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Al-Cu-Fe (Aluminum-Copper-Iron)

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The previous review of this system by [1992Rag] presented two partial liquidus surfaces for Al-rich and Cu-rich alloys, and an isothermal section at 600 °C, mainly from the work of [1939Bra], [1953Phi], and [1971Pre]. The occurrence of a stable quasi-crystalline, icosahedral phase in Al-rich alloys of this system [1987Tsa] has stimulated a number of studies in the Al-rich region in recent years.

Binary Systems

The Al-Cu phase diagram [Massalski2] depicts a number of intermediate phases and invariant reactions. The *C*16 tetragonal phase $CuAl_2$ (θ) is well known, due to its presence in age-hardening Al alloys. CuAl (η) has two crystal modifications, the high-temperature orthorhombic and the low-temperature monoclinic forms. The two forms of the ζ phase have a composition range of 55.2 to 59.8 at.% Cu and are stable below 590 °C. Two modifications of the ε phase occur around the composition Cu_3Al_2 and are stable above 560 °C. For other phases richer in Cu, see the review in [Massalski2]. In the Fe-Al phase diagram [1993Kat], the solid solution based on face-centered cubic (fcc) Fe is restricted by a γ loop. The solid solution based on body-centered cubic (bcc) Fe (α) exists in both the disordered (*A*2) and the ordered (*B*2 and $D0_3$) forms. The *A*2 (α) → *B*2 transition is second order down to ~600 °C; below that, a two-phase field of (*A*2 + *B*2) intervenes, which is indicative of a first-order transition. Apart from the high-temperature ε phase, there are three intermediate phases in the system with restricted ranges of homogeneity: $FeAl_2$ (triclinic, denoted υ); Fe_2Al_5 (orthorhombic, μ); and $FeAl_3$ or Fe_4Al_{13} (monoclinic, λ). The Cu-Fe phase diagram [Massalski2] has no intermediate phases. A metastable liquid miscibility gap is known in this system.

Ternary Phases

The review by [1992Rag] summarized the ternary phases in this system. $Al_{23}CuFe_4$ (τ_1), denoted α in some reports, has the Al_6Fe-type orthorhombic structure. Al_7Cu_2Fe (ω, denoted τ_2 by [1992Rag]) has tetragonal symmetry. $Al_{10}Cu_{10}Fe$ (φ, denoted τ_3 by [1992Rag]) has a structure related to the hexagonal phase Ni_2Al_3. [2003Zha4] and [2004Zha1] studied the formation and stability of the φ phase. [2003Zha4] summarized the reactions in which it takes part in the ternary region. $Al_{18}Cu_{10}Fe$, denoted χ by [1939Bra], could not be confirmed [1971Pre, 1992Gay1]. [1992Gay1] reported a new phase at ~$Al_{56.5}Cu_{42}Fe_{1.5}$ after prolonged annealing at 550 °C. It seems to be metastable and has a unit cell related to the *B*2 structure.

Al_6Cu_2Fe, earlier denoted ψ [1939Bra, 1971Pre], was identified as the stable icosahedral phase *i* by [1987Tsa] and [1991Fau]. A number of new reports have appeared recently on the icosahedral phase and its variants [1992Gay2, 1993Fau, 1993Gra, 1994Hol, 1994Was, 2001Gui, 2001Ros, 2003Luc, 2003Zha5, 2004Zha2]. At 680 °C, [1993Gra] found that the icosahedral region extends approximately over a triangular region with the three vertices at Al-Cu-Fe (in at.%) equal to 62.4-24.4-13.2, 65-23-12, and 61-28.4-10.6, respectively. This region consists of three fields: (1) the perfect icosahedral phase, stable down to the lowest possible annealing temperature with composition around $Al_{62.3}Cu_{24.9}Fe_{12.8}$, (2) a well-defined periodic phase *R* with rhombohedral lattice, which transforms reversibly to *i* near 710 °C in the lower part of the triangular region, and (3) to the left of the *R* phase lies the pentagonal variant (the *P* phase). Figure 1 is from the results of [1993Fau], showing a partial isothermal section at 700 °C in the region of the *i* phase and its variants The region marked β is a cubic phase with either the bcc or the *B*2 structure.

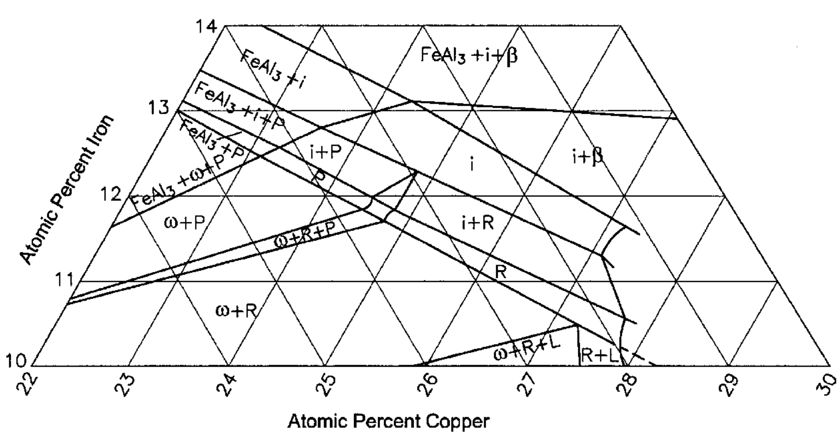


Fig. 1 Al-Cu-Fe isothermal section at 700 °C near the *i* region. *P* (pentagonal) and *R* (rhombohedral) are two variants of *i* [1993Fau].

The Liquidus Projection

There have been several recent reports on the liquidus surface of this system [1992Gay2, 1993Fau, 2002Zha, 2003Mie, 2003Zha1, 2003Zha5]. Using high-purity metals, [2003Zha1] melted alloy compositions in an arc furnace under an Ar atmosphere. Differential thermal analysis (DTA) was carried out at a heating rate of 10 °C/min and a cooling rate of 10 to 40 °C/min. Magnetothermal analysis was carried out on a high-sensitivity magnetic balance. The cooled samples were studied by x-ray diffraction, optical microscopy, and scanning electron microscopy with energy-dispersive x-ray spectroscopy. The liquidus surface constructed by [2003Zha1] is redrawn in Fig. 2. The liquidus line for the Fe_2Al_5 (μ) + $FeAl_2$ (υ) + L equilibrium shown by [2003Zha1] as originating from the Fe-Al side is omitted, as $FeAl_2$ forms through a peritectoid reaction in the accepted version of the Fe-Al phase diagram [1993Kat]. The *i* phase forms through a ternary peritectic reaction P at 882 °C [2003Zha1]. The reactions p_1 and p_2 corresponding to the peritectic formation of the ternary phases ω and τ_1 start from temperature maxima, the former lying on the $FeAl_3$-$CuAl_2$ join. Isotherms are shown at 50 °C intervals in Fig. 2. The phases of primary crystallization are marked. The region marked β is either *B*2 or the disordered form (bcc).

Isothermal Sections

Isothermal sections in the *i* region were constructed in several studies: at 550 °C [1992Gay1]; at 800, 720, 700, and 680 °C [1992Gay2]; at 700 °C [1993Fau]; at 850 °C [2001Ros]; at 900 and 870 °C [2003Zha1]; and at 800, 700, 645, 620, 617, 600, 592, and 560 °C [2003Zha3]. Five representative isothermal sections at 900, 800, 700, 600, and 560 °C are redrawn from [2003Zha1] and [2003Zha3] in Fig. 3 to 7 to agree with the accepted binary data. The region marked β in Fig. 3 to 7 is either *B*2 or the disordered form (bcc). The sections reflect the progressive changes in the phase distribution, as invariant reactions occur on cooling. Table 1 depicts a reaction scheme for the solidification reactions in Al-rich alloys [2003Zha1]. The U-type transition reactions in Table 1 are numbered sequentially in order of decreasing temperature of the reaction. This numbering sequence may not tally with that given by [2003Zha1]. [2003Zha3] presented a more detailed reaction scheme incorporating the solid-state reactions.

Experimental isothermal sections for Al-poor Fe-Cu alloys were constructed at 1200 °C by [1997Oht], and at 1000, 900, and 800 °C by [1998Wan]. Combining the experimental results of [1997Oht] with their own findings, [1998Wan] computed isothermal sections at 1300, 1200, 1100, 1000, 900, and 800 °C. For Al-poor Fe-Cu alloys, [2003Mie] reported computed sections at 1300, 1200, 1100, 1000, 900, and 800 °C. Also, [2003Mie] computed isothermal sections at 1085, 1075, 1065, and 1055 °C for Cu-rich alloys to illustrate the development of the miscibility gap in the bcc phase with falling temperature. He also compared computed isothermal sections at 1000, 800, 700, 672, 600, and 550 °C with early experimental results on this system. As examples from the large number of the above-listed results, the computed isothermal section by [1998Wan] at 1200 °C, based on the experimental results of [1997Oht], is redrawn in Fig. 8. The experimental section of [1998Wan] at 800 °C in the order-disorder region is redrawn in Fig. 9, which clarifies the phase relationships among the α (*A*2), *B*2, β (A2), and fcc (Cu) structures. Similar phase distribution is seen at 900 and 1000 °C [1998Wan]. [2001Liu] measured the compositions of the coexisting phases in the fcc-bcc and bcc-$D8_3$ (Al_4Cu_9) equilibria at 800 and 700 °C in alloys containing up to 1 at.% Fe.

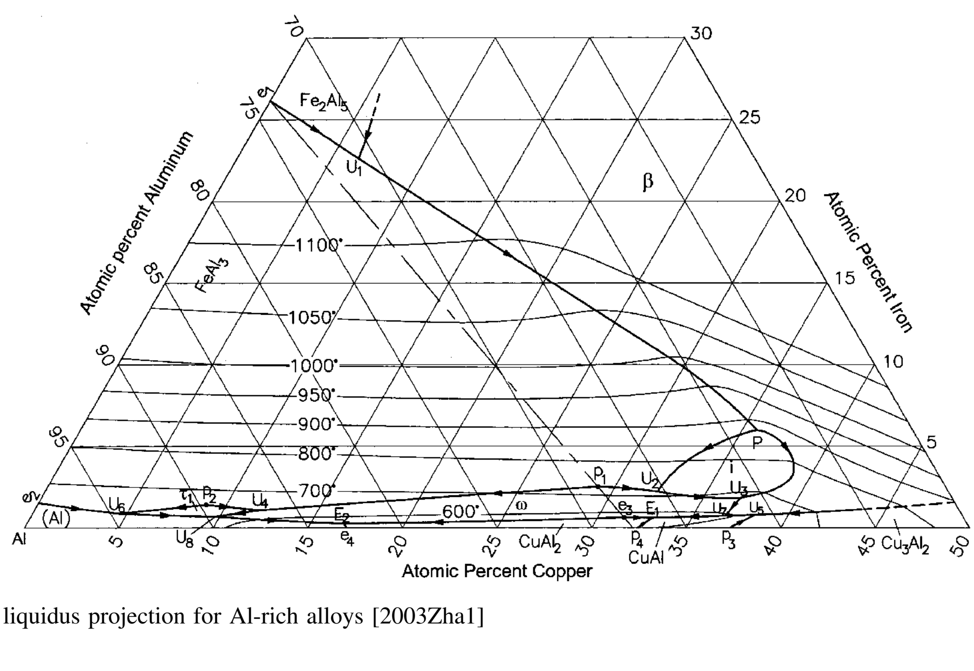
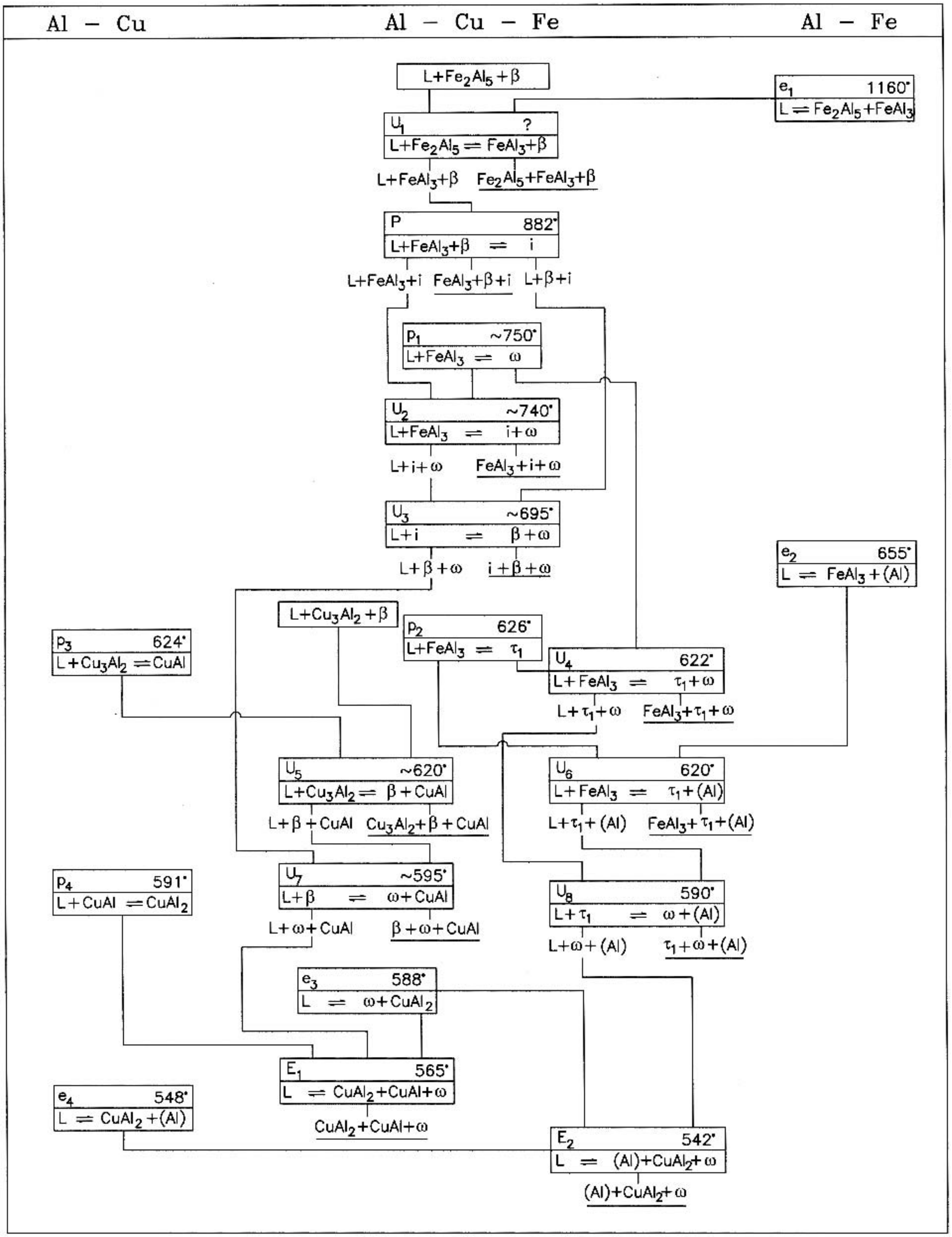


Fig. 2 Al-Cu-Fe liquidus projection for Al-rich alloys [2003Zha1]

Table 1 Al-Cu-Fe Reaction Scheme for Solidification of Al-Rich Alloys [2003Zha1]



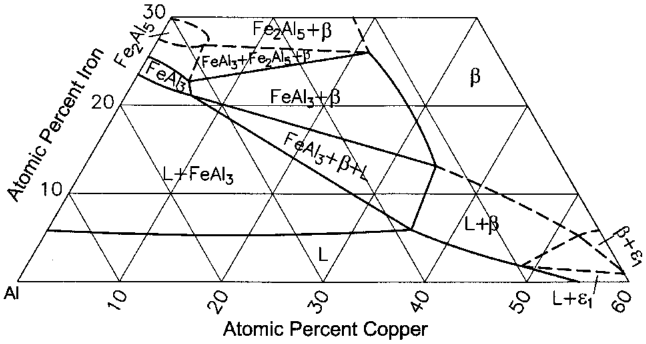


Fig. 3 Al-Cu-Fe isothermal section at 900 °C [2003Zha1]

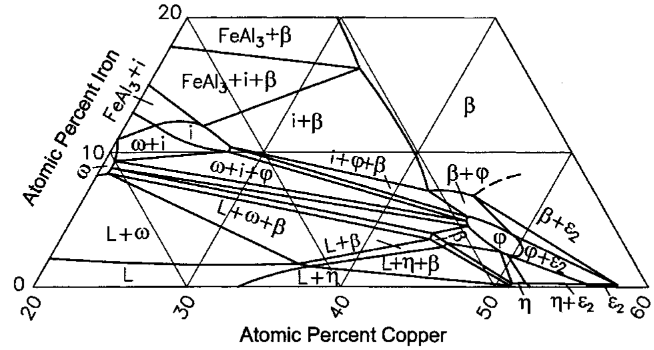


Fig. 6 Al-Cu-Fe isothermal section at 600 °C [2003Zha3]

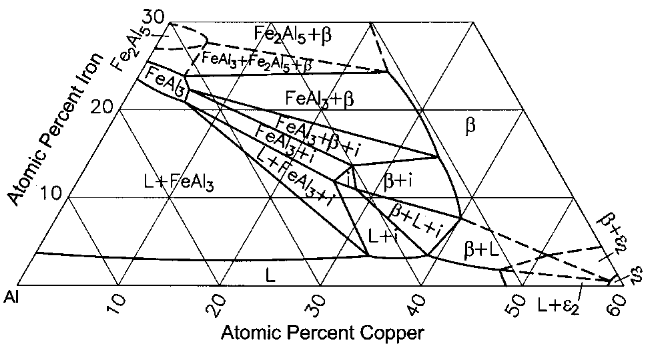


Fig. 4 Al-Cu-Fe isothermal section at 800 °C [2003Zha3]

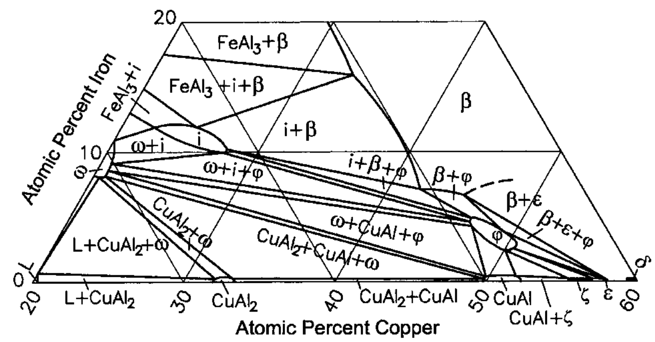


Fig. 7 Al-Cu-Fe isothermal section at 560 °C [2003Zha3]

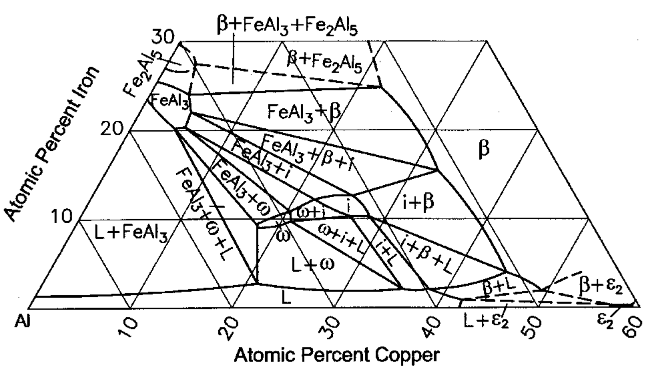


Fig. 5 Al-Cu-Fe isothermal section at 700 °C [2003Zha3]

Vertical Sections

Using their experimental results from DTA and magneto-thermal analysis, [2003Zha2] constructed a number of vertical sections for Al-rich alloys, checking their consistency with the liquidus projection and the isothermal sections. The vertical sections are at a constant Fe content of 5, 7.5, 10, 11, and 12 at.%, at a constant Cu content of 25 at.%, and along the $Al_{77.2}Fe_{22.8}$-$Al_{42.5}Cu_{57.5}$, $Al_{90}Cu_{10}$-$Al_{50}Cu_{30}Fe_{20}$, $Al_{62.5}Cu_{37.5}$-$Al_{59}Cu_{21}Fe_{20}$, $Al_{61}Cu_{39}$-$Al_{62.5}Cu_{17.5}Fe_{20}$, and $Al_{85.5}Fe_{14.5}$-$Al_{46.5}Cu_{50}Fe_{3.5}$ joins. [1993Fau] presented two vertical sections at a constant Fe content of 12 at.% and a Cu-to-Fe atom ratio of 2. For Al-poor alloys, [1998Wan] computed three vertical sections at 5, 10, and 15 wt.% Al. [2003Mie] computed vertical sections at a constant Al content of 2, 4, 6, 8, and 10 wt.%, and at a constant Fe content of 2 and 4 wt.% The vertical section at 2 wt.% Al is redrawn in Fig. 10 from [2003Mie]. For more details on vertical sections, the interested reader may consult the above references.

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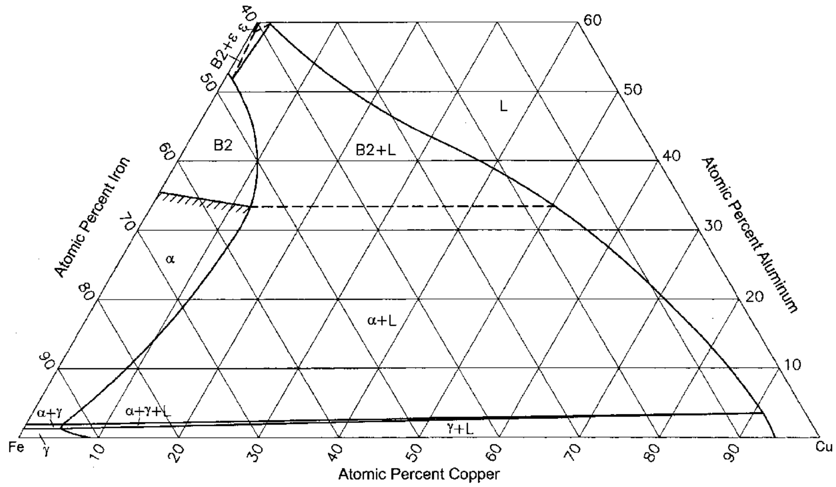

Fig. 8 Al-Cu-Fe isothermal section at 1200 °C [1998Wan]

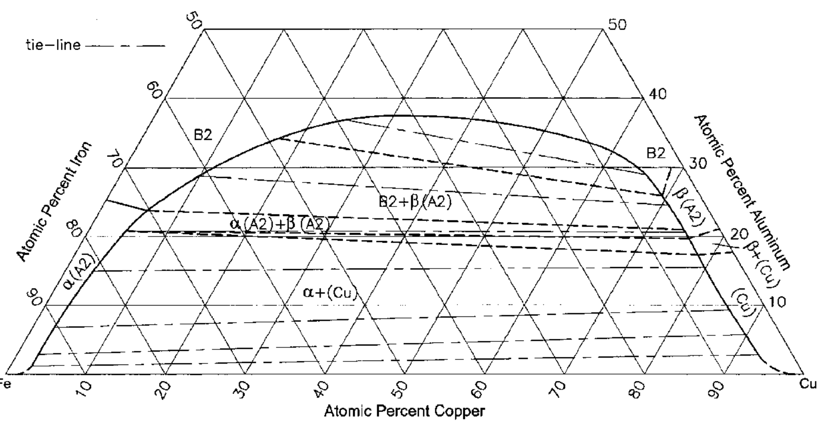

Fig. 9 Al-Cu-Fe isothermal section at 800 °C for Al-poor alloys [1998Wan]

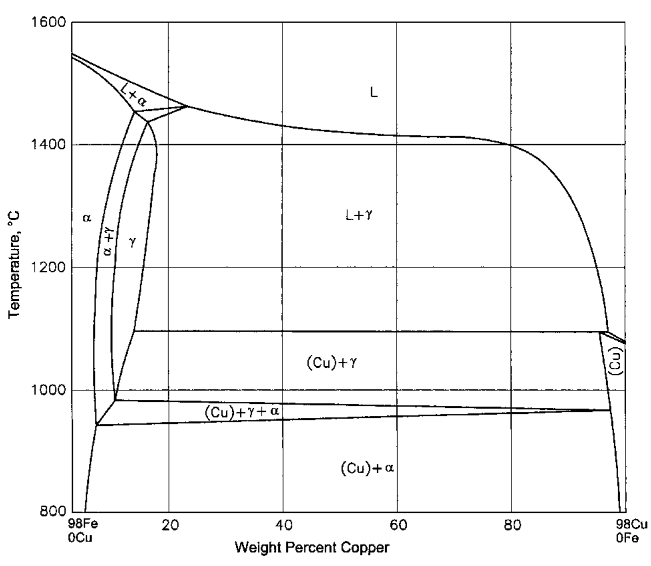

Fig. 10 Al-Cu-Fe computed vertical section at 2 wt.% Al [2003Mie]

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