

Aluminium – Chromium – Magnesium

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Literature Data

Information about the phase equilibria in the aluminium-rich region are due to the results obtained by different investigators [1940Erd, 1940Hof, 1943Mon, 1948Lit, 1956Vul, 1960Zol1, 1960Zol2, 1973Ohn1, 1973Ohn2]. [1940Erd] was the first to examine the phase relations in the Al-rich corner within the range of 0 to 23 mass% Cr and 0 to 37 mass% Mg by means of thermal analysis ($\pm 0.5^\circ\text{C}$, 60 grams of alloy) and optical metallography of a total of 140 alloys. A liquidus projection was established for the Al-rich and Cr-poor region (3 mass% Cr and 35 mass% Mg, see also [1941Han]). All samples were prepared by melting the Al in a graphite crucible internally-lined with sintered Al_2O_3 prior to adding the proper amounts of Cr in the form of an Al-10 mass% Cr master alloy followed by the Mg. To prevent oxidation, a protective layer of Hydrasal was used and, due to a retarded solubility of Al-Cr crystals, the melts had to be kept for prolonged periods at temperature. Starting materials were 99.99 % Al and Mg and 99.86 % pure electrolyte Cr containing 0.095 mass% H, 0.03 % Fe, 0.01 % Si, 0.01 % Cr and 0.003 % S. To avoid separation by gravity, melts were cast in flat 10×15 mm thin-walled iron molds. Phases were specified by selective etching using NaOH (1 %) at 50°C for CrAl_7 (15-45 s, brown, no attack on $\text{Cr}_2\text{Al}_{11}$ and T), and HNO_3 (20 %) at 70°C for Mg_2Al_3 (dark brown, no attack on Al). For an isothermal section at 400°C , the alloys were sealed in silica ampoules under 1 bar of air with addition of Mg filings as a getter material, and heat treated for 720 h at 400°C . Solid solubility limits of a series of alloys (1.96 to 2.07 mass% Mg, 0.12 to 1.6 mass% Cr, balance Al) have been derived at three different temperatures (400, 500 and 600°C) from electrical resistivity measurements and by X-ray examination [1940Hof]; alloys were prepared by casting into thick-walled brass crucibles, annealing at 600 to 620°C for 48 h and subsequently hot drawing (at 420 to 450°C) into a wire of 4 mm diameter, quenching, sealing in silica capsules and finally annealing at 400, 500 and 600°C , respectively. The results of [1940Erd], in particular the existence of a ternary phase T, were essentially confirmed by [1948Lit] in a reinvestigation of the ternary system in the region of 0 to 20 mass% Mg and 0 to 10 mass% Cr on a series of more than 60 samples which were prepared by melting Al and proper amounts of an Al-8.6 mass% Cr master alloy in fluorspar-lined Al_2O_3 crucibles before adding the Mg. The reguli were then sealed in evacuated hard glass tubes, annealed for 380 to 720 h at 460°C and examined by chemical analysis (some), by optical metallography and by X-ray analysis and a partial isothermal section at 460°C was established. Etchants used were hot alkaline permanganate solutions at 60 to 70°C . T was generally outlined by a 1 min swab etch with aqueous hydrofluoric acid. In contradiction to these observations by [1940Erd], [1941Han] and [1948Lit], the ternary phase T was considered by [1943Mon] to constitute a solid solution of Mg in binary $\text{Cr}_2\text{Al}_{11}$ (in this assessment called CrAl_5) rather than a true ternary compound - as a consequence the primary field of the T phase is eliminated in the liquidus projection and the primary field of CrAl_7 will extend further up to 20 mass% of Mg; similarly, the isothermal section proposed by [1943Mon] for a temperature of 447°C is without a ternary compound. In a later review by [1952Han], Mondolfo's version of the phase diagram was rejected on the basis of significant differences between T and the proposed solution of Mg in $\text{Cr}_2\text{Al}_{11}$ as seen under polarized light. The present evaluation was published in the MSIT Evaluation Program earlier and reflects today's state of knowledge.

Binary Systems

The binary system Al-Cr was accepted after [Mas2]. The binary Al-Cr compounds CrAl_7 and $\text{Cr}_2\text{Al}_{11}$ are called here Θ and η , respectively. The new version of the Al-Mg binary system was accepted after [1998Lia]. It is modified according to the documented homogeneity range of the β phase [1997Su], which was not taken into account by the calculation. The small homogeneity range of the ϵ phase [1997Su] is not well established. The Al-Mg phase diagram is accepted from [2003Luk].

