°
600
500
400
AlPd
Al3Pd
Al3Pd2
AlPd2
1645°
Liquid
1558°
~1430°
1315°
60
(AlPd)(H)
1050°
74
(Pd)
940°
28
855°
785°
20
740°
46·5
615°
7·5
(AlPd)(L)
540°
56
0 10 20 30 40 50 60 70 80 90 100
At.% Pd

Al–Pd

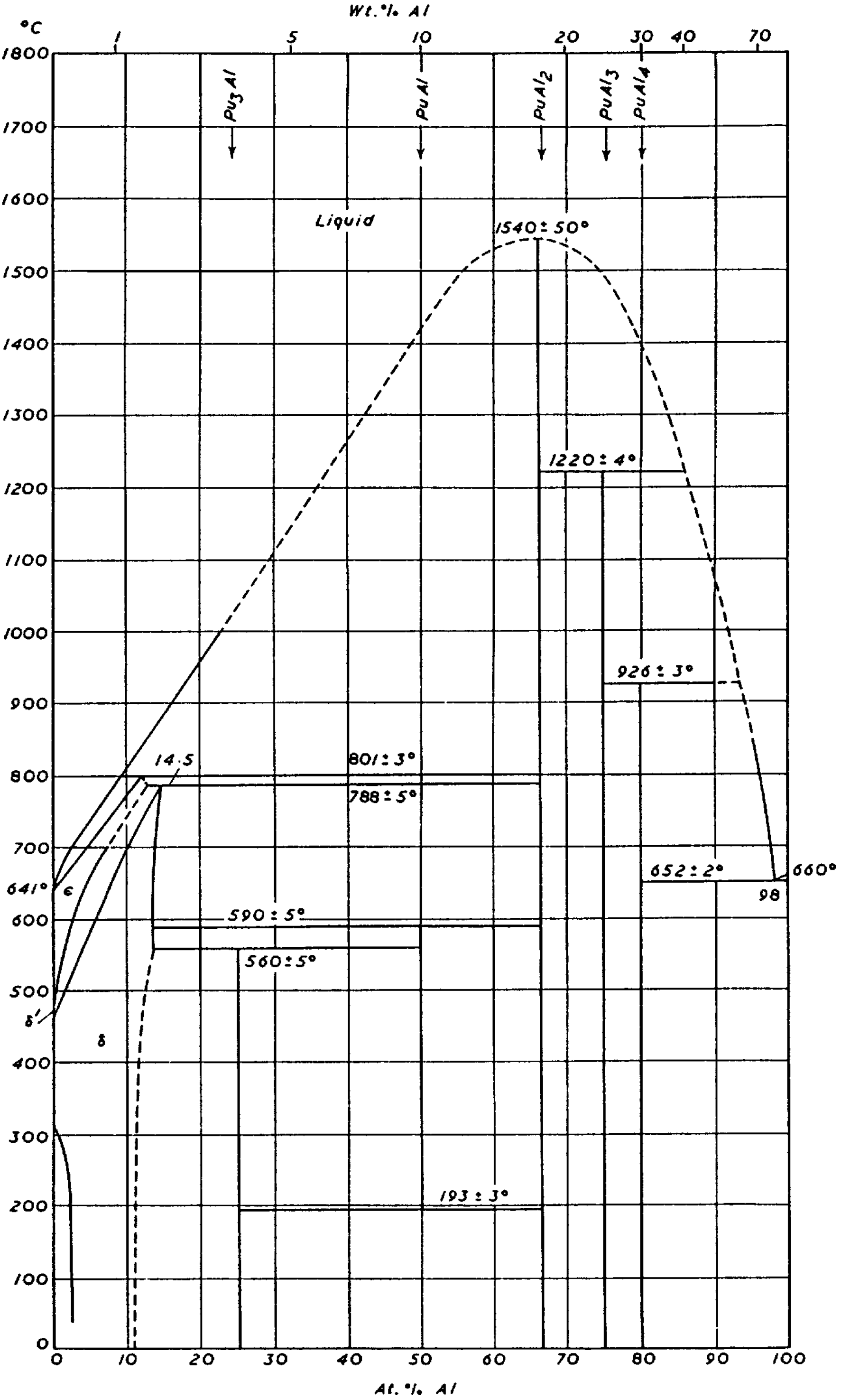

Wt.% Pr
°C
10 30 50 70 80 85 90 94 96 98
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
660°
600
500
400
300
200
100
Al2Pr
AlPr
Liquid
AlPr2
Al3Pr
Al4Pr
1480°
AlPr3
Liquid
1240°
1075°
965°
905°
935°
775°
735°
640°
650°
630°
330°
0 10 20 30 40 50 60 70 80 90 100
At.% Pr

Al–Pr

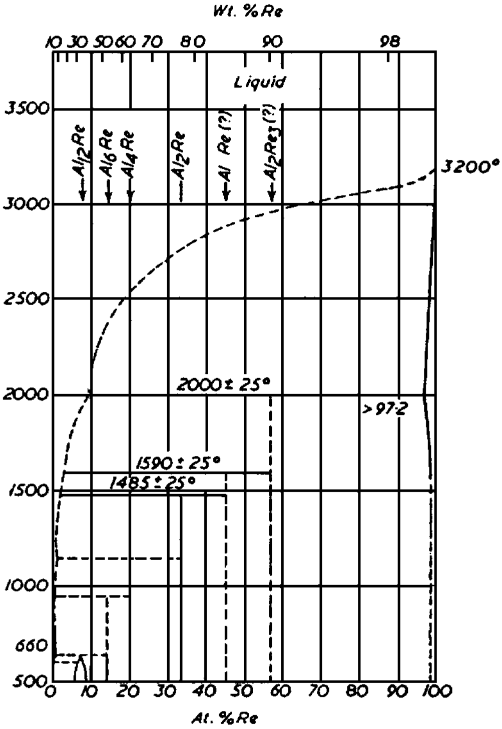
Al–Pt


Wt.%Pt
°C
10
30
50
70
80
90
95
98
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
660°
600
Al4Pt
Al3Pt
Al2Pt
Al3Pt2
AlPt
Al2Pt3
Al3Pt5
AlPt3
AlPt4
1778°
1554°
1556°
1527°
1507°
1468°
1465°
Liquid
1406°
1397°
1260°
?
1127°
806°
657°
0
10
20
30
40
50
60
70
80
90
100
At. %Pt

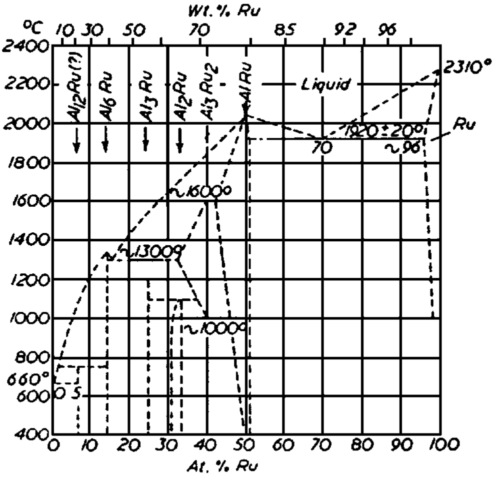
Al–Pu


°C
Wt.% Al
1
5
10
20
30
40
70
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
641°
600
500
400
300
200
100
0
Pu_3Al
PuAl
$PuAl_2$
$PuAl_3$
$PuAl_4$
Liquid
1540 ± 50°
1220 ± 4°
926 ± 3°
14·5
801 ± 3°
788 ± 5°
652 ± 2°
660°
98
ε
590 ± 5°
560 ± 5°
δ'
δ
193 ± 3°
0
10
20
30
40
50
60
70
80
90
100
At.% Al

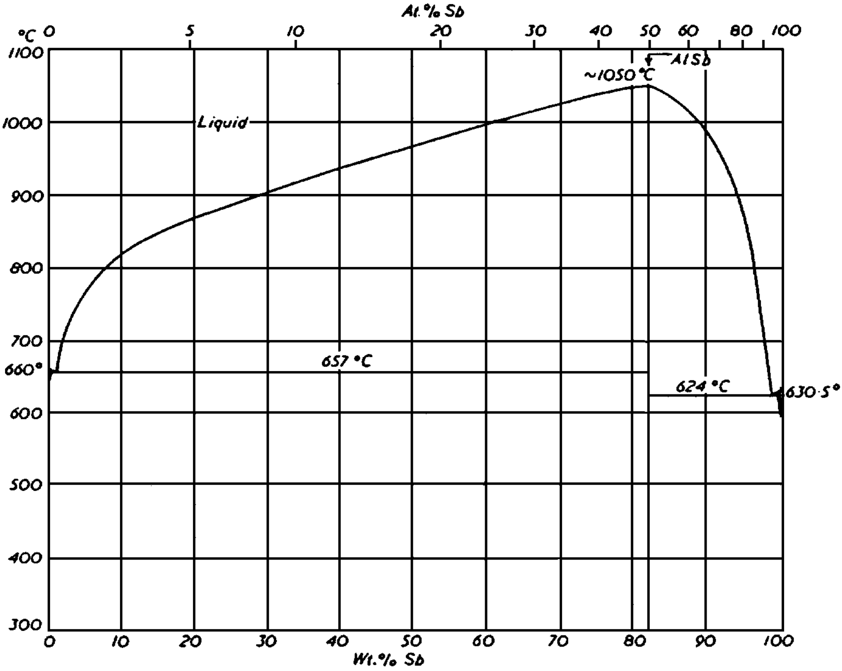
Al–Re


Wt. % Re
10 30 50 60 70 80 90 98
Liquid
3200°
Al12Re
Al6Re
Al4Re
Al2Re
Al Re (?)
Al2Re3 (?)
2000 ± 25°
>97·2
1590 ± 25°
1485 ± 25°
3500
3000
2500
2000
1500
1000
660
500
0 10 20 30 40 50 60 70 80 90 100
At. % Re

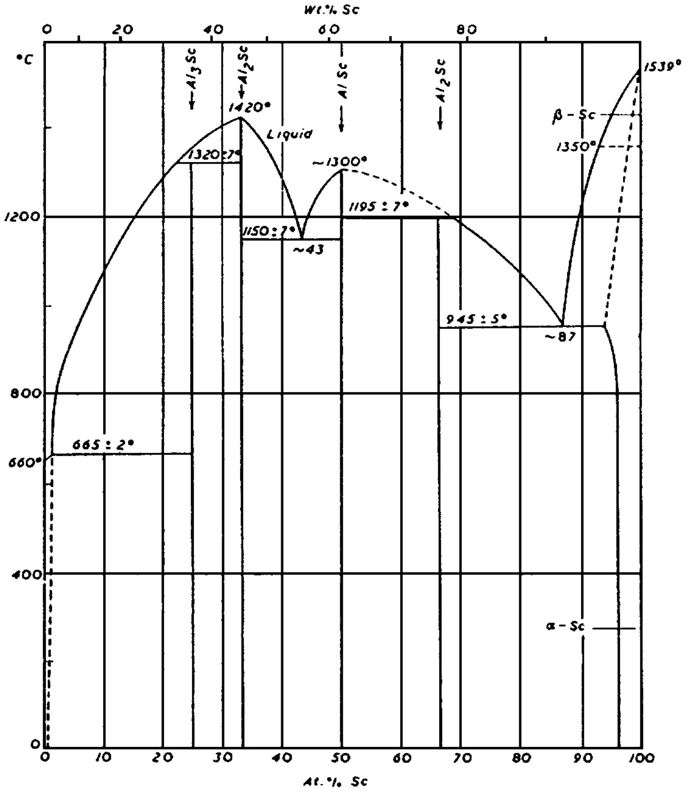
Al–Ru


Wt. % Ru
°C 10 30 50 70 85 92 96
Al12Ru (?)
Al6Ru
Al3Ru
Al2Ru
Al3Ru2
AlRu
Liquid
2310°
1920 ± 20°
Ru
70
~96
~1600°
~1300°
~1000°
0 5
2400
2200
2000
1800
1600
1400
1200
1000
800
660°
600
400
0 10 20 30 40 50 60 70 80 90 100
At. % Ru

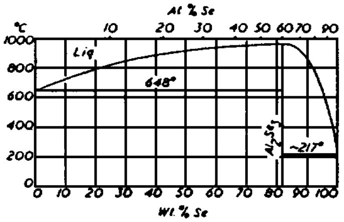
Al–Sb


At.% Sb
0
5
10
20
30
40
50
60
80
100
°C
1100
1000
900
800
700
660°
600
500
400
300
AlSb
~1050°C
Liquid
657 °C
624 °C
630·5°
0
10
20
30
40
50
60
70
80
90
100
Wt.% Sb

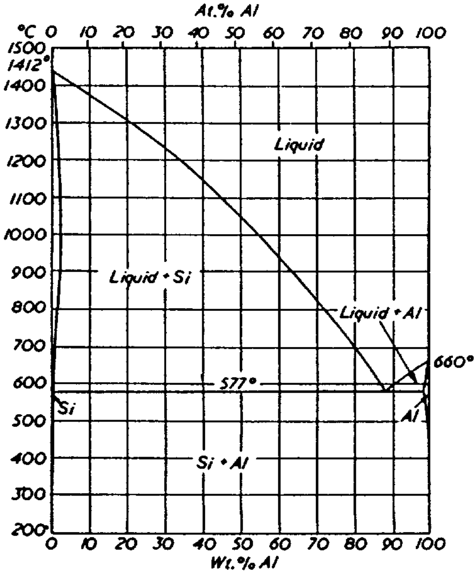
Al–Sc


Wt.% Sc
0
20
40
60
80
°C
Al3Sc
Al2Sc
AlSc
AlSc2
1420°
Liquid
1320 ± 7°
~1300°
1539°
β - Sc
1350°
1200
1195 ± 7°
1150 ± 7°
~43
945 ± 5°
~87
800
665 ± 2°
660°
400
α - Sc
0
0
10
20
30
40
50
60
70
80
90
100
At.% Sc

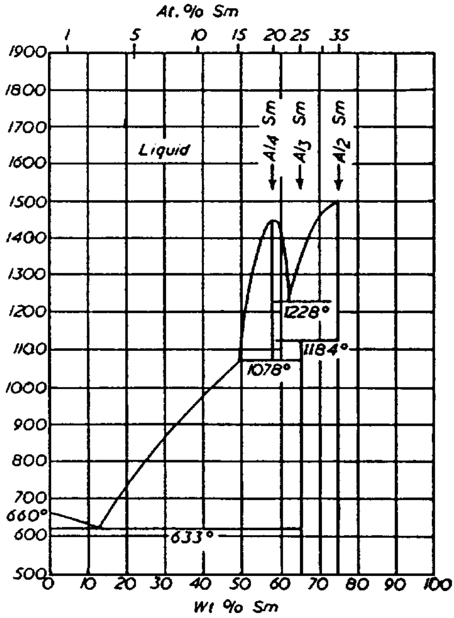
Al–Se



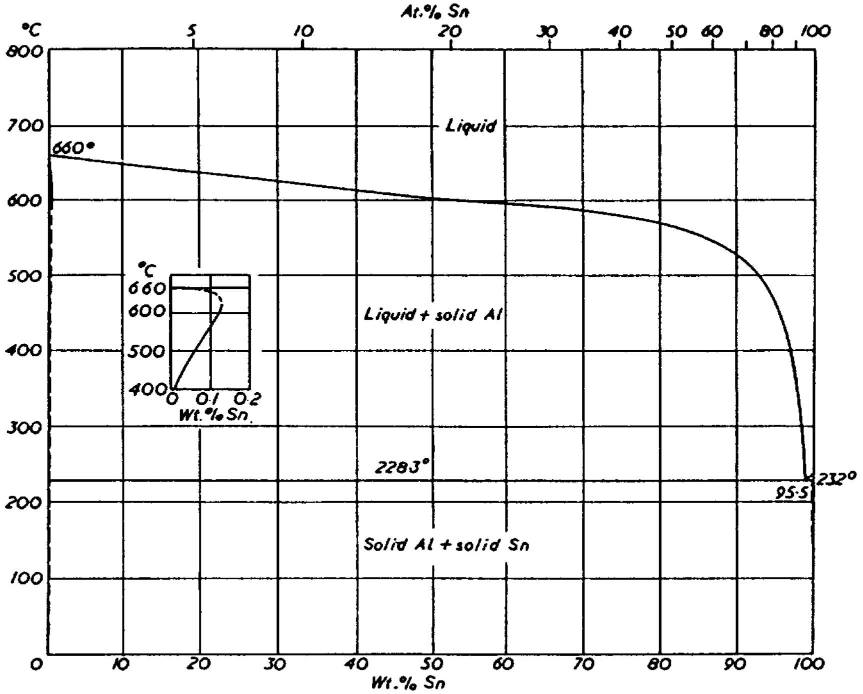
Al–Si



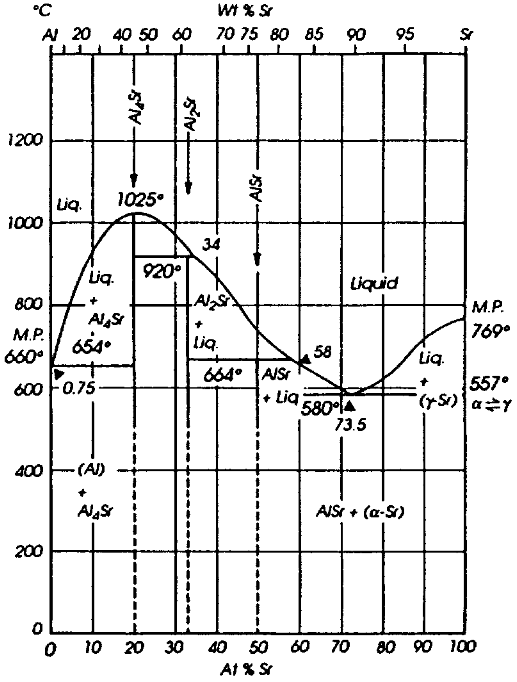
Al–Sm



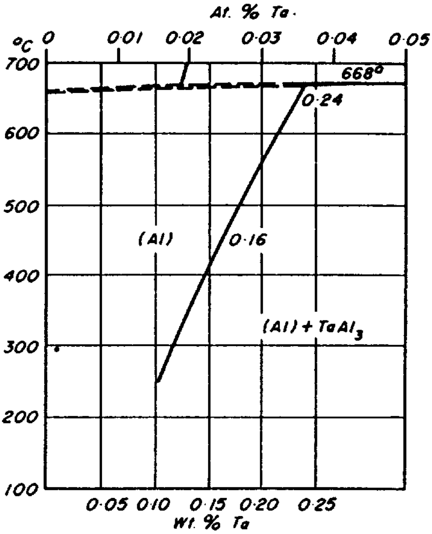
Al–Sn


At.% Sn
°C
5
10
20
30
40
50
60
80
100
800
700
600
500
400
300
200
100
0
Liquid
660°
°C
660
600
500
400
0
0.1
0.2
Wt.% Sn.
Liquid + solid Al
228.3°
232°
95.5
Solid Al + solid Sn
10
20
30
40
50
60
70
80
90
100
Wt.% Sn

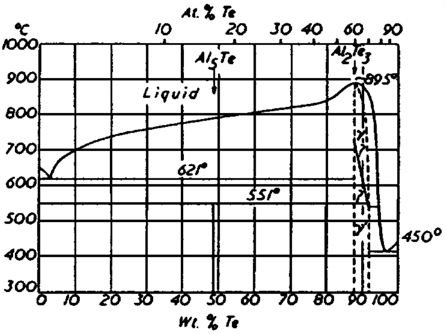
Al–Sr


°C
Wt % Sr
Al
20
40
50
60
70
75
80
85
90
95
Sr
1200
1000
800
600
400
200
0
Al4Sr
Al2Sr
AlSr
Liq.
1025°
920°
34
Liq. + Al4Sr
654°
M.P. 660°
0.75
Al2Sr + Liq.
664°
AlSr + Liq
58
580°
73.5
Liquid
M.P. 769°
Liq. + (γ-Sr)
557°
α ⇌ γ
(Al) + Al4Sr
AlSr + (α-Sr)
0
10
20
30
40
50
60
70
80
90
100
At % Sr

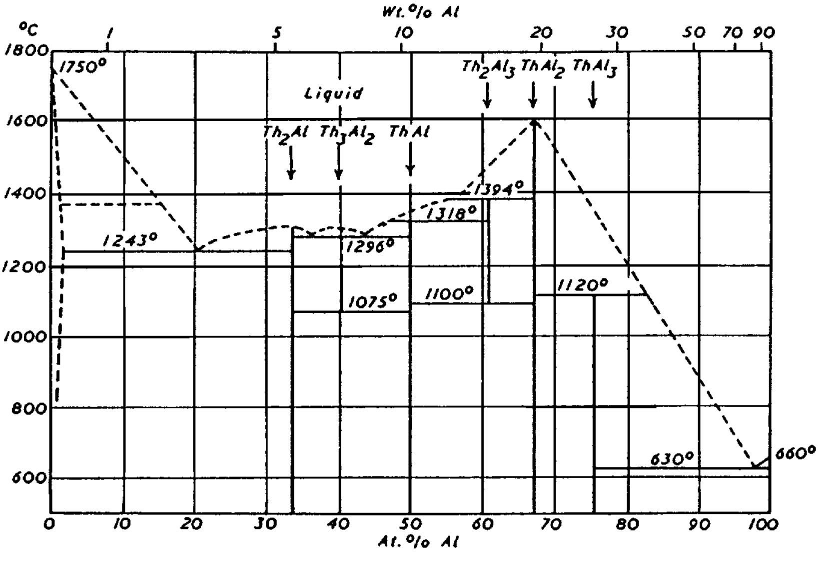
Al–Ta



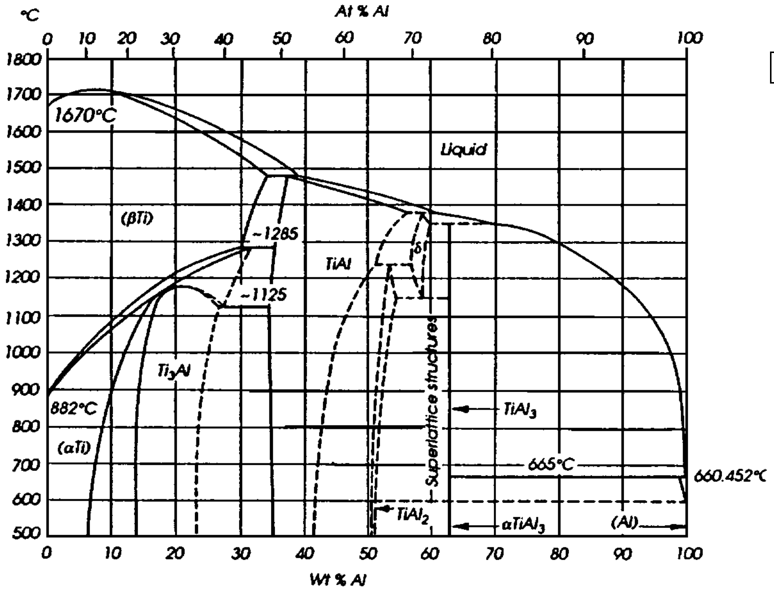
Al–Te



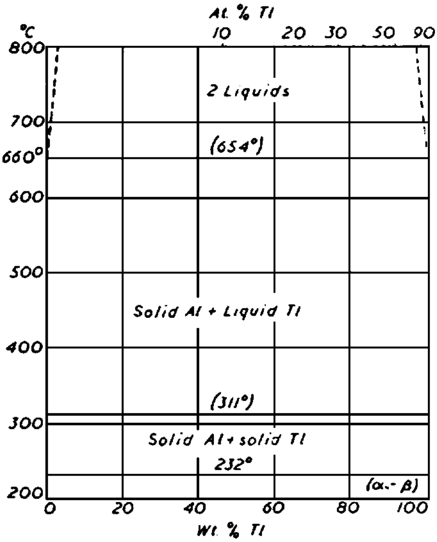
Al–Th



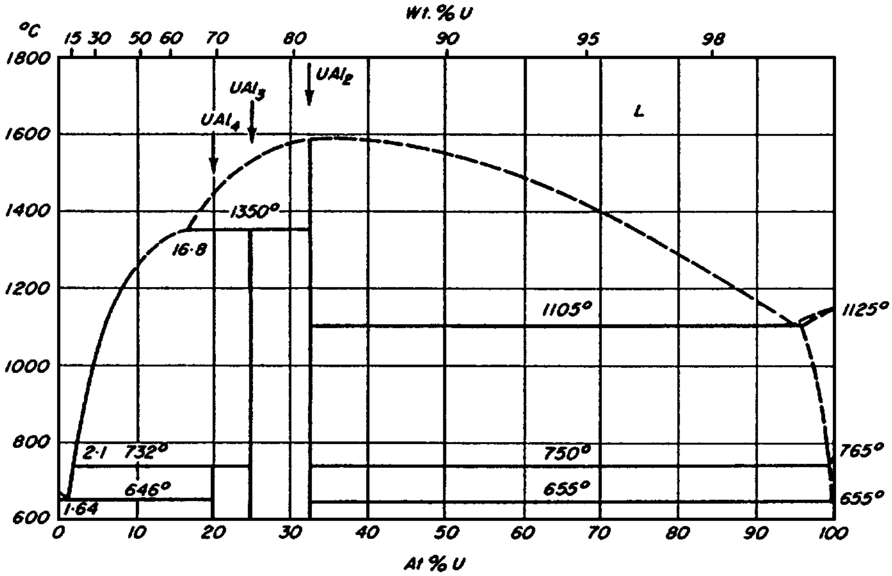
Al–Ti


°C
At % Al
0 10 20 30 40 50 60 70 80 90 100
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
1670°C
Liquid
(βTi)
~1285
TiAl
~1125
δ
Ti_3Al
882°C
(αTi)
Superlattice structures
$TiAl_3$
665°C
660.452°C
$TiAl_2$
$\alpha TiAl_3$
(Al)
0 10 20 30 40 50 60 70 80 90 100
Wt % Al

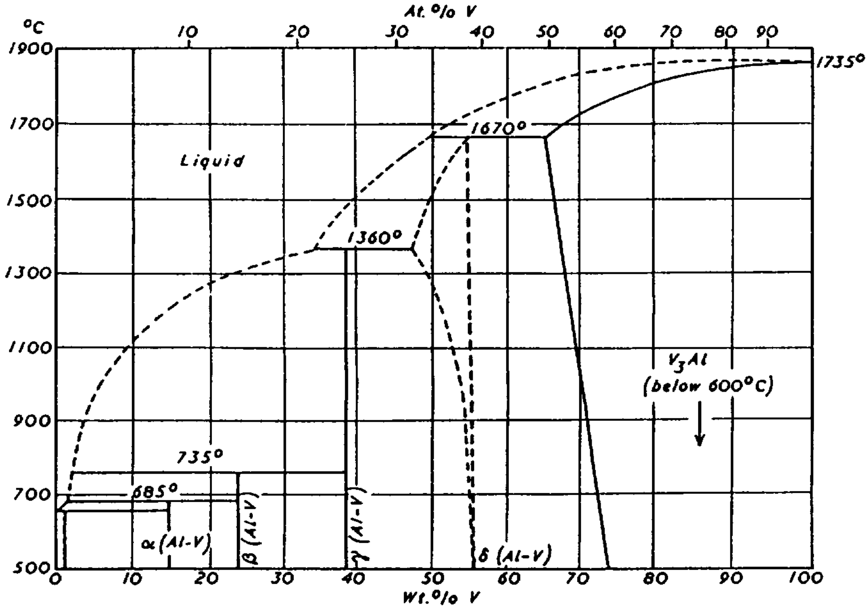
Al–Tl


At. % Tl
10 20 30 50 90
°C
800
700
660°
600
500
400
300
200
2 Liquids
(654°)
Solid Al + Liquid Tl
(311°)
Solid Al + solid Tl
232°
(α - β)
0 20 40 60 80 100
Wt. % Tl

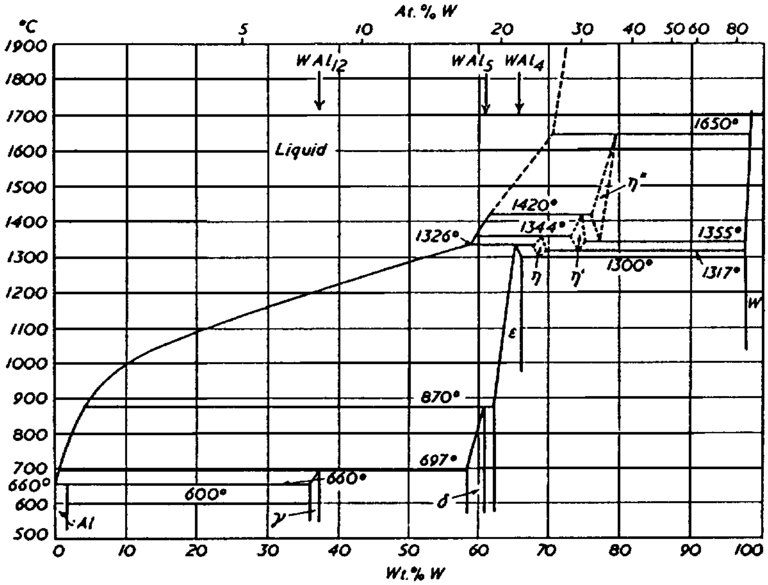
Al–U


Wt.% U
°C
15
30
50
60
70
80
90
95
98
1800
1600
1400
1200
1000
800
600
UAl$_2$
UAl$_3$
UAl$_4$
L
1350°
16·8
1105°
1125°
2·1
732°
750°
765°
646°
655°
1·64
655°
0
10
20
30
40
50
60
70
80
90
100
At % U

