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Al-Ni-Ru (Aluminum-Nickel-Ruthenium)

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The compilation of data on this ternary system by [1995Vil] presented two isothermal sections for Al-poor alloys at 1250 and 1000 °C from [1986Cha], a full isothermal section at 800 °C from [1985Pet], and a full section at 550 °C from [1980Tsu]. More recently, several isothermal sections for Al-rich alloys depicting new ternary compounds have been reported by [2003Mi2].

Binary Systems

The Al-Ni phase diagram [1993Oka] shows five intermediate phases: $NiAl_3$ ($D0_{11}$, Fe_3C-type orthorhombic), Ni_2Al_3 ($D5_{13}$-type hexagonal), NiAl ($B2$, CsCl-type cubic, also denoted β), Ni_5Al_3 (Ga_3Pt_5-type orthorhombic), and Ni_3Al ($L1_2$, $AuCu_3$-type cubic; denoted γ'). The Al-Ru partial phase diagram recently determined by [2003Mi3] is shown in Fig. 1. It depicts six intermediate phases: $RuAl_6$ (orthorhombic, space group *Cmcm)*, Ru_4Al_{13} (monoclinic, space group $C2/m$), Ru_2Al_5 (orthorhombic, space group *Cmcm*), $RuAl_2$ ($C54$, $TiSi_2$-type orthorhombic), Ru_2Al_3 (Os_2Al_3-type tetragonal), and RuAl ($B2$, CsCl-type cubic). This diagram differs significantly from the updated version of [2004Oka] in several respects. Here, Ru_4Al_{13} is stoichiometric, with no shift to the Ru-rich side as given by [2004Oka]. Ru_2Al_5 is a high-temperature phase stable between 1492 and 1340 °C [2003Mi3]. Ru_2Al_3 forms peritectoidally at 1675 °C, in contrast to the peritectic formation suggested in the results reviewed by [2004Oka]. Recently, [2005Gob] redetermined the homogeneity range of RuAl and found that it extends from near-stoichiometry to 53.8 at.% Al at room temperature and to 54.5 at.% Al at 1200 °C. The Ni-Ru phase diagram computed by [2004Hal] is a simple peritectic system with maximum solubility of 34.1 at.% Ru in (Ni) and 47.4 at.% Ni in (Ru) at the peritectic temperature of 1564 °C.

Ternary Phases

No ternary phases were reported in any of the isothermal sections given in [1995Vil]. Recent work, however, has shown the occurrence of several ternary phases in the Al-rich region [2000Hoh, 2000Sun, 2002Sun, 2003Mi1]. According to [2003Mi1], five ternary phases denoted C, D, H, O, and m occur in this region. $Al_{71.8}Ni_{11.2}Ru_{17}$ (C) is cubic (space group $Pm\bar{3}$, $a = 0.7674$ nm). The decagonal phase D occurs at the composition ~$Al_{73}Ni_{16}Ru_{11}$ and has a periodicity of 1.6 nm along the tenfold axis. The hexagonal phase H ($Al_{75.5}Ni_{16}Ru_{8.5}$) has lattice parameters of $a = 1.2132$ nm and $c = 2.7020$ nm. The O phase $Al_{13}(Ru,Ni)_4$ is orthorhombic (space group $P2_1mn$, $a = 1.4960$ nm, $b = 0.8253$ nm, and $c = 1.2668$ nm). The m phase $Al_9(Ru,Ni)_2$ is monoclinic (space group $P2_1/a$, $a = 0.8636$ nm, $b = 0.6333$ nm, $c = 0.6273$ nm and $\beta = 95.12°$). In addition to the decagonal phase, [2002Sun] reported an icosahedral phase (I). [2003Mi2] did not find the I phase in the isothermal sections between 1100 and 700 °C.

