Phase Equilibria of the Al–Co–Er System at 400°C and 600°C

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Abstract
The 400°C and 600°C isothermal sections of the Al–Co–Er system were studied assisted with X-ray diffraction (XRD), scanning electron microscopy (SEM) and electron probe microanalysis (EPMA) techniques. 18 three-phase fields were identified in the 400°C isothermal section. The maximum solid solubilities of Al in Co3Er and Co2Er were 13.93 at.% and 16.13 at.%, respectively. Whereas the maximum solid solubilities of Co in Al2Er, Al2Er3 and AlEr2 were 6.93 at.%, 6.65 at.% and 6.49 at.%, respectively. And the solid solution range of λ is from 22.22 at.% Al to 44.44 at.% Al. While the 600°C isothermal section included 20 three-phase fields. The maximum solid solubilities of Al in Co17Er2 and Co7Er2 were 10.17 at.% and 10.24 at.%, respectively. Whereas the maximum solid solubilities of Co in Al2Er and Al2Er3 were 3.63 at.% and 2.01 at.%, respectively.

Keywords: Phase Equilibria, Al–Co–Er, Aluminum alloys

1. Introduction
Since Alfred Wilm[1–2] discovered age hardening in 1901, the development of high-strength Al alloys has gained much attention globally. Materials scientists often improve the strength of aluminum alloys by controlling the defects that prevent dislocation movement, however, this reinforcement effect cannot be expanded indefinitely.[3–4]

Recent studies have shown that amorphization is also an effective method for improving the strength of Al alloy materials.[5–7] A bulk aluminum alloy with a record-high yield strength of 1.7GPa and Young's modulus of 120GPa has been designed based on the absence of grain boundaries and dislocations in the amorphous structure.[8] Therefore, the development of Al alloys with good amorphous-forming ability has become the key to designing high-strength Al alloys. However, the practical application of Al-based amorphous alloys has been greatly limited by the low glass-forming ability (GFA) of the alloys. In recent years, Al–TM–RE (TM: transition metals, RE: rare-earth elements) alloy systems,[9–10], which mainly includes Al-Cu-RE, Al-Co-RE, Al-Ni-RE, and Al-Fe-RE, have become a research focus owing to their good GFA and wide amorphous-forming range.[11–12]

Reliable phase diagram information of the Al–TM–RE-related systems is indispensable for establishing accurate phase-diagram thermodynamic databases; these databases can in turn be used to predict the thermal stability of nanostructures and the GFA for the design and fabrication of these intermetallic alloys.[13–16]

The phase diagrams of the three binary systems Al-Co, Al-Er, and Co-Er have been investigated in the literature. In 1902, Guillet[17] studied the Al–Co phase diagram for the first time. Subsequently, Gwyer[18], Panteleimonov[19], and McAister[20] successively studied the Al–Co system and established the thermodynamic database. In 2013, Stein et al.[21] systematically analyzed the previous work and reevaluated the Al–Co binary system phase diagram based on the work by Dupin and Ansara[22] on the controversies about the Al–Co system. There are few studies on the Al–Er phase diagram, mainly based on the works by Buschow[23] in 1965 and Cacciamani[24] in 2002. In 1971, Buschow et al.[25] first studied the Co–Er binary system. In 1993, Okamoto and Massalski[26] recalculated and constructed the phase diagram of the Co–Er binary system according to the
crystallographic data provided in Pearson’s Handbook. In 1993, Wu et al.\textsuperscript{[27]} reevaluated the phase diagram of the Co–Er binary system evaluated by Okamoto and Massalski\textsuperscript{[28]} . In 2009, Wang et al.\textsuperscript{[29]} thermodynamically assessed the Co–Er binary system on the basis of the experimental data on the thermodynamic properties and phase equilibria. The authors found that the calculated results agreed with the experimental data.

Crystal structures of phases in the Al–Co–Er ternary system are listed in Table 1,\textsuperscript{[20, 30–35]} however, the experimental phase-equilibrium information on the Al–Co–Er system is still lacking\textsuperscript{[36–45]}, and further experiments are needed to support thermodynamic optimization calculations. Therefore, in the current study, the phase equilibria at 400°C and 600°C in the Al–Co–Er system were investigated via scanning electron microscopy (SEM), electron probe microanalysis (EPMA), and X-ray diffraction (XRD).

