JPEDAV (2006) 27:284-287
DOI: 10.1361/154770306X109845
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Al-Fe-Zr (Aluminum-Iron-Zirconium)

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The previous review of this system by [1992Rag] presented an isothermal section at 900 °C from the work of [1969Bur]. An update by [2003Rag] reviewed a partial isothermal section at 1150 °C determined by [1999Ste]. A recent and more complete study by [2004Ste] presented a partial liquidus projection and isothermal sections at 1150, 1000, and 800 °C.

Binary Systems

The Al-Fe phase diagram [1993Kat] shows that the face-centered cubic (fcc) solid solution based on Fe is restricted by a γ loop. The body-centered cubic (bcc) solid solution α exists in the disordered *A*2 form as well as the ordered *B*2 and $D0_3$ forms. Apart from the high-temperature phase ε,

Table 1 Al-Fe-Zr crystal structure and lattice parameter data

Phase	Composition, at.%	Pearson symbol	Space group	Prototype	Lattice parameter, nm
$(Fe,Al)_2Zr(\lambda_1)$	20-51.7 Al	*hP*12	$P6_3/mmc$	$MgZn_2$	$a \sim 0.501$ to 0.520
	23.2-35.2 Zr				$c \sim 0.820$ to 0.852
$(Al,Fe)_2Zr(\lambda_2)$	50.9-59.6 Al	*cF*24	$Fd\bar{3}m$	$MgCu_2$	$a \sim 0.738$ to 0.746
	33.9-34.9 Zr				
$(Fe,Al)_{12}Zr(\tau_1)$	37.4-61.6 Al	*tI*26	*I*4/*mmm*	$ThMn_{12}$	$a \sim 0.8481$ to 0.8625
	7.9-8.5 Zr				$c \sim 0.4950$ to 0.5015
$FeAl_2Zr_6(\tau_2)$	~19.2 Al	*hP*9	$P\bar{6}2m$	Al_2CoZr_6	$a = 0.7904$ to 0.7981
	~67.4 Zr				$c = 0.3351$ to 0.3375
$Fe_7Al_{67}Zr_{26}(\tau_3)$	66.1-67.8 Al	*cP*4	$Pm\bar{3}m$	$AuCu_3$	$a = 0.4069$ to 0.4076
	26.0-26.4 Zr				

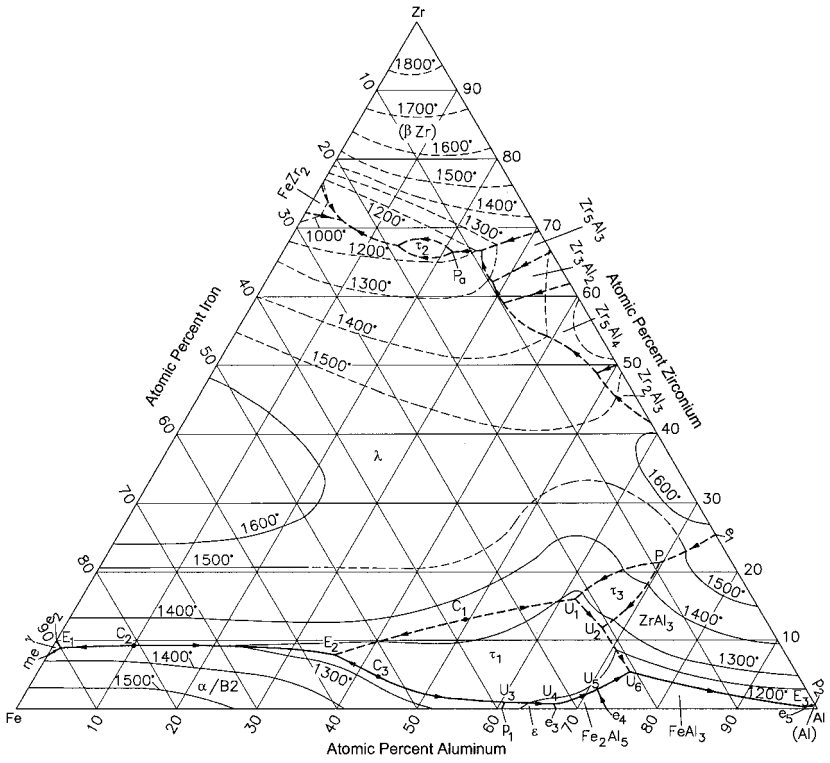

Fig. 1 Al-Fe-Zr liquidus projection [after 2004Ste]

