Experimental Investigation of Fe–Co–La System: Liquidus and Solidus Projections

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Submitted: 10 January 2020 / in revised form: 17 March 2020 / Published online: 20 April 2020
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Abstract Phase equilibria in the Co–Fe–La system were studied using differential thermal analysis (DTA), X-ray diffraction analysis, scanning electron microscopy (SEM), and electron probe microanalysis (EPMA). Liquidus and solidus projections and a melting diagram for this system over the whole concentration range and a Scheil diagram for solidification were constructed. The ternary compound (Co,Fe)₁₇La₂ (τ) (Th₂Zn₁₇-type structure) forms by peritectic reaction $L + (\gamma\text{Co,Fe}) + \text{Co}_{13}\text{La} \rightleftharpoons \tau$ at 978 °C. This ternary compound is located along the isoconcentrate of 11 at.% La and extends from 45.8 to 79.3 at.% Co. The Co₁₃La phase has the widest homogeneity region and dissolves up to 43.3 at.% Fe. The solubilities of Fe in Co₅La, Co₇La₂, Co₁₉La₅, and Co₃La₂ were established to be 10.3, 9.2, 4.7, and 3.2 at.%, respectively. The solubility of Fe in Co_{1.7}La₂ and CoLa₃ according to EPMA does not exceed 1 at.%. The maximum solubility of La in (γ Co,Fe) and (α Co,Fe) is determined to be less than 1 at.%.

Keywords Co–Fe–La · Co–La · Liquidus surface · Phase diagrams · Solidus surface

This invited article is part of a special tribute issue of the *Journal of Phase Equilibria and Diffusion* dedicated to the memory of Günter Effenberg. The special issue was organized by Andrew Watson, Coventry University, Coventry, United Kingdom; Svitlana Iljenko, MSI, Materials Science International Services GmbH, Stuttgart, Germany; and Rainer Schmid-Fetzer, Clausthal University of Technology, Clausthal-Zellerfeld, Germany.

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1 Introduction

Rare-earth (R) and transition-metal (M) compounds have many potential applications such as the production of permanent magnets^[1,2] as well as practical applications in a number of important high-technology branches of modern industry including solid-state electronics, aviation and space technology, and nuclear energy, among others. Permanent magnets based on rare-earth metals such as RCo₅, R₂Co₇, and R₂Co₁₇ have very high magnetic crystallographic anisotropy and are characterized by record values of coercive force.^[1,3–7]

R-TM alloys are well established as hydrogen-storage materials due to their excellent performance, being applied as such in engines and automobiles due to their good ability to absorb hydrogen.^[8,9] However, data on the phase equilibria and types of transformations in the R–Fe–TM and R–Fe–C systems remain limited, and information on the phase equilibria in these systems during crystallization is practically absent. Thus, obtaining systematic information on the phase diagrams of the R–Fe–TM and R–Fe–C ternary systems (M = Mn, Co, Ni; R = La, Ce) over the whole concentration and temperature ranges is relevant. Recently, the phase equilibria in the {La, Ce}–Fe–C and Ce–Fe–{Mn, Co, Ni} systems were investigated.^[10–19] We present herein the results of a study on the phase equilibria in the La–Fe–Co system.

2 Literature Survey

2.1 Binary La–Fe System

Only limited experimental information is available for the phase diagram of the La–Fe system. An abnormal shape of

the liquidus was observed between 8 and 19 at.% La^[20] and has been discussed in a number of papers^[21–24] in terms of the possible existence of a stable or metastable miscibility gap in the liquid.

Recently, an experimental investigation of the binary La–Fe system was carried out by Mardani et al.^[10] Our experimental observations did not confirm the presence of a stable miscibility gap in the liquid phase of the La–Fe system. The La–Fe system is of simple eutectic type with eutectic reaction $l \rightleftharpoons (\alpha\text{Fe}) + (\beta\text{La})$ at 788 °C and 88 at.% La. In addition, there is a metatectic reaction $(\delta\text{Fe}) \rightleftharpoons l + (\gamma\text{Fe})$ at 1383 °C due to $(\delta\text{Fe}) \rightleftharpoons (\gamma\text{Fe})$. The liquid phase in the metatectic reaction contains ~ 50 at.% La.

2.2 Binary Fe–Co System

The phase diagram of the Fe–Co system adopted in the current work is according to Ohnuma et al.^[25] The following crystalline phases are formed in the system: (δFe) -phase (high-temperature bcc solution based on iron), $(\alpha\text{Co}, \gamma\text{Fe})$ -phase (fcc solution based on pure components), (αFe) -phase (low-temperature bcc solution based on iron), ordered cubic phase FeCo (α') (B2 prototype of CsCl), and (ϵCo) -phase (hcp-solution based on cobalt). On the liquidus and solidus lines of the $(\alpha\text{Co}, \gamma\text{Fe})$ phase, a minimum is present.

The temperature of the γ (fcc) $\rightarrow \alpha$ (bcc) transition increases with increasing Co concentration and reaches a maximum at 979 °C and 44 at.% Co. At ~ 50 at.% Co and 730 °C, the bcc αFe phase is transformed into an ordered cubic structure B2 with CsCl-type structure (α'). The solid solution $(\alpha\text{Co}, \gamma\text{Fe})$ at a temperature of 239 °C and 94.7 at.% Co decomposes by eutectoid reaction into $\alpha'(\text{CoFe}) + (\epsilon\text{Co})$.

2.3 Binary La–Co System

The phase diagram of the La–Co system adopted in this work is according to thermodynamic modeling by Wang et al.,^[26] which generally agrees well with the experimental data of Buschow and Velge.^[27] The system is characterized by the presence of seven intermetallic compounds: CoLa_3 , $\text{Co}_{1.7}\text{La}_2$, Co_3La_2 , Co_7La_2 , $\text{Co}_{19}\text{La}_5$, Co_5La , and Co_{13}La . Only the CoLa_3 compound melts congruently, at a temperature of 543 °C, while the remaining six compounds are formed by peritectic reactions at 570 °C, 695 °C, 800 °C, 868 °C, 1090 °C, and 1185 °C, respectively. The Co_7La_2 compound exists in two polymorphic modifications; however, the transformation temperature is unknown.

The La–Co system also contains two eutectics: $l \rightleftharpoons \text{Co}_{1.7}\text{La}_2 + \text{CoLa}_3$ with coordinates 523 °C and

31.5 at.% Co, and $l \rightleftharpoons \text{Co}_{1.7}\text{La}_2 + \text{CoLa}_3$ with coordinates 521 °C and 18.7 at.% Co.^[26] However, note that the temperatures of these eutectics according to different authors differ significantly. Therefore, in this work, the temperature and composition of these eutectics were verified.

2.4 Ternary La–Fe–Co System

There is a lack of experimental data for the La–Fe–Co system. Kharchenko et al.^[28] investigated phase equilibria in the system at 800 °C (in the range up to 20 at.% La) and 400 °C (in the range from 20 to 100 at.% La) using SEM and X-ray diffraction. The existence of the ternary compound $(\text{Co}, \text{Fe})_{17-x}\text{La}_2$ ($\text{Th}_2\text{Zn}_{17}$ -type structure, $R\bar{3}m$, $a = 8.524$, $c = 12.37$ Å) had been reported by Kharchenko et al.^[28] This compound has a homogeneity region of 17–22 at.% Fe. It was reported that the solubility of Fe in Co_{13}La extends up to 30 at.%^[28] However, data about phase equilibria in the La–Fe–Co system during crystallization are completely absent, as well as information on the temperature and nature of the formation of the ternary compound.

3 Experimental Methods

3.1 Sample Preparation

The samples were melted from starting materials with purity of Fe–99.99%, Co–99.9%, and La–99.9% in an arc furnace with an inconsumable tungsten electrode on a water-cooled copper hearth in an Ar atmosphere purified by a Ti melt. The samples were remelted four or five times to ensure their chemical homogeneity. The weight loss was no more than 0.1%. The ingot weight was 3 g. The composition of each sample was analyzed by microprobe analysis, revealing good agreement with the composition of the initial alloy mixture.

To study equilibria at solidus temperature, after preparation, some of the samples were annealed at subsolidus temperatures. The annealing was performed in a tube furnace (Nabertherm RHTV 120/300/1700) with temperature accuracy of ± 3 °C in Ar atmosphere. The samples were placed in an Al_2O_3 crucible and additionally wrapped by a titanium lid to avoid oxidation. After annealing, some samples were quenched in oil to retain the equilibrium microstructures. On the whole, a few hours was sufficient to achieve equilibrium during annealing at subsolidus temperature. However prolonged annealing time was necessary for some samples. Annealing temperatures were selected to be 5–10 °C below [$T_{\text{ann}} = T_{\text{sol}} - (5\text{--}10 \text{ °C})$] solidus temperatures determined from the DTA curves of

the as-cast and annealed alloys. The annealing temperatures and times are summarized in Table 4.

3.2 Microstructure Analysis

Samples for microstructure analysis were prepared using a grinder and polisher (Struers Labopol-5) machine. Grinding was carried out with SiC paper and continued with polishing using diamond discs with grain size of 9, 3, and 1 microns, respectively. Diamond suspension was applied at regular intervals during the preparation.

The prepared samples were examined by optical microscopy (OM, Olympus-GX71F-5) and scanning electron microscopy (SEM) using a TESCAN VEGA LMH microscope with a LaB₆ cathode and an energy-dispersive X-ray microanalysis system (Oxford Instruments Advanced AZtecEnergy). For analysis, both backscattered electron and secondary-electron imaging were used. A four-crystal wave spectrometer was used during the electron probe microanalysis (EPMA) of all the phases (analyzed particle size larger than 2 μm). The EPMA acceleration voltage was set at 20 kV. The measurement error in determining the concentration of elements using X-ray analysis was 0.1 wt.%.

3.3 Differential Thermal Analysis

A DSC LABSYS evo Setaram was used to measure the phase-transition temperatures of the alloys. For calibration, pure metal standards Sn (99.9995%), Al (99.995%), Ag (99.99%), Cu (99.999%), and Ni (99.99%) were used. DTA samples were placed in an Al₂O₃ crucible, and experiments were carried out under flow of argon with 99.998% purity on as-cast and annealed samples. The heating and cooling rate was 5 and 10 °C/min. The temperatures of the invariant reactions were determined from the onset. Data for phase-transition temperatures were taken from heating curves. The liquidus temperatures on heating were evaluated from the peak maximum, and those on cooling from the corresponding onset. Pronounced supercooling effects were not observed for the investigated alloys, and the liquidus temperatures for some alloys were therefore taken from the corresponding cooling curve since thermal effects are shown more clearly on cooling. At the end of the heating and cooling process, Calisto Processing software was used to obtain the DTA curves, which were later calibrated based on the equipment's calibration factor.

3.4 X-Ray Diffraction Analysis

X-ray diffraction (XRD) analysis was carried out to determine the phases present in the alloys, using Cu K_α filtered radiation on fine powder samples prepared by

grinding in an agate mortar. XRD measurements were performed on a multipurpose X-ray diffractometer (Bruker-AXS D8 Discover) and DRON-3.0 diffractometer (Bourestnik, Inc., St. Petersburg, Russia). The lattice parameters were refined by the least-squares method. The phases were determined by comparing diffraction patterns with literature or patterns calculated using the PowderCell^[29] and WINXPOW^[30] software packages. Both the PowderCell and WINXPOW software packages were used to calculate lattice parameters based on the least-squares method.

4 Experimental Investigation

4.1 La–Co System

The temperature of the peritectic reaction for the formation of compound La₅Co₁₉, $L + \text{LaCo}_5 \rightleftharpoons \text{La}_5\text{Co}_{19}$, was reported to be 868 °C by Wang et al.^[26] and Ray and Strnat,^[31] while this temperature was not observed by Buschow and Velge.^[27] Therefore, to verify the temperature of this reaction, 30La-70Co alloy was prepared. The microstructure of this as-cast sample is shown in Fig. 1(a) and (b). The solidification path of this alloy is rather complex: after primary crystallization of the LaCo₅ phase (dark grains), the phases La₅Co₁₉ (dark-gray grains), La₂Co₇ (gray grains), La₂Co₃ (light-gray grains), and La₂Co_{1.7} (white) form through a sequence of peritectic reactions. The DTA curve of this alloy upon heating up to 1150 °C is shown in Fig. 2, indicating five phase transformations. The cooling curve also shows these transformations with slight overcooling. The thermal effect at 854 °C corresponds to the peritectic reaction for the formation of La₅Co₁₉ phase ($L + \text{LaCo}_5 \rightleftharpoons \text{La}_5\text{Co}_{19}$), being somewhat lower than proposed in literature.^[26,31] The thermal effect at 840 °C corresponds to the peritectic reaction $L + \text{La}_5\text{Co}_{19} \rightleftharpoons \text{La}_2\text{Co}_7$, which is significantly higher than proposed in literature.^[26,27] The thermal effect for the peritectic reaction $L + \text{La}_2\text{Co}_7 \rightleftharpoons \text{La}_2\text{Co}_3$ was measured at 694 °C, in good agreement with literature.^[26,27] The effect at 710 °C, which has not been previously observed, probably corresponds to the polymorphic transformation of the phase La₂Co₇.