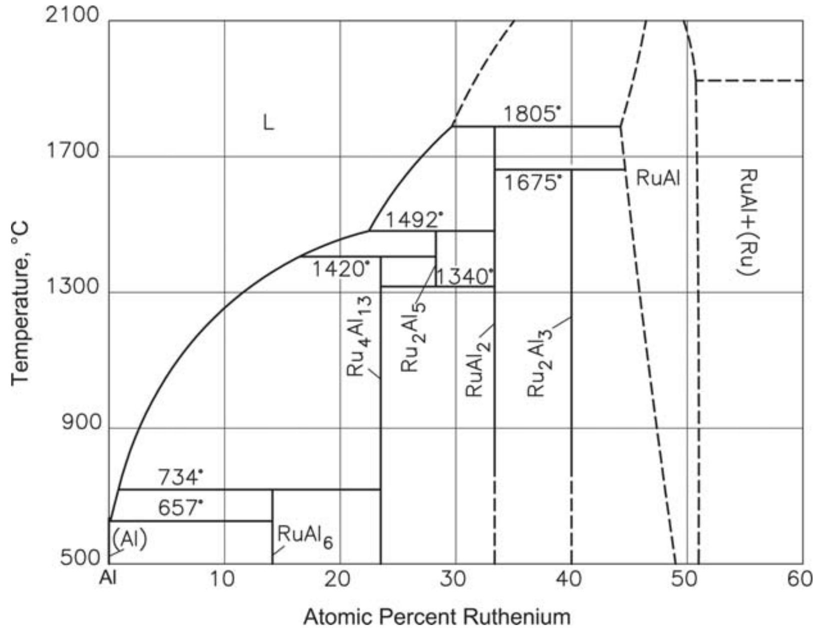

Fig. 1 Al-Ru phase diagram for the Al-rich region [2003Mi3]

There has been some controversy regarding the extent of mutual solid solubility between NiAl and RuAl (both with *B*2, CsCl-type cubic structure) [1980Tsu, 1985Cha, 1985Pet, 1986Cha, 1998Hor]. [1980Tsu] reported a miscibility gap between NiAl and RuAl, with NiAl dissolving 5 at.% Ru and RuAl dissolving 8 at.% Ni at 550 °C. [1985Pet], on the other hand, reported complete solid solubility between NiAl and RuAl at 800 °C. [1985Cha] found that the miscibility gap extends up to the solidus in this system. The lattice parameter mismatch between coexisting solid solutions is, however, very small (~0.17 to 0.55%). The measured lattice parameter ranges for the NiAl-based and RuAl-based phases overlap in the ternary region. Due to the nonstoichiometric nature of the *B*2 compounds, there is a variation in the lattice parameters of the pure binary phases as well. [1985Cha] stated that the evidence obtained by them does not preclude the possibility of the miscibility gap closing at high Al contents in the ternary region. [1998Hor] reexamined this problem with arc melted samples and with samples annealed at 1600 or 1500 °C for 12 h. The equilibria were studied with scanning electron microscope (SEM) and x-ray diffraction (XRD). Their SEM images show evidence for coring, with an indistinct boundary between adjacent grains. Measurements of the composition with energy dispersive x-ray (EDX) spectroscopy showed a continuous variation in composition across the indistinct boundary and not an abrupt change as would be expected between phases in equilibrium. Hardness measurements along the AlNi-AlRu join showed a peak around the midcomposition. With these results, [1998Hor] concluded that a continuous solid solution exists between AlNi and AlRu, as shown in Fig. 2.

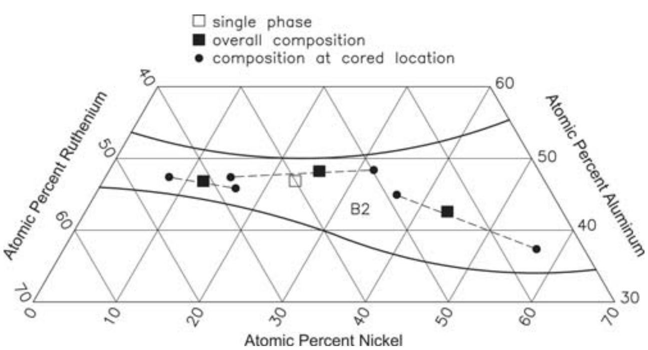

Fig. 2 Al-Ni-Ru continuous *B*2 solid solution of Al(Ni,Ru) [1998Hor]

Liquidus Surface

With starting metals of 99.99% Al, 99.99% Ni, and ~99.9% Ru, [1986Cha] arc melted eight ternary alloys in the Al-poor region of the system. The phase equilibria were studied with optical microscopy (OM), scanning electron microscopy (SEM), electron probe microanalysis (EPMA), and XRD. Based on the binary information and observations on as-cast and annealed alloys, [1986Cha] constructed a partial liquidus projection for the Al-poor region. [1997Hor1] studied four Al-poor alloys and produced a schematic liquidus surface for this region. The two liquidus projections differ significantly. As no differential thermal analysis was carried out by either group, the temperatures of the invariant reactions are not known. In Fig. 3, a schematic liquidus projection is shown for this region, as proposed by [1986Cha], except that amendment is made for the formation of a continuous solid solution between AlNi and AlRu as proposed by [1997Hor1].

[1997Hor2] and [2000Hoh] arc melted under Ar atm Al-rich ternary alloys starting from 99.9% purity metals. The phase equilibria of as-cast and annealed samples were studied by OM, SEM, EPMA, and XRD. The deduced liquidus surface shows the primary crystallization of one ternary compound ~$RuNi_2Al_{14}$. This composition lies close to that of the m phase found by [2003Mi1] and [2003Mi2].

