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Al-Fe-Ni-Ti (Aluminum-Iron-Nickel-Titanium)

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The review of the phase equilibria of this quaternary system by [1996Rag] presented two pseudo-ternary sections at 1000 and 750 °C along the Ni_3Al-Ni_3Ti-'Ni_3Fe' join from the work of [1957Tay]. An update by [2006Rag] gave partial isothermal sections on the FeAl-FeTi-NiTi-NiAl plane at 1300, 1200, 1000, and 900 °C from the studies of [1997Kai]. Recently, [2008Yan] made an in-depth study of the equilibria involving the quaternary Laves phases at 900 °C. This forms one of the first detailed experimental study and analysis in characterizing the complex shape of single phase regions and their equilibrium with adjoining phases in a higher order system.

Ternary Subsystems

A number of recent studies and reviews are available on all the constituent ternary systems: Al-Fe-Ni [2006Ele, 2007Chu, 2008Chu, 2008Zha, 2009Rag1]; Al-Fe-Ti [2006 Pal]; Al-Ni-Ti [1999Hun, 2001Din, 2005Rag, 2006Sch, 2007Sch, 2009Rag2]; and Fe-Ni-Ti [2006Cac]. At the temperature of interest here (900 °C), in the Al-Fe-Ti and Fe-Ni-Ti systems [2006Pal, 2006Cac], the Fe_2Ti-based, $MgZn_2$-type hexagonal Laves phase dissolves more than 35 at.% Al and 20 at.% Ni respectively. This phase will be denoted as λ_1 (λ_{Fe} by [2008Yan]). The other $MgZn_2$-type phase is present in the Al-Ni-Ti system within the ternary region at 900 °C [1999Hun] and has a homogeneity range of $Al_{30.5}Ni_{27.5}Ti_{42}$-$Al_{50}Ni_{16}Ti_{34}$. This phase will be denoted λ_2 (λ_{Ni} by [2008Yan] and τ_3 by [2007Sch]). The ternary phases that come into equilibrium with the Laves phases are: $MnCu_2Al$-type Heusler phase, occurring in the Al-Ni-Ti system, will be denoted $L2_1$ (τ_4 by [1999Hun] and [2008Yan]); and $AuCu_3$-type phase occurring in the ternary region of the Al-Fe-Ti and Al-Ni-Ti systems is denoted $L1_2$ (in Al-Fe-Ti, τ_3 by [2006Pal] and τ_1 by [2008Yan] and in Al-Ni-Ti, τ_1 by [2001Din], [2007Sch], and [2008Yan]); in Al-Ni-Ti, $Mn_{23}Th_6$-derivative phase occurring within the ternary region will be denoted G (τ_2 by [1999Hun] and [2006Sch]). [2008Yan] noted that the G phase changes its symmetry as a function of composition, going from $Fm\bar{3}m$ at the Al-rich end to $F\bar{4}3m$ at the Al-poor end. The binary phases FeTi and NiTi with the CsCl-type cubic structure