There is some controversy concerning the composition of the eutectic reaction $L \rightleftharpoons \text{La}_3\text{Co} + \text{La}_2\text{Co}_{1.7}$. Verification of the temperature and composition of this eutectic was performed on an as-cast sample with composition 69La-31Co. The obtained results are presented in Table 1 and 2 and Fig. 1(c). The microstructure of this alloy (Fig. 2c) is completely eutectic (La₃Co + La₂Co_{1.7}). The eutectic temperature was measured to be 514 °C, higher than proposed in Ref. ^[27,32] but lower than proposed by

Fig. 1 Microstructure of as-cast alloys of La–Co system: **a** 30La–70Co, $\times 1000$, $\text{LaCo}_5 + \text{La}_5\text{Co}_{19} + \text{La}_2\text{Co}_7 + \text{La}_2\text{Co}_3 + \text{La}_2\text{Co}_{1.7}$; **b** 30La–70Co, $\times 2000$, $\text{LaCo}_5 + \text{La}_5\text{Co}_{19} + \text{La}_2\text{Co}_7 + \text{La}_2\text{Co}_3 +$

$\text{La}_2\text{Co}_{1.7}$; **c** 69La–31Co, $\times 2000$, eutectic ($\text{La}_2\text{Co}_{1.7} + \text{La}_3\text{Co}$); **d** 80La–20Co, $\times 5000$, $(\beta\text{La}) + \text{La}_3\text{Co} + \text{eutectic } ((\beta\text{La}) + \text{La}_3\text{Co})$

Fig. 2 Heating curve for as-cast alloy 30La–70Co

Table 1 Phase composition of alloys of La–Co system and temperature of phase transformations during crystallization

Alloy, at.%		Temperature, °C		Solidification path	Phase composition at solidus
La	Co	Liquidus	Solidus		
30	70	1087	694	L → LaCo₅ ^a → La ₅ Co ₁₉ → La ₂ Co ₇ → La ₂ Co ₃ → La ₂ Co _{1.7}	La ₂ Co ₇ + La ₂ Co ₃
69	31	–	514	L → eutectic (La ₂ Co _{1.7} + La ₃ Co)	La ₂ Co _{1.7} + La ₃ Co
80	20	559	530	L → (βLa) → La ₃ Co → eutectic ((βLa) + La ₃ Co)	(βLa) + La ₃ Co
90	10	756	530	L → (βLa) → La ₃ Co → eutectic ((βLa) + La ₃ Co)	(βLa) + La ₃ Co

^aBold shows the primary phase**Table 2** Chemical composition of phases of as-cast alloys of La–Co system according to EPMA

Alloy composition, at.%				EPMA data, at.%		
Nominal		Measured		Phase	La	Co
La	Co	La	Co			
30	70	30.9	69.1	LaCo ₅	82.6 ± 0.1	17.4 ± 0.1
				La ₂ Co ₇	77.0 ± 0.1	23.0 ± 0.1
				La ₂ Co ₃	59.5 ± 0.1	40.5 ± 0.1
				La ₂ Co _{1.7}	47.1 ± 0.3	52.9 ± 0.3
69	31	69.5	30.5	eutectic	69.4	30.6
				(La ₂ Co _{1.7} + La ₃ Co)	69.5	30.5
80	20	19.7	80.3	(βLa)	0.0 ± 0.0	100.0 ± 0.0
				La ₃ Co	23.8 ± 0.2	76.2 ± 0.2
				eutectic	19.8	80.2
				((βLa) + La ₃ Co)	20.3	79.7
					19.4	80.6

Wang et al.^[26] The eutectic composition according to EPMA data was 30.5 at.% Co, in good agreement with Buschow and Velge.^[27]

Verification of the temperature and composition for the eutectic $L \rightleftharpoons (\beta\text{La}) + \text{La}_3\text{Co}$ was performed on as-cast samples 10La-90Co and 20La-80Co. The results obtained are presented in Table 1 and Fig. 1(d). The microstructure of this alloy (Fig. 1d) shows the primary (βLa)-phase and the eutectic ((βLa) + La₃Co). The composition of this eutectic was established by the microprobe method as 19.8 at.% Co, in good agreement with Ref. [27,32]. The eutectic temperature was measured to be 530 °C, slightly higher than proposed in Ref. [26,27,32]. The revised phase diagram of the La–Co system is shown in Fig. 3.

4.2 La–Fe–Co System

The phase equilibria in the La–Fe–Co system were investigated during solidification. The resulting liquidus (Fig. 4a) and solidus projections (Fig. 4b) and the melting diagram (Fig. 4c) of the La–Fe–Co system have been constructed over the whole concentration range. The phase compositions of the studied alloys and chemical

compositions of the phases of the La–Fe–Co system according to the EPMA results are reported in Table 3 and 4, respectively. Table 3 also presents the liquidus and solidus temperatures of the investigated alloys. The compositions of the investigated alloys in Fig. 4 correspond to measured compositions of alloys, whereas in Table 3 nominal compositions are given, and in Table 4 both nominal and measured compositions are given. The microstructures of some as-cast and annealed samples are shown in Fig. 5 and 6, respectively. The XRD patterns of some as-cast alloys are shown in Fig. 7. The crystal structure and lattice parameters of the phases of the Fe–Co–La system are presented in Table 5.

4.2.1 Ternary Compound (Co,Fe)₁₇La₂ (τ)

The existence of the ternary compound (Co,Fe)₁₇La₂ (τ) (structure type Th₂Zn₁₇, *R*-3*m*), which was previously reported,^[28,33,34] was confirmed in our study. It was shown that ternary compound τ forms by peritectic reaction $L_{P1} + \text{LaCo}_{13} + \text{LaCo}_5 \rightleftharpoons \tau$ at 978 °C and has a wide homogeneity range from 45.8 to 79.5 at.% Co located along the isoconcentrate of ~ 11 at.% La. This somewhat

Fig. 3 Revised phase diagram of La–Co system: open triangles—DTA data

contradicts the data of Kharchenko et al.,^[28] who reported that the homogeneity region of the τ phase is located along the isoconcentrate of 15 at.% La. The iron-rich boundary of the region of homogeneity of the τ phase is defined as 45.8 at.% Co according to the EPMA data of alloy #1 (Fig. 5a, Table 4). The homogeneity region of the cobalt-rich side τ phase is defined as 79.5 at.% Co according to the EPMA data of alloy #2 (Table 4).

4.2.2 Solid Phases

In addition to the ternary compound $(\text{Co,Fe})_{17}\text{La}_2$ (τ) in the La–Co–Fe system, other phases based on the binary compounds Co_{13}La , Co_5La , $\text{Co}_{19}\text{La}_5$, Co_7La_2 , Co_3La_2 , $\text{Co}_{1.7}\text{La}_2$, and CoLa_3 and components (δFe), ($\gamma\text{Co,Fe}$), ($\alpha\text{Co,Fe}$), (γLa), and (βLa) take part in phase equilibria.

Among the binary compounds, Co_{13}La (structural type NaZn_{13} , $cF112\text{-}Fm\text{-}3c$) has the widest homogeneity region at solidus temperature and, according to EPMA data of as-cast alloys #3 and #4 (Table 4), dissolves up to 43.3 at.% Fe. The homogeneity region of this phase is located along the isoconcentrate of 7 at.% La and extends widely into a ternary system, which reflects significant mutual substitution of Co and Fe atoms. The lattice parameter a of Co_{13}La

phase gradually increases with increasing Fe content (Table 5).

According to the EPMA data of as-cast alloy #5, the solubility of Fe in Co_5La is 10.3 at.% (Table 4). The solubility of Fe in Co_7La_2 at solidus temperature reaches 9.2 at.% according to the EPMA data of cast alloy #6. The homogeneity regions of the remaining phases are smaller. The solubility of Fe in the $\text{Co}_{19}\text{La}_5$ phase at solidus temperature is 4.7 at.% according to the EPMA data of alloy #7 annealed at subsolidus temperature (810 °C, 4 h). The solubility of Fe in Co_3La_2 is even less and amounts to 3.2 at.% at solidus temperature. The solubility of Fe in $\text{Co}_{1.7}\text{La}_2$ and CoLa_3 according to EPMA does not exceed 1 at.%. The maximum solubility of La in ($\gamma\text{Co,Fe}$) and ($\alpha\text{Co,Fe}$) phases is determined to be less than 1 at.% (Table 4).

4.2.3 Liquidus Projection

The liquidus surface of the Fe–La–Co system (Fig. 4a) is characterized by the 13 primary solidification fields of the ternary compound $(\text{Co,Fe})_{17}\text{La}_2$ (τ), solid solutions based on binary phases Co_{13}La , Co_5La , $\text{Co}_{19}\text{La}_5$, Co_7La_2 , Co_3La_2 , $\text{Co}_{1.7}\text{La}_2$, and CoLa_3 , and component-based solid solutions (δFe), ($\gamma\text{Co,Fe}$), ($\alpha\text{Co,Fe}$), (γLa), and (βLa),

Fig. 4 Liquidus (a) and solidus (b) projections and the melting diagram (c) of the La–Co–Fe system: open circle—composition of sample, dotted circle—two-phase sample, filled circle—three-phase sample, open and filled triangle—EPMA data for as-cast and annealed alloys, respectively

(a)

(b)

Fig. 4 continued

separated by appropriate monovariant curves and participating in ten four-phase invariant equilibria. One four-phase invariant equilibrium is of eutectic type, two are of peritectic type, the the rest are of transitional type.

The primary solidification field of the $(\gamma\text{Co,Fe})$ -phase occupies the major part of the liquidus (Fig. 4a). Analysis of the microstructures of the as-cast samples showed that the compositions of most of the investigated alloys (#3, 4, 6, 8–33) are located in the primary solidification field of the $(\gamma\text{Co,Fe})$ phase. Typical microstructures of alloys from this region are shown in Fig. 5(b) and (c). The solidification of alloy #8 begins with formation of the $(\gamma\text{Co,Fe})$ -phase (black grains), continues with the formation of τ phase (gray grains) around the primary grains, then phases Co_3La_2 (light-gray grains) and $\text{Co}_{1.7}\text{La}_2$ (light grains) are formed, and the solidification finishes with eutectic reaction $(\text{Co}_{1.7}\text{La}_2 + \text{CoLa}_3)$ (Fig. 5b). For alloy #10, the crystallization path is also rather complex: after the primary crystallization of the $(\gamma\text{Co,Fe})$ phase (black grains), the phases Co_{13}La (dark-gray grains), Co_5La (gray grains), Co_7La_2 (light-gray grains), and Co_3La_2 (light grains) crystallize by peritectic reactions (Fig. 5c).

Alloys #1, 34–43 are located in the field of primary crystallization of the $(\alpha\text{Co,Fe})$ phase (Fig. 5a, d, e). The border of this field is limited by the composition of alloys #1, 36–39, in which only a small amount of primary grains of $(\alpha\text{Co,Fe})$ phase are observed (Fig. 5a, d, e).

Alloys #2, 7, 44–53 are located in the field of primary crystallization of the Co_{13}La phase (Fig. 5f–i). The observation of primary $(\gamma\text{Co,Fe})$ in sample #8 (Fig. 5b) in contrast to primary Co_{13}La in samples #44 and #46 (Fig. 5f, g) indicates that the monovariant curve $L + (\gamma\text{Co,Fe}) \rightleftharpoons \text{Co}_{13}\text{La}$ of joint crystallization of the phases $(\gamma\text{Co,Fe})$ and Co_{13}La is located between the compositions of these alloys. Note that the monovariant curve $L + (\gamma\text{Co,Fe}) \rightleftharpoons \text{Co}_{13}\text{La}$ has a saddle point corresponding to the maximum temperature on the solidus surface $(\gamma\text{Co,Fe}) + \text{Co}_{13}\text{La}$ at $\sim 1300^\circ\text{C}$.

The location of the monovariant curve P_1U_1 , separating the fields of primary solidification of Co_{13}La and τ , is evident from the observation of the primary Co_{13}La in samples #45 and #50 (Fig. 5g) in contrast to τ -phase in samples #54–56. Some attention should be focused on the microstructure of samples #45 and #50 (Fig. 5g), where questions arise regarding whether the primary solidified

Table 3 Phase composition of studied alloys of Co–Fe–La system and temperature of phase transformations at crystallization

