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Fe-Si-Ti (Iron-Silicon-Titanium)

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The previous review of this ternary system by [1987Rag] presented a liquidus surface for Fe-rich alloys from the studies of [1938Vog] and an isothermal section at 800 °C from [1966Mar]. Recently, [2008Wei] reinvestigated the solidification characteristics over the entire composition range and presented a liquidus projection, a corresponding reaction sequence and a tentative isothermal section at 900 °C. Earlier, [2002Lof] investigated the Si-lean region and presented three partial isothermal sections at 1150, 1000, and 800 °C. This unpublished thesis result was quoted by [2005Ste], who presented the isothermal sections at 1150 and 800 °C. The isothermal section at 800 °C of [2002Lof] was also reproduced by [2004Lof], who studied the mechanical properties of Si-lean alloys.

Binary Systems

The Fe-Si phase diagram [Massalski2] is characterized by a gamma loop enclosing (γFe) (fcc). The bcc α phase is present in the disordered α (*A*2) form and the ordered α_1 ($D0_3$, BiF_3-type cubic) and α_2 (*B*2, CsCl-type cubic) forms. The intermediate phases are: Fe_2Si (hexagonal), Fe_5Si_3 ($D8_8$, Mn_5Si_3-type hexagonal), FeSi (*B*20-type cubic), α$FeSi_2$ (orthorhombic), and β$FeSi_2$ (tetragonal). The Fe-Ti phase diagram [1998Dum] depicts the following intermediate phases: Fe_2Ti (*C*14, $MgZn_2$-type hexagonal) and FeTi (*B*2, CsCl-type cubic). The Si-Ti phase diagram [Massalski2, 2008Wei] depicts the following intermediate phases:

Table 1 Fe-Si-Ti crystal structure and lattice parameter data [2008Wei]

Phase	Composition, at.%	Space group	Prototype	Lattice parameter, nm
$FeSi_2Ti$ (τ_1)	24-25 Fe	*Pbam*	$MnSi_2Ti$	*a* = 0.86115
	49-50 Si			*b* = 0.95427
	25-26 Ti			*c* = 0.76313
FeSiTi (τ_2)	31-33 Fe	*Ima*2	FeSiTi	*a* = 0.69869
	33-35 Si			*b* = 1.0827
	33-35 Ti			*c* = 0.62991
Fe_4Si_3Ti (τ_3)	49 Fe	*P*6/*mmm*	$Pd_{40}Sn_{31}Y_{13}$	*a* = 1.72073
	35.5 Si			*c* = 0.79819
	15.5 Ti			
τ_4	28 Fe	...	...	...
	45.6 Si			
	26.3 Ti			
τ_5	7.4 Fe	...	...	...
	64.3 Si			
	28.3 Ti			
τ_6	~12.5 Fe	...	...	...
	~49 Si			
	~38.5 Ti			
τ_7	10 Fe	...	...	...
	40 Si			
	50 Ti			
τ_8	20 Fe	...	...	...
	40 Si			
	40 Ti			
τ_9	17 Fe	...	...	...
	43 Si			
	40 Ti			
Fe_7Si_2Ti	69 Fe	$I\bar{4}3m$	$Fe_5Si_2V_3$	*a* = 0.8837
	20 Si			
	11 Ti			
Fe_2SiTi (metastable)	50 Fe	$Fm\bar{3}m$	$MnCu_2Al$	*a* = 0.5709
	25 Si			
	25 Ti			

Ti_3Si (Ti_3P-type tetragonal), Ti_5Si_3 ($D8_8$, Mn_5Si_3-type hexagonal), Ti_5Si_4(o) (Sm_5Ge_4-type orthorhombic; low-temperature modification), Ti_5Si_4(t) (Zr_5Si_4-type tetragonal; high-temperature modification), TiSi ($B27$, FeB-type orthorhombic), and $TiSi_2$ ($C54$-type orthorhombic).