Solid Phases

Despite arguments by [1943Mon] (see above) the ternary compound originally labeled T (“CrMgAl₈”) by [1940Erd] and [1941Han] has been confirmed by [1948Lit, 1952Han, 1956Vul, 1973Ohn1] and [1973Ohn2] and an extended homogeneous range was indicated from X-ray and chemical analysis on electrochemically extracted single crystals, then revealing a Cr content of about 11.8 to 12.6 mass% Cr; a tie line construction furthermore resulted in a Mg content varying from 8.2 to 13.5 mass% Mg (“Cr₂Mg₃₋₄Al₂₄₋₂₅”) [1948Lit]. The large lattice parameter, as observed by [1953Lit] for “Cr₂Mg₃Al₂₅” confirms the existence of an extended homogeneous range towards compositions richer in Mg than Cr₂Mg₃Al₁₈, as was also indicated from the investigation by [1948Lit]. Assuming complete occupation of all atom sites in the unit cell, and taking further into account the various results obtained from chemical analyses [1940Erd, 1948Lit], the homogeneous range, however, appears to be at higher Cr contents as indicated by [1948Lit], and thus might be represented by the formula: Cr₂Mg₄Al₁₇ to Cr₂Mg₂Al₁₉ (see also Fig. 6). In contrast to a preliminary X-ray investigation by [1953Lit], a complete determination of the crystal structure by means of single crystal X-ray Weissenberg photographs revealed cubic symmetry $Fd\bar{3}m$ due to observed extinctions (hhl) for $h+l=2n+1$ [1954Sam, 1958Sam]. At a reliability factor of $R = 0.116$ the atom parameters were (origin of cell at $1/8\ 1/8\ 1/8$ from 1): Al1 in 96 g (0.0666(3), 0.0666, 0.2998(4)), Al2 in 48 f (0.1407(6), 0, 0), Mg1 in 16 d (5/8, 5/8, 5/8), Mg2 in 8 b (1/2, 1/2, 1/2) and Cr in 16 c (1/8, 1/8, 1/8)) [1958Sam]. The crystal structure was confirmed using X-ray powder data [1973Ohn1, 1987Ker]. Besides the existence of T (Cr₂Mg₃Al₁₈) the formation of at least one further ternary phase (denoted T_x) was claimed by [1940Erd], but no details were given. Solid solubility of Mg in CrAl₇ and in Cr₂Al₁₁ were observed to be very small [1940Erd] or negligible [1960Zol2]. Solid solubility limits for Cr and Mg in (Al) as derived by [1940Hof] were: 0.56 Cr mass% at 0.0 mass% Mg, 600°C, and 0.38 mass% Cr at 2.0 mass% Mg, 600°C; 0.3 mass% Cr at 0.0 mass% Mg, 500°C and 0.2 mass% Cr at 2.0 mass% Mg, 500°C. These data and later observations by [1948Lit] at 460°C (0.3 mass% Cr at 1.1 mass% Mg) are slightly higher than the more recent findings by [1973Ohn1] and [1973Ohn2] at 400, 450 and 550°C, respectively. Crystallographic data of the solid phases appearing in the diagrams are listed in Table 1.

Invariant Equilibria

Four ternary invariant equilibria were reported by [1940Erd] and [1941Han] in the Al-rich region of the system (35 mass% Mg, 3 mass% Cr; see Table 2): eutectic decomposition of the liquid at $447.3 \pm 0.5^\circ\text{C}$ and three transition type reactions U₁, U₂, U₃, for which a reaction temperature was measured only for U₂ at 632.7°C . The compositions of the liquids are given explicitly [1940Erd, 1941Han], those of the solid phases are corrected in view of later investigations by [1948Lit] and [1973Ohn1, 1973Ohn2] (see also section Isothermal Sections). The anomalous nature of the ternary eutectic was also discussed by [1960Spe]. Based on the information by [1940Erd] on the formation of at least two ternary phases T and T_x, the reaction scheme (Fig. 1) and a projection of the invariant equilibrium planes and the connecting lines of double saturation (Fig. 2) are presented for the Al-rich region of the Al–Cr–Mg system. Due to the lack of detailed information, however, the diagram is partly estimated.

