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# Al-Mo-Ti (Aluminum-Molybdenum-Titanium)

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The compilation of data on this ternary system by [1995Vil] includes a liquidus projection, a partial solidus projection, partial isothermal sections for Ti-rich alloys at 1100, 1000, 950, 925, 900, 850, 800, 700, and 600 °C, and vertical sections at 5, 10, 15, 20, 25, 30, and 40 wt.% Al, at 0.5 and 5 wt.% Mo and at 7 at.% Ti. In the review by [1993Bud], isothermal sections at 1600, 1300, and 900 °C, partial sections at 700 and 400 °C, and a vertical section at 7 at.% Mo are given. Recently, partial isothermal sections for Ti-poor alloys were reported by [2003Nin] between 1400 and 1100 °C.

## Binary Systems

The Al-Mo phase diagram [1997Sau], with an added update for the Al-$Mo_3Al_8$ region by J.F. Smith (Editor of the *Journal of Phase Equlibria and Diffusion*), shows the following intermediate phases: $MoAl_{12}$ ($WAl_{12}$-type cubic); $MoAl_5$ (with three modifications); $Mo_5Al_{22}$; $Mo_4Al_{17}$; $MoAl_4$ (monoclinic); $Mo_{1-x}Al_{3+x}$ (cubic); $MoAl_3$ (monoclinic); $Mo_3Al_8$ (monoclinic); MoAl (body-centered cubic [bcc]); and $Mo_3Al$ (*A*15, $Cr_3Si$-type cubic). The updated version of the Al-Ti phase diagram [2005Rag] depicts a number of intermediate phases. $TiAl_3$ has two crystal modifications: $TiAl_3$ (high temperature [HT]) ($D0_{22}$-type tetragonal) forms peritectically at 1387 °C and decomposes eutectoidally at 735 °C. $TiAl_3$ (low temperature [LT]) (tetragonal) forms at ~950 °C and is stable at low temperatures. $Ti_5Al_{11}$ is a superstructure based on the AuCu-type tetragonal phase. It forms peritectically at 1416 °C and decomposes eutectoidally at 995 °C to $TiAl_2$ and $TiAl_3$ (HT). $TiAl_2$ ($HfGa_2$-type tetragonal) forms congruently at