Ternary Phases

[1987Rag] summarized the then-available structural details of the ternary phases of this system: $FeSi_2Ti$ (τ_1) ($MnSi_2Ti$-type orthorhombic), FeSiTi (τ_2) (FeSiTi-type orthorhombic), Fe_4Si_3Ti (τ_3) ($Pd_{40}Sn_{31}Y_{13}$-type hexagonal), $Fe_{10}Si_{44}Ti_{46}$ (X′) (unknown structure), and $Fe_{15}Si_{40}Ti_{45}$ (X″) (unknown structure). In the ordered phase Fe_3Si (α_1), Ti dissolves up to $x = 0.7$ in $Fe_{3-x}SiTi_x$. The $L2_1$-type Fe_2SiTi is a metastable superstructure based on Fe_3Si. [2008Wei] reported a number of additional ternary phases τ_4, τ_5, τ_6, τ_7, τ_8, and τ_9. The compositions of these phases were determined, but the crystal structures were not. The compositions of the ternary phases X′ and X″ reported by [1966Mar] were found by [2008Wei] to be two-phase mixtures of τ_9 + Ti_5Si_4(o) and $\tau_7 + \tau_8$, respectively. In addition to the above, [2002Lof] reported a ternary phase at the composition Fe_7Si_2Ti. The composition region within which this phase occurs was not investigated by [2008Wei]. The above phases are listed in Table 1 with updated structural data.

Liquidus Projection

With starting metals of 99.98% Fe, 99.99% Si, and 99.98% Ti, [2008Wei] arc-melted in Ar atm more than 80 ternary alloys. The alloys were annealed at 1000, 950, and 900 °C for 2 weeks (or more) and quenched in water. Differential thermal analysis was carried out at a heating/cooling rate of 5 °C per min. The arrests were read from the heating curves. X-ray powder diffraction and energy dispersive x-ray analysis on a scanning electron microscope were employed for structure identification and for determination of local composition.

To identify the invariant reactions, [2008Wei] assigned the first strong peak during the heating cycle in thermal analysis with "the formation of liquid phase from three solid phases." The three co-existing solid phases were identified from the annealing experiments in the solid state. All three solid phases melt to form the liquid in a ternary eutectic reaction. One out of the three solid phases melts during a ternary peritectic reaction. The transition reactions, on the other hand, are characterized by the interchange of the tie-lines with no fresh melting at the invariant temperature. Using the reaction sequence derived from the invariant temperatures, the liquidus projection was constructed by [2008Wei], as shown in Fig. 1. The fields of primary crystallization are marked. For clarity, the U-type transition reactions are not numbered. The ternary eutectic reactions E_1, E_2, E_3, and E_4 occur at 1254, 1175, 1151, and 1034 °C,

