JPEDAV (2007) 28:192–196
DOI: 10.1007/s11669-007-9028-7
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Al-Mn-Si (Aluminum-Manganese-Silicon)

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The pre-1990 experimental results of this ternary system were evaluated by [1993Pri]. The evaluated data were presented as liquidus and solidus projections near the Al corner, a full isothermal section at 950 °C from [1982Gas], partial sections near the Al corner at 720, 600, and 460 °C and two vertical sections at 4 mass % Si and 6 mass % Mn respectively. A comprehensive experimental and thermodynamic study of this ternary system was reported recently by [2002Kre] and [2004Du].

Binary Systems

The Al-Mn phase diagram [Massalski2, 1996Liu] has the following intermediate phases: ϵ (close packed hexagonal, 55–72 at. % Mn), γ (body centered cubic, ~ 34.5–52 at. % Mn), γ_1 (~ 30–38.7 at. % Mn, structure not known), γ_2 ($D8_{10}$, Cr_5Al_8-type rhombohedral, ~ 31.4–50 at. % Mn,) Mn_4Al_{11} (triclinic), μ (hexagonal, 19–20.8 at. % Mn), λ (hexagonal, 16.8–19 at. % Mn), and $MnAl_6$ ($D2_h$-type orthorhombic). The Al-Si phase diagram is a simple eutectic system with the eutectic at 577 °C and 12.2 at. % Si. The Mn-Si phase diagram [1991Oka] depicts the following intermediate phases: Mn_6Si (rhombohedral, denoted R), Mn_9Si_2 (orthorhombic, denoted ν), βMn_3Si ($D0_3$-type cubic), Mn_5Si_2 (tetragonal), Mn_5Si_3 ($D8_8$-type hexagonal), MnSi ($B20$, FeSi-type cubic), and $Mn_{11}Si_{19}$ (tetragonal, denoted $Mn_{15}Si_{26}$ by [2002Kre]).Krendelsberger et al [2002Kre] reported new lattice parameter measurements for the above intermediate phases. [2004Du] presented computed phase diagrams of the above binary systems.

Table 1 Al-Mn-Si crystal structure and lattice parameter data [2002Kre]

Phase	Composition, atomic %	Pearson symbol	Space group	Prototype	Lattice parameter, nm
$Al_2Mn_2Si_3$ (τ_1)	28.5 Al	*hP*21	$P\bar{6}$	...	*a* = 0.96121
	28 Mn	...	...	...	*c* = 0.35640
	43.5 Si	...	...	...	...
$Al_3Mn_3Si_4$ (τ_2)	29 Al	*hP*9	$P6_222$	$CrSi_2$	*a* = 0.44874
	34 Mn	...	...	...	*c* = 0.64419
	37 Si	...	...	...	...
AlMnSi (τ_3)	34 Al	*oF*24	*Fddd*	$TiSi_2$	*a* = 0.78695
	34 Mn	...	...	...	*b* = 0.45375
	32 Si	...	...	...	*c* = 0.85175
Al_3MnSi_2 (τ_4)	52 Al	*tP*48	*P*4/*n*	...	*a* = 1.2312
	15.5 Mn	...	...	...	*c* = 0.4908
	32.5 Si	...	...	...	
$Al_3Mn_4Si_2$ (τ_5)	33.3-40 Al	...	...	...	*a* = 2.295
	44.4-40 Mn	...	...	...	*b* = 3.159
	22.3-20 Si	...	...	...	*c* = 1.226
$Al_{2-x}Mn_{2+x}Si$ (τ_6)	40-30 Al	...	...	...	...
	40-50 Mn	...	...	...	...
	20 Si	...	...	...	...
$Al_{-5}Mn_{-4}Si_{-1}$ (τ_7)	50-52 Al	...	...	...	...
	39-37 Mn	...	...	...	...
	11 Si	...	...	...	...
βAlMnSi (τ_8) ($Mn_3(Al,Si)_{10}$)	70-61 Al	*hP*26	$P6_3/mmc$	Mn_3Al_{10}	*a* = 0.74491
	25-23 Mn	...	...	...	*c* = 0.77330
	5-16 Si	...	...	...	...
αAlMnSi (τ_9) (Al_9Mn_2Si)	71 Al	*cP*138	$Pm\bar{3}$	...	*a* = 1.26576
	17.1 Mn	...	...	...	...
	11.9 Si	...	...	...	...
Al_2MnSi_3 (τ_{10})	35 Al	*tI*24	*I*4/*mcm*	Ga_5Pd	*a* = 0.60607
	17 Mn	...	...	...	*c* = 0.94422
	48 Si	...	...	...	...