#	Alloy, at. %			Liquidus temperature, °C	Solidification path	Solidus temperature, °C	Phase composition at solidus surface
	Fe	Co	La				
1	10	40	50	–	$L \rightarrow (\alpha\text{Co,Fe})^a \rightarrow \tau \rightarrow \text{La}_2\text{Co}_{1,7} \rightarrow \text{eutectic} (\text{La}_2\text{Co}_{1,7} + \text{La}_3\text{Co})$	515	$(\alpha\text{Co,Fe}) + \text{La}_3\text{Co} + \text{La}_2\text{Co}_{1,7}$
2	5	70	25	–	$L \rightarrow \text{LaCo}_{13} \rightarrow \text{LaCo}_5 \rightarrow \text{La}_2\text{Co}_7 \rightarrow \text{La}_2\text{Co}_3 \rightarrow \text{La}_2\text{Co}_{1,7}$	–	$\text{La}_2\text{Co}_3 + \text{La}_2\text{Co}_7$
3	53	40	7	1438	$L \rightarrow (\gamma\text{Co,Fe}) \rightarrow \text{LaCo}_{13} \rightarrow \tau \rightarrow \text{La}_2\text{Co}_3 \rightarrow \text{La}_2\text{Co}_{1,7}$	–	$(\alpha\text{Co,Fe}) + \text{La}_2\text{Co}_3 + \text{La}_2\text{Co}_{1,7}$
4	49	40	11	1398	$L \rightarrow (\gamma\text{Co,Fe}) \rightarrow \text{LaCo}_{13} \rightarrow \tau \rightarrow \text{La}_2\text{Co}_3 \rightarrow \text{La}_2\text{Co}_{1,7}$	–	$(\alpha\text{Co,Fe}) + \text{La}_2\text{Co}_3$
5	5	60	35	971	$L \rightarrow \text{LaCo}_5 \rightarrow \text{La}_2\text{Co}_7 \rightarrow \text{La}_2\text{Co}_3 \rightarrow \text{La}_2\text{Co}_{1,7}$	669	$\text{La}_2\text{Co}_3 + \tau$
6	23	70	7	1447	$L \rightarrow (\gamma\text{Co,Fe}) \rightarrow \text{LaCo}_{13} \rightarrow \text{LaCo}_5 \rightarrow \text{La}_2\text{Co}_7 \rightarrow \text{La}_2\text{Co}_3$	–	$(\gamma\text{Co,Fe}) + \text{LaCo}_{13}$
7	5	75	20	1282	$L \rightarrow \text{LaCo}_{13} \rightarrow \text{LaCo}_5 \rightarrow \text{La}_5\text{Co}_{19} \rightarrow \text{La}_2\text{Co}_7 \rightarrow \text{La}_2\text{Co}_3$	818	$\text{La}_2\text{Co}_7 + \text{LaCo}_5 + \text{La}_5\text{Co}_{19}$
8	20	45	35	1099	$L \rightarrow (\gamma\text{Co,Fe}) \rightarrow \tau \rightarrow \text{La}_2\text{Co}_3 \rightarrow \text{La}_2\text{Co}_{1,7} \rightarrow \text{eutectic} (\text{La}_2\text{Co}_{1,7} + \text{La}_3\text{Co})$	570	$(\alpha\text{Co,Fe}) + \text{La}_2\text{Co}_3 + \text{La}_2\text{Co}_{1,7}$
9	38	55	7	1457	$L \rightarrow (\gamma\text{Co,Fe}) \rightarrow \text{LaCo}_{13} \rightarrow \text{La}_2\text{Co}_3$	–	$(\gamma\text{Co,Fe}) + \text{LaCo}_{13}$
10	14	75	11	–	$L \rightarrow (\gamma\text{Co,Fe}) \rightarrow \text{LaCo}_{13} \rightarrow \text{LaCo}_5 \rightarrow \text{La}_2\text{Co}_7 \rightarrow \text{La}_2\text{Co}_3$	–	$\text{LaCo}_{13} + \tau$
11	33	50	17	1351	$L \rightarrow (\gamma\text{Co,Fe}) \rightarrow \text{LaCo}_{13} \rightarrow \text{La}_2\text{Co}_3 \rightarrow \text{La}_2\text{Co}_{1,7}$	646	$\tau + \text{La}_2\text{Co}_3$
12	48	45	7	1472	$L \rightarrow (\gamma\text{Co,Fe}) \rightarrow \text{LaCo}_{13} \rightarrow \tau \rightarrow \text{La}_2\text{Co}_3 \rightarrow \text{La}_2\text{Co}_{1,7}$	651	$(\alpha\text{Co,Fe}) + \tau$
13	44	45	11	1438	$L \rightarrow (\gamma\text{Co,Fe}) \rightarrow \text{LaCo}_{13} \rightarrow \tau \rightarrow \text{La}_2\text{Co}_3 \rightarrow \text{La}_2\text{Co}_{1,7}$	650	$(\alpha\text{Co,Fe}) + \text{La}_2\text{Co}_3$
14	15	83	2	1492	$L \rightarrow (\gamma\text{Co,Fe}) \rightarrow \text{LaCo}_{13} \rightarrow \text{La}_2\text{Co}_7 \rightarrow \text{La}_2\text{Co}_3$	–	$(\gamma\text{Co,Fe}) + \text{LaCo}_{13}$
15	60	25	15	1433	$L \rightarrow (\gamma\text{Co,Fe}) \rightarrow \text{eutectic} (\text{La}_2\text{Co}_{1,7} + \text{La}_3\text{Co})$	516	$(\alpha\text{Co,Fe}) + \text{La}_3\text{Co} + \text{La}_2\text{Co}_{1,7}$
16	40	25	35	1330	$L \rightarrow (\gamma\text{Co,Fe}) \rightarrow \text{eutectic} (\text{La}_2\text{Co}_{1,7} + \text{La}_3\text{Co})$	516	$(\alpha\text{Co,Fe}) + \text{La}_3\text{Co} + \text{La}_2\text{Co}_{1,7}$
17	60	15	25	1399	$L \rightarrow (\gamma\text{Co,Fe}) \rightarrow \text{La}_3\text{Co} \rightarrow (\beta\text{La})$	541	$(\alpha\text{Co,Fe}) + \text{La}_3\text{Co}$
18	40	35	25	1332	$L \rightarrow (\gamma\text{Co,Fe}) \rightarrow \text{La}_2\text{Co}_{1,7} \rightarrow \text{eutectic} (\text{La}_2\text{Co}_{1,7} + \text{La}_3\text{Co})$	515	$(\alpha\text{Co,Fe}) + \text{La}_3\text{Co} + \text{La}_2\text{Co}_{1,7}$
19	35	15	50	–	$L \rightarrow (\gamma\text{Co,Fe}) \rightarrow \text{La}_3\text{Co} \rightarrow (\beta\text{La})$	527	$(\alpha\text{Co,Fe}) + \text{La}_3\text{Co} + (\beta\text{La})$
20	25	25	50	–	$L \rightarrow (\gamma\text{Co,Fe}) \rightarrow \text{eutectic} (\text{La}_2\text{Co}_{1,7} + \text{La}_3\text{Co})$	516	$(\alpha\text{Co,Fe}) + \text{La}_3\text{Co} + \text{La}_2\text{Co}_{1,7}$
21	63	30	7	1442	$L \rightarrow (\gamma\text{Co,Fe}) \rightarrow \text{La}_2\text{Co}_3 \rightarrow \text{La}_2\text{Co}_{1,7}$	517	$(\alpha\text{Co,Fe}) + \text{La}_2\text{Co}_{1,7}$
22	10	79	11	1395	$L \rightarrow (\gamma\text{Co,Fe}) \rightarrow \text{LaCo}_{13} \rightarrow \text{LaCo}_5 \rightarrow \text{La}_2\text{Co}_7 \rightarrow \text{La}_2\text{Co}_{1,7}$	978	$\text{LaCo}_{13} + \text{LaCo}_5$
23	29	60	11	1376	$L \rightarrow (\gamma\text{Co,Fe}) \rightarrow \text{LaCo}_{13} \rightarrow \tau \rightarrow \text{La}_2\text{Co}_3 \rightarrow \text{La}_2\text{Co}_{1,7}$	–	$\tau + \text{La}_2\text{Co}_3$
24	14	79	7	1445	$L \rightarrow (\gamma\text{Co,Fe}) \rightarrow \text{LaCo}_{13} \rightarrow \text{LaCo}_5 \rightarrow \text{La}_2\text{Co}_7 \rightarrow \text{La}_2\text{Co}_3$	–	$(\gamma\text{Co,Fe}) + \text{LaCo}_{13}$
25	41	48	11	1402	$L \rightarrow (\gamma\text{Co,Fe}) \rightarrow \text{LaCo}_{13} \rightarrow \tau \rightarrow \text{La}_2\text{Co}_3 \rightarrow \text{La}_2\text{Co}_{1,7}$	–	$(\alpha\text{Co,Fe}) + \tau$
26	43	50	7	1428	$L \rightarrow (\gamma\text{Co,Fe}) \rightarrow \text{LaCo}_{13} \rightarrow \tau \rightarrow \text{La}_2\text{Co}_3 \rightarrow \text{La}_2\text{Co}_{1,7}$	–	$(\alpha\text{Co,Fe}) + \text{LaCo}_{13}$
27	5	84	11	1363	$L \rightarrow (\gamma\text{Co,Fe}) \rightarrow \text{LaCo}_{13} \rightarrow \text{LaCo}_5 \rightarrow \text{La}_2\text{Co}_7 \rightarrow \text{La}_2\text{Co}_{1,7}$	1057	$\text{LaCo}_{13} + \text{LaCo}_5$
28	5	88	7	–	$L \rightarrow (\gamma\text{Co,Fe}) \rightarrow \text{LaCo}_{13} \rightarrow \text{LaCo}_5 \rightarrow \text{La}_5\text{Co}_{19} \rightarrow \text{La}_2\text{Co}_7 \rightarrow \text{La}_2\text{Co}_3$	1293	$(\gamma\text{Co,Fe}) + \text{LaCo}_{13}$
29	68	25	7	1484	$L \rightarrow (\gamma\text{Co,Fe}) \rightarrow \text{eutectic} (\text{La}_2\text{Co}_{1,7} + \text{La}_3\text{Co})$	516	$(\alpha\text{Co,Fe}) + \text{La}_2\text{Co}_{1,7} + \text{La}_3\text{Co}$
30	59	30	11	–	$L \rightarrow (\gamma\text{Co,Fe}) \rightarrow \text{La}_2\text{Co}_3 \rightarrow \text{La}_2\text{Co}_{1,7}$	–	$(\alpha\text{Co,Fe}) + \text{La}_2\text{Co}_{1,7}$
31	18	44	38	–	$L \rightarrow (\gamma\text{Co,Fe}) \rightarrow \tau \rightarrow \text{La}_2\text{Co}_3 \rightarrow \text{La}_2\text{Co}_{1,7} \rightarrow \text{eutectic} (\text{La}_2\text{Co}_{1,7} + \text{La}_3\text{Co})$	573	$(\alpha\text{Co,Fe}) + \text{La}_2\text{Co}_3 + \text{La}_2\text{Co}_{1,7}$
32	12	77	11	1439	$L \rightarrow (\gamma\text{Co,Fe}) \rightarrow \text{LaCo}_{13} \rightarrow \text{LaCo}_5 \rightarrow \text{La}_2\text{Co}_7 \rightarrow \text{La}_2\text{Co}_3$	977	$\text{LaCo}_{13} + \tau$