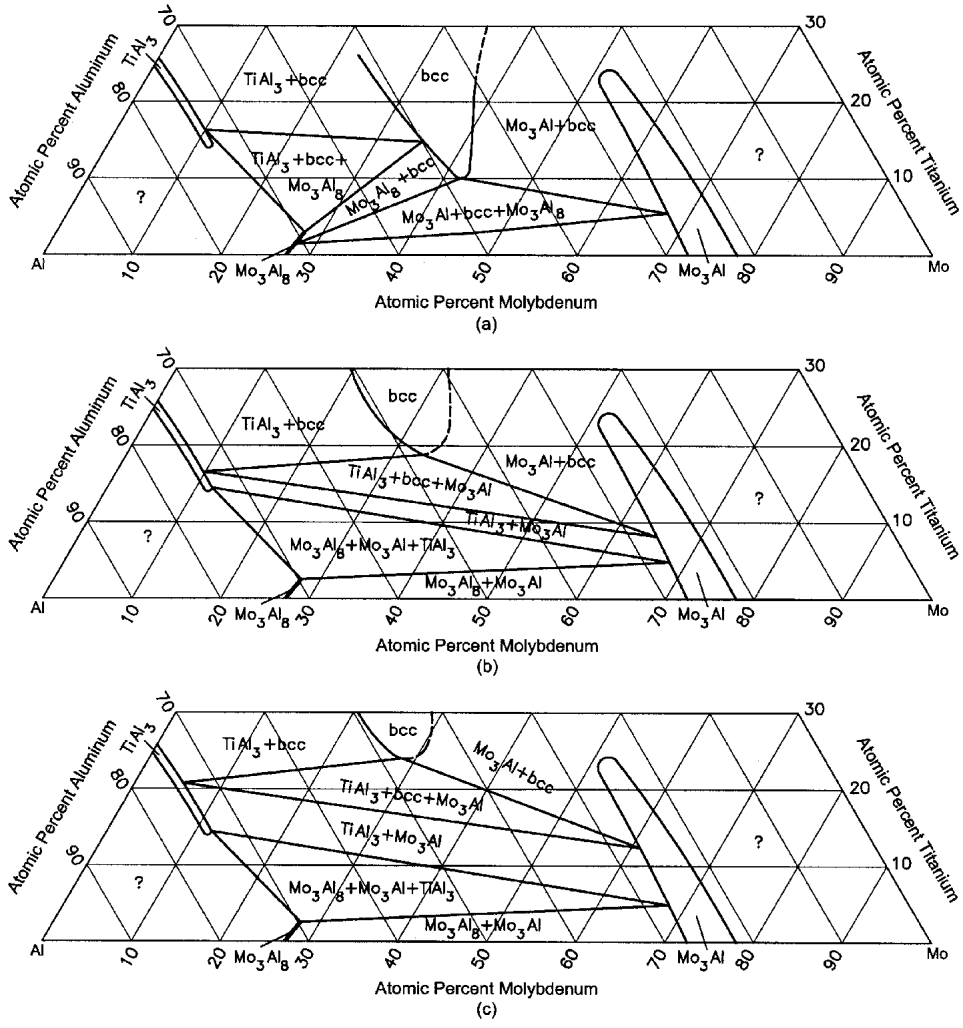


**Fig. 1** Al-Mo-Ti partial isothermal sections for Ti-poor alloys at (a) 1300 °C, (b) 1200 °C, and (c) 1100 °C [2003Nin]

1215 °C from $Ti_5Al_{11}$ and is stable at low temperatures. $Ti_{1-x}Al_{1+x}$ (AuCu-type tetragonal) is stable between 1445 and 1170 °C. $Ti_3Al_5$ is an LT phase that is stable below 810 °C. TiAl, often designated γ, has the $L1_0$, AuCu-type tetragonal structure and forms peritectically at 1460 °C. (βTi) (bcc, also denoted β) and liquid undergo a peritectic reaction at 1490 °C to yield (αTi) (close-packed hexagonal, also denoted α). $Ti_3Al$, commonly labeled $\alpha_2$, has the $D0_{19}$, $Ni_3Sn$-type hexagonal structure and forms congruently from (αTi) at 1176 °C. The Mo-Ti phase diagram [Massalski2] depicts a continuous bcc solid solution between βTi and Mo over a wide range of temperatures. A miscibility gap occurs in this solution at lower temperatures, with a monotectoid reaction (βTi) → (αTi) + (Mo) at 695 °C.

## Ternary Isothermal Sections

[2003Nin] arc-melted under Ar atmosphere 11 Al-Mo alloys with Ti in the range of 3 to 17 at.%. The samples were annealed at 1400 to 1500 °C for 1 day and were quenched in water. Some quenched samples were isothermally aged at 1150 to 900 °C for 1 to 3 days and were quenched in water. The phase equilibria were studied by x-ray diffraction and scanning electron microscopy with an energy-dispersive spectroscopy attachment. Differential thermal analysis was done at a cooling/heating rate of 10 °C/min. Partial isothermal sections were constructed at 1400, 1300, 1267, 1200, and 1100 °C. The isothermal sections at 1300, 1200, and 1100 °C are redrawn in Fig. 1 to agree with the accepted binary data. The following U-type transition reaction occurs at 1267 °C: $Mo_3Al_8$ + bcc ↔ $Mo_3Al$ + $TiAl_3$. At 1400 °C, the bcc phase originating from the Ti-Mo binary side is close the Al-Mo side but does not make contact with it. This is consistent with the fact that the MoAl (bcc) intermediate phase decomposes eutectoidally at 1470 °C [1997Sau]. It is possible that the bcc phase extends up to the Al-Mo side above this temperature and recedes from this side, as the temperature falls below 1470 °C. [2003Nin] ruled out the possibility of coexistence of two bcc phases of different composition in the temperature range studied by them. The isothermal section at 1600 °C determined by [1988Ere] (reviewed in [1993Bud]) depicts two bcc phases of different composition. The decomposition of the bcc phase containing 13 to 17 at.% Ti results in a lamellar structure, which is characteristic of the Al-Mo eutectoid reaction at 1470 °C. The stabilizing effect of Ti on MoAl enables slower quenching rates to retain this bcc phase and to obtain a finer lamellar structure on subsequent aging [2002Miu, 2003Nin]. [2003Nin] did not find the σ phase (~$Al_2MoTi$) in the composition and temperature range studied by them. It is probably stable only below the lowest temperature studied by them (1100 °C). Earlier, the σ phase was reported by [1970Han] at 925 °C.