| Phase          | Structure type | Space group | SG No. | Lattice parameters/Å | β   | γ   | Ref. |
|----------------|----------------|-------------|--------|----------------------|-----|-----|------|
| λ-AlCo₂Er₃    | MgZn₂          | P6₃/mmc     | 194    | 5.399 8.599           | 120°|      | [29] |
| λ-AlCoEr      | MgZn₂          | P6₃/mmc     | 194    | 5.299 8.475           | 120°|      | [30] |
| Al₁₃Co₅Er₃₄  | Cu₂Mg          | Fd-3m       | 227    | 7.380               |      |      | [29] |
| AlCo₂Er₂     | Cu₂Mg          | Fd-3m       | 227    | 7.272               |      |      | [31] |
| τ₂-AlCo₂Er₂  | AlCo₂₃Y₂       | Cmcm        | 63     | 12.738 7.509 9.378   |      |      | [32] |
| τ₅-AlCo₂Er₂  | W₂CoB₂         | Immm        | 71     | 4.042 5.436 8.327    |      |      | [33] |
| t₂-AlCo₂Er₂  | Cu₂Mg          | Fd-3m       | 227    | 7.681               |      |      | [31] |
| α-Co         | Cu             | Fd-3m       | 227    | 3.563               |      |      | [29] |
| e-Co         | Mg             | P6₃/mmc     | 194    | 2.506 4.069          |      |      | [29] |
| Al₄Co₂      | Al₃Co₂         | P2₁/a       | 14     | 8.565 6.290 6.213    | 94.76°|      | [34] |
| Al₁₃Co₄    | Al₁₂Co₄        | Cm           | 8      | 15.183 8.122 12.340 107.90°|      |      | [29] |
| Al₂₃Co₄    | Al₁₃Co₄        | Pmn₂₁       | 31     | 8.158 12.342 14.452  |      |      | [29] |
| Al₃Co      | T₂-Al₁₃Co₄     |              |        | 12.5 8.1 14.6       |      |      | [29] |
| Al₂Co₂      | Al₂Co₂         | P6₃/mmc     | 194    | 7.656 7.593          |      |      | [29] |
| AlCo        | CsCl           | Pm-3m       | 221    | 2.863               |      |      | [29] |
| Al₁₃Al₁₃₃   | Cu             | Fm-3m       | 227    | 3.568               |      |      | [29] |
| Al₁₃Er      | Cu₃Au          | Pm-3m       | 221    | 4.215               |      |      | [29] |
| Al₁₂Er     | Cu₂Mg          | Fm-3m       | 227    | 7.775               |      |      | [29] |
| AlEr        | Al₃Dy          | Pbcm        | 57     | 5.801 11.272 5.570   |      |      | [29] |
| Al₂Er₃     | Al₂Gd₃         | P₄₁mm       | 102    | 8.123 7.484         | 120°|      | [29] |
| Al₂Er₃     | SiCo₃          | Pnma        | 62     | 6.516 5.015 9.279   |      |      | [29] |
| CoEr₃      | CFe₃           | Pnma        | 62     | 6.902 9.191 6.189   |      |      | [29] |
| Co₇Er₁₂    | Co₂Ho₁₂        | P₂₁/c       | 14     | 8.305 11.165 13.825 138.7°| 120°|      | [29] |
| Co₃Er₄    | Co₂Ho₄         | P6₃/m       | 176    | 11.32 3.967         |      |      | [20] |
| Co₂Er      | Cu₂Mg          | Fd-3m       | 227    | 7.155               | 120°|      | [29] |
| Co₂Er      | Be₃Nb          | R-3m        | 166    | 4.978 24.258        | 120°|      | [29] |
| Co₂Er₂    | Co₂Er₂         | R-3m        | 166    | 4.973 36.111        | 120°|      | [29] |
| Co₇Er     | Cu₃Ca          | P6₃/mmc     | 191    | 4.870 4.002         | 120°|      | [29] |
| Co₁₇Er₂   | Ni₁₇Th₂        | P6₃/mmc     | 194    | 8.313 8.131         | 120°|      | [29] |

2. Experimental
More than 70 alloy samples were prepared for the determination of the isothermal sections of the Al–Co–Er ternary system at 400°C and 600°C. The raw materials, Al, Co, and Er (99.99% purity), supplied by China Materials Technology Co., Ltd., were smelted to obtain the experimental alloy samples. The weight of each sample was about 6 g. The composition of each sample was designed based on the existing phase diagram information, and the amount of each starting material was obtained by weighing with an analytical balance. The samples were arc-smelted in a vacuum consumable electrode arc furnace under an argon atmosphere in a water-cooled copper crucible, and the alloyed samples were smelted together with Ti as an oxygen getter to prevent oxidation during smelting. To ensure the uniformity of the samples, each button sample was turned and remelted at least three times during smelting, with the weight loss not exceeding 1%. The obtained button alloy samples were sealed in silica capsules backfilled with high-purity argon to resist oxidation and then annealed in a tube furnace at 400°C for 2880 hours and 600°C for 2160 hours. Afterward, the alloy samples were immediately immersed in ice water to quench and cool to room temperature.

The microstructures of these alloy samples were investigated via EPMA (JEOL JXA-8530F) after the samples were polished. The total mass of all the elements in each phase ranged from 97% to 103%, and the standard deviation of the measured concentration was ± 0.5 at.%. The phases in the alloy samples were identified using a Rigaku D-max/2500 X-ray diffractometer operated at 40 kV and 200 mA. The phase-identification results were analyzed using the Jade 6.0 program, and the diffraction patterns were obtained.