Table 3 continued

Alloy, at.%				Liquidus temperature, °C	Solidification path	Solidus temperature, °C	Phase composition at solidus surface
#	Fe	Co	La				
33	16	73	11	–	$L \rightarrow (\gamma\text{Co,Fe}) \rightarrow \text{LaCo}_{13} \rightarrow \text{LaCo}_5 \rightarrow \text{La}_2\text{Co}_7 \rightarrow \text{La}_2\text{Co}_3$	–	$\text{LaCo}_{13} + \tau$
34	10	30	60	–	$L \rightarrow (\alpha\text{Co,Fe}) \rightarrow \text{eutectic} (\text{La}_2\text{Co}_{1,7} + \text{La}_3\text{Co})$	515	$(\alpha\text{Co,Fe}) + \text{La}_3\text{Co} + \text{La}_2\text{Co}_{1,7}$
35	10	25	65	580	$L \rightarrow (\alpha\text{Co,Fe}) \rightarrow \text{La}_3\text{Co} \rightarrow \text{eutectic} (\text{La}_2\text{Co}_{1,7} + \text{La}_3\text{Co})$	515	$(\alpha\text{Co,Fe}) + \text{La}_3\text{Co} + \text{La}_2\text{Co}_{1,7}$
36	10	10	80	701	$L \rightarrow (\alpha\text{Co,Fe}) \rightarrow (\beta\text{La}) \rightarrow \text{La}_3\text{Co}$	–	$(\alpha\text{Co,Fe}) + \text{La}_3\text{Co} + (\beta\text{La})$
37	2	38	60	622	$L \rightarrow (\alpha\text{Co,Fe}) \rightarrow \text{La}_2\text{Co}_{1,7} \rightarrow \text{La}_3\text{Co} \rightarrow \text{eutectic} (\text{La}_2\text{Co}_{1,7} + \text{La}_3\text{Co})$	515	$(\alpha\text{Co,Fe}) + \text{La}_3\text{Co} + \text{La}_2\text{Co}_{1,7}$
38	2	33	65	540	$L \rightarrow (\alpha\text{Co,Fe}) \rightarrow \text{La}_2\text{Co}_{1,7} \rightarrow \text{eutectic} (\text{La}_2\text{Co}_{1,7} + \text{La}_3\text{Co})$	515	$(\alpha\text{Co,Fe}) + \text{La}_3\text{Co} + \text{La}_2\text{Co}_{1,7}$
39	2	23	75	563	$L \rightarrow (\alpha\text{Co,Fe}) \rightarrow \text{La}_3\text{Co} \rightarrow \text{eutectic} ((\alpha\text{Co,Fe}) + \text{La}_3\text{Co} + (\beta\text{La}))$	526	$(\alpha\text{Co,Fe}) + \text{La}_3\text{Co} + (\beta\text{La})$
40	15	15	70	–	$L \rightarrow (\alpha\text{Co,Fe}) \rightarrow \text{La}_3\text{Co}$	–	$(\alpha\text{Co,Fe}) + \text{La}_3\text{Co} + (\beta\text{La})$
41	15	25	60	–	$L \rightarrow (\alpha\text{Co,Fe}) \rightarrow \text{eutectic} (\text{La}_2\text{Co}_{1,7} + \text{La}_3\text{Co})$	–	$(\alpha\text{Co,Fe}) + \text{La}_3\text{Co} + \text{La}_2\text{Co}_{1,7}$
42	15	35	50	–	$L \rightarrow (\gamma\text{Co,Fe}) \rightarrow \text{La}_2\text{Co}_{1,7} \rightarrow \text{eutectic} (\text{La}_2\text{Co}_{1,7} + \text{La}_3\text{Co})$	–	$(\alpha\text{Co,Fe}) + \text{La}_3\text{Co} + \text{La}_2\text{Co}_{1,7}$
43	15	40	45	–	$L \rightarrow (\alpha\text{Co,Fe}) \rightarrow \tau \rightarrow \text{La}_2\text{Co}_{1,7} \rightarrow \text{eutectic} (\text{La}_2\text{Co}_{1,7} + \text{La}_3\text{Co})$	–	$(\alpha\text{Co,Fe}) + \text{La}_3\text{Co} + \text{La}_2\text{Co}_{1,7}$
44	10	75	15	–	$L \rightarrow \text{LaCo}_{13} \rightarrow \text{LaCo}_5 \rightarrow \text{La}_2\text{Co}_7 \rightarrow \text{La}_2\text{Co}_3$	–	$\text{LaCo}_{13} + \text{LaCo}_5$
45	10	65	25	1016	$L \rightarrow \text{LaCo}_{13} \rightarrow \tau \rightarrow \text{LaCo}_5 \rightarrow \text{La}_2\text{Co}_7 \rightarrow \text{La}_2\text{Co}_3 \rightarrow \text{La}_2\text{Co}_{1,7} \rightarrow \text{eutectic} (\text{La}_2\text{Co}_{1,7} + \text{La}_3\text{Co})$	669	$\text{La}_2\text{Co}_3 + \tau + \text{La}_2\text{Co}_7$
46	20	55	25	1185	$L \rightarrow \text{LaCo}_{13} \rightarrow \text{La}_2\text{Co}_3 \rightarrow \text{La}_2\text{Co}_{1,7} \rightarrow \text{eutectic} (\text{La}_2\text{Co}_{1,7} + \text{La}_3\text{Co})$	548	$\text{La}_2\text{Co}_3 + \tau$
47	10	70	20	1268	$L \rightarrow \text{LaCo}_{13} \rightarrow \text{LaCo}_5 \rightarrow \text{La}_2\text{Co}_7 \rightarrow \text{La}_2\text{Co}_3 \rightarrow \text{La}_2\text{Co}_{1,7}$	794	$\tau + \text{La}_2\text{Co}_7$
48	15	65	20	1253	$L \rightarrow \text{LaCo}_{13} \rightarrow \text{LaCo}_5 \rightarrow \text{La}_2\text{Co}_7 \rightarrow \text{La}_2\text{Co}_3 \rightarrow \text{La}_2\text{Co}_{1,7}$	668	$\tau + \text{La}_2\text{Co}_3$
49	15	67.5	22.5	1231	$L \rightarrow \text{LaCo}_{13} \rightarrow \text{LaCo}_5 \rightarrow \text{La}_2\text{Co}_7 \rightarrow \text{La}_2\text{Co}_3 \rightarrow \text{La}_2\text{Co}_{1,7}$	669	$\text{La}_2\text{Co}_3 + \tau + \text{La}_2\text{Co}_7$
50	15	60	25	–	$L \rightarrow \text{LaCo}_{13} \rightarrow \tau \rightarrow \text{LaCo}_5 \rightarrow \text{La}_2\text{Co}_3 \rightarrow \text{La}_2\text{Co}_{1,7}$	–	$\text{La}_2\text{Co}_3 + \tau$
51	10	73	17	1264	$L \rightarrow \text{LaCo}_{13} \rightarrow \text{LaCo}_5 \rightarrow \text{La}_2\text{Co}_7 \rightarrow \text{La}_2\text{Co}_3$	–	$\text{LaCo}_5 + \text{La}_2\text{Co}_7$
52	2	78	20	1289	$L \rightarrow \text{LaCo}_{13} \rightarrow \text{LaCo}_5 \rightarrow \text{La}_3\text{Co}_{19} \rightarrow \text{La}_2\text{Co}_7 \rightarrow \text{La}_2\text{Co}_3 \rightarrow \text{La}_2\text{Co}_{1,7}$	–	$\text{LaCo}_5 + \text{La}_3\text{Co}_{19}$
53	11	72	17	1298	$L \rightarrow \text{LaCo}_{13} \rightarrow \text{LaCo}_5 \rightarrow \text{La}_2\text{Co}_7 \rightarrow \text{La}_2\text{Co}_3$	–	–
54	10	62	28	–	$L \rightarrow \tau \rightarrow \text{LaCo}_5 \rightarrow \text{La}_2\text{Co}_7 \rightarrow \text{La}_2\text{Co}_3 \rightarrow \text{La}_2\text{Co}_{1,7}$	671	$\text{La}_2\text{Co}_3 + \tau + \text{La}_2\text{Co}_7$
55	15	55	30	–	$L \rightarrow \tau \rightarrow \text{La}_2\text{Co}_7 \rightarrow \text{La}_2\text{Co}_3$	645	$(\alpha\text{Co,Fe}) + \text{La}_2\text{Co}_3 + \tau$
56	15	50	35	–	$L \rightarrow \tau \rightarrow \text{La}_2\text{Co}_3 \rightarrow \text{La}_2\text{Co}_{1,7} \rightarrow \text{eutectic} (\text{La}_2\text{Co}_{1,7} + \text{La}_3\text{Co})$	–	$(\alpha\text{Co,Fe}) + \text{La}_2\text{Co}_3 + \text{La}_2\text{Co}_{1,7}$
57	10	60	30	922	$L \rightarrow \tau \rightarrow \text{La}_2\text{Co}_7 \rightarrow \text{La}_2\text{Co}_3 \rightarrow \text{La}_2\text{Co}_{1,7} \rightarrow \text{eutectic} (\text{La}_2\text{Co}_{1,7} + \text{La}_3\text{Co})$	–	$\text{La}_2\text{Co}_3 + \tau$
58	10	55	35	808	$L \rightarrow \tau \rightarrow \text{La}_2\text{Co}_3 \rightarrow \text{La}_2\text{Co}_{1,7} \rightarrow \text{eutectic} (\text{La}_2\text{Co}_{1,7} + \text{La}_3\text{Co})$	569	$(\alpha\text{Co,Fe}) + \text{La}_2\text{Co}_3 + \text{La}_2\text{Co}_{1,7}$
59	10	50	40	751	$L \rightarrow \tau \rightarrow \text{La}_2\text{Co}_3 \rightarrow \text{La}_2\text{Co}_{1,7} \rightarrow \text{eutectic} (\text{La}_2\text{Co}_{1,7} + \text{La}_3\text{Co})$	570	$(\alpha\text{Co,Fe}) + \text{La}_2\text{Co}_3 + \text{La}_2\text{Co}_{1,7}$
60	10	45	45	669	$L \rightarrow \tau \rightarrow \text{La}_2\text{Co}_3 \rightarrow \text{La}_2\text{Co}_{1,7} \rightarrow \text{eutectic} (\text{La}_2\text{Co}_{1,7} + \text{La}_3\text{Co})$	516	$(\alpha\text{Co,Fe}) + \text{La}_2\text{Co}_{1,7}$
61	15	45	40	–	$L \rightarrow \tau \rightarrow \text{La}_2\text{Co}_3 \rightarrow \text{La}_2\text{Co}_{1,7} \rightarrow \text{eutectic} (\text{La}_2\text{Co}_{1,7} + \text{La}_3\text{Co})$	–	$(\alpha\text{Co,Fe}) + \text{La}_2\text{Co}_{1,7}$
62	5	50	45	753	$L \rightarrow \tau \rightarrow \text{La}_2\text{Co}_3 \rightarrow \text{La}_2\text{Co}_{1,7} \rightarrow \text{eutectic} (\text{La}_2\text{Co}_{1,7} + \text{La}_3\text{Co})$	569	$(\alpha\text{Co,Fe}) + \text{La}_2\text{Co}_3 + \text{La}_2\text{Co}_{1,7}$

Table 3 continued

#	Alloy, at. %			Liquidus temperature, °C	Solidification path	Solidus temperature, °C	Phase composition at solidus surface
	Fe	Co	La				
63	5	10	85	670	L → (βLa) → La ₃ Co	528	(αCo,Fe) + La ₃ Co + (βLa)
64	2	18	80	–	L → (βLa) → La ₃ Co → eutectic ((αCo,Fe) + La ₃ Co + (βLa))	527	(αCo,Fe) + La ₃ Co + (βLa)
65	2	53	45	825	L → LaCo₅ → La ₂ Co ₇ → La ₂ Co ₃ → La ₂ Co _{1.7}	568	(αCo,Fe) + La ₂ Co ₃ + La ₂ Co _{1.7}
66	2	48	50	688	L → τ → La ₂ Co ₃ → La ₂ Co _{1.7} → eutectic (La ₂ Co _{1.7} + La ₃ Co)	569	(αCo,Fe) + La ₂ Co ₃ + La ₂ Co _{1.7}
67	2	20	78	–	L → eutectic ((αCo,Fe) + La ₃ Co + (βLa))	528	(αCo,Fe) + La ₃ Co + (βLa)

^aPrimary phase shown in bold

phase is Co₁₃La phase (black grains) or τ phase (dark-gray grains). Both Co₁₃La and τ appear primary. Possibly, the primary phase in these alloys is the Co₁₃La phase, then after primary crystallization of Co₁₃La, the liquid becomes depleted of lanthanum, and the τ phase crystallizes as primary, as well. This indicates that these alloys are located almost on a monovariant curve $L + \text{Co}_{13}\text{La} \rightleftharpoons \tau$. In alloy #45, after crystallization of the Co₁₃La phase (black grains) and τ phase (dark-gray grains), the phases LaCo₅, La₂Co₇, and La₂Co₃ crystallize. Solidification finishes with the formation of the eutectic (La₂Co_{1.7} + CoLa₃) (Fig. 5g).

Alloys #54–62 are located in the field of primary crystallization of the τ-phase (Fig. 5j). The relative position of both monovariant curves and the composition of the ternary compound allow us to conclude that the compound melts incongruently. The incongruent formation of the τ phase is also confirmed by the nature of crystallization and liquidus temperature of the alloys in this composition range.

In alloy #1, which is shown in Fig. 5(a), the primary grains of the (αCo,Fe)-phase with a typical cubic shape (black) are clearly visible, then the τ phases (dark gray) crystallize in this alloy and also appear primary. This indicates that this alloy is located very close to the monovariant curve of joint crystallization of the phases τ and (αCo,Fe). The solidification in this alloy continues with the formation of the Co_{1.7}La₂ phase (gray grains) and finishes with the formation of the eutectic (Co_{1.7}La₂ + CoLa₃) (Fig. 5a).

In the La-rich corner and along the Co–La side, the fields of primary crystallization of phases based on the components (βLa) and (γLa) and phases based on binary compounds Co₁₉La₅, Co₇La₂, Co₃La₂, Co_{1.7}La₂, and CoLa₃ are present. They are all very narrow. The field (βLa) is plotted by observation of the primary (βLa) phase in alloys #63 and #64 in contrast to the primary (αCo,Fe)-phase in alloy #36. The field of (γLa), as well as (δFe), is shown tentatively.

The boundaries of the fields of primary crystallization of phases based on cobalt lanthanides Co₁₉La₅, Co₇La₂, Co₃La₂, Co_{1.7}La₂, and CoLa₃ are determined mainly from the microstructure of the alloys located along the isoconcentrate 2 at.% Fe. The field of primary crystallization of the Co₅La phase is determined from the microstructure of alloys #5 and #65 (Fig. 5k), which shows that these alloys are located in the field of primary crystallization of the Co₅La phase. Moreover, the microstructure of alloy #65 contains a small amount of primary grains of the Co₅La (black grains). After the primary crystallization of Co₅La (black grains), the Co₇La₂ phase (dark-gray grains) forms around the primary grains, then the Co₇La₂, Co₃La₂, and Co_{1.7}La₂ phases crystallize (Fig. 5k). The location of the

Table 4 Composition of Co–Fe–La phases according to EPMA data

#	Phase composition, at.%						Heat treatment	EPMA data, at.%					
	Nominal			Measured				Phase	Fe	Co	La		
	Fe	Co	La	Fe	Co	La							
1	10	40	50	7.9	39.9	52.2	as-cast	τ	42.4 ± 0.3	45.8 ± 0.3	11.8 ± 0.2		
								La ₂ Co _{1.7}	0.5 ± 0.1	45.9 ± 0.3	53.6 ± 0.3		
								La ₃ Co	0.0 ± 0.1	25.1 ± 0.8	74.9 ± 0.8		
							510 °C, 1 h	eutectic (La ₂ Co _{1.7} + La ₃ Co)		0.3	30.8	68.9	
						8.2		40.0	51.8	(αCo,Fe)	74.1 ± 0.4	25.0 ± 0.5	0.9 ± 0.2
								La ₂ Co _{1.7}	0.0 ± 0.0	46.5 ± 0.1	53.5 ± 0.1		
2	5	70	25	4.5	68.9	26.6	as-cast	La ₃ Co	0.0 ± 0.0	25.0 ± 0.1	75.0 ± 0.1		
								τ	9.1 ± 0.1	79.4 ± 0.1	11.5 ± 0.1		
								LaCo ₅	5.9 ± 0.1	77.1 ± 0.1	17.0 ± 0.2		
								La ₂ Co ₇	4.7 ± 0.3	72.2 ± 0.4	23.1 ± 0.3		
								La ₂ Co ₃	1.6 ± 0.1	58.1 ± 0.1	40.3 ± 0.2		
								(γCo,Fe)	62.0 ± 0.6	37.7 ± 0.6	0.3 ± 0.2		
3	53	40	7	52.8	39.7	7.5	as-cast	LaCo ₁₃	43.3 ± 0.9	49.0 ± 0.9	7.7 ± 0.2		
								La ₂ Co ₃	3.2	57.2	39.6		
								La ₂ Co _{1.7}	0.9	47.0	52.1		
								(γCo,Fe)	62.4 ± 0.9	37.1 ± 0.9	0.5 ± 0.1		
4	49	40	11	48.4	39.0	12.6	as-cast	LaCo ₁₃	43.3 ± 0.4	49.0 ± 0.6	7.7 ± 0.2		
								τ	39.0 ± 0.3	49.5 ± 0.3	11.5 ± 0.1		
								La ₂ Co ₃	3.2	56.1	40.7		
								La ₂ Co _{1.7}	1.0	46.8	52.2		
								LaCo ₅	10.3 ± 0.2	72.4 ± 0.1	17.3 ± 0.3		
5	5	60	35	4.9	58.8	36.3	as-cast	La ₂ Co ₇	7.7 ± 0.5	69.3 ± 0.7	23.0 ± 0.3		
								La ₂ Co ₃	1.8 ± 0.2	57.4 ± 0.4	40.8 ± 0.2		
								La ₂ Co _{1.7}	0.5 ± 0.2	46.2 ± 0.4	53.3 ± 0.3		
								(γCo,Fe)	28.7 ± 0.1	70.9 ± 0.1	0.4 ± 0.1		
								LaCo ₁₃	20.3 ± 0.2	72.2 ± 0.1	7.5 ± 0.1		
6	23	70	7	23.1	69.5	7.4	as-cast	La ₂ Co ₇	9.2 ± 0.2	68.6 ± 0.4	22.2 ± 0.3		
								La ₂ Co ₃	2.1	57.6	40.3		
								LaCo ₁₃	8.7 ± 0.1	83.4 ± 0.1	7.9 ± 0.1		
								LaCo ₅	4.1 ± 0.1	78.7 ± 0.1	17.2 ± 0.2		
7	5	75	20	4.9	74.0	21.1	as-cast	La ₅ Co ₁₉	3.8 ± 0.3	74.6 ± 0.2	21.6 ± 0.1		
								La ₂ Co ₇	3.8 ± 0.1	73.1 ± 0.3	23.1 ± 0.4		
								La ₂ Co ₃	1.1 ± 0.1	58.6 ± 0.1	40.3 ± 0.1		
								(γCo,Fe)	6.0 ± 0.2	76.6 ± 0.3	17.4 ± 0.1		
								La ₅ Co ₁₉	4.7 ± 0.1	73.8 ± 0.1	21.5 ± 0.1		
								La ₂ Co ₇	4.4 ± 0.2	72.7 ± 0.1	22.9 ± 0.1		
8	20	50	30	19.8	46.8	33.4	as-cast	(γCo,Fe)	53.3 ± 0.3	45.6 ± 0.2	1.1 ± 0.1		
								τ	35.0	53.7	11.3		
								La ₂ Co ₃	2.3 ± 0.1	57.0 ± 0.1	40.7 ± 0.1		
								La ₂ Co _{1.7}	0.7 ± 0.1	46.4 ± 0.2	52.9 ± 0.2		
								(γCo,Fe)	46.1 ± 0.1	53.6 ± 0.1	0.3 ± 0.1		
9	38	55	7	38.2	54.6	7.2	as-cast	LaCo ₁₃	34.2 ± 0.1	58.2 ± 0.1	7.6 ± 0.1		
								La ₂ Co ₃	3.0	56.9	40.1		
								(γCo,Fe)	49.4 ± 0.2	50.2 ± 0.2	0.4 ± 0.1		
								LaCo ₁₃	37.3 ± 0.3	55.2 ± 0.3	7.5 ± 0.1		
								38.4	54.7	6.9	950 °C, 94 h		

