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Experimental investigation of phase equilibria in the Fe–Nb–Si ternary system

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ABSTRACT

The phase equilibria of the Fe–Nb–Si ternary system were investigated by electron probe microanalyzer (EPMA), back scattered electron (BSE), X-ray diffraction (XRD) and differential scanning calorimetry (DSC) on the equilibrated alloys. In this study, three isothermal sections of the Fe–Nb–Si ternary system at 1200 °C, 1100 °C and 1000 °C were respectively determined and six ternary compounds were confirmed. The obtained experimental results show that there are large solubilities of Si in the εNbFe$_2$ and μFeNb phases. The newly determined phase equilibria of the Fe–Nb–Si system will provide useful information for silicon steels development.

1. Introduction

Silicon steels are excellent soft magnetic materials that exhibit high permeability, low coercivity, and near-zero magnetostriction. They have potential for applications in high frequency fields by reducing the energy consumption and noise pollution such as transformers, power generators, and electric relays [1–9]. The magnetic flux (B10) and core loss value (W17/50) are basic parameters affecting the quality of silicon steels; both of them are sensitive to the composition of silicon steels [10–13]. Alloying with strong carbonitride formers, such as Nb and Ti [14–18], has been instrumental in successful development of new silicon steel products with enhanced properties. Therefore, Fe–Nb–Si ternary system is an important subsystem for the silicon steels. However, earlier developed Fe–Nb–Si alloys have been obtained mainly by trial-and-error due to the scarcity of phase equilibria information for the Fe–Nb–Si ternary system. In order to better understand the relationships among composition, microstructure and properties of Fe–Nb–Si alloys, phase equilibria information of this ternary system is required.

In this study, three binary systems of Fe–Si, Fe–Nb and Nb–Si constituting the Fe–Nb–Si ternary system have been reviewed by the previous investigations [19–21], as shown in Fig. 1. Five intermediate phases are known in the Fe–Si system, namely βFe$_2$Si, εFeSi, ηFe$_5$Si$_3$, αFeSi$_2$ and βFeSi$_2$. The Fe–Nb system has two intermediate phases, εNbFe$_2$ and μFeNb. The Nb–Si system shows the following intermediate phases: Nb$_3$Si, βNb$_5$Si$_3$, αNb$_5$Si$_3$ and NbSi$_2$. The stable solid phases and their crystal structures in all three binary systems are listed in Table 1.

There were several investigations on phase equlibria of Fe–Nb–Si system [22–35]. The first comprehensive work had been reported by Goldschmidt [22], who revealed that at least six or possible nine ternary compounds exist in this system, but their crystal structures were not still resolved. In the later studies, six ternary compounds had been confirmed, including NbFeSi$_2$ (τ_1) [23], Nb$_2$FeSi$_2$ (τ_2) [24], Nb$_4$Fe$_3$Si$_5$ (τ_3) [25], Nb$_4$FeSi (τ_4) [26], Nb$_4$Fe$_4$Si$_7$ (τ_5 (V)) [27,28], NbFeSi (τ_6 (E)) [28,29], as listed in Table 2. Denham [30] investigated the region of the Laves phase in the Fe–Nb–Si system, and found that the region of the Laves phase in the Fe–Nb–Si system was smaller with the temperature range from 1000 °C to 1300 °C than that given by Goldschmidt [22]. Additionally, several isothermal sections of this system had been reported in the previous investigations [25,31–33]. Fig. 2 shows an isothermal section at 1150 °C provided by Raghavan [32]. Furthermore, Goldschmidt [22] determined the liquidus temperatures of a number of ternary alloys in this system, and Haour et al. [34] revealed a ternary eutectic reaction at 1360 °C with composition of Fe$_{75.5}$–Si$_{21.5}$–Nb$_3$ (at.%). Based on their results [22,34] and binary data [19–21], the liquidus projection was constructed