Liquidus Surface

Figure 3 shows some isotherms of the liquidus surface and the melting grooves separating five areas of primary crystallization in the Al-rich region of the system: α , Θ , η , β , T. Figure 3 is essentially based on the experimental results of [1940Erd] and [1960Zol2]. In contrast to [1940Erd], and based on liquid extraction experiments on a series of alloys with constant Mg contents of 1.5, 2.0 and 3.0 mass%, the experiments of [1960Zol2] revealed that with increasing Mg content up to 7 mass% Mg, the α field of primary crystallization contracts.

Isothermal Sections

Figures 4, 5 and 6 reveal the isothermal sections in the Al-rich region at 550, 450 and 400°C according to [1973Ohn1] and [1973Ohn2]. The phase field distribution at 400°C is mainly based on [1940Erd] with

minor corrections regarding the position and homogeneous range of the ternary T phase [1958Sam] which was found from the 460°C section by [1948Lit]. Furthermore, according to the investigations by [1948Lit] and [1973Ohn1, 1973Ohn2], the vertex of the three phase field $\alpha + \Theta + T$ is generally located at smaller Mg and Cr contents, as also suggested by [1952Han] in view of the earlier data by [1940Hof].

Notes on Materials Properties and Applications

[1952Han] and [1956Vul] report on the hardness of the ternary compound T in comparison with binary Cr-aluminides. Whereas [1952Han] measured 540 kg·mm⁻², the variation of the microhardness of “CrMg₂Al₁₂” was given as 461 kg·mm⁻² at 20°C (30 s), 402 kg·mm⁻² at 300°C (30 s) and 358 kg·mm⁻² at 300°C after 60 min [1956Vul]. Furthermore, the influence of “Cr₂Mg₄Al₂₄” (Cr₂Mg₄Al₁₇) on the heat resistance of aluminium alloys was investigated at 300°C. The fatigue limit σ_{100} at 300°C for the alloy containing 0.63 mass% Cr and 2.30 mass% Mg was found to be 4.7 kg·mm⁻² [1956Vul].

Structure and mechanical properties of rapidly solidified Al-(3-6)Mg-(0-9)Cr (at.%) alloys were investigated by [1994Abr]. Authors report that Al–Cr–Mg alloys exhibit higher strength and hardness (Table 3) comparing with corresponding values of binary Al–Cr alloys. However, the use of magnesium as alloying element produced a drastic reduction in tensile ductility.