3. Results and Discussion

3.1. Isothermal Section at 400°C

Table 2 Equilibrium compositions at 400°C measured with EPMA method

| No. | Alloy/at.% | Phase equilibrium | Phase composition/at.% |
|-----|------------|-------------------|------------------------|
|     | Al | Co | Er | Phase 1/Phase 2/Phase 3 | Phase 1 | Phase 2 | Phase 3 |
|     |    |    |    | Al | Co |     | Al | Co |     |
| #A1 | 70 | 20 | 10 | Al19Co6Er2/Al13Co2/Al1Co  | 70.78 | 22.31 | 71.51 | 28.30 | 74.64 | 25.20 |
| #A2 | 85 | 5  | 10 | Al/Al13Er/Al13Co2 | 99.79 | 0.10 | 74.80 | 1.94 | 82.45 | 17.22 |
| #A3 | 77.5 | 20 | 2.5 | Al6Co2/Al13Co6Er2/Al1Er | 82.45 | 17.06 | 71.81 | 20.99 | 74.03 | 3.42 |
| #A4 | 55 | 5  | 40 | Al6Er/Al13Er/AlEr | 61.17 | 6.93 | 35.02 | 6.65 | 48.40 | 4.43 |
| #A5 | 72.5 | 25 | 2.5 | Al6Co2/Al13Co/Al1CoEr | 71.95 | 27.78 | 52.20 | 47.05 | 64.13 | 21.96 |
| #A6 | 50 | 30 | 20 | AlCo/Al12Co3Er3/Er | 50.17 | 49.28 | 54.12 | 29.90 | 44.71 | 23.94 |
| #A7 | 62.5 | 20 | 17.5 | Al6Co2Er/Al13Co2/Al2Er | 66.56 | 19.30 | 74.09 | 3.10 | 67.72 | 1.43 |
| #A8 | 65 | 30 | 5  | Al6Co2/Al13Co/Al1CoEr2 | 71.68 | 27.80 | 52.99 | 46.67 | 64.09 | 22.41 |
| #A9 | 55 | 30 | 15 | AlCo/Al12Co3Er3/Er | 50.31 | 49.07 | 56.28 | 28.34 | 44.36 | 23.68 |
| #A10| 70 | 25 | 5  | Al13Er/Al19Co6Er/Al1Co2 | 74.45 | 4.15 | 71.30 | 21.56 | 80.91 | 14.59 |
| #A11| 55 | 5  | 40 | Al6Er/Al12Co3Er3/Al2Er | 63.72 | 5.32 | 62.51 | 21.99 | 57.34 | 22.36 |
| #A12| 70 | 15 | 15 | Al13Er/Al19Co6Er/Al1CoEr2 | 74.79 | 2.21 | 72.33 | 20.42 | 65.61 | 20.78 |
| #A13| 60 | 10 | 30 | Al2Er/Al13Co3Er3/Al2Er | 63.22 | 4.89 | 61.94 | 22.00 | 54.62 | 24.58 |
| #A14| 75 | 15 | 10 | Al6Co2/Al19Co6Er3/Al1Co4 | 82.26 | 17.35 | 71.74 | 21.30 | 76.37 | 23.15 |
| #A15| 45 | 40 | 15 | Al6Co2Er/Al19Co6Er3/Al1Co2 | 64.20 | 22.08 | 71.06 | 21.62 | 71.97 | 27.56 |
| #A16| 70 | 5  | 25 | Al6Er/Al19Co6Er3/Al1CoEr2 | 74.02 | 3.28 | 72.34 | 20.98 | 65.76 | 20.78 |
| #A17| 75 | 20 | 5  | Al6Co2/Al19Co6Er3/Al1Co4 | 82.05 | 17.69 | 71.15 | 21.87 | 76.04 | 23.82 |
| #A18| 60 | 25 | 15 | AlCo/Al19Co6Er3 | 52.15 | 47.09 | 56.53 | 23.62 | 64.58 | 21.37 |
According to Fig. 9D, the alloy #A30, which features Al and Al
either in Fig. 3(h). Meanwhile, alloy #A27 was located in the
AlCo/Er and AlCo/Er phase microstructure of alloy #A12, and the XRD result is presented in Fig. 2(f). The
alloy #A30, which features a three-phase area of Co3Er+AlCo2Er+AlCo that agrees with the XRD result in Fig. 3(h). Alloy #A32 showed the same result as alloy #A30.

| #A19 | 75 | 22.5 | 2.5 | Al_{19}Er/Al_{19}Co_{9}Er_{2}/Al_{9}Co_{2} | 72.04 | 5.19 | 70.36 | 21.28 | 81.10 | 13.43 |
| #A20 | 55 | 5 | 40 | Co_{2}Er/AlCo_{2}Er | 16.13 | 51.25 | 21.45 | 44.56 | 25.54 | 47.28 |
| #A21 | 35 | 5 | 60 | AlCo/Er | 45.74 | 15.18 | 17.61 | 16.39 | 29.42 | 6.49 |
| #A22 | 40 | 35 | 25 | AlCo/Er | 50.81 | 47.61 | 43.72 | 26.70 |
| #A23 | 20 | 75 | 5 | AlCo/Er | 5.52 | 15.16 | 15.50 | 19.48 | 15.94 | 33.58 |
| #A24 | 50 | 30 | 20 | AlCo/Er | 60.09 | 32.47 | 45.23 | 22.12 |
| #A25 | 20 | 10 | 70 | AlCo/Er | 45.74 | 18.51 | 34.97 | 4.31 | 30.12 | 6.37 |
| #A26 | 30 | 60 | 10 | AlCo/Er | 16.78 | 29.21 | 36.99 | 22.70 | 15.75 | 20.81 |
| #A27 | 20 | 60 | 20 | Er/AlCo/Er | 54.15 | 9.66 | 33.24 | 3.98 | 0.00 | 5.82 |
| #A28 | 35 | 5 | 60 | AlCo/Er | 27.25 | 45.15 | 33.29 | 4.22 |
| #A29 | 25 | 30 | 45 | AlCo/Er | 12.03 | 11.11 | 33.18 | 4.39 | 25.94 | 29.44 |
| #A30 | 25 | 65 | 10 | Co_{5}Er/AlCo_{2}Er/AlCo | 10.36 | 65.35 | 30.89 | 52.92 | 49.72 | 50.02 |
| #A31 | 40 | 35 | 25 | AlCo/Er | 50.96 | 40.68 | 30.93 | 44.82 | 26.32 | 48.20 |
| #A32 | 40 | 50 | 10 | Co_{3}Er/AlCo_{2}Er/AlCo | 51.44 | 40.89 | 26.82 | 48.66 | 13.93 | 61.72 |
| #A33 | 22.5 | 47.5 | 30 | AlCo_{2}Er | 23.03 | 30.95 | 22.78 | 39.48 |
| #A34 | 20 | 75 | 5 | AlCo/Er | 21.26 | 56.88 | 46.32 | 43.42 |
| #A35 | 40 | 40 | 20 | AlCo/Er | 44.76 | 47.56 | 30.56 | 30.26 |