Table 4 continued

#	Phase composition, at.%						Heat treatment	EPMA data, at.%			
	Nominal			Measured				Phase	Fe	Co	La
	Fe	Co	La	Fe	Co	La					
10	15	75	10	14.3	74.4	11.3	as-cast	(γ Co,Fe)	21.3 $\pm$ 0.1	78.0 $\pm$ 0.2	0.7 $\pm$ 0.1
								LaCo ₁₃	15.2 $\pm$ 0.1	77.0 $\pm$ 0.1	7.8 $\pm$ 0.1
								LaCo ₅	9.9 $\pm$ 0.3	72.6 $\pm$ 0.5	17.5 $\pm$ 0.2
								La ₂ Co ₇	7.8 $\pm$ 0.1	69.3 $\pm$ 0.1	22.9 $\pm$ 0.1
								La ₂ Co ₃	2.3	57.1	40.6
11	33	50	17	33.3	49.3	17.4	as-cast	(γ Co,Fe)	53.2 $\pm$ 0.2	46.4 $\pm$ 0.3	0.4 $\pm$ 0.1
								LaCo ₁₃	35.9 $\pm$ 0.2	56.2 $\pm$ 0.2	7.9 $\pm$ 0.1
								La ₂ Co ₃	2.5 $\pm$ 0.3	56.9 $\pm$ 0.2	40.6 $\pm$ 0.1
								La ₂ Co _{1.7}	0.9 $\pm$ 0.1	46.2 $\pm$ 0.5	52.9 $\pm$ 0.6
12	48	45	7	48.1	44.6	7.3	as-cast	(γ Co,Fe)	56.5 $\pm$ 0.3	43.0 $\pm$ 0.3	0.5 $\pm$ 0.1
								τ	39.4 $\pm$ 0.7	48.9 $\pm$ 0.6	11.7 $\pm$ 0.4
								La ₂ Co ₃	3.0	56.0	41.0
								La ₂ Co _{1.7}	1.0	46.9	52.1
13	44	45	11	44.1	44.2	11.7	as-cast	(γ Co,Fe)	57.2 $\pm$ 0.4	42.1 $\pm$ 0.4	0.7 $\pm$ 0.1
								τ	40.5	48.2	11.3
								La ₂ Co ₃	3.0	56.4	40.6
								La ₂ Co _{1.7}	1.0	46.6	52.4
14	15	83	2	15.5	82.5	2.0	as-cast	(γ Co,Fe)	16.3 $\pm$ 0.1	83.6 $\pm$ 0.1	0.1 $\pm$ 0.1
								LaCo ₁₃	12.0 $\pm$ 0.2	80.7 $\pm$ 0.2	7.3 $\pm$ 0.1
								La ₂ Co ₇	6.4 $\pm$ 0.4	70.7 $\pm$ 0.2	22.9 $\pm$ 0.6
15	40	25	35	38.3	25.2	36.5	as-cast	(γ Co,Fe)	82.1	17.0	0.9
								eutectic (La ₂ Co _{1.7} + La ₃ Co)	0.9	29.0	70.1
16	60	25	15	59.0	25.0	16.0	as-cast	(γ Co,Fe)	78.8 $\pm$ 0.2	20.6 $\pm$ 0.1	0.6 $\pm$ 0.1
								eutectic (La ₂ Co _{1.7} + La ₃ Co)	0.9 $\pm$ 0.1	29.7 $\pm$ 0.1	69.4 $\pm$ 0.1
17	60	15	25	57.5	15.6	26.9	as-cast	(γ Co,Fe)	88.8 $\pm$ 0.2	10.4 $\pm$ 0.2	0.8 $\pm$ 0.1
								(β La)	0.0 $\pm$ 0.0	0.0 $\pm$ 0.0	100.0 $\pm$ 0.0
								La ₃ Co	0.0	24.2	75.8
18	40	35	25	39.0	34.3	26.7	as-cast	(γ Co,Fe)	69.4	29.7 $\pm$ 0.5	0.9 $\pm$ 0.1
								La ₂ Co _{1.7}	1.0 $\pm$ 0.1	46.0 $\pm$ 0.3	53.0 $\pm$ 0.2
19	35	15	50	31.1	16.3	52.6	as-cast	–	–	–	–
20	25	25	50	19.6	26.4	54.0	as-cast	–	–	–	–
21	63	30	7	62.4	30.3	7.3	as-cast	(γ Co,Fe)	72.0 $\pm$ 0.3	27.6 $\pm$ 0.3	0.4 $\pm$ 0.1
								La ₂ Co ₃	1.3	57.8	40.9
								La ₂ Co _{1.7}	1.0	46.4	52.6
22	10	79	11	10.2	78.2	11.6	as-cast	(γ Co,Fe)	15.5 $\pm$ 0.2	83.9 $\pm$ 0.2	0.6 $\pm$ 0.1
								LaCo ₁₃	11.1 $\pm$ 0.2	81.3 $\pm$ 0.1	7.6 $\pm$ 0.1
								LaCo ₅	7.2 $\pm$ 0.5	75.9 $\pm$ 0.3	16.9 $\pm$ 0.3
								La ₂ Co ₇	6.2 $\pm$ 0.2	71.1 $\pm$ 0.5	22.7 $\pm$ 0.2
				–	–	–	970 °C, 3 h	LaCo ₁₃	12.6 $\pm$ 0.3	79.7 $\pm$ 0.3	7.7 $\pm$ 0.1
								LaCo ₅	5.7 $\pm$ 0.3	77.1 $\pm$ 0.3	17.2 $\pm$ 0.2
23	29	60	11	28.5	59.3	12.2	as-cast	(γ Co,Fe)	40.3 $\pm$ 0.4	59.0 $\pm$ 0.4	0.7 $\pm$ 0.2
								LaCo ₁₃	28.2 $\pm$ 0.3	64.2 $\pm$ 0.4	7.6 $\pm$ 0.1
								La ₂ Co ₃	2.8 $\pm$ 0.1	56.9 $\pm$ 0.2	40.3 $\pm$ 0.3

Table 4 continued

#	Phase composition, at.%						Heat treatment	EPMA data, at.%			
	Nominal			Measured				Phase	Fe	Co	La
	Fe	Co	La	Fe	Co	La					
28	5	88	7	5.1	87.5	7.4	as-cast	(γ Co,Fe)	7.0 $\pm$ 0.1	92.6 $\pm$ 0.2	0.4 $\pm$ 0.1
								LaCo ₁₃	4.8 $\pm$ 0.1	87.7 $\pm$ 0.1	7.5 $\pm$ 0.1
								LaCo ₅	3.1 $\pm$ 0.1	80.1 $\pm$ 0.1	16.8 $\pm$ 0.2
								La ₅ Co ₁₉	2.7 $\pm$ 0.1	76.0 $\pm$ 0.2	21.3 $\pm$ 0.2
								La ₂ Co ₇	2.5 $\pm$ 0.1	74.5 $\pm$ 0.1	23.0 $\pm$ 0.2
29	68	25	7	68.2	25	6.8	as-cast	(γ Co,Fe)	76.7 $\pm$ 0.8	23.3 $\pm$ 0.8	0.0 $\pm$ 0.0
31	18	45	37	17.4	44.4	38.2	as-cast	(γ Co,Fe)	55.7 $\pm$ 0.9	43.4 $\pm$ 0.9	0.9 $\pm$ 0.1
								τ	31.4 $\pm$ 0.4	57.1 $\pm$ 0.5	11.5 $\pm$ 0.3
								La ₂ Co ₃	2.5 $\pm$ 0.2	57.0 $\pm$ 0.4	40.5 $\pm$ 0.3
								La ₂ Co _{1.7}	0.6 $\pm$ 0.7	46.4 $\pm$ 0.1	53.0 $\pm$ 0.7
								La ₃ Co	0.0	24.8	75.2
								eutectic (La ₂ Co _{1.7} + La ₃ Co)	1.2	31.6	67.2
									0.1	32.2	67.7
32	12	77	11	12.0	76.8	11.2	as-cast	(γ Co,Fe)	18.3 $\pm$ 0.1	81.1 $\pm$ 0.1	0.6 $\pm$ 0.1
								LaCo ₁₃	13.0 $\pm$ 0.2	79.3 $\pm$ 0.1	7.7 $\pm$ 0.1
								LaCo ₅	8.9 $\pm$ 0.7	74.2 $\pm$ 0.7	16.9 $\pm$ 0.1
								La ₂ Co ₇	6.8 $\pm$ 0.4	70.7 $\pm$ 0.6	22.5 $\pm$ 0.4
								La ₂ Co ₃	3.6	56.1	40.3
34	10	30	60	9.3	29.9	60.8	as-cast	(α Co,Fe)	76.4 $\pm$ 0.1	23.0 $\pm$ 0.1	0.6 $\pm$ 0.1
								eutectic (La ₂ Co _{1.7} + La ₃ Co)	0.4 $\pm$ 0.2	31.1 $\pm$ 0.6	68.5 $\pm$ 0.6
				9.0	29.3	61.7	510 $^{\circ}$ C, 1 h	(α Co,Fe)	74.7 $\pm$ 0.1	24.7 $\pm$ 0.1	0.6 $\pm$ 0.1
								La ₂ Co _{1.7}	0.0 $\pm$ 0.0	46.5 $\pm$ 0.2	53.5 $\pm$ 0.2
								La ₃ Co	0.0 $\pm$ 0.0	24.8 $\pm$ 0.1	75.2 $\pm$ 0.1
35	10	25	65	8.2	25.2	66.6	as-cast	(α Co,Fe)	82.6 $\pm$ 0.3	16.5 $\pm$ 0.3	0.9 $\pm$ 0.1
								La ₃ Co	0.0 $\pm$ 0.1	24.9 $\pm$ 0.2	75.1 $\pm$ 0.2
36	10	10	80	9.2	10.1	80.7	as-cast	(β La)	0.0 $\pm$ 0.0	0.0 $\pm$ 0.0	100.0 $\pm$ 0.0
								La ₃ Co	0.2 $\pm$ 0.3	23.2 $\pm$ 0.2	76.6 $\pm$ 0.3
								(α Co,Fe)	96.3	3.0	0.7
				9.3	10.1	80.6	520 $^{\circ}$ C, 2 h	(α Fe,Co)	95.9 $\pm$ 0.4	3.2 $\pm$ 0.2	0.9 $\pm$ 0.1
								(β La)	0.0 $\pm$ 0.0	0.0 $\pm$ 0.0	100.0 $\pm$ 0.0
								La ₃ Co	0.0 $\pm$ 0.1	24.2 $\pm$ 0.2	75.8 $\pm$ 0.2
38	2	33	65	1.5	32.5	66.0	as-cast	La ₂ Co _{1.7}	0.8 $\pm$ 0.1	45.7 $\pm$ 0.4	53.5 $\pm$ 0.4
								La ₃ Co	0.1 $\pm$ 0.1	25.0 $\pm$ 0.6	74.9 $\pm$ 0.5
								eutectic (La ₂ Co _{1.7} + La ₃ Co)	0.9 $\pm$ 0.1	30.9 $\pm$ 0.1	68.2 $\pm$ 0.3
39	2	23	75	1.9	23.0	75.1	as-cast	(α Co,Fe)	81.2	18.4	0.4
								La ₃ Co	0.2 $\pm$ 0.2	24.0 $\pm$ 0.1	75.8 $\pm$ 0.3
37	2	38	60	1.8	37.3	60.9	as-cast	(α Co,Fe)	59.0 $\pm$ 0.3	40.4 $\pm$ 0.4	0.6 $\pm$ 0.1
								La ₂ Co _{1.7}	0.7 $\pm$ 0.1	45.5 $\pm$ 0.2	53.8 $\pm$ 0.2
								La ₃ Co	0.0 $\pm$ 0.1	25.2 $\pm$ 0.3	74.8 $\pm$ 0.3
42	15	35	50	15.8	35.9	48.3	as-cast	(γ Co,Fe)	67.2 $\pm$ 0.6	31.9 $\pm$ 0.5	0.9 $\pm$ 0.1
								La ₂ Co _{1.7}	0.0 $\pm$ 0.0	46.3 $\pm$ 0.3	53.7 $\pm$ 0.3
								La ₃ Co	0.0 $\pm$ 0.0	25.2 $\pm$ 0.5	74.8 $\pm$ 0.5