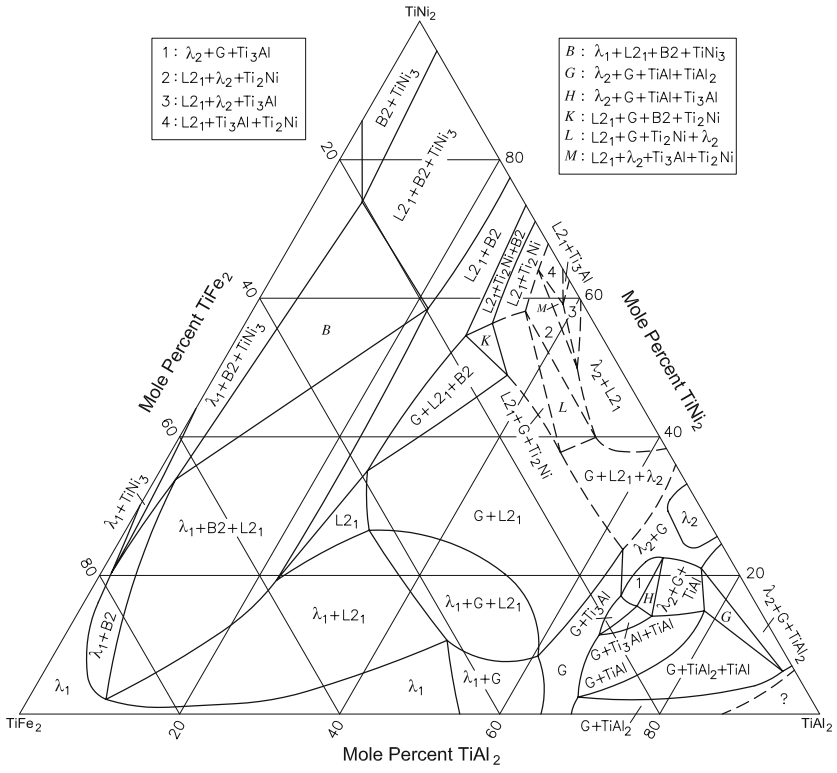

Fig. 1 Al-Fe-Ni-Ti isothermal section at 900 °C on the $TiAl_2$-$TiFe_2$-$TiNi_2$ plane [2008Yan]. The symbols in italics indicate four-phase regions

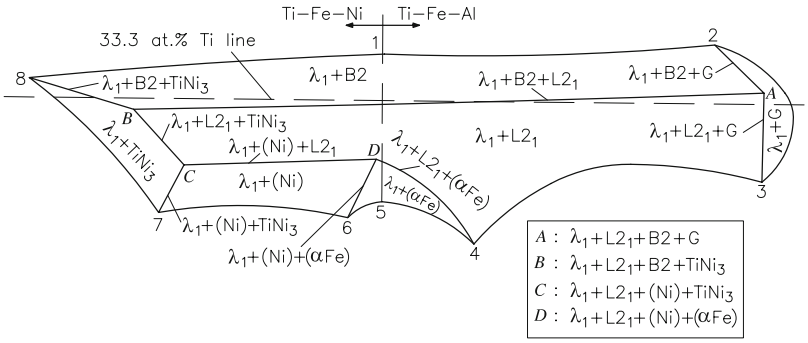

Fig. 2 Al-Fe-Ni-Ti schematic illustration of the λ_1 region [2008Yan]. Plane 123451 lies on the Ti-Fe-Al face. Plane 567815 lies on the Ti-Fe-Ni face

occurring in Al-Fe-Ti and Fe-Ni-Ti systems form a continuous solid solution with quaternary extension and will be denoted by *B*2 (denoted υ_1 by [2008Yan]). The FeAl and NiAl phases with the *B*2 structure form a continuous solid solution (denoted υ_2 by [2008Yan]), which does not come into equilibrium with the Laves phases. The other binary phases with small ternary and quaternary solubility are denoted by the nominal formula: $TiAl_3$ (tetragonal), $TiAl_2$ ($HfGa_2$-type tetragonal), TiAl ($L1_0$, AuCu-type tetragonal, denoted γ), Ti_3Al ($D0_{19}$-type hexagonal), $NiTi_2$ ($NiTi_2$-type cubic) and $TiNi_3$ ($D0_{24}$-type hexagonal). Phases based on elements are denoted in the usual way: (Ni), (βTi), (αTi) and (αFe).

Quaternary Phase Equilibria

With starting metals of >99.9 mass% purity, [2008Yan] arc-melted more than 120 alloys. The compositions of the alloys were selected so as to establish the homogeneity range of the Laves phases in the quaternary system. The alloys were annealed at 900 °C for 10 days and quenched in water. The phase equilibria were studied with optical and scanning electron microscopy, x-ray and neutron powder diffraction, single crystal diffraction and electron probe microanalysis.