References

- [1940Erd] Erdmann-Jesnitzer, F., “The Al Corner of the Al–Mg–Cr Ternary System” (in German), *Alum. Arch.*, **29**, 1-15 (1940) (Crys. Structure, Equi. Diagram, Experimental, 11)
- [1940Hof] Hofmann W., Herzer, R.W., “The Solid Solubility of Cr in Al with up to 2 mass% Mg” (in German), *Metallwirtschaft*, **191**, 141-143 (1940) (Equi. Diagram, Experimental, 7)
- [1941Han] Hanemann, H., Schrader, A., “On the Al Ternary Systems” (in German), *Z. Metallkd.*, **33**, 20-21 (1941) (Review, 3)
- [1943Mon] Mondolfo, L.F., “Metallography of Aluminium Alloys”, Wiley & Sons, Inc., New York, London, Chapman and Hall Ltd., London, 71-73 (1943) (Equi. Diagram, Review, 1)
- [1948Lit] Little, K., Axon, H.J., Hume-Rothery, W., “The Constitution of Aluminium–Magnesium–Zinc–Chromium Alloys at 460°C”, *J. Inst. Met.*, **75**, 39-50 (1948-49) (Crys. Structure, Equi. Diagram, Experimental, 12)
- [1952Han] Hanemann, H., Schrader, A., “Ternary Aluminium Alloys” in “*Atlas Metallogr. III*”, (in German), 2, Verlag Stahleisen GmbH, Dusseldorf, 66-69, Tables 4, 5 (1952) (Equi. Diagram, Review, 4)
- [1953Lit] Little, K., “The Ternary Compound E in the System Aluminium–Chromium–Magnesium”, *J. Inst. Met.*, **82**, 463-464 (1953) (Crys. Structure, Experimental, 5)
- [1954Sam] Samson, S., “Crystal Structure of the Intermetallic Compound Mg₃Cr₂Al₁₈”, *Nature*, **173**, 1185-1186 (1954) (Crys. Structure, Experimental, 3)
- [1956Vul] Vul'f, B.K., Chernov, M.N., “The Effect of Ternary Metallic Compound E (AlCrMg) on Heat Resistance of Aluminium Alloys”, *Russ. J. Inorg. Chem.*, **1**(1), 163-168 (1956), translated from *Zh. Neorg. Khim.*, **1**(1), 158-162 (1956) (Experimental, 11)
- [1958Sam] Samson, S., “The Crystal Structure of the Intermetallic Compound Mg₃Cr₂Al₁₈”, *Acta Crystallogr.*, **11**, 851-857 (1958) (Crys. Structure, Experimental, 23)
- [1960Spe] Spengler, H., “The Importance of Research on Eutectics and its Applications to Ternary Eutectic Aluminium Alloys” (in German), *Metall*, **14**, 201-206 (1960) (Review, 11)
- [1960Zol1] Zoller, H., “The Influence of Zn, Mg, Si, Cu, Fe, Mn and Ti on the Primary Crystallization of Al₇Cr” (in German), *Schweiz. Arch. angew. Wiss. u. Techn.*, **26**, 437-448 (1960) (Equi. Diagram, Experimental, 33)
- [1960Zol2] Zoller, H., “The Influence of Zn, Mg, Si, Cu, Fe, Mn and Ti on the Primary Crystallization of Al₇Cr” (in German), *Schweiz. Arch. Angew. Wiss. u. Techn.*, **26**, 478-491 (1960) (Equi. Diagram, Experimental, 33)
- [1968Sam] Samson, S., Gordon, E.K., “The Crystal Structure of ϵ Mg₂₃Al₃₀”, *Acta Crystallogr.*, **B24**, 1004-1013 (1968) (Experimental, Crys. Structure, 32)

- [1973Ohn1] Ohnishi, T., Nakatani, Y., Shimizu, K., “Phase Diagrams and Ternary Compounds of the Al-Mg-Cr and the Al-Mg-Mn Systems in the Al-rich Side” (in Japanese), *J. Jpn. Inst. Light Met.*, **23**, 202-209 (1973) (Crys. Structure, Equi. Diagram, Experimental, 16)
- [1973Ohn2] Ohnishi, T., Nakatani, Y., Shimizu, K., “Phase Diagram in the Al-rich Side of the Al-Mg-Cr Quaternary System” (in Japanese), *J. Jpn. Inst. Light Met.*, **23**, 437-443 (1973) (Equi. Diagram, Experimental, 2)
- [1981Sch] Schürmann, E., Voss, H.J., “Investigation of the Equilibrium Containing Liquid of Mg-Li-Al Alloys” (in German), *Giessereiforschung*, **33**, 43-46 (1981) (Equi. Diagram, Experimental, Review, 17)
- [1987Ker] Kerimov, K.M., Dunaev, S.F., Sljusarenko, E.M., “Investigation of the Structure of Ternary Phases in Al-Mg-Ti, Al-Mg-V and Al-Mg-Cr Systems”, *J. Less-Common Met.*, **133**, 297-302 (1987) (Experimental, Crys. Structure, 9)
- [1994Abr] Abramov, V.O., Sommer, F., “Structure and Mechanical Properties of Rapidly Solidified Al-(Fe,Cr) and Al-Mg-(Fe,Cr) Alloys”, *Mater. Lett.*, **20**, 251-255, (1994) (Experimental, Mechan. Prop., Crys. Structure, 6)
- [1997Su] Su, H.-L., Harmelin, M., Donnadieu, P., Baetzner, C., Seifert, H. J., Lukas, H. L., Effenberg, G., Aldinger, F., “Experimental Investigation of the Mg-Al Phase Diagram from 47-63 at.% Al”, *J. Alloys Compd.*, **247**, 57-65 (1997) (Equi. Diagram, Experimental, 20)
- [1998Lia] Liang, P., Su, H.-L., Donnadieu, P., Harmelin, M.G., Quivy, A., Ochin, P., Effenberg, G., Seifert, H. J., Lukas, H.-L., Aldinger, F., “Experimental Investigation and Thermodynamic Calculation of the Central Part of the Mg-Al Phase Diagram”, *Z. Metallkd.*, **89**, 536-540 (1998) (Equi. Diagram, Thermodyn, Experimental, Theory, Calculation, 33)
- [2003Cor] Cornish, L., Saltykov, P., Cacciamani, G., Velikanova, T., “Al-Cr (Aluminum - Chromium)”, MSIT Binary Evaluation Program, in *MSIT Workplace*, Effenberg, G. (Ed.), MSI, Materials Science International Services GmbH, Stuttgart, to be published, 2003 (Equi. Diagram, Review, 51)
- [2003Luk] Lukas, H.L., “Al-Mg (Aluminium-Magnesium)”, MSIT Binary Evaluation Program, in *MSIT Workplace*, Effenberg, G. (Ed.), MSI, Materials Science International Services GmbH, Stuttgart; to be published, (2003) (Crys. Structure, Equi. Diagram, Assessment, 49)