[1994Has] used HT x-ray diffractometry and differential thermal analysis to study the phase equilibria between 1300 and 1100 °C in Mo-poor alloys. The partial isothermal section constructed by them at 1200 °C is redrawn in Fig. 2 to agree with the accepted binary data. The solubility of Mo in (αTi) and γ is small. Mo acts as a strong bcc stabilizer.

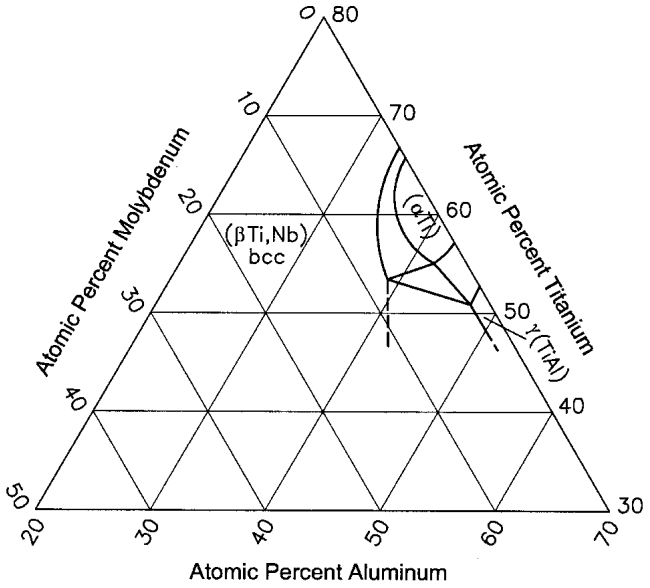


**Fig. 2** Al-Mo-Ti partial isothermal section for Mo-poor alloys at 1200 °C [1994Has]

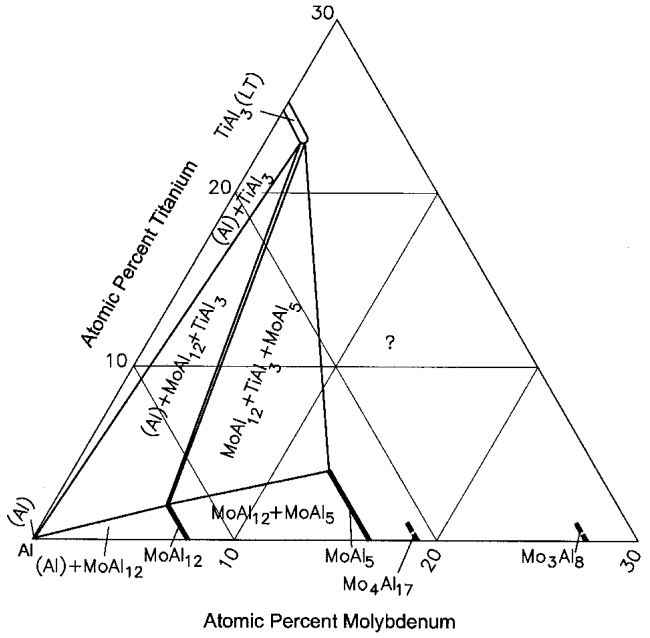


**Fig. 3** Al-Mo-Ti partial isothermal section at 497 °C [1994Sok]

With starting metals of 99.9% Al, 99.6% Mo, and 99.5% Ti, [1994Sok] melted 17 Al-rich alloys containing up to 25 at.% each of Mo and Ti in an arc furnace under Ar atmosphere. The alloys were annealed at 497 °C (770 K) for 1000 h and quenched. The phase equilibria were studied with x-ray powder diffraction and metallography. The partial isothermal section determined by [1994Sok] near the Al corner is redrawn in Fig. 3 to agree with the accepted binary data. The binary compound $MoAl_3$ shown by [1994Sok] is omitted, as this phase decomposes at 818 °C [1997Sau].