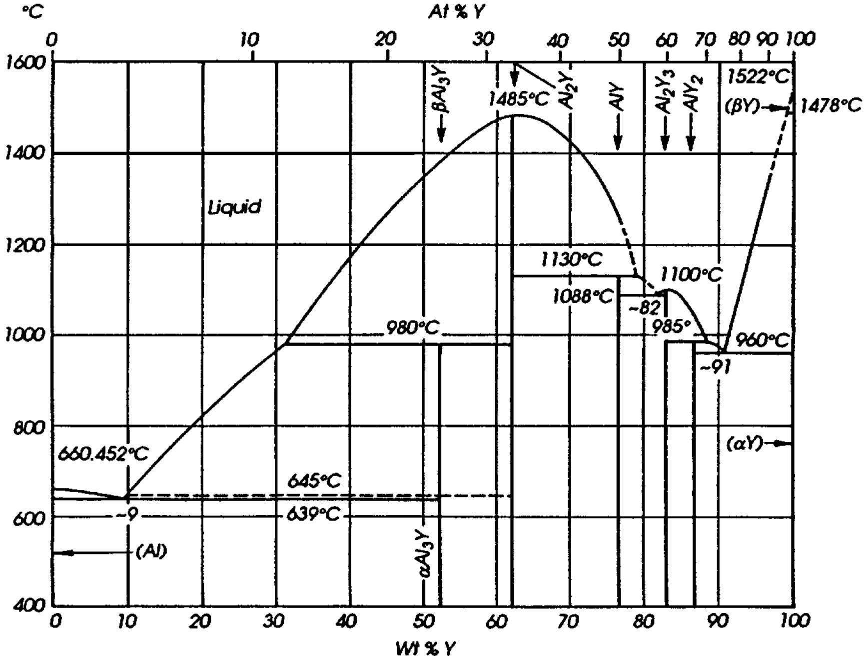
Al–V


At. % V
10
20
30
40
50
60
70
80
90
°C
1900
1700
1500
1300
1100
900
700
500
1735°
1670°
Liquid
1360°
V$_3$Al
(below 600°C)
735°
685°
α (Al-V)
β (Al-V)
γ (Al-V)
δ (Al-V)
0
10
20
30
40
50
60
70
80
90
100
Wt. % V

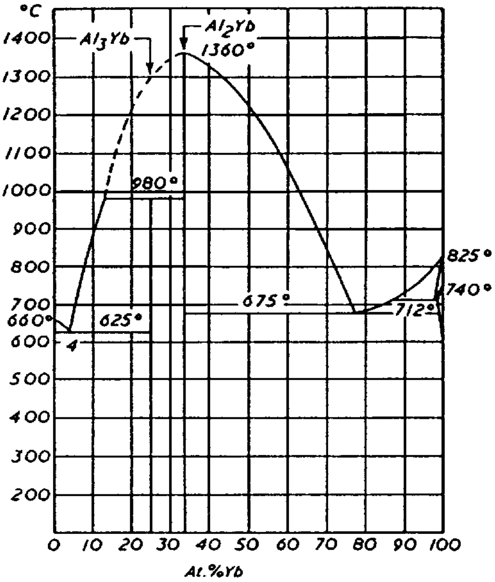
Al–W


At. % W
5
10
20
30
40
50
60
80
°C
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
660°
600
500
WAl12
WAl5
WAl4
Liquid
1650°
1420°
1344°
1326°
1355°
1300°
1317°
η″
η
η′
ε
W
870°
697°
660°
600°
δ
γ
Al
0
10
20
30
40
50
60
70
80
90
100
Wt.% W

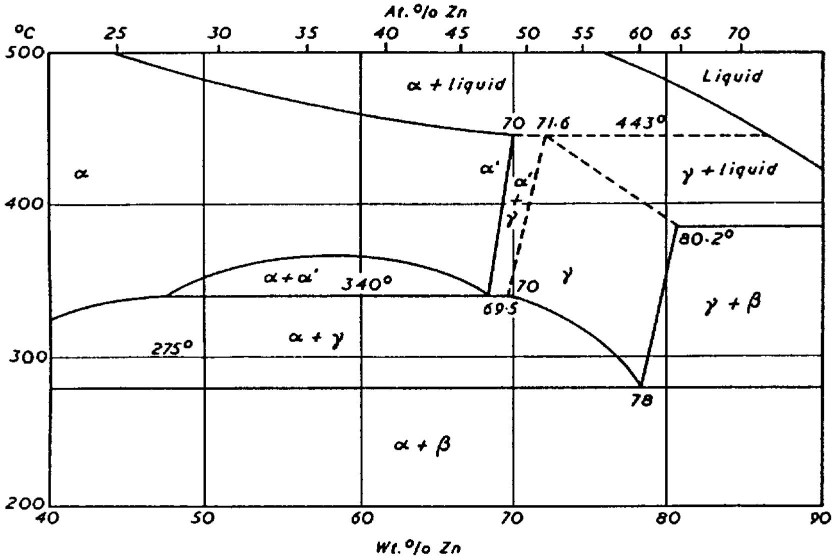
Al–Y

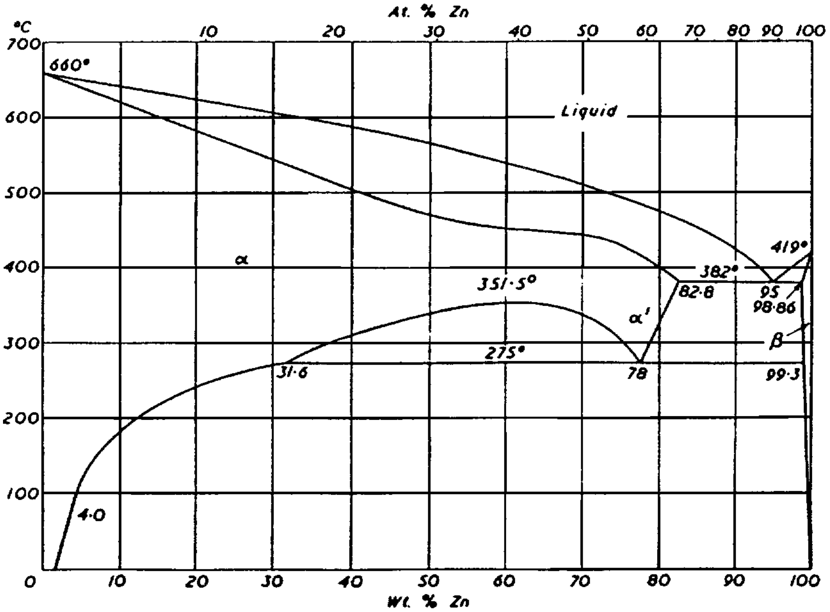

°C
At % Y
0
10
20
30
40
50
60
70
80
90
100
1600
1400
1200
1000
800
600
400
βAl3Y
1485°C
Al2Y
AlY
Al2Y3
AlY2
1522°C
(βY)
1478°C
Liquid
1130°C
1100°C
1088°C
~82
985°
980°C
960°C
~91
(αY)
660.452°C
645°C
~9
639°C
(Al)
αAl3Y
0
10
20
30
40
50
60
70
80
90
100
Wt % Y

Al–Yb

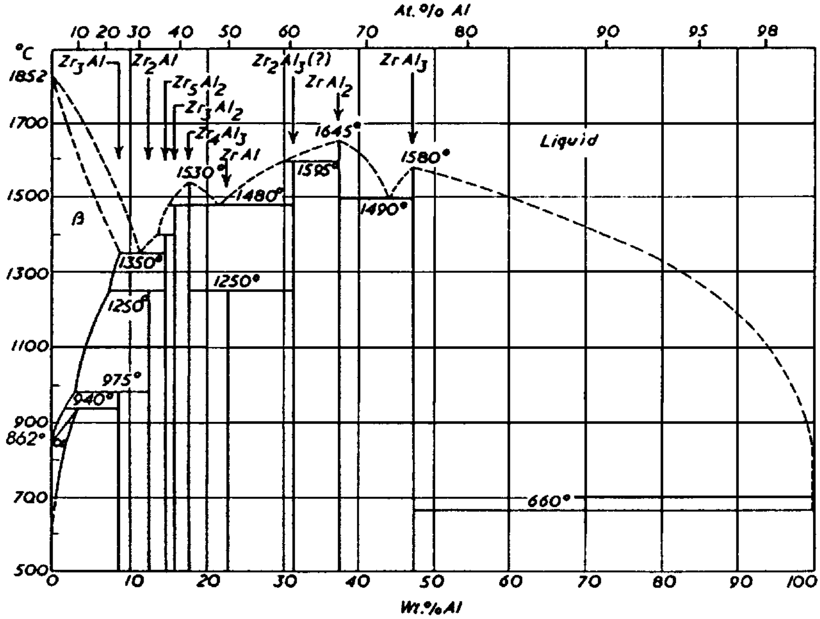

°C
1400
1300
1200
1100
1000
900
800
700
660°
600
500
400
300
200
Al3Yb
Al2Yb
1360°
980°
825°
740°
675°
712°
625°
4
0 10 20 30 40 50 60 70 80 90 100
At.%Yb

Al–Zn


At.% Zn
25 30 35 40 45 50 55 60 65 70
°C
500
400
300
200
α + liquid
Liquid
70 71·6
443°
α
α'
α' + γ
γ + liquid
80·2°
α + α'
340°
70
γ
69·5
γ + β
275°
α + γ
78
α + β
40 50 60 70 80 90
Wt.% Zn

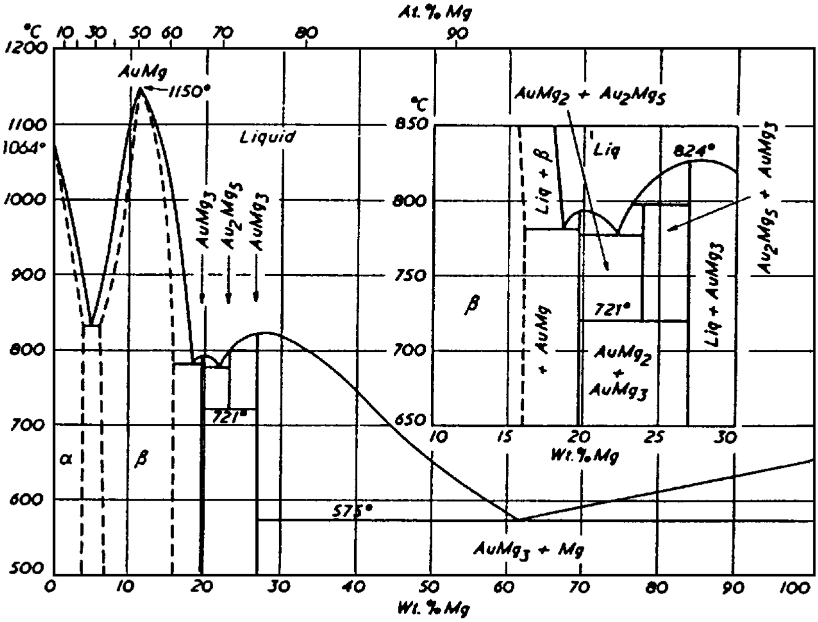

At. % Zn
10
20
30
40
50
60
70
80
90
100
°C
700
600
500
400
300
200
100
0
660°
Liquid
α
419°
382°
351·5°
82·8
95
98·86
α′
β
275°
31·6
78
99·3
4·0
10
20
30
40
50
60
70
80
90
100
Wt. % Zn

Al–Zn

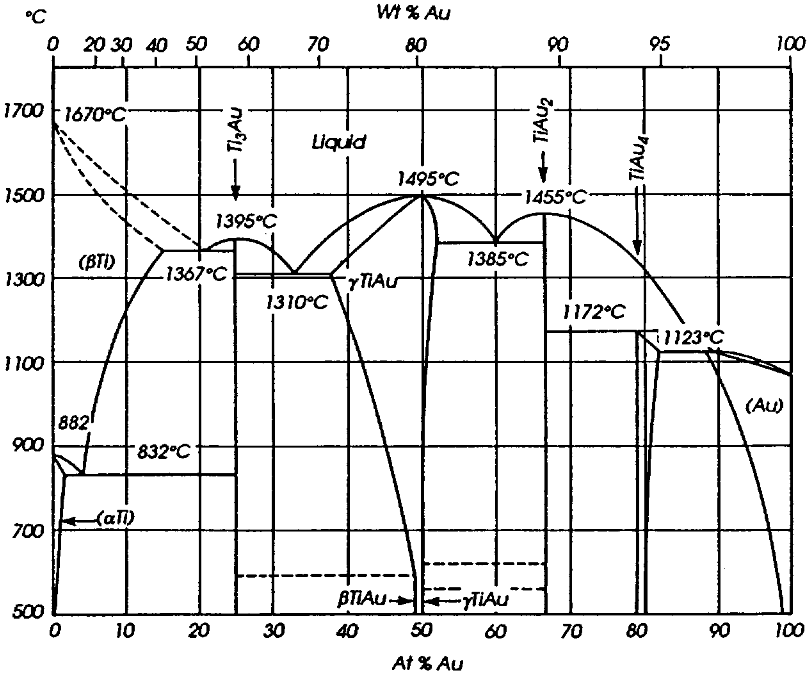

At.% Al
10
20
30
40
50
60
70
80
90
95
98
°C
1852
1700
1500
1300
1100
900
862°
700
500
Zr₃Al
Zr₂Al
Zr₅Al₂
Zr₃Al₂
Zr₄Al₃
ZrAl
Zr₂Al₃(?)
ZrAl₂
ZrAl₃
1645°
1580°
Liquid
1530°
1595°
1480°
1490°
β
1350°
1250°
1250°
975°
940°
α
660°
0
10
20
30
40
50
60
70
80
90
100
Wt.%Al

Al–Zr

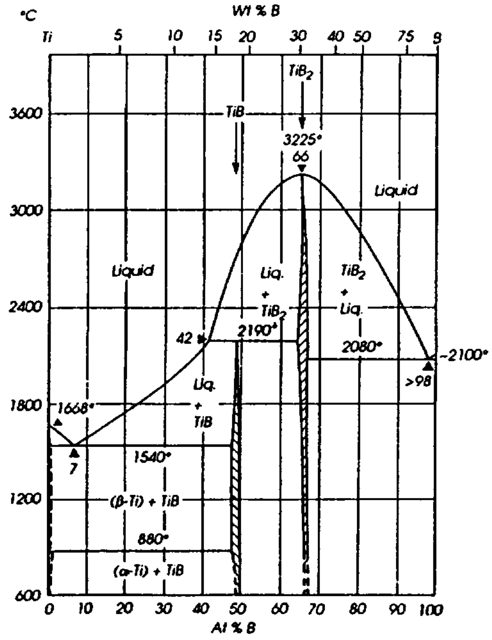
Au–Mg


At.% Mg
°C
10
30
50
60
70
80
90
1200
1100
1064°
1000
900
800
700
600
500
AuMg
1150°
Liquid
AuMg$_3$
Au$_2$Mg$_5$
AuMg$_3$
721°
575°
α
β
AuMg$_3$ + Mg
0
10
20
30
40
50
60
70
80
90
100
Wt.% Mg
°C
850
800
750
700
650
AuMg$_2$ + Au$_2$Mg$_5$
Liq + β
Liq
824°
Au$_2$Mg$_5$ + AuMg$_3$
β
+ AuMg
721°
AuMg$_2$ + AuMg$_3$
Liq + AuMg$_3$
10
15
20
25
30
Wt.% Mg

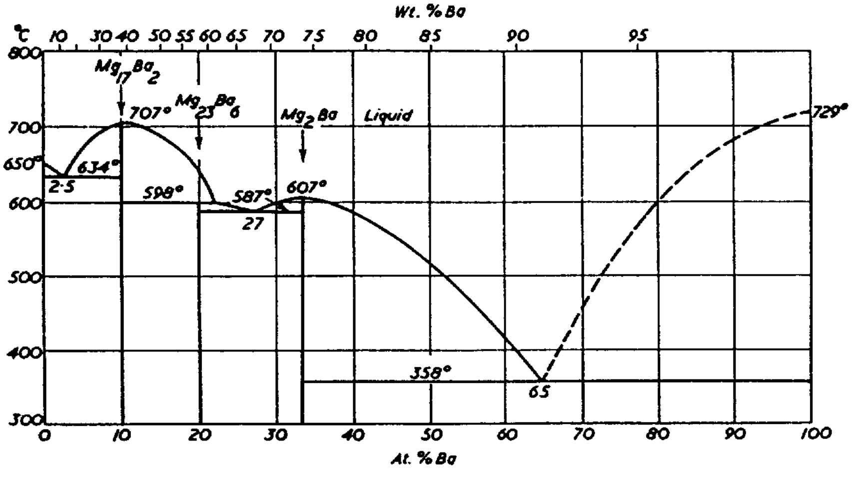
Au–Ti


°C
Wt % Au
0
20
30
40
50
60
70
80
90
95
100
1700
1500
1300
1100
900
700
500
1670°C
Ti$_3$AU
Liquid
1495°C
TiAU$_2$
1455°C
TiAU$_4$
1395°C
(βTi)
1367°C
1310°C
γTiAu
1385°C
1172°C
1123°C
(Au)
882
832°C
(αTi)
βTiAu
γTiAu
0
10
20
30
40
50
60
70
80
90
100
At % Au

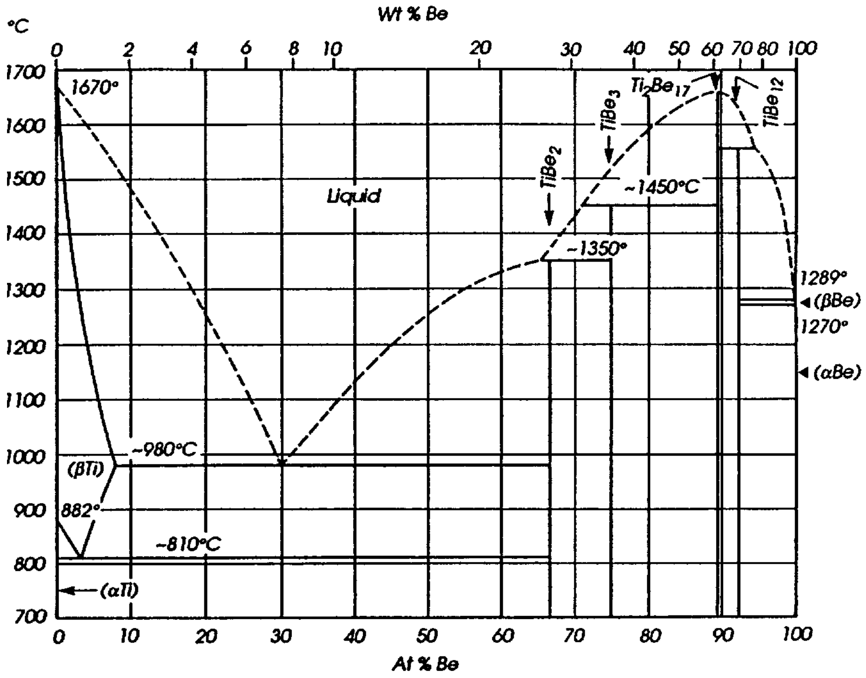
B–Ti


°C
Wt % B
Ti
5
10
15
20
30
40
50
75
B
3600
3000
2400
1800
1200
600
TiB$_2$
TiB
3225°
66
Liquid
Liquid
Liq. + TiB$_2$
TiB$_2$ + Liq.
42
2190°
2080°
~2100°
>98
1668°
7
Liq. + TiB
1540°
(β-Ti) + TiB
880°
(α-Ti) + TiB
0
10
20
30
40
50
60
70
80
90
100
At % B

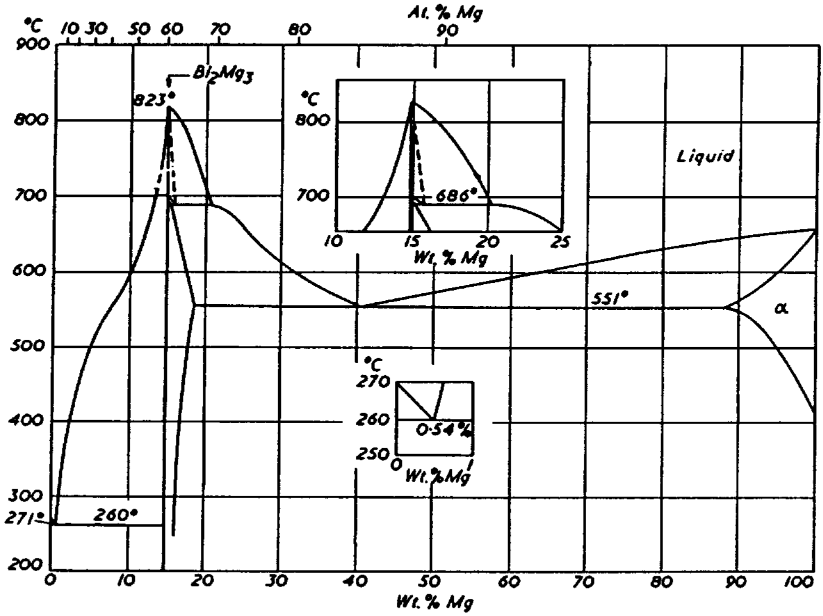
Ba–Mg


Wt. % Ba
°C
10
30
40
50
55
60
65
70
75
80
85
90
95
800
700
650°
600
500
400
300
Mg$_{17}$Ba$_2$
707°
Mg$_{23}$Ba$_6$
Mg$_2$Ba
Liquid
729°
634°
2·5
598°
587°
27
607°
358°
65
0
10
20
30
40
50
60
70
80
90
100
At. % Ba

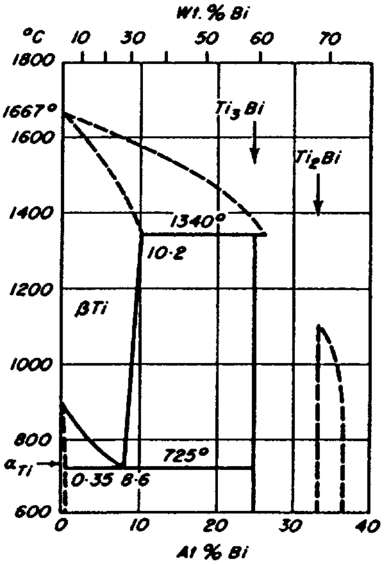
Be–Ti


Wt % Be
°C
0
2
4
6
8
10
20
30
40
50
60
70
80
100
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
1670°
Liquid
TiBe2
TiBe3
Ti2Be17
TiBe12
~1450°C
~1350°
1289°
(βBe)
1270°
(αBe)
~980°C
(βTi)
882°
~810°C
(αTi)
0
10
20
30
40
50
60
70
80
90
100
At % Be

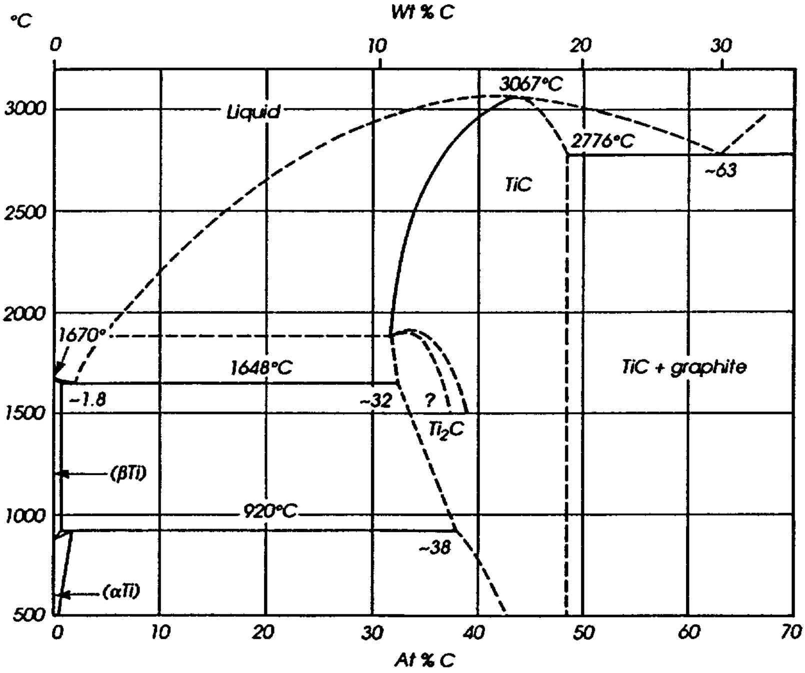
Bi–Mg


At. % Mg
°C
10
30
50
60
70
80
90
900
800
700
600
500
400
300
271°
200
Bi2Mg3
823°
260°
°C
800
700
686°
10
15
20
25
Wt. % Mg
Liquid
551°
α
°C
270
260
250
0·54%
0
1
Wt.%Mg
0
10
20
30
40
50
60
70
80
90
100
Wt. % Mg

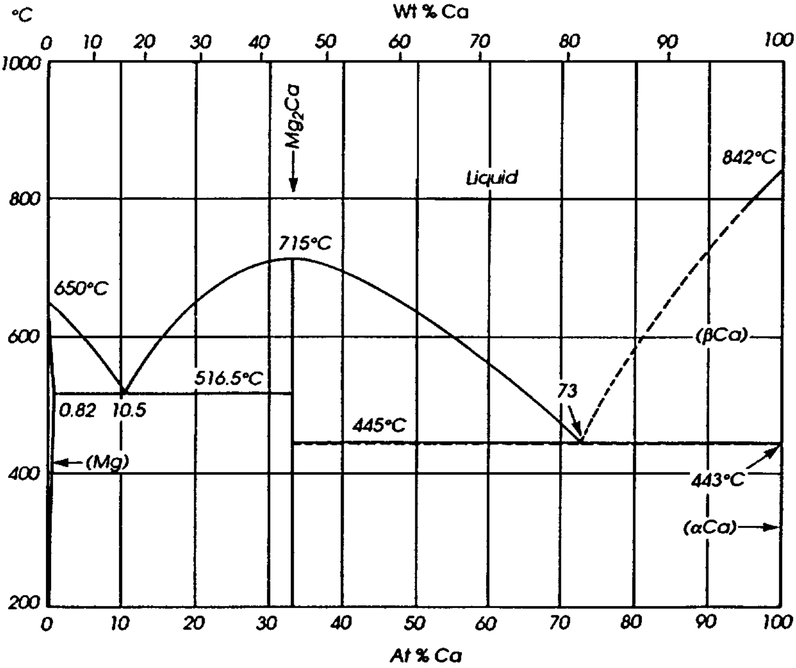
Bi–Ti


Wt.% Bi
°C
10
30
50
60
70
1800
1667°
1600
1400
1200
1000
800
α_{Ti}
600
Ti_3Bi
Ti_2Bi
1340°
10·2
βTi
725°
0·35
8·6
0
10
20
30
40
At % Bi

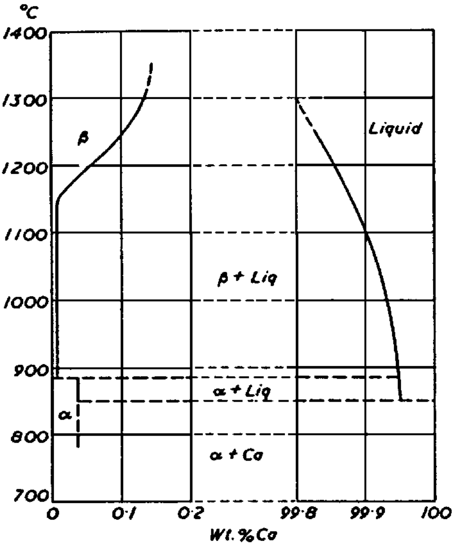
C–Ti


Wt % C
°C
0
10
20
30
3000
2500
2000
1500
1000
500
3067°C
Liquid
2776°C
~63
TiC
1670°
1648°C
TiC + graphite
~1.8
~32
?
Ti_2C
(βTi)
920°C
~38
(αTi)
0
10
20
30
40
50
60
70
At % C

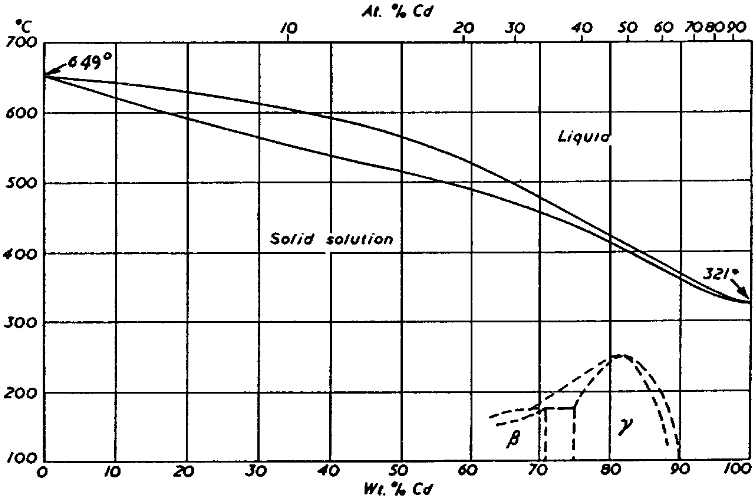
Ca–Mg


°C
Wt % Ca
0
10
20
30
40
50
60
70
80
90
100
1000
800
600
400
200
Mg2Ca
Liquid
842°C
715°C
650°C
(βCa)
516.5°C
73
0.82
10.5
445°C
(Mg)
443°C
(αCa)
0
10
20
30
40
50
60
70
80
90
100
At % Ca

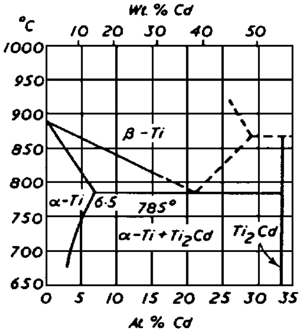
Ca–Ti


°C
1400
1300
1200
1100
1000
900
800
700
β
Liquid
β + Liq
α + Liq
α
α + Ca
0
0·1
0·2
99·8
99·9
100
Wt.% Ca