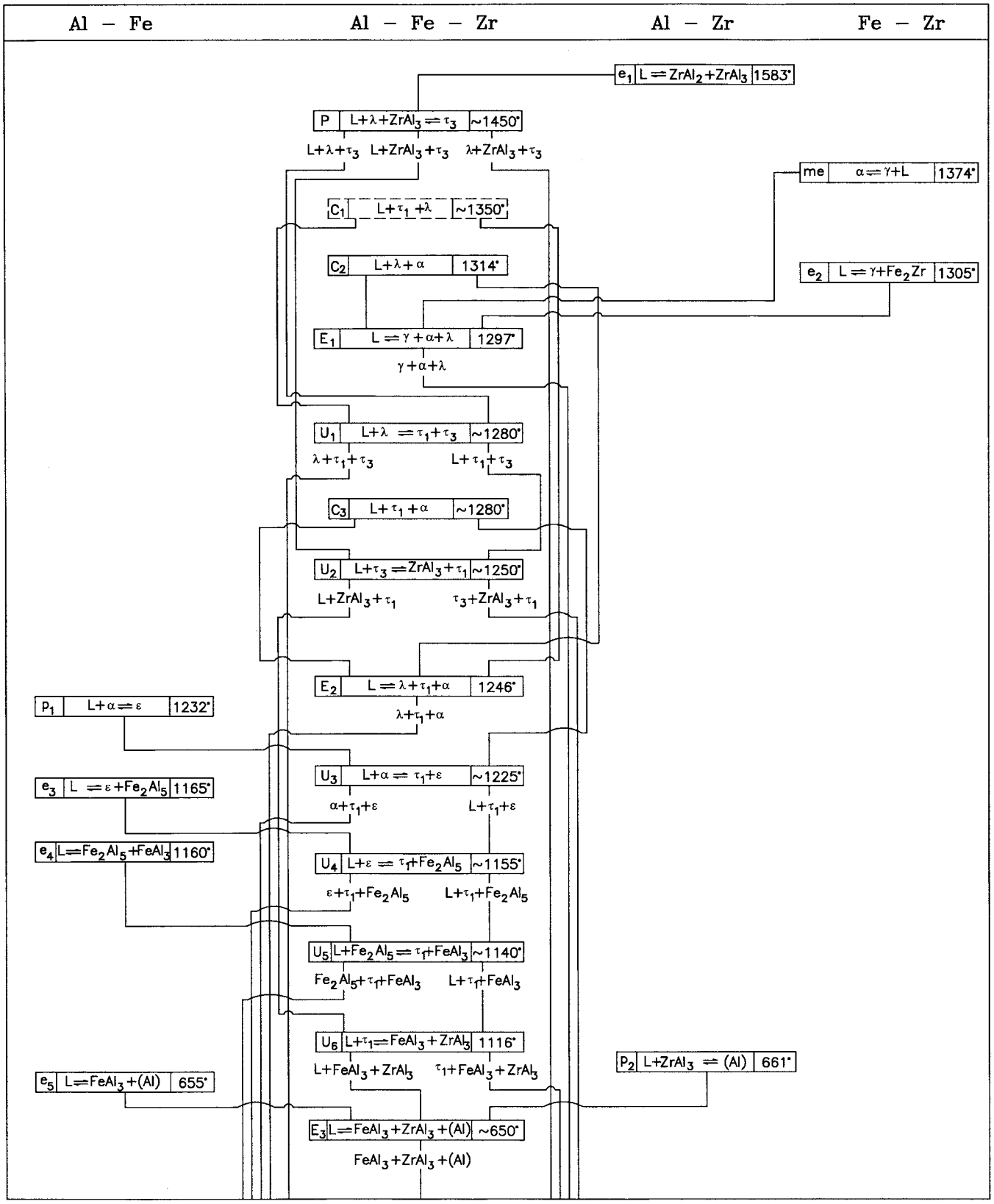

Fig. 2 Al-Fe-Zr reaction sequence during solidification of Zr-lean alloys

there are three other intermediate phases: $FeAl_2$ (triclinic), Fe_2Al_5 (orthorhombic), and $FeAl_3$ (monoclinic). The Al-Zr phase diagram [2001Wan, Massalski2] depicts ten intermediate phases: $ZrAl_3$ ($D0_{23}$-type tetragonal), $ZrAl_2$ ($C14$, $MgZn_2$-type hexagonal), Zr_2Al_3 (orthorhombic), ZrAl (orthorhombic), Zr_5Al_4 (Ga_4Ti_5-type hexagonal), Zr_4Al_3 (Ir_4Al_3-type hexagonal), Zr_3Al_2 (tetragonal), Zr_5Al_3 ($D8_m$, W_5Si_3-type tetragonal), Zr_2Al ($B8_2$, Ni_2In-type hexagonal), and Zr_3Al ($L1_2$, $AuCu_3$-type cubic). [2002Ste] reported new determinations of the lattice parameters of the Al-Fe and Al-Zr intermediate phases. The Fe-Zr phase diagram [2002Ste] depicts three intermediate phases: Fe_2Zr (1345-1240 °C: $C36$-type hexagonal; 1673-25 °C: $C15$-type cubic), $FeZr_2$ ($C16$, $CuAl_2$-type tetragonal), and $FeZr_3$ ($E1_a$, Re_3B-type orthorhombic).