Table 4 continued

#	Phase composition, at.%						Heat treatment	EPMA data, at.%			
	Nominal			Measured				Phase	Fe	Co	La
	Fe	Co	La	Fe	Co	La					
44	10	75	15	10.0	74.3	15.7	as-cast	LaCo ₁₃	13.2 ± 0.3	79.1 ± 0.3	7.7 ± 0.1
								LaCo ₅	8.2 ± 0.4	75.0 ± 0.4	16.8 ± 0.2
								La ₂ Co ₇	6.2 ± 0.3	71.3 ± 0.2	22.5 ± 0.2
								La ₂ Co ₃	2.2 ± 0.1	57.7 ± 0.1	40.1 ± 0.1
45	10	65	25	9.4	64.2	26.4	as-cast	LaCo ₁₃	17.9	74.3	7.8
								τ	16.7 ± 0.2	72.1 ± 0.3	11.2 ± 0.1
								LaCo ₅	8.6 ± 0.6	74.1 ± 0.6	17.3 ± 0.1
								La ₂ Co ₇	7.4 ± 0.1	69.8 ± 0.2	22.8 ± 0.2
								La ₂ Co ₃	2.0 ± 0.2	57.4 ± 0.3	40.6 ± 0.2
								La ₂ Co _{1.7}	0.7 ± 0.2	46.5 ± 0.2	52.8 ± 0.1
								eutectic (La ₂ Co _{1.7} + La ₃ Co)	1.0 ± 0.1	32.1 ± 0.1	66.9 ± 0.2
				9.3	64.2	26.5	660 °C, 2 h	τ	20.1 ± 0.7	68.2 ± 0.9	11.7 ± 0.2
								La ₂ Co ₃	1.1 ± 0.1	58.2 ± 0.1	40.7 ± 0.1
								La ₂ Co ₇	8.3 ± 0.4	68.8 ± 0.4	22.9 ± 0.4
46	20	55	25	20.3	54.2	25.5	as-cast	LaCo ₁₃	33.6 ± 0.3	58.5 ± 0.3	7.9 ± 0.1
								La ₂ Co ₃	1.9 ± 0.1	57.5 ± 0.3	40.6 ± 0.2
47	10	70	20	9.9	68.7	21.4	as-cast	LaCo ₁₃	16.2 ± 0.3	75.9 ± 0.4	7.9 ± 0.1
								LaCo ₅	9.0 ± 0.2	74.0 ± 0.2	17.0 ± 0.1
								La ₂ Co ₇	7.5 ± 0.3	69.4 ± 0.3	23.1 ± 0.2
								La ₂ Co ₃	2.1 ± 0.1	57.5 ± 0.3	40.4 ± 0.3
48	15	65	20	14.9	63.9	21.2	as-cast	LaCo ₁₃	22.7 ± 0.3	69.4 ± 0.3	7.9 ± 0.1
								LaCo ₅	9.2 ± 0.2	73.3 ± 0.5	17.5 ± 0.3
								La ₂ Co ₇	7.8 ± 0.4	69.3 ± 0.5	22.9 ± 0.2
								La ₂ Co ₃	2.5 ± 0.3	57.2 ± 0.3	40.3 ± 0.3
								La ₂ Co _{1.7}	0.7 ± 0.2	47.3 ± 0.1	52.2 ± 0.1
49	10	67.5	22.5	9.8	66.3	23.9	as-cast	LaCo ₁₃	17.4 ± 0.3	74.7 ± 0.3	7.9 ± 0.1
								LaCo ₅	8.4 ± 0.9	74.3 ± 0.9	17.3 ± 0.3
								La ₂ Co ₇	7.5 ± 0.2	69.3 ± 0.3	23.2 ± 0.1
								La ₂ Co ₃	2.4 ± 0.1	57.1 ± 0.1	40.5 ± 0.1
								La ₂ Co _{1.7}	0.0 ± 0.0	47.1 ± 0.3	52.9 ± 0.3
50	15	60	25	14.6	58.7	26.7	as-cast	LaCo ₁₃	27.5 ± 0.2	64.6 ± 0.3	7.9 ± 0.1
								τ	24.7 ± 0.3	63.9 ± 0.3	11.4 ± 0.1
								La ₂ Co ₇	6.8 ± 0.4	70.3 ± 0.5	22.9 ± 0.1
								La ₂ Co ₃	2.0 ± 0.2	57.2 ± 0.2	40.8 ± 0.3
								La ₂ Co _{1.7}	0.0 ± 0.0	46.5 ± 0.2	53.5 ± 0.0
54	10	62	28	8.9	62.3	28.8	as-cast	τ	18.0 ± 0.2	70.7 ± 0.1	11.3 ± 0.1
								LaCo ₅	8.2 ± 0.5	74.3 ± 0.2	17.5 ± 0.2
								La ₂ Co ₇	7.4 ± 0.3	69.5 ± 0.7	23.1 ± 0.4
								La ₂ Co ₃	1.6 ± 0.2	57.7 ± 0.3	40.7 ± 0.3
								La ₂ Co _{1.7}	0.9 ± 0.2	46.3 ± 0.9	52.8 ± 0.8
				8.5	63.1	28.4	660 °C, 2 h	τ	17.5 ± 0.2	70.9 ± 0.2	11.6 ± 0.1
								La ₂ Co ₃	1.2 ± 0.2	58.5 ± 0.2	40.3 ± 0.1
								La ₂ Co ₇	7.9 ± 0.2	69.5 ± 0.3	22.6 ± 0.2

Table 4 continued

#	Phase composition, at.%						Heat treatment	EPMA data, at.%			
	Nominal			Measured				Phase	Fe	Co	La
	Fe	Co	La	Fe	Co	La					
55	15	55	30	14.3	53.8	31.9	as-cast	τ	29.6 ± 0.4	58.9 ± 0.2	11.5 ± 0.2
								La_2Co_3	1.7 ± 0.2	57.5 ± 0.1	40.8 ± 0.1
								$\text{La}_2\text{Co}_{1.7}$	0.3 ± 0.4	46.0 ± 0.3	53.7 ± 0.4
								eutectic ($\text{La}_2\text{Co}_{1.7} + \text{La}_3\text{Co}$)	0.1	30.2	69.7
57	10	60	30	9.6	58.6	31.8	as-cast	τ	20.5 ± 0.2	68.1 ± 0.2	11.4 ± 0.1
								La_2Co_7	7.9 ± 0.5	69.3 ± 0.5	22.8 ± 0.1
								La_2Co_3	2.2 ± 0.1	57.1 ± 0.2	40.7 ± 0.1
								$\text{La}_2\text{Co}_{1.7}$	0.5 ± 0.4	46.0 ± 0.5	53.5 ± 0.4
								eutectic ($\text{La}_2\text{Co}_{1.7} + \text{La}_3\text{Co}$)	0.3	29.8	69.9
58	10	55	35	9.8	53.5	36.6	as-cast	τ	25.8 ± 0.5	62.8 ± 0.3	11.4 ± 0.1
								La_2Co_3	1.1 ± 0.1	58.5 ± 0.1	40.4 ± 0.1
								$\text{La}_2\text{Co}_{1.7}$	0.9 ± 0.3	46.0 ± 0.1	53.1 ± 0.2
								eutectic ($\text{La}_2\text{Co}_{1.7} + \text{La}_3\text{Co}$)	0.6 ± 0.3	30.0 ± 0.9	69.4 ± 0.6
59	10	50	40	8.9	49.8	41.3	as-cast	τ	28.9 ± 0.2	59.5 ± 0.2	11.6 ± 0.1
								La_2Co_3	1.7 ± 0.2	57.6 ± 0.2	40.7 ± 0.1
								$\text{La}_2\text{Co}_{1.7}$	0.8 ± 0.2	45.8 ± 0.6	53.4 ± 0.5
								eutectic ($\text{La}_2\text{Co}_{1.7} + \text{La}_3\text{Co}$)	0.6	33.3	66.1
				8.7	49.7	41.6	560 °C, 2 h	($\alpha\text{Co,Fe}$)	62.5 ± 0.3	37.1 ± 0.5	0.4 ± 0.1
								La_2Co_3	2.2 ± 0.1	57.1 ± 0.3	40.7 ± 0.1
								$\text{La}_2\text{Co}_{1.7}$	0.0 ± 0.2	47.0 ± 0.2	53.0 ± 0.2
60	10	45	45	9.8	43.6	46.6	as-cast	τ	38.0 ± 0.1	50.2 ± 0.1	11.8 ± 0.1
								La_2Co_3	2.2 ± 0.1	56.9 ± 0.1	40.9 ± 0.2
								$\text{La}_2\text{Co}_{1.7}$	0.7 ± 0.2	45.6 ± 0.4	53.7 ± 0.3
								eutectic ($\text{La}_2\text{Co}_{1.7} + \text{La}_3\text{Co}$)	0.5 ± 0.1	31.5 ± 0.9	68.0 ± 0.9
61	15	45	40	14.3	44.3	41.4	as-cast	τ	40.3 ± 0.3	48.0 ± 0.1	11.7 ± 0.2
								La_2Co_3	2.3 ± 0.1	57.1 ± 0.1	40.6 ± 0.1
								$\text{La}_2\text{Co}_{1.7}$	0.4 ± 0.5	45.7 ± 0.3	53.9 ± 0.3
								eutectic ($\text{La}_2\text{Co}_{1.7} + \text{La}_3\text{Co}$)	0.1	31.3	68.6
62	5	50	45	4.3	47.8	47.9	as-cast	τ	25.7 ± 0.3	62.8 ± 0.3	11.5 ± 0.1
								La_2Co_3	1.6 ± 0.1	57.8 ± 0.2	40.6 ± 0.1
								$\text{La}_2\text{Co}_{1.7}$	0.6 ± 0.1	45.9 ± 0.3	53.5 ± 0.2
								La_3Co	0.0 ± 0.0	25.7 ± 0.3	74.3 ± 0.3
								eutectic ($\text{La}_2\text{Co}_{1.7} + \text{La}_3\text{Co}$)	1.3 ± 0.3	29.9 ± 0.9	68.8 ± 0.9
				4.7	48.3	47.0	560 °C, 2 h	($\alpha\text{Co,Fe}$)	61.4 ± 0.6	38.1 ± 0.7	0.5 ± 0.1
								La_2Co_3	2.0 ± 0.1	57.1 ± 0.3	40.9 ± 0.2
								$\text{La}_2\text{Co}_{1.7}$	0.0 ± 0.0	47.1 ± 0.3	52.9 ± 0.3
63	5	10	85	5.4	12.0	82.6	as-cast	(βLa)	0.0 ± 0.0	0.1 ± 0.1	99.9 ± 0.1
								La_3Co	0.0 ± 0.0	23.2 ± 0.1	76.8 ± 0.1
								$\text{La}_2\text{Co}_{1.7}$	0.9 ± 0.2	46.1 ± 0.2	53.0 ± 0.1
								eutectic ($\text{La}_2\text{Co}_{1.7} + \text{La}_3\text{Co}$)	0.9 ± 0.5	30.1 ± 0.9	69.0 ± 0.8
65	2	18	80	1.7	18.3	80.0	as-cast	(βLa)	0.0 ± 0.0	0.0 ± 0.0	100.0 ± 0.0
								La_3Co	0.0 ± 0.0	23.4 ± 0.3	76.6 ± 0.3
								eutectic (($\alpha\text{Co,Fe}$) + La_3Co + (βLa))	1.7 ± 0.3	20.2 ± 0.2	78.1 ± 0.1

Table 4 continued

#	Phase composition, at. %						Heat treatment	EPMA data, at. %			
	Nominal			Measured				Phase	Fe	Co	La
	Fe	Co	La	Fe	Co	La					
65	2	53	45	1.8	51.8	46.4	as-cast	La ₂ Co ₇	6.3 ± 0.3	70.5 ± 0.3	23.2 ± 0.5
								La ₂ Co ₃	1.1 ± 0.1	58.3 ± 0.2	40.6 ± 0.1
								La ₂ Co _{1.7}	0.5 ± 0.1	46.4 ± 0.4	53.1 ± 0.4
66	2	48	50	1.9	47.5	50.6	as-cast	τ	28.2 ± 0.9	60.0 ± 0.9	11.8 ± 0.2
								La ₂ Co ₃	2.3 ± 0.1	57.1 ± 0.1	40.6 ± 0.1
								La ₂ Co _{1.7}	0.5 ± 0.2	45.8 ± 0.3	53.7 ± 0.2
								eutectic (La ₂ Co _{1.7} + La ₃ Co)	0.7 ± 0.1	30.2 ± 0.5	69.1 ± 0.6
67	2	20	78	1.1	20.4	78.5	as-cast	eutectic ((αCo,Fe) + La ₃ Co + (βLa))	1.1 ± 0.1	20.4 ± 0.2	78.5 ± 0.3

monovariant curve P_1U_3 , separating the fields of primary solidification of τ and Co_5La , is evident from the observation of the primary τ in samples #54, 57, and 62 in contrast to Co_5La in samples #5 and #65 (Fig. 5k).