The nominal chemical compositions of 35 alloy samples and the chemical compositions of each individual phase at 400°C obtained via EPMA are summarized in Table 2.

Figures 1(a) and 1(b) display the microstructure and phase composition of alloy #A1, respectively; the alloy contained AlCo (dark phase), AlCo2Er (bright phase), and AlCo2 (gray phase). Figure 1(c) shows the microstructure of alloy #A2, which contained Al3Er (light gray phase), AlCo2 (gray phase), and Al (dark phase), based on the XRD result in Fig. 1(d). According to Fig. 1(e, f), alloy #A4 was located in a three-phase equilibrium field: Al2Er+Al2Er3+AlEr, while alloy #A5 was located in another three-phase area: Al2Co3+AlCo+Al3Co2Er, based on the EPMA and XRD results shown in Fig. 1(g, h). Meanwhile, alloy #A8 was in the same area as alloy #A5.

As shown in Fig. 2(a), alloy #A7 comprised AlCo3Er2 (dark-gray phase), Al3Er (light-gray phase), and Al2Er (the brightest phase). From the microstructure results and XRD pattern analyses, it can be judged that the alloys #A3, #A10, and #A19 were located in the same three-phase equilibrium field: Al3Er+AlCo3Er2+AlCo2 (Fig. 2c). Figure 2(e) shows the three-phase microstructure of Al3Er+AlCo3Er2+AlCo3Er2 of alloy #A12, and the XRD result is presented in Fig. 2(f). Alloys #A14 and #A17 also contained the same three phases: Al3Co4+Al19Co18Er2+AlCo2 (Fig. 2g).

Alloy #A15 was composed of AlCo3Er2, Al19Co6Er2, and AlCo2 (Fig. 3a). The existence of the three-phase field Al3Co3Er14+AlCo2Er6+AlCo2Er2 and its location were also established based on the EPMA and XRD data of alloy #A23 (Fig. 3c and d). Meanwhile, alloy #A27 was located in the Al3Co3Er14+AlEr3+Er three-phase area (Fig. 3e). Figure 3(g) displays the EPMA micrograph of alloy #A30, which features a three-phase area of Co3Er+AlCo2Er+AlCo that agrees with the XRD result in Fig. 3(h). Alloy #A32 showed the same result as alloy #A30.
Figure 1: EPMA images and XRD results of 400°C-annealed alloys containing three phases after quenching: (a) microstructure of alloy #A1; (b) XRD result of alloy #A1; (c) microstructure of alloy #A2; (d) XRD result of alloy #A2; (e) microstructure of alloy #A4; (f) XRD result of alloy #A4; (g) microstructure of alloy #A5; (h) XRD result of alloy #A5.

Figure 2: EPMA images and XRD results of 400°C-annealed alloys containing three phases after quenching: (a) microstructure of alloy #A7; (b) XRD result of alloy #A7; (c) microstructure of alloy #A10; (d) XRD result of alloy #A10; (e) microstructure of alloy #A12; (f) XRD result of alloy #A12; (g) microstructure of alloy #A14; (h) XRD result of alloy #A14.

Figure 3: EPMA images and XRD results of 400°C-annealed alloys containing three phases after quenching: (a) microstructure of alloy #A15; (b) XRD result of alloy #A15; (c) microstructure of alloy #A23; (d) XRD result of alloy #A23; (e) microstructure of alloy #A27; (f) XRD result of alloy #A27; (g) microstructure of alloy #A30; (h) XRD result of alloy #A30.
Figure 4 EPMA images and XRD results of 400°C-annealed alloys containing three phases after quenching: (a) microstructure of alloy #A6; (b) XRD result of alloy #A6; (c) microstructure of alloy #A31; (d) XRD result of alloy #A31

Figure 4(a) shows the microstructure of alloy #A6, which is comprised of AlCo (dark phase), Al$_{12}$Co$_4$Er$_3$ (gray phase), and $\lambda$ (bright phase). The same result was obtained for alloys #A9 and #A18. Among the three phases, phase $\lambda$ was confirmed to be a solid solution including AlCoEr and Al$_3$Co$_2$Er$_3$, and it also existed in alloys #A31 (Fig. 4c), #A20 (Fig. 5a), #A21 (Fig. 5c), #A25 (Fig. 5e), and #A26 (Fig. 5g). As presented in Fig. 4(c, d) and Fig. 5, these five alloy samples exhibited the following three-phase fields: AlCo+$\lambda$+AlCoEr, Co$_2$Er+$\lambda$+AlCoEr, $\lambda$+Al$_3$Co$_3$Er$_{14}$+AlEr$_2$, $\lambda$+AlEr$_2$+Al$_2$Er$_3$, and AlCo$_2$Er$_2$+$\lambda$+Al$_3$Co$_3$Er$_{14}$, respectively.

