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Al-Gd-Mg (Aluminum-Gadolinium-Magnesium)

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Several reports on the phase equilibria of this ternary system have appeared in recent years [1996Rok, 1997Rok, 2000Can, 2000Gro, 2001Gro, 2003Den, 2003Cac]. The system is characterized by the presence of a ternary phase Al_4GdMg (τ) and extensive solubility of the third component in the binary compounds GdMg and $GdAl_2$.

Binary Systems

The Al-Gd system [2003Den, 2003Cac] has the following intermediate phases: $GdAl_3$ ($D0_{19}$, Ni_3Sn-type hexagonal), $GdAl_2$ ($C15$, $MgCu_2$-type cubic), GdAl (ErAl-type orthorhombic), Gd_3Al_2 (Zr_3Al_2-type tetragonal), and Gd_2Al ($C23$, Co_2Si-type orthorhombic). The Al-Mg phase diagram [1998Lia] shows the following intermediate phases: Mg_2Al_3 (cubic, denoted β), R or ε (rhombohedral) and $Mg_{17}Al_{12}$ ($A12$, αMn-type cubic, denoted γ). The Gd-Mg phase diagram [2003Den, 2003Cac] has four intermediate phases: $GdMg_5$ ($GdMg_5$-type cubic), $GdMg_3$ ($D0_3$, BiF_3-type cubic), $GdMg_2$ ($C15$, $MgCu_2$-type cubic), and GdMg ($B2$, CsCl-type cubic).

Ternary Phase Equilibria

With starting metals of 99.99% Al, 99.85% Gd, and 99.96% Mg, [1996Rok] and [1997Rok] melted Gd-lean alloys in a resistance furnace or an induction furnace under Ar atm. For isothermal studies, [1996Rok] annealed alloys at 400 °C for 100 h. For determining the thermal arrests, [1997Rok] employed differential thermal analysis (DTA) at a heating/cooling rate of 18 °C per min. The phase equilibria were studied with optical and scanning electron microscopy and x-ray diffraction. From the results of about 60 ternary alloys, [1996Rok] constructed an isothermal section at 400 °C. The main feature of this section is the presence a ternary compound Al_4GdMg (τ) with the $MgZn_2$-type hexagonal structure and lattice parameters of a = 0.552 nm and c = 0.888 nm [1996Rok]. From the DTA results and metallographic observations, [1997Rok] constructed a liquidus projection, which depicts nine four-phase invariant reactions. [1997Rok] also constructed three vertical sections at a constant Al content of 50 mass%, and along the Mg-$GdAl_2$ and the Al32Mg-Al25Gd (mass%) joins respectively.

[2000Gro] and [2001Gro] carried out thermodynamic calculations of the phase equilibria of this system. The calculations of [2001Gro] indicated that the ternary liquidus temperatures are much higher than what was reported by [1997Rok] and that the thermal arrests below 700 °C observed by [1997Rok] are to be attributed to other phase equilibria involving the liquid phase (below the liquidus). To check the thermodynamic predictions, [2001Gro] designed key experiments with three alloys. Using starting metals of 99.8% Al, 99.95% Gd and 99.98% Mg, the alloys were made by arc-melting under Ar atm and were subjected to DTA measurements and x-ray diffraction studies. A liquidus projection, an isothermal section at 400 °C and four vertical sections at a constant 9 mass % Mg, 50 mass % Al, and 70 mass % Al and along the Mg-$GdAl_2$ join respectively were computed by [2001Gro]. The vertical sections are shown in Fig. 1-4. Thermal arrests from [1997Rok] or [2001Gro] are shown. The agreement is satisfactory. One arrest point from [2001Gro] at 1254 °C in Fig. 2 lies close to the calculated $GdAl_2$-liquidus curve, thus confirming the higher liquidus temperatures found by calculation.

With starting metals of 99.999% Al, 99.9% Gd, and 99.99% Mg, [2003Den] induction-melted five ternary alloys. Differential thermal analysis (DTA) was carried out at a heating/cooling rate of 10 °C/min. For isothermal studies, the samples were annealed at 400 °C for 850 h and water quenched. The phase equilibria were studied with optical and electron microscopy, x-ray powder diffraction and electron probe microanalysis. These experimental results were used in the thermodynamic optimization by [2003Cac]. The computed isothermal section shown in Fig. 5 agrees well with the experimental results. An Al-rich ternary phase τ is present at 400 °C. It has a