No alloys were investigated in the primary crystallization field of the $\text{La}_5\text{Co}_{19}$ phase, but note that this field is the narrowest and is limited by the composition point of alloy #65. The monovariant curves $\text{L} + \text{LaCo}_5 \rightleftharpoons \text{La}_5\text{Co}_{19}$ (p_5U_1) and $\text{L} + \text{La}_5\text{Co}_{19} \rightleftharpoons \text{La}_2\text{Co}_7$ (p_6U_1) do not extend appreciably into the ternary system. The intersections of these curves give the composition of the liquid U_1 . The composition of the liquid at point U_1 cannot contain more than 1 at.% Fe.

The primary solidification field of the La_2Co_7 phase is also very small. There were no alloys inside this field, but the border of this field is limited by the composition of alloys #62, 65, and 66, in which the primary phase is τ , LaCo_5 , and La_2Co_3 , respectively (Fig. 5k).

Only alloy #66 is located in the field of primary solidification of the phase La_2Co_3 . The solidification of this alloy continues with the formation of the $\text{La}_2\text{Co}_{1.7}$ phase, and finishes with the formation of the eutectic ($\text{Co}_{1.7}\text{La}_2 + \text{CoLa}_3$).

The primary solidification field of the $\text{Co}_{1.7}\text{La}_2$ and CoLa_3 phases are very narrow and limited by the composition of alloys #37, 38, and 39, respectively, in which only a small amount of primary grains of ($\alpha\text{Co,Fe}$) phase is observed (Fig. 5e). In alloys #37 and #38, after primary crystallization of the ($\alpha\text{Co,Fe}$) phase (black grains), the $\text{La}_2\text{Co}_{1.7}$ phase crystallizes, and solidification finishes with the formation of the eutectic ($\text{La}_2\text{Co}_{1.7} + \text{CoLa}_3$) (Fig. 5e). The very small amount of primary ($\alpha\text{Co,Fe}$) grains in these alloys indicates that the primary crystallization field of the $\text{Co}_{1.7}\text{La}_2$ phase does not extend into the ternary system more than up to 2 at.% Fe (Fig. 5e). In alloy #39, the

Fig. 5 Microstructure of as-cast alloys of La–Co–Fe system: **a** 40Ce–50Co–10Fe (#1), $\times 1000$, ($\alpha\text{Co,Fe}$) + τ + $\text{La}_2\text{Co}_{1.7}$ + eutectic ($\text{La}_2\text{Co}_{1.7} + \text{La}_3\text{Co}$); **b** 20Fe–50Co–30La (#8), $\times 2000$, ($\gamma\text{Co,Fe}$) + τ + La_2Co_3 + $\text{La}_2\text{Co}_{1.7}$ + eutectic ($\text{La}_2\text{Co}_{1.7} + \text{La}_3\text{Co}$); **c** 15Fe–75Co–10La (#10), $\times 2000$, ($\gamma\text{Co,Fe}$) + $\text{LaCo}_{13} + \text{LaCo}_5 + \text{La}_2\text{Co}_7 + \text{La}_2\text{Co}_3$; **d** 10Fe–10Co–80La (#36), $\times 2000$, ($\alpha\text{Co,Fe}$) + (βLa) + La_3Co ; **e** 2Fe–33Co–65La (#38), $\times 1000$, ($\alpha\text{Co,Fe}$) + $\text{La}_2\text{Co}_{1.7}$ + eutectic ($\text{La}_2\text{Co}_{1.7} + \text{La}_3\text{Co}$); **f** 10Fe–75Co–15La (#44), $\times 2000$, $\text{LaCo}_{13} + \text{LaCo}_5 + \text{La}_2\text{Co}_7 + \text{La}_2\text{Co}_3$; **g** 10Fe–65Co–25La (#45), $\times 2000$, $\text{LaCo}_{13} + \tau + \text{La}_2\text{Co}_7 + \text{La}_2\text{Co}_3 + \text{La}_2\text{Co}_{1.7}$ + eutectic ($\text{La}_2\text{Co}_{1.7} + \text{La}_3\text{Co}$); **h** 20Fe–55Co–25La (#46), $\times 2000$, $\text{LaCo}_{13} + \text{La}_2\text{Co}_3 + \text{La}_2\text{Co}_{1.7}$ + eutectic ($\text{La}_2\text{Co}_{1.7} + \text{La}_3\text{Co}$); **i** 5Fe–75Co–20La (#7), $\times 1000$, $\text{LaCo}_{13} + \text{LaCo}_5 + \text{La}_5\text{Co}_{19} + \text{La}_2\text{Co}_7 + \text{La}_2\text{Co}_3 + \text{La}_2\text{Co}_{1.7}$; **j** 15Fe–45Co–40La (#61), $\times 2000$, $\tau + \text{La}_2\text{Co}_7 + \text{La}_2\text{Co}_3$ + eutectic ($\text{La}_2\text{Co}_{1.7} + \text{La}_3\text{Co}$); **k** 2Fe–53Co–45La (#65), $\times 2000$, $\text{LaCo}_5 + \text{La}_2\text{Co}_7 + \text{La}_2\text{Co}_3 + \text{La}_2\text{Co}_{1.7}$; **l** 2Fe–20Co–78La (#67), $\times 2000$, eutectic (($\alpha\text{Co,Fe}$) + La_3Co + (βLa))

($\alpha\text{Co,Fe}$) phase solidifies as a primary phase, then the CoLa_3 phase crystallizes, and solidification finishes with the formation of the ternary eutectic (($\alpha\text{Co,Fe}$) + (βLa) + CoLa_3). Note that the monovariant curve $\text{L} \rightleftharpoons (\alpha\text{Co,Fe}) + \text{CoLa}_3$ has a saddle point corresponding to the maximum temperature on the solidus surface ($\alpha\text{Co,Fe}$) + CoLa_3 at 540 °C.

Analysis of the microstructure of alloy #67 showed the presence of a ternary eutectic ((βLa) + ($\alpha\text{Fe,Co}$) + La_3Co). This eutectic is very fine. Therefore, this alloy was heated and cooled in DTA equipment at the rate of 5 °C/min in order to obtain the solidification morphologies of this alloy. Only the microstructure of this alloy after DTA (Fig. 5l) allowed the identification of three phases in the eutectic: (βLa) (white grains), La_3Co (gray matrix), and ($\alpha\text{Fe,Co}$) (black grains). This ternary eutectic was also observed in alloys #39 and #64; moreover, in the first alloy the ($\alpha\text{Fe,Co}$) phase is primary, and in the second alloy (βLa). The composition of the ternary eutectic

(a)

(b)

(c)

(d)

(e)

(f)

(g)

(h)

(i)

(j)

(k)

(l)

Fig. 6 Microstructure of alloys of La–Co–Fe system annealed at subsolidus temperatures: **a** 5Fe–75Co–20La (#7), 810 °C, $\times 2000$, La_2Co_7 + LaCo_5 + $\text{La}_5\text{Co}_{19}$; **b** 10Fe–62Co–25La (#54), 660 °C, $\times 2000$, La_2Co_3 + τ + La_2Co_7 ; **c** 5Fe–50Co–45La (#62), 560 °C,

$\times 500$, $(\alpha\text{Co,Fe})$ + La_2Co_3 + $\text{La}_2\text{Co}_{1.7}$; **d** 10Fe–30Co–60La (#34), 510 °C, $\times 2000$, $(\alpha\text{Co,Fe})$ + La_3Co + $\text{La}_2\text{Co}_{1.7}$; **e** 10Fe–10Co–80La (#36), 520 °C, $\times 2000$, $(\alpha\text{Co,Fe})$ + La_3Co + (βLa)

Fig. 7 X-ray diffraction patterns of as-cast alloys in La–Co–Fe system: **a** 5Fe–75Co–20La (#7), as-cast, $\text{LaCo}_{13} + \text{LaCo}_5 + \text{La}_5\text{Co}_{19} + \text{La}_2\text{Co}_7 + \text{La}_2\text{Co}_3$; **b** 15Fe–60Co–25La (#50), as-cast, $\text{LaCo}_{13} + \tau + \text{LaCo}_5 + \text{La}_2\text{Co}_3 + \text{La}_2\text{Co}_{1.7}$

((βLa) + ($\alpha\text{Fe,Co}$) + La_3Co) according to the EPMA data of alloys #64 and 67 is 1.4Fe–20.3Co–78.3La (Table 4, Fig. 5l).

The isotherms of the liquidus surface (Fig. 4a) are constructed based on the DTA results (Table 3), and additionally refined via the constructed vertical sections, so that each alloy is involved in at least three sections.

4.2.4 Solidus Projection

Figure 4b shows the solidus surface projection of the Fe–Co–La system in the whole composition range resulting from this research. The solidus surface of this system is characterized by the presence of the following three-phase regions: $\tau + \text{LaCo}_{13} + \text{LaCo}_5$, $\text{La}_5\text{Co}_{19} + \text{LaCo}_5 + \text{La}_2\text{Co}_7$, $\text{La}_2\text{Co}_7 + \tau + \text{La}_2\text{Co}_3$, $\text{LaCo}_5 + \text{La}_2\text{Co}_7 + \tau$, $\tau + (\alpha\text{Co,Fe}) + \text{La}_2\text{Co}_3$, $\text{LaCo}_{13} + \tau + (\alpha\text{Co,Fe})$, $\text{La}_2\text{Co}_3 + \text{La}_2\text{Co}_{1.7} + (\alpha\text{Co,Fe})$, $(\alpha\text{Co,Fe}) + \text{La}_3\text{Co} + \text{La}_2\text{Co}_{1.7}$, $(\alpha\text{Co,Fe}) + \text{La}_3\text{Co} + (\beta\text{La})$, and $(\alpha\text{Co,Fe}) + \text{Co}_{13}\text{La} + (\gamma\text{Co,Fe})$ and the corresponding two-phase regions. The corners of these triangles are plotted using the microprobe results for individual phases (Table 4). The solidus temperatures of the three-phase regions, as measured by DTA (Table 3), are shown in the solidus projection in Fig. 4b.

The existence and position of the very narrow three-phase region $\text{La}_5\text{Co}_{19} + \text{LaCo}_5 + \text{La}_2\text{Co}_7$ with the participation of the $\text{La}_5\text{Co}_{19}$ phase is established based on the SEM and EPMA results for alloy #7 annealed at the solidus temperature (810 °C, 4 h) (Table 3, 4, Fig. 6a). The microstructure of this alloy clearly shows three phases (Fig. 6a): dark, gray, and light gray. These correspond to $\text{La}_5\text{Co}_{19}$, LaCo_5 , and La_2Co_7 , respectively. The heating curve of this alloy shows that the temperature of the corresponding isothermal plane is 818 °C. Therefore, this three-phase region $\text{La}_5\text{Co}_{19} + \text{LaCo}_5 + \text{La}_2\text{Co}_7$ is formed via U-type reaction $\text{L} + \text{La}_5\text{Co}_{19} \rightleftharpoons \text{La}_2\text{Co}_7 + \text{LaCo}_5$ taking place at 818 °C.

The SEM and EMPA results of alloys #45 and 54 annealed at the solidus temperature (660 °C, 2 h) clearly show the three phases La_2Co_7 (dark-gray grains) + τ (gray grains) + La_2Co_3 (light-gray grains) (Fig. 6b). The composition of the solid phases in this equilibrium was measured by the microprobe method (Table 4). The three-phase structure ($\text{La}_2\text{Co}_7 + \tau + \text{La}_2\text{Co}_3$) of these alloys (Fig. 6b) and invariant effects at 673 °C on their heating curves (Table 3) (corresponding to U-type reaction) determine the position and temperature of the relevant three-phase region.

Two very narrow three-phase regions with the participation of the τ phase are also formed on the solidus surface in the Co-rich corner: $\tau + \text{LaCo}_{13} + \text{LaCo}_5$ and $\text{LaCo}_5 + \text{La}_2\text{Co}_7 + \tau$. The boundaries of the three-phase region $\tau + \text{LaCo}_{13} + \text{LaCo}_5$ are established based on the SEM and EPMA data for the two-phase $\text{LaCo}_{13} + \text{LaCo}_5$ alloy #22, annealed at solidus temperature (970 °C, 3 h) and the EPMA data of alloy #2 containing the τ -phase (Table 4). There were no samples corresponding to this three-phase region; however, it should be pointed out that this region is very narrow. Even though there is no experimental evidence concerning the exact position of this region, it cannot differ substantially from that shown in Fig. 4(b). The high content of Co in the τ -phase (79.3 at.% according to EPMA data of alloy #2) leads to the conclusion that alloy #22 lies very close to the associated boundary tie-lines of the $\tau + \text{LaCo}_{13} + \text{LaCo}_5$ three-phase region. The heating curve of this alloy shows that the temperature of the respective isothermal plane is 978 °C (Table 3). The existence of the $\text{LaCo}_5 + \text{La}_2\text{Co}_7 + \tau$ three-phase region is obvious in terms of phase equilibrium rules. Since there are no alloys in this composition range, the vertices of the respective tie-line triangle are shown tentatively. The temperature of this isothermal plane (687 °C) is determined from the heating curve of some as-cast alloys (#45, 47, 49) in which the respective phase region is not in equilibrium.