Figure 5 EPMA images and XRD results of 400°C-annealed alloys containing three phases after quenching: (a) microstructure of alloy #A20; (b) XRD result of alloy #A20; (c) microstructure of alloy #A21; (d) XRD result of alloy #A21; (e) microstructure of alloy #A25; (f) XRD result of alloy #A25; (g) microstructure of alloy #A26; (h) XRD result of alloy #A26

Figure 6 shows the EPMA micrographs and XRD patterns of alloys #A22, #A28, and #A33, which featured the following two-phase equilibrium fields: AlCo+$\lambda$, Al$_2$Er$_3$+$\lambda$, and AlCo$_2$Er$_2$+$\lambda$, respectively. Phase $\lambda$ occurred in the three fields, as confirmed by the occurrence of solid solubility. Likewise, Fig. 7 presents the experimental results of other two-phase fields: Al$_2$Er+Al$_{12}$Co$_4$Er$_3$, AlEr$_2$+Al$_3$Co$_3$Er$_{14}$, and AlCo$_2$Er+AlCo.
According to the EPMA data and XRD patterns in Table 2, the isothermal section of the Al–Co–Er ternary system at 400°C was established (Fig. 8). As shown in Fig. 8, eight ternary intermediate compounds were detected in the Al–Co–Er system at 400°C: Al₁₀Co₉Er₂, Al₇Co₃Er₂, Al₁₂Co₁₃Er₃, λ (solid solution including AlCoEr and Al₄Co₂Er₃), AlCo₂Er, AlCo₂Er₂, AlCo₂Er₆, and Al₃Co₂Er₁₄. Five of these ternary intermediate compounds (Al₁₀Co₉Er₂, Al₁₂Co₁₃Er₃, AlCo₂Er, AlCo₂Er₂, and Al₃Co₂Er₁₄) have not been previously reported. Although alloy samples of pure ternary intermediate compounds were not obtained, their existence can be proved by combining the EPMA data with the XRD results. The maximum solid solubilities of Al in Co₃Er and Co₂Er were 13.93 at.% and 16.13 at.%, respectively, whereas those of Co in Al₂Er, Al₂Er₃, and AlEr₂ were 6.93 at.%, 6.65 at.%, and 6.49 at.%, respectively. The solubility range of AlCo was from 46.32 at.% Al to 52.15 at.% Al, and the solid solution range of λ was from 22.22 at.% Al to 44.44 at.% Al.

From the data analysis above, 18 three-phase equilibrium regions and 6 two-phase equilibrium regions were detected in the isothermal section of the Al-Co-Er system at 400°C: (Al)+Al₃Er+Al₃Co₂, Al₃Er+Al₂Er₃+Al₃Co, Al₁₉Co₉Er₂+Al₃Co₂+Al₃Co, Al₃Er+Al₁₀Co₆Er₂+Al₃Co₂, Al₃Co₂+Al₁₀Co₆Er₂+Al₁₃Co₄, Al₃Co₂+AlCo+Al₃Co₂Er₂, Al₅Co₂Er₂+Al₃Er+Al₂Er, Al₁₉Co₉Er₂+Al₃Co₂Er₂, Al₁₅Co₉Er₂+Al₂Er, Al₂Er₂+Al₃Co₂Er₁₄, Co₃Er+AlCo₂Er +AlCo, AlCo+Al₁₃Co₁₇Er₃+λ, AlCo+λ+AlCo₂Er, Co₂Er+λ+AlCo₂Er, Al₁₃Co₁₇Er₁₄+AlEr₂, λ+Al₂Er₂+AlEr₂, Al₁₅Co₉Er₂+Al₂Er₂+λ+Al₃Co₁₇Er₁₄, AlCo+λ, Al₂Er₂+λ, AlCo₂Er₂+λ, Al₂Er₂+Al₁₃Co₁₇Er₃, AlEr₂+Al₃Co₁₇Er₁₄, AlCo₂Er+AlCo. Then, according to the determination of the phase equilibrium relationships, six undetected phase regions were obtained by prediction (shown by dashed lines in Fig. 8).
3.2. Isothermal Section at 600°C

According to the EPMA data and XRD patterns in Table 3, the isothermal section of the Al–Co–Er ternary system at 600°C was established (Fig. 13).

According to the data from Table 3, the isothermal sections of Al–Co–Er system at 400°C and 600°C had 9 three-phase fields in common: (Al)+Al13Er+Al9Co2, Al2Er+Al2Er3+AlEr, Al3Er+Al19Co6Er2+Al9Co2, Al9Co2+Al19Co6Er2+Al13Co4, Al3Co2+AlCo+Al9Co3Er2, Al9Co2Er2+Al3Er+Al2Er, Al3Er+Al19Co6Er2+Al9Co3Er2, Al9Co3Er2+Al19Co6Er2+Al3Co2, and AlCo+Al12Co4Er3+λ.