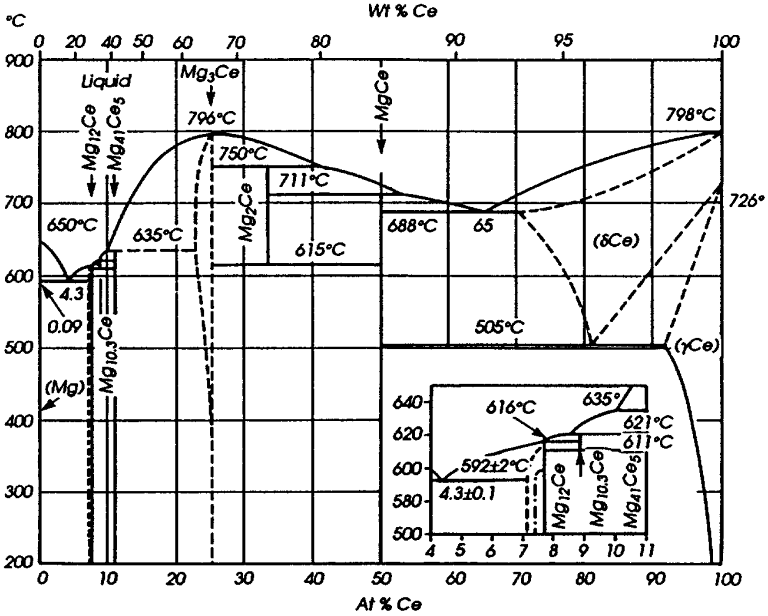
Cd–Mg



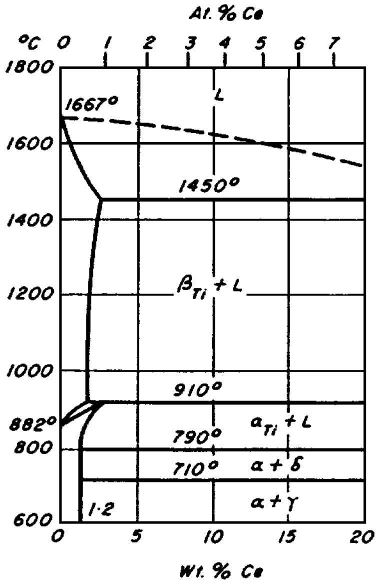
Cd–Ti



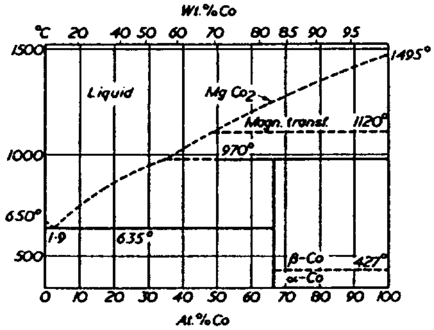
Ce–Mg



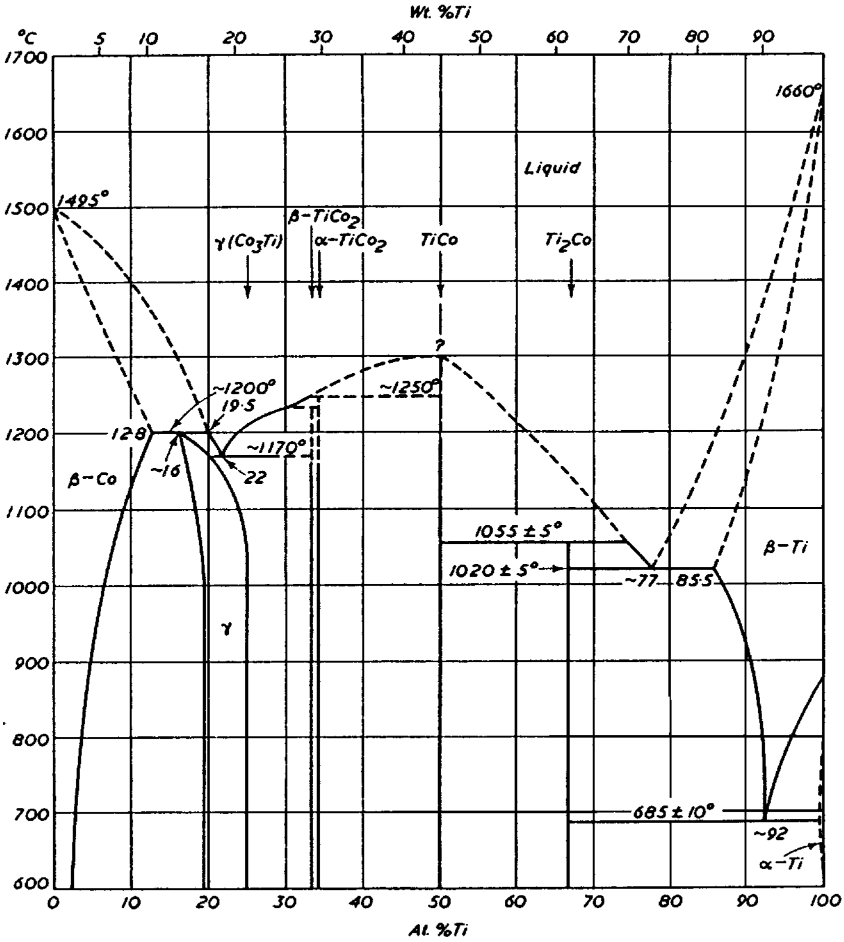
Ce–Ti


At. % Ce
°C
0
1
2
3
4
5
6
7
1800
1600
1400
1200
1000
882°
800
600
1667°
L
1450°
β_{Ti} + L
910°
α_{Ti} + L
790°
710°
α + δ
α + γ
1·2
0
5
10
15
20
Wt. % Ce

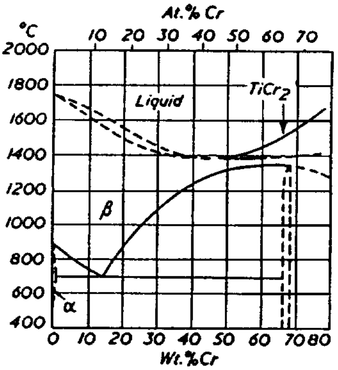
Co–Mg


Wt.% Co
°C
20
40
50
60
70
80
85
90
95
1500
1000
650°
500
1495°
Liquid
Mg Co2
Magn. transf.
1120°
970°
1·9
635°
β-Co
427°
α-Co
0
10
20
30
40
50
60
70
80
90
100
At.% Co

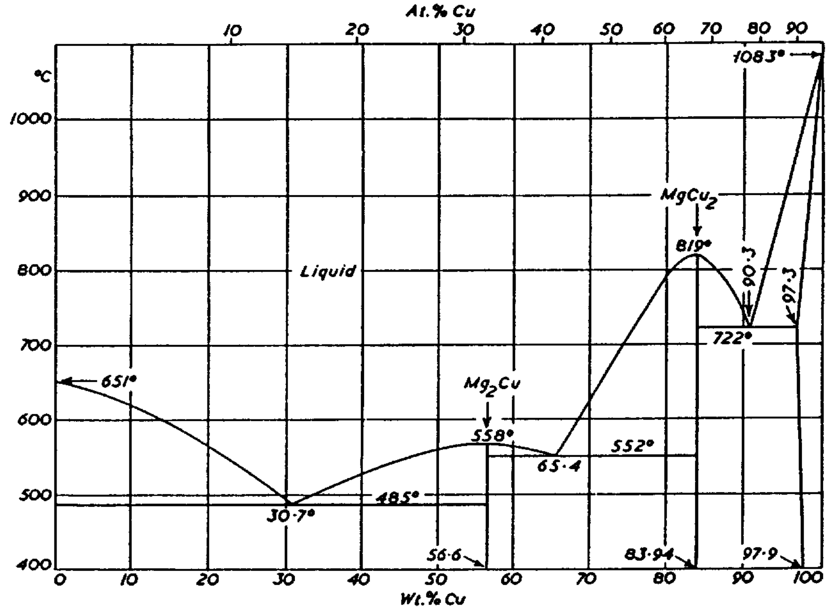
Co–Ti


Wt. %Ti
°C
5
10
20
30
40
50
60
70
80
90
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
1660°
Liquid
1495°
β-TiCo₂
γ(Co₃Ti)
α-TiCo₂
TiCo
Ti₂Co
?
~1200°
19·5
~1250°
12·8
~1170°
~16
22
β-Co
1055 ± 5°
1020 ± 5°
~77
85·5
β-Ti
γ
685 ± 10°
~92
α-Ti
0
10
20
30
40
50
60
70
80
90
100
At. %Ti

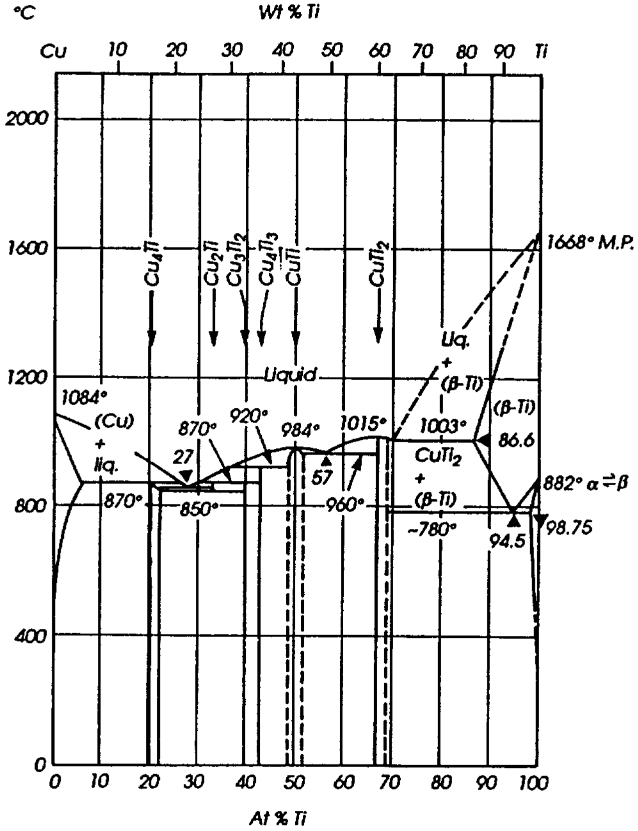
Cr–Ti

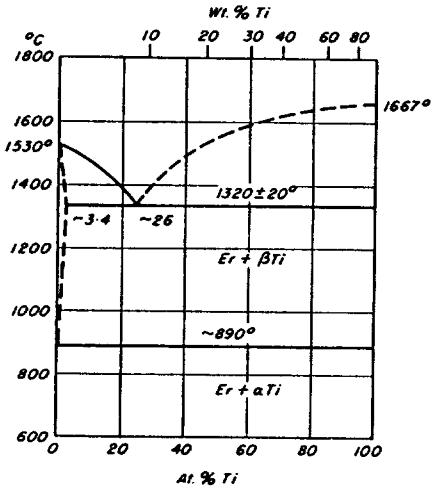

At.% Cr
°C
10
20
30
40
50
60
70
2000
1800
1600
1400
1200
1000
800
600
400
Liquid
TiCr₂
β
α
0
10
20
30
40
50
60
70
80
Wt.%Cr

Cu–Mg

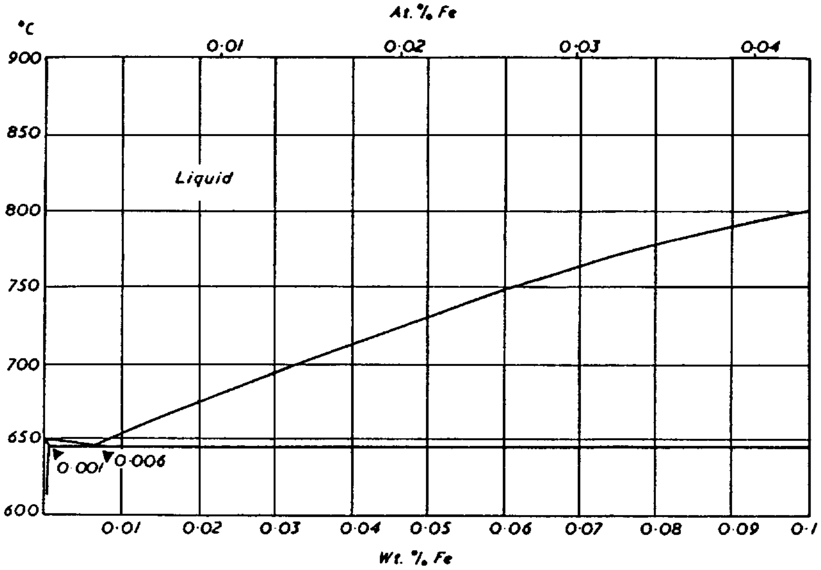

At.% Cu
10
20
30
40
50
60
70
80
90
°C
1000
900
800
700
600
500
400
1083°
MgCu2
819°
90.3
97.3
Liquid
722°
651°
Mg2Cu
558°
552°
65.4
485°
30.7°
56.6
83.94
97.9
0
10
20
30
40
50
60
70
80
90
100
Wt.% Cu

Cu–Ti


°C
Wt % Ti
Cu
10
20
30
40
50
60
70
80
90
Ti
2000
1600
1200
800
400
0
Cu4Ti
Cu2Ti
Cu3Ti2
Cu4Ti3
CuTi
CuTi2
1668° M.P.
Liq.
+
(β-Ti)
Liquid
1084°
(Cu)
+
liq.
870°
920°
984°
1015°
1003°
(β-Ti)
86.6
27
57
CuTi2
+
(β-Ti)
870°
850°
960°
882° α ⇌ β
~780°
94.5
98.75
0
10
20
30
40
50
60
70
80
90
100
At % Ti

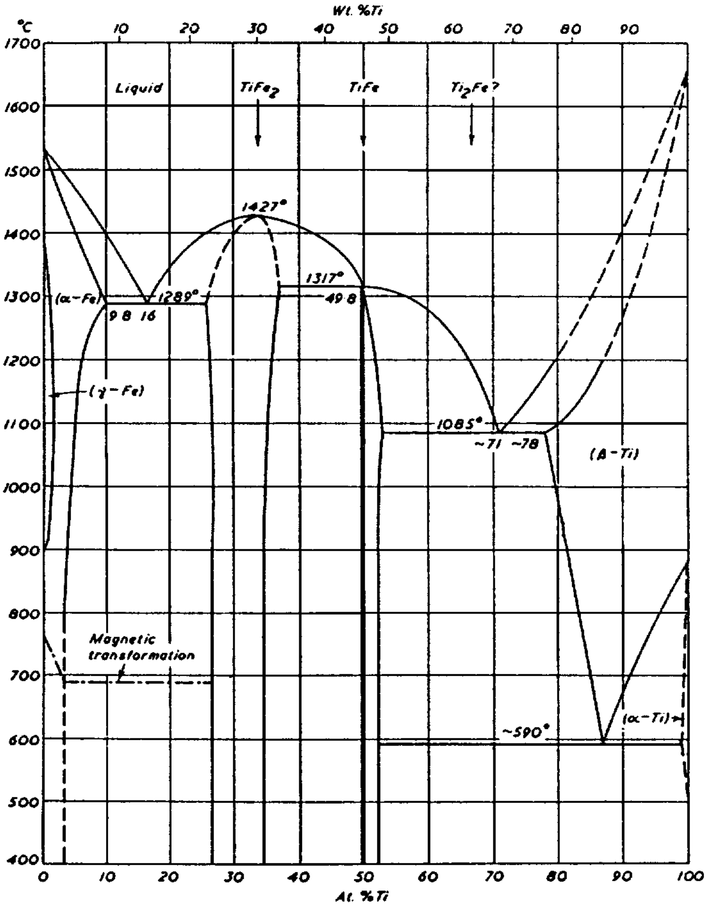

Wt. % Ti
10
20
30
40
60
80
°C
1800
1600
1530°
1400
1200
1000
800
600
1667°
1320±20°
~3·4
~26
Er + βTi
~890°
Er + αTi
0
20
40
60
80
100
At. % Ti

Er–Ti

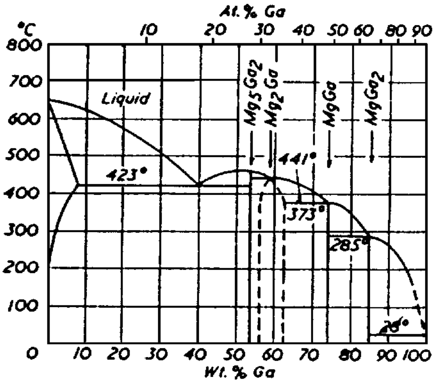

At. % Fe
0·01
0·02
0·03
0·04
°C
900
850
800
750
700
650
600
Liquid
0·001
0·006
0·01
0·02
0·03
0·04
0·05
0·06
0·07
0·08
0·09
0·1
Wt. % Fe

Fe–Mg

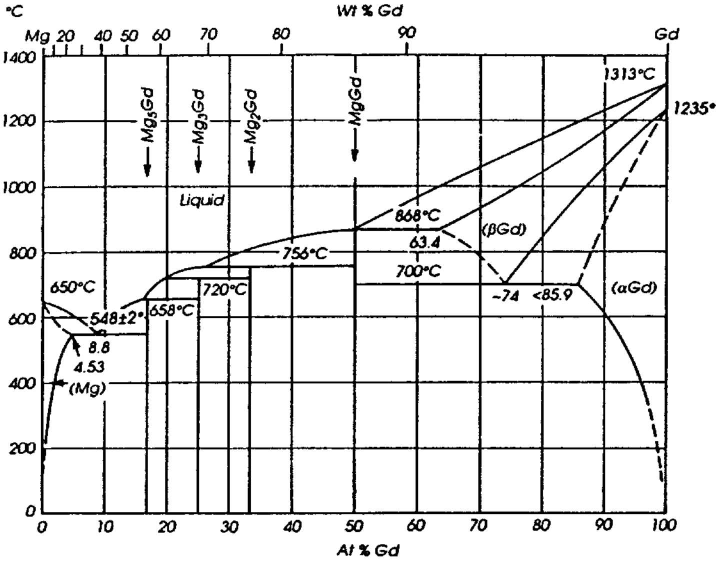
Fe–Ti


Wt. %Ti
°C
10 20 30 40 50 60 70 80 90
1700 1600 1500 1400 1300 1200 1100 1000 900 800 700 600 500 400
Liquid
TiFe₂
TiFe
Ti₂Fe?
1427°
1317°
(α-Fe)
1289°
9 8 16
49 8
(γ-Fe)
1085°
~71 ~78
(β-Ti)
Magnetic transformation
~590°
(α-Ti)
0 10 20 30 40 50 60 70 80 90 100
At. %Ti

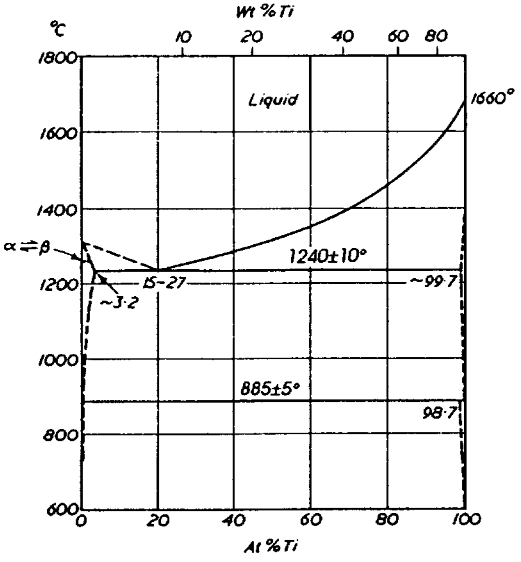
Ga–Mg


At. % Ga
°C
10 20 30 40 50 60 80 90
800 700 600 500 400 300 200 100 0
Liquid
Mg₅Ga₂
Mg₂Ga
MgGa
MgGa₂
423°
441°
373°
285°
26°
10 20 30 40 50 60 70 80 90 100
Wt. % Ga

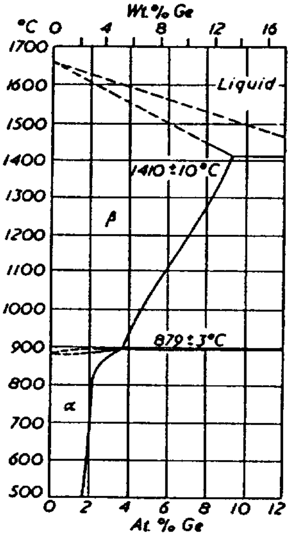
Gd–Mg


°C
Wt % Gd
Mg
20
40
50
60
70
80
90
Gd
1400
1200
1000
800
600
400
200
0
Mg$_5$Gd
Mg$_3$Gd
Mg$_2$Gd
MgGd
Liquid
1313°C
1235°
868°C
(βGd)
63.4
756°C
700°C
650°C
720°C
658°C
548±2°
8.8
4.53
(Mg)
~74
<85.9
(αGd)
0
10
20
30
40
50
60
70
80
90
100
At % Gd

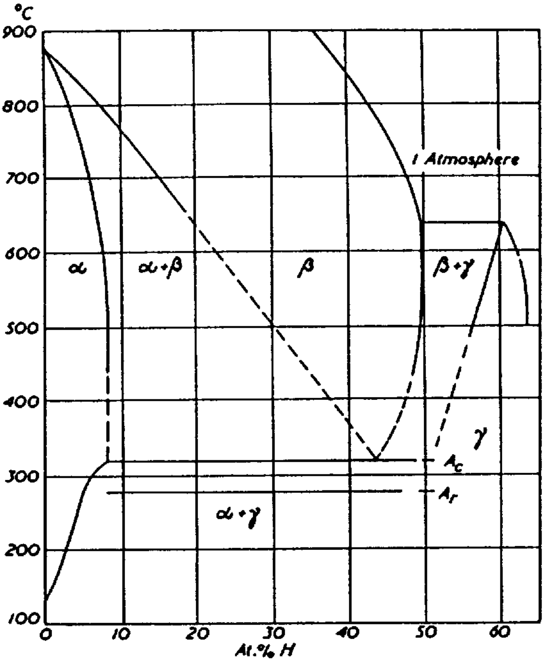
Gd–Ti


°C
Wt % Ti
10
20
40
60
80
1800
1600
1400
1200
1000
800
600
Liquid
1660°
α⇌β
1240±10°
15–27
~99·7
~3·2
885±5°
98·7
0
20
40
60
80
100
At % Ti

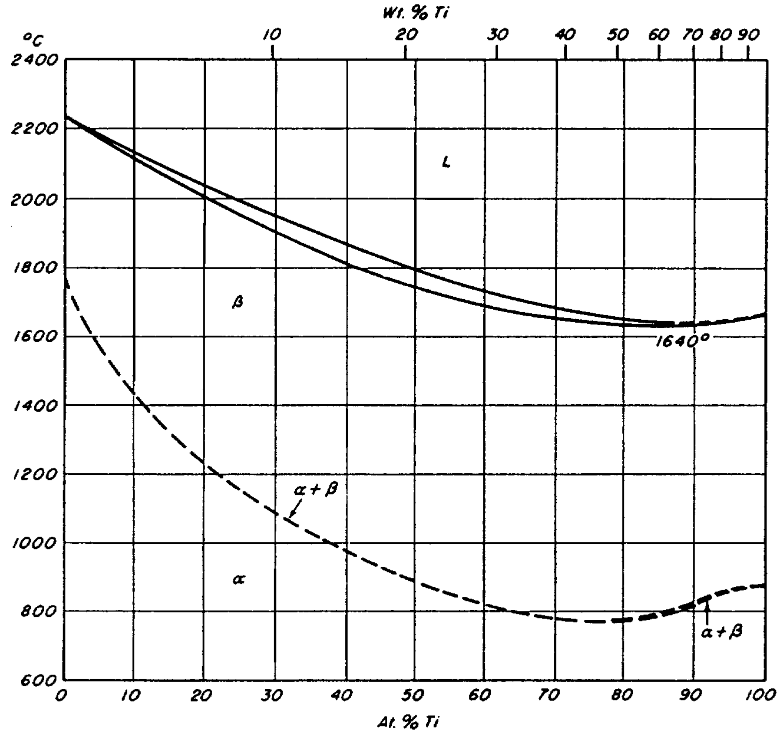
Ge–Ti


Wt.% Ge
°C
0
4
8
12
16
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
Liquid
1410 ± 10°C
β
879 ± 3°C
α
0
2
4
6
8
10
12
At.% Ge

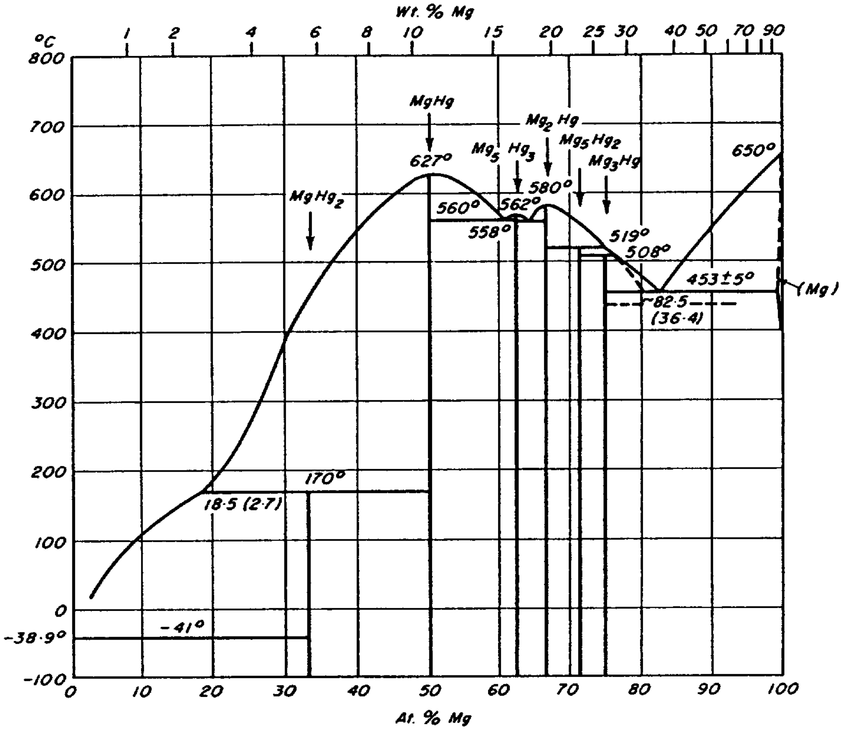
H–Ti


°C
900
800
700
600
500
400
300
200
100
1 Atmosphere
α
α+β
β
β+γ
γ
A_c
A_r
α+γ
0
10
20
30
40
50
60
At.% H

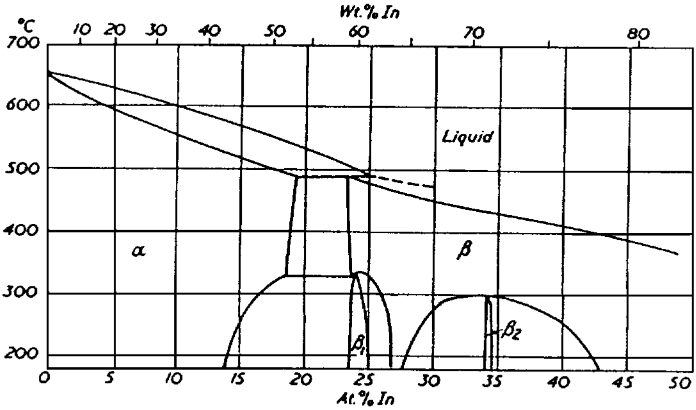
Hf–Ti


Wt. % Ti
10
20
30
40
50
60
70
80
90
°C
2400
2200
2000
1800
1600
1400
1200
1000
800
600
L
β
1640°
α + β
α
α + β
0
10
20
30
40
50
60
70
80
90
100
At. % Ti