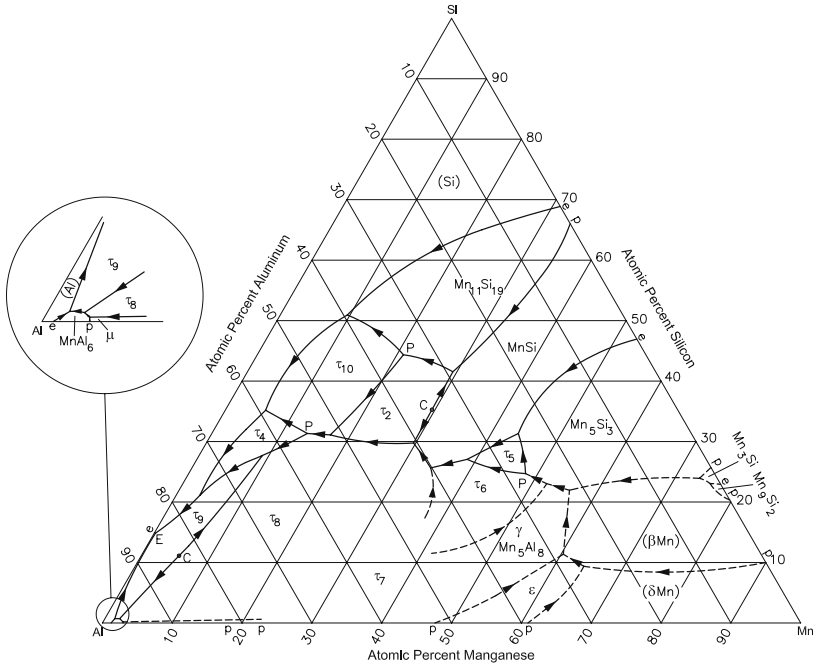

Fig. 1 Al-Mn-Si liquiudus projection [2002Kre]

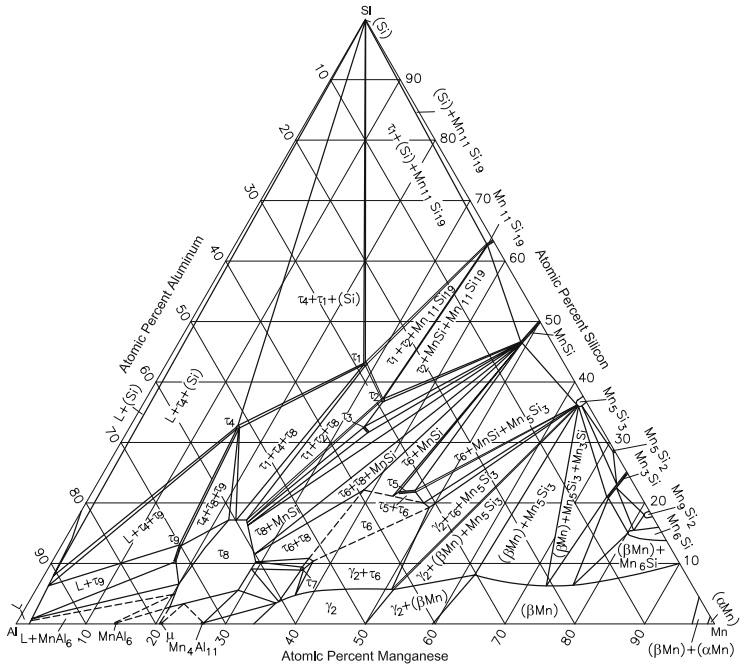

Fig. 2 Al-Mn-Si isothermal section at 700 °C [2002Kre]

Ternary phases

Krendelsberger et al [2002Kre] confirmed ten ternary phases found in earlier work and determined their structural characteristics as listed in Table 1. αAlMnSi (τ_9) and βAlMnSi (τ_8) were the first ternary phases to be identified in this system. τ_6 and τ_8 have significant ranges of homogeneity. Al_2MnSi_3 (τ_{10}) is stable only between 846 °C and 743 °C. The presence of $Al_{\sim 5}Mn_{\sim 4}Si_{\sim 1}$ (τ_7) was detected only by energy dispersive x-ray analysis; neither its crystal structure nor the x-ray powder patterns were elucidated [2002Kre].