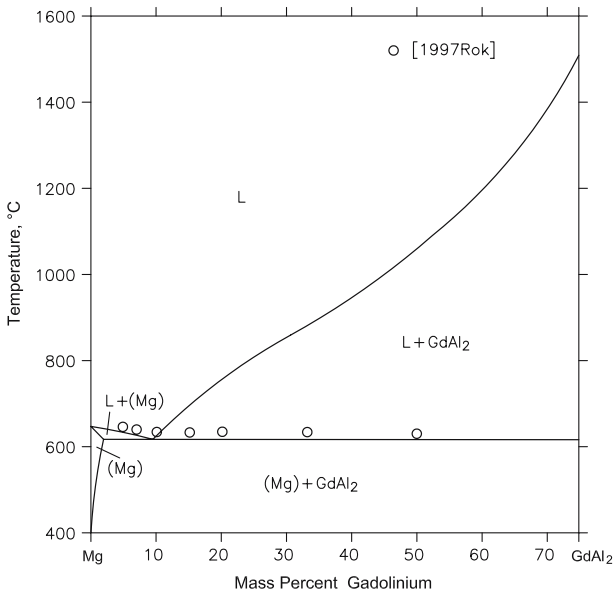

Fig. 1 Al-Gd-Mg computed vertical section along Mg-$GdAl_2$ [2001Gro]

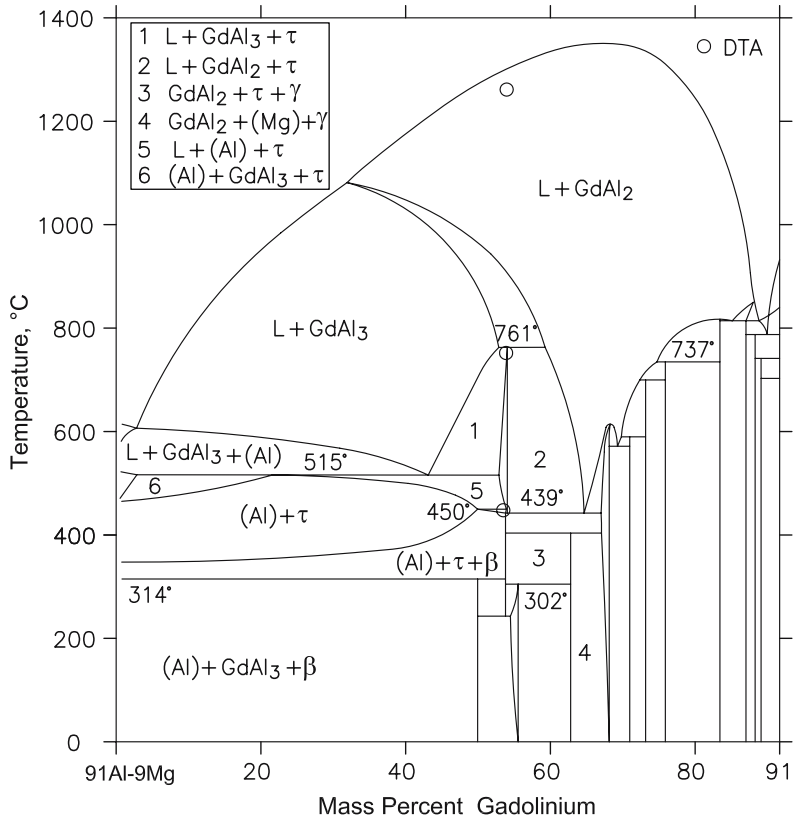

Fig. 2 Al-Gd-Mg computed vertical section at a constant 9 mass% Mg [2001Gro]