The section on the $TiAl_2$-$TiFe_2$-$TiNi_2$ plane at 900 °C constructed by [2008Yan] is shown in Fig. 1. The Fe_2Ti-based Laves phase λ_1 forms tie-lines with G, $L2_1$, *B*2 and $TiNi_3$ phases. The extension of the Heusler phase $L2_1$ beyond the 33.3 at.% Ti line, limits the spread of the λ_1 phase on this section. The other Laves phase λ_2 is separated from λ_1 by the intervening G phase field. The solubility of the fourth component Fe in λ_2 is limited to about 5 at.% at 900 °C. At elevated temperatures, the two Laves phases form a continuous solution [2008Yan]. The sections of the tie-tetrahedra appear as triangles in Fig. 1. Not all tie-tetrahedra intersect the $TiAl_2$-$TiFe_2$-$TiNi_2$ section. The measured compositions of the co-existing phases in all the 11 tie-tetrahedra in the investigated region were listed by [2008Yan]. A connectivity scheme at 900 °C was presented by [2008Yan]. This scheme shows the relationship between

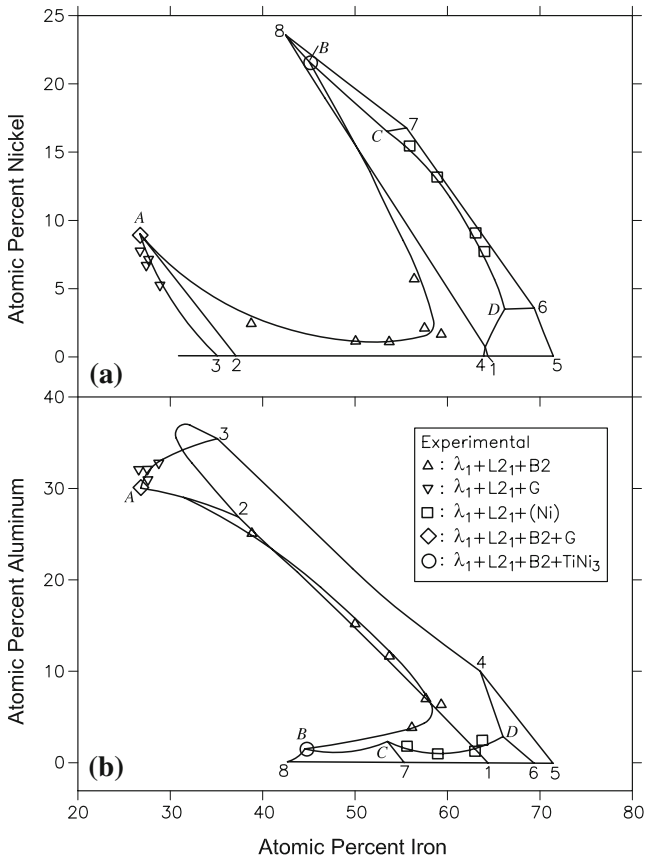

Fig. 3 Al-Fe-Ni-Ti projections of λ_1 region along (a) Ni-Fe and (b) Al-Fe directions [2008Yan]. Notations used are the same as in Fig. 2

the tie-tetrahedra and the three-phase regions that lie between adjoining tetrahedra or on the ternary faces.

Figure 2 is a schematic illustration of the λ_1 phase field at 900 °C [2008Yan]. The λ_1 phase originates along a line on the Fe-Ti side and spreads on both sides into the Ti-Fe-Al and Ti-Fe-Ni faces and into the quaternary region. As indicated in Fig. 2, the faces are in contact with two-phase regions, lines are in contact with three-phase regions and the