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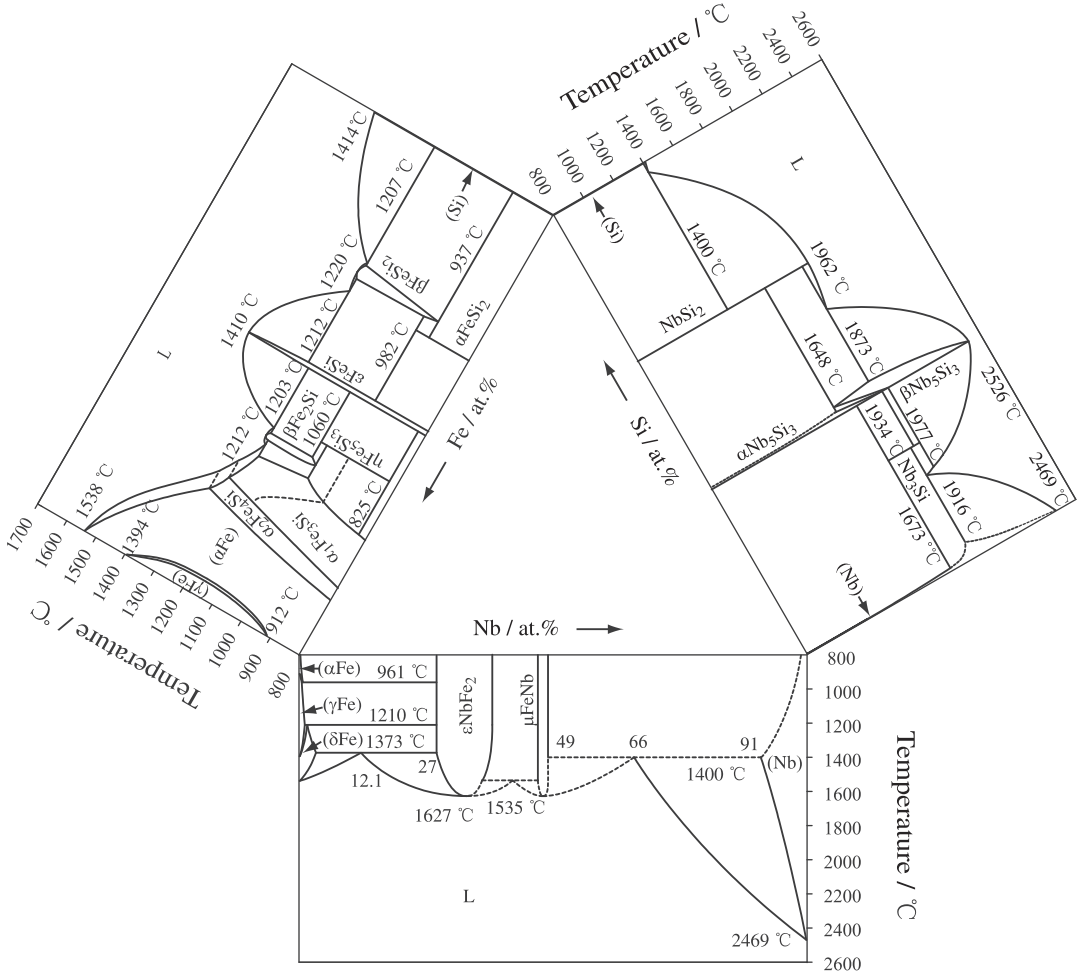

Fig. 1. Binary phase diagrams constituting the Fe–Nb–Si ternary system [19–21].

Table 1
The stable solid phases in the three binary systems and ternary system.

System	Phase	Pearson's symbol	Prototype	Space group	Struktur-bericht	Refs.
Fe–Si	αFe	*cI*2	W	*Im-3m*	*A*2	[19]
	γFe	*cF*4	Cu	*Fm-3m*	*A*1	[19]
	α_2Fe_4Si	*cP*2	CsCl	*Pm-3m*	*B*2	[19]
	α_1Fe_3Si	*cF*16	BiF_3	*Fm-3m*	DO_3	[19]
	βFe_2Si	*hP*6		*P-3m*1		[19]
	ηFe_5Si_3	*hP*16	Mn_5Si_3	$P6_3/mcm$	$D8_8$	[19]
	εFeSi	*cP*8	FeSi	$P2_13$	*B*20	[19]
	$\alpha FeSi_2$	*oC*48		*Cmca*		[19]
	$\beta FeSi_2$	*tP*3		*P*4/*mmm*		[19]
	(Si)	*cF*8	C(diamond)	*Fd-3m*	*A*4	[19]
Fe–Nb	αFe	*cI*2	W	*Im-3m*	*A*2	[20]
	γFe	*cF*4	Cu	*Fm-3m*	*A*1	[20]
	δFe	*cI*2	W	*Im-3m*	*A*2	[20]
	$\varepsilon NbFe_2$	*hP*12	$MgZn_2$	$P6_3/mmc$	*C*14	[20]
	μFeNb	*hR*13	Fe_7W_6	*R-3m*	$D8_5$	[20]
	(Nb)	*cI*2	W	*Im-3m*	*A*2	[20]
Nb–Si	(Nb)	*cI*2	W	*Im-3m*	*A*2	[21]
	Nb_3Si	*tP*32	PTi_3	$P4_2/n$		[21]
	βNb_5Si_3	*tI*32	Si_3W_5	*I*4/*mcm*	$D8_m$	[21]
	αNb_5Si_3	*tI*32	Cr_5B_3	*I*4/*mcm*	$D8_l$	[21]
	$NbSi_2$	*hP*9	$CrSi_2$	$P6_422$	*C*40	[21]
	(Si)	*cF*8	C(diamond)	*Fd-3m*	*A*4	[21]
Fe–Si–Nb	$NbFeSi_2$ (τ_1)	*orthorho-mbic*	$TiMnSi_2$ or $TiFeSi_2$			[23]
	Nb_2FeSi_2 (τ_2)	*tetragonal*		$P4_2/mcm$		[24]
	$Nb_4Fe_3Si_5$ (τ_3)	*orthorho-mbic*		$P2_1mn$		[25]
	Nb_4FeSi (τ_4)	*tI*12	Al_2Cu	*I*4/*mcm*	*C*16	[26]
	$Nb_4Fe_4Si_7$ (τ_5 (V))	*tetragonal*	$Zr_4Co_4Ge_7$	*I*4/*mmm*		[27,28]
	NbFeSi (τ_6 (E))	*oP*12	TiNiSi or $PbCl_2$	*pnma*	*C*23	[28,29]