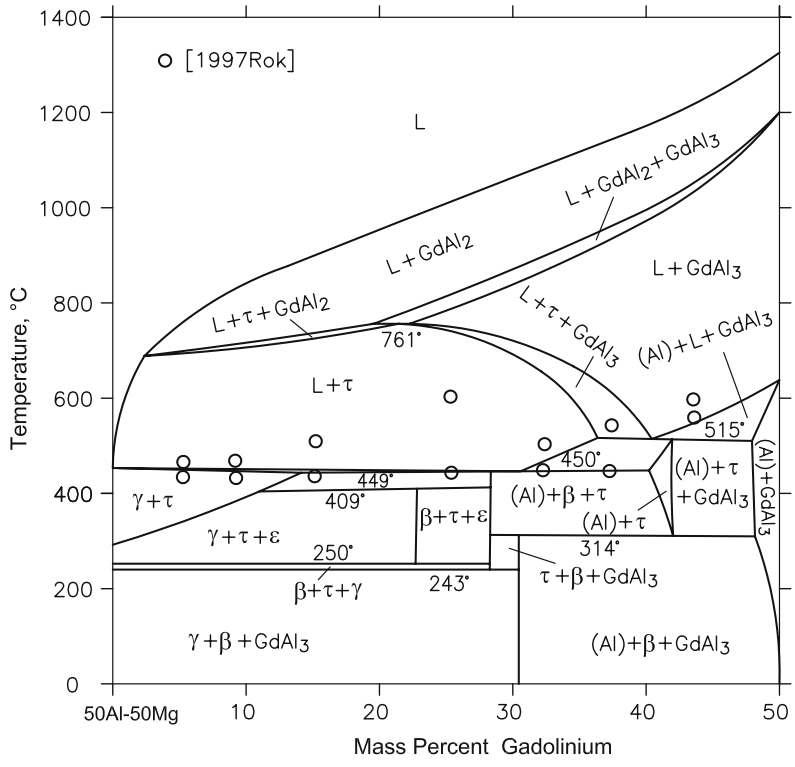

Fig. 3 Al-Gd-Mg computed vertical section at a constant 50 mass% Al [2001Gro]

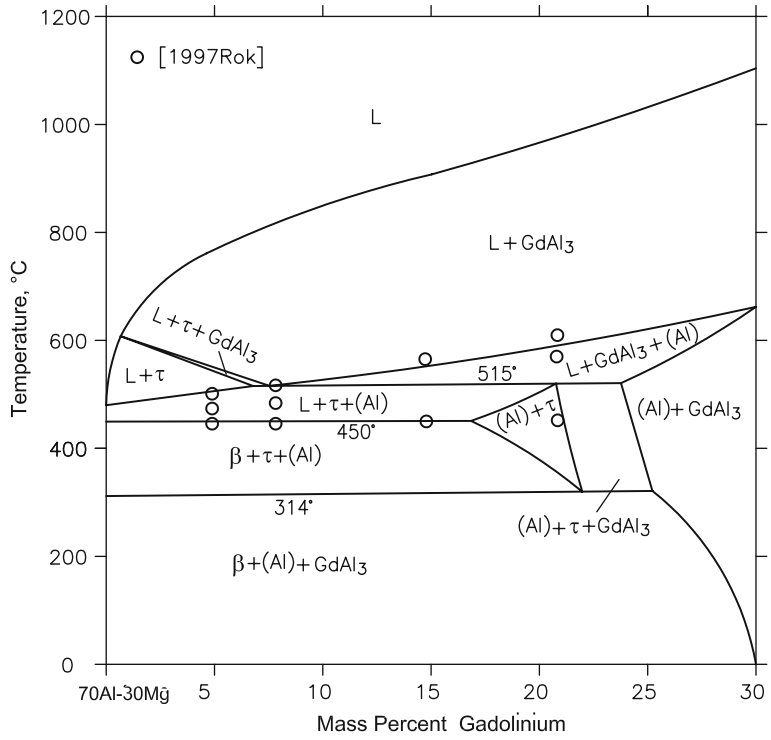

Fig. 4 Al-Gd-Mg computed vertical section at a constant 70 mass% Al [2001Gro]