Table 1: Crystallographic Data of Solid Phases

Phase/ Temperature Range [°C]	Pearson Symbol/ Space Group/ Prototype	Lattice Parameters [pm]	Comments/References
α , (Al) < 660.452	<i>cF4</i> <i>Fm$\bar{3}m$</i> Cu	$a = 404.96$	at 25°C [Mas2]
δ , (Mg) < 650	<i>hP2</i> <i>P6₃/mmc</i> Mg	$a = 320.94$ $c = 521.07$	at 25°C [Mas2]
β , Mg ₂ Al ₃ < 452	<i>cF1168</i> <i>Fd$\bar{3}m$</i> Mg ₂ Al ₃	$a = 2823.9$	1168 atoms on 1704 sites per unit cell [2003Luk] 60-62 at.% Al [1997Su]
ϵ , Mg ₂₃ Al ₃₀ 410-250	<i>hR159</i> <i>R$\bar{3}$</i> Mg ₂₃ Al ₃₀	$a = 1282.54 \pm 0.03$ $c = 2174.78 \pm 0.09$	[V-C, 1968Sam, 1981Sch] 159 atoms refer to hexagonal unit cell [2003Luk]

Phase/ Temperature Range [°C]	Pearson Symbol/ Space Group/ Prototype	Lattice Parameters [pm]	Comments/References
γ , $\text{Mg}_{17}\text{Al}_{12}$ < 458	<i>cI58</i> <i>I43m</i> αMn	$a = 1054.38$ $a = 1048.11$ $a = 1053.05$ $a = 1057.91$	[V-C], $\rho_x = 2.068 \text{ Mg}\cdot\text{m}^{-3}$ 52.58 at.% Mg [L-B] 56.55 at.% Mg [L-B] 60.49 at.% Mg [L-B]
η , $\text{Cr}_2\text{Al}_{11}$ ≤ 940	<i>oC584</i> <i>Cmcm</i>	$a = 1240$ $b = 3460$ $c = 2020$ $a = 1252.1$ $b = 3470.5$ $c = 2022.3$ $a = 1260$ $b = 3460$ $c = 2000$	[2003Cor] quenched from 920°C 16.9 to 19.2 at. % Cr; single crystal "εCrAl ₄ " "εCrAl ₄ "
Θ , CrAl_7 ≤ 790	<i>mC104</i> <i>C2/m</i> Al_{45}V_7	$a = 2519.6$ $b = 757.4$ $c = 1094.9$ $\beta = 128.80^\circ$	$\rho_{\text{obs}} = 2.78 \text{ Mg}\cdot\text{m}^{-3}$ at 13.2 at.% Cr [V-C]
* $\text{T}^{\text{a b}}$, $\text{Cr}_2\text{MgAl}_{18}$	<i>cF184</i> <i>Fd3m</i> $\text{Al}_{18}\text{Cr}_2\text{Mg}_3$	$a = 1455$ $a = 1453 \pm 1$ $a = 1468$	[1958Sam], sp. group <i>Fd3m</i> $\rho_x = 2.86 \text{ Mgm}^{-3}$ [1954Sam] $\rho_{\text{exp}} = 2.80 \text{ Mgm}^{-3}$ [1954Sam] [1987Ker] [1948Lit, 1953Lit] for "Al ₂ Cr ₂ Mg ₃ " converted from kX-units
* T_x	unknown structure -		[1940Erd]

^a Earlier denoted as "Al₈CrMg" by [1940Erd] or as E by [1948Lit] who, from X-ray powder and single crystal oscillation photographs, reported *Fm3m* as the most probable space group due to the lack of extinctions observed for the (hhl)-reflections.