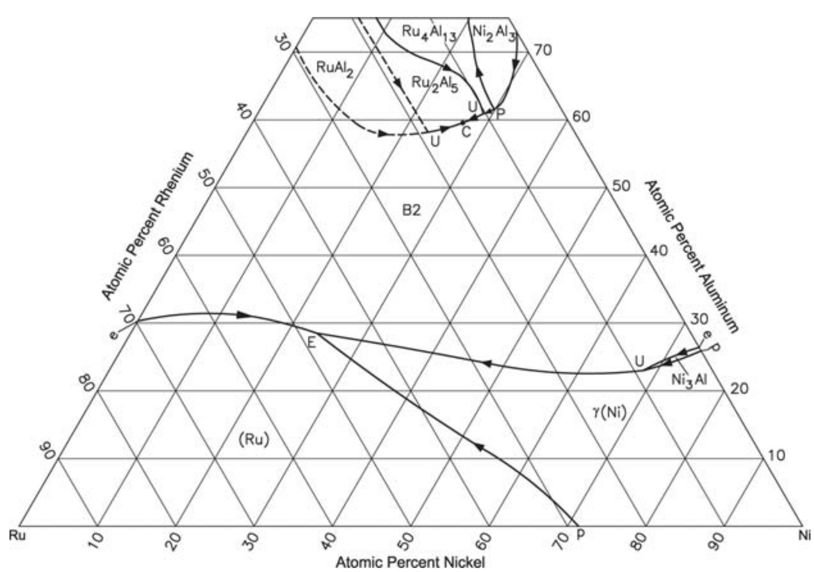

Fig. 3 Al-Ni-Ru tentative liquidus projection [after 1986Cha, 2000Hoh]

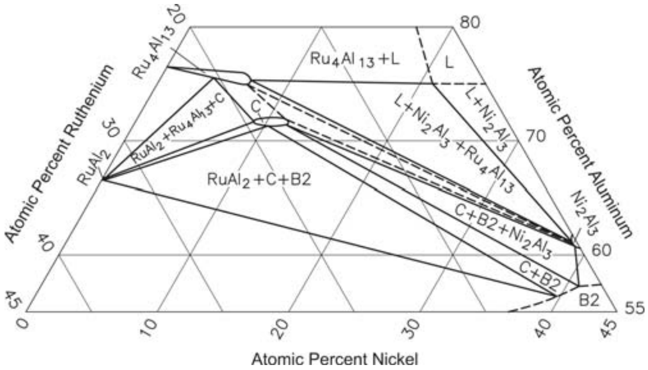

Fig. 4 Al-Ni-Ru partial isothermal section at 1100 °C [2003Mi2]

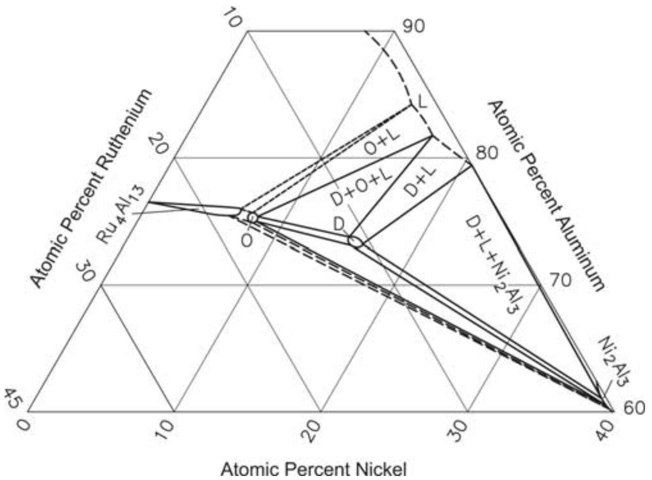

Fig. 5 Al-Ni-Ru partial isothermal section at 1000 °C [2003Mi2]

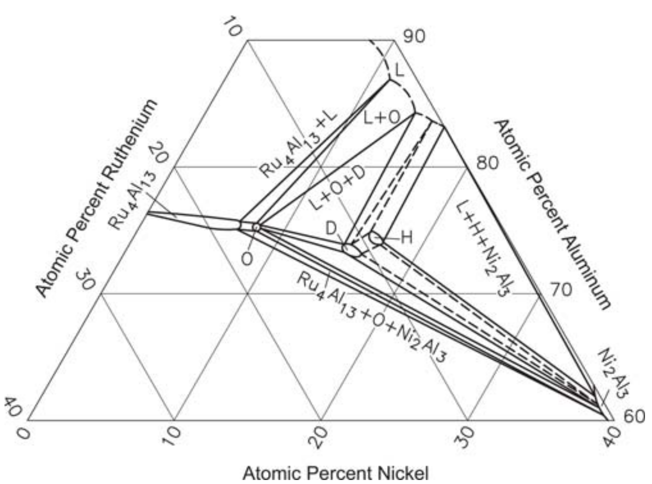

Fig. 6 Al-Ni-Ru partial isothermal section at 900 °C [2003Mi2]