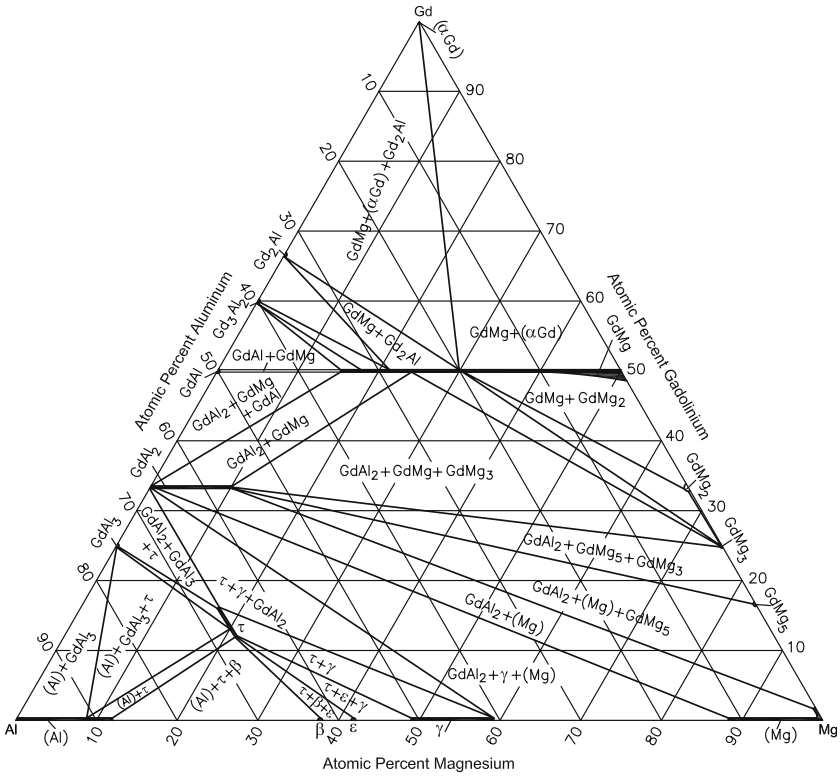

Fig. 5 Al-Gd-Mg computed isothermal section at 400 °C [2003Den, 2003Cac]. Thin two-phase regions are omitted

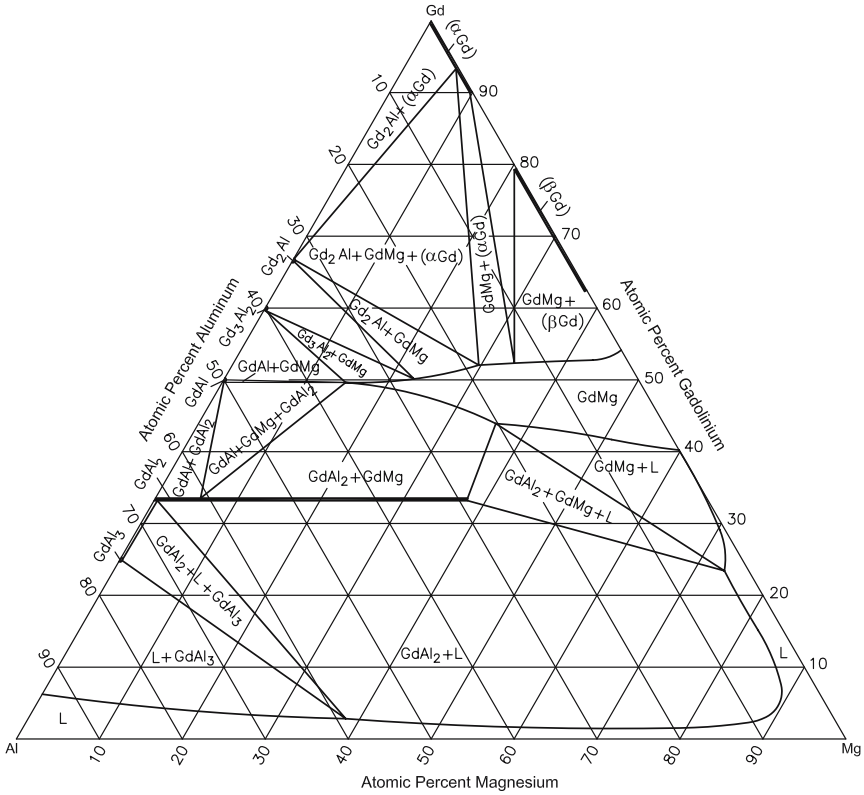

Fig. 6 Al-Gd-Mg computed isothermal section at 800 °C [2003Cac]