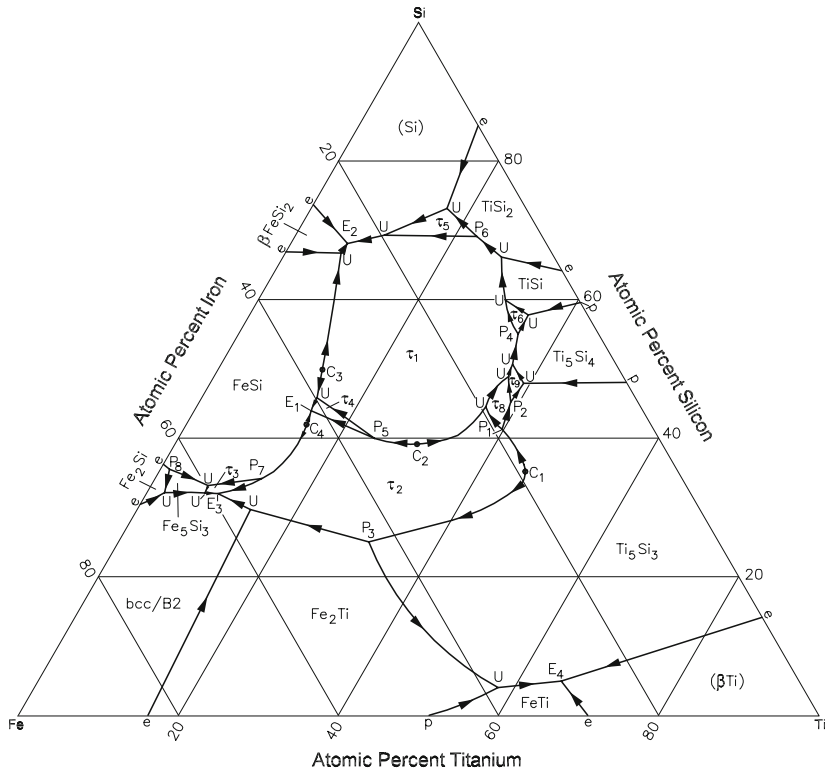

Fig. 1 Fe-Si-Ti liquidus projection [2008Wei]

respectively. The ternary phases τ_3, τ_4, τ_5, τ_6, τ_8, and τ_9 form through ternary peritectic reactions P_7 (1241 °C), P_5 (1414 °C), P_6 (1263 °C), P_4 ($1450 < T < 1480$ °C), P_1 (1640 °C), and P_2 (1597 °C), respectively. The ternary phases τ_1 and τ_2 form at temperature maxima of C_3 (1328 °C) and C_1 (>1662 °C), respectively. The binary phases Fe_2Ti and Fe_5Si_3 nucleate in the ternary region through peritectic reactions P_3 and P_8 at 1591 and 1201 °C, respectively. The ternary phase τ_7 does not take part in the liquid-solid equilibria. Among the ternary phases, τ_1 and τ_2 have large areas of primary crystallization.

The tentative isothermal section constructed by [2008Wei] at 900 °C is shown in Fig. 2. The ternary phases τ_1, τ_2, τ_3, τ_5, τ_7, τ_8, and τ_9 are present. The phases τ_4 and τ_6 decompose above 1000 °C [2008Wei]. The phase τ_7 forms in the solid state and is found to be stable at 900 °C. The

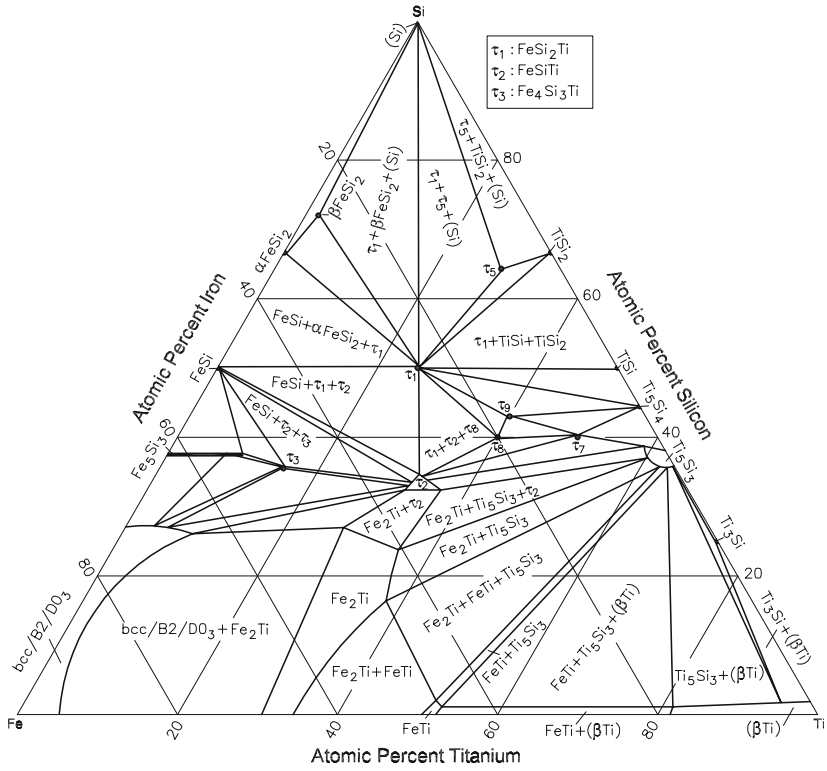

Fig. 2 Fe-Si-Ti tentative isothermal section at 900 °C [2008Wei]. Narrow two-phase regions are omitted