^b Assuming complete occupation of all atom sites in the structure, the large lattice parameter of [1953Lit] suggests an extended homogeneity range towards compositions richer in Mg than Al₁₈Cr₂Mg₃. Taking further into account the various results obtained from chemical analysis [1940Erd, 1948Lit] the homogeneity range might be Al_{17–19}Cr₂Mg_{4–2} (this range is assumed in Fig. 6).

Table 2: Invariant Equilibria

Reaction	T [°C]	Type	Phase	Composition (at.%)		
				Al	Cr	Mg
$L + \eta \rightleftharpoons \Theta + T$	~ 750	U_1	L_1	84.9	1.2	13.9
			η_1	84.6	15.4	0.0
			Θ_1	87.2	12.8	0.0
			T_1	78.3	8.7	13.0
$L + \Theta \rightleftharpoons \alpha + T$	633	U_2	L_2	85.0	0.9	14.1
			Θ_2	87.5	12.5	0.0
			α_2	97.5	0.3	2.2
			T_2	81.3	8.6	10.1
$L + T_x \rightleftharpoons \beta + T$	448	U_3	L_3	64.6	1.1	34.3
			T_{x3}	unknown		
			β_3	60.5	0.0	39.5
			T_3	74.0	8.7	17.3
$L \rightleftharpoons \alpha + \beta + T$	447	E	L_4	65.5	0.9	33.6
			α_4	85.6	0.0	14.4
			β_4	61.5	0.0	38.5
			T_4	78.6	8.4	13.0

Table 3: Mechanical Properties of Al–Cr–Mg and Al–Cr Alloys [1994Abr]

Composition (at.%)			Yield strength [MPa]	UTS [MPa]	Elongation (%)	Hardness [MPa]
Al	Cr	Mg				
99.5	0.5	0	185	198	16.5	566
98.5	1.5	0	233	235	8.5	755
98.0	2.0	0	241	257	8.0	950
92.0	2.0	6.0	498	520	4.0	1610