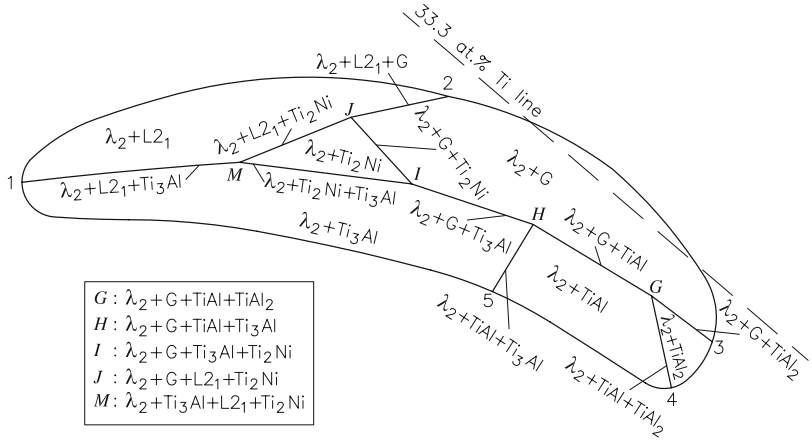

Fig. 4 Al-Fe-Ni-Ti schematic illustration of λ_2 region [2008Yan]. The banana-like plane 123451 lies on the Al-Ni-Ti face

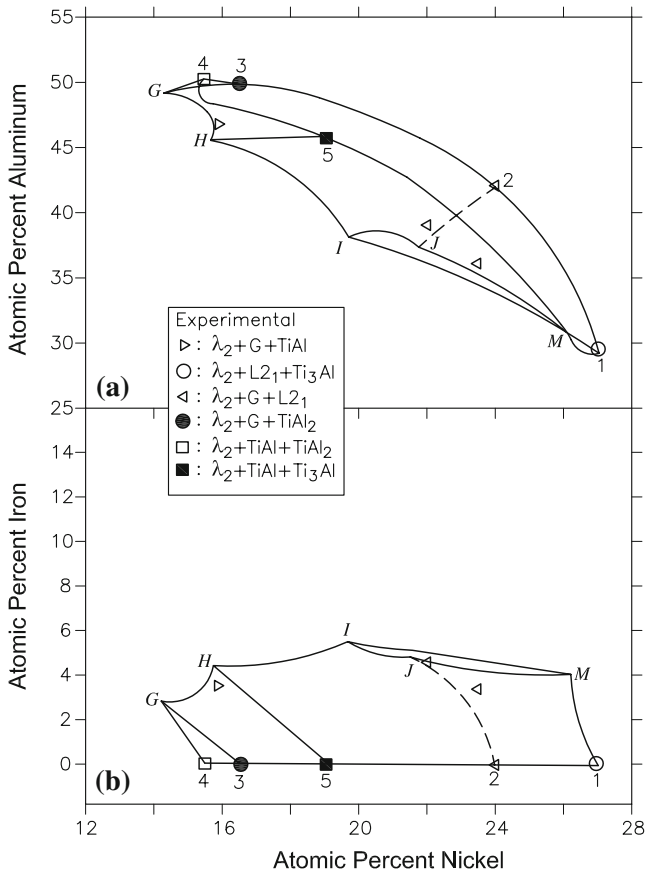

Fig. 5 Al-Fe-Ni-Ti projections of λ_2 region along (a) Ni-Al and (b) Fe-Ni directions [2008Yan]. Notations used are the same as in Fig. 4

corner points are in contact with four-phase regions. Figure 3 is the projection of the λ_1 region along the Ni-Fe and Al-Fe directions. The corresponding points are marked using the same notation in Fig. 2 and 3.

Figure 4 is a schematic illustration of the λ_2 region at 900 °C [2008Yan]. The circumferential line of this region lies on the Al-Ni-Ti plane and has the so-called banana- or boomerang-like shape, indicating the complex site substitution of atoms in the ternary phase. The region extends into the quaternary region with Fe substitution in the phase. As before, the contact with two-, three- or four-phase regions occurs on a surface, along a line or at a corner respectively. Figure 5 is the projection of the λ_2 region along the Al-Ni and Fe-Ni directions. The corresponding points are marked the same way in Fig. 4 and 5.

Among the other results, [2008Yan] made a detailed analysis of the diffraction data of selected compositions of the Laves phases to determine interatomic distances and site occupancies.

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