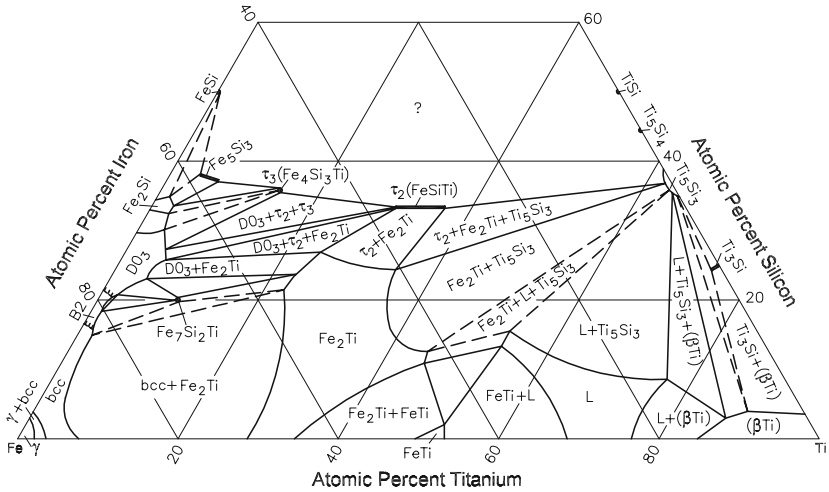

Fig. 3 Fe-Si-Ti isothermal section at 1150 °C [2002Lof, 2005Ste]

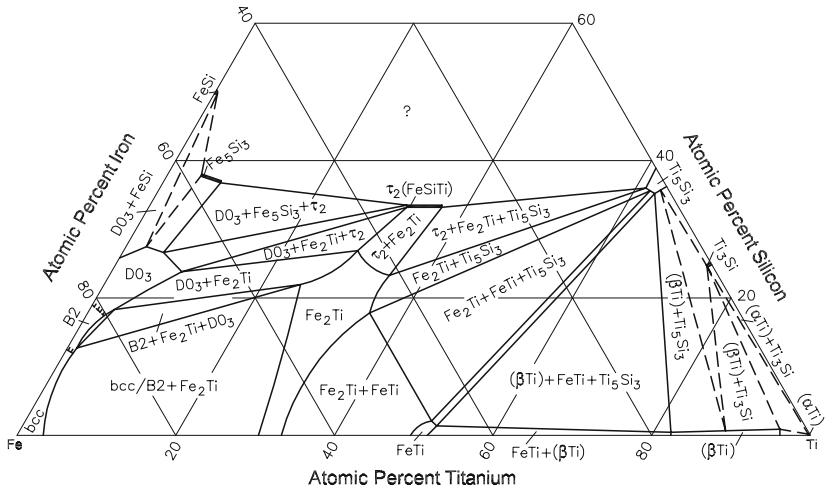

Fig. 4 Fe-Si-Ti isothermal section at 800 °C [2002Lof, 2005Ste]

isothermal sections at 1150 and 800 °C in the Si-lean region determined by [2002Lof] are redrawn in Fig. 3 and 4 from [2005Ste]. At 1150 °C (Fig. 3), the ternary phases FeSiTi (τ_2), Fe_4Si_3Ti (τ_3) and Fe_7Si_2Ti are present. At 800 °C (Fig. 4), only FeSiTi (τ_2) is present. The binary phase Fe_5Si_3 is stable between 1050 and 825 °C. The presence of Ti increases the temperature range of stability of this phase. It is seen within the ternary region at 1150 and 800 °C in Fig. 3 and 4. At all three temperatures (Fig. 2-4), Fe_2Ti dissolves large amounts of Si.

The work of [2008Wei] marks a step forward in characterizing the phase equilibria in this complex system. More detailed studies, especially on the crystal structures of ternary compounds, are needed to establish a complete picture.

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