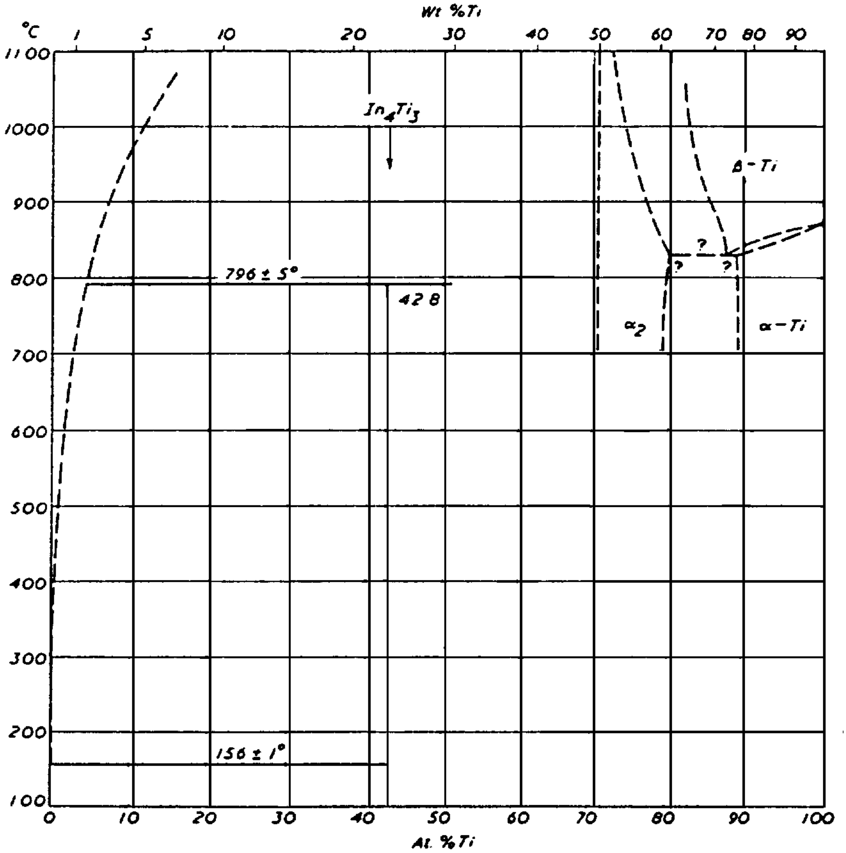
Hg–Mg

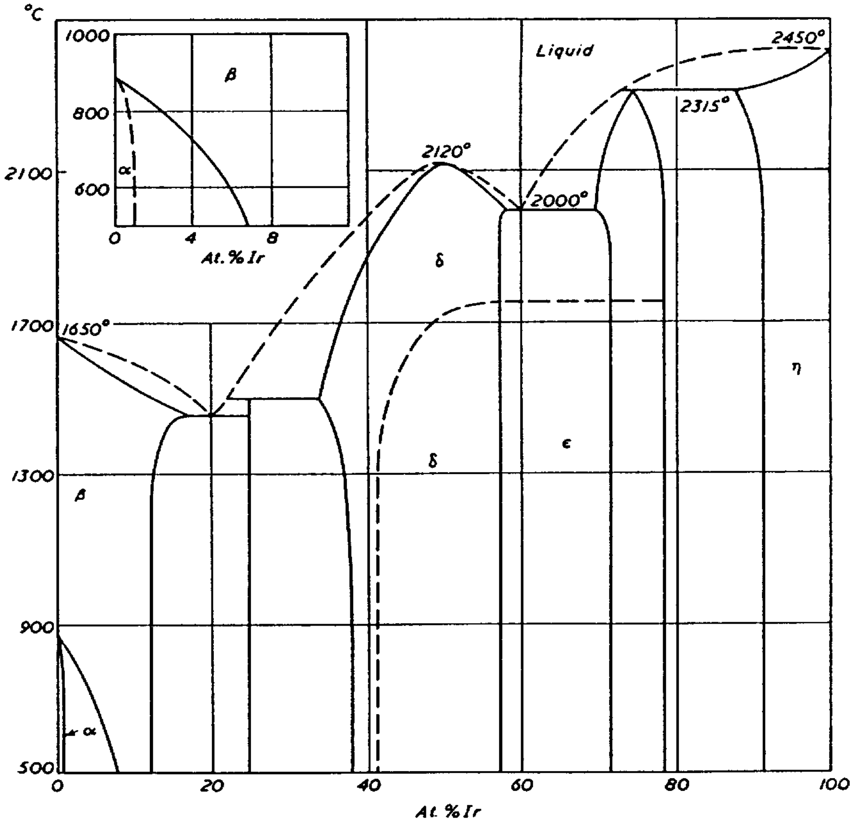

Wt. % Mg
1
2
4
6
8
10
15
20
25
30
40
50
70
90
°C
800
700
600
500
400
300
200
100
0
−38·9°
−100
MgHg
627°
Mg₂ Hg
Mg₅ Hg₃
Mg₅Hg₂
Mg₃Hg
650°
MgHg₂
580°
560°
562°
558°
519°
508°
453±5°
(Mg)
82·5
(36·4)
170°
18·5 (2·7)
−41°
0
10
20
30
40
50
60
70
80
90
100
At. % Mg

In–Mg

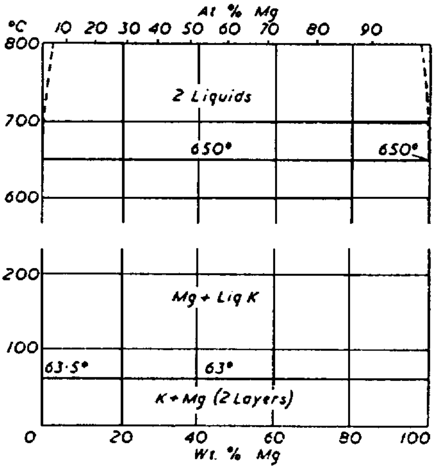

Wt.% In
°C
10
20
30
40
50
60
70
80
700
600
500
400
300
200
Liquid
α
β
β_1
β_2
0
5
10
15
20
25
30
35
40
45
50
At.% In

In–Ti


Wt %Ti
°C
1
5
10
20
30
40
50
60
70
80
90
1100
1000
900
800
700
600
500
400
300
200
100
In_4Ti_3
β-Ti
?
?
?
796 ± 5°
42.8
α_2
α-Ti
156 ± 1°
0
10
20
30
40
50
60
70
80
90
100
At. %Ti

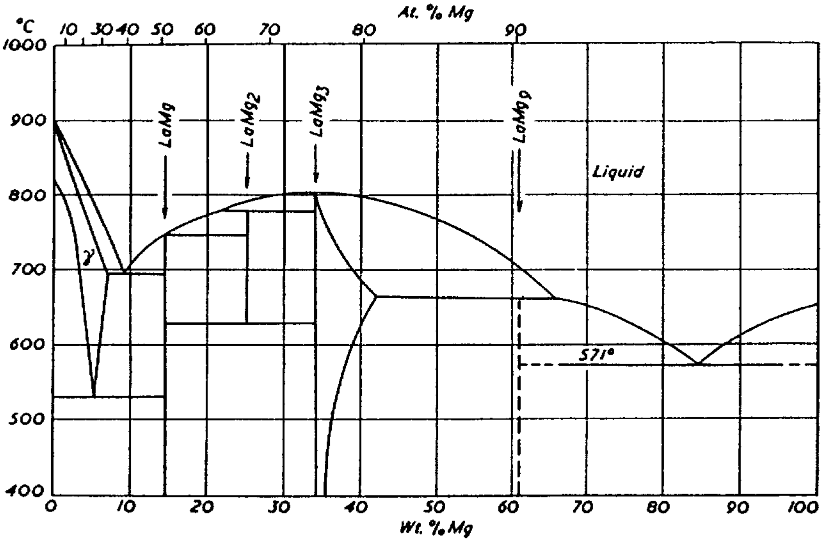

°C
1000
800
600
β
α
0
4
8
At.% Ir
2100
1700
1300
900
500
1650°
2120°
2000°
2315°
2450°
Liquid
δ
δ
ε
η
β
α
0
20
40
60
80
100
At. % Ir

Ir–Ti

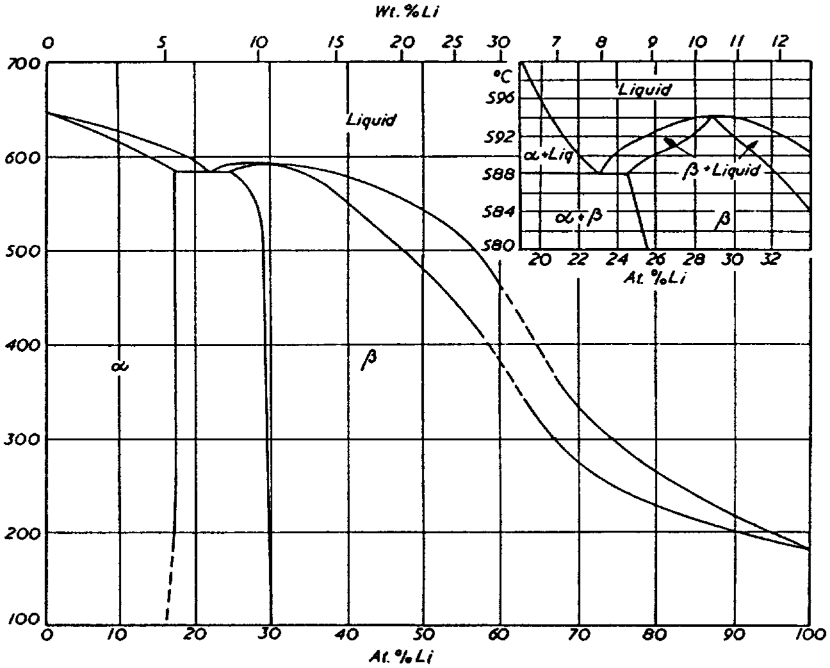

At % Mg
10 20 30 40 50 60 70 80 90
°C
800
700
600
200
100
0
2 Liquids
650°
650°
Mg + Liq K
63·5°
63°
K + Mg (2 Layers)
20
40
60
80
100
Wt. % Mg

K–Mg

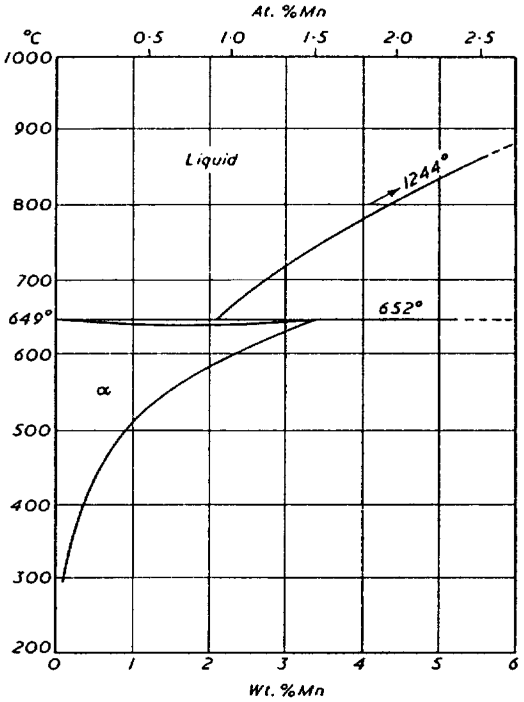
La–Mg


At. % Mg
°C
10
30
40
50
60
70
80
90
1000
900
800
700
600
500
400
LaMg
LaMg2
LaMg3
LaMg9
Liquid
γ
571°
0
10
20
30
40
50
60
70
80
90
100
Wt. % Mg

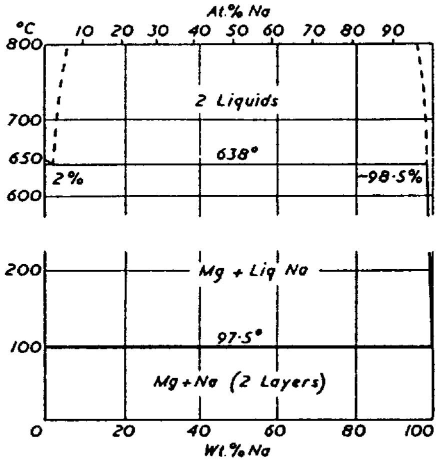
Li–Mg


Wt. % Li
0
5
10
15
20
25
30
7
8
9
10
11
12
700
600
500
400
300
200
100
°C
596
592
588
584
580
Liquid
α+Liq
β+Liquid
α+β
β
20
22
24
26
28
30
32
At. % Li
Liquid
α
β
0
10
20
30
40
50
60
70
80
90
100
At. % Li

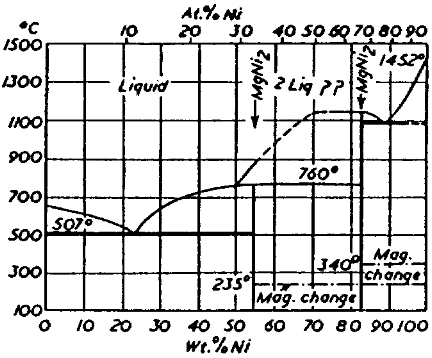
Mg–Mn


At. %Mn
°C
0·5
1·0
1·5
2·0
2·5
1000
900
800
700
649°
600
500
400
300
200
Liquid
1244°
652°
α
0
1
2
3
4
5
6
Wt. %Mn

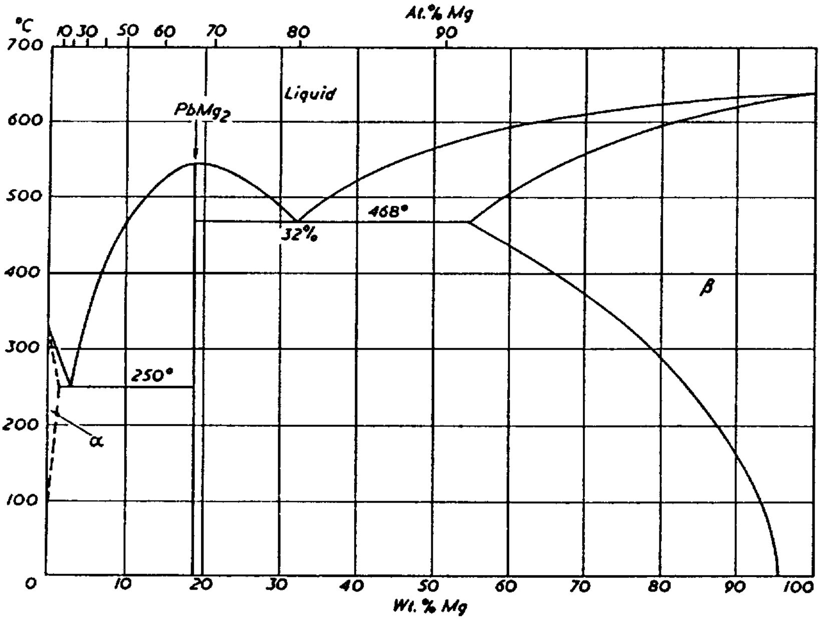
Mg–Na


At.% Na
°C
10
20
30
40
50
60
70
80
90
800
700
650
600
200
100
2 Liquids
638°
2%
~98·5%
Mg + Liq Na
97·5°
Mg+Na (2 Layers)
0
20
40
60
80
100
Wt.% Na

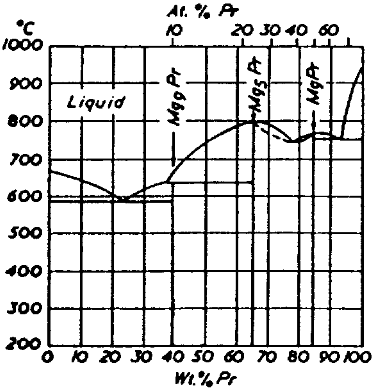
Mg–Ni

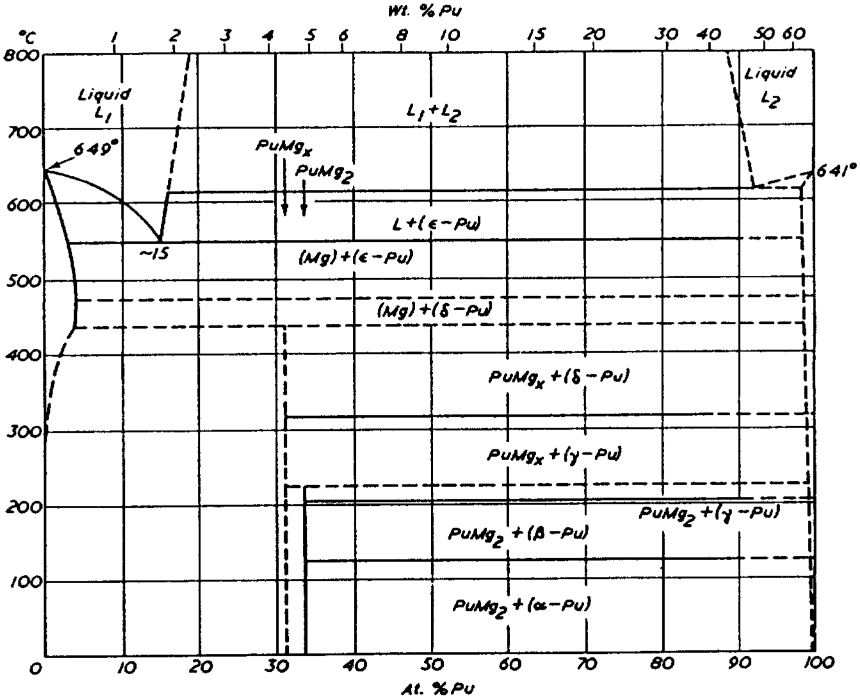


Mg–Pb

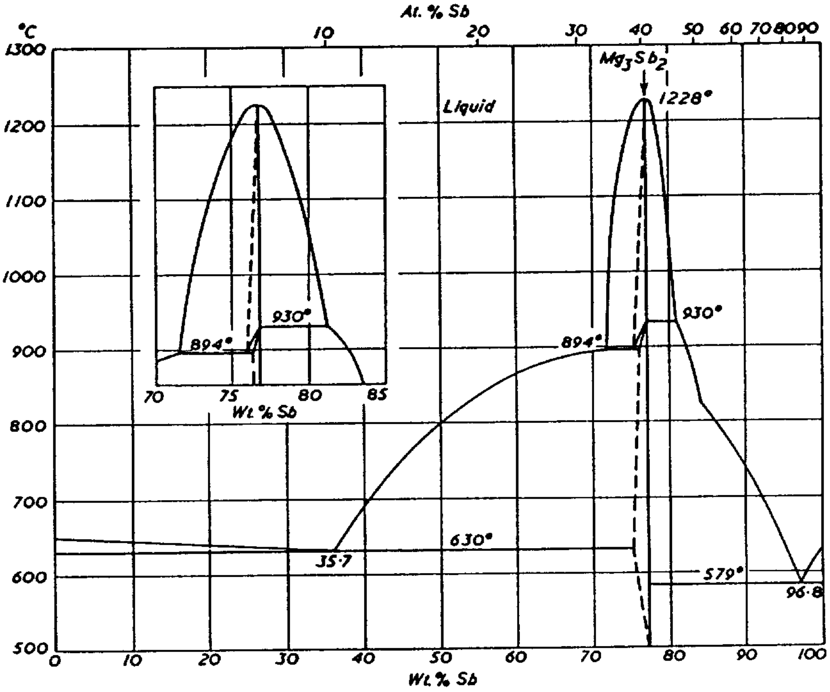


Mg–Pr



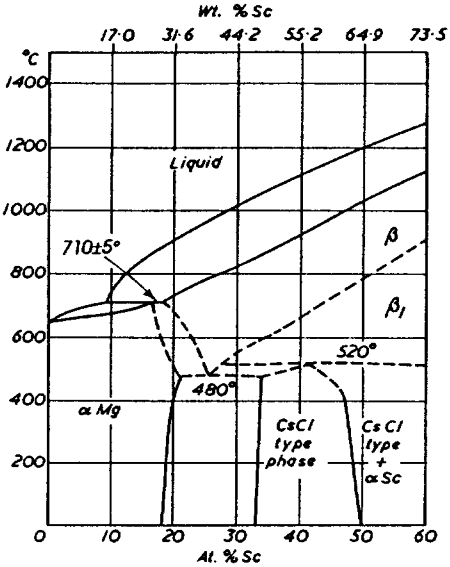

Wt. % Pu
°C
1
2
3
4
5
6
8
10
15
20
30
40
50 60
800
700
600
500
400
300
200
100
0
Liquid L_1
649°
~15
PuMg$_x$
PuMg$_2$
L_1+L_2
Liquid L_2
641°
L+(ε−Pu)
(Mg)+(ε−Pu)
(Mg)+(δ−Pu)
PuMg$_x$+(δ−Pu)
PuMg$_x$+(γ−Pu)
PuMg$_2$+(γ−Pu)
PuMg$_2$+(β−Pu)
PuMg$_2$+(α−Pu)
10
20
30
40
50
60
70
80
90
100
At. % Pu

Mg–Pu

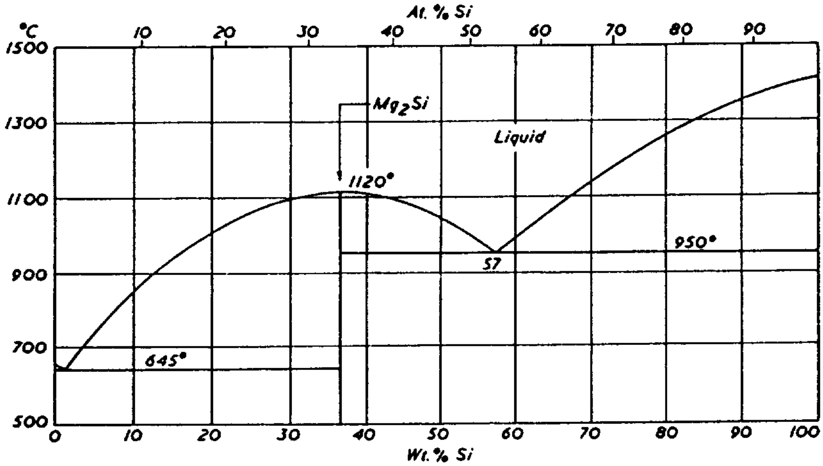

At. % Sb
°C
10
20
30
40
50
60
70
80
90
1300
1200
1100
1000
900
800
700
600
500
Mg$_3$Sb$_2$
1228°
Liquid
930°
894°
630°
35·7
579°
96·8
930°
894°
70
75
80
85
Wt % Sb
0
10
20
30
40
50
60
70
80
90
100
Wt. % Sb

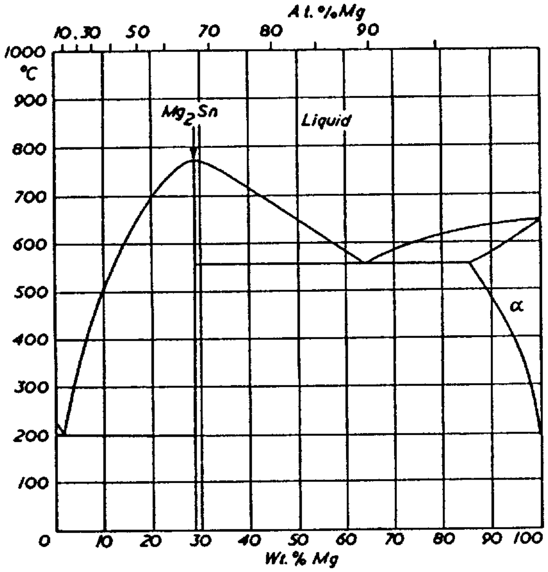
Mg–Sb

Mg–Sc

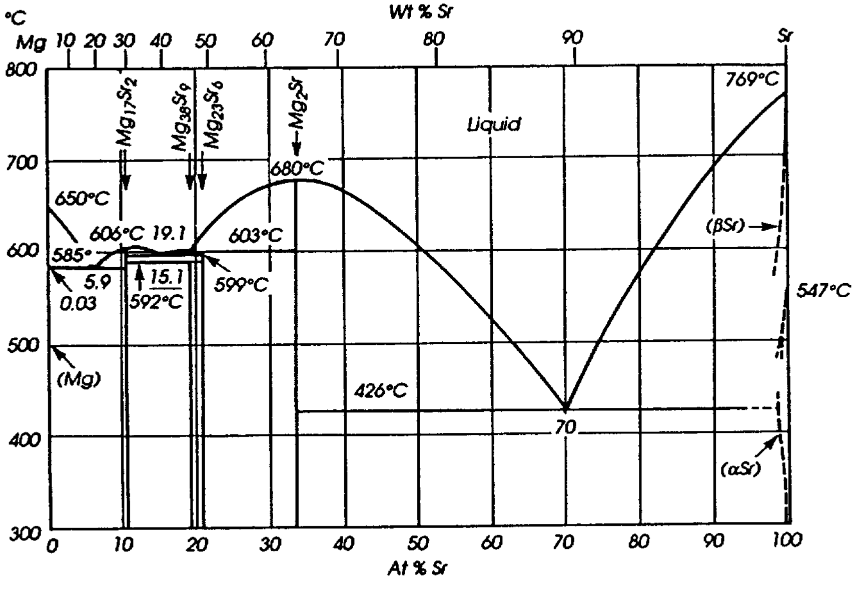

Wt. % Sc
17·0
31·6
44·2
55·2
64·9
73·5
°C
1400
1200
1000
800
600
400
200
Liquid
710±5°
β
β1
520°
480°
α Mg
CsCl type phase
CsCl type + α Sc
0
10
20
30
40
50
60
At. % Sc

Mg–Si


At. % Si
10
20
30
40
50
60
70
80
90
°C
1500
1300
1100
900
700
500
Mg2Si
Liquid
1120°
950°
57
645°
0
10
20
30
40
50
60
70
80
90
100
Wt. % Si

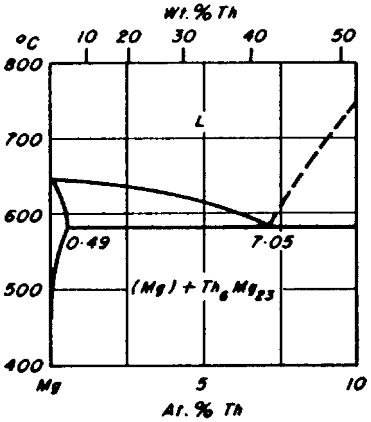

At.%Mg
10
30
50
70
80
90
1000 °C
900
800
700
600
500
400
300
200
100
0
Mg2Sn
Liquid
α
10
20
30
40
50
60
70
80
90
100
Wt.% Mg

Mg–Sn

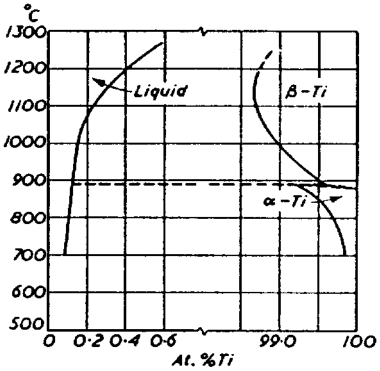

°C
Wt % Sr
Mg
10
20
30
40
50
60
70
80
90
Sr
800
700
600
500
400
300
Mg17Sr2
Mg38Sr9
Mg23Sr6
Mg2Sr
769°C
Liquid
680°C
650°C
606°C
19.1
603°C
585°
5.9
0.03
15.1
592°C
599°C
(βSr)
547°C
(Mg)
426°C
70
(αSr)
0
10
20
30
40
50
60
70
80
90
100
At % Sr

Mg–Sr

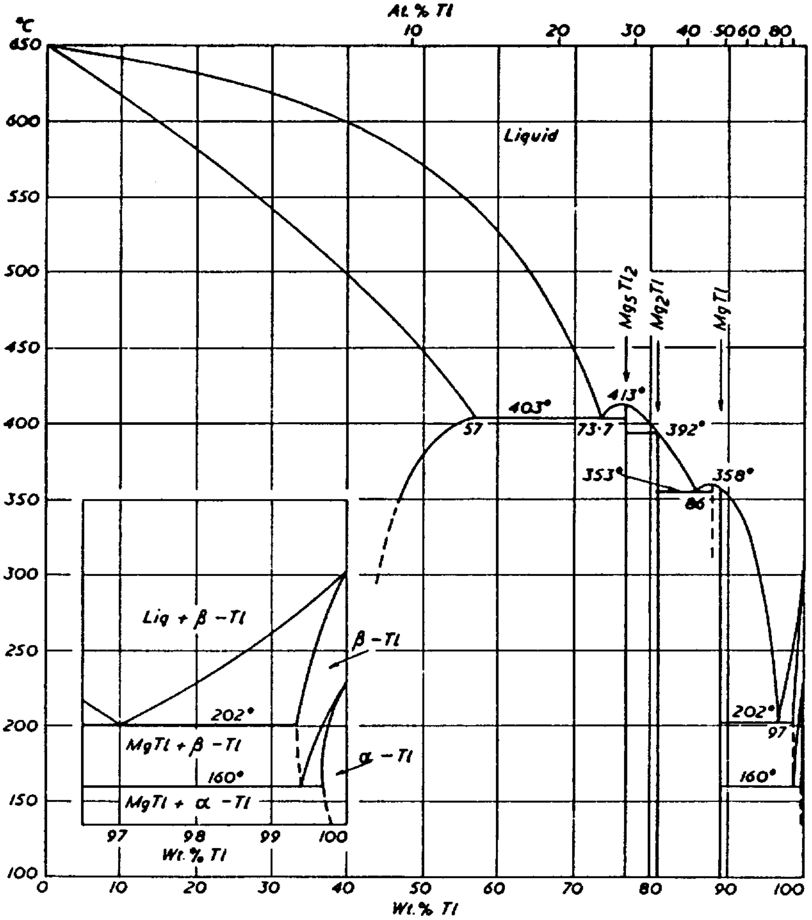
Mg–Th



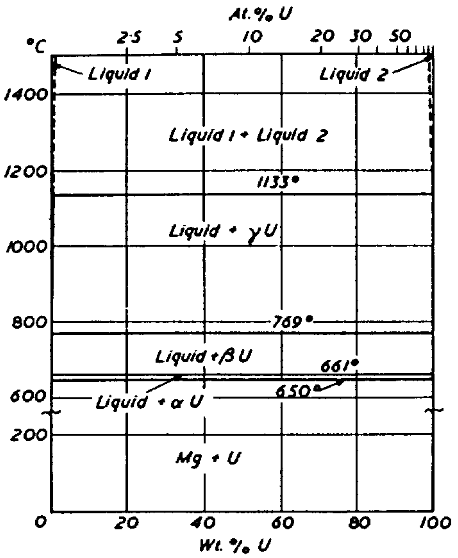
Mg–Ti



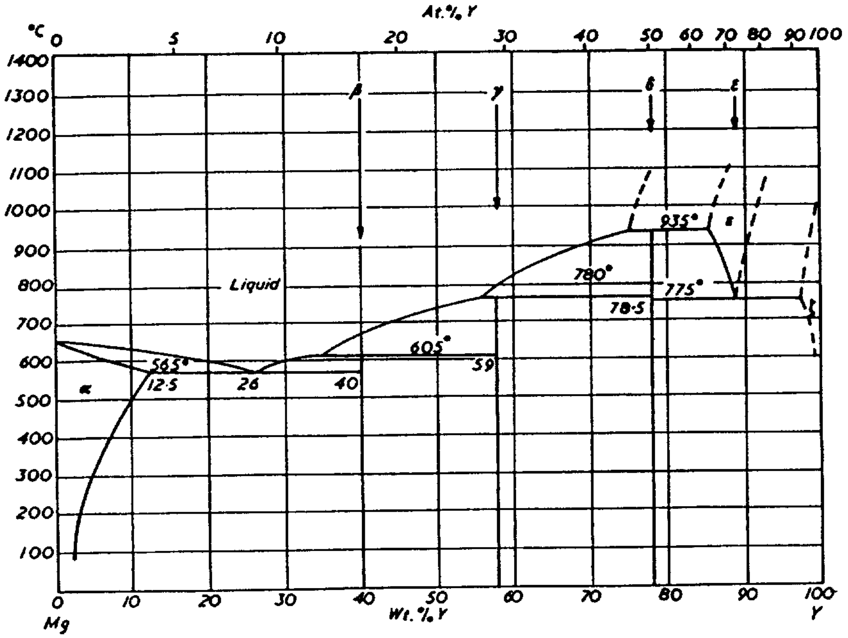
Mg–Tl



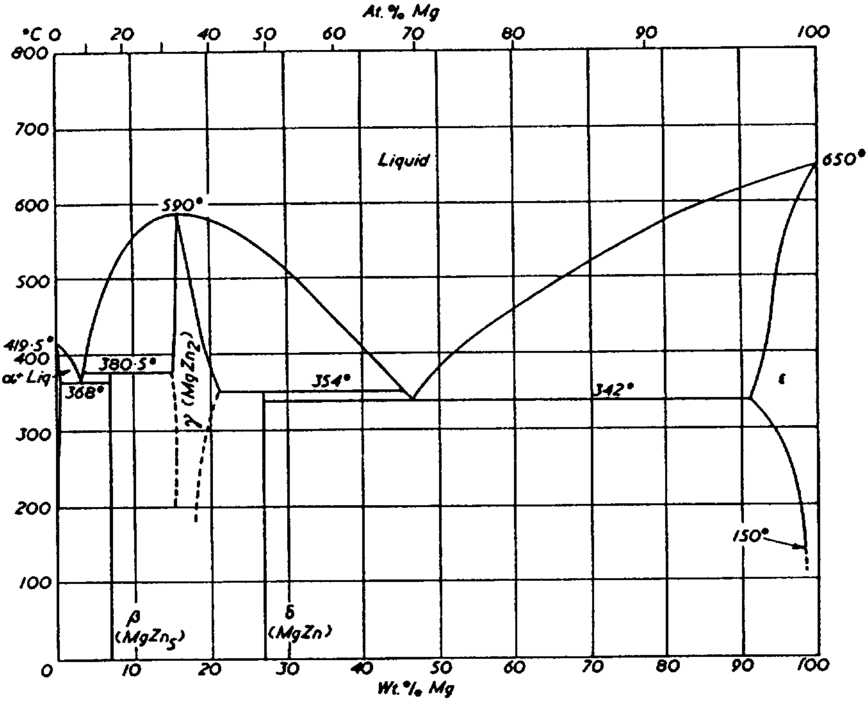
Mg–U


At.% U
°C
2·5
5
10
20
30
50
Liquid 1
Liquid 2
1400
Liquid 1 + Liquid 2
1200
1133°
Liquid + γU
1000
800
769°
Liquid + βU
661°
650°
600
Liquid + α U
200
Mg + U
0
20
40
60
80
100
Wt.% U