[2003Mi1] found evidence for the melting of the other Al-rich ternary phases C, D, and H as well. As such, these also should appear on the liquidus surface as primary phases, but they were not found by [2000Hoh]. For Al content more than 50 at.%, the liquidus projection of [2000Hoh] is shown

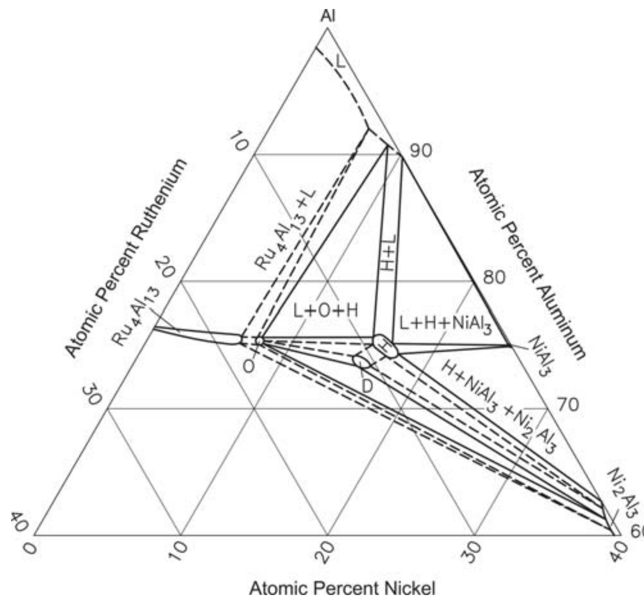

Fig. 7 Al-Ni-Ru partial isothermal section at 800 °C [2003Mi2]

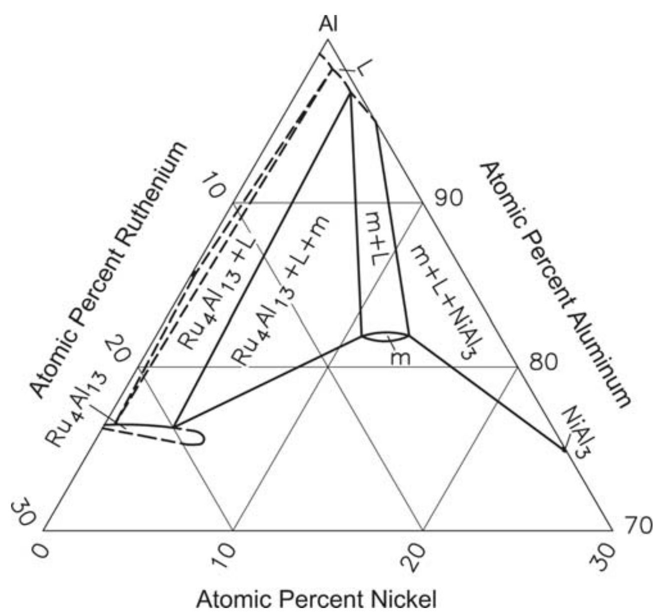

Fig. 8 Al-Ni-Ru partial isothermal section at 700 °C [2003Mi2]

tentatively in Fig. 3, modified to agree with the accepted Al-Ru diagram. The Al-rich corner is omitted.

Isothermal Sections

With starting metals of 99.999% Al, 99.999% Ni, and 99.9% Ru, [2003Mi2] prepared a number of Al-rich alloys by levitation induction melting under Ar atm. The alloys were annealed at temperatures between 1100 and 700 °C for 20 to 2760 h. The phase equilibria were studied with SEM, XRD, and SEM-EDX. Some compositions were also analyzed by inductively coupled plasma optical emission spectroscopy. The partial isothermal sections constructed by [2003Mi2] between 1100 and 700 °C are redrawn in Fig. 4 to 8. At 1100 °C (Fig. 4), Ru_4Al_{13} dissolves up to 7 at.% Ni. The cubic C phase $Al_5(Ru,Ni)_2$ has a composition of 72 at.% Al and 9 to 11.8 at.% Ni. It may be noted that the binary phase Al_5Ru_2 has orthorhombic symmetry. At 1000 °C (Fig. 5), the C phase is not stable. The O phase forms tie-lines with Ru_4Al_{13}, D, and liquid. The decagonal D phase has a composition of ~$Al_{73.1}Ni_{15.7}Ru_{11.2}$. At 900 °C (Fig. 6), the H phase is stable [2004Mi]. At 800 °C (Fig. 7), the composition range of H has increased and it now forms tie-lines with O, D, L, $NiAl_3$, and Ni_2Al_3. At 700 °C (Fig. 8), the ternary m phase is present. At this temperature, the ternary phases at lower Al contents were not identified by [2003Mi2].

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