Table 3 Equilibrium compositions at 600°C measured with EPMA method

| No. | No. | Co | Er | Phase equilibrium | Phase composition/ at.% |
|-----|-----|----|----|-------------------|-------------------------|
|     |     |    |    |                   | Phase 1       | Phase 2       | Phase 3       |
|     |     |    |    |                   | Al | Co | Er | Al | Co | Er | Al | Co |
| #B1 | 85  | 5  | 10 | Al/Al9Co2/Al1Er   | 99.76 | 0.17 | 82.59 | 17.41 | 76.73 | 1.34 |
| #B2 | 77.5| 20 | 2.5| Al9Co2/Al13Co/Al19Co6Er2 | 81.31 | 18.60 | 76.05 | 22.98 | 70.87 | 22.21 |
| #B3 | 75  | 15 | 10 | Al19Co2/Al13Co6Er/Al1Er | 81.95 | 18.05 | 70.59 | 22.41 | 75.15 | 4.02  |
| #B4 | 75  | 20 | 5  | Al9Co2/Al19Co6Er2/Al1Er | 81.66 | 17.99 | 72.43 | 22.23 | 74.33 | 3.34  |
| #B5 | 75  | 22.5| 2.5| Al19Co6Er2/Al9Co3/Al1Co | 72.70 | 21.10 | 81.75 | 18.25 | 75.62 | 24.38 |
| #B6 | 72.5| 25 | 2.5| Al9Co2/AlCo/Al2Co3Er2 | 71.20 | 28.72 | 52.64 | 47.36 | 64.24 | 22.77 |
| #B7 | 72.5| 22.5| 5  | Al9Co2/Al19Co6Er2 | 71.39 | 27.14 | 70.59 | 22.56 |       |       |
| #B8 | 70  | 25 | 5  | Al9Co2/Al19Co6Er2/Al9Co3Er2 | 71.25 | 28.58 | 70.99 | 22.28 | 64.50 | 21.81 |
| #B9 | 70  | 20 | 10 | Al19Co6Er2/Al9Co3Er2/Al3Er | 70.86 | 21.67 | 64.43 | 21.61 | 75.02 | 2.00  |
| #B10| 70  | 15 | 15 | Al19Co6Er2/Al9Co3Er2/Al3Er | 71.53 | 21.50 | 64.26 | 21.60 | 74.85 | 1.97  |
| #B11| 70  | 10 | 20 | Al9Co6Er2/Al9Co3Er2/Al3Er | 72.86 | 19.89 | 65.50 | 20.76 | 75.54 | 1.79  |
| #B12| 70  | 5  | 25 | Al9Co6Er2/Al9Co3Er2/Al3Er | 65.99 | 20.05 | 75.40 | 2.28  | 71.43 | 20.88 |
| #B13| 65  | 30 | 5  | Al9Co6Er2/Al9Co3Er2/Al3Er | 69.24 | 30.13 | 50.94 | 47.78 | 63.46 | 22.65 |
Furthermore, the EPMA micrographs and XRD patterns of alloys #B5, #B14 and #B17 (Fig. 9) featured the following three-phase fields: Al\(_{12}\)Co\(_3\)Er\(_2\)/Al\(_5\)Co\(_2\)+Al\(_3\)Co, Al\(_{12}\)Co\(_3\)Er\(_3\)/Al\(_5\)Co\(_2\)Er\(_2\)+ Al\(_3\)Er, and Al\(_{12}\)Co\(_3\)Er\(_3\)/Al\(_5\)Co\(_2\)Er\(_2\)+ AlCo, respectively.

Alloys #B21 and #B24 were respectively located in the following adjacent three-phase equilibrium fields: AlCo\(_2\)Er\(_5\)+AlCo\(_2\)Er\(_2\)+Al\(_5\)Co\(_4\)Er\(_11\), and AlCo\(_2\)Er\(_2\)+Al\(_5\)Co\(_4\)Er\(_11\)+\(\lambda\) (Fig. 10), with both alloys containing two same phases: AlCo\(_2\)Er\(_2\) and Al\(_5\)Co\(_4\)Er\(_11\). Phase Al\(_5\)Co\(_4\)Er\(_11\) has not yet been reported in the literature; thus, the exact atomic ratio and the lattice parameters of the phase need further study.
Figure 9 EPMA images and XRD results of 600°C-annealed alloys containing two phases after quenching: (a) microstructure of alloy #B5; (b) XRD result of alloy #B5; (c) microstructure of alloy #B14; (d) XRD result of alloy #B14; (e) microstructure of alloy #B17; (f) XRD result of alloy #B17

Figure 10 EPMA images and XRD results of 600°C-annealed alloys containing two phases after quenching: (a) microstructure of alloy #B21; (b) XRD result of alloy #B21; (c) microstructure of alloy #B24; (d) XRD result of alloy #B24
As shown in Fig. 11(a, c, e), one distinct three-phase field occurred in each of alloys #B25, #B27, and #B30. According to the XRD pattern analysis (Fig. 11b, d, f), alloys #B25 and #B27 were located in the following three-phase fields: Al$_2$Er$_3$+Al$_3$Co$_2$Er$_{14}$+λ and Al$_2$Er$_3$+Al$_5$Co$_3$Er$_{14}$+Al$_3$CoEr$_2$, respectively. Because of the tiny spot of the dark phase in alloy #B30, the third phase could not be confirmed, however, according to the peripheral phase regions and phase law, #B30 is assumed to be in the three-phase field Al$_2$Er$_3$+Al$_5$Co$_3$Er$_{14}$+AlCoEr$_2$.