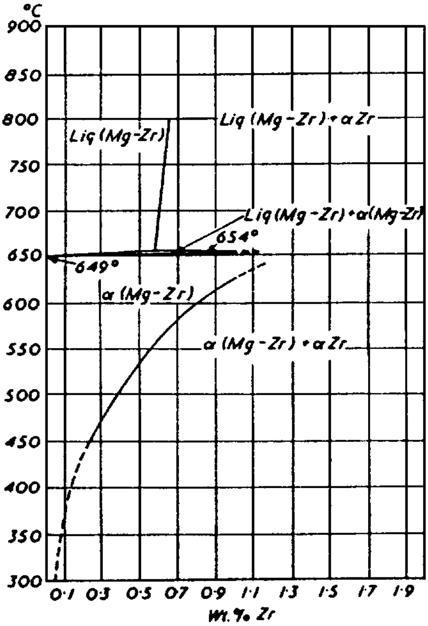
Mg–Y


At.% Y
°C
0
5
10
20
30
40
50
60
70
80
90
100
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
β
γ
δ
ε
935°
ε
780°
775°
78·5
Liquid
605°
59
565°
12·5
26
40
α
ζ
0
10
20
30
40
50
60
70
80
90
100
Mg
Wt.% Y
Y

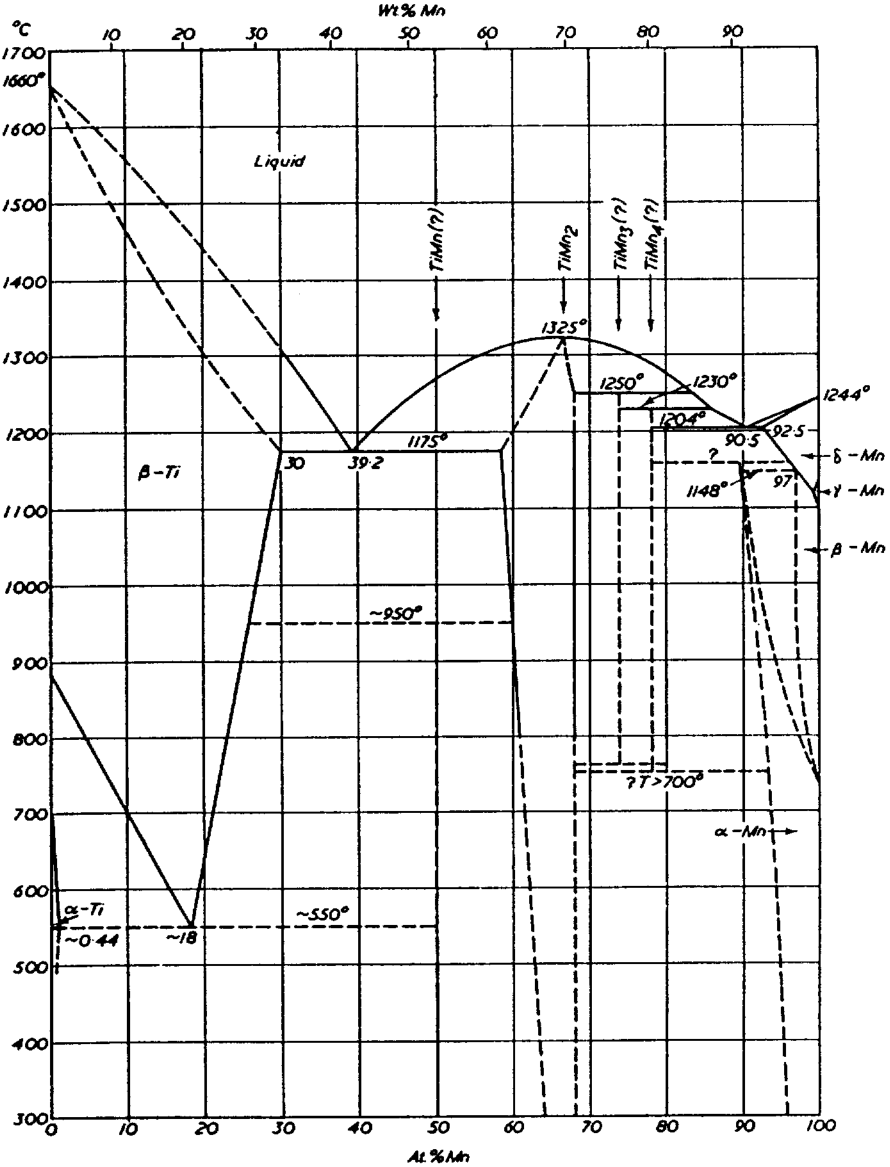
Mg–Zn


At.% Mg
°C
0
20
40
50
60
70
80
90
100
800
700
600
500
400
300
200
100
0
Liquid
650°
590°
419·5°
α+Liq
380·5°
368°
γ (MgZn2)
354°
342°
ε
150°
β
(MgZn5)
δ
(MgZn)
10
20
30
40
50
60
70
80
90
100
Wt.% Mg

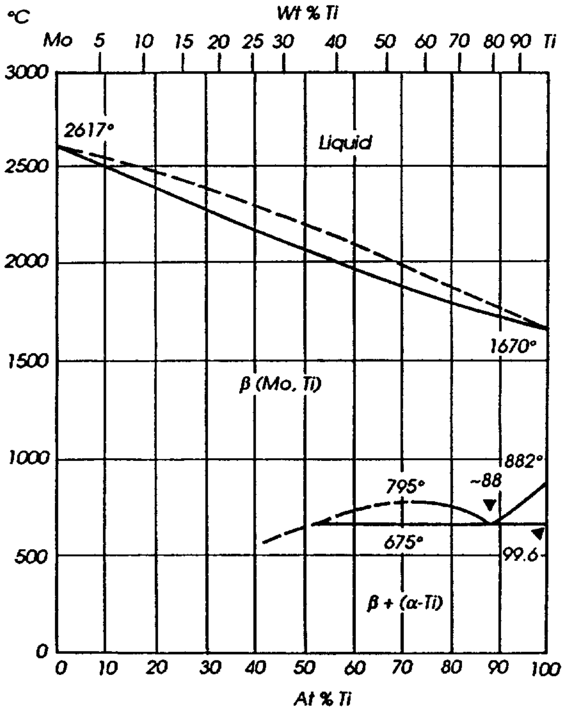
Mg–Zr


°C
900
850
800
750
700
650
600
550
500
450
400
350
300
Liq (Mg-Zr)
Liq (Mg-Zr) + α Zr
Liq (Mg-Zr) + α(Mg-Zr)
654°
649°
α (Mg-Zr)
α (Mg-Zr) + α Zr
0·1
0·3
0·5
0·7
0·9
1·1
1·3
1·5
1·7
1·9
Wt.% Zr

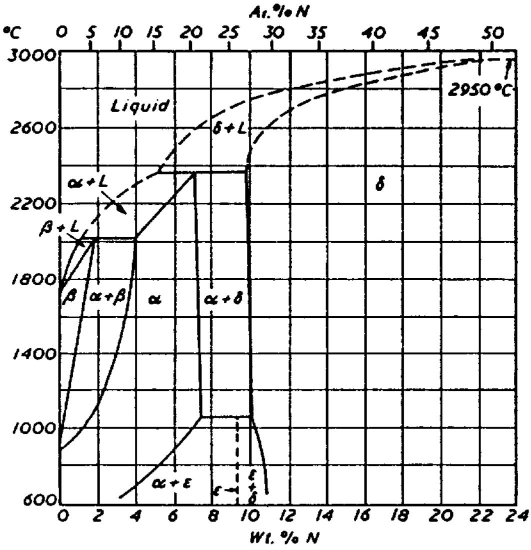
Mn–Ti

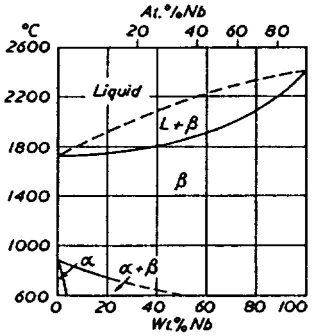

Wt.% Mn
10
20
30
40
50
60
70
80
90
°C
1700
1660°
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
Liquid
TiMn(?)
TiMn2
TiMn3(?)
TiMn4(?)
1325°
1250°
1230°
1244°
1204°
92·5
90·5
1175°
?
1148°
97
30
39·2
β-Ti
δ-Mn
γ-Mn
β-Mn
~950°
?T>700°
α-Mn
α-Ti
~550°
~0·44
~18
0
10
20
30
40
50
60
70
80
90
100
At.% Mn

Mo–Ti

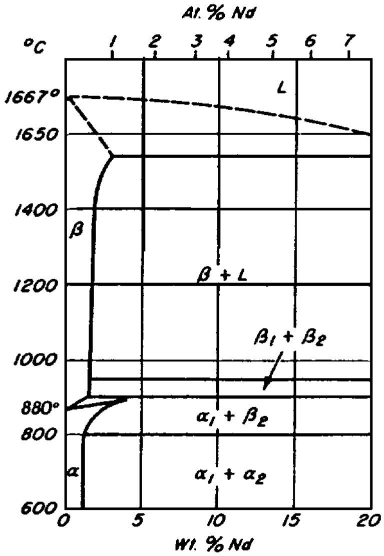

°C
Wt % Ti
Mo
5
10
15
20
25
30
40
50
60
70
80
90
Ti
3000
2500
2000
1500
1000
500
0
2617°
Liquid
1670°
β (Mo, Ti)
882°
795°
~88
675°
99.6
β + (α-Ti)
0
10
20
30
40
50
60
70
80
90
100
At % Ti

N–Ti


At.% N
°C
0
5
10
15
20
25
30
35
40
45
50
3000
2600
2200
1800
1400
1000
600
2950 °C
Liquid
δ + L
α + L
δ
β + L
β
α + β
α
α + δ
α + ε
ε
ε + δ
0
2
4
6
8
10
12
14
16
18
20
22
24
Wt. % N

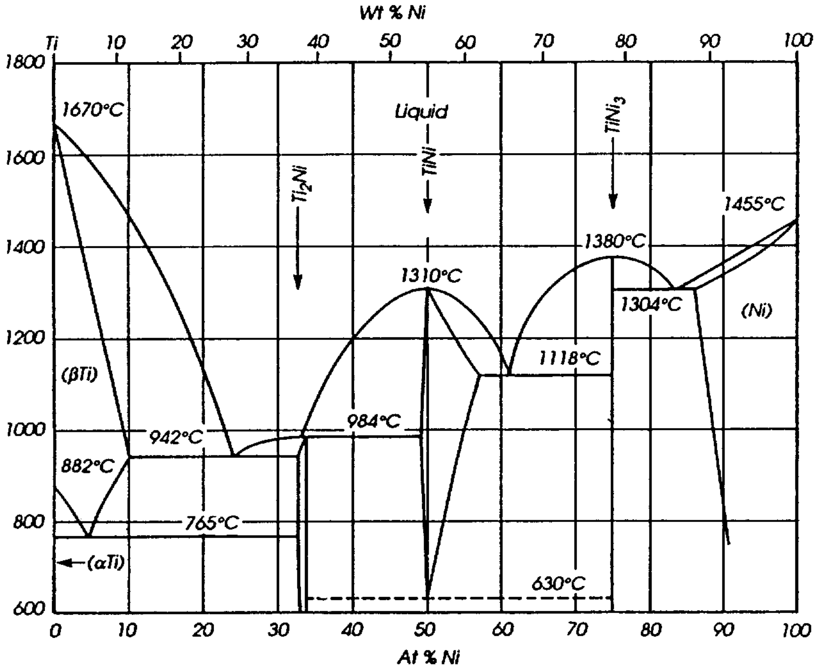

At.%Nb
20
40
60
80
°C
2600
2200
1800
1400
1000
600
Liquid
L+β
β
α
α+β
0
20
40
60
80
100
Wt.%Nb

Nb–Ti

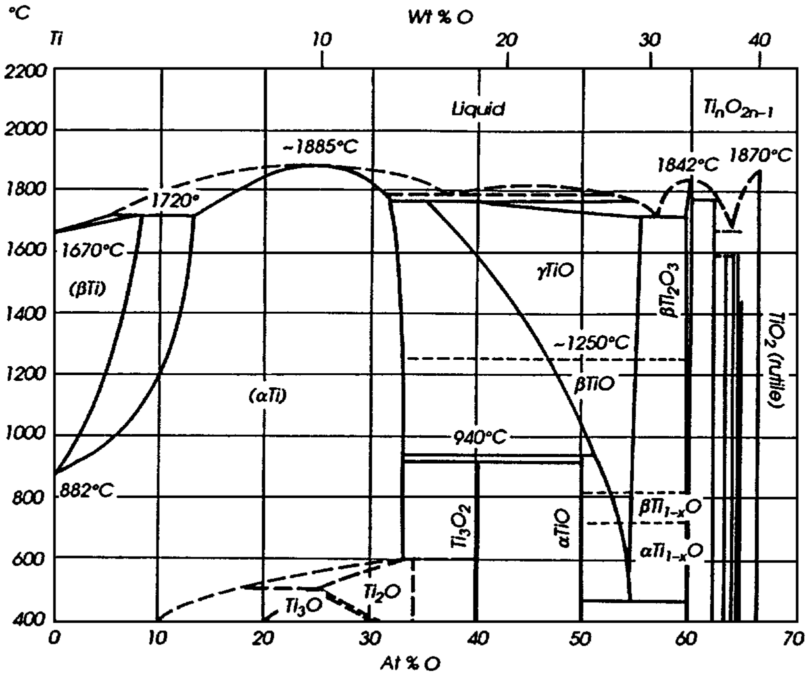

At.% Nd
°C
1
2
3
4
5
6
7
1667°
1650
1400
1200
1000
880°
800
600
L
β
β + L
β1 + β2
α1 + β2
α1 + α2
α
0
5
10
15
20
Wt. % Nd

Nd–Ti

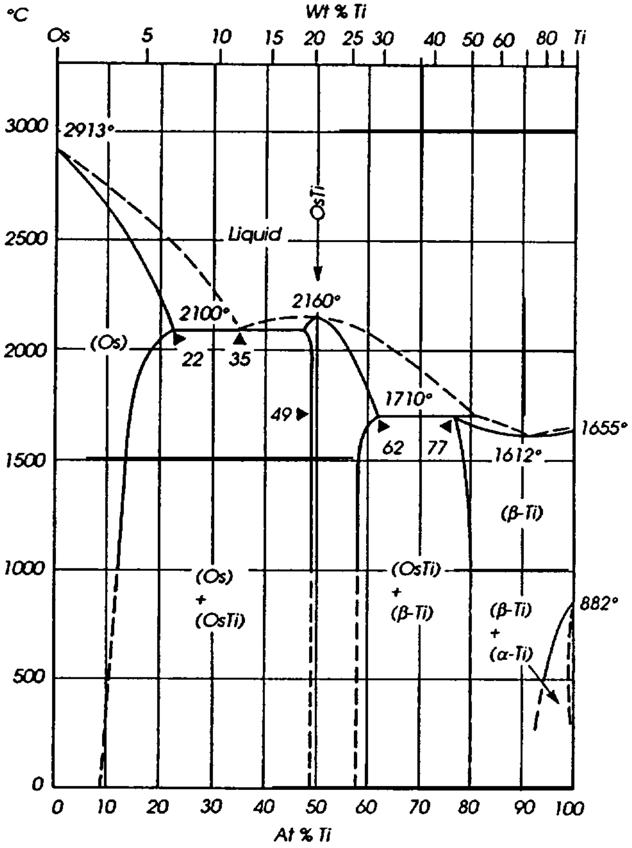
Ni–Ti


Wt % Ni
Ti
10
20
30
40
50
60
70
80
90
100
1800
1600
1400
1200
1000
800
600
1670°C
Liquid
Ti$_2$Ni
TiNi
TiNi$_3$
1455°C
1380°C
1310°C
1304°C
(Ni)
1118°C
(βTi)
984°C
942°C
882°C
765°C
(αTi)
630°C
0
10
20
30
40
50
60
70
80
90
100
At % Ni

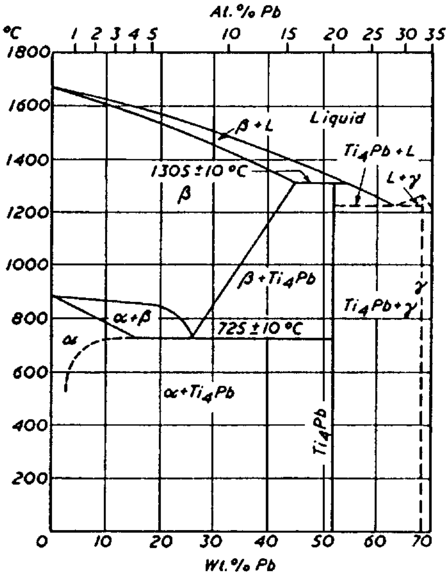
O–Ti


°C
Wt % O
Ti
10
20
30
40
2200
2000
1800
1600
1400
1200
1000
800
600
400
Liquid
Ti$_n$O$_{2n-1}$
~1885°C
1842°C
1870°C
1720°
1670°C
(βTi)
γTiO
βTi$_2$O$_3$
TiO$_2$ (rutile)
~1250°C
βTiO
(αTi)
940°C
882°C
Ti$_3$O$_2$
αTiO
βTi$_{1-x}$O
αTi$_{1-x}$O
Ti$_2$O
Ti$_3$O
0
10
20
30
40
50
60
70
At % O

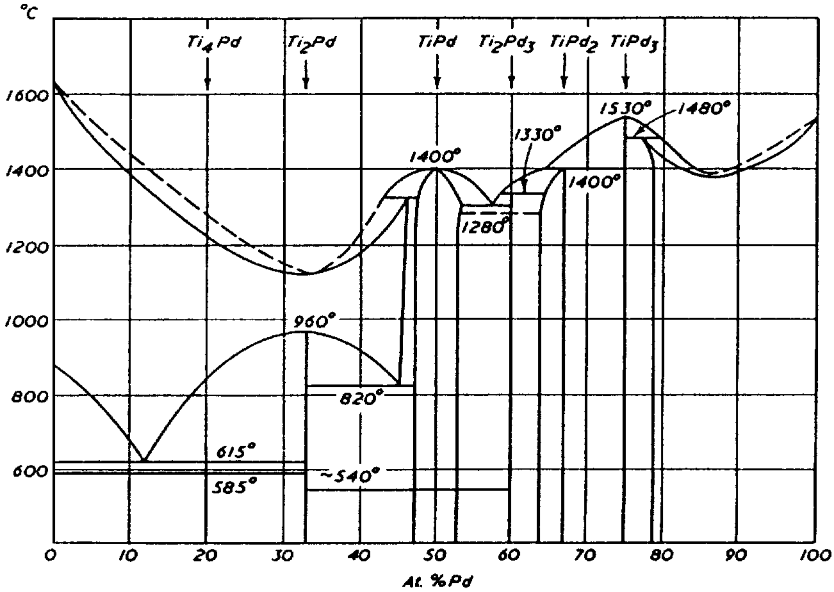
Os–Ti


°C
Wt % Ti
Os
5
10
15
20
25
30
40
50
60
80
Ti
3000
2500
2000
1500
1000
500
0
2913°
Liquid
OsTi
2160°
2100°
(Os)
22
35
49
1710°
62
77
1655°
1612°
(β-Ti)
(Os)
+
(OsTi)
(OsTi)
+
(β-Ti)
(β-Ti)
+
(α-Ti)
882°
0
10
20
30
40
50
60
70
80
90
100
At % Ti

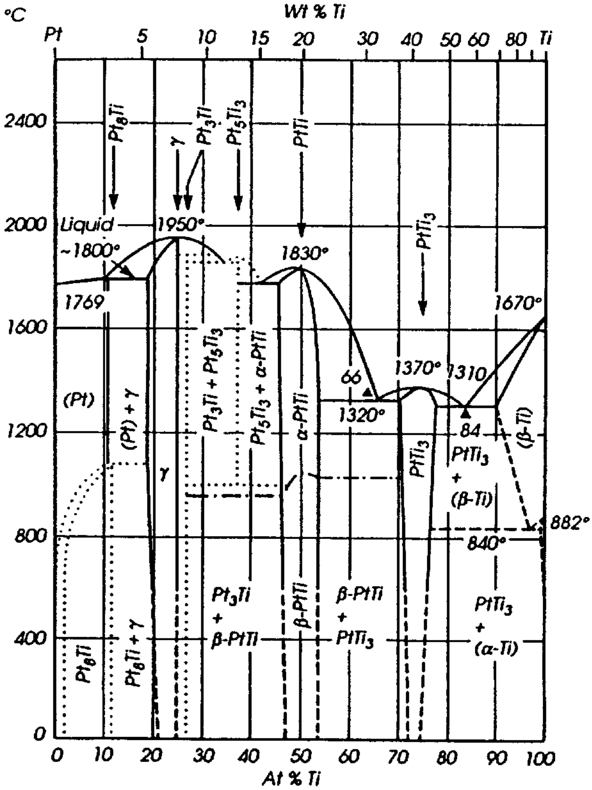
Pb–Ti


At.% Pb
°C
1
2
3
4
5
10
15
20
25
30
35
1800
1600
1400
1200
1000
800
600
400
200
0
β + L
Liquid
Ti₄Pb + L
1305 ± 10 °C
L + γ
β
β + Ti₄Pb
γ
Ti₄Pb + γ
α + β
725 ± 10 °C
α
α + Ti₄Pb
Ti₄Pb
10
20
30
40
50
60
70
Wt.% Pb

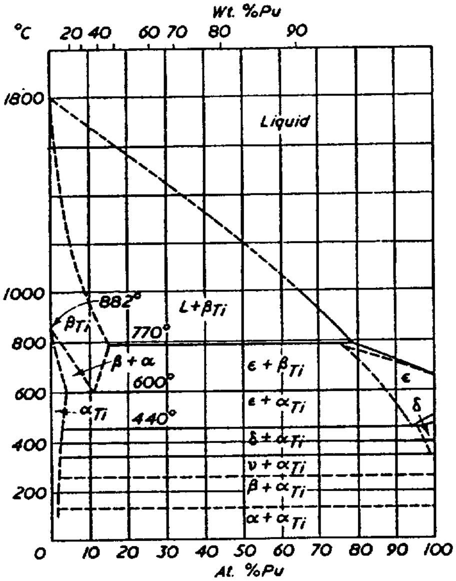
Pd–Ti


°C
Ti_4Pd
Ti_2Pd
TiPd
Ti_2Pd_3
$TiPd_2$
$TiPd_3$
1600
1400
1200
1000
800
600
1530°
1480°
1330°
1400°
1400°
1280°
960°
820°
615°
~540°
585°
0
10
20
30
40
50
60
70
80
90
100
At. % Pd

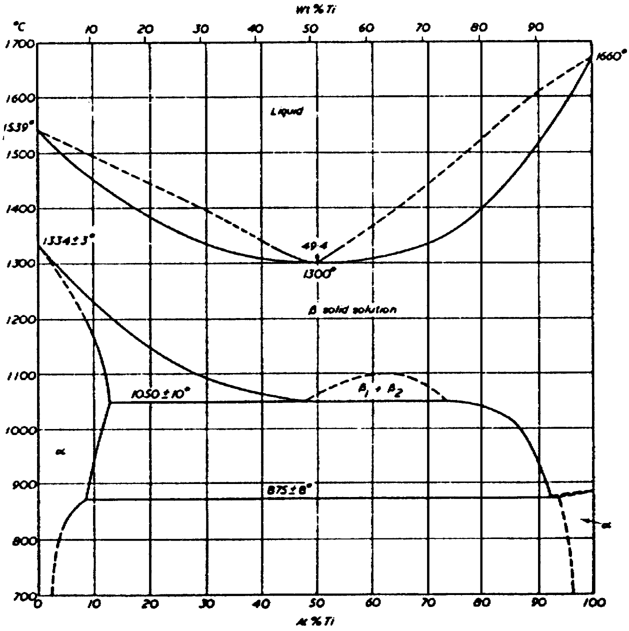
Pt–Ti


°C
Wt % Ti
Pt
5
10
15
20
30
40
50
60
80
Ti
2400
2000
1600
1200
800
400
0
Pt_8Ti
γ
Pt_3Ti
Pt_5Ti_3
PtTi
$PtTi_3$
Liquid
1950°
~1800°
1830°
1769
1670°
66
1370°
1310
1320°
84
(Pt)
(Pt) + γ
$Pt_3Ti + Pt_5Ti_3$
Pt_5Ti_3 + α-PtTi
α-PtTi
$PtTi_3$
$PtTi_3$ + (β-Ti)
(β-Ti)
882°
840°
Pt_3Ti + β-PtTi
β-PtTi
β-PtTi + $PtTi_3$
$PtTi_3$ + (α-Ti)
Pt_8Ti
Pt_8Ti + γ
0
10
20
30
40
50
60
70
80
90
100
At % Ti

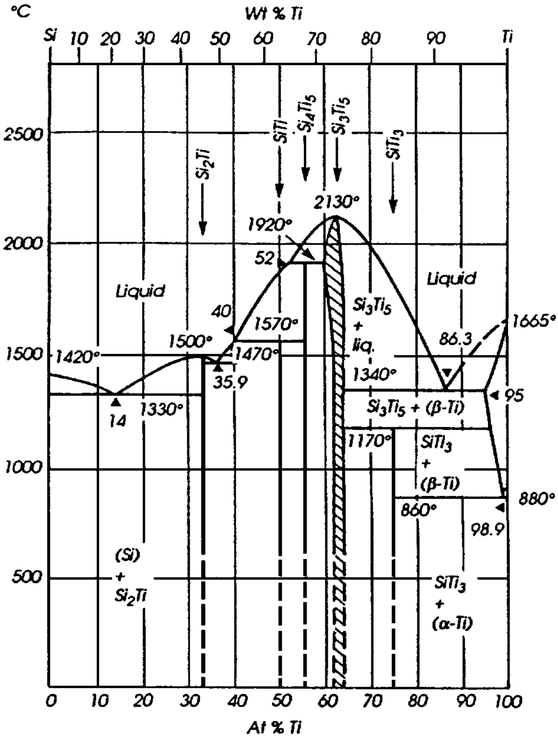
Pu–Ti


Wt. %Pu
°C
20
40
60
70
80
90
1800
1000
800
600
400
200
0
Liquid
882°
L+βTi
βTi
770°
β+α
600°
αTi
440°
ε+βTi
ε+αTi
δ+αTi
ν+αTi
β+αTi
α+αTi
ε
δ
10
20
30
40
50
60
70
80
90
100
At. %Pu

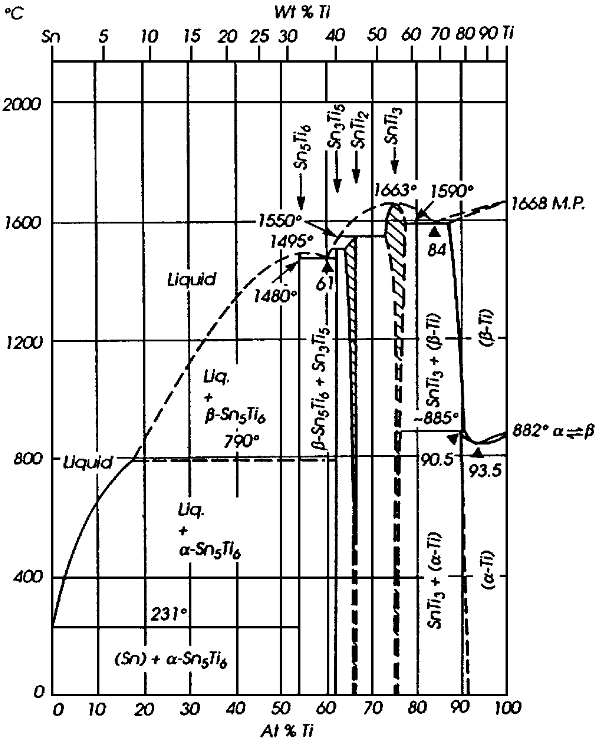
Sc–Ti


Wt % Ti
°C
10
20
30
40
50
60
70
80
90
1700
1600
1539°
1500
1400
1334±3°
1300
1200
1100
1000
900
800
700
1660°
Liquid
49·4
1300°
β solid solution
1050±10°
β1 + β2
α
875±8°
α
0
10
20
30
40
50
60
70
80
90
100
At % Ti