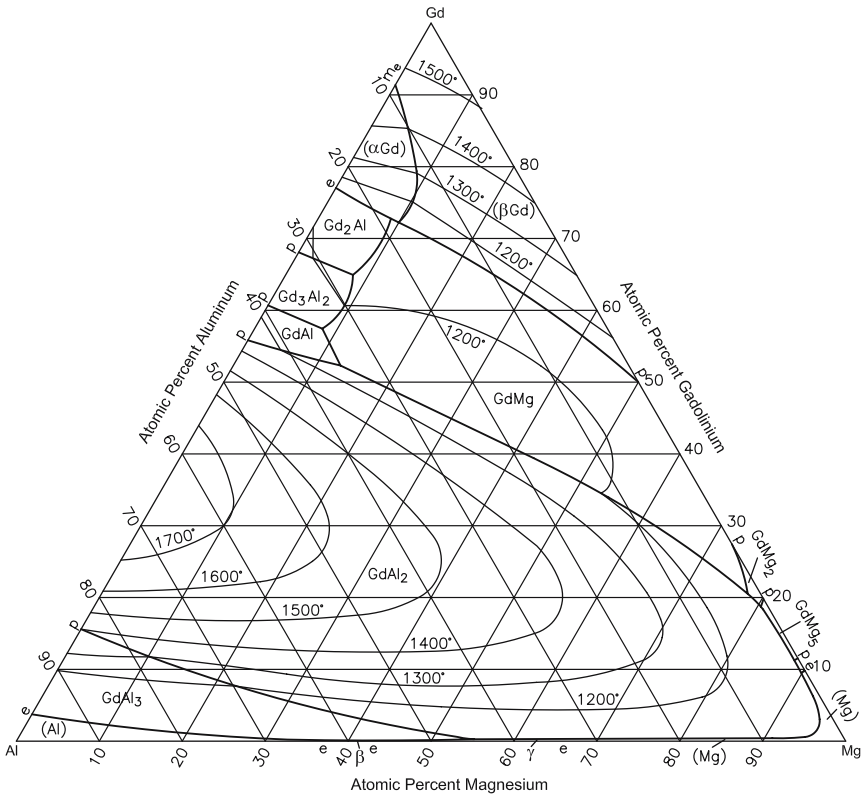

Fig. 7 Al-Gd-Mg computed liquidus projection [2003Cac]

composition near $Al_2Gd_{0.5}Mg_{0.5}$ and the *C*36,$MgNi_2$-type hexagonal structure, with $a = 0.5525$ nm and $c = 1.777$ nm. At 400 °C, the binary phase GdMg (denoted *B*2) dissolves up to 33-34 at.% Al. $GdAl_2$ dissolves about 10 at.% Mg. Another isothermal section at 800 °C computed by [2003Cac] is shown in Fig. 6. The solubility of Mg in $GdAl_2$ is larger here, as compared to that in Fig. 5. The τ phase is absent at this temperature. The computed formation temperature of τ is ~450 °C, which is much lower than 761 °C reported by [2001Gro]. The computed liquidus projection of [2003Cac] is shown in Fig. 7. The primary fields of crystallization are marked. The authors did not indicate the direction of decreasing temperature on the liquidus lines and did not label the invariant reactions on the liquidus surface. Pending resolution of the differences on the temperature of formation of τ, the liquidus projection in Fig. 7 may be considered tentative.

References

1996Rok: L.L. Rokhlin, N.R. Bochvar, and E.V. Lysova, Phase Equilibria in the Al-Gd-Mg System in Solid State, *J. Mater. Sci. Lett.*, 1996, **15**, p 2077-2079

1997Rok: L.L. Rokhlin, N.R. Bochvar, and E.V. Lysova, Liquidus Surface of Al-Gd-Mg System, *Metally*, 1997, (5), p 122-126, in Russian; TR: *Russ. Metall.*, 1997, (5), p 144-150

1998Lia: P. Liang, H.L. Su, P. Donnadieu, M.G. Harmelin, A. Quivy, P. Ochin, G. Effenberg, H.J. Seifert, H.L. Lukas, and F. Aldinger, Experimental Investigation and Thermodynamic Calculation of the Central Part of the Mg-Al Phase Diagram, *Z. Metallkd.*, 1998, **89**(8), p 536-540

2000Can: F. Canepa, M.L. Fornasini, F. Merlo, M. Napoletano, and M.J. Pani, Crystallographic, Magnetic and Magnetocaloric Properties of GdMgX (X=Al,Ga,In) Intermetallic Phases, *J. Alloys Compd.*, 2000, **312**, p 12-16

2000Gro: J. Grobner, D. Kevorkov, A. Pisch, and R. Schmid-Fetzer, Mg-Al-(Sc,Gd) Alloy Design Using Computational Thermochemistry, *Magnesium Alloys and Their Applcations 2000, Conf.*, ed., K.U. Kainer, Wiley-VCH Verlag GmbH, Weinheim, 2000, p 79-83

2001Gro: J. Grobner, D. Kevorkov, and R. Schmid-Fetzer, Thermodynamic Calculation of Al-Gd and Al-Gd-Mg Phase Equilibria Checked by Key Experiments, *Z. Metallkd.*, 2001, **92**(1), p 22-27

2003Cac: G. Cacciamani, S. De Negri, A. Saccone, and R. Ferro, The Al-R-Mg (R = Gd, Dy, Ho) Systems. Part II: Thermodynamic Modeling of the Binary and Ternary Systems, *Intermetallics*, 2003, **11**, p 1135-1151

2003Den: S. De Negri, A. Saccone, G. Cacciamani, and R. Ferro, The Al-R-Mg (R = Gd, Dy, Ho) Systems. Part I: Experimental Investigation, *Intermetallics*, 2003, **11**, p 1125-1134