Figure 12(a) shows the three-phase microstructures of AlCo+Co$_7$Er$_2$+Co$_2$Er$_2$ of alloy #B22, and the XRD result is shown in Fig. 12(b). According to the SEM, EPMA, and XRD data of alloys #B28 (Fig. 12c, d) and #B34 (Fig. 12e, f), the alloys were respectively located in the AlCo+Co$_7$Er$_2$+Co$_2$Er and AlCo$_2$Er+AlCo+Co$_3$Er three-phase fields.

Based on the above analysis and the EPMA data in Table 3, the isothermal section of the Al–Co–Er ternary system at 600°C was established (Fig. 13). As shown in Fig. 13, 10 ternary intermediate compounds were detected in the Al–Co–Er system at 600°C: Al$_{10}$Co$_8$Er$_2$, Al$_9$Co$_3$Er$_2$, Al$_{12}$Co$_4$Er$_3$, λ (a solid solution including AlCoEr and Al$_4$Co$_2$Er$_3$), AlCo$_2$Er, Al$_5$Co$_3$Er$_2$, AlCo$_2$Er$_2$, AlCo$_2$Er$_6$, Al$_3$Co$_3$Er$_{14}$, and Al$_5$Co$_4$Er$_{11}$. Six of these compounds (Al$_{19}$Co$_8$Er$_2$, Al$_{12}$Co$_4$Er$_3$, AlCo$_2$Er, AlCo$_2$Er$_2$, AlCo$_2$Er$_6$, Al$_3$Co$_3$Er$_{14}$, and Al$_5$Co$_4$Er$_{11}$) have not been previously reported. The maximum solid solubilities of Al in Co$_7$Er$_2$ and Co$_2$Er$_2$ were 10.17 at.% and 10.24 at.%, respectively. Whereas those of Co in Al$_2$Er and Al$_5$Co$_3$Er$_2$ were 3.63 at.% and 2.01 at.%, respectively. Moreover, the solubility range of AlCo was from 44.76 at.% Al to 50.94 at.% Al.

Through the analysis of 34 equilibrium alloy samples, 20 three-phase equilibrium fields and 6 two-phase equilibrium fields were determined: (Al)+Al$_3$Er+Al$_5$Co$_2$, Al$_2$Er+Al$_5$Co$_3$Er+Al$_3$Er, Al$_5$Co$_2$+Al$_{10}$Co$_8$Er$_2$+Al$_3$Co$_4$, Al$_5$Co$_2$+AlCo$_2$+Al$_5$Co$_3$Er$_2$,
Al$_5$Co$_3$Er$_2$+Al$_3$Er+Al$_2$Er, Al$_3$Er+Al$_9$Co$_6$Er$_2$+Al$_6$Co$_3$Er$_2$, Al$_8$Co$_5$Er$_2$+Al$_9$Co$_6$Er$_2$+Al$_5$Co$_2$, AlCo+Al$_2$Co$_4$Er$_3$+λ, Al$_9$Co$_2$Er$_2$+Al$_2$Co$_4$Er$_3$+AlCo, Al$_6$Co$_3$Er$_2$+Al$_2$Co$_4$Er$_3$+Al$_2$Er, Al$_3$Co+Al$_9$Co$_6$Er$_2$+Al$_6$Co$_2$, AlCo$_2$Er$_2$+AlCo$_2$Er$_6$+ Al$_6$Co$_4$Er$_1$, AlCo+Co$_1$Er$_2$+Co$_2$Er$_2$, λ+AlCo$_2$Er$_2$+ Al$_5$Co$_2$Er$_1$, λ+Al$_2$Er+Al$_2$Co$_4$Er$_1$, AlCo$_3$λ+λ+Al$_3$Co$_2$Er$_2$, AlCo+Co$_1$Er$_2$+Co$_3$Er$_2$, Al$_3$Er+Al$_2$Co$_4$Er$_1$+Al$_2$Er, AlCo+AlCo$_2$Er$_2$+λ, Al$_5$Co$_2$+Al$_9$Co$_6$Er$_2$, Al$_1$Co$_2$Er$_3$+Al$_2$Er, Al$_2$Er+Al$_2$Er, AlCo+Co$_1$Er$_2$, Co$_1$Er$_2$+Co$_2$Er$_2$, λ+AlCo. Then, according to the extrapolation of the three binary optimized phase diagrams and the actual determination of the phase equilibrium relationship, the undetected phase fields were obtained by prediction (shown by dashed lines in Fig. 13).