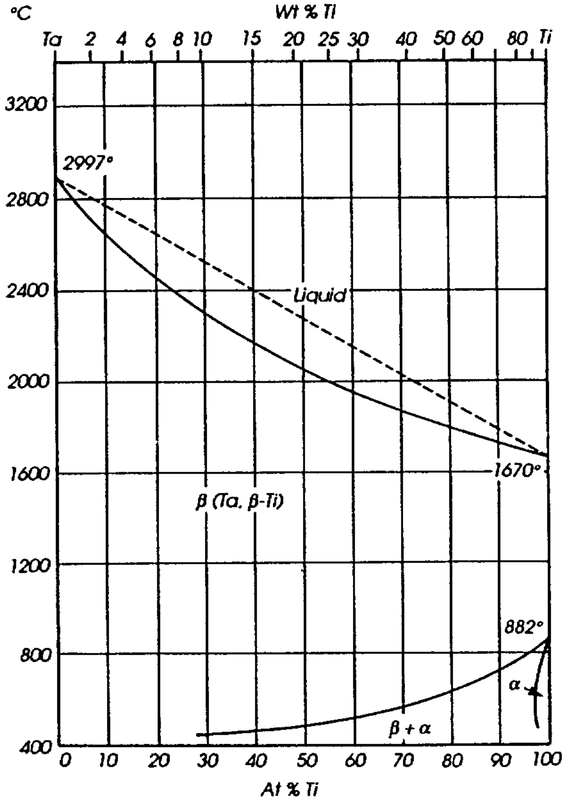
Si–Ti


°C
Wt % Ti
Si 10 20 30 40 50 60 70 80 90 Ti
2500
2000
1500
1000
500
Si2Ti
SiTi
Si4Ti5
Si3Ti5
SiTi3
2130°
1920°
52
Liquid
Liquid
40
1570°
Si3Ti5 + liq.
1665°
86.3
1500°
1420°
1470°
35.9
1340°
14
1330°
95
Si3Ti5 + (β-Ti)
1170°
SiTi3 + (β-Ti)
880°
860°
98.9
(Si) + Si2Ti
SiTi3 + (α-Ti)
0 10 20 30 40 50 60 70 80 90 100
At % Ti

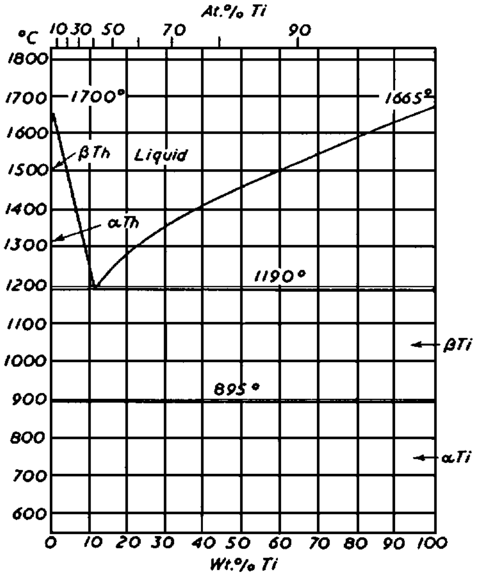
Sn–Ti


°C
Wt % Ti
Sn 5 10 15 20 25 30 40 50 60 70 80 90 Ti
2000
1600
1200
800
400
0
Sn5Ti6
Sn3Ti5
SnTi2
SnTi3
1663°
1590°
1668 M.P.
1550°
1495°
84
61
Liquid
1480°
β-Sn5Ti6 + Sn3Ti5
SnTi3 + (β-Ti)
(β-Ti)
Liq. + β-Sn5Ti6
790°
~885°
882° α ⇌ β
Liquid
90.5
93.5
Liq. + α-Sn5Ti6
SnTi3 + (α-Ti)
(α-Ti)
231°
(Sn) + α-Sn5Ti6
0 10 20 30 40 50 60 70 80 90 100
At % Ti

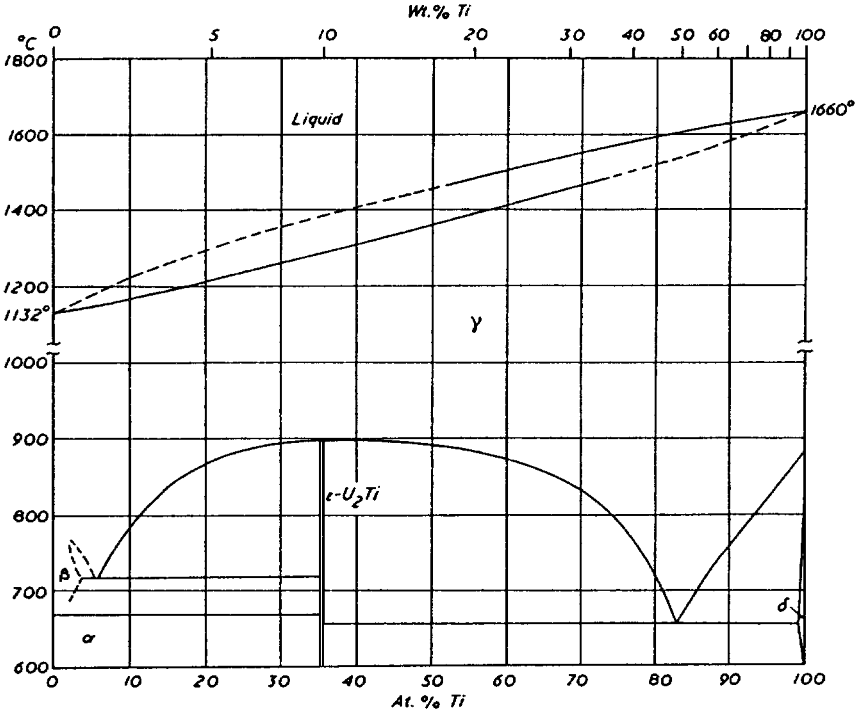
Ta–Ti


°C
Wt % Ti
Ta 2 4 6 8 10 15 20 25 30 40 50 60 80 Ti
3200
2800
2400
2000
1600
1200
800
400
2997°
Liquid
1670°
β (Ta, β-Ti)
882°
α
β + α
0 10 20 30 40 50 60 70 80 90 100
At % Ti

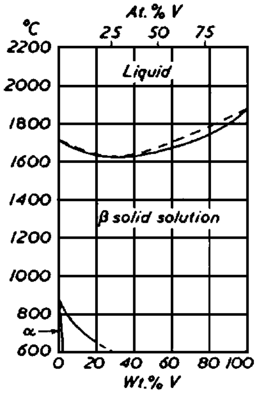
Th–Ti

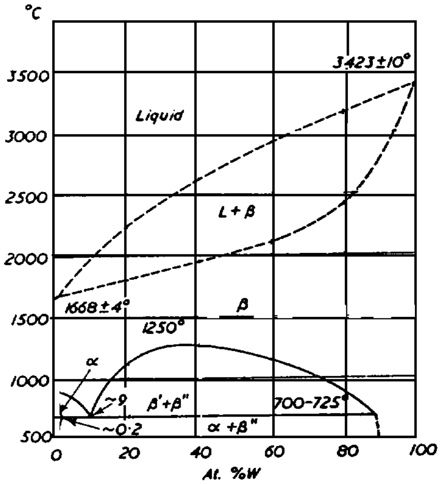

At.% Ti
10 30 50 70 90
°C
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
1700°
1665°
βTh
Liquid
αTh
1190°
βTi
895°
αTi
0 10 20 30 40 50 60 70 80 90 100
Wt.% Ti

Ti–U


Wt.% Ti
0
5
10
20
30
40
50
60
80
100
°C
1800
1600
1400
1200
1132°
1000
900
800
700
600
Liquid
1660°
γ
ε-U₂Ti
β
α
δ
0
10
20
30
40
50
60
70
80
90
100
At.% Ti

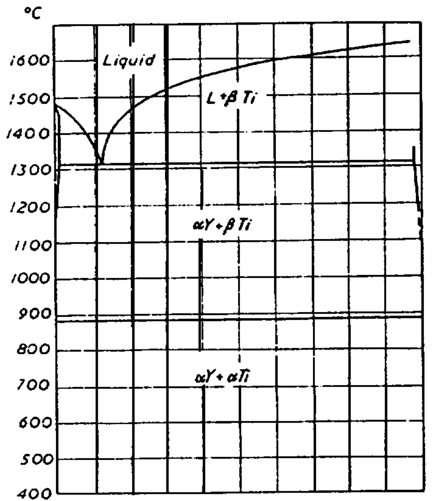
Ti–V


At.% V
25
50
75
°C
2200
2000
1800
1600
1400
1200
1000
800
α
600
Liquid
β solid solution
0
20
40
60
80
100
Wt.% V



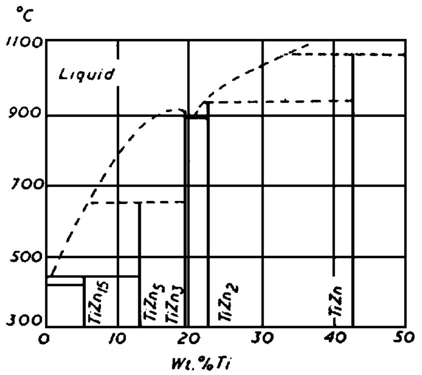
Ti–W

°C
3500
3000
2500
2000
1500
1000
500
3423±10°
Liquid
L+β
β
1668±4°
1250°
α
≈9
β'+β"
700-725°
~0·2
α+β"
0
20
40
60
80
100
At. %W



Ti–Y

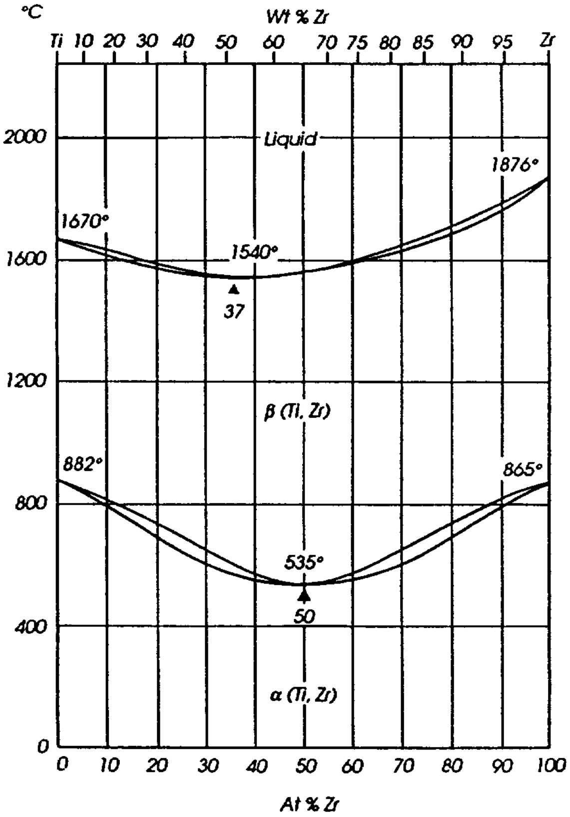
°C
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
Liquid
L+β Ti
αY+β Ti
αY+αTi
0
10
20
30
40
50
60
70
80
90
100
Wt.%Y



Ti–Zn

°C
1100
900
700
500
300
Liquid
$TiZn_{15}$
$TiZn_5$
$TiZn_3$
$TiZn_2$
TiZn
0
10
20
30
40
50
Wt.%Ti

Ti–Zr


°C
Wt % Zr
Ti 10 20 30 40 50 60 70 75 80 85 90 95 Zr
2000
1600
1200
800
400
0
Liquid
1876°
1670°
1540°
37
β (Ti, Zr)
882°
865°
535°
50
α (Ti, Zr)
0 10 20 30 40 50 60 70 80 90 100
At % Zr

6 Metallography of light alloys

Metallography can be defined as the study of the structure of materials and alloys by the examination of specially prepared surfaces. Its original scope was limited by the resolution and depth of field in focus by the imaging of light reflected from the metallic surface. These limitations have been overcome by both transmission and scanning electron microscopy (TEM, STEM and SEM). The analysis of X-rays generated by the interaction of electron beams with atoms at or near the surface, by wavelength or energy dispersive detectors (WDX, EDX), has added quantitative determination of local composition, e.g. of intermetallic compounds, to the deductions from the well-developed etching techniques. Surface features can also be studied by collecting and analysing electrons diffracted from the surface. A diffraction pattern of the surface can be used to determine its crystallographic structure (low-energy electron diffraction or LEED). These electrons can also be imaged as in a conventional electron microscope (Low-energy electron microscopy or LEEM). This technique is especially useful for studying dynamic surface phenomena such as those occurring in catalysis. X-rays photoelectron microscopy (XPS or ESCA) now enables the metallographer to analyse the atoms in the outermost surface layer to a depth of a few atoms (0.3–5.0 nm) and provides information about the chemical environment of the atom. Auger spectroscopy uses a low-energy electron beam instead of X-rays to excite atoms, and analysis of the Auger electrons produced provides similar information about the atoms from which the Auger electron is ejected.

Nevertheless, the conventional optical techniques still have a significant role to play and their interpretation is extended and reinforced by the results of the electronic techniques.

6.1 Metallographic methods for aluminium alloys

PREPARATION

Aluminium and its alloys are soft and easily scratched or distorted during preparation. For cutting specimens, sharp saw-blades should be used with light pressure to avoid local overheating. Specimens may be ground on emery papers by the usual methods, but the papers should preferably have been already well used, and lubricated or coated with a paraffin oil ('white spirit' is suitable), paraffin wax or a solution of paraffin wax in paraffin oil. Silicon carbide papers (down to 600-grit) which can be well washed with water are preferred for harder alloys, the essential point being to avoid the embedding of abrasive particles in the metal. For pure soft aluminium, a high viscosity paraffin is needed to avoid this. Polishing is carried out in two stages: initial polishing with fine α-alumina, proprietary metal polish, or diamond, and final polishing with γ-alumina or fine magnesia, using a slowly rotating wheel (not above 150 rev. min^{-1}). It is essential to use properly graded or levigated abrasives and it is preferable to use distilled water only; it is an advantage to boil new polishing cloths in water for some hours in order to soften the fibres. Many aluminium alloys contain hard particles of various intermetallic compounds, and polishing times should in general be as short as possible owing to the danger of producing excessive relief. Relief may be minimized by experience and skill in polishing; blanket felt may with advantage be substituted for velveteen or selvyt cloth as a polishing pad, while the use of parachute silk on a cork pad is also useful for avoiding relief in the initial stages of the process, but a better general alternative is to use diamond polishing, followed by a very brief final polishing with magnesia.

Many aluminium alloys contain the reactive compound Mg_2Si. If this constituent is suspected, white spirit should be substituted for water during all but the initial stages of wet polishing, to avoid loss of the reactive particles by corrosion.

Table 6.1 MICROCONSTITUENTS WHICH MAY BE ENCOUNTERED IN ALUMINIUM ALLOYS

Microconstituent	*Appearance in unetched polished sections*
Al_3Mg_2	Faint, white. Difficult to distinguish from the matrix.
Mg_2Si	Slate grey to blue. Readily tarnishes on exposure to air and may show irridescent colour effects. Often brown if poorly prepared. Forms Chinese script eutectic.
$CaSi_2$	Grey. Easily tarnished
$CuAl_2$	Whitish, with pink tinge. A little in relief; usually rounded
$NiAl_3$	Light grey, with a purplish pink tinge
Co_2Al_9	Light grey
$FeAl_3^{(1)}$	Lavender to purplish grey; parallel-sided blades with longitudinal markings
$MnAl_6$	Flat grey. The other constituents of binary aluminium-manganese alloys ($MnAl_4$, $MnAl_3$ and 'δ') are also grey and appear progressively darker. May form hollow parallelograms
$CrAl_7$	Whitish grey; polygonal. Rarely attacked by etches
Silicon	Slate grey. Hard, and in relief. Often primary with polygonal shape – use etch to outline
α(AlMnSi)$^{(2)}$	Light grey, darker and more buff than $MnAl_6$
β(AlMnSi)$^{(2)}$	Darker than α(AlMnSi), with a more bluish grey tint. Usually occurs in long needles
Al_2CuMg	Like $CuAl_2$ but with bluish tinge
Al_6Mg_4Cu	Flat, faint and similar to matrix
(AlCuMn)$^{(3)}$	Grey
α(AlFeSi)$^{(4)}$	Purplish grey. Often occurs in Chinese-script formation. Isomorphous with α(AlMnSi)
β(AlFeSi)$^{(4)}$	Light grey. Usually has a needle-like formation
(AlCuFe)$^{(5)}$	Grey α phase lighter than β phase (*see* Note 5)
(AlFeMn)$^{(6)}$	Flat grey, like $MnAl_6$
(AlCuNi)	Purplish grey
(AlFeSiMg)$^{(7)}$	Pearly grey
$FeNiAl_9$	Very similar to and difficult to distinguish from $NiAl_3$
(AlCuFeMn)	Light grey
$Ni_4Mn_{11}Al_{60}$	Purplish grey
$MgZn_2$	Faint white; no relief

In Table 10.1 constituents are designated by symbols denoting the compositions upon which they appear to be based, or by the elements, in parentheses, of which they are composed. The latter nomenclature is adopted where the composition is unknown, not fully established, or markedly variable. The superscript numbers in column 1 refer to the following notes:

(1) On very slow cooling under some conditions, $FeAl_3$ decomposes into Fe_2Al_7 and Fe_2Al_5. The former is micrographically indistinguishable from $FeAl_3$. The simpler formula is retained for consistency with most of the original literature.
(2) α(AlMnSi) is present in all slowly solidified aluminium-manganese-silicon alloys containing more than 0.3% of manganese and 0.2% of silicon, while β(AlMnSi), a different ternary compound, occurs above approximately 3% of manganese for alloys containing more than approximately 1.5% of silicon. α(AlMnSi) has a variable composition in the region of 30% of manganese and 10–15% of silicon. The composition of β(AlMnSi) is around 35% of manganese and 5–10% of silicon.
(3) (AlCuMn) is a ternary compound with a relatively large range of homogeneity based on the composition $Cu_2Mn_3Al_{20}$.
(4) α(AlFeSi) may contain approximately 30% of iron and 8% of silicon, while β(AlFeSi) may contain approximately 27% of iron and 15% of silicon. Both constituents may occur at low percentages of iron and silicon.
(5) The composition of this phase is uncertain. Two ternary phases exist. α(AlCuFe) resembles $FeAl_3$; β(AlCuFe) forms long needles.
(6) The phase denoted as (AlFeMn) is a solid solution of iron in $MnAl_6$.
(7) This constituent is only likely to be observed at high silicon contents.

It should be noted that some aluminium alloys are liable to undergo precipitation reactions at the temperatures used to cure thermosetting mounting resins; this applies particularly to aluminium-magnesium alloys, in which grain boundary precipitates may be induced.

ETCHING

The range of aluminium alloys now in use contains many complex alloy systems. A relatively large number of etching reagents have therefore been developed, and only those whose use has become more or less standard practice are given in Table 6.2. Many etches are designed to render the distinction between the many possible microconstituents easier, and the type of etching often depends on the magnification to be used. The identification of constituents, which is best accomplished by using cast specimens where possible, depends to a large extent on distinguishing between the

Table 6.2 ETCHING REAGENTS FOR ALUMINIUM AND ITS ALLOYS

No.	*Reagent*		*Remarks*
1	Hydrofluoric acid (40%) Hydrochloric acid (1.19) Nitric acid (1.40) Water (Keller's etch)[†]	0.5 ml 1.5 ml 2.5 ml 95.5 ml	15 s immersion is recommended. Particles of all common microconstituents are outlined. Colour indications: Mg$_2$Si and CaSi$_2$: blue to brown α(AlFeSi) and (AlFeMn): darkened β(AlCuFe): light brown MgZn$_2$, NiAl$_3$, (AlCuFeMn), Al$_2$Cu Mg and Al$_6$CuMg: brown to black α(AlCuFe) and (AlCuMn): blackened Al$_3$Mg$_2$: heavily outlined and pitted The colours of other constituents are little altered. Not good for high Si alloys
2	Hydrofluoric acid (40%) Water	0.5 ml 99.5 ml	15 s swabbing is recommended. This reagent removes surface flowed layers, and reveals small particles of constituents, which are usually fairly heavily outlined. There is little grain contrast in the matrix. Colour indications: Mg$_2$Si and CaSi$_2$: blue FeAl$_3$ and MnAl$_6$: slightly darkened NiAl$_3$: brown (irregular) α(AlFeSi): dull brown (AlCrFe): light brown Co$_2$Al$_9$: dark brown (AlFeMn): brownish tinge α(AlCuFe), (AlCuMg) and (AlCuMn): blackened α(AlMnSi), β(AlMnSi) and (AlCuFeMn) may appear light brown to black β(AlFeSi) is coloured red brown to black The remaining possible constituents are little affected
3	Sulphuric acid (1.84) Water	20 ml 80 ml	30 s immersion at 70 °C; the specimen is quenched in cold water. Colour indications: Mg$_2$Si, Al$_3$Mg$_2$ and FeAl$_3$: violently attacked, blackened and may be dissolved out CaSi$_2$: blue α(AlMnSi) and β(AlMnSi): rough and attacked NiAl$_3$ and (AlCuNi): slightly darkened β(AlFeSi): slightly darkened and pitted α(AlFeSi), (AlCuMg) and (AlCuFeMn): outlined and blackened Other constituents are not markedly affected
4	Nitric acid (1.40) Water	25 ml 75 ml	Specimens are immersed for 40 s at 70 °C and quenched in cold water. Most constituents (not MnAl$_6$) are outlined. Colour indications: β(AlCuFe) is slightly darkened Al$_3$Mg$_2$ and AlMnSi: attacked and darkened slightly Mg$_2$Si, CuAl$_2$, (AlCuNi) and (AlCuMg) are coloured brown to black
5	Sodium hydroxide Water	1 g 99 ml	Specimens are etched by swabbing for 10 s. All usual constituents are heavily outlined, except for Al$_3$Mg$_2$ (which may be lightly outlined) and (AlCrFe) which is both unattacked and uncoloured. Colour indications: FeAl$_3$ and NiAl$_3$: slightly darkened (AlCuMg): light brown α(AlFeSi): dull brown* α(AlMnSi): rough and attacked; slightly darkened* MnAl$_6$ and (AlFeMn): coloured brown to blue (uneven attack) MnAl$_4$: tends to be darkened The colours of other constituents are only slightly altered

continued overleaf

Table 6.2 (*continued*)

No.	*Reagent*		*Remarks*
6	Sodium hydroxide Water	10 g 90 ml	Specimens immersed for 5 s at 70 °C, and quenched in cold water. Colour indications: β(AlFeSi): slightly darkened Mn_{11} Ni_4Al_{60}: light brown β(AlCuFe): light brown and pitted $CuAl_2$: light to dark brown $FeAl_3$: dark brown ($FeAl_3$ is more rapidly attacked in the presence of $CuAl_2$ than when alone) $MnAl_6$, $NiAl_3$, (AlFeMn), $CrAl_7$ and AlCrFe: blue to brown α(AlFeSi), α(AlCuFe), $CaSi_2$ and (AlCuMn): blackened
7	Sodium hydroxide Sodium carbonate (in water)	3%–5% 3%–5%	Useful for sensitive etching where reproducibility is essential. In general, the effects are similar to those of Reagent 5, but the tendency towards colour variations for a given constituent is diminished. Particularly useful for distinguishing $FeNiAl_9$ (dark blue) from $NiAl_3$ brown). Potassium salts can be used.
8	Nitric acid Hydrofluoric acid Glycerol	20 ml 20 ml 60 ml	A reliable reagent for grain boundary etching, especially if the alternate polish and etch technique is adopted. The colours of particles are somewhat accentuated
9	Nitric acid, 1% to 10% by vol. in alcohol		Recommended for aluminium-magnesium alloys. Al_3Mg_2 is coloured brown. 5–20% chromium trioxide can be used
10	Picric acid Water	4 g 96 ml	Etching for 10 min darkens $CuAl_2$, leaving other constituents unaffected. Like reagent 4
11	Orthophosphoric acid Water	9 ml 91 ml	The reagent is used cold. Recommended for aluminium-magnesium alloys in which it darkens any grain boundaries containing thin β-precipitates. Specimen is immersed for a long period (up to 30 min). Mg_2Si is coloured black, Al_3Mg_2 a light grey, and the ternary (AlMnFe) phase a dark grey
12	Nitric acid		10 s immersion colours Al_6CuMg_4 greenish brown and distinguishes it from Al_2CuMg, which is slightly outlined but not otherwise affected
13	Nitric acid (density 1.2) Water Ammonium molybdate, $(NH_4)_6Mo_7O_{24}$, $4H_2O$	20 ml 20 ml 3 g	20 ml of reagent are mixed with 80 ml alcohol. Specimens are immersed, and well washed with alcohol after etching. Brilliant and characteristic colours are developed on particles of intermetallic compounds. The effects depend on the duration of etching, and for differentiation purposes standardisation against known specimens is advised
14	Sodium hydroxide (various strengths, with 1 ml of zinc chloride per 100 ml of solution)		Generally useful for revealing the grain structure of commercial aluminium alloy sheet[67]
15	Hydrochloric acid (37%) Hydrofluoric acid (38%) Water	15.3 ml 7.7 ml 77.0 ml	Recommended (30 s immersion at room temperature) for testing the diffusion of copper through claddings of aluminium, aluminium-manganese-silicon, or aluminium-manganese on aluminium-copper-magnesium sheet. Zinc contents up to 2% in the clad material do not influence the result[68]
16	Ammonium oxalate Ammonium hydroxide, 15% in water	1 g 100 ml	Develops grain boundaries in aluminium-magnesium-silicon alloys. Specimens are etched for 5 min at 80 °C in a solution freshly prepared for each experiment

*These are isomorphous and the colour depends on the proportion of Mn and Fe.

†Sodium fluoride can be used in place of HF in mixed acid etches.

colours of particles, so that the illumination should be as near as possible to daylight quality. It is recommended that a set of specially prepared standard specimens, containing various known metallographic constituents, be used for comparison.

It is very easy to obtain anomalous etching effects, such as ranges of colour in certain types of particles, and carefully standardized procedure is necessary. It should be remembered that the form and colour of the microconstituents may vary according to the degree of dispersion brought about by mechanical treatments, and also that the etching characteristics of a constituent may vary according to the nature of the other constituents present in the same section.

Some etching reagents for aluminium require the use of a high temperature; in such cases the specimen should be preheated to this temperature by immersion in hot water before etching. For washing purposes, a liberal stream of running water is advisable.

Electrolytic etching for aluminium alloys. In addition to the reagents given for aluminium in Table 6.2 the following solutions have been found useful for a restricted range of aluminium-rich alloys:

1. The following solution has been used for grain orientation studies:

Orthophosphoric acid (density 1.65)	53 ml
Distilled water	26 ml
Diethylene glycol monoethyl ether	20 ml
Hydrofluoric acid (48%)	1 ml

   The specimen should be at room temperature and electrolysis is carried out at 40 V and less than 0.1 $\mathrm{A\,dm^{-2}}$. An etching time of 1.5–2 min is sufficient for producing grain contrast in polarized light after electropolishing.

2. The solution below is also used for the same purpose and is more reliable for some alloys:

Ethyl alcohol	49 ml
Water	49 ml
Hydrofluoric acid	2 ml (quantity not critical)

   The specimen is anodized in this solution at 30 V for 2 min at room temperature. A glass dish must be used. Not suitable for high-copper alloys.

3. For aluminium alloys containing up to 7% of magnesium:

Nitric acid (density 1.42)	2 ml
40% hydrofluoric acid	0.1 ml
Water	98 ml

   Electrolysis is carried out at a current density of 0.3 $\mathrm{A\,dm^{-2}}$ and a potential of 2 V. The specimen is placed 7.6 cm from a carbon cathode.

4. For cast duralumin:

Citric acid	100 g
Hydrochloric acid	3 ml
Ethyl alcohol	20 ml
Water	977 ml

   Electrolysis is carried out at 0.2 $\mathrm{A\,dm^{-2}}$ and a potential of 12 V.

5. For commercial aluminium:

Hydrofluoric acid (40%)	10 ml
Glycerol	55 ml
Water	35 ml

   This reagent, used for 5 min at room temperature, with a current density of 1.5 $\mathrm{A\,dm^{-2}}$ and a voltage of 7–8 V, is suitable for revealing the grain structure after electropolishing.[72]

6. For distinguishing between the phases present in aluminium-rich aluminium-copper-magnesium alloys, electrolytic etching in either ammonium molybdate solution or 0.880 ammonia has been recommended. In both cases, Al_2CuMg is hardly affected, $CuAl_2$ is blackened, Al_6Mg_4Cu is coloured brown, while Mg_2Al_3 is thrown into relief without change of colour.[73]

GRAIN-COLOURING ETCH

For many aluminium alloys containing copper, and especially for binary aluminium-copper alloys, it is found that Reagent No. 1 of Table 6.2 gives copper films on cubic faces which are subject to preferential attack and greater roughening of the surface. Subsequent etching with 1% caustic soda solution converts the copper into bronze-coloured cuprous oxide, and a brilliant and contrasting representation of the underlying surfaces is obtained. The technique is of use in orientation studies in so far as the films are dark and unbroken on (100) surfaces, but shrink on drying on other surfaces. In particular (111) faces have a bright yellow colour with a fine network on drying, which has no preferred orientation, while (110) faces develop lines (cracks in film) which are parallel to a cube edge.