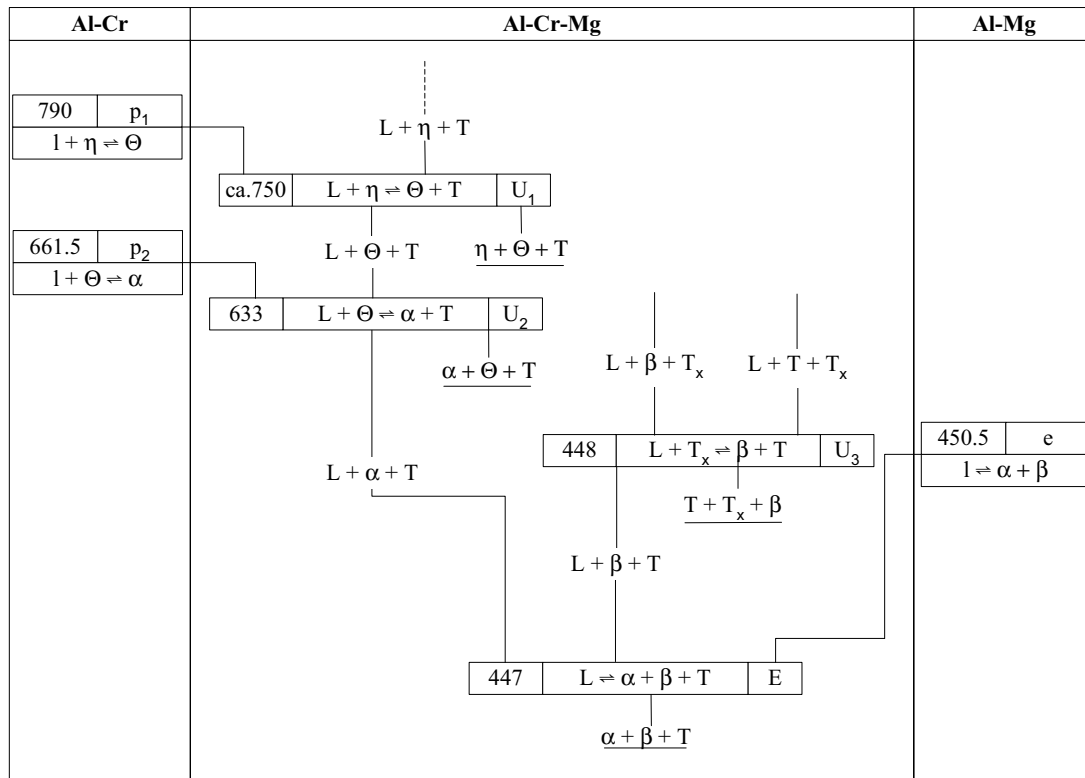
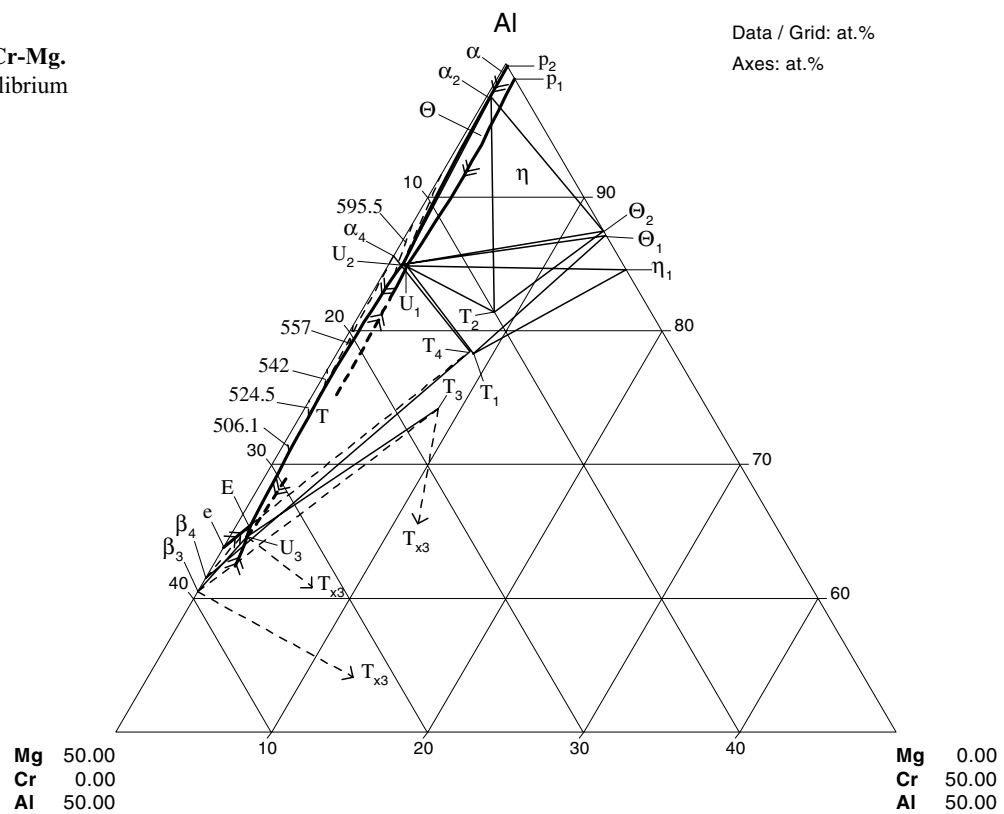