Table 5 Crystal structure and lattice parameters of La–Fe–Co phases

Phase	Crystal structure	Lattice parameter, Å	Remarks	Ref.
(δFe)	W, <i>cI2-Im-3 m</i>	$a = 2.9315$	at > 1394 °C	[35]
(γFe)	Cu, <i>cF4-Fm-3 m</i>	$a = 3.6467$	at > 912 °C	[35]
(αFe)	W, <i>cI2-Im-3 m</i>	$a = 2.8665$	at 25 °C	[35]
(εFe)	Mg, <i>hP2-P6₃/mmc</i>	$a = 2.468$, $c = 3.96$	at 25 °C, > 13 GPa	[35]
(γLa)	W, <i>cI2-Im-3 m</i>	$a = 4.26$	at > 865 °C	[35]
(βLa)	Cu, <i>cF4-Fm-3 m</i>	$a = 5.303$	at > 310 °C	[35]
(αLa)	αLa, <i>hP4-P6₃/mmc</i>	$a = 3.7740$, $c = 12.171$	at 25 °C	[35]
(αCo)	Cu, <i>cF4-Fm-3 m</i>	$a = 3.5447$	at > 422 °C	[35]
(εCo)	Mg, <i>hP2-P6₃/mmc</i>	$a = 2.5071$, $c = 4.0686$	at 25 °C	[35]
Co ₁₃ La	NaZn ₁₃ , <i>F112-Fm-3c</i>	$a = 11.344(1)$ $a = 11.386(1)$ $a = 11.487(1)$ $a = 11.376(1)$ $a = 11.437(2)$	1000 °C, 3 days 75Co-10Fe-15La, as-cast 55Co-20Fe-25La, as-cast 75Co-5Fe-20La, as-cast 60Co-15Fe-25La, as-cast	[27] Th.w. Th.w. Th.w. Th.w.
Co ₅ La	CaCu ₅ , <i>hP6-P6/mmm</i>	$a = 5.100(5)$, $c = 3.968(5)$ $a = 5.117$, $c = 3.975$ $a = 5.120(1)$, $c = 3.999(1)$ $a = 5.101(3)$, $c = 4.007(1)$	– – 75Co-10Fe-15La, as-cast 75Co-5Fe-20La, as-cast	[27] [36] Th.w. Th.w.
Co ₁₉ La ₅	Ce ₅ Co ₁₉ , <i>hR72-R-3m</i>	$a = 5.123$, $c = 48.74$ $a = 5.130(1)$, $c = 48.82(1)$ $a = 5.141(2)$, $c = 49.50(4)$	– at 1073 K for 10 h 75Co-5Fe-20La, as-cast	[32] [37] Th.w.
βCo ₇ La ₂	Gd ₂ Co ₇ , <i>hR54-R-3m</i>	$a = 5.11(1)$, $c = 36.69(2)$ $a = 5.109$, $c = 36.701$ $a = 5.149(1)$, $c = 36.90(2)$ $a = 5.141(2)$, $c = 36.98(2)$ $a = 5.148(1)$, $c = 36.953(2)$	– – 75Co-10Fe-15La, as-cast 75Co-5Fe-20La, as-cast 60Co-15Fe-25La, as-cast	[27] [36] Th.w. Th.w. Th.w.
αCo ₇ La ₂	Ce ₂ Ni ₇ , <i>hP36-P6₃/mmc</i>	$a = 5.101(5)$, $c = 24.511(8)$ $a = 5.109$, $c = 24.523$	– –	[27] [36]
Co ₃ La ₂	La ₂ Ni ₃ , <i>oS20-Cmca</i>	$a = 10.34(1)$, $b = 4.886(7)$, $c = 7.811(5)$ $a = 10.373(7)$, $b = 4.898(4)$, $c = 7.836(5)$ $a = 10.366(6)$, $b = 4.893(3)$, $c = 7.833(5)$	– 75Co-5Fe-20La, as-cast 60Co-15Fe-25La, as-cast	[27] Th.w. Th.w.
Co _{1.7} La ₂	Co _{1.7} La ₂ , <i>mS8-C2/m</i>	$a = 8.45361(1)$, $b = 4.8807(1)$, $c = 4.2723(2)$ $a = 8.461(1)$, $b = 4.897(1)$, $c = 4.344(4)$	– 60Co-15Fe-25La, as-cast	[38] Th.w.
CoLa ₃	Fe ₃ C, <i>oP16-Pnma</i>	$a = 7.277(9)$, $b = 10.02(1)$, $c = 6.575(8)$	–	[27]
τ, (Co,Fe) ₁₇ La ₂	Th ₂ Zn ₁₇ , <i>R-3m</i>	$a = 8.524$, $c = 12.37$ $a = 8.545(2)$, $c = 12.44(1)$	– 60Co-15Fe-25La, as-cast	[28] Th.w.

Th.w.—result of this work

The τ-phase in addition to the LaCo₁₃, LaCo₅, La₂Co₇, and La₂Co₃ phases is in equilibrium with the (αCo,Fe) phase, forming two more three-phase regions: τ + (αCo,Fe) + La₂Co₃ and LaCo₁₃ + τ + (αCo,Fe). There were no samples corresponding to these three-phase regions; however, it should be pointed out that these regions are very narrow. Even though there is no experimental evidence concerning the exact position of these regions, it cannot differ substantially from that shown in

Fig. 4(b). The position of the vertices of the respective tie-line triangles is determined from the data of neighboring two-phase alloys and the mutual arrangement of the regions of phase homogeneity.

The existence of the three-phase region (αCo,Fe) + La₂Co₃ + La₂Co_{1.7} and its location were established directly, on the basis of the investigation of three-phase samples. The SEM and EMPA results of alloys #59 and #62 annealed at the subsolidus temperature

Table 6 Invariant equilibria in the Fe–Co–La system

Liquid point	Invariant equilibrium	Temperature, °C	Composition of the liquid, at. %		
			Fe	Co	La
E ₁	$L_{E1} \rightleftharpoons La_3Co + (\beta La) + (\alpha Co, Fe)$	527	1.5	20.0	78.5
P ₁	$L_{P1} + LaCo_{13} + LaCo_5 \rightleftharpoons \tau$	978	9.0	64.5	26.5
P ₂	$L_{P2} + LaCo_{13} + (\gamma Co, Fe) \rightleftharpoons (\alpha Co, Fe)$	~ 970	17.5	45.5	37.0
U ₁	$L_{U1} + LaCo_{13} \rightleftharpoons \tau + (\alpha Co, Fe)$	~ 950	16.5	46.5	37.0
U ₂	$L_{U2} + La_5Co_{19} \rightleftharpoons LaCo_5 + La_2Co_7$	818	1.0	51.5	47.5
U ₃	$L_{U3} + LaCo_5 \rightleftharpoons \tau + La_2Co_7$	687	2.0	50.5	47.5
U ₄	$L_{U4} + La_2Co_7 \rightleftharpoons \tau + La_2Co_3$	673	2.0	47.5	50.5
U ₅	$L_{U5} + \tau \rightleftharpoons (\alpha Co, Fe) + La_2Co_3$	645	5.0	41.5	53.5
U ₆	$L_{U6} + La_2Co_3 \rightleftharpoons (\alpha Co, Fe) + La_2Co_{1.7}$	573	2.0	37.0	61.0
U ₇	$L_{U7} + (\alpha Co, Fe) \rightleftharpoons La_3Co + La_2Co_{1.7}$	515	0.5	31.0	68.5

(560 °C, 2 h) clearly show the three phases (Fig. 6c). The dark and gray regions are the $(\alpha Co, Fe)$ and La_2Co_3 phases, respectively. The light-gray regions correspond to $La_2Co_{1.7}$. The compositions of the solid phases in these equilibria were measured by the microprobe method (Table 4). According to the DTA data of these alloys and alloys #8, 31, 58, 65, and 66, the temperature of the respective isothermal plane is 569 °C (Table 3). This three-phase region is formed by the transition-type reaction $L + La_2Co_3 \rightleftharpoons (\alpha Co, Fe) + La_2Co_{1.7}$ at 569 °C.

According to the SEM and EPMA results, the alloy #34, annealed at subsolidus temperature (510 °C), is located in the three-phase region $La_3Co + La_2Co_{1.7} + (\alpha Co, Fe)$. Three phases can be well distinguished in the microstructure of this alloy (Fig. 6d). They were identified as follows: black grains corresponds to $(\alpha Co, Fe)$, gray and light-gray grains correspond to $La_2Co_{1.7}$ and La_3Co , respectively. The heating curves of this alloys, as well as as-cast alloys #1, 15, 16, 18, 20, 29, 34, 35, 37, and 38, show an invariant effect at 515 °C (Table 3). The types of equilibria are confirmed both by the relative positions of the points of liquid and solid phases in equilibria, and by their temperature in comparison with those of incoming and outgoing ones. A three-phase region of the solidus surface $La_3Co + La_2Co_{1.7} + (\alpha Co, Fe)$ results from a four-phase invariant transition-type reaction $L + (\alpha Co, Fe) \rightleftharpoons La_3Co + La_2Co_{1.7}$ at 515 °C, rather than a eutectic type. The arguments for this conclusion are as follows: (1) the solidus temperature of the field $La_3Co + La_2Co_{1.7} + (\alpha Co, Fe)$ is higher than the temperature of the eutectic $L \rightleftharpoons La_3Co + La_2Co_{1.7}$ in the Co–La binary system (DTA analysis of the binary eutectic alloy 69La–31Co indicates the temperature of the eutectic reaction $L \rightleftharpoons La_3Co + La_2Co_{1.7}$ to

be 514 °C); (2) in most alloys, the eutectic ($La_3Co + La_2Co_{1.7}$) was observed. This could not be observed in the alloys if the invariant equilibrium were of the eutectic type $L \rightleftharpoons (\alpha Co, Fe) + La_3Co + La_2Co_{1.7}$. To confirm this experimentally, a comparative thermal analysis, at a very low heating rate of 5 °C/min, was carried out on the ternary alloy #38 and the binary eutectic alloy 69La–31Co. It was observed that the binary alloy began to melt earlier than the ternary alloy. Further DTA tests at a heating rate of 5 K/min revealed that the temperatures of the ternary alloy #38 and binary alloy 69La–31Co were 515 °C and 514 °C, respectively.

There is one additional isothermal plane, $(\alpha Co, Fe) + La_3Co + (\beta La)$, involving the $(\alpha Co, Fe)$ -phase, which forms on the solidus surface. The boundaries of this three-phase region are established based on the SEM and EPMA data for the three-phase region $(\alpha Co, Fe)$ (black grains) + La_3Co (gray grains) + (βLa) (light-gray grains) for alloy #36 annealed at the subsolidus temperature (520 °C, 2 h) (Table 4, Fig. 6e). The heating curve of this alloy, as well as as-cast alloys #39, 63, 64, and 67, shows an invariant effect at 527 °C (Table 3). This three-phase region forms via eutectic-type reaction $L \rightleftharpoons (\alpha Co, Fe) + La_3Co + (\beta La)$ at 527 °C. The eutectic type of this equilibrium is confirmed by the ternary eutectic microstructure $(\alpha Co, Fe) + La_3Co + (\beta La)$ of alloy #37 (Fig. 5l).

4.2.5 Invariant Equilibria

The superposition of the liquidus and solidus surfaces of the Fe–Co–La system in the form of a melting diagram is shown in Fig. 4(c). The three-phase regions of the solidus

Fig. 8 Scheil diagram for solidification of La-Co-Fe alloys

surface are the result of invariant four-phase reactions. Three-phase fields at the solidus surface result from one eutectic $L_{E1} \rightleftharpoons La_3Co + (\beta La) + (\alpha Co, Fe)$, two peritectic $L_{P1} + LaCo_{13} + LaCo_5 \rightleftharpoons \tau$ and $L_{P2} + (\gamma Co, Fe) + Co_{13}La \rightleftharpoons (\alpha Co, Fe)$, and seven U-type four-phase invariant equilibria $L_{U1} + LaCo_{13} \rightleftharpoons (\alpha Co, Fe) + \tau$, $L_{U2} + La_5Co_{19} \rightleftharpoons LaCo_5 + La_2Co_7$, $L_{U3} + LaCo_5 \rightleftharpoons \tau + La_2Co_7$, $L_{U4} + La_2Co_7 \rightleftharpoons \tau + La_2Co_3$, $L_{U5} + \tau \rightleftharpoons (\alpha Co, Fe) + La_2Co_3$, $L_{U6} + La_2Co_3 \rightleftharpoons (\alpha Co, Fe) + La_2Co_{1.7}$, and $L_{U7} + (\alpha Co, Fe) \rightleftharpoons La_3Co + La_2Co_{1.7}$, taking place at 527, 978, ~ 970, ~ 950, 818, 687, 673, 645, 569, and 515 °C, respectively. In the two-phase areas $(\gamma Co, Fe) + LaCo_{13}$ and $(\alpha Co, Fe) + La_3Co$, the solidus

surface has maximum temperatures of ~ 1300 and 540 °C, respectively. All invariant equilibria are summarized in Table 6. Figure 8 shows the Scheil diagram for the solidification of Co-Fe-La alloys.

5 Conclusions

Phase equilibria in the Fe–Co–La system over the whole concentration range during solidification have been studied using DTA, X-ray diffraction analysis, SEM, and electron probe microanalysis. Liquidus and solidus projections, as

well as the melting diagram and a Scheil diagram were constructed for this system.

The ternary compound $(\text{Co,Fe})_{17}\text{La}_2$ (τ) forms by peritectic reaction $\text{L}_{\text{P1}} + \text{LaCo}_{13} + \text{LaCo}_5 \rightleftharpoons \tau$ at 978 °C and has a wide homogeneity range from 45.8 to 79.5 at.% Co at solidus temperature, which is linear and located along the isoconcentrate of ~ 11 at.% La.

The Co_{13}La phase has the widest homogeneity range at solidus temperature and dissolves up to 43.3 at.% Fe.

Acknowledgments The study was supported by Russian Science Foundation project no. 18-73-10219.

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