6.2 Metallographic methods for magnesium alloys

PREPARATION

1. Magnesium is soft and readily forms mechanical twins and so deformed layers should be avoided.
2. Abrasives and polishing media tend to become embedded. Therefore use papers well-covered with paraffin making sure the deformed layer is removed.
3. Some phases in magnesium alloys are attacked by water. If these are present use paraffin or ethanol as lubricant.
4. Some very hard intermetallics can be present. Therefore keep polishing times short to avoid relief.

The recommended procedure is to grind carefully to 600-grit silicon carbide papers. Then polish with fine α-alumina slurry or 4–6 μm diamond paste. This is followed by polishing on a fine cloth using light magnesia paste made with distilled water or a chemical attack polish of 1 g MgO, 20 ml ammon. tartrate soln. (10%) in 120 ml of distilled water. In reactive alloys, white spirit replaces distilled water and chemical attack methods avoided.

ETCHING

The general grain structure is revealed by examination under cross-polars. This will also detect mechanical twins formed during preparation. A selection of etching reagents suitable for magnesium and its alloys is given in Table 6.3. Of these, 4 and 1 are the most generally useful reagents for cast alloys, while 16 is a useful macro-etchant and, followed by 4, is invaluable for showing up the grain structure in wrought alloys.

Table 6.3 ETCHING REAGENTS FOR MAGNESIUM AND ITS ALLOYS

No.	*Etchant*		*Remarks*
1	Nitric acid Diethylene glycol Distilled water	1 ml 75 ml 24 ml	This reagent is recommended for general use, particularly with cast, die-cast and aged alloys. Specimens are immersed for 10–15 s, and washed with hot distilled water. The appearance of common constituents following this treatment is outlined in Table 6.4. Mg-RE and Mg-Th alloys also
2	Nitric acid Glacial acetic acid Water Diethylene glycol	1 ml 20 ml 19 ml 60 ml	Recommended for solution-heat-treated castings, and wrought alloys. Grain boundaries are revealed. The proportions are somewhat critical. Use 1–10 s
3	Citric acid Water	5 g 95 ml	This reagent reveals grain boundaries, and should be applied by swabbing. Polarized light is an alternative
4	Nitric acid, 2% in alcohol		A generally useful reagent
5	Nitric acid, 8% in alcohol		Etching time 4–6 s. Recommended for cast, extruded and rolled magnesium-manganese alloys
6	Nitric acid, 4% in alcohol		Used for magnesium-rich alloys containing other phases, which are coloured light to dark brown
7	Nitric acid, 5% in water		Etching time 1–3 s. Recommended for cast and forged alloys containing approximately 9% of aluminium
8	Oxalic acid 20 $\mathrm{g\,l^{-1}}$ in water		Etching time 6–10 s. Used also for extruded magnesium-manganese alloys
9	Acetic acid, 10% in water		Etching time 3–4 s. Used for magnesium-aluminium alloys with 3% of aluminium

Table 6.3 (*continued*)

No.	*Etchant*	*Remarks*
10	Tartaric acid 20 $\mathrm{g\,l^{-1}}$ of water	Etching time 6 s These regants are recommended for magnesium-aluminium alloys with 3 to 6% of aluminium
11	Orthophosphoric acid, 13% in glycerol	Etching time 12 s
12	Tartaric acid 100 $\mathrm{g\,l^{-1}}$ of water	Used for wrought alloys. Mg_2Si is roughened and pitted. 10 s to 2 min for Mg-Mn-Al-Zn alloys. Grain contrast in cast alloys
13	Citric acid and nitric acid in glycerol	Used for magnesium-cerium and magnesium-zirconium alloys. The magnesium-rich matrix is darkened and the other phases left white
14	Orthophosphoric acid 0.7 ml Picric acid 4 g Ethyl alcohol 100 ml	Recommended for solution-heat-treated castings. The specimen is lightly swabbed, or immersed with agitation for 10–20 s. The magnesium-rich matrix is darkened, and other phases (except Mg_2Sn) are little affected. The maximum contrast between the matrix and $Mg_{17}Al_{12}$ is developed. The darkening of the matrix is due to the development of a film, which must not be harmed by careless drying
15	Picric acid saturated in 95% alcohol 10 ml Glacial acetic acid 1 ml	A grain boundary etching reagent; especially for Dow metal (Al 3% Zn 1%, Mn 0.3%). Reveals cold work and twins
16	Picric acid, 5% in ethyl alcohol 50 ml Glacial acetic acid 20 ml Distilled water 20 ml	Useful for magnesium-aluminium-zinc alloys. On etching for 15 s an amorphous film is produced on the polished surface. When dry, the film cracks parallel to the trace of the basal plane in each grain. The reagent may be used to reveal changes of composition within grains, and other special purposes
17	Picric acid, 5% in ethyl alcohol 50 ml Glacial acetic acid 16 ml Distilled water 20 ml	As for Reagent 16, but suitable for a more restricted range of alloy composition
18	Picric acid, 5% in ethyl alcohol 100 ml Glacial acetic acid 5 ml Nitric acid (1.40) 3 ml	General reagent
19	Picric acid, 5% in ethyl alcohol 10 ml Distilled water 10 ml	Mg_2Si is coloured dark blue and manganese-bearing constituents are left unaffected
20	Hydrofluoric acid (40%) 10 ml Distilled water 90 ml	Useful for magnesium-aluminium-zinc alloys. $Mg_{17}Al_{12}$ is darkened, and $Mg_3Al_2Zn_3$ is left unetched. If the specimen is now immersed in dilute picric acid solution (1 vol. of 5% picric acid in alcohol and 9 vol. of water) the matrix turns yellow, and the ternary compound remains white
21	Picric acid, 5% in ethyl alcohol 100 ml Distilled water 10 ml Glacial acetic acid 5 ml	Reveals grain-boundaries in both cast and wrought alloys. This reagent is useful for differentiating between grains of different orientations, and for revealing internally stressed regions
22	Nitric acid conc.	Recommended for pure metal only. Specimen is immersed in the cold acid. After 1 min a copious evolution of NO_2 occurs, and then almost ceases. At the end of the violent stage, the specimen is removed, washed and dried. Surfaces of very high reflectivity result, and grain boundaries are revealed

The appearance of constituents after etching. The micrographic appearances of the commonly occurring microconstituents in cast alloys are as given in Table 6.4.

ELECTROLYTIC ETCHING OF MAGNESIUM ALLOYS

This has been recommended for forged alloys. The specimen is anodically treated in 10% aqueous sodium hydroxide containing 0.06 $\mathrm{g\,l^{-1}}$ of copper. A copper cathode is used, and a current density of

Table 6.4 THE MICROGRAPHIC APPEARANCE OF CONSTITUENTS OF MAGNESIUM ALLOYS

Microconstituent	*Appearance in polished sections, etched with Reagent 1 (zirconium-free alloys)*
$Mg_{17}Al_{12}^{(1)}$	White, sharply outlined and brought into definite relief
$MgZn_2^{(2)}$	Appearance very similar to that of $Mg_{17}Al_{12}$
$Mg_3Al_2Zn_3^{(3)}$	Appearance similar to those of $Mg_{17}Al_{12}$ and $MgZn_2$
$Mg_2Si^{(4)}$	Watery blue green; the phase usually has a characteristic Chinese-script formation, but may appear in massive particles. Relief less than for manganese
$Mg_2Sn^{(4)}$	Tan to brown or dark blue, depending on duration of etching. Individual particles may differ in colour
Manganese$^{(5)}$	Grey particles, usually rounded and in relief. Little affected by etching
(MgMnAl)$^{(5)}$	Grey particles, angular in shape and in relief. Little affected by etching
Microconstituent	*Appearance in polished sections etched with Reagent 4 (zirconium-bearing alloys)*
Primary Zr (undissolved in molten alloy)	Hard, coarse, pinkish grey rounded particles, readily visible before etching
Zinc-rich particles$^{(6)}$	Fine, dark particles, loosely clustered and comparatively inconspicuous before etching
Mg_9Ce	Compound or divorced eutectic in grain boundaries. Appearance hardly changed by few per cent of zinc or silver
Mg_5Th	Compound or divorced eutectic in grain boundaries (bluish). Appearance hardly changed by few per cent of zinc if Zn exceeds Th
Mg-Th-Zn	Brown acicular phase. Appears in Mg-Th-Zn-Zr alloys when Th $\geq$ Zn
$MgZn_2$	Compound or divorced eutectic in grain boundaries. Absent from alloys containing RE or Th

The superscript numbers in column 1 refer to the following notes:

(1) This is the γ-phase of the magnesium-aluminium system; it is also frequently called Mg_4Al_3 or Mg_3Al_2.
(2) Although the phase MgZn may be observed in equilibrium conditions, $MgZn_2$ is frequently encountered in cast alloys.
(3) This ternary compound occurs in alloys based on the ternary system magnesium-aluminium-zinc, and may be associated with $Mg_{17}Al_{12}$.
(4) Blue unetched.
(5) These constituents are best observed in the unetched condition.
(6) Alloys of zirconium with interfering elements such as Fe, Al, Si, N and H, separating as a Zr-rich precipitate in the liquid alloy. Co-precipitation of various impurities makes the particles of indefinite composition.

Note: The microstructure of all zirconium-bearing cast alloys with satisfactory dissolved zirconium content is characterised by Zr-rich coring in the centre of most grains. In the wrought alloys zirconium is precipitated from the cored areas during preheating or working, resulting in longitudinal striations of fine precipitate which become visible on etching.

0.53 $A\,dm^{-2}$ is applied at 4 V. After etching, the specimen is successively washed with 5% sodium hydroxide, distilled water and alcohol, and is finally dried.

NON-METALLIC INCLUSIONS IN MAGNESIUM-BASE ALLOYS

The detection and identification of accidental flux and other inclusions in magnesium alloys involves the exposure of a prepared surface to controlled conditions of humidity, when corrosion occurs at the site of certain inclusions, others being comparatively unaffected. The corrosion product or the inclusion may then be examined by microchemical techniques.

The surface to be examined should be carefully machined and polished by standard procedures. The polishing time should be short, and alcohol or other solvent capable of dissolving flux must be avoided. As soon as possible the prepared specimens are placed in a humidity chamber, having been protected in transit by wrapping in paper. A suitable degree of humidity is provided by the air above a saturated solution of sodium thiosulphate. The presence of corrosive inclusions is indicated by the development of corrosion spots. At this stage the corroded area may be lightly ground away to expose the underlying structure for microexamination so that the micrographic features which are holding the flux become visible. With other specimens, or with the same specimens re-exposed to the humid conditions, identification of the inclusions may be proceeded with, as follows:

1. Detection of chloride

The corrosion product is scraped off, and dissolved on a microscope slip in 5% aqueous nitric acid. A 1% silver nitrate solution is then added, and a turbidity of silver chloride indicates the presence of the chloride ion. The solution of the corrosion product should preferably be heated before adding the silver nitrate to remove any sulphide ion, which also gives rise to turbidity. Alternatively, a 10% solution of chromium trioxide may be added directly to the corrosion spot, when chloride is indicated by an evolution of gas bubbles from the metal surface, and the development of a brown stain. This method is less specific than the silver nitrate method, and may give positive reactions in the presence of relatively large amounts of sulphates and nitrates.

2. Detection of calcium

Scrapings of corrosion product are dissolved in a small watch glass on a hot plate in 2 ml water and one drop of glacial acetic acid. To the hot solution a few drops of saturated ammonium oxalate solution are added. The presence of calcium is indicated by turbidity or precipitation. Spectroscopic identification of calcium in the solution is also possible.

3. Detection of boric acid in inclusions

Scrapings of corrosion product and metal are placed in a test tube with 1 ml of water. The inclusion dissolves, and complete solution of the sample is effected by adding a small portion of sulphuric acid (density 1.84) from 9 ml carefully measured and contained in a graduated cylinder. When solution is complete, the remainder of the acid is added and the mixture is well shaken; 0.5 ml of a 0.1% solution of quinalizarin in 93% (by wt.) of sulphuric acid is now added, mixed in, and allowed to stand for 5 min. A blue colour indicates the presence of boric acid. The colour in the absence of boric acid varies from bluish violet to red according to the dilution of the acid, which must thus be carefully controlled as described.

4. Detection of nitride

A drop of Nessler’s solution applied directly to the metal surface in the presence of nitride, gives an orange brown precipitate, which may take about 1 min to develop. This test should be made on freshly prepared surfaces on which no water has been used, since decomposition of nitride to oxide occurs in damp air.

5. Detection of sulphide

The corrosion product is added to a few drops of water slightly acidified with nitric acid. A drop of the solution placed on a silver surface gives rise to a dark stain if sulphide was present in the corrosion product. Sulphur printing may also be applied.

6. Detection of iron

The corrosion product is dissolved in hydrochloric acid. A drop of nitric acid is added with several drops of distilled water. In the presence of iron, the addition of a crystal of ammonium thiocyanate develops a blood-red colouration.

In all the above tests, a simultaneous *blank* test should be carried out.

Iron-printing, analogous to sulphur-printing, can be applied using cleaned photographic paper impregnated with a freshly prepared solution of potassium ferricyanide and potassium ferrocyanide acidified with nitric or hydrochloric acid.

6.3 Metallographic methods for titanium alloys

PREPARATION

The preparation of titanium samples by ordinary methods of grinding is straightforward but needs care; final polishing is difficult. Specimens are easily scratched, and mechanical working of the surface during polishing causes twin-formation which may obscure other metallographic features.

Other ‘false’ structures may be caused by the presence of local, randomly dispersed areas of cold work, which give a duplex appearance to homogeneous specimens. Electrolytic polishing of surfaces ground wet by ordinary methods to the 000 grade of emery paper is therefore recommended.

Mechanical polishing, if preferred, may be carried out with diamond preparation, with a final fine polish (if required) with alumina, both with a trace of hydrofluoric acid.

Examination for hydride is carried out in polarised light between crossed polaroids; the hydride then appears bright and anisotropic. This also reveals the grain structure of α-titanium.

ETCHING

The presence of surface oxide films on titanium and its alloys necessitates the use of strongly acid etchants. Those given in Table 6.5 are useful.

Table 6.5 ETCHING REAGENTS FOR TITANIUM AND ITS ALLOYS

No.	*Etchant*		*Conditions*	*Remarks*
1	Hydrofluoric acid (40%)	1–3 ml	5–30 s	Mainly unalloyed titanium; reveals hydrides
	Nitric acid (1.40)	10 ml		
	Lactic acid	30 ml		
2	Hydrofluoric acid (40%)	1 ml	5–30 s	As Etchant 1
	Nitric acid (1.40)	30 ml		
	Lactic acid	30 ml		
3	Hydrofluoric acid (40%)	1–3 ml	3–10 s	Most useful general etch
	Nitric acid (1.40)	2–6 ml		
	Water	to 100 ml		
	(Kroll's reagent)			
4	Hydrofluoric acid (40%)	10 ml	5–30 s	Chemical polish and g.b. etch
	Nitric acid (1.40)	10 ml		
	Lactic acid	30 ml		
5	Potassium hydroxide (40%)	10 ml	3–20 s	Useful for α/β alloys. α is attacked or stained. β unattacked
	Hydrogen peroxide (30%)	5 ml		
	Water	20 ml		
	(can be varied to suit alloy)			
6	Hydrofluoric acid (40%)	20 ml	5–15 s	General purpose, TiAlSn alloys
	Nitric acid	20 ml		
	Glycerol	40 ml		
7	Hydrofluoric acid	1 ml	3–20 s	TiAlSn alloys
	Nitric acid (1.40)	25 ml		
	Glycerol	45 ml		
	Water	20 ml		

7 Heat treatment of light alloys

7.1 Aluminium alloys

7.1.1 Annealing

For softening aluminium alloys that have been hardened by cold work:
Alloys 1080A, 1050, 1200, 5251, 5154A, 5454, 5083 –360 °C for 20 min.
Alloys 3103, 3105 – 400–425 °C for 20 min.
Heat-treatable alloys that have not been heat treated – 360 °C ± 10 °C for 1 h and cool in air.
Alloys that have been heat treated – 400–425 °C for 1 h and cool at 15 °C/h to 300 °C.
For Al-Zn-Mg alloys of the 7000 series, after cooling in air, reheat to 225 °C for 2–4 h.

7.1.2 Stabilizing

To relieve internal stress. Normally heat to 250 °C followed by slow cooling is adequate.

7.1.3 Hardening

Conditions for solution treatment and ageing for both cast and wrought aluminium alloys are given in Tables 7.1 and 7.2. For the alloy designation system and compositions see Chapter 3. Temper designations are given in Table 7.3.

Table 7.1 HEAT TREATMENT DATA FOR ALUMINIUM CASTING ALLOYS

Material designation and temper	*Alloy type*	*Solution treatment*		*Quench*[2] *medium*	*Precipitation treatment*	
		Temperature °C	*Time*[1] h		*Temperature* °C	*Time*[3] h
BS 1490						
LM 4–TF	Al Si5 Cu3	505–520	6–16	Hot water	150–170	6–18
LM 9–TE	Al Si12 Mg	–	–	–	150–170	16
–TF		520–535	2–8	Water	150–170	16
LM 10–TB	Al Mg10	425–435	8	Oil at 160 °C max[4]	–	–
LM 13–TE	Al Si11 Mg Cu	–	–	–	160–180	4–16[†]
–TF		515–525	8	Hot water	160–180	4–16
–TF7		515–525	8	Hot water	200–250	4–16
LM 16–TB	Al Si5 Cu1 Mg	520–530	12	Hot water	–	–
–TF		520–530	12	Hot water	160–179	8–10
LM 22–TB	Al Si6 Cu3 Mn	515–530	6–9	Hot water	–	–

continued overleaf

Table 7.1 (*continued*)

Material designation and temper	*Alloy type*	*Solution treatment*		*Quench*[2] *medium*	*Precipitation treatment*	
		Temperature °C	*Time*[1] h		*Temperature* °C	*Time*[3] h
LM 25–TB7	Al Si7 Mg	525–545	4–12	Hot water	250	2–4
–TE		–	–	–	155–175	8–12
–TF		525–545	4–12	Hot water	155–175	8–12
LM 26–TE	Al Si9 Cu3 Mg	–	–	–	200–210	7–9
LM 28–TE	Al Si19 Cu Mg Ni	–	–	–	185	†
–TF		495–505	4	Air blast	185	8
LM 29–TE	Al Si23 Cu Mg Ni	–	–	–	185	†
–TF		495–505	4	Air blast	185	8
LM 30–TS	Al Si17 Cu4 Mg	–	–	–	175–225	8
BS ‘L’ series						
(4L 35)	Al Cu4 Ni2 Mg2	500–520	6	Boiling water	95–110 or room temperature	2 5 days
3L 51	Al Si2 Cu Ni Fe Mg	–	–	–	150–175	8–24
(3L 52)	Al Cu2 Ni Si Fe Mg	520–540	4	Water at 30–100 °C	150–180 or 195–205	8–24 2–5
(4L 53)	Al Mg10	425–435	8	Oil at 160 °C max[4]	–	–
3L 78	Al Si4 Cu1	520–530	12	Hot water	160–170	8–10
(2L 91)	Al Cu4	525–545	12–16	Hot water	120–140	1–2
2L 92	Al Cu4	525–545	12–16	Hot water	120–170	12–14
(L 99)	Al Si6	535–545	12	Hot water	150–160	4
(L 119)	Al Cu5 Ni1	542 ± 5	5	Boiling water or oil at 80 °C	215 ± 5	12–16
L 154	Al Cu4 Si1	510 ± 5	16	Water (50–70 °C)	–	30 days
L 155	Al Cu4 Si1	510 ± 5	16	Water (50–70 °C)	140 ± 10	16
DTD specifications						
722B	Al Si5				165 ± 10	8–12
727B	Al Si5	540 ± 5	4–12	Water (80–100 °C) or oil	130 ± 10	1–2
735B	Al Si5	540 ± 5	4–12	Water (80–100 °C)	165 ± 10	8–12
5008B	Al Zn5 Mg	–	–	–	180 ± 5	10
5018A	Al Mg7 Zn	430 ± 5	8	Oil > 160 °C > 1 h then oil at room temperature, or air	–	–
or		440 ± 5	8			
then		495 ± 5	8	Boiling water	–	–

[1] Single figures are minimum times at temperature for average castings and may have to be increased for particular castings.

[2] Hot water means water at 70–80 °C unless otherwise stated.

[3] The exact number of hours depends on the mechanical properties required.

[4] The castings may be allowed to cool to 385–395 °C in the furnace before quenching. The castings shall be allowed to stay in the oil for not more than 1 h and may then be quenched in water or cooled in air.

† The duration of the treatment shall be such as will produce the specified Brinell hardness in the castings.

* For temper designation see Table 7.2.

() Specification now withdrawn.

Table 7.2 TYPICAL HEAT TREATMENT DATA FOR WROUGHT ALUMINIUM ALLOYS
Times and temperatures within the limits shown. some specifications give tighter limits

Material designation	*Alloy type*	*Temper*‡	*Solution treatment*		*Ageing temperature* °C	*Time at temperature* h
			Temperature °C	*Quench medium*†		
2011	Al Cu5.5 Pb Bi	T 3 (TD)	510 ± 5	Water	Room	48
		T 6 (TF)	510 ± 5	Water	155–165	12

Table 7.2 (*continued*)

Material designation	*Alloy type*	*Temper*[‡]	*Solution treatment*		*Ageing temperature* °C	*Time at temperature* h
			Temperature °C	*Quench medium*[†]		
2014A	Al Cu4 Si Mg	T 3 (TD)	505 ± 5	Water	Room	48
		T 4 (TB)	505 ± 5	Water	Room	48
		T 6 (TF)	505 ± 5	Water	155–190	5–20
		T 651	505 ± 5	Water	155–190	5–20
2024	Al Cu4 Mg1	T 351	495 ± 5	Water	Room	48
		T 4 (TB)	495 ± 5	Water	Room	48
		T 42	495 ± 5	Water	Room	48
2031	Al Cu2 Ni1 Mg Te Si	T 4 (TB)	525 ± 10	Water or oil	155–205	2–20
2117	Al Cu2 Mg	T 4 (TB)	495 ± 5	Water	Room	96
2618A	Al Cu2 Mg15 Te1 Ni1	T 6 (TF)	530 ± 5	Water	160–200	16–24
6061	Al Mg1 Si Cu	T 4 (TB)	525 ± 15	Water	Room	–
		T 6 (TF)	525 ± 15	Water	165–195	3–12
6063	Al Mg Si	T 4 (TB)	525 ± 5	Water	Room	–
		T 5 (TE)	–	–	160–180	5–15
		T 6 (TF)	525 ± 5	Water	160–180	5–15
6082	Al Si1 Mg Mn	T 4 (TB)	530 ± 10	Water	Room	1 20
		T 6 (TF)	530 ± 10	Water	175–185	7–12
		T 651	525 ± 15	Water	165–195	3–12
6101A	Al Mg Si	T 4 (TB)	525 ± 5	Water	Room	1 20
		T 6 (TF)	525 ± 5	Water	170 ± 10	
6463	Al Mg Si	T 4 (TB)	525 ± 5	Water	Room	1 20
		T 6 (TF)	525 ± 5	Water	170 ± 10	5–15
7010	Al Zn6 Mg2 Cu2	T 351	475 ± 10	Water	–	–
		T 7651	475 ± 10	Water	172 ± 3[*]	6–15
				or	120 ± 3	24
				followed by	172 ± 3	6–15
		T 73651	465 ± 10	Water	172 ± 3[*]	10–24
7014	Al Zn5.5 Mg2 Cu Mn	T 6 (TF)	460 ± 10	Water 85 °C or oil	135 ± 5	12
		T 6510	460 ± 10	Water or oil	135 ± 5	12
7075	Al Zn6 Mg Cu	T 6 (TF)	460 ± 10	Water	135 ± 5	12
		T 651	460 ± 10	Water	135 ± 5	12
		T 73	465 ± 5	Water (60–80 °C)	110 ± 5	6–24
				or	120 ± 5	20–30
				followed by	177 ± 5	6–10
		T 7351	465 ± 5	Water	110 ± 5	6–24
				followed by	177 ± 5	5–12
		T 7352	465 ± 5	Water 70 °C	110 ± 5	6–24
				or	120 ± 5	20–30
				followed by	177 ± 5	6–10

[*] Heating to temperature at not more than 20 °C/h.

[†] Water below 40 °C unless otherwise stated.

[‡] For temper designation see Table 7.3

Table 7.3 ALUMINIUM ALLOY TEMPER DESIGNATIONS

Symbol	*Condition*
Casting alloys BS 1490	
M	As cast
TB	Solution treated and naturally aged
TB7	Solution treated and stabilized
TE	Artificially aged
TF	Solution treated and artificially aged
TF7	Solution treated, artificially aged and stabilized
TS	Thermally stress relieved

continued overleaf

Table 7.3 (*continued*)

Symbol	*Condition*
BSEN515	
T 1	Cooled from elevated temperature shaping process and naturally aged to stable condition
T 2	As T 1 but cold worked after cooling from elevated temperature
T 3 (TD)	Solution treated, cold worked and naturally aged to stable condition
T 4 (TB)	Solution treated and naturally aged to stable condition
T 5 (TF)	Cooled from elevated temperature shaping process and artificially aged
T 6	Solution treated and artificially aged
T 7	Solution treated and stabilized (over-aged)
T 8 (TH)	Solution treated, cold worked and then artificially aged
T 9	Solution treated, artificially aged and then cold worked
T 10	Cooled from elevated temperature shaping process artificially aged and then cold worked

*British equivalents in parenthesis.

7.2 Magnesium alloys

7.2.1 Safety requirements

A potential fire hazard exists in the heat treatment of magnesium alloys. Overheating and direct access to radiation from heating elements must be avoided and the furnace must be provided with a safety cutout which will turn off heating and blowers if the temperature goes more than 6 °C above the maximum permitted. In a gastight furnace a magnesium fire can be extinguished by introducing boron trifluoride gas through a small opening in the closed furnace after the blowers have been shut down.

7.2.2 Environment

For temperature over 400 °C, surface oxidation takes place in air. This can be suppressed by addition of sufficient sulphur dioxide, carbon dioxide or other suitable oxidation inhibitor.

In the case of castings to MEL ZE63A and related specifications, solution treatment should be carried out in an atmosphere of hydrogen and quenching of castings from solution treatment temperature of MEL QE22 is to be done in hot water.

If microscopic examination reveals eutectic melting or high temperature oxidation, rectification cannot be achieved by reheat-treatment. Quench from solution treatment should be rapid, either forced air or water quench. From ageing treatment, air cool.

7.2.3 Conditions for heat treatment of magnesium alloys castings

These are shown in Table 7.4 and for some wrought magnesium alloys in Table 7.5. Stress relief treatments are given in Table 7.6.

Table 7.4 HEAT TREATMENT OF MAGNESIUM CASTING ALLOYS

		Solution treatment		*Ageing*	
Specifications	*Composition*	*Temperature* (°C)	*Time* (h) *quench*	*Temperature* (°C)	*Time* (h) *quench*
MEL ZRE1 BS 2L126 BS 2970 MAG 6 ASTM EZ33A UNS M12330	Zn2.5 Zr0.6 RE3.5	–	–	250	16 AC

Table 7.4 (*continued*)

		Solution treatment		*Ageing*	
Specifications	*Composition*	*Temperature* (°C)	*Time* (h) *quench*	*Temperature* (°C)	*Time* (h) *quench*
MEL RZ5 BS 2L128 BS 2970 MAG 5 ASTM ZE41A UNS M16410	Zn4.2 Zr0.7 RE1.3	–	–	330 +170–180	2 AC 10–16 AC
MEL ZE63A DTD 5045 ASTM ZE63A	Zn5.8 Zr0.7 RE2.5	480*	10–72 WQ	140	48 AC
MELZT1 DTD 5005A BS 2970 MAG 8 ASTM HZ32A	Zn2.2 Zr0.7 Th3.0	–	–	315	16 AC
MEL TZ6 DTD 5015A BS 2970 MAG 9 ASTM ZH62A UNS M16620	Zn5.5 Zr0.7 Th1.8	–	–	330 +170–180	2 AC 10–16 AC
MEL EQ21A	Ag1.5 Zr0.7 Cu0.07 Nd(RE)2.0	520	8 WQ	200	12–16 AC
MEL MSR-B DTD 5035A	Ag2.5 Zr0.6 Nd(RE)2.5	520–530	4–8 WQ	200	8–16 AC
MEL QE22 (MSR) DTD 5055 ASTM QE22A UNS M18220	Ag2.5 Zr0.6 Nd(RE)2.0	520–530	4–8 WQ Hot WQ	200	8–16 AC
MEL A8 BS 3L122 BS 2970 MAG1 ASTM AZ81A UNS M11818	Al8.0 Zn0.5 Mn0.3	380–390 410–420	8 AC 16 AC	–	–
MEL AZ91 (ST) BS 3L124 BS 2970 MAG 3	Al9.0 Zn0.5 Mn0.3 Be0.0015	380–390 410–420	8 AC 16 AC	–	–
ASTM AZ91C (ST&PT) UNS M11914	Al9.0 Zn0.5 Mn0.3 Be0.0015	380–390 410–420	8 AC 16 AC	200	10 AC
MEL MAG 7 (ST) BS 2970 MAG 7	Al7.5/9.5 Zn0.3/1.5 Mn0.15	380–390 410–420	8 AC 16 AC	–	–
MEL MAG 7 (ST&PT)	Al7.5/9.5 Zn0.3/1.5 Mn0.15	380–390 410–420	8 AC 16 AC	200	10 AC

*In hydrogen. Max 490 °C.