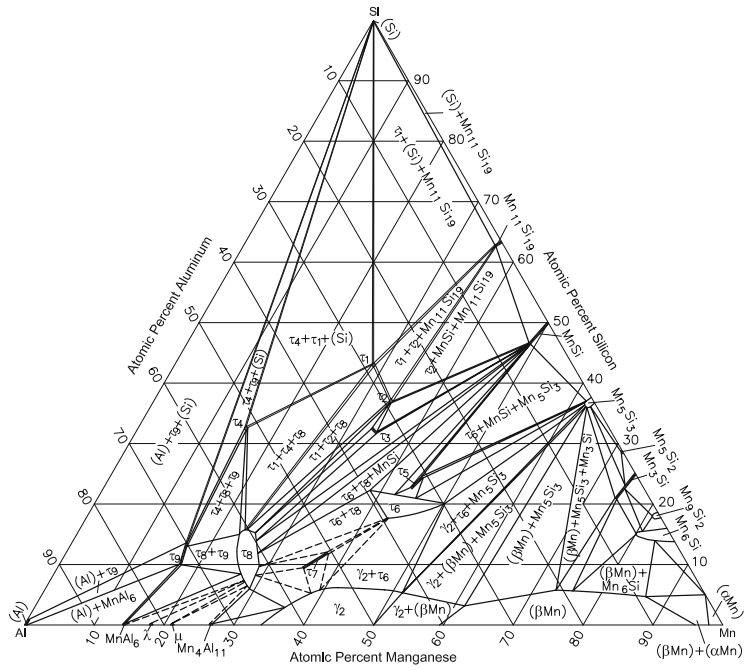

Fig. 3 Al-Mn-Si isothermal section at 550 °C [2002Kre]

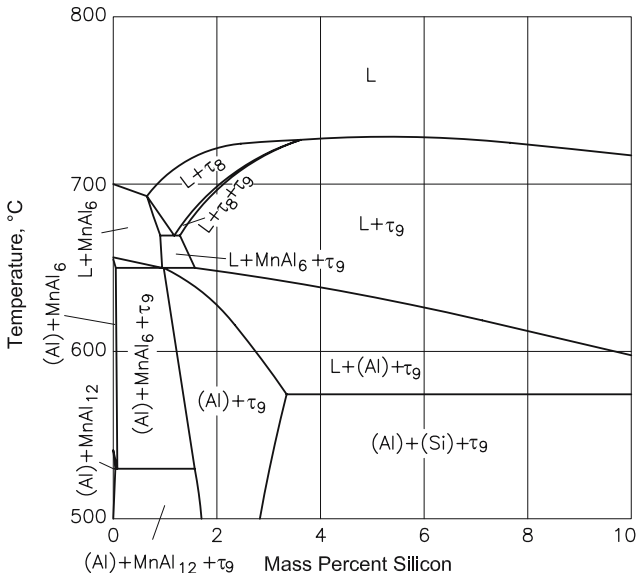

Fig. 4 Al-Mn-Si computed vertical section at 4 mass % Mn [2004Du]

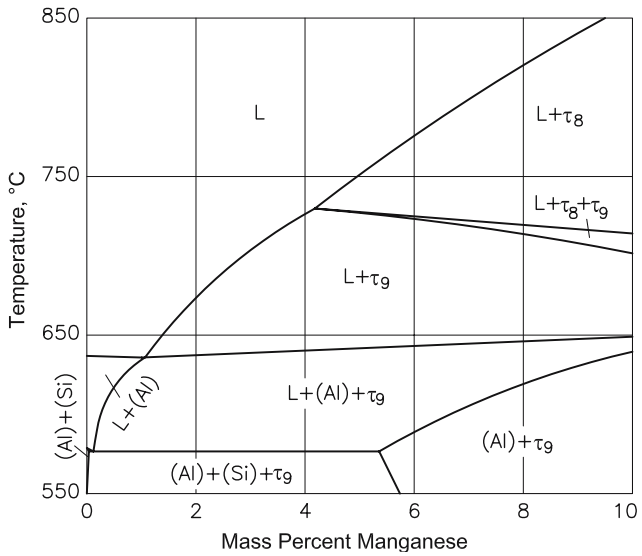

Fig. 5 Al-Mn-Si computed vertical section at 4 mass % Si [2004Du]