**Table 1 Tie-line and tie-triangle compositions in a Ti-50Al-15Mo alloy [1997Che]**

| Annealing temperature, °C | Phase | Composition, at.% Ti | Al | Mo |
|---|---|---|---|---|
| 1400 | bcc (*B*2) (single phase) | 35.7 | 49.7 | 14.6 |
| 1350 | bcc (*B*2) | 36.3 | 47.5 | 16.2 |
| | (αTi) | 35.8 | 52.5 | 11.9 |
| 1200 | bcc (*B*2) | 35.2 | 45.7 | 19.1 |
| | TiAl (γ) | 35.5 | 55.8 | 8.9 |
| 1000 | bcc (*B*2) | 36.7 | 42.1 | 21.2 |
| | TiAl (γ) | 34.0 | 56.7 | 9.3 |
| 800 | bcc (*B*2) | 40.7 | 37.1 | 22.2 |
| | γ′ ($D0_{22}$) | 33.2 | 57.4 | 9.4 |
| | γ″(a) | 25.0 | 60.8 | 14.2 |

(a) See [1997Che] for structural details

$TlAl_3$ dissolves up to 2 at.% Mo. $MoAl_{12}$ and $MoAl_5$ dissolve up to 2 and 4 at.% Ti, respectively [1994Sok].

Among the other studies, [1997Sin] investigated 12 Molean ternary alloys containing 44 to 50 at.% Al and 2 to 6 at.% Mo. They were heat-treated at 1400 to 1100 °C for 1 to 6 h and were quenched in water. [1997Sin] pointed out that the annealing times that they used were not adequate to establish equilibrium. Tentative partial isothermal sections were drawn at 1400, 1300, 1200, and 1100 °C. At 1400 °C, with increasing Mo content, alloys containing 48 to 50 at.% Al lie successively in the (αTi) + γ → (αTi) → (αTi) + (βTi) → (βTi) fields, whereas alloys with 44 to 46 at.% Al pass through (αTi) → (αTi) + (βTi) → (βTi) fields. At 1100 °C, the (*B*2 + γ) mixture dominates. [1997Che] annealed a Ti-50Al-15Mo alloy at 1400, 1350, 1200, 1000, and 800 °C for 1.5, 2, 96, 144, and 504 h, respectively, and quenched it in water. The tie-line and the tie-triangle compositions determined by them as a function of temperature are listed in Table 1.

The stabilizing effect of Mo on the formation of the CsCl-type *B*2 phase in $Ti_3Al$-based and TiAl-based compositions was studied by [1991Dja], [1993Gro], [1993Tho], and [1998Yi]. First principle calculations of the equilibria between bcc, hexagonal close-packed, *B*2, $Ti_3Al$, and TiAl structures were reported by [2001Kan] and [2004Alo].

## References


**1970Han:** R.C. Hansen and A. Raman, Alloy Chemistry of σ (βU) Related Phases. III. Sigma Phases with Non-transition Elements, *Z. Metallkd.,* Vol 61, 1970, p 115-120

**1988Ere:** V.N. Eremenko, S.A. Sukhaya, and L.A. Tertyachenko, Phase Equilibria in the Ti-Al-Mo System at 1600°C, *Tsvetn. Met.,* (No. 4), 1988, p 97-100 (in Russian)

**1991Dja:** S. Djanarthany, C. Servant, and R. Penelle, Phase Transformations in $Ti_3Al$ and $Ti_3Al$ + Mo Aluminides, *J. Mater. Res.,* Vol 6 (No. 5), 1991, p 969-986

**1993Bud:** P. Budberg and R. Schmid-Fetzer, Aluminum-Molybdenum-Titanium, *Ternary Alloys,* Vol 7, G. Petzow and G. Effenberg, Ed., VCH Verlagsgesellschaft, Weinheim, Germany, 1993, p 229-238