Table 7.5 HEAT TREATMENT OF MAGNESIUM WROUGHT ALLOYS

			Solution treatment		*Ageing*	
Specifications	*Composition*	*Form*	*Temperature* (°C)	*Time* (h) *quench*	*Temperature* (°C)	*Time* (h) *quench*
MEL AZ80 ASTM AZ80A	Al8.5 Zn0.5 Mn0.12	Ex	–	–	177	16 AC
UNS M11800		F	400	2-4 WQ	177	16-24 AC

continued overleaf

Table 7.5 (*continued*)

			Solution treatment		*Ageing*	
Specifications	*Composition*	*Form*	*Temperature* (°C)	*Time* (h) *quench*	*Temperature* (°C)	*Time* (h) *quench*
ASTM HM31A UNS 13310	Th2.5-4.0 Zn0.3 Zr0.4-1.0	Ex	–	–	232	16 AC
ASTM 60A UNS 16600	Zn5.5	F T6	500	2 WQ	150	24 AC
		F T4	500	2 WQ	–	–
		F T5	–	–	150	24 AC

Notes: Ex – extrusions, F – forgings, T4 – solution treated, T5 – cooled and artificially aged, T6 – solution treated and artificially aged, AC – air cool, WQ – water quench.

Table 7.6 STRESS RELIEF TREATMENTS FOR WROUGHT MAGNESIUM ALLOYS

Specifications	*Composition*	*Form*	*Temperature* (°C)	*Time* (min)
MEL AZM	Al6.0 Zn1.0	Ex&F	260	15
ASTM Al61A	Mn0.3	SH	204	60
UNS 11610		SA	343	120
MEL AZ80	Al8.5 Zn0.5	Ex&F	260	15
ASTM AZ80	Mn0.12 min	Ex&F*	204	60
UNS 11311				
MEL AZ31	Al3.0 Zn1.0	Ex&F	260	15
ASTM AZ31B	Mn0.3	SH	149	60
UNS 11311		SA	343	120

Notes: Ex – extrusions, F – forgings, SH – sheet hard rolled, SA – sheet annealed, * – cooled and artificially aged.

8 Metal finishing

The processes and solutions described in this section are intended to give a general guide to surface finishing procedures. To operate these systems on an industrial scale would normally require recourse to one of the Chemical Supply Houses which retail properietary solutions.

8.1 Cleaning and pickling processes

VAPOUR DEGREASING

Used to remove excess oil and grease. Components are suspended in a solvent vapour, such as tri- or tetrachloroethylene.
Note: Both vapours are toxic and care should be taken to ensure efficient condensation or extraction of vapours.

EMULSION CLEANING

An emulsion cleaner suitable for most metals can be prepared by diluting the mixture given below with a mixture of equal parts of white spirit and solvent naphtha.

Pine oil	62 g
Oleic acid	10.8 g
Triethanolamine	7.2 g
Ethylene glycol-monobutyl ether	20 g

This is used at room temperature and should be followed by thorough swilling.

Table 8.1 ALKALINE CLEANING SOLUTIONS

Metal to be cleaned	*Composition of solution*			*Temperature*		*Remarks*
		oz gal^{-1}	g l^{-1}	°F	°C	
All common metals other than aluminium and zinc, but including magnesium	Sodium hydroxide (NaOH)	6	37.5	180–200	80–90	For heavy duty
	Sodium carbonate (Na_2CO_3)	4	25.0			
	Tribasic sodium phosphate ($Na_3PO_4.12H_2O$)	1	6.2			
	Wetting agent	$\frac{1}{4}$	1.5			

continued overleaf

Table 8.1 (*continued*)

Metal to be cleaned	*Composition of solution*			*Temperature*		*Remarks*
		oz gal^{-1}	g l^{-1}	°F	°C	
	Sodium hydroxide	2	12.5	180–200	80–90	For medium duty
	Sodium carbonate	4	25.0			
	Tribasic sodium phosphate	2	12.5			
	Sodium metasilicate ($Na_2SiO_3.5H_2O$)	2	12.5			
	Wetting agent	$\frac{1}{8}$	0.75			
	Tribasic sodium phosphate	4	25.0	180–200	80–90	For light duty
	Sodium metasilicate	4	25.0			
	Wetting agent	$\frac{1}{8}$	0.75			
Aluminium and zinc	Tribasic sodium phosphate	2	12.5	180–200	80–90	–
	Sodium metasilicate	4	25.0			
	Wetting agent	$\frac{1}{8}$	0.75			
Most common metals	Sodium carbonate	2	12.5	180–200	80–90	Electrolytic cleaner, 6 V Current density
	Tribasic sodium phosphate	4	25.0			100/A ft^{-2} (10/A dm^{-2})
	Wetting agent	$\frac{1}{4}$	1.5			Article to be cleaned may be made cathode or anode or both alternately
Most common metals	Sodium carbonate	6	37.5	Room	Room	May be used electrolytically
	Sodium hydroxide	1	6.25			
	Tribasic sodium phosphate	2	12.5			
	Sodium cyanide (NaCN)	2	12.5			
	Sodium metasilicate	1	6.25			
	Wetting agent	$\frac{1}{8}$	0.75			

Table 8.2 PICKLING SOLUTIONS

Metal to be pickled	*Composition of solution*			*Temperature*		*Remarks*
		oz gal^{-1}	g l^{-1}	°F	°C	
Aluminium (wrought)	*For etching*					
	Sodium hydroxide (NaOH)	8	56	104–176	40–80	Articles dipped until they gas freely, then swilled, and dipped in nitric acid 1 part by vol. to 1 of water (room temperature)
Aluminium (cast and wrought)	Nitric acid, s.g. 1.42	1 gal	11	Room	Room	Articles first cleaned in solvent degreaser. Use polythene or PVC tanks
	Hydrofluoric acid (52%)	1 gal	11			
	Water	8 gal	81			

Table 8.2 (*continued*)

Metal to be pickled	*Composition of solution*			*Temperature*		*Remarks*
		oz gal^{-1}	g l^{-1}	°F	°C	
	Bright dip					
	Chromic acid	0.84 oz	5.2 g	195	90	Immerse for $1\frac{1}{2}$ min. Solution has limited life. AR chemicals and deionized or distilled water should be used
	Ammonium bifluoride	0.72 oz	4.5 g			
	Cane syrup	0.68 oz	4.2 g			
	Copper nitrate	0.04 oz	0.25 g			
	Nitric acid (s.g. 1.4)	4.8 oz	30 ml			
	Water (distilled) to	1 gal	11			
Aluminium and other non-ferrous metals	*Bright dip*					
	Phosphoric acid (s.g. 1.69)	8.4 gal	9.41	195	90	Immerse for several min. Agitate work and solution. Good ventilation necessary. Addition of acetic acid
	Nitric acid (s.g. 1.37)	0.6 gal	0.61			
Magnesium and magnesium alloys	*General cleaner*					
	Chromic acid	16–32	100–200	Up to b.p.	Up to b.p.	For removal of oxide films, corrosion products, etc. Should not be used on oily or painted material
	Sulphuric acid pickle					
	Sulphuric acid*	3%	–	Room	Room	Should be used on rough castings or heavy sheet only. Removes approx. 0.002 in. in 20–30 s
	Nitro-sulphuric pickle					
	Nitric acid	8%	–	Room	Room	
	Sulphuric acid*	2%	–			
	Bright pickle for wrought products					
	Chromic acid	23	150	Room	Room	Lustrous appearance. Involves metal removal
	Sodium nitrate	4	25			
	Calcium or magnesium fluoride	$\frac{1}{8}$	$\frac{3}{4}$			
	Bright pickle for castings					
	Chromic acid	$37\frac{1}{2}$	235	Room	Room	
	Concentrated nitric acid (70%)	$3\frac{1}{4}$	20			
	Hydrofluoric acid (50%)	1	6.2			
	Acetic acid	8 approx.	50 approx.	Room	Room	Special purpose pickles
	Citric acid	8 approx.	50 approx.	Room	Room	Special purpose pickles

Note: It is almost universal practice to use an inhibitor in the pickling bath. This ensures dissolution of the scale with practically no attack on the metal. Inhibitors are usually of the long chain amine type and often proprietary materials. Examples are Galvene and Stannine made by ICI.

8.2 Anodizing and plating processes

Table 8.3 ANODIZING PROCESSES FOR ALUMINIUM
Good ventilation above the bath and agitation of the bath is advisable in all cases.

Composition of solution			*Temperature*		*Current density* amp ft^{-2} (A dm^{-2})	*Time and voltage*	*Cathodes*	*Vat*	*Hangers*	*Remarks*
	oz gal^{-1}	g l^{-1}	°F	°C						
Chromic acid (CrO$_3$), chloride content must not exceed 0.2 g l^{-1} sulphate less than 0.5 g l^{-1} (After Bengough- Stuart)	5–16	30–100	103–108	38 42	Current controlled by voltage. Average 3–4 (0.3–0.4) d.c.	†1–10 min 0–40 V increased in steps of 5 V 5–35 min Maintain at 40 V 3–5 min Increase gradually to 50 V 4–5 min Maintain at 50 V	Tank or stainless steel	Steel (exhausted)	Pure aluminium or titanium	Slight agitation is required This process cannot be used with alloys containing more than 5% copper
Sulphuric acid (s.g. 1.84)	32	200	60–75	15–24	10–20 (1–2) d.c.	12–18 V 20–40 min	Aluminium or lead plates (tank if lead lined)	Lead lined steel	Pure aluminium or titanium	The current must not exceed 0.2 Al^{-1} of electrolyte
Hard anodizing Hardas process Sulphuric acid	32	200	23–41	−5– + 5	25–400 (2.5–40) d.c.	40–120 V	Lead	Lead lined steel	Aluminium or titanium	Agitation required. Gives coating 1–3 thou. thick
Eloxal GX process Oxalic acid (COOH)$_2$.2H$_2$O	12.8	80	70	20	10–20 (1–2) d.c.	50 V 30–60 min	Vat lining	Lead lined steel	Aluminium or titanium	Oxalic acid processes are more expensive than sulphuric acid anodizing; but coatings are thicker and are coloured.

Eloxal WX process Oxalic acid	12.8	80	75–95	25–35	20–30 (2–3) a.c.	20–60 V 40–60 min	Vat lining	Lead lined steel	Aluminium or titanium	
Integral colour Anodizing Kalcolor process Sulphuric acid Sulphosalicylic acid	0.8 16	5 100	72	22	30 (3) d.c.	25–60 V 20–45 min	Lead	Lead lined steel	Aluminium or titanium	Aluminium level in solution must be maintained between 1.5 and 3 $g\,l^{-1}$

† Period according to degree of protection Complete cycle normally 40 min.

Table 8.4 ANODIZING PROCESSES FOR MAGNESIUM ALLOYS

Composition of solution			*Temperature*		*Current density* A ft^{-2} (A dm^{-2})	*Time and voltage*	*Cathodes*	*Vat*	*Hangers*	*Remarks*
	oz gal^{-1}	g l^{-1}	F	C						
HAE process										
Potassium hydroxide	19.2	120	<95	<35	12–15 (1.2–1.5)	90 min at 85 V approx. a.c. preferred	Mg alloy for a.c. Mg or steel if d.c. used	Mild steel or rubber lined	Mg alloy	Matt hard, brittle, corrosion resistant, dark brown 25–50 μm thick, abrasion resistant
Aluminium	1.7	10.4								
Potassium fluoride	5.5	34								
Trisodium phosphate	5.5	34								
Potassium manganate	3.2	20								
Dow 17 process										
Ammonium bifluoride	39	232	160–180	70–85	5–50 (0.5–5)	10–100 min up to 110 V a.c. or d.c.	Mg alloy for a.c. Mg or steel for d.c.	Mild steel or rubber lined	Mg alloy	Matt dark green, corrosion resistant, 25 μm thick approx., abrasion resistant
Sodium dichromate	16	100								
Phosphoric acid 85% H_3PO_4	14	88								
Cr 22 process										
Chromic acid	4	25	165–205	75–95	15 (1.5)	12 min 380 V a.c.	–	Mild steel	Mg alloy	Matt dark green, corrosion resistant, 25 μm thick approx.
Hydrofluoric acid (50%)	4	25								
Phosphoric acid H_3PO_4 (85%)	13.5	84								
Ammonia solution	25–30	160–180								
MEL process Fluoride anodize										
Ammonium bifluoride	16	100	<86	<30	5–100 (0.5–10)	30 min 120 V a.c. preferred	Mg alloy for a.c. Mg or steel for d.c.	Rubber lined	Mg alloy	Principally a cleaning process to improve corrosive resistance by dissolving or ejecting cathodic particles from the surface

8.3 Plating processes for magnesium alloys

DOW PROCESS (H. K. DELONG)

This process depends on the formation of a zinc immersion coat in a bath of the following composition:

Component	*Concentration* oz gal^{-1}	g l^{-1}
Tetrasodium pyrophosphate	16	120
Zinc sulphate	5.3	40
Potassium fluoride	1.0	7

The treatment time is 3–5 min at a temperature of 175–185 F (80–85 °C) with mild agitation. The pH of the bath should be 10–10.4.

The steps of the complete process are:

1. Solvent or vapour degreasing.
2. Hot caustic soda clean or cathodic cleaning in alkaline cleaner.
3. Pickle $\frac{1}{4}$–$1\frac{1}{2}$ min in 1% hydrochloric acid and rinse.
4. Zinc immersion bath as above without drying off from the rinse.
5. Cold rinse and immediately apply copper strike as under.

Component	*Concentration* oz gal^{-1}	g l^{-1}
Copper cyanide	4.2	26
Potassium cyanide	7.4	46
Potassium carbonate	2.4	15
Potassium hydroxide	1.2	7.5
Potassium fluoride	4.8	30
Free cyanide	1.2	7.5
pH	12.8–13.2	–
Temperature	140 °F (60 °C)	–

CONDITIONS

30–40 A ft^{-2} (3–4 A dm^{-2}) for $\frac{1}{2}$–1 min, reducing to 15–20 A ft^{-2} (1.5–2 A dm^{-2}) for 5 min or longer.

If required, the copper thickness from the above strike can be built up in the usual alkaline or proprietary bright plating baths. Following the above steps, further plating may be carried out in conventional electroplating baths.

ELECTROLESS PLATING ON MAGNESIUM

Deposits of a compound of nickel and phosphorus can be obtained on magnesium alloy components by direct immersion in baths of suitable compositions. Details of the process may be obtained from the inventors. The Dow Chemical Co. Inc., Midland, Michigan, USA.

‘GAS PLATING’ OF MAGNESIUM (VAPOUR PLATING)

Deposits of various metals on magnesium components (as on other metals) can be produced by heating the article in an atmosphere of a carbonyl or hydride of the metal in question.

9 Superplasticity of light metal alloys

Superplasticity is the name given to the ability of a material to sustain extremely large deformations at low flow stresses at a temperature around half the melting point expressed in Kelvin. It is only found in metals and alloys, which have, and can maintain during forming, a very fine grain structure. A parameter which indicates the degree of superplasticity is the strain rate sensitivity m, given by the high temperature flow equation: $\sigma = K\dot{e}^m$, σ is the stress for plastic flow, $\dot{e}$ the applied strain rate and K is a constant. Superplastic materials have m values normally between 0.4 and 0.6, while most other metals and alloys at elevated temperatures have m values of 0.2; viscous materials (e.g. glass) behave like a Newtonian fluid and have m values of 1.

A full discussion of the mechanism of superplasticity, including methods for determining m, can be found in K. A. Padmanabhan and G. J. Davies, 'Superplasticity', Berlin, Springer-Verlag, 1980.

The tables in this chapter give alloy systems with the temperature range over which they show superplasticity, the maximum possible percentage elongation, and the m value. The values of about 10^{-4} quoted under remarks are preferred strain rates.

Table 9.1 NON-FERROUS-SYSTEMS (LIGHT METAL ALLOY)

Alloy system	*Temperature range* °C	*Maximum elongation* %	*m*	*Remarks*
Al (commercial)	380–580	6 000	0.2	
Al–7.6Ca	400–600	850	0.78	Euratom alloy
Al–7.6Ca	~500	570	0.32	Optimum 500 °C at 4.16×10^{-4}
Al–5Ca–5Zn	450			Alcan 08050
Al–17Cu	400–520	600	0.35	
Al–32:74Cu	~510	>160	0.7	After 25% pre-deformation at 510 °C
Al–33Cu	380–520	1 150	0.9	
Al–6Cu–0.5Zr	400–500	2 000	0.5	TI Supral
Al–2.59Cu–2.26Li–0.16Zr(2090)	450–480	1 800	–	Optimum 520 °C at 5×10^{-4}
Al–4.40Cu–0.70Mg–0.80Si–0.75Mn(2014) + 15%SiC	450–480	160	0.4	Elong% 350% at 5.25 MPa hydrostatic pressure
Al–25–33Cu–7–11Mg	420–480	>600	0.72	
Al–Ga–Ti	RT	–	0.3–0.5	
Al–4Ge	400–500	230	–	
Al–2.4Li–2.0Cu–0.70Mg–0.08Zr(8091	490–550	1 350	0.6	Optimum 530 °C at 10^{-3} – 10^{-4}
Al–2.5Li–1.2Cu–0.6Mg–0.1Zr(8090)	520–530	660–1200	0.65	2–3 mm sheet at $2–5 \times 10^{-4}$

Table 9.1 (*continued*)

Alloy system	*Temperature range* °C	*Maximum elongation* %	*m*	*Remarks*
Al–2.4Li–1.2Cu–0.60Mg–0.12Zr(8090)	~530	>1 000	0.68	2 mm sheet at 5×10^{-4} and 5–10 micron grain size
Al–1.56Mg–5.6Zn	530	500	0.7	
Al–3Mg–6Zn	340–360	400	0.35	TI BA 480
Al–0.93Mg–10.72Zn–0.42Zr	550	1 550	0.9	
Al–5.8Mg–0.37Zr + others	520	>800	0.6	
Al–4.89 Mg–1.19Cr	482–520	>1 000		Optimum 520 °C at 1.6×10^{-2}
Al–8.0Mg–1.0Li–0.15Zr	300	>1 000		
Al–5.70Zn–2.30Mg–1.50Cu–0.22Cr(7475) + 15% SiC	495–515	97	0.43	Elong% 310% at 5.25 MPa hydrostatic pressure
Al–5.70Zn–2.30Mg–1.50Cu–0.22Cr(7475)	~530	1 300		Optimum 530 °C at 2.8×10^{-4}
Mg–33Al	350–400	2 100	0.8	Eutectic
Mg–9Li	180	460	0.52	At 3×10^{-4}; 6.1 micron grain size
Mg–9Li	200	445	0.47	At 1×10^{-3}; 7.1 micron grain size
Mg–9Li	250	310	0.44	At 1×10^{-4}; 14.2 micron grain size
Mg–4.3Al–3Zn–0.5Mn				Russian MA 15
Mg–30.7Cd	450	250	–	
Mg–5.5Zn–0.5Zr	270–310	1 000	0.6	ZK 60
Mg–0.5Zr	500	150	0.3	
Ti (commercial)	900	–	0.8	RC 70
Ti–4Al–0.250$_2$	950–1 050	–	0.6	
Ti–5Al–2.5Sn	900–1 100	450	0.72	
Ti–6Al–4V	750–1 000	1 000	0.85	Commercial alloy used throughout world
Ti–6Al–5Zr–4Mo–1Cu–0.25Si	800	300	–	IMI 700
Ti–8Mn	580–900	140	0.95	
Ti–15Mo	580–900	450	0.6	
Ti–11Sn–5Zr–2.25Al–1Mo–0.25Si	800	500	–	IMI 679

10 Light metal-matrix composites

Metal-matrix composites are engineered materials comprising reinforceants of high elastic modulus and high strength in a matrix of a more ductile and tougher metal of lower elastic modulus and strength. The metal-matrix composite has a better combination of properties than can be achieved by either component material by itself. The objective of adding the reinforceant is to transfer the load from the matrix to the reinforceant so that the strength and elastic modulus of the composite are increased in proportion to the strength, modulus and volume fraction of the added material.

The reinforcement can take one of several forms. The least expensive and most readily available on the market are the particulates. These can be round but are usually irregular particles of ceramics, of which SiC and Al_2O_3 are most frequently used. Composites reinforced by particulates are isotropic in properties but do not make best use of the reinforceant. Fine fibres are much more effective though usually more costly to use. Most effective in load transfer are long parallel continuous fibres. Somewhat less effective are short parallel fibres. Long fibres give high axial strength and stiffness, low coefficients of thermal expansion and, in appropriate matrices, high creep strength. These properties are very anisotropic and the composites can be weak and brittle in directions normal to that of the fibres. Where high two-dimensional properties are needed, cross-ply or interwoven fibres can be used. Short or long randomly oriented fibres provide lower efficiencies in strengthening (but are still more effective than particulates). These are most frequently available as SiC whiskers or as short random alumina (‘Saffil’) fibres or alumino-silicate matts.

Long continuous fibres include drawn metallic wires, mono-filaments deposited by CVD or multi-filaments made by pyrolysis of polymers. The properties of some typical fibres are compared in Table 10.1. The relative prices are given as a very approximate guide.

Because most composites are engineered materials, the matrix and the reinforceant are not in thermodynamic equilibrium and so at a high enough temperature, reaction will occur between them which can degrade the properties of the fibre in particular and reduce strength and more especially fatigue resistance. As many composites are manufactured by infiltration of the liquid metal matrix into the pack of fibres, reaction may occur at this stage. Some typical examples of interaction are listed in Table 10.2.

In order to obtain load transfer in service, it is essential to ensure that the reinforceant is fully wetted by the matrix during manufacture. In many cases, this requires that the fibre is coated with a thin interlayer which is compatible with both fibre and matrix. In many cases, this also has the advantage of preventing deleterious inter-diffusion between the two component materials. The data on most coatings are proprietary knowledge. However, it is well known that silicon carbide is used as an interlayer on boron and on carbon fibres to aid wetting by aluminium alloys.

The routes for manufacturing composites are still being developed but the most successful and lowest cost so far is by mixing particulates in molten metal and casting to either foundry ingot or as billets for extrusion or rolling. This is applied commercially to aluminium alloy composites. Another practicable route is co-spraying in which SiC particles are injected into an atomized stream of aluminium alloy and both are collected on a substrate as a co-deposited billet which can then be processed conventionally. This is a development of the Osprey process and can be applied more widely to aluminium and other alloys. Other routes involve the infiltration of molten metal into fibre pre-forms of the required shape often contained within a mould to ensure the correct final shape. This can be done by squeeze casting or by infiltrating semi-solid alloys to minimize interaction between the fibre and metal. Fibres can also be drawn through a melt to coat them and then be consolidated by hot-pressing.

Table 10.1 PROPERTIES OF REINFORCING FIBRES AT ROOM TEMPERATURE

Fibre	*Form*	*Preparation route*	*Diameter* μm	*Density* g cm^{-3}	*Fracture stress* MPa	*Elastic modulus* GPa	*Coefficient of thermal expansion* K^{-1} × 10^{6}	*Price relative to glass fibre*
SiC	Cont. mono-filament	Chemical vapour depos.	150	3.4	3 800	450	4.5	500
SiC	Cont. multi-filament	Polymer fibre pyrolysis	10–15	2.6	2 500	200	4.5	100
SiC	Whisker (random, short)	Polymer fibre pyrolysis	0.1–2.0	3.2	10 000	700	4.5	150
∼Al_2O_3	Multi-filament	Oxide/salt fibre	15–25	3.9	1 500	380	7.0	100
∼Al_2O_3	Random short fibres	pyrolysis	2–4	3.5	2 000	300	7.0	25
C(high modulus)	Cont. multi-filament	Polymer fibre pyrolysis	10	2.0	3 000	600	0	1 000
C(med. strength)	Cont. multi-filament	Polymer fibre pyrolysis	8	1.9	4 200	300	0	100

Table 10.2 TYPICAL INTERACTIONS IN SOME FIBRE-MATRIX SYSTEMS

System	*Potential interaction*	*Temperature of significant interaction* °C
Al–C	Formation of Al_4C_3 at interface. Degradation of C fibre properties.	550 ~495
Al–Al_2O_3	No significant reaction at normal fabrication temperatures	
Al–oxide (Al_2O_3–SiO_3–B_2O_3)	B_2O_3 reacts with Al to form borides.	770
Al–B	Boride formation; interlayer of SiC needed.	500
Al/Li–Al_2O_3	Interfacial layer of $LiAl_5O_8$ on liquid infiltration.	~650
Al–SiC	No significant reaction below melting point.	m.p. 660
	Al_4C_3 and Si can form in liquid Al.	>700
Al–steel	Formation of iron aluminides.	500
Mg(AZ91)–C	No significant reaction at m.p. of alloy provided O and N avoided during infiltration.	
Ti–B	Formation of TiB_2.	750
Ti–SiC	Formation of TiC, $TiSi_2$ and Ti_5Si_3.	700

Table 10.3 MECHANICAL PROPERTIES OF ALUMINIUM ALLOY COMPOSITES AT ROOM TEMPERATURE

Base Alloy	*Nominal composition*	*Form*	*Heat treatment*	*% particulate*	*0.2% proof stress* MPa	*Tensile stress* MPa	*Elongation* %	*Elastic modulus* GPa	*Fracture toughness* $\mathrm{MPa\,m^{-1/2}}$	*Density* $\mathrm{g\,cm^{-3}}$
6061	Mg 1.0	Extrusion	T6	Nil	276	310	20.0	69.9	29.7	2.71
	Si 0.6			10% Al_2O_3	297	338	7.6	81.4	24.1	2.81
	Cu 0.2			15% Al_2O_3	317	359	5.4	87.6	22	2.86
	Cr 0.25			20% Al_2O_3	359	379	2.1	98.6	21.5	2.94
				13% SiC	317	356	4.9	89.5	17.9	–
				20% SiC	440	585	4.0	120.0	–	–
				30% SiC	570	795	2.0	140.0	–	–
2014A	Cu 4.4	Extrusion	T6	Nil	414	483	13.0	73.1	25.3	2.80
	Mg 0.7			10% Al_2O_3	483	517	3.3	84.1	18.0	2.92
	Si 0.8			15% Al_2O_3	476	503	2.3	91.7	18.8	2.97
	Mn 0.75			20% Al_2O_3	483	503	0.9	101.4	–	2.98
				10% SiC	457	508	1.8	91.2	17.7	–
		Sheet	T6	8.2% SiC	448	516	4.5	82.5	–	–
2219	Cu 6.0	Extrusion	T6	Nil	290	414	10.0	73.1	–	–
	Mn 0.3			15% Al_2O_3	359	428	3.8	88.3	–	–
	V 0.1			20% Al_2O_3	359	421	3.1	91.7	–	–
2618	Cu 2.0	Sheet	T6	~10% SiC	396	468	3.3	93.6		–
	Mg 1.5	Extrusion	T6	Nil	320	400	–	75.0	–	–
	Si 0.9	Extrusion	T6	13% SiC	333	450	6.0	89.0	28.9	–
	Fe 0.9									–
	Ni 1.0									
7075	Zn 5.6	Extrusion	T6	Nil	617	659	11.3	71.1	–	–
	Mg 2.2			12% SiC	597	646	2.6	92.2	–	–
	Cu 1.5									
	Cr 0.2									
8090	Li 2.5	Extrusion (18 mm)	T6	Nil	480	550	5.0	79.5	–	–
	Cu 1.3		T6	12% SiC	486	529	2.6	100.1	–	–
	Mg 0.95									
	Zr 0.1									

Table 10.4 MECHANICAL PROPERTIES OF ALUMINIUM ALLOY COMPOSITES AT ELEVATED TEMPERATURES

Base Alloy	*Nominal composition*	*Form*	*Heat treatment*	*% particulate*	*Temperature* °C	*0.2% proof stress* MPa	*Tensile strength* MPa
6061	Mg 1.0	Extrusion	T6	15% Al_2O_3	22	317	359
	Si 0.6			15% Al_2O_3	93	290	331
	Cu 0.2			15% Al_2O_3	150	269	303
	Cr 0.25			15% Al_2O_3	204	241	262
				15% Al_2O_3	260	172	179
				15% Al_2O_3	316	110	117
				15% Al_2O_3	371	62	69
2014A	Cu 4.4	Extrusion	T6	15% Al_2O_3	22	476(413)	503(483)
	Mg 0.7			15% Al_2O_3	93	455(393)	490(434)
	Si 0.8			15% Al_2O_3	150	407(352)	434(379)
	Mn 0.75			15% Al_2O_3	204	317(283)	338(310)
				15% Al_2O_3	260	200(159)	214(172)
				15% Al_2O_3	316	103(62)	110(76)
				15% Al_2O_3	371	55(35)	55(41)

Figures in parentheses are for basic alloy without particulate.

Table 10.5 MECHANICAL PROPERTIES OF MAGNESIUM ALLOY COMPOSITES AT ROOM TEMPERATURE

Base Alloy	*Nominal composition*	*Form*	*% reinforcement*	*0.2% proof stress* MPa	*Tensile strength* MPa	*Elongation* %	*Elastic modulus* GPa
ZK60A	Mg–5.5Zn–0.5Zr	Extruded rod	Nil	260	325	15.0	44
			15% SiC(partic.)	330	420	4.7	68
			20% SiC(partic.)	370	455	3.9	74
			15% SiC(whisker)	450	570	2.0	83
			20% B_4C(partic.)	405	490	2.0	83
	Mg–12Li	Squeeze infiltration	Nil	–	80	8.0	–
		Squeeze infiltration	12% Al_2O_3(fibre)	–	200	3.5	–
		Squeeze infiltration	24% Al_2O_3(fibre)	–	280	2.0	–
		Extruded rod	Nil	–	75	10.0	45
		Extruded rod	20% SiC(whisker)	–	338	0.8	112

Table 10.6 MECHANICAL PROPERTIES OF TITANIUM ALLOY COMPOSITES

Base Alloy	*Form*	*% particulate*	*Temperature* °C	*0.2% proof stress* MPa	*Tensile strength* MPa	*Elongation* %	*Elastic modulus* GPa
Ti-6Al-4V	Forging	10% TiC	21	800	806	1.13	106–120
		10% TiC	427	476(393)	524(510)	1.70(11.6)	–
		10% TiC	538	414(359)	455(441)	2.40(8.5)	–
		10% TiC	649	369(221)	317(310)	2.90(4.2)	–
		10% B_4C	21	–	1055(890)	–	205

Figures in parentheses are for basic alloy without particulate.

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