Fig. 1: Al-Cr-Mg. A partial reaction scheme

Fig. 2: Al-Cr-Mg.
Invariant equilibrium
planes

Data / Grid: at. %
Axes: at. %

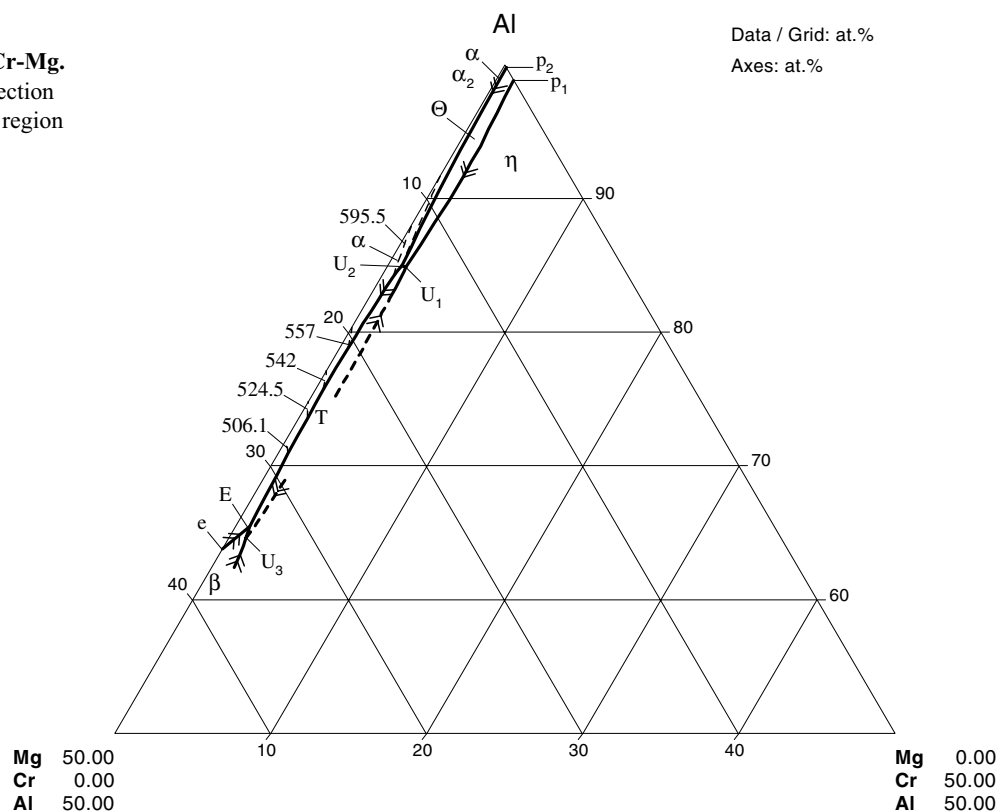


Fig. 5: Al-Cr-Mg.
Phase equilibria in
the Al corner at
450°C

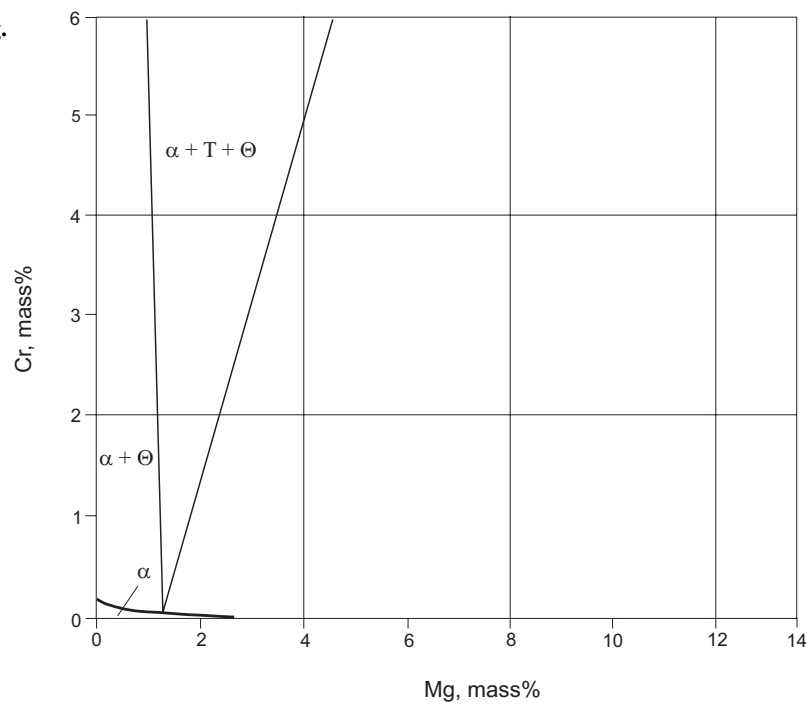


Fig. 6: Al-Cr-Mg.
Partial isothermal
section at 400°C