**1993Gro:** F. Grosman and J. Sieniawski, Effect of β-Stabilizing Elements and Heating/Cooling Rate on Phase Transformations in Multicomponent Ti Alloys with Constant Aluminum Content, *Arch. Metall.* Vol 38 (No. 1), 1993, p 61-68

**1993Tho:** M. Thomas and S. Naka, Phase Stability in $Ti_3Al$ + X Base (X = Nb, Mo, V, Ta, Fe) Alloys, *Titanium '92: Sci. Technol. Proc. Symp.,* Vol 2, F.H. Froes and I..L. Caplan, Ed., Miner. Met. Mater. Soc., 1993, p 1243-1250

**1994Has:** K. Hashimoto,Y. Mizuhara, T. Hanamura, and M. Kimura, Phase Stability of Ti-Al-X at High Temperatures, *Microstruct. Prop. Relations Ti Alloys Proc. Harold Margolin Symp.,* S. Ankem and J.A. Hall, Ed., Miner. Met. Mater. Soc., 1994, p 225-234

**1994Sok:** E.M. Sokolovskaya, E.F. Kazakova, E.I. Poddyakova, and V.K. Portnoi, Isothermal Section of the Al-Mo-Ti System at 770 K, *Vestn. Mosk. Univ. Ser 2: Khim.,* Vol 35 (No. 1), 1994, p 95-97 (in Russian)

**1995Vil:** P. Villars, A. Prince, and H. Okamoto, Al-Mo-Ti, *Handbook of Ternary Alloy Phase Diagrams,* Vol 4, ASM International, 1995, p 4068-4088

**1997Che:** Z. Chen, I.P. Jones, and C.J. Small, The Structure of the Alloy Ti-50Al-15Mo between 800°C and 1400°C, *Acta Mater.,* Vol 45 (No. 9), 1997, p 3801-3815

**1997Sau:** N. Saunders, The Al-Mo (Aluminum-Molybdenum) System, *J. Phase Equilib.,* Vol 18 (No. 4), 1997, p 370-378

**1997Sin:** A.K. Singh and D. Banerjee, Transformations in $\alpha_2$ + γTiAl Alloys Containing Mo. Part II. Heat Treatment, *Metall. Mater. Trans. A,* Vol 28A, 1997, p 1745-1753

**1997Yi:** S. Yi, "Phase Equilibria and Development of β + γ Two-Phase Microstructures in γ Based Ti-Al-Mo Ternary Alloys," Ph.D. dissertation, University of Wisconsin, Madison, 1997

**2001Kan:** S.Y. Kang and H. Onodera, Analysis of HCP/$D0_{19}$ and $D0_{19}/L1_0$ Phase Boundaries in Ti-Al-X (X = V, Mn, Nb, Cr, Mo, Ni and Co) Systems by the Cluster Variation Method, *J. Phase Equilib.,* Vol 22 (No. 4), 2001, p 424-430

**2002Miu:** S. Miura, J. Fujinaka, and T. Mohri, Microstructural Control of $Al_3Ti$ Based Alloys Designed by Multicomponent Phase Diagrams, *Process. Fabri. Advanced Materials X, Proc. Symp., 2001,* T.S. Srivatsan and R.A. Varin, Ed., ASM International, 2002, p 287-300

**2003Nin:** R. Nino, J. Fujinaka, H. Shimamura, S. Miura, and T. Mohri, Phase Equilibria and Microstructure Evolution of Al-Mo-Ti Ternary Alloys, *Intermetallics,* Vol 11 (No. 6), 2003, p 611-623

**2004Alo:** P.R. Alonso and G.H. Rubiolo, Ordering and Phase Separation Around $Ti_{50}Al_{25}Mo_{25}$ Alloys, *J. Alloys Compd.,* Vol 363, 2004, p 90-98

**2005Rag:** V. Raghavan, Al-Ti (Aluminum-Titanium), *J. Phase Equilib. Diffusion,* Vol 26 (No. 2), 2005, p 171-172