![Diagram](image)

**Figure 13** Isothermal section of Al–Co–Er system at 600°C

4 Conclusions

The isothermal sections of the Al–Co–Er ternary system at 400°C and 600°C were determined via EPMA and XRD. Eight ternary intermediate compounds were detected in the Al–Co–Er system at 400°C, which included five ternary intermediate compounds that have not been reported in the literature (Al$_1$Co$_6$Er$_2$, Al$_2$Co$_4$Er$_3$, AlCo$_2$Er$_2$, AlCo$_2$Er$_6$, and Al$_3$Co$_3$Er$_1$). Furthermore, 18 three-phase equilibrium regions and 6 two-phase equilibrium regions were detected in the isothermal section of the Al–Co–Er system at 400°C. Ten ternary intermediate compounds were detected in the Al–Co–Er system at 600°C, among which six have not been reported in the literature (Al$_1$Co$_6$Er$_2$, Al$_2$Co$_4$Er$_3$, AlCo$_2$Er$_2$, AlCo$_2$Er$_6$, Al$_3$Co$_3$Er$_1$, and Al$_3$Co$_3$Er$_2$). In addition, 20 three-phase equilibrium fields and 6 two-phase equilibrium fields were determined in the isothermal section of the Al–Co–Er system at 600°C. The solution range of the solid solution phase λ was confirmed to be from 22.22 at.% Al to 44.44 at.% Al.

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Figures captions

Figure 1 EPMA images and XRD results of 400°C-annealed alloys containing three phases after quenching: (a) microstructure of alloy #A1; (b) XRD result of alloy #A1; (c) microstructure of alloy #A2; (d) XRD result of alloy #A2; (e) microstructure of alloy #A4; (f) XRD result of alloy #A4; (g) microstructure of alloy #A5; (h) XRD result of alloy #A5

Figure 2 EPMA images and XRD results of 400°C-annealed alloys containing three phases after quenching: (a) microstructure of alloy #A7; (b) XRD result of alloy #A7; (c) microstructure of alloy #A10; (d) XRD result of alloy #A10; (e) microstructure of alloy #A12; (f) XRD result of alloy #A12; (g) microstructure of alloy #A14; (h) XRD result of alloy #A14

Figure 3 EPMA images and XRD results of 400°C-annealed alloys containing three phases after quenching: (a) microstructure of alloy #A15; (b) XRD result of alloy #A15; (c) microstructure of alloy #A23; (d) XRD result of alloy #A23; (e) microstructure of alloy #A27; (f) XRD result of alloy #A27; (g) microstructure of alloy #A30; (h) XRD result of alloy #A30

Figure 4 EPMA images and XRD results of 400°C-annealed alloys containing three phases after quenching: (a) microstructure of alloy #A6; (b) XRD result of alloy #A6; (c) microstructure of alloy #A31; (d) XRD result of alloy #A31

Figure 5 EPMA images and XRD results of 400°C-annealed alloys containing three phases after quenching: (a) microstructure of alloy #A20; (b) XRD result of alloy #A20; (c) microstructure of alloy #A21; (d) XRD result of alloy #A21; (e) microstructure of alloy #A25; (f) XRD result of alloy #A25; (g) microstructure of alloy #A26; (h) XRD result of alloy #A26

Figure 6 EPMA images and XRD results of 400°C-annealed alloys containing two phases after quenching: (a) microstructure of alloy #A22; (b) XRD result of alloy #A22; (c) microstructure of alloy #A28; (d) XRD result of alloy #A28; (e) microstructure of alloy #A33; (f) XRD result of alloy #A33

Figure 7 EPMA images and XRD results of 400°C-annealed alloys containing two phases after quenching: (a) microstructure of alloy #A11; (b) XRD result of alloy #A11; (c) microstructure of alloy #A29; (d) XRD result of alloy #A29; (e) microstructure of alloy #A34; (f) XRD result of alloy #A34

Figure 8 Isothermal section of Al–Co–Er system at 400°C

Figure 9 EPMA images and XRD results of 600°C-annealed alloys containing two phases after quenching: (a) microstructure of alloy #B5; (b) XRD result of alloy #B5; (c) microstructure of alloy #B14; (d) XRD result of alloy #B14; (e) microstructure of alloy #B17; (f) XRD result of alloy #B17

Figure 10 EPMA images and XRD results of 600°C-annealed alloys containing two phases after quenching: (a) microstructure of alloy #B21; (b) XRD result of alloy #B21; (c) microstructure of alloy #B24; (d) XRD result of alloy #B24

Figure 11 EPMA images and XRD results of 600°C-annealed alloys containing two phases after quenching: (a) microstructure of alloy #B25; (b) XRD result of alloy #B25; (c) microstructure of alloy #B27; (d) XRD result of alloy #B27; (e) microstructure of alloy #B30; (f) XRD result of alloy #B30

Figure 12 EPMA images and XRD results of 600°C-annealed alloys containing two phases after quenching: (a) microstructure of alloy #B22; (b) XRD result of alloy #B22; (c) microstructure of alloy #B28; (d) XRD result of alloy #B28; (e) microstructure of alloy #B34; (f) XRD result of alloy #B34

Figure 13 Isothermal section of Al–Co–Er system at 600°C
**Table captions**

**Table 1** The intermetallic compounds have been reported in literature for the Al-Co-Er system along with crystal structure data

**Table 2** Equilibrium compositions at 400°C measured with EPMA method

**Table 3** Equilibrium compositions at 600°C measured with EPMA method