Ternary Phases

Five ternary phases are known in this system [1969Bur, 1992Rag, 2004Ste]. These are listed in Table 1, with the homogeneity ranges and the lattice parameters taken from [2004Ste]. λ_1 and λ_2 are $C14$ and $C15$ type ternary Laves phases, respectively, which are present around the 33.3 at.% Zr line. The homogeneity ranges of λ_1 and λ_2 are 20-51.7 and 50.9-59.6 at.% Al, respectively. The $C15$ type binary phase Fe_2Zr extends up to ~20 at.% Al. Above 60.1 at.% Zr, the $C14$ type Al_2Zr-based Laves phase is stable. Among these, Fe_2Zr and λ_1 show significant variations in Zr content as well. The lattice parameters of the Laves phases increase linearly with increasing Al content. The lattice parameters also increase with increasing Zr content. The experimental results clearly indicated the presence of narrow two-phase fields between the Laves phases [2004Ste]. The extension of the $C36$ phase, stable between 1345 and 1240 °C in the Fe-Zr binary diagram, into the ternary region is probably small. It was not found by [2004Ste] in an alloy with 10 at.% Al.

The $ThMn_{12}$-type tetragonal phase τ_1 is stable at least from 1270 °C to room temperature. The variation in the Zr content of τ_1 is less than 1 at.%. The homogeneity range of the hexagonal τ_2 phase is small, and the compound decomposes above 1077 °C [2004Ste]. The range of the $L1_2$ type cubic phase τ_3 is very small. [2004Ste] found other impurity-stabilized ternary phases such as $(Fe,Al,X)_{23}Zr_6$ with the $Mn_{23}Th_6$-type structure.

Liquidus Projection

Using metallographic observations and results from differential thermal analysis, [2004Ste] constructed a partial tentative liquidus surface for this system. This is redrawn in Fig. 1. The phases of primary crystallization are marked in the figure. The dominant primary field of the Laves phases is marked λ in the figure, without distinguishing between the four Laves phases that occur along the 33.3 at.% Zr line [2004Ste]. In the Zr-rich region, the experimental data are meager. The liquidus projection is extended schematically in this region in Fig. 1. The ternary compound τ_2 is postulated here to form through a ternary peritectic reaction P_a: $L + \lambda + (\beta Zr) \rightarrow \tau_2$ at 1077 °C.

A partial reaction sequence for the solidification reactions in the Zr-lean region is given in Fig. 2. All four-phase

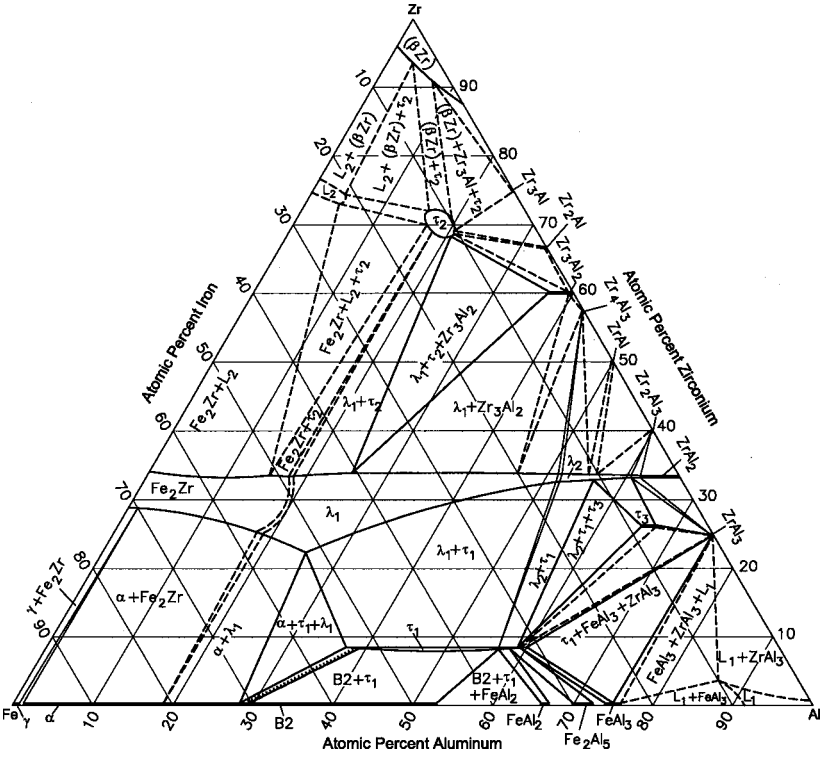

Fig. 3 Al-Fe-Zr isothermal section at 1000 °C [2004Ste]