Liquidus Projection

With starting metals of 99.999 % Al, 99.95 % Mn and 99.99 % Si, [2002Kre] prepared about 100 ternary alloys. A liquidus surface was determined by metallographic inspection of the as-cast alloys, combined with the differential thermal analysis data of annealed samples. The liquidus projection constructed by [2002Kre] is shown in Fig. 1. Except for the ternary invariant reactions P and E, all other unmarked ternary reactions are U-type transition reactions. The phases of primary crystallization are marked in the figure. The regions of primary separation of τ_8 and τ_7 are not fully characterized. The primary separation of τ_1 and τ_3 was not observed by [2002Kre].

Isothermal Sections

Krendelsberger et al [2002Kre] annealed the as-cast alloys for 2–3 weeks at 700 °C or for 1 month at 550 °C

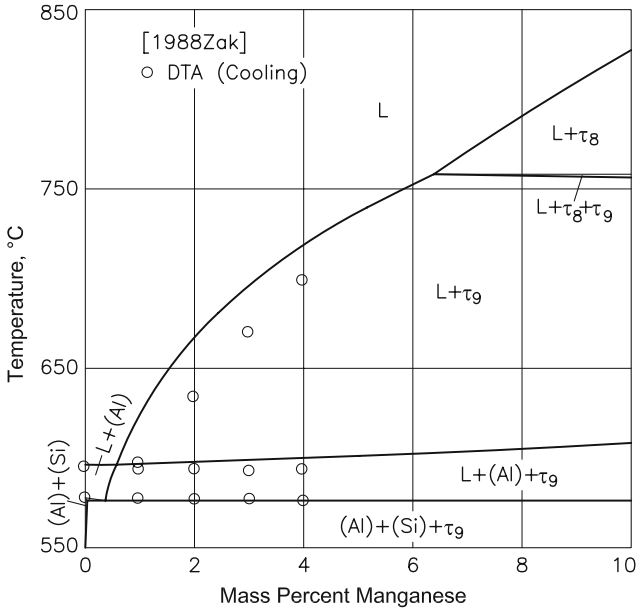

Fig. 6 Al-Mn-Si computed vertical section at 10 mass % Si [2004Du]

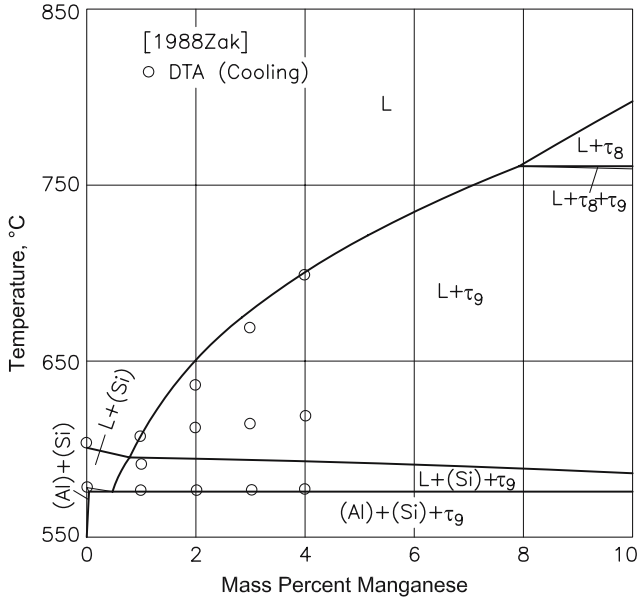

Fig. 7 Al-Mn-Si computed vertical section at 14 mass % Si [2004Du]

and quenched them in water. The phase equilibria were studied by x-ray powder diffraction and electron probe microanalysis. The isothermal sections constructed by [2002Kre] at 700 and 550 °C are shown in Figs. 2 and 3. The ternary phase τ_{10} is not present at these temperatures.

Computed Phase Equilibria

In their thermodynamic optimization of this system, [2004Du] employed all the experimental data of [2002Kre]. Krendelsberger et al [2002Kre] used high purity starting metals and adequate annealing times and their measured equilibria with different techniques were consistent with one another. The data of [2002Kre] were supplemented with the reviewed data of [1993Pri]. In addition, data from a vertical section at 4 mass % Si determined by [1998Rob] were used. The thermochemical data used in the optimization include the heat capacity of τ_9 from [1990Red] and the enthalpy of formation of τ_8 from [2000Leg].

The Gibbs energy of the liquid and the terminal solid solutions (fcc, bcc, *A*12 and *A*13) were modeled using a single lattice. The ternary compounds τ_1, τ_2, τ_3, τ_4, τ_5, and τ_{10} were treated as stoichiometric compounds. A sublattice model, which is consistent with the measured structural details, was used for τ_8 and τ_9. The ternary phase τ_6 was modeled as $(Al,Mn)_4Si$ with a constant Si content and variation of Al and Mn within the known range. The τ_7 phase was excluded from the thermodynamic description.

Du et al[2004Du] also supplemented the experimental results of [2002Kre] by determining the liquidus temperatures of about 40 ternary alloys and used the new results in conjunction with those of [2002Kre] in the optimization. The calculated liquidus projection and the isothermal sections at 700 and 550 °C were found to be in good agreement with the experimental sections shown in Figs. 1–3. The computed vertical sections at 4 mass % Mn and 4 mass % Si are shown in Figs. 4 and 5. In Figs. 6 and 7, the DTA data of [1988Zak] (not used in the optimization by [2004Du]) are compared with the vertical sections at 10 and 14 mass % Si respectively. The agreement is satisfactory.

References

1982Gas: M.I. Gasik and O.I. Polyakov, Investigation of the Phase Equilibria in the Mn-Si-Al System, *Izv. Akad. Nauk SSSR, Metally*, 1982, (4), p 196-203 in Russian; TR: *Russ. Metall.*, 1982, (4), p 177-185

1988Zak: A.M. Zakharov, I.T. Guldin, A.A. Arnold, and Yu.A. Matsenko, Study of the Al-Si-Mn System in the Concentration Range 10-14 mass % Si and 0-4 mass % Mn, *Tsvetn. Metall.*, 1988, (2), p 90-94 in Russian

1990Red: K. Redford, J.E. Tibballs, and R. McPherson, Calorimetric Data for α-AlMnSi and the $\alpha \rightarrow \beta$ Decomposition, *Thermochim. Acta*, 1990, **158**(1), p 115-123

1991Oka: H. Okamoto, Mn-Si (Manganese-Silicon), *J. Phase Equilibria*, 1991, **12**(4), p 505-507

1993Pri: A. Prince, Aluminum-Manganese-Silicon, *Ternary Alloys*, Vol. 7, G. Petzow and G. Effenberg, Eds., VCH Verlagsgesellschaft, Weinheim, Germany, 1993, p 110-128

1996Liu: X.J. Liu, R. Kainuma, H. Ohtani, and K. Ishida, Phase Equilibria in the Mn-Rich Portion of the Binary System Mn-Al, *J. Alloys Compd.*, 1996, **235**, p 256-261

1998Rob: J.A.J. Robinson, F.H. Hayes, A. Serneels, F. Weitzer, and P. Rogl, *COST 507–Definition of Thermochemical and Thermophysical Properties to Provide a Database for the Development of New Light Alloys*, COST Secretariat, Brussels, Belgium, 1998, Vol. 1, p 230-235

2000Leg: B. Legendre, Y. Li, and B. Kolby, Enthalpy of Formation of the α Phase AlMnSi, *Thermochim. Acta*, 2000, **354**(1-2), p 1-6

2002Kre: N. Krendelsberger, F. Weitzer, and J.C. Schuster, On the Constitution of the System Al-Mn-Si, *Metall. Mater. Trans. A*, 2002, **33A**, p 3311-3319

2004Du: Y. Du, J.C. Schuster, F. Weitzer, N. Krendelsberger, B. Huang, Z. Jin, W. Gong, Z. Yuan, and H. Xu, A Thermodynamic Description of the Al-Mn-Si System over the Entire Composition and Temperature Ranges, *Metall. Mater. Trans. A*, 2004, **35A**, p 1613-1628