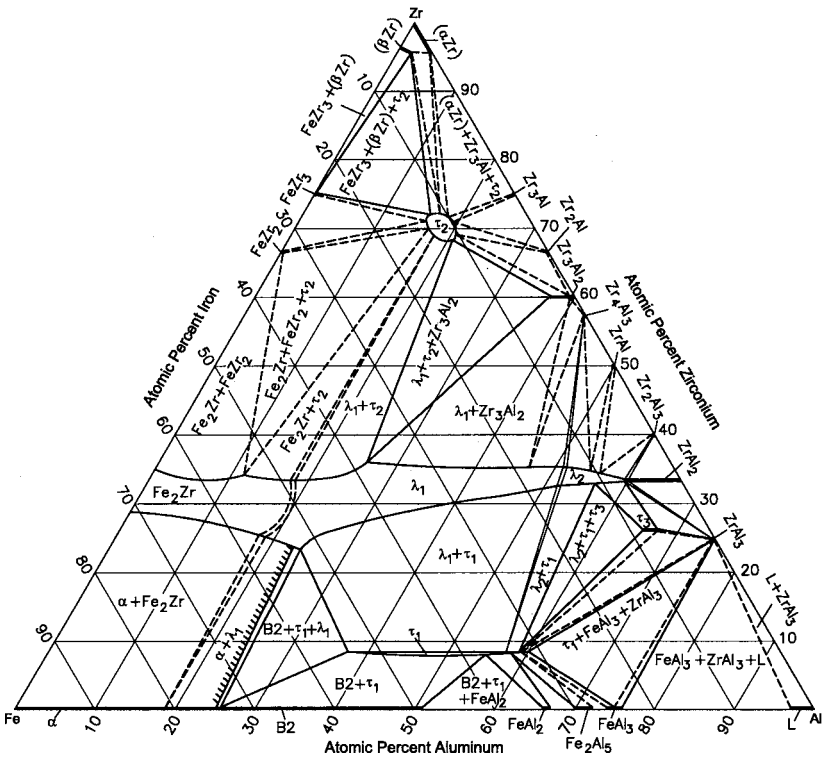

Fig. 4 Al-Fe-Zr isothermal section at 800 °C [2004Ste]

invariant reactions are those proposed by [2004Ste]. Approximate values of temperature are given. An upper critical point C_1 is postulated here to account for the formation of τ_1. Thermal analysis results of [2004Ste] indicate two other temperature maxima C_2 and C_3 (Fig. 1 and 2). A third temperature maximum indicated by [2004Ste] very close to the invariant reaction at 1116 °C is omitted here, pending further experimental confirmation.

Isothermal Sections

With starting metals of 99.999% Al, 99.95% Fe, and 99.8% Zr, [2004Ste] prepared 12 binary and 48 ternary alloys by levitation or induction melting. The final anneal of the alloys was at 1150, 1000, and 800 °C for 100, 200, and 500 h, respectively, followed by quenching in iced brine. The phase equilibria were studied by optical and scanning-electron metallography, x-ray powder diffraction, and electron probe microanalysis. The diffusion couple technique and differential thermal analysis were also used.

The isothermal section at 1150 °C constructed by [2004Ste] is similar to the one reviewed in [2003Rag] from the work of the same group of authors [1999Ste]. However, the triangulation near the Al corner is different in the later publication. The three-phase fields of (τ_1 + τ_3 + $ZrAl_3$) and (τ_1 + L + $ZrAl_3$) are present in the revised figure of [2004Ste]. The isothermal section at 1000 °C constructed by [2004Ste] is redrawn in Fig. 3. [2003Rag] postulated two U-type transition reactions between 1150 and 1000 °C. According to [2004Ste], the first reaction $\tau_3 + L \rightarrow \tau_1 + ZrAl_3$ occurs at 1250 °C (labeled U_2 in Fig. 1 and 2). The second reaction $\tau_1 + L \rightarrow FeAl_3 + ZrAl_3$ occurs at 1116 °C (labeled U_6 in Fig. 1 and 2). The isothermal section at 800 °C is redrawn in Fig. 4. At 800 °C, the solidification in Zr-rich alloys is complete, with additional phases $FeZr_2$, $FeZr_3$, and (αZr) appearing